IDEAS EN CIENCIAS DE LA INGENIERÍA

Migración vertical de agua residual tratada inyectada en el acuífero salino de Playa del Carmen, Quintana Roo

Vertical migration of treated wastewater injected into the saline aquifer of Playa del Carmen, Quintana Roo

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Resumen

El acuífero que subyace la ciudad de Playa del Carmen Quintana Roo es la única fuente de agua potable. El acuífero se localiza en la costa de la Península de Yucatán, es no confinado y consiste de tres capas: agua dulce, mezcla y agua salada. La geología consiste de calizas kársticas fracturadas altamente permeables. Debido a las condiciones hidrogeológicas de la zona, el agua residual tratada se inyecta hacia la capa de agua salina que subyace el agua dulce, por medio de pozos. Debido al deterioro de la calidad del agua de algunos pozos y cenotes localizados cerca de las plantas de tratamiento de aguas residuales, se consideró necesario caracterizar los flujos del agua residual inyectada para determinar posibles interconexiones hidrogeológicas, entre los sitios de absorción del agua residual y el agua dulce contaminada. Se utilizaron métodos hidrogeoquímicos, trazadores químicos fluorescentes, e isotopos estables del agua, para determinar las posibles interconexiones. Los trazadores indicaron que el agua residual inyectada en las plantas de tratamiento, emerge en las zonas de agua dulce adyacentes a las plantas de tratamiento, así como en algunos cenotes. Los isótopos estables mostraron que el agua del pozo Ejidal, así como los cenotes Chano A, Chaak-Tun, Tulipanes, y Lindavista, contienen agua residual. Los perfiles verticales de temperatura y conductividad, mostraron que el agua residual no permanece en el estrato salino donde se inyectó, sino que asciende hasta el estrato de agua dulce. Este estudio de caso reveló que el sistema de eliminación de aguas residuales que se utiliza actualmente de forma generalizada en la península de Yucatán, podría contaminar el acuífero de agua dulce y en última instancia,

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la zona costera. **Palabras clave:** *agua residual, migración vertical, contaminación de acuífero, métodos hidrogeoquímicos, isótopos estables del agua*

ABSTRACT

The aquifer that underlies the city of Playa del Carmen Quintana Roo is the only source of drinking water. The aquifer is located in the Caribbean coast of the Yucatan Peninsula. It is unconfined and consists of three layers: freshwater, mixing layer, and saline water. The geology consists of highly permeable fractured karstic limestones. Due to the hydrogeological conditions of the area, treated wastewater is injected into the deep saline layer below the freshwater lens through sewage disposal wells. Due to the deterioration of the water quality of some wells and cenotes (sinkholes) located near the city's wastewater treatment plants, it was considered necessary to characterize the flow patterns of the wastewater injected to determine possible hydrogeological interconnections between the wastewater absorption sites and the freshwater resources contaminated. Hydrogeochemical methods, stable isotopes of water, and fluorescent chemical tracers were used to investigate the possible interaction. The fluorescent tracer tests indicated that the wastewater injected in the disposal wells of the treatment plants emerges in the freshwater zone adjacent to the plants, as well as in some sinkholes. The application of stable isotopes showed that the Colonia Ejidal well, as well as the Chano A, Chaak-Tun, Tulipanes, and Lindavista sinkholes, contain water that is a mixture of rainwater and wastewater. The vertical conductivity and temperature profiles showed that the wastewater does not remain in the deep brackish water stratum where it was injected, but rises to the freshwater lens. This case study revealed that wastewater disposal system currently in widespread use in the Yucatán Peninsula could contaminate the overlying freshwater aquifer, and eventually the coastal zone.

Keywords: *sewage, vertical migration, aquifer contamination, hydrogeochemical methods, stable water isotopes*

INTRODUCTION

The city of Playa del Carmen Quintana Roo is located in the Caribbean coast of the Yucatan Peninsula. The city is a rapidly growing tourism and recreational area, whose population increased from 10,000 habitants in 1996 to 304,942 in 2020 [1, 2]. The study area is located between the coordinates 20°44' 50.40"N; 87°16'41.33"W and 20°42' 33.26"N, 87°00' 48.36"W (Figure 1).

The aquifer that underlies the city of Playa del Carmen is the only source of fresh water to provide drinking water to the population. The aquifer is unconfined and consists of three zones: the freshwater zone, the mixing zone, and the saline water zone [3, 4]. A high water-table, around 8 meters below the surface, is due to the aquifer's high porosity and flat topography [5]. Groundwater flows through a range of scales, from small-scale fractures up to large fault-fractured zones and caves [6]. The geology consists of highly-permeable karst limestone deposits that allow rapid infiltration of microbial and chemical contaminants to the subsurface [3]. In fact, the presence of pathogens in the groundwater of the Yucatan Peninsula causes gastrointestinal diseases that result in a high percentage of deaths of children under six years old [7]. Likewise, domestic wastewater compounds including stimulants (caffeine and cotinine), prescription drugs and illicit drugs (cocaine) were detected in passive samplers deployed in cave systems near Playa del Carmen [8], and coastal lagoons of the Yucatán Peninsula [9].

Waste disposal wells (injections wells) and septic tanks are the principal methods of wastewater disposal in the Yucatan Peninsula. Mexican Official Standard NOM-001-Semarnat-2021, which regulates the permissible limits of contaminants in wastewater discharges to the subsoil, authorizes drinking water service providers - who are also responsible for sanitation - to inject processed water from secondary treatment into the aquifer. Due to a highly permeable fractured karstic limestone and a thin soil layer, the subsurface does not filter out microbial and chemical contaminants of untreated wastewater, allowing direct infiltration into the aquifer [10–12]. The typical septic tank design only retains solids, and provides for retention times of only a few hours [13]. There is evidence that such disposal practices are contaminating the groundwater with fecal coliforms and nitrate [3, 14, 15]. Persistent organic pollutants (POPs), which are toxic chemicals that bio-accumulate in aquatic and terrestrial species, have recently been documented in cenotes of the Yucatan Peninsula [16]. Likewise, Fecal coliforms and *E. coli* were detected recently in cenotes along the Playa del Carmen-Tulum corridor [17].

The reefs of the coast of Quintana Roo are part of the Mesoamerican Reef System, which spans approximately 1,000 km from Mexico to Honduras. Recent studies document [18–20] that the reef sites with the highest degree of degradation are those bordering cities with high housing density, in the tourist corridor from Cancun to Tulum.

In the Yucatan Peninsula there are 6,756 wastewater discharge permits issued by CONAGUA covering a total volume of 956.25 million cubic meters [21, 22]. Of this volume, 68 % corresponds to service use, another 16.5 % to industrial use, 10 % to urban public use, 3.6 % to aquaculture use and 0.67 % to livestock use [21, 22]. Municipal wastewater treatment plants discharge 97.76 Mm^3/year through 163 injection wells [21, 22]. There are 15 injection wells located in the municipality of Solidaridad, where Playa del Carmen is settled [21, 22]. The total volume of injection in the municipality of Solidaridad, authorized by CONAGUA is 13.8 Mm^3/year [21, 22]. Wastewater treated at the Playa de Carmen WWTP (Waste Water Treatment Plant) is injected into a sewage disposal well. Another injection well is used to inject untreated wastewater in excess of the WWTP capacity. Both wells inject the wastewater into the saline water layer.

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Geophysical studies carried out in the city of Playa del Carmen reveal three resistivity layers (U1, U2, U3) [23]. The U1 layer extends from the surface to a depth of approximately 25 meters. It is composed of reef limestones and calcareous sandstone, with abundant fractures and cavities. It contains a freshwater aquifer. The U2 layer is composed of limestones, with abundant fractures and cavities produced by high karst development. The fractures and cavities are saturated with seawater. This layer constitutes what is considered the saline aquifer and is approximately 45 meters thick. The U3 layer is composed of hard limestones with high resistivity and little karst development. The layer extends from 70 m up to 110 m. It represents a hydrogeological basement. There is no impermeable layer between the U1 layer (freshwater aquifer) and the underlying U2 layer (saline aquifer).

Due to the deterioration of the water quality of some wells and cenotes (sinkholes) located near the city's wastewater treatment plants, it was considered necessary to characterize the flow patterns of the wastewater injected in the plants to determine possible hydrogeological interconnection between the wastewater absorption sites and the freshwater resources contaminated. Hydrogeochemical methods, hydrogen and oxygen isotopes of water, and fluorescent chemical tracers were used to investigate the possible interaction.

Methods

Aquifer monitoring network

An aquifer monitoring network was designed, considering the infrastructure installed in the portion between the city´s landfill and the coastline. This monitoring network allowed the collection of water samples to evaluate the isotopic composition and quality of the groundwater, observe the presence of artificially added fluorescent tracers, and elaborate piezometric levels. The wells integrating the network are shown in Table 1 and Figure 1.

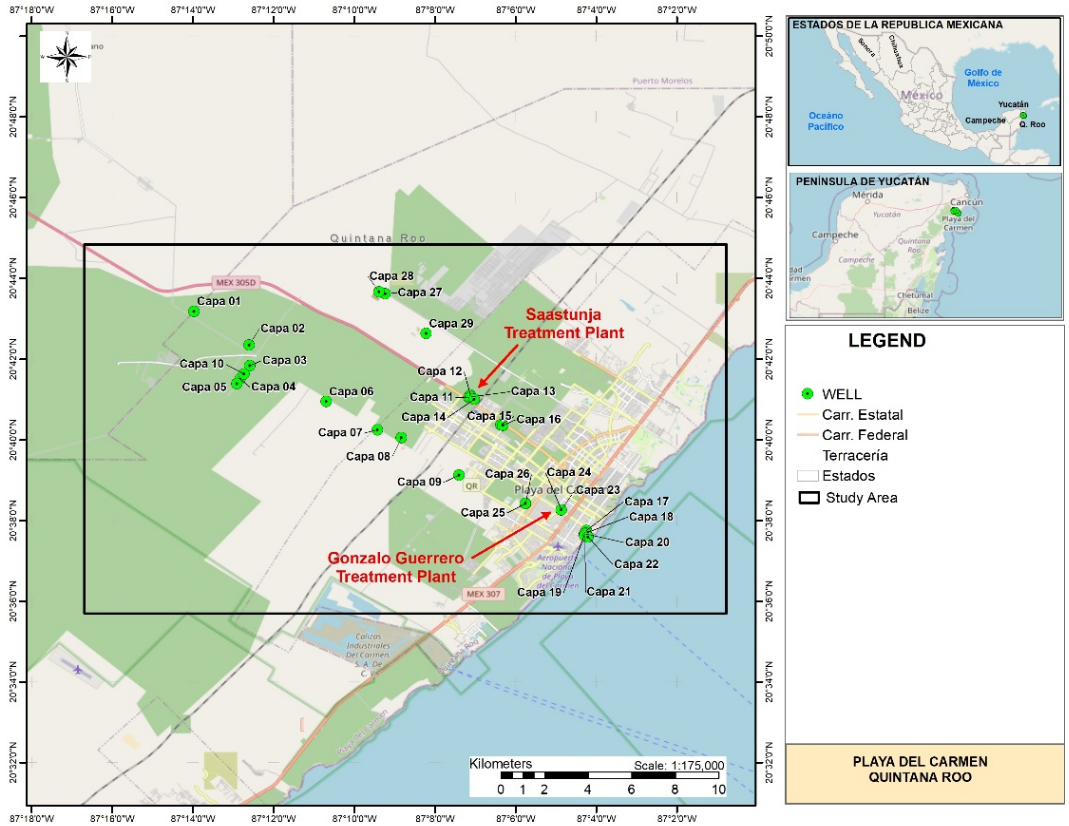

FIGURE 1. *Study area and monitoring network. Source: own elaboration.*

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TABLE 1. *Monitoring network. Source: own elaboration.*

ID	Name	Longitude	Latitude
Capa 01	Rosa María	475758	2291147
Capa 02	Pozo 16	478119	2289606
Capa 03	Pozo 22	478157	2288661
Capa 04	Pozo 8	477731	2288051
Capa 05	Pozo 20	477600	2287836
Capa 06	Yumbálam	481442	2287018
Capa 07	Pozo 5	483645	2285717
Capa 08	Pozo 3	484666	2285362
Capa 09	Lindavista	487153	2283657
Capa 10	Pozo 21	477901	2288273
Capa 11	Saastunja N1	487566	2287200
Capa 12	Saastunja S2	487641	2287303
Capa 13	Saastunja E3	487655	2287222
Capa 14	Saastunja E4	487814	2287122
Capa 15	Chano A	488964	2285954
Capa 16	Chano B	489043	2285915
Capa 17	Tulipanes	492636	2281111
Capa 18	INAH	492609	2280987
Capa 19	SACBE	492559	2280953
Capa 20	Chiapanecas	492564	2280959
Capa 21	Tropical	492564	2280869
Capa 22	Recodo	492702	2280812
Capa 23	G. Guerrero PO4	491551	2282057
Capa 24	G. Guerrero PO8	491547	2282050
Capa 25	Ejidal PO	490032	2282347
Capa 26	Ejidal PC	490019	2282350
Capa 27	Relleno san. Pozo 2	483978	2291945
Capa 28	Relleno san. Pozo 1	483717	2292028
Capa 29	Aguas nativas	485740	2290120

Groundwater flow net is shown in Figure 2. The highly-permeable karst limestone rocks and the flat topography of the area combine to produce a very small hydraulic gradient.

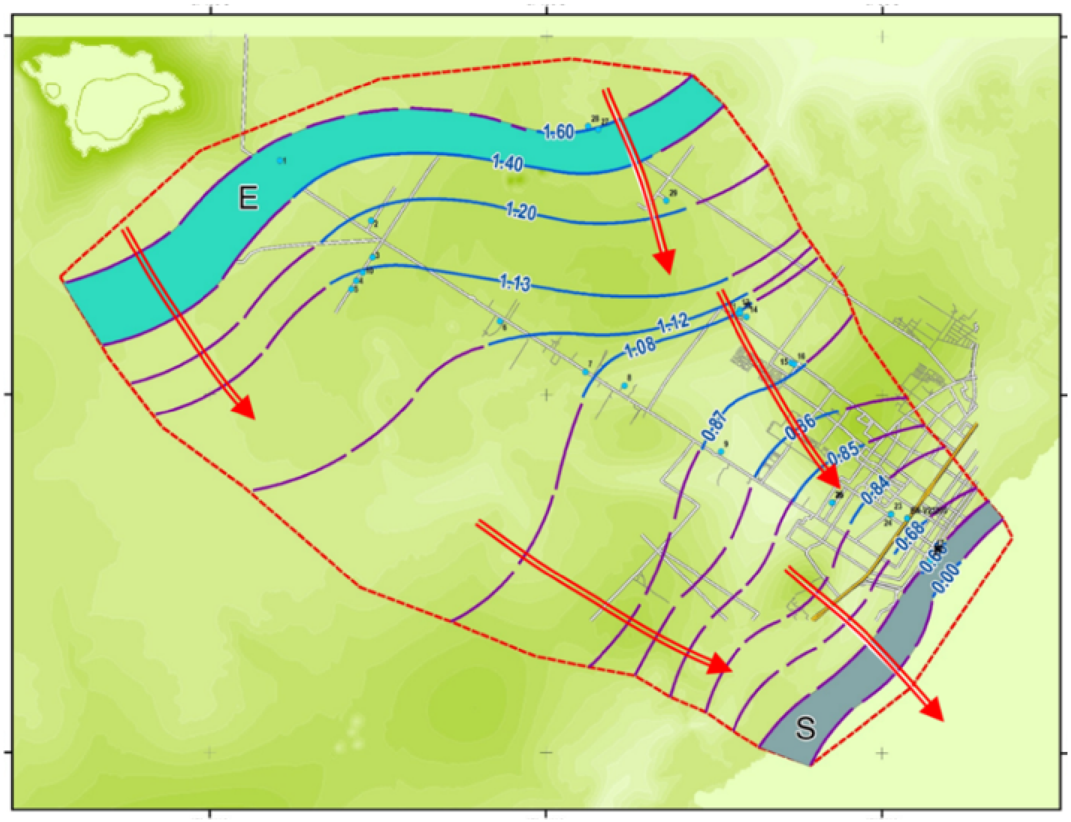

FIGURE 2. *Groundwater flow net. Source: own elaboration.*

Fluorescent tracer tests

The design and planning of the fluorescent tracer tests was based on the geological and hydrogeological characteristics of the studied area. The values of flow velocity, secondary porosity and hydraulic conductivity used in the design of the tests were taken from the available literature [24,25] and from tests carried out in the area of Cancun, Q. Roo [26,27]. The magnitude of the main variables that characterize the groundwater flow and the karst conditions of the aquifer, allowed to determine the quantities of tracer to be injected (Rhodamine WT and Fluorescein), and their transit times in the aquifer from the site of the tests to the sites of possible emergence.

The sites where the tests were performed, as well as the types and amounts of tracer added are shown in Table 2. The Rhodamine WT and Fluorescein injections carried out at the Wastewater Treatment Plants are shown in Figure 3.

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TABLE 2. *Application sites and quantities of tracers used. Source: own elaboration.*

Site	Tracer	Volume	Active Ing.
Saastun-ja well 3	Rhodamine WT	23 kg	20 %
Saastun-ja well 4	Rhodamine WT	23 kg	20 %
Saastun-ja bypass	Fluorescein	29 kg	20 %
G. Guerrero well	Rhodamine WT	11 kg	20 %

FIGURE 3. *Application of Rhodamine WT and Fluorescein. Source: own elaboration.*

Stable isotopes of water

Water samples were filtered using cellulose membranes with 0.45 µm pore size and collected in high-density polyethylene bottles with conical and polyseal insert caps, filled with no headspace, and stored at 5°C until analysis.

Stable isotope analyses were conducted at the isotope hydrology laboratory of the Mexican Institute of Water Technology (IMTA), using laser water isotope analyzers Picarro L2110-i and Los Gatos Research LWIA-45EP. The analytical precision of the measurements was ± 0.5‰(Vs. VSMOW) for δ^2H and ±

0.13‰(Vs. VSMOW) for δ^{18}O.

Stable isotope values are represented in delta notation δ (‰), relating the ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ (Vienna Standard Mean Ocean Water; V-SMOW2) as:

$$\delta = \left[\left(\frac{R_s}{R_{std}}\right) - 1\right] \bullet 1000 \tag{1}$$

where R is the $^{2}H/^{1}H$ or $^{18}O/^{16}O$ abundance ratio, and R_s and R_{std} are the ratios in the sample and standard, respectively. The deuterium excess (d-excess [28]) was calculated as:

$$d\text{-excess} = \delta^{2}\mathrm{H} - 8 \bullet \delta^{18}\mathrm{O} \tag{2}$$

Vertical profiles of electrical conductivity and temperature

Vertical profiles of electrical conductivity and temperature were carried out using a multiparameter sonde, whose characteristics are described in Table 3.

TABLE 3. *Multiparameter sonde. Source: own elaboration.*

Parameter	Range	Resolution	Accuracy
Conductivity	0 a 100 mS/cm	.001 mS/cm	± 0.5 %
Temperature	-5 a 50 °C	0.01 °C	± 0.15 °C

Results

Vertical profiles of electrical conductivity and temperature

Figure 4 illustrate the design of the injection well. The total depth is 90 m, with 42 m of blank casing and 48 m of well screen. Figure 4 also display the vertical electrical conductivity profile of the aquifer before the wastewater injection. The freshwater layer is approximately 30 m thick, the mixing zone 10 m and the saline zone 50 m.

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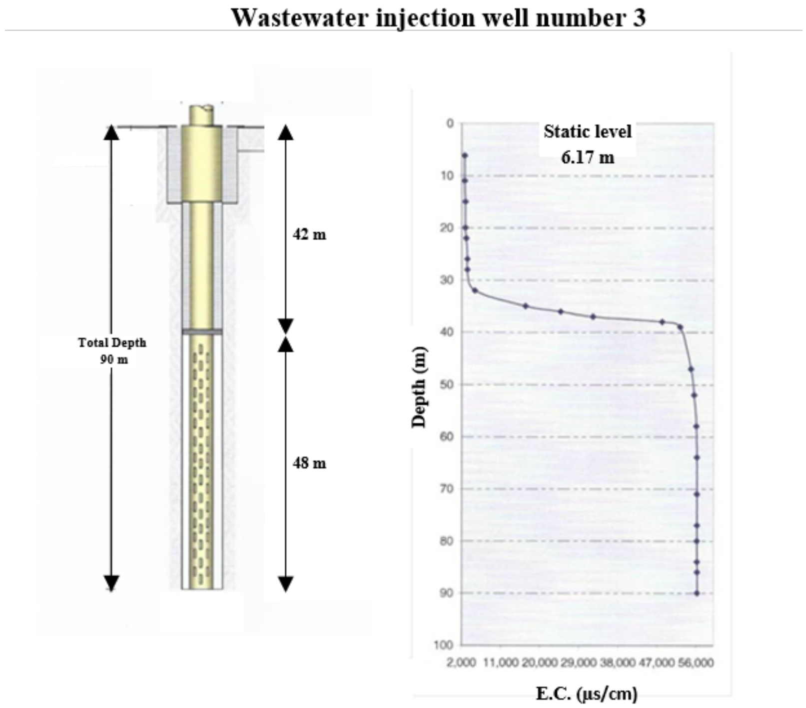

FIGURE 4. *Design of wastewater injection well and vertical profile before injection. Source: own elaboration.*

After wastewater injection, the layer of fresh water extends to a depth of 70 m, as shown by the vertical electrical conductivity and temperature profiles of Figure 5.

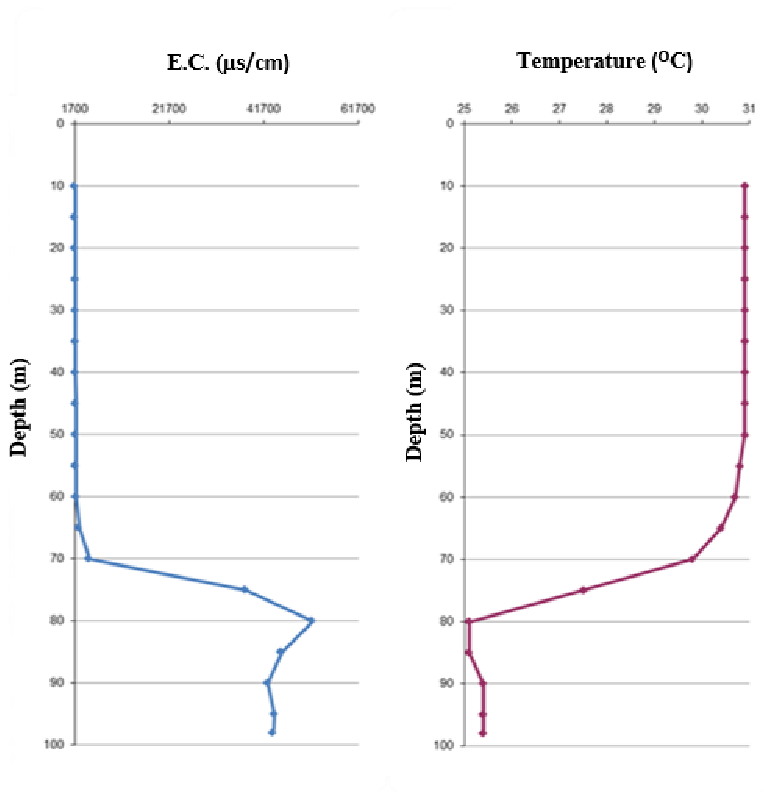

FIGURE 5. *Vertical profiles after wastewater injection. Source: own elaboration.*

Three months after the wastewater was injected, the freshwater layer is reduced to a thickness of 40 m, as revealed by the vertical electrical conductivity and temperature profiles (Figure 6).

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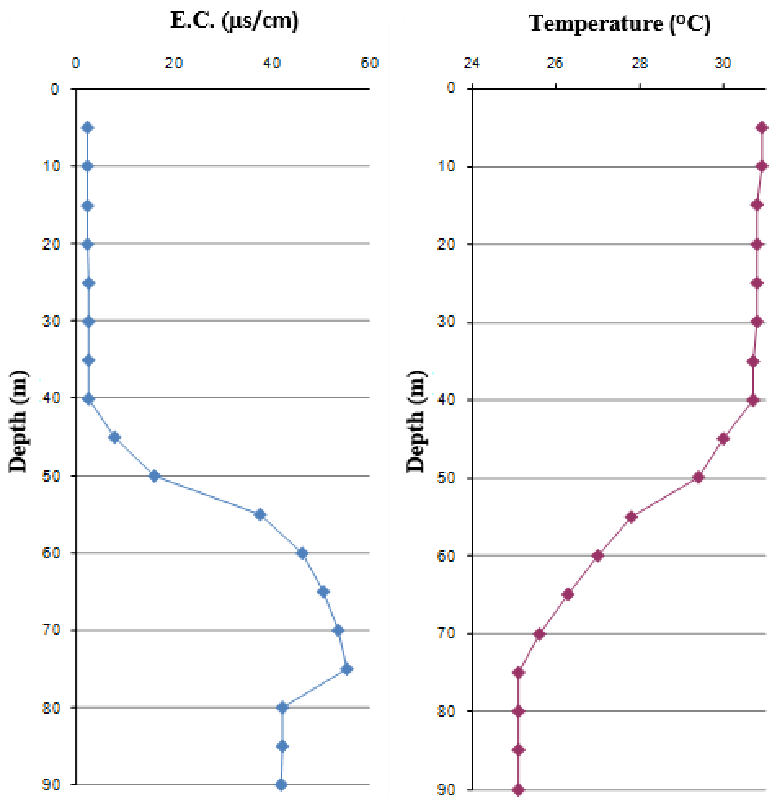

FIGURE 6. *Vertical profiles three months after wastewater injection. Source: own elaboration.*

Fluorescent tracer tests

Figure 7 shows a water sample collected from the freshwater zone of a monitoring well near injection well 3 in the Saástun-Já Plant, thirty minutes after the tracer was injected. High concentrations of Rhodamine WT can be observed in the sample.

FIGURE 7. *Water sample collected 30 minutes after tracer injection. Source: own elaboration.*

High values of fluorescence were measured in water samples of the Saástun-Já plant monitoring wells and the cenote Chano A (Table 4). These relatively high values, by more than an order of magnitude compared to those of other sites, indicate the influence of the wastewater injected on the water quality of the Chano A sinkhole.

TABLE 4. *Values of rhodamine and fluorescein prior to and after injection. Source: own elaboration.*

Sample	Rh (prior)	Rh (after)	Fl (prior)	Fl (after)
Cenote Chano A	0.36	5.05	6.92	6.92
Monitoring well SJ	0.72	26.84	2.65	55
Monitoring well GG	0.18	0.56	1.99	3.23
Landfill well	0.39	2.13	8.26	14.7
Colonia Ejidal well	0	0.08	0	0.12
Cenote Linda Vista	0	0.04	0.26	0.29
Cenote Tulipanes	0	0.21	0.18	1.11

Based on the fluorescence values, it was calculated that around 12 % of the water received by the Chano A sinkhole (cenote) comes from wastewater discharged in the injection wells of the Saástun-Já

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plant. A simple tracer mixing model was used to calculate the percentages (Figure 8):

$$F_{CHANO\ A} = XF_B + YF_{IW} \tag{3}$$

$$1 = X + Y \tag{4}$$

Where $F_{CHANO\ A} = 5{,}05$ µg/L, $F_B = 0{,}36$ µg/L, $F_{IW} = 39{,}44$ µg/L.

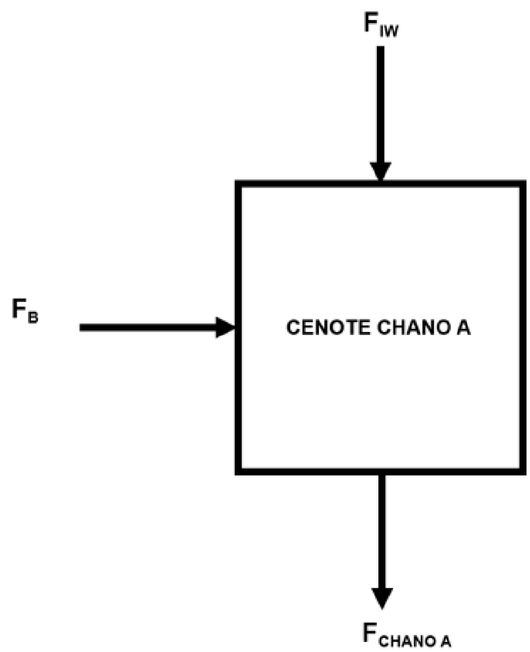

FIGURE 8. *Tracer mixing model. Source: own elaboration.*

Stable isotopes of water

At the Saástun-Já and Gonzalo Guerrero Treatment Plants, the sewage is aerated for several hours in storage tanks. The aeration process is an essential part of the secondary treatment. The injection of air into the reactor tanks supports the growth of microorganisms that break down the organic and nitrogenous matter in the wastewater [29]. This process causes intense evaporation of the water.

Physically, stable isotopes are atoms which take the same position in the table of elements, but have a different number of neutrons and therefore mass. The most relevant isotopes for atmospheric and hydrologic sciences are ^{18}O and ^{16}O for oxygen, and ^{2}H and ^{1}H for hydrogen [30, 31]. These stable isotope molecules are termed stable water isotopes. During phase changes, such as evaporation and condensation, stable isotopes become enriched in one phase and depleted in the other. This process is termed isotopic fractionation [32].

For example, consider the process of evaporation of water. Isotopically lighter water molecules will evaporate preferentially forming depleted atmospheric vapour, and leave behind an enriched water body. Since the aeration process of wastewater causes evaporation, the water at the reactor tanks must be isotopically enriched. This particularity motivated the possibility of using stable water isotopes in this case.

The stable isotope data of oxygen and hydrogen (Table 5) in a scatter plot δ^{18}O vs. δ^{2}H (Figure 9) identify three groups of waters. The first group includes wells 3, 11, 21, and the landfill monitoring well, as well as the Chiapanecas, INAH, and Sac-be sinkholes. The isotopic values are located around the Meteoric Line of Playa del Carmen [33] which indicates that its recharge comes from rainfall in the Playa del Carmen area. The second group includes the injection and monitoring wells of the Saástun-Ja and Gonzalo Guerrero treatment plants. The isotopic values are located to the right of the Meteoric Line of Playa del Carmen, indicating that the water of these samples was subject to intense evaporation processes. The third group includes wells Colonia Ejidal and 5, as well as the Chano A, Chaak-Tun, Tulipanes, and Lindavista sinkholes. The isotopic values are located between the Meteoric Line of Playa del Carmen and the second group, which indicates that its recharge is a mixture of rainfall and effluents of the treatment plants.

The Deuterium excess (d-excess) values are shown in Table 5 and Figure 10. The deuterium excess values of group 1 are higher than the global precipitation mean ($\sim$ 10). High values of group 1 are due to terrestrial moisture recycling (i.e. local evapotranspiration) [34]. The d-excess values of group 1 are typical of the Caribbean Sea domain [35]. The deuterium excess values of group 2 are lower than the global precipitation mean ($\sim$ 10). Low values of group 2 are due to the evaporation which produces enrichment of δ^{18}O and δ^{2}H, and decreases the excess of deuterium in the liquid phase [36]. In general, evaporation decreases and moisture recycling increases the d-excess [36]. The d-excess values for group 3 fall between those for group 1 and group 2, indicating that the water in group 3 is a mixture of rainwater and wastewater.

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TABLE 5. *Stable isotopes of wastewater and groundwater. Source: own elaboration.*

ID	Sample	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	d-excess ‰
1	Inj. well 3 SJ	-4.3	-26	8.4
2	Inj. well 4 SJ	-4.4	-28	7.2
3	Bypass SJ	-4.5	-27	9
4	Mon. well SJ	-4.2	-26	7.6
5	Mon. well 1 GG	-4.5	-28	8
6	Mon. well 2 GG	-4.6	-29	7.8
7	Inj. well GG	-4.2	-27	6.6
8	Landfill well	-6	-38	10
9	Mon. well Ejidal	-5	-30	10
10	Water well Ejidal	-5.1	-31	9.8
11	Well 11	-4.8	-27	11.4
12	Well 3	-5	-29	11
13	Well 5	-4.9	-30	9.2
14	Well 21	-4.8	-28	10.4
15	Cenote Chiapanecas	-4.6	-26	10.8
16	Cenote Chano A	-4.2	-27	6.6
17	Cenote Chaak.tun	-5.1	-32	8.8
18	Cenote INAH	-4.8	-28	10.4
19	Cenote Sac-be	-4.8	-28	10.4
20	Cenote Tulipanes	-4.8	-30	8.4
21	Cenote Linda Vista	-5.2	-32	9.6

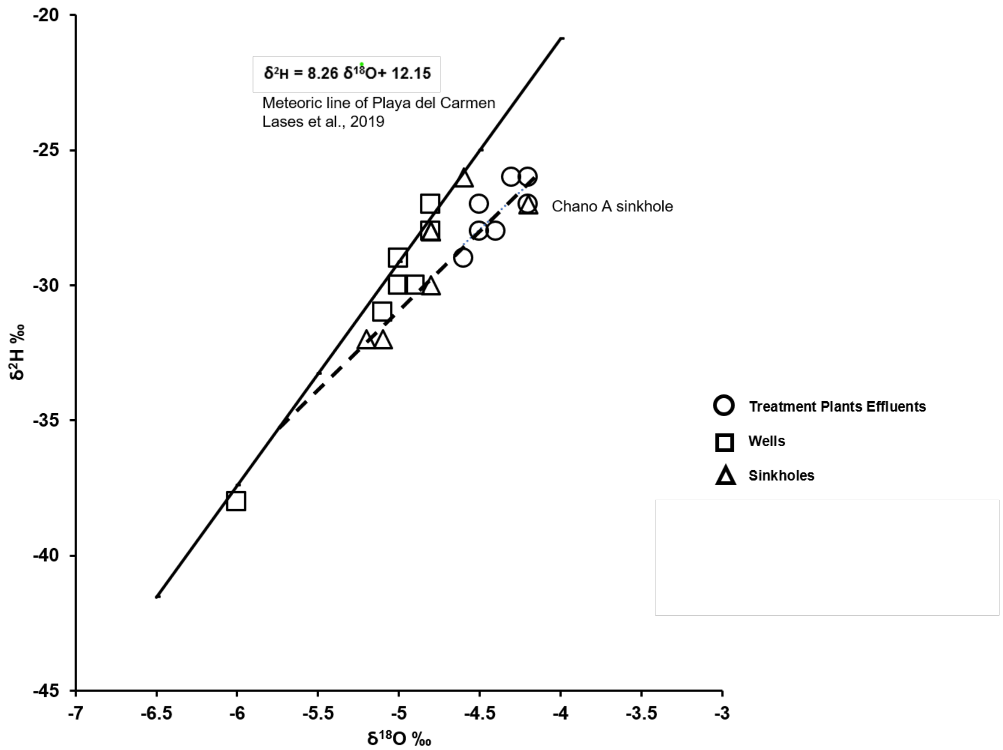

FIGURE 9. *Isotopic composition of groundwater and wastewater. Source: own elaboration.*

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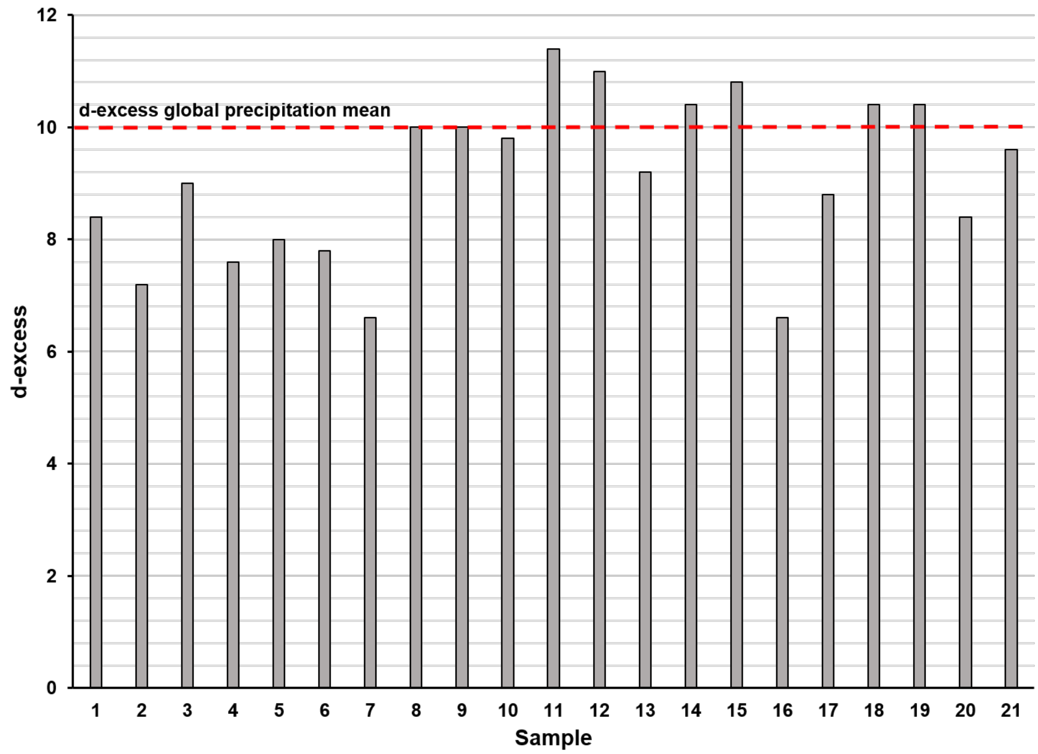

FIGURE 10. *d-excess values of groundwater and wastewater. Source: own elaboration.*

CONCLUSIONS

Waste disposal wells (injections wells) and septic tanks are the principal methods of wastewater disposal in the Yucatan Peninsula. The injections wells are designed and constructed to disseminate the treated wastewater in a deep saline layer below the freshwater lens. Due to the deterioration of the water quality of some wells and cenotes (sinkholes) located near the treatment plant of Playa del Carmen, the flow patterns of the wastewater injected in the waste disposal wells of the plant were characterized.

Hydrogeochemical methods, hydrogen and oxygen isotopes of water, and fluorescent chemical tracers, allowed to determine the behavior of the treated wastewater injected into the saline aquifer which underlies the freshwater aquifer. Overall, our results reveal that the wastewater does not remain in the deep brackish water stratum where it was injected, but rises to the freshwater lens. This buoyancy effect is due to the fact that wastewater has a temperature six degrees higher than saline water, and a lower density of approximately 25 grams per liter. The results also indicate that Wells Colonia Ejidal and 5, as well as the Chano A, Chaak-Tun, Tulipanes, and Lindavista sinkholes, contain water that is a mixture of rainwater and wastewater.

This case study revealed that wastewater disposal system currently in widespread use in the Yucatán

Peninsula could contaminate the overlying freshwater aquifer, and eventually the coastal zone.

Author Contributions

Miguel A. Mejía-González: conceptualization, investigation, writing – original draft, methodology, validation, writing – review and editing, formal analysis, data curation. **Luis González-Hita:** conceptualization, investigation, funding acquisition, writing – original draft, methodology, validation, visualization, writing – review and editing, formal analysis, data curation, supervision, resources, project administration. **Blanca Carteño-Martinez:** writing – review and editing, investigation. **Dustin S. Mañon-Flores:** data curation, writing – review and editing, investigation.

Referencias

[1] INEGI, "Censo de población y vivienda 2020," *INEGI*, 2020.

[2] J. D. Ruiz-Ramírez, "Vulnerability and sea level rise in the coastal tourism city of playa del carmen, quintana roo, mexico," in *IntechOpen*, 2023.

[3] R. Leal-Bautista, M. Lenczewski, C. Morgan, A. Gahala, and J. McLain, "Assessing fecal contamination in groundwater from the tulum region, quintana roo, mexico," *Journal of Environmental Protection*, vol. 4, pp. 1272–1279, 2013.

[4] E. Cejudo, G. Acosta-González, D. Ortega-Camacho, J. A. Perera-Burgos, and R. M. Leal Bautista, "Caracterización hidroquímica y geofísica de una descarga de agua subterránea en quintana roo, méxico," *Ecosistemas y Recursos Agropecuarios*, vol. 9, no. 2, p. e3211, 2022.

[5] M. Villasuso and R. Ramos, "A conceptual model of the aquifer of the yucatan peninsula, population, development, and environment on the yucatan peninsula: From ancient maya to 2030," International Institute for Applied Systems Analysis, Laxenburg, Austria, Tech. Rep., 2000.

[6] C. Narvaez-Montoya, R. Mondragón Bonilla, N. Goldscheider *et al.*, "Groundwater salinization patterns in the yucatan peninsula reveal contamination and vulnerability of the karst aquifer," *Communications Earth & Environment*, vol. 6, p. 468, 2025.

[7] D. O. Dohering and J. H. Buttler, "Hydrogeologic constraints on yucatan development," *Science*, vol. 186, no. 4164, pp. 591–595, 1974.

[8] C. D. Metcalfe, G. Gold-Bouchot, T. L. Metcalfe, H. Li, P. A. Beddows, and H. Van Lavieren, "Domestic wastewater as a source of contaminants in freshwater aquifers in the mayan riviera tourism region of mexico," UNU-INWEH, Tech. Rep., 2009. [Online]. Available: http://www.inweh.unu.edu/Coastal/POPs/2009_Dominica/Metcalfeposter.pdf

https://doi.org/10.36677/rici.v4i1.26915 ISSN: 2992-7447 Enero - Junio 2026 págs. 17- 38

[9] Y. Martínez-Casales, K. León-Aguirre, E. Lamas-Cosió, E. Norena-Barroso, J. Herrera-Silveira, and F. Arcega-Cabrera, "Caffeine and paraxanthine as tracers of anthropogenic wastewater in coastal lagoons in yucatan, mexico," *Bulletin of Environmental Contamination and Toxicology*, vol. 108, pp. 182–189, 2022.

[10] J. Pacheco, A. Cabrera, and L. Marin, "Bacteriological contamination in the karstic aquifer of yucatan, mexico," *Geofísica Internacional*, vol. 39, no. 3, pp. 285–291, 2000.

[11] P. A. Beddows, "Where does the sewage go? the karst groundwater system of municipalidad solidaridad, quintana roo," *Association for Mexican Cave Studies Activities*, pp. 47–52, 2002.

[12] P. J. Carpenter, R. F. Adams, M. Lenczewski, and R. M. Leal-Bautista, "Ground-penetrating radar, resistivity and spontaneous potential investigations of a contaminated aquifer near cancún, mexico," in *Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst*, Carlsbad, New México, 2023, pp. 231–237.

[13] B. L. Morris, "Impact of urbanization on groundwater in merida, mexico, final report," British Geological Survey, Technical Reports, Tech. Rep. WC/94138, 1994.

[14] J. Alcocer, A. Lugo, L. E. Marín, and E. Escobar, "Hydrochemistry of waters from five cenotes and evaluation of their suitability for drinking-water supplies, northeastern yucatan, mexico," *Hydrogeology Journal*, vol. 6, no. 2, pp. 293–301, 1998.

[15] C. E. Graniel, L. B. Morris, and J. J. Carrillo-Rivera, "Effects of urbanization on groundwater resources of merida, yucatan, mexico," *Environmental Geology*, vol. 37, pp. 303–312, 1999.

[16] P. A. Moreno-Pérez, M. Hernández-Téllez, and A. Bautista-Gálvez, "In danger one of the largest aquifers in the world, the great mayan aquifer, based on monitoring the cenotes of the yucatan peninsula," *Archives of Environmental Contamination and Toxicology*, vol. 81, pp. 189–198, 2021.

[17] S. Kopczynski, R. Nolen, D. Hala, F. Lases-Hernandez, W. Escobedo-Hinojosa, F. Arcega-Cabrera, I. Oceguera-Vargas, and A. Quigg, "Investigation of anthropogenic and emerging contaminants in sinkholes (cenotes) of the great mayan aquifer, yucatán peninsula," *Archives of Environmental Contamination and Toxicology*, 2025.

[18] E. Pérez-Cervantes, E. Navarro-Espinoza, N. A. Estrada-Saldívar *et al.*, "Estado de conservación de los arrecifes de coral de la península de yucatán," Technical Report, Tech. Rep., 2017.

[19] M. McField, P. Kramer, A. Giró-Petersen *et al.*, "Mesoamerican reef report card," Tech. Rep., 2020.

[20] Healthy Reefs for Healthy People, "Mesoamerican reef report card. an evaluation of ecosystem health," Tech. Rep., 2024. [Online]. Available: https://marfund.org/es/wp-content/uploads/2024/12/Healthy-Reefs-Report-Card.pdf

[21] REPDA, CONAGUA, "Registro público de derechos de agua," 2020.

[22] CONAGUA, "Programa hídrico regional 2021–2024: Región hidrológico-administrativa xii península de yucatán," CONAGUA, Tech. Rep., 2020. [Online]. Available: https://files.conagua.gob.mx/conagua/generico/PNH/PHR_2021-2024_RHA_XII_Pen%C3%ADnsula_de_Yucat%C3%A1n.pdf

[23] JICA, "Estudio de manejo de saneamiento ambiental en la costa del estado de quintana roo en los estados unidos mexicanos," GE-JR, Tech. Rep. 04-012, 2004.

[24] W. Back and H. Paloc, "Coastal karst formed by ground water discharge, yucatan, mexico," *International Association of Hydrogeologists, Hydrogeology of selected karst regions*, vol. 13, pp. 461–467, 1992.

[25] Y. Moore, H. Stoessell, K. Ronald, and H. Easley, "Fresh-water/sea-water relationship within a ground water flow system, northeastern coast of the yucatan peninsula," *Groundwater*, vol. 30, no. 3, 1992.

[26] J. L. Morales, H. Boa, C. F. Chablé, and E. J. Balmes, "Estudio de la calidad del agua del sistema lagunar nichupte, q. roo," CNA Gerencia Estatal en Quintana Roo, Tech. Rep., 1992.

[27] L. González-Hita and F. Lara, "Interacción de las aguas subterráneas con la laguna de nichupté, quintana roo," IMTA Informe interno, Tech. Rep., 1998.

[28] W. Dansgaard, "Stable isotopes in precipitation," *Tellus*, vol. 16, no. 4, pp. 436–468, 1964.

[29] A. Aghajanzadeh, C. Wray, and A. McKane, "Opportunities for automated demand response in california wastewater treatment facilities," Lawrence Berkeley National Laboratory, Tech. Rep. LBNL-1003845, 2015.

[30] J. R. Gat, "Oxygen and hydrogen isotopes in the hydrologic cycle," *Annual Review of Earth and Planetary Sciences*, vol. 24, pp. 225–262, 1996.

[31] W. M. E. Mook, *Environmental Isotopes in the Hydrological Cycle. Principles and Applications*. UNESCO/IAEA, 2001.

https://doi.org/10.36677/rici.v4i1.26915 ISSN: 2992-7447 Enero - Junio 2026 págs. 17- 38

[32] M. F. Cotrufo and Y. Pressler, "Isotopic fractionation," in *A Primer on Stable Isotopes in Ecology*. Oxford Academic, 2023.

[33] F. Lases-Hernandez, M. Medina-Elizalde, S. Burns, and M. DeCesare, "Long term monitoring of drip water and groundwater stable isotopic variability in the yucatán peninsula: Implications for recharge and speleothem rainfall reconstruction," *Geochimica et Cosmochimica Acta*, vol. 246, pp. 41–59, 2019.

[34] R. Sánchez-Murillo, A. M. Durán-Quesada, G. Esquivel-Hernández *et al.*, "Deciphering key processes controlling rainfall isotopic variability during extreme tropical cyclones," *Nature Communications*, vol. 10, p. 4321, 2019.

[35] R. Sánchez-Murillo, L. González-Hita, M. A. Mejía-González *et al.*, "Tracing isotope precipitation patterns across mexico," *PLOS Water*, vol. 10, p. e0000136, 2023.

[36] K. Froehlich, M. Kralik, W. Papesch, D. Rank, H. Scheifinger, and W. Stichler, "Deuterium excess in precipitation of alpine regions – moisture recycling," *Isotopes in Environmental and Health Studies*, vol. 44, no. 1, pp. 61–70, 2008.