EurJChem An International Open Access Journal

European Journal of Chemistry

ATLANTA PUBLISHING HOUSE

Check for updates

View Journal Online
View Article Online

Isotopic study of rainfall and definition of local meteoric water lines: Case of the rainfall stations of the city of Bangui in Central African Republic

Eric Foto *, Oscar Allahdin, Olga Biteman and Nicole Poumaye

Bangui University, Faculty of Sciences, Hydrosciences Lavoisier Laboratory, BP:908, Bangui, Central African Republic

* *Corresponding author at: Bangui University, Faculty of Sciences, Hydrosciences Lavoisier Laboratory, BP:908, Bangui, Central African Republic.*
e-mail: fotoeric@hotmail.com (E. Foto).

RESEARCH ARTICLE

10.5155/eurjchem.14.4.445-450.2445

Received: 16 May 2023
Received in revised form: 14 June 2023
Accepted: 17 September 2023
Published online: 31 December 2023
Printed: 31 December 2023

KEYWORDS

Bangui
Altitude
Meteoric
Precipitation
Pseudo-effect
Isotopic signatures

ABSTRACT

The study of the isotopic composition of rainwater discussed in this article allows isotopic characterization of rainfall recorded in the Bangui region over 11 years at two stations. It will highlight the relationships between isotopes, climatic parameters, and temporal variation before defining the local meteoric line, which constitutes the reference point for the region. The results obtained after a follow-up of eleven years without interruption showed two major physical effects, the effect of the rainfall influences more strongly the composition in isotopes, the contents in isotopes vary inversely with the precipitation. For example, heavy rainfall in August and September saw a strong depletion of $\delta^{18}O$ and $\delta^{2}H$ contents. These values reach up to -4.96‰ for $\delta^{18}O$ and -28.3‰ for $\delta^{2}H$. Similar, although weaker, effects are observed for July and October precipitation. We also note that the isotope contents at the Bangui University station are lower than those measured at the Bangui Sodeca station located at 386 m altitude on the Lower Ubangi Hill, which is similar to a pseudo-altitude effect. The evolution of stable isotope content in water as a function of meteorological parameters (temperature, rainfall, altitude) has allowed us to determine a local meteorological line for the city of Bangui from two measuring stations defined as follows: $\delta^{2}H = 7.6 \times \delta^{18}O + 10.4$ ($R^2 = 0.9909$) Université de Bangui, $\delta^{2}H = 8.4 \times \delta^{18}O + 12.5$ ($R^2 = 0.9909$) Bangui-Sodeca and $\delta^{2}H = 7.9 \times \delta^{18}O + 11.3$ ($R^2 = 0.9939$) Bangui local meteoric water lines.

Cite this: *Eur. J. Chem.* **2023**, *14(4)*, 445-450 **Journal website**: www.eurjchem.com

1. Introduction

If we consider that precipitation water corresponds to the input signal in a hydrogeological system, the isotopic monitoring of rainfall on a national scale would allow us to establish a reference for the input function of aquifers in a region. In the natural environment, water molecules are mainly formed of four stable isotopes ($H_2{}^{16}O$, 99.7%; $H_2{}^{18}O$, 0.2%; $H_2{}^{17}O$, 0.05% and $H_D{}^{16}O$, 0.03%) [1]. The physical properties of the different isotopes (saturation vapor pressure and diffusivity in air) lead to isotopic fractionation during phase changes in the atmospheric water cycle. The result of these fractionations is a certain spatial and temporal distribution of the precipitation isotopic ratios (expressed in relation to international standard mean ocean water (SMOW) with $\delta^{2}H/\delta^{2}H = 155.76\times10^{-6}$ and $^{18}O/^{16}O = 2005.2\times10^{-6}$). Since the 1960s, observations of precipitation in monthly time steps have been conducted by the International Atomic Energy Agency (IAEA). These observations have allowed us to characterize the spatial and temporal distribution of the isotopic composition of precipitation and to link climate variability and isotopic variability. Thus, two phenomena are of particular interest in paleoclimatology: (i) the apparent relationship between the isotopic ratio of precipitation and local temperature (isotopic thermometer) and (ii) the relationship between $\delta^{18}O$ and $\delta^{2}H$ contents of the same sample (deuterium excess) [1]. Long-term precipitation monitoring is, in fact, a heavy task and costly in analytical terms. One of the difficulties is collecting sufficient quantities and homogeneous data on the scale of the study area. Taking into account the importance of the temporal variability of the isotopic signal in the same place, it is necessary to have precipitation chronicles (*e.g.*, $\delta^{18}O$, $\delta^{2}H$, and rainfall) over several hydrological cycles in order to obtain a weighted average signal. The multiplication of such chronicles is hardly feasible [1,2].

2. Experimental

2.1. Geographic location

Located in the heart of the African continent, the Central African Republic extends over 623,000 km^2 from the 2nd to the 11th parallel north and the 13th to the 27th meridional east. A vast plateau located between 600 and 700 m above sea level, the Central African Republic is bounded to the east by its Sudanese neighbor, by the watershed between the Nile and Ubangi-Congo rivers, to the north by the Akouale and Bar Aouk (Chari) rivers of Chad, to the west by the Sangha basin of Cameroon, to the southwest by the Lobaye basin of the Congo and to the south by the Ubangi river of the Democratic Republic

ISSN 2153-2249 (Print) / ISSN 2153-2257 (Online)
https://dx.doi.org/10.5155/eurjchem.14.4.445-450.2445

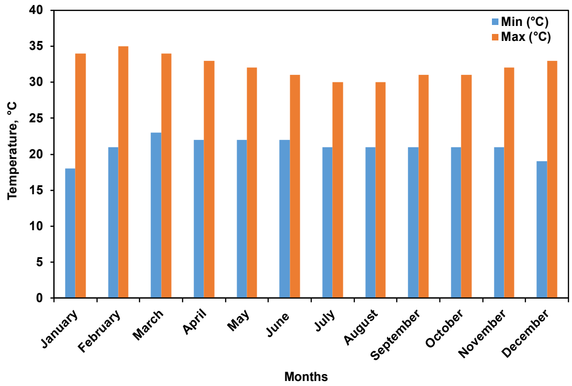

Figure 1. Bangui average annual temperature (2010-2020).

of Congo. The country is surrounded by Sudan, South Sudan, Chad, Cameroon, Congo, and the Democratic Republic of Congo.

2.2. Climate

The climate in Bangui is tropical, with a dry season from December to March. During the rest of the year, rainfall is fairly frequent, especially from July to October. The city is the capital of the Central African Republic and is located in the south of the country, approximately 4 degrees north of the Equator, at an altitude of 350 meters, on the banks of the Oubangui River, beyond which lies the city of Zongo, in the Democratic Republic of Congo (DRC). Daytime temperatures are highest in the dry season, but also in March and April, in the early months, when the rains begin to gradually increase. However, December to February is also the period during which the coolest temperatures are recorded during the night. Figure 1 shows the annual temperatures recorded during the period 2010 to 2020. Based on data collected between 2010 and 2020, the average temperature is 26.7 °C. The average minimum temperature is 21.2 °C in January and the average maximum is 32.4 °C in March.

2.3. Study of rainfall

Previous studies on rainfall on an annual or interannual, monthly and daily scale have made it possible to identify their quantity and regularity in time and space, as well as their susceptibility to influence surface and groundwater flows. For our part, we have monitored rainfall in the city of Bangui for a period of 11 years (2010-2020) from two sampling sites: (i) One on the campus of the University of Bangui at the Lavoisier Laboratory of Hydrosciences (Global Network of Isotopes in Precipitation (GNIP), Bangui University (N04°22'37.5''; E1 8°33'44.9''; 363 m) and (ii) The other on the Sodeca estate, located in a wooded area on the eastern hillside of Bangui (GNIP, Bangui-Sodeca (N04°21'56.5''; E18°35'14 .1''; 386 m).

2.3.1. Monthly precipitation

Based on meteorological data recorded from 2010 to 2020 (11 years), August is the month in which monthly rainfall is generally the highest (with an average of 414.05 mm at Sodeca and 325.05 mm at the University station). About 40% of the rainfall falls during the months of July, August, September, and October. August is also very rainy, with a peak of 414.05 mm and 18 rainy days. Rainfall is very low in the dry season, with monthly averages as follows: December: 1.89 mm, January: 8.5 mm, February: 43.79 mm (Figure 2).

2.3.2. Annual precipitation

The total rainfall collected over 11 years ranges from 1036.05 to 5321.5 mm at the University station and from 1406.7 to 8849 mm at the Sodeca site in Bangui. The recorded interannual average is 1258.9 mm per year. Furthermore, comparing the Bangui University and Bangui Sodeca collection stations from 2010 to 2020 (Figure 2b), we observe that the amounts of water follow almost the same evolution, with a difference of approximately 80 mm of rainfall between the Bangui University station, which totals an average of 1299 and 1220 mm/year for Bangui Sodeca. The low variability of rainfall between the two stations may be the result of their location, as the latter is surrounded by small groves. We also note that 2020 appears to be a year of high rainfall (7085.25 mm on average for the two sites) compared to the other years studied.

2.4. Sampling and analytical methods

The two stations were selected according to the criteria mentioned above and were sampled monthly. A series of samples was taken for different isotopic analyzes. The monthly sampling was carried out in a totalizer canister throughout the year and then stored in 2 30 ml pillboxes for the analysis of deuterium and oxygen-18, without any air bubbles to limit as much as possible the isotopic fractionation related to evaporation and the effects of temperature. The samples were then stored in a refrigerator and sent to the laboratory for analysis.

2.5. Analyses

The contents of stable isotopes of the water molecule ($\delta^{18}O$ and $\delta^{2}H$) were measured by gas source mass spectrometry in the International Atomic Energy Agency (IAEA) isotope analysis laboratory in Vienna, Austria. The principle of mass spectrometry is to separate molecules according to their mass. The samples were distilled beforehand. For the analysis of oxygen-18, the water was then equilibrated with CO_2 of known isotopic composition at 25 °C. For deuterium analysis, water was equilibrated with hydrogen of known composition. Samples were analyzed in nonconsecutive duplicates on two different ABB EP-35 TWIA OA-ICOS laser spectrometers with dry synthetic air carrier gas. Each of these analyzes consisted of 9 injections. The enriched and depleted MNCs came from Lake Kyoga and the STD09 standard (Greenland ice). Controls were provided in standard STD11 (Monaco Lagoon) and STD6 (Heidelberg tap water) for quality assurance/quality control purposes. Data reduction was performed in LIMS for lasers using residual memory correction after ignoring the first four injections. Normalization to the VSMOW-SLAP scale used two reference points.

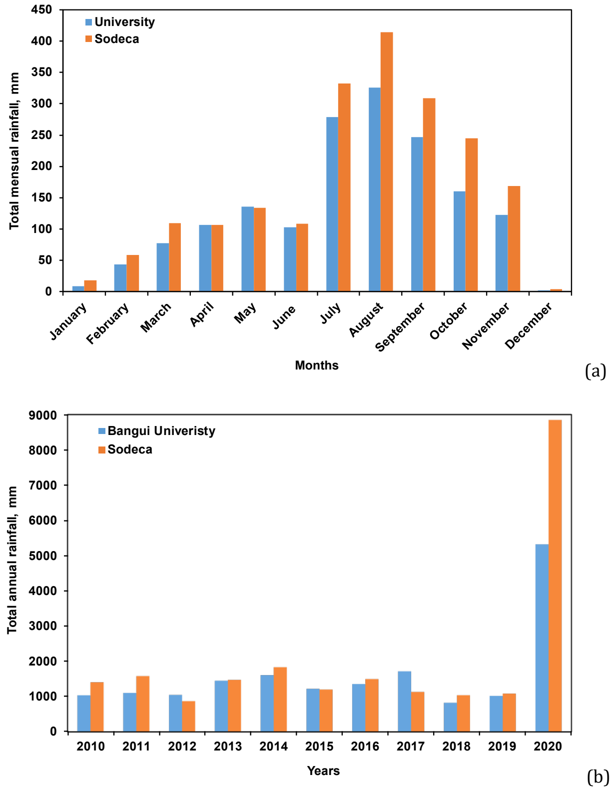

Figure 2. Total monthly (a) and annual (b) rainfall in Bangui at the two stations.

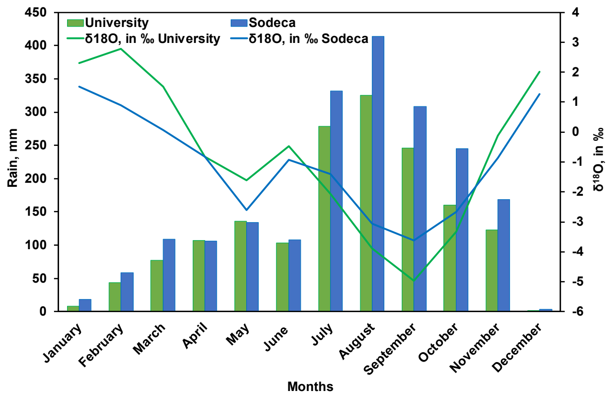

Figure 3. Evolution of rainfall and δ^{18}O levels over the year, defined from an 11-year chronicle.

The measurement uncertainty, expressed as the long-term standard deviation of the control samples, is 0.2 ‰ or better for δ^{18}O and 1.0 ‰ or better for δ^{2}H.

3. Results and discussion

In this study, we discuss data on the isotopic composition of precipitation. Variations in δ^{18}O and δ^{2}H contents are associated with isotopic (and therefore also physical) equilibrium conditions along the global meteoric line of slope 8 (GMD). For less detailed hydrological studies, it is generally accepted that the values of δ^{18}O and δ^{2}H are coupled at equilibrium. However, it should be emphasized that measuring both oxygen and hydrogen isotopes provides additional information in the subsequent study.

3.1. Isotopic effects observed in precipitation

The isotope contents were measured in the IAEA laboratory. Figures 3 and 4 show the evolution of the average isotope content over the year from an eleven-year chronicle at the two stations that collect rainfall data. These figures also show the relationship between the altitude of the rain gauges and the isotope content. It can be seen that the isotope content varies inversely with precipitation. For example, heavy precipitation in August and September saw a strong depletion of δ^{18}O and δ^{2}H contents. These values reach -4.96469 ‰ for δ^{18}O and -28.27481‰ for δ^{2}H. Similar effects are observed for precipitation in July and October, although weaker. A relationship between the amount of precipitation and the isotope contents was observed: Isotope content varies inversely with rainfall. From this observation emerges the effect of the mass of precipitated water that would be at the origin of the depletion of the stable isotopes of water. The seasonal variations of δ^{18}O and δ^{2}H values at the Bangui University station located at 363 m appear to be lower than the average annual variations at Bangui Sodeca located at 386 m altitude on the Lower Ubangi Hill. If we consider that this decrease is essentially related to the decrease in air temperature with altitude, in a systematic way

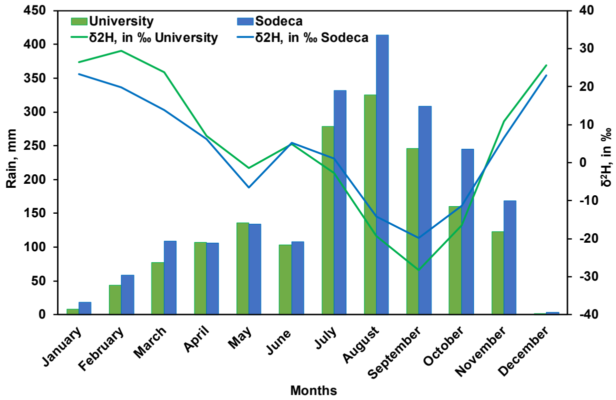

Figure 4. Evolution of rainfall and δ^2H levels over the year, defined from an 11-year chronicle.

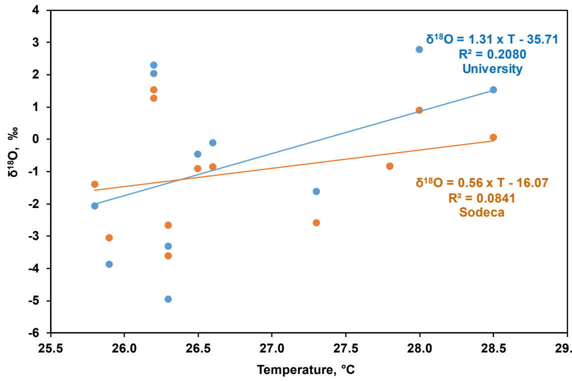

Figure 5. Correlation between temperature and the average annual $\delta^{18}O$ content of rainfall.

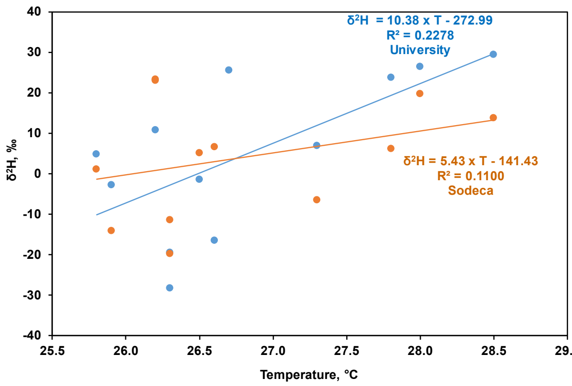

Figure 6. Correlation between temperature and the average annual δ^2H content of rainfall.

the isotopic composition of precipitation evolves with the altitude of the ground and becomes increasingly depleted in ^{18}O and ^2H as it rises, we can observe a pseudoaltitude effect [3,4]. This effect of altitude is thermally dependent, because condensation is caused by the decrease in temperature associated with increasing altitude [2-5].

3.2. Correlation effect between isotopic contents and annual mean temperature

The values of the *R* coefficient shown in Figures 5 and 6 are not significant in correlating the isotopic contents with the annual average temperature at the two rainfall collection stations. The lack of correlation between these two variables shows us that the isotopic contents in the Mediterranean region are not simply related to temperature, but are probably related to the origin and path of the air masses [6,7].

3.3. Definition of the isotopic input signal

The isotopic data recorded at the two monitoring stations are relatively contrasted and differentiated (Figure 7), which may be related to the particular geographical location of the two measuring stations, the GNIP University station is located in the central plain of Bangui, while Sodeca's GNIP station is located on the Panthères hill on the western slopes of Bangui. hill at a slightly higher altitude. The rainfall amounts recorded at these two stations can differ relatively from each other, which is related to the very stormy and therefore spatially variable characteristics of summer rainfall in Bangui.

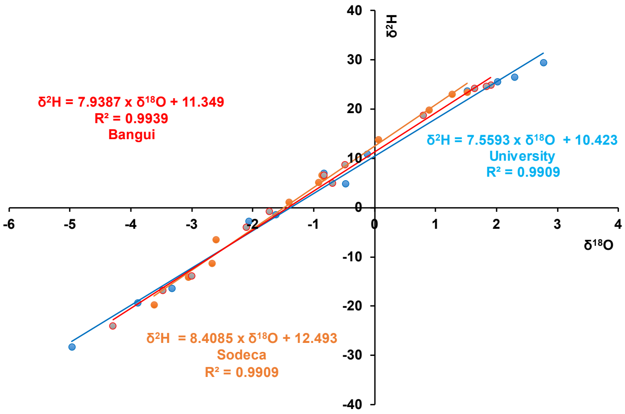

Figure 7. $\delta^{18}O$ or $\delta^{2}H$ relationship in stations Bangui Sodeca and Bangui University.

The data collected from the two sampling stations were used to calculate a local meteoric water line.

$\delta^2H = 7.56 \times \delta^{18}O + 10.42$ ($R^2 = 0.9909$) Bangui University (1)

$\delta^2H = 8.41 \times \delta^{18}O + 12.49$ ($R^2 = 0.9909$) Bangui Sodeca and (2)

$\delta^2H = 7.94 \times \delta^{18}O + 11.35$ ($R^2 = 0.9939$) Local meteoric water line in Bangui (3)

This relationship is close to that observed in similar climatic contexts in West Africa under a Sudano-Sahelian climate. It is also close to the meteoric line of Douala, which in a context much closer to the coast is subject to the same influences [8-10]. The excess of deuterium above 10 reflects the remobilization of atmospheric water vapor of continental origin during the path of air masses from the Gulf of Guinea over the surrounding tropical forest [11,12]. The calibration of stable isotope-temperature relationships was refined by quantifying the relative impact of site temperatures at seasonal, interannual, and interdecadal levels [8,13]. At the interannual level, the variability is such that the correlations obtained are weak. At the seasonal level, linear analysis of seasonal cycles (slightly out of phase) and simple isotope modeling are consistent, showing the strong impact of site temperature on $\delta^{18}O$ or δ^2H [9,13-16].

4. Conclusion

The objective of this study is to translate precipitation isotope data into a spatialized mapping of $\delta^{18}O$ and δ^2H signatures at two locally installed rainfall stations. The use of precipitation isotopes is of great interest due to the highly contrasting climatic situations in recent years. The isotopic contents have allowed us to highlight two important physical phenomena: (i) the effects of precipitation and (ii) the effects of altitude. However, there is no significant correlation between mean monthly temperature and oxygen content 18O and 2H. This makes it impossible to determine the origin of the rainfall. It can be said that the isotopic composition of precipitation at a given station will depend on the conditions of rain formation, temperature in particular, but also rainfall [17,18]. The available data allowed us to calculate a local meteorological line for these two stations: (i) $\delta^2H = 7.56 \times \delta^{18}O + 10.42$, ($R^2 = 0.9909$) for Bangui University, and (ii) $\delta^2H = 8.41 \times \delta^{18}O + 12.49$ ($R^2 = 0.9909$) for Bangui Sodeca. The local meteorological line for the Bangui region based on data from 2010 to 2020 is as follows: $\delta^2H = 7.94 \times \delta^{18}O + 11.35$ ($R^2 = 0.9939$). The initial excess deuterium in rainfall deviates from 10 in relation to the evaporation conditions at the origin of the vapor and the influence of continental vapor [17-19]. This probably reflects the recycling of air masses by water vapor from water body evaporation and soil evapotranspiration [2,20,21].

Acknowledgements

This work was initiated by the International Agency Energy Atomic within the framework of the project GNIP/GNIR. The authors thank the IAEA staff for collecting and analyzing the sample.

Disclosure statement DS

Conflict of interest: The authors declare that they have no conflict of interest.
Ethical approval: All ethical guidelines have been adhered to.

CRediT authorship contribution statement CR

Conceptualization: Eric Foto; Methodology: Eric Foto, Oscar Allahdin; Validation: Eric Foto, Oscar Allahdin, Olga Biteman; Formal Analysis: Olg Biteman, Eric Foto, Oscar Allahdin; Investigation: Eric Foto, Oscar Allahdin; Data Curation: Eric Foto, Oscar Allahdin; Writing - Original Draft: Eric Foto, Oscar Allahdin, Olga Biteman, Nicole Poumaye; Writing - Review and Editing: Eric Foto, Oscar Allahdin; Visualization: Eric Foto, Oscar Allahdin, Olga Biteman, Nicole Poumaye; Supervision: Eric Foto, Oscar Allahdin; Project Administration: Eric Foto, Oscar Allahdin.

ORCID and Email

Eric Foto
fotoeric@hotmail.com
fotoeric@lavoisier.org
https://orcid.org/0000-0003-2875-9556
Oscar Allahdin
allahdin25@yahoo.fr
https://orcid.org/0009-0009-8477-7207
Olga Biteman
bomobili@yahoo.fr
https://orcid.org/0009-0004-8537-434X
Nicole Poumaye
poumaye06@yahoo.fr
https://orcid.org/0009-0005-6648-652X

References

[1]. Celle, H.; Daniel, M.; Mudry, J.; Blavoux, B. Signal pluie et traçage par les isotopes stables en Méditerranée occidentale. Exemple de la région avignonnaise (Sud-Est de la France). *C. R. Acad. Sci. (Ser. 2a) (Sci. Terre Planete/Earth Planet. Sci.)* **2000**, *331*, 647–650.

[2]. Craig, H. Isotopic variations in meteoric waters. *Science* **1961**, *133*, 1702–1703.

[3]. Stewart, M. K. Stable isotope fractionation due to evaporation and isotopic exchange of falling waterdrops: Applications to atmospheric processes and evaporation of lakes. *J. Geophys. Res.* **1975**, *80*, 1133–1146.

[4]. Werner, M.; Heimann, M.; Hoffmann, G. Isotopic composition and origin of polar precipitation in present and glacial climate simulations. *Tellus B Chem. Phys. Meteorol.* **2001**, *53*, 53–71.
[5]. Casado, M. Water stable isotopic composition on the East Antarctic Plateau: measurements at low temperature of the vapour composition, use as an atmospheric tracer and implication for paleoclimate studies, Ph.D. Thesis, Universite de Saint-Quentin enYveline, 2016.
[6]. Kendall, C.; Coplen, T. B. Distribution of oxygen-18 and deuterium in river waters across the United States. *Hydrol. Process.* **2001**, *15*, 1363–1393.
[7]. Rozanski, K.; Sonntag, C.; Münnich, K. O. Factors controlling stable isotope composition of European precipitation. *Tellus A* **1982**, *34*, 142–150.
[8]. Brodersen, C.; Pohl, S.; Lindenlaub, M.; Leibundgut, C.; Wilpert, K. v. Influence of vegetation structure on isotope content of throughfall and soil water. *Hydrol. Process.* **2000**, *14*, 1439–1448.
[9]. Liu, W. J.; Liu, W. Y.; Li, J. T.; Wu, Z. W.; Li, H. M. Isotope variations of throughfall, stemflow and soil water in a tropical rain forest and a rubber plantation in Xishuangbanna, SW China. *Hydrol. Res.* **2008**, *39*, 437–449.
[10]. Celle-Jeanton, H.; Travi, Y.; Blavoux, B. Isotopic typology of the precipitation in the Western Mediterranean Region at three different time scales. *Geophys. Res. Lett.* **2001**, *28*, 1215–1218.
[11]. Gat, J. R.; Carmi, I. Evolution of the isotopic composition of atmospheric waters in the Mediterranean Sea area. *J. Geophys. Res.* **1970**, *75*, 3039–3048.
[12]. Criss, R. E. *Principles of Stable Isotope Distribution*; Oxford University Press: New York, NY, 1999.
[13]. Novel, J. P.; Dray, M.; Fehri, A.; Jusserand, C.; Nicoud, G.; Olive, P.; Puig, J. M.; Zuppi, G. M. Homogénéisation des signaux isotopiques, 18O et 3H, dans un système hydrologique de haute montagne: la Vallée d'Aoste (Italie). *Rev. Sci. Eau/J. Water Sci.* **2005**, *12*, 3–21.
[14]. Baertschi, P. Absolute18O content of standard mean ocean water. *Earth Planet. Sci. Lett.* **1976**, *31*, 341–344.
[15]. Smith, G. I.; Friedman, I.; Gleason, J. D.; Warden, A. Stable isotope composition of waters in southeastern California: 2. Groundwaters and their relation to modern precipitation. *J. Geophys. Res.* **1992**, *97*, 5813.
[16]. Gibson, J. J. A new conceptual model for predicting isotopic enrichment of lakes in seasonal climates. *Pages (Bern)* **2002**, *10*, 10–11.
[17]. Cappa, C. D. Isotopic fractionation of water during evaporation. *J. Geophys. Res.* **2003**, *108*, 4525, D16.
[18]. Petelet-Giraud, E.; Casanova, J.; Chery, L.; Negrel, P.; Bushaert, S. Essai de caractérisation isotopique (δ18O et δ2H) du signal metéorique actuel à partir des lacs et réservoirs: application au quart sud-ouest de la France. *Houille Blanche* **2005**, *91*, 57–62.
[19]. Ciais, P.; Jouzel, J. Deuterium and oxygen 18 in precipitation: Isotopic model, including mixed cloud processes. *J. Geophys. Res.* **1994**, *99*, 16793–16803.
[20]. Millet, A.; Bariac, T.; Grimaldi, C.; Boulègue, J. Signature isotopique et chimique des précipitations (pluies et pluviolessivats) en Guyane française. *Rev. Sci. Eau/J. Water Sci.* **2005**, *12*, 729–751.
[21]. Clark, I. D.; Fritz, P. *Environmental Isotopes in Hydrogeology*; CRC Press, 2013.