2022, Instituto Mexicano de Tecnología del Agua

DOI: 10.24850/j-tyca-2022-02-10

Notes

Water stable isotopes (δ^2H and $\delta^{18}O$) in the Yucatán Peninsula, Mexico

Isótopos estables del agua (δ^2H y $\delta^{18}O$) en la península de Yucatán, México

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Abstract

The hydrogen and oxygen isotopic composition of water is a very important tool to estimate water balance, groundwater recharge, and evaporation. Stable water isotopes integrated with hydrogeological and dating tools have been used to increase our understanding of the distribution and amounts of renewable and non-renewable groundwater. Isotopic data from precipitation and groundwater are widely available in Mexico, though there is little information on the Yucatan Peninsula, an area heavily relying on groundwater for which current estimates of groundwater availability are uncertain. In this paper, we compiled published and unpublished δ^{2}H and δ^{18}O data on precipitation as well as ground- and soil waters to obtain a regional meteoric water line (RMWL) at the Peninsula level, expressed by the equation $\delta^{2}H = 8.18\ \delta^{18}O + 10.29$ The current data set suggests that precipitation originates in convective systems, low-pressure events, frontal events, and re-cycled moisture. The evaporation lines from groundwater isotope data suggest a mix of water with different isotopic compositions, but also provide clues to recent rapid recharge from precipitation, likely from rain events of great intensity. We present a groundwater isoscape of the Yucatan Peninsula and finally address the potential use of isotope data for groundwater management.

Keywords: Meteoric water, groundwater, isotopes, isoscape.

Resumen

La composición isotópica del agua (hidrógeno y oxígeno) es una herramienta muy útil para estimar balances hídricos, recarga de agua subterránea y evaporación. Los isótopos estables del agua en conjunto con herramientas hidrogeológicas y de datación, se han utilizado para aumentar nuestro conocimiento de la distribución y la cantidad de agua subterránea renovable y no renovable. La composición isotópica de la precipitación y el agua subterránea están disponibles en algunas partes de México, aunque hay poca información de la Península de Yucatán, un área que depende casi por completo del agua subterránea; para la cual, la estimación actual de disponibilidad de agua subterránea es incierta. En esta nota, recopilamos los datos publicados y no publicados de δ^2H y $\delta^{18}O$ en el agua meteórica (la precipitación), así como aguas subterráneas y del suelo, para obtener una línea de agua meteórica regional (LAMR) a escala peninsular, expresada por la ecuación $\delta^2H = 8.18\ \delta^{18}O + 10.29$. Los datos que se tienen actualmente sugieren que la precipitación pluvial se origina en sistemas de convección, eventos de baja presión, de humedad de eventos frontales y humedad condensada. Las líneas de evaporación del agua subterránea sugieren mezcla de agua con diferente composición isotópica, pero también proporcionan información sobre rápida recarga del agua meteórica, probablemente debido a eventos de lluvia de gran intensidad. Presentamos un paisaje isotópico de aguas subterráneas de la Península de Yucatán y finalmente abordamos el potencial uso de datos isotópicos para el manejo de las aguas subterráneas.

Palabras clave: agua meteórica, agua subterránea, isótopos, paisaje isotópico.

Received: 06/07/2020

Accepted: 01/04/2021

Introduction

Environmental (or stable) isotopic ratios of water, $\delta^{18}O$ and $\delta\ ^{2}H$ (or δD, standard notation for deuterium) have been used to identify the origin of groundwater, water balances, geochemical reactions, soil-water-plant-atmosphere interactions (Clark & Fritz, 1997; Gat, 2010). One of the tools most recurrently used for estimating water budgets and groundwater recharge is the isotopic composition (both, stable and tritium) of meteoric water, *i.e.*, water from precipitation. The most common representation of the isotopic composition of meteoric water and related water vapor is a dual-isotope plot ($\delta^{18}O$ versus $\delta^{2}H$) that reveals the Global Meteoric Water Line (GMWL). Derived from the plot, the *d-excess* coefficient helps to identify the most probable conditions at which vapor is formed; thus, deviations from the GMWL are controlled by evaporation or condensation at different temperatures (Mook, 2002), non-equilibrium evaporation (Clark & Aravena, 2005), or re-evaporated precipitation (Peng *et al*., 2010). At different scales, Regional Meteoric Water Line (RMWL) or Local Meteoric Water Lines (LMWL) are particularly useful to define the range of input parameters (e.g., precipitation) and to estimate infiltration and recharge.

Isotopes are essential to building an improved understanding of the spatial distribution and amounts of non-renewable or fossil groundwater (Kendall & Doctor, 2003). At present, there is a significant amount of isotope data from aquifers worldwide, which has aided in developing continental-scale assessments of water resources (Aggarwal, Froehlich, Gonfiantini, & Gat, 2005). In Mexico, studies of precipitation and groundwater isotopes have been carried out in the central area of the country (Cortes & Farvolden, 1989; Cortés, Durazo, & Farvolden, 1997; Edmunds, Carrillo-Rivera, & Cardona, 2002; Peñuela-Arévalo & Carrillo-Rivera, 2013). However, there is little information regarding the isotopic composition of water in the Yucatan Peninsula (YP). Most of the isotopic data has been obtained from sinkholes, locally known as cenotes and representing the free aquifer exposed to the surface (Socki, Perry, & Romanek, 2002; Wassenaar, Van-Wilgenburg, Larson, & Hobson, 2009; Haukebo, 2014; Lases-Fernandez, Medina-Elizalde, Burns, & DeCesare, 2019); lakes (Curtis, Hodell, & Brenner, 1996; Pérez *et al*., 2011; Hodell *et al*., 2012), and coastal lagoons. Some studies have used isotopic data to assess groundwater recharge and residence time (Marín *et al*., 1990; Perry, Vazquez-Oliman, & Socki, 2003). Wassennar *et al*. (2009) generated nationwide groundwater isoscapes. An isoscape, *i.e*., an isotopic landscape, is a representation of the spatial-temporal distribution of isotopes in any environmental compartment (Bowen, 2010). Recently, the isotopic composition of rainwater and a local meteoric water line has been obtained for the northern area of Quintana Roo (Lases-Fernández *et al*., 2019). However, further sampling is required to improve water budgets in regions where groundwater is the primary source and whose water balance has neither been verified nor calibrated. Regarding sap isotopic data (mostly water transpired by trees), there are few studies presenting soil water as a possible source of the water transpired by plants (Hasselquist, Allen, & Santiago, 2010; Estrada-Medina, Santiago, Graham, Allen, & Jiménez-Osornio, 2013). However, there is no evidence of tree roots tapping the aquifer, a situation previously observed in groundwater-dependent ecosystems with an identified dry season (Barbeta & Peñuelas, 2017).

Objectives

Our objective is to contribute to the state of the art of meteoric water isotopes that will assist hydrogeological, ecohydrological,

paleoclimatic, physiological, or other sorts of research, not only in Mexico but also in the Great Caribbean and other locations with similar geographic and climatic conditions. In this paper, we compile available published information, together with unpublished data on stable isotopes of water (^{2}H and ^{18}O) from four hydrosphere reservoirs (precipitation, groundwater, lakes, and coastal lagoons) of potential use in water and environmental management. A preliminary interpretation of this information is attempted to provide a baseline and infrastructure for further research: a Peninsular Meteoric Water Line (YPMWL) and evaporation lines for groundwater are elaborated. Finally, we aim at opening a discussion on the potential uses of stable isotope information in groundwater management.

Methods

Isotopic data on the Yucatan Peninsula

We data-mined published papers, dissertations, proceedings, databases, websites, and unpublished data on oxygen and hydrogen isotopes of water (δ^2H and $\delta^{18}O$) in the three Mexican States comprised in the YP: Campeche, Quintana Roo, and Yucatan (Figure 1). Data mining was conducted using the search engines Google Scholar, Scopus, Internet Archive, Web of Science, Scielo, Redalyc, and the "Virtual Library and Catalogue" at www.cicy.mx/biblioteca/biblioteca-virtual using the search terms *Isotopes*, *Water* (as well as their Spanish language equivalents, namely: *Isótopos*, *Agua*), *Campeche, Quintana Roo* and *Yucatan*. Boolean operators (AND, OR) were used to connect keywords appropriately. A total of 17 publications were identified with quality data on the required characteristics. We acknowledge that there might be uncertainty in the data because they are coming from different laboratories. The oldest available data (Covich & Stuiver, 1974) does not report analytical precision, whereas most of the other sources include precision or estimated error. We focused on water isotopes only and did not include data on sediments, shells, or other compartments. All data were organized following the template of the Global Network for Isotopes in Precipitation, GNIP. We included all the available information: location (state), geographic coordinates (decimal degree), author or authors, type of water reported (precipitation, groundwater, seawater, and surface water: lake), date (month-year) $\delta^{18}O$, $\delta^{2}H$, *d*-excess, altitude (meters above sea level), aquifer, historical annual precipitation (in mm), soil type, hydrogeological sub-region, geology (type and class) and analysis providers (*Supplementary Material 1*). Due to the characteristics of the aquifers systems in the YP, hereby groundwater is considered as the expression of the free aquifer, either exposed to the atmosphere (open sinkholes) or not exposed to the atmosphere, such as water wells, covered sinkholes, inundated caverns or dissolution channels, among the most important. Likewise, the lakes included in this paper are also the expression of the free aquifer open to the land surface due to karstification processes. Unfortunately, most of the data compiled for groundwater did not include information about sampling depth.

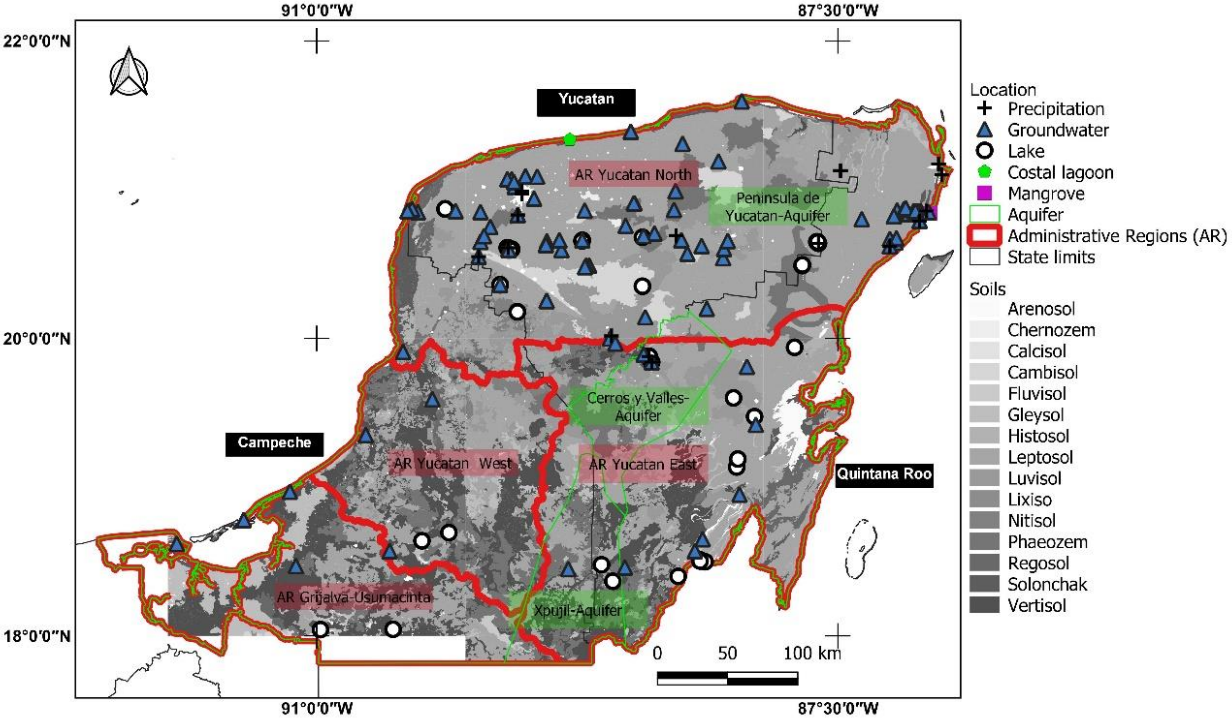


Figure 1. Locations in the Yucatan Peninsula with isotopic data (δ^{2}H and/or δ^{18}O) on precipitation, **groundwater**, and surface water: lakes and coastal lagoons. State boundaries, hydrological administrative regions (AR), aquifers, and soils are also shown.

Isotopic data from precipitation waters were used to create the YPMWL with data from locations in the YP (north of latitude 20° N). Data on groundwater, seawater, coastal lagoons, and lakes were included in the RMWL for comparison purposes. We provide three evaporation lines for groundwater ($\delta^{18}O$ *versus* $\delta^{2}H$), considering the political division by states (*Supplementary Material 2*). For cases in which only $\delta^{18}O$ was reported, we used linear interpolation from evaporation lines per state to obtain the "theoretical" $\delta^{2}H$ data (representing 7 % of the $\delta^{2}H$ data). In spite of the limitations, this approach has been previously used when direct measurements are not possible (Gibson, Prepas, & McEachern, 2002).

The dominant climates in the YP are warm, dry climate with annual mean temperatures from 24 to 28 °C and wide variations in total annual precipitation (from 400 to 2 000 mm; INEGI, 2018). The Yucatan Peninsula has three seasons: a) winter cold season (*nortes*) with rain from frontal events (transition zone between two air masses) from September to January, with a short period of storms and northerly winds; b) dry season from the end of February until the end of May, with occasional rains derived from moist convection (vertical transport of moisture in the atmosphere); and c) summer rainy season, from

June to early October with rain largely originating in low-pressure systems (tropical cyclones) (Carrillo, Palacios-Hernández, Ramírez, & Morales-Vela, 2009; De-la-Barreda, Metcalfe, & Boyd, 2020).

Geographic Information System

The data were processed, and maps were produced using free software QGIS 3.8. For the isoscape map, contour lines of $\delta^{18}O$ and $\delta^{2}H$ were obtained by interpolating the data collected for this study. We did not use data deeper than 30 m below ground level (Socki *et al*., 2002); thereby, the isoscape represents the phreatic level as surface exposure of groundwater in lakes and sinkholes, and depth at screened wells. The Inverse Distance Weighted (IDW) method was applied to the database to obtain an interpolation, subsequently, the contour lines were generated, isolines were given a basic smoothing technique

(Smoothing Via Iterative Averaging, SIA) (Mansouryar & Hedayati, 2012). Equidistant intervals were used at the standard precision of the analytical techniques, usually ±2.0 ‰ for δ^2H and ± 0,2 ‰ for $\delta^{18}O$.

Results and discussion

The data in this paper account for precipitation (*n* = 130), groundwater (*n* = 213), and lakes and coastal lagoons (*n* = 128); lakes distinguished from groundwater as waterbodies representing the phreatic level but exposed to intense evaporation. One of the main observations is that the geographic distribution of the data is not spatially homogeneous; 51 % of the data corresponds to the state of Quintana Roo and 46 % to the state of Yucatan; the state of Campeche has had little sampling effort so far (Figure 1). The focus of research on water isotopes has been mainly on groundwater (44 %), whereas precipitation (27 %) and lakes (27 %) have been less sampled and analyzed. Table 1 summarises the main characteristics of the isotopic data compiled (*n*, locations, references, dates of sampling, water types, aquifers, administrative regions, altitude, and $\delta^{18}O$ – $\delta^{2}H$ providers).

Table 1. Summary of the main characteristics of the isotopic data compiled in the Yucatan Peninsula, Mexico.

Category	**Descriptor**
States	3[a]
Data points (locations)	170[a]
Data sources (references)	17
Range of dates	Aug 1973 – Aug 2018
Aquifers	3[a]
Administrative regions	4[a]
Altitude (m.a.s.l.)	0 – 210
Isotopic composition of water (‰) [b]	

Precipitation $\delta^{18}O$ (n = 128)	-2.74 (-9.7, 0.83)
Precipitation $\delta^{2}H$ (n = 124)	-11.36 (-67, 17.33)
Groundwater $\delta^{18}O$ (n = 213)	-3.19 (-8.82, 6.81)
Groundwater $\delta^{2}H$ (n = 199)	-18.66 (-58.52, 28.17)
Seawater $\delta^{18}O$ (n = 7)	0.77 (-0.3, 1.3)
Seawater $\delta^{2}H$ (n = 7)	7.56 (-4.1, 14.0)
Coastal lagoon $\delta^{18}O$ (n = 2)	2.1 (1, 3.2)
Coastal lagoon $\delta^{2}H$ (n = 2)	5.39 (-0.29, 11.07)
Lake $\delta^{18}O$ (n = 126)	1.8 (-5.4, 5.82)
Lake $\delta^{2}H$ (n = 110) [c]	4.69 (-39, 23.21)
Mangrove $\delta^{18}O$ (n = 1)	6.1
Mangrove $\delta^{2}H$ (n = 1)	29.2
$\delta^{18}O$ – $\delta^{2}H$ analysis providers	11[d]

[a] See Figure 1.

[b] Isotopic data are in per mil (‰) mean, minimum and maximum.

[c] Missing δ^2H data interpolated from evaporation lines. See *Supplementary Material 2*.

[d] ARES Division, Johnson Space Center; Atomic Energy Commission Contract AT (30-1)3204; Auburn, Alabama (ANIMAL); Department of Geological Sciences, University of Florida; Geoscience Mass-Amherst; Instituto Mexicano de Tecnología del Agua; National Geophysical Data Center, Boulder – Colorado; Stable Isotope Facility of the University of California at Davis; Stable Isotope Laboratory Environment Canada; Texas A&M Galveston; Yale University.

The uneven distribution of sampling efforts is due to two particular situations. First, the isotopic data compiled in this paper were collected for a variety of scientific purposes, whose endeavors have focused on geochemical and paleoclimate studies, which use sediments; this way, the lake water was collected in single sampling events. Second, groundwater volume extraction is different among the three states due to different population and economical activities. Sampling efforts have been focused on regions where a drop in the water table is probable and water quality needs to be frequently measured. The state of Yucatan accounts for 46 % of the extracted volume, whereas Campeche and Quintana Roo extract around 28 % and 26 %, respectively (Rios-Ponce, Acosta-Gonzalez, & Cejudo, 2020). Groundwater sampling in Campeche has not been as intensive as in other regions.

Peninsular Meteoric Water Line

The available isotopic data on precipitation (n = 130) allowed us to create a Peninsular meteoric line YPMWL (Figure 2), Equation (1) (r^2 = 0.9413):

$$\delta^2 H = 8.18\, \delta^{18} O + 10.29 \tag{1}$$

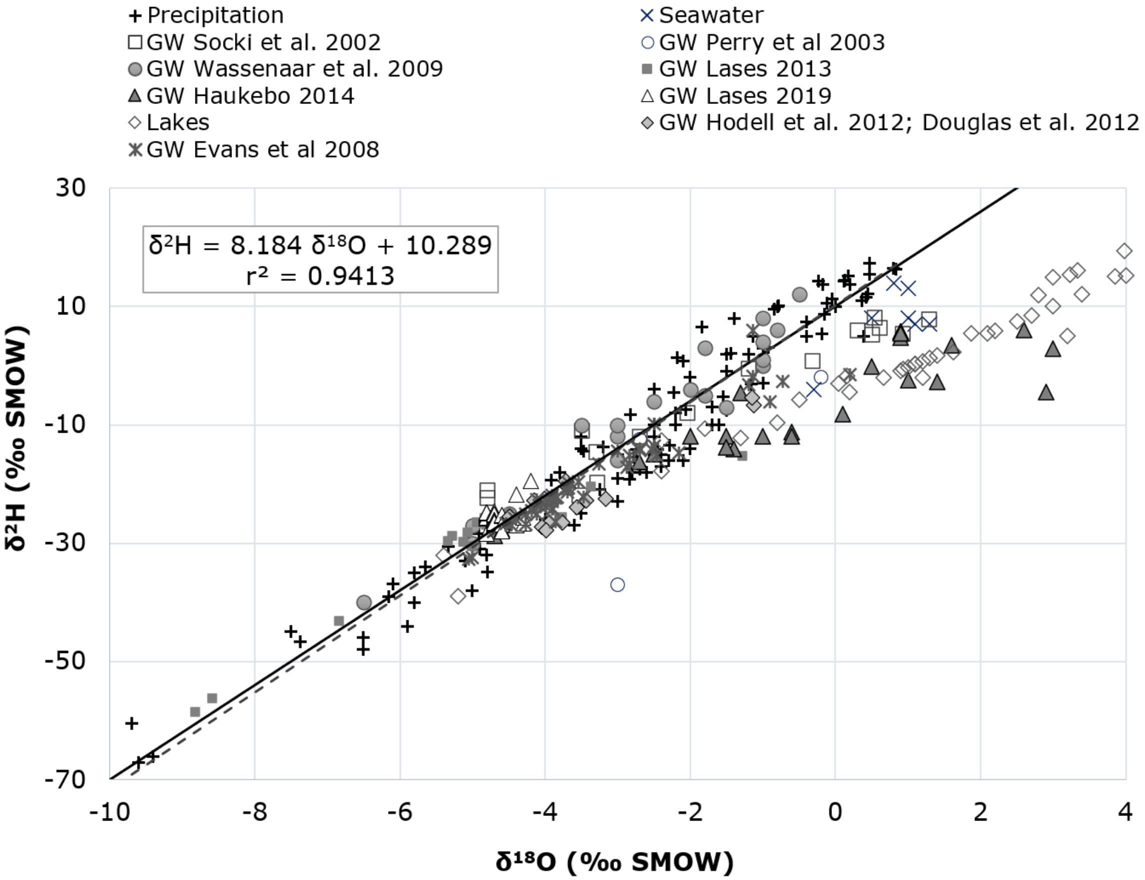


Figure 2. Peninsular meteoric water line (dashed line). A solid black line represents the GMWL. Seawater, lakes, and groundwater isotopic

composition in the Yucatan Peninsula. Data are available in Supplementary Material 1.

Our YPMWL compares very well with the local meteoric water line for the northeast coast of Quintana Roo (20° 35.2′, -87° 8.04′) determined by Lases-Fernandez *et al*. (2019) ($\delta^2H = 8.17\ \delta^{18}O + 11.698$) with no difference in the slopes ($t = -0.34$, $p = 0.37$). Although both match well, we propose to use Equation (1) as the YPMWL given that it includes sampling points from other longitudes. We stress the regional demarcation because the majority of the data compiled in this paper represents locations northern than latitude 20 °N. There are very few data points representing the central-south area of the territory (see Figure 1).

The $\delta^{18}O$ distribution of the data (from 0.83 to -9.7 ‰) represents seasonal variability and meteorological conditions in which the precipitation formed. Lower $\delta^{18}O$ values (and lower δ^2H values) correspond to the largest rainouts of the air mass, observed as depletion of the heavier isotope (^{18}O) (and ^2H) in rain in both summer and winter (Rozanski, Araguás-Araguás, & Gonfiantini, 1993) Tropical storms also deliver rain that is ^{18}O depleted in comparison with regular precipitation (Lawrence & Gedzelman, 1996; Perry *et al*., 2003).

It is assumed that data with *d*-excess close to the global average (10 ‰, Figure 3) represent evaporation from the average source (*i.e.*, oceanic water) at 25 °C of seawater temperature and relative humidity of 80 % (Dansgaard, 1964; Merlivat & Jouzel, 1979) *d*-excess lower than 10 ‰ could be from convective systems, low-pressure precipitation events, evaporation below the cloud effects, or mixing with seawater in coastal areas affected by the marine intrusion (Guan, Zhang, Skrzypek, Sun, & Xu, 2013); whereas *d*-excess higher than 10 ‰ might represent precipitation from air that has undergone more than one condensation, moisture from frontal events (Clark & Fritz, 1997; Guan *et al*., 2013), or recycled moisture (Wassenaar *et al*., 2009).

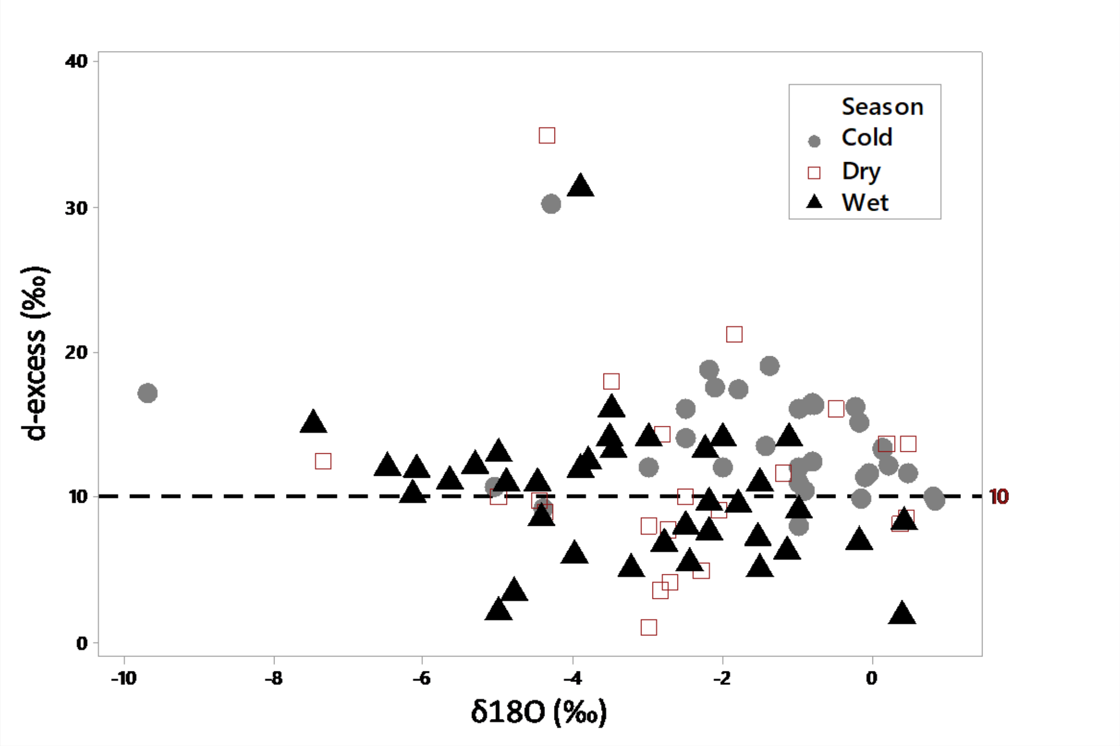


Figure 3. *d*-excess plot considering the three representative seasons in the Yucatan Peninsula. The cold season is from November to February; the dry season is from March to May; the wet season is from June to October.

In the YP convective rains occur not only in the dry season, but they can also occur through the year, resulting in depleted ^{18}O and ^{2}H; cold front events, common from November to March, would result in *d*-excess higher than 10‰. The wide distribution of *d*-excess in the wet season (July to October) and the increase in isotope deltas at different times of the year can be attributed to the entrance of different air masses with variable moisture (Li *et al*., 2015).

Following the grouping proposed by Dansgaard (1964) with the IAEA-WMO precipitation survey stations, the difference between $\delta^{2}H$ in summer and winter months (δs-δw = -3.56 ‰) suggest that the north of the YP would be part of the continental stations at low latitude. Under some circumstances, evaporation from falling droplets would modify the trend of the line, which then might resemble evaporation lines of surface waters (Gat, 2010). Occasionally, meteoric water lines join separate clusters of data or rain events associated with air masses of different origins; under such circumstances, the best-fit line for the data might not be completely accurate (Gat, 2010; Li *et al*., 2015). With the information available, the YPMWL represents a region with similar climatic conditions and it is similar in slope to GMWL. However, its validity is still spatially limited (Gat, 2005). We do not fully explore the amount effect because the amount of precipitation *in situ* was not systematically recorded, or it was not measured close to the sampling point. When exploring the altitude effect in a north-to-south cross-section, we neither observe nor suggest a trend for $\delta^{18}O$ at elevations higher than 100 m.a.s.l. because the current isotopic data represents only an area with low relief. Perhaps sampling the longest N-S cross-section, including the highest altitudes in the Peninsula (≈ 120 m in the Ticul range and ≈220 m in the south), might yield a trend as the one observed in northern Central America (Lachniet & Patterson, 2009).

Groundwater

Groundwater has been slightly more intensively sampled and most of the reports account for single samples analyzed for specific purposes.

The reduced amount of isotopic data on groundwater limits the possibility of hypothesizing about preferential summer or winter recharge; however, since the region has a seasonal precipitation pattern, we believe that the greatest recharge occurs in the rainy season. In northern Yucatan, we have observed a drop in the phreatic level around 1.5 m in the dry season and a corresponding increase in the rainy season. A large part of the dataset corresponds to the region called the ring of sinkholes (the north-western portion of the YP), which has been well characterized: as a semi-circular system of faults with high permeability, high hydraulic conductivity, reduced storage capacity, and seasonal response to precipitation measured in the water table (Marín *et al*., 1990; Perry, Velazquez-Oliman, & Marín, 2002). Considering these features, it is reasonable to think that in this area groundwater would retain the isotopic signature of precipitation. Few studies have been designed for systematic groundwater measurement. For instance, in a study in the area around San José Tzal, Yucatan (20.83° N, -89.650° W), both precipitation samples and rainfall amount data were collected simultaneously (May 2007 to April 2008). In this case, an artesian well was specifically drilled to collect groundwater samples. The observed groundwater isotope composition is like precipitation in the first half of the year when sampling was carried out in both reservoirs (unpublished data, Figure 4). With the limited data set, this trend only hints that in such year the groundwater retained the meteoric isotopic signature, which might be due to fast water travel time after precipitation (Hamdan, Wiegand, Toll, & Sauter, 2016) or its fast infiltration (Uugulu & Wanke, 2020).

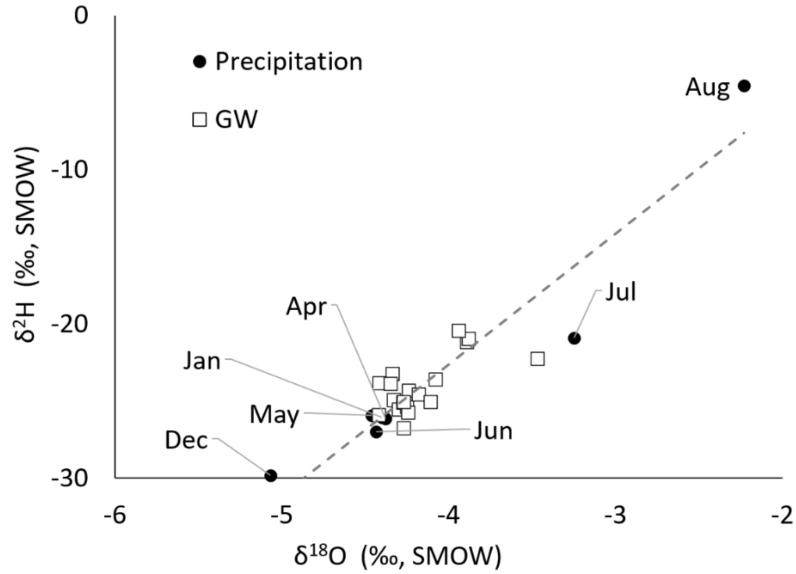


Figure 4. Isotopic composition of precipitation (circles) and groundwater (squares) in San José Tzal (NW of the Yucatan Peninsula). The dashed line represents the Local Meteoric Water Line for the location. Data from May 2007 to April 2008.

After precipitation, the passing of meteoric water through the surface and vadose zone entails partial evaporation in open surfaces or the soil column (Gat, 2010). A large number of the groundwater samples collected in the three states of YP does not follow the YPMWL, partly because its spatial representation is reduced (most groundwater samples are north of 20° N), in addition to highly probable evaporative effects due to hydrogeological features, type of soils, geomorphology and presence of open water bodies, among others. Previous research works have addressed the hydrogeology of the YP identifying fast infiltration, facilitated flow in faults, fractures, and dissolution conduits and few well-recognized groundwaters divide (Steinich, Olimán, Marín, & Perry, 1996; Perry *et al*., 2002; Bauer-Gottwein *et al*., 2011; Andrade-Gomez, Rebolledo-Vieyra, Andrade, López, & Estrada-Contreras, 2019). There are several types of soils in the YP, from

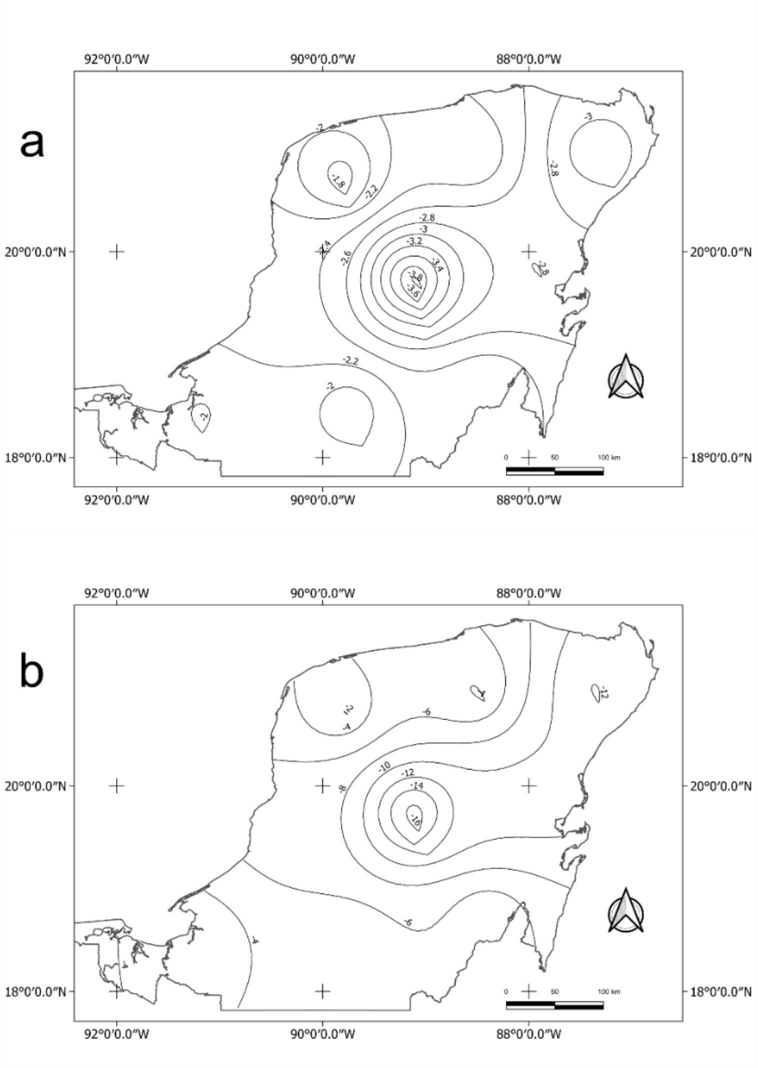
Leptosols and Cambisols in karstic plains, to Gleysols and Histosols in flooded areas. The first group of soils can be shallow with relatively high infiltration capacity, whereas hydric soils will retain pore water (Bautista, Palacio-Aponte, Quintana, & Zinck, 2011). The latter might be relevant in keeping pools or stagnant water on top of the soil, which may show a greater evaporation effect. Other factors, such as the existence of negative landforms, might be more important as water is retained for longer periods and evaporation could have stronger isotopic effects. Aguilar-Duarte *et al*. (2010) and Fragoso-Servon, Bautista, Frausto, and Pereira (2014) mentioned that the number and surface area covered by karstic depressions in the YP is significant and a large part of them stores water permanently or occasionally. These geomorphological features possibly enhance evaporation; thus, their effects in the isotopic signal of groundwater across the study region may contribute to the evaporation lines hereby presented (Figure 5).

Figure 5. Isotopic composition of groundwater relative to the Yucatan Peninsula Meteoric Waterline (YPMWL).

Considering groundwater as the long-term integrator of precipitation and infiltration, shifts in the groundwater samples down and to the right of the YPMWL suggest evaporation and mixing of water with different isotopic compositions. We observed a shallower slope for groundwater in Quintana Roo (4.6), whereas Yucatan and Campeche had greater slopes, 5.2 and 5.7, respectively. Following the common interpretation that evaporation yields lines with different slopes from the original source of water (Kendall & Caldwell, 1998), one could assume that evaporation in Quintana Roo occurs in less humid conditions than in the other states; however, the reduced data set for Campeche makes it very difficult to compare the three lines. In any case, the slopes of the three lines suggest that in the YP, infiltration occurs after evaporative loss (Clark & Fritz 1997; Wassenaar *et al*., 2009), considering that particular atmospheric conditions would yield differences in evaporated water that infiltrates deep into the aquifer. For instance, Benettin *et al*. (2018) reported numerical simulations of the isotopic composition of soil water that underwent evaporation under different seasonal scenarios and found that summer and winter evaporation lines had different slopes and that greater deviation from the YPMWL represents greater variability in evaporative fractionation.

Groundwater isoscape

Previous efforts (Wassenaar *et al*., 2009) representing the groundwater isoscape of the YP, considered that the isotope composition of groundwater is representative of precipitation because no great modifying effects have been identified in the groundwater. We present a more detailed isoscape with the information available (Figure 6), which likely includes processes such as isotope effects produced at the soil and groundwater and mixed masses of water with different isotopic compositions. Large portions of the data corresponding to the ring of sinkholes (more intensively studied than the southern region) have $\delta^{18}O$ values between 0 ‰ and -2 ‰ because those sinkholes are less exposed to the atmosphere. It is necessary to increase the amount of data on the southern portion of the Peninsula given the need for accurate estimates of water availability, differences between regional precipitation, and the complex patterns in which water infiltrates and flows in different areas of the Peninsula (Bauer-Gottwein *et al*., 2011; Sandoval-Montes & Heredia-Escobedo, 2018).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-12
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-16
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-4
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50
100 km

Figure 6. Groundwater isoscape of the Yucatan Peninsula: a) $\delta^{18}O$ and b) $\delta^{2}H$.

Tracing sources of water for and from plants

Water isotopes have been used to identify sources of water by specific plant species assuming there is not isotopic fractionation during plant water uptake (Dawson, Mambelli, Plamboeck, Templer, & Tu, 2002). With the aid of $\delta^{18}O$ values of groundwater and tree stem water (sap) samples, it has been found that perennial and deciduous trees in northern Yucatan (Querejeta, Estrada-Medina, Allen, Jiménez-Osornio, & Ruenes, 2006) and Quintana Roo (Hasselquist *et al*., 2010) overcome seasonal water limitations by alternatively using water from the aquifer or water stored in the vadose zone (the upper 2.5 m of the soil profile). In some cases, plants seem to take water from the unconsolidated rock (locally named sascab), which can hold up to 3 % of gravimetric water during the dry season (Estrada-Medina, Tuttle, Graham, Allen, & Jimenez-Osornio, 2010). The same approach was used by Querejeta, Estrada-Medina, Allen and Jiménez-Osornio (2007); Gu *et al*. (2015), and Carrière *et al*. (2019) to identify water sources and investigate water used by mature trees individuals. They all found that trees rely on water from the vadose zone (either shallow or deep), but some species probably penetrate deeper through pores, fractures, and cavities in the rock, reaching deeper sources of water. Estrada-Medina *et al*. (2013) also traced the sources of water utilized by two deciduous species (*Gimnopodyum floribundum* and *Piscidia piscipula*); they found that both species relied on the soil as their main source of water during the wet season. In the dry season, *P. piscipula* relies more on soil water, while *G. floribundum* relies more on water from bedrock. The evidence obtained from research in karstic areas and other environments suggests that plant transpiration relies more on soil moisture and water in the vadose zone rather than on groundwater (Cardella-Dammeyer, Schwinning, Schwartz, & Moore, 2016; Evaristo & McDonnell, 2017). In addition, the study on *P. piscipula* showed that $\delta^{18}O$ was different from that of the soil and bedrock during some precipitation events (November through February), suggesting that this species can take advantage of dew, at least over that season (Estrada-Medina *et al*., 2013). Thus, it is important to include soil water in isotopic studies, as it has not been included in ecohydrological studies as part of the groundwater–soil–plant–atmosphere interphase.

Stable isotopes for better groundwater management

We have not found dependable information regarding the amount of groundwater that can be sustainably removed (*sensu* Bierkens & Wada, 2019) and with the stable isotope information we currently have in hand, we are not able to meaningfully interpret data for site-specific estimates of groundwater availability, much less can we make regional estimates. When the availability of water is estimated only based on meteorological data within administrative boundaries, stable water isotopes may aid in generating better estimates and the delineation of appropriate hydrogeological boundaries. The existence of few isotopic data and the inherent difficulty of delimitating groundwater divide, recharge, and discharge areas in karstic landscapes, need to be strategically addressed. The disparity between the number of concessions and concessional volume (*i.e.*, groundwater extraction, Rios-Pounce *et al*., 2020), together with reduced precipitation under current climatic change predictions (Lyra *et al*., 2017), might pose additional hydric stress on areas with high population, agricultural activities as well as touristic destinations. We think that water isotopes may be of most help in the study area assisting to define the groundwater flow system, identifying recharge and discharge areas, and developing better water budgets when integrated with climate, hydrogeology, and accurate groundwater extraction.

Future research

Water stable isotopes provide valuable information to assess groundwater infiltration, recharge, instantaneous discharge, and residence time. The current lack of extensive water isotope data on the YP precludes us from fully understanding the groundwater situation of the region. One future approach may be sampling both precipitation and groundwater over a long N-S cross-section of the YP, including the highest altitudes in the Peninsula (~120 m in the Ticul range and ~220 m in the south). This strategy might yield a trend similar to the one observed in Northern Central America (Lachniet & Patterson, 2009) and will provide information about the altitudinal effect in areas with very low relief. Ideally, sampling points should be sites where phreatic levels are not greatly disturbed, as extraction might promote the movement of water from other areas. The specifics of a sampling transect such as this are difficult to define, namely, the appropriate number of sites and samples to achieve sufficient resolution. In an area with mild orography and an extensive coastal karstic aquifer, we consider it desirable to collect water samples on a short-term temporal distribution (*i.e.*, two hydrological years) on a grid-like pattern, given that the isotope composition of precipitation may be most helpful to understand local and regional hydrology and guide water management.

Presently, we are developing a more detailed meteoric water line of the YP, with systematically collected precipitation samples in 11 locations distributed across the states of Campeche (*n* = 4), Quintana Roo (*n* = 4), and Yucatan (*n* = 3). With those results, we will obtain several local meteoric water lines; all of them aiding to improve water balance and water budgets of the aquifers in this Administrative Region. However, it is necessary to perform preliminary estimates of water availability on each of the aquifers, and hydrological sub-basins as well, based on meteorological and isotopic data, evapotranspiration, natural discharge, concessional volumes, and considering provision for environmental flow for each one of the identified hydrogeological units. This approach will assist us on distinguishing regional water balances and differential water availability and identifying regions with current and future hydric stress. As groundwater is the only source of freshwater for human use, it is necessary to ensure the water required for all economic activities without risking the recharge; that is, keeping the balance.

Conclusions

We created and made available a database of published and unpublished water isotopic data as a baseline to analyze regional water dynamics in the Yucatan Peninsula. We produced a regional meteoric water line for the Peninsula which, due to lack of data, only represents north locations, 20° N and above. The observed distribution of $\delta^{18}O$ and *d*-excess represent the seasonal variability and meteorological conditions in which precipitation was collected, for instance, convective rains in the dry season, cold front events from November to March, and the passing of air masses with different moisture sources. Groundwater and its isotopic value have been more intensively studied and the information published so far suggests that groundwater isotope composition is a combination of fast recharge after precipitation, water mixture due to surface interception, and evaporation from lakes and sinkholes. Perennial and deciduous trees can use water from the vadose zone, from the aquifer, and even from the unconsolidated rock.

The current stable water isotope data provide only information from specific areas preventing a complete interpretation for the whole YP; thus, a more robust database is needed to make water planning and management at a regional scale.

Data availability

Data are available at http://dx.doi.org/10.17632/wnz7my6y5r.1

Acknowledgments

Conacyt Project CB286049 *(Línea de agua meteórica de la Península de Yucatán)* and Cátedras CONACYT Project 2944 (*Modelación del ciclo del agua en la Península de Yucatán*). Daniel Rios-Ponce helped with data analysis for concessional volumes. Eugene Perry provided important comments to the manuscript. Mark Brenner and Jason Curtis granted access to databases and provided helpful suggestions. J. Curtis proofread the manuscript. Anonymous reviewers made comments and suggestion improving the paper.

Annex 1

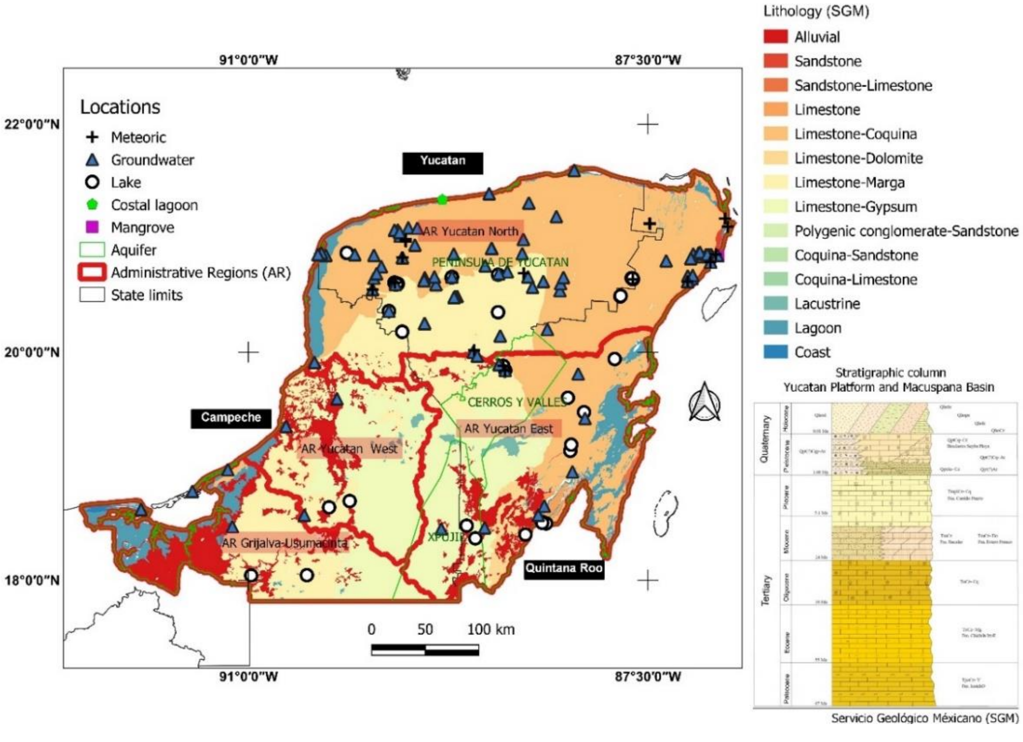

Figure 1S. Locations in the Yucatan Peninsula with isotopic data (δ^2H and/or $\delta^{18}O$). State boundaries, hydrological administrative regions (AR), aquifers, lithology (SGM, 2008) and stratigraphic column are also showed (SGM, 2005).

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