Journal of Applied and Advanced Research, 2019: 4(5) 141–145
http://dx.doi.org/10.21839/jaar.2019.v4i5.309
ISSN 2519-9412 / © 2019 Phoenix Research Publishers

Research Article – Hydrology

Identification of groundwater origin using environmental isotopes (^{18}O and ^{2}H) in the upper catchment of Ikopa, Antananarivo District

J. R. Randriantsivery[1*], J. Rajaobelison[1,2], V. Ramaroson[1,2], N. Rabesiranana[1,2], L. P. Fareze[2], F. F. A. Razafitsalama[2], C. U. Rakotomalala[2]
[1]*Faculté des Sciences de l'Université d'Antananarivo, B.P 906, Madagascar*
[2]*Département d'Hydrologie Isotopique, Institut National des Sciences et Techniques Nucléaires, B.P 3907, Antananarivo, Madagascar*

(Received: 15-10-2019; Accepted 12-11-2019; Published Online 20-12-2019)
*Corresponding author (E-mail. jrem.randriantsivery@gmail.com)

Abstract

The upper catchment of Ikopa has great potential for surface or sub-surface water resources. The Ikopa River plays an important role in the water supply of the plain of Antananarivo. Knowing that surface water is abundant but exposed to the high risk of pollution, and groundwater remains less exploited because of the insufficiency of the study concerning the recharge and the sources of their mineralization. The objective of this research is to use the isotope method to characterize groundwater to determine their origin and recharge process. The results of chemical analysis show three different facies type of groundwater which dominated by the sodium, nitrate and chloride ions. The isotopic compositions of the waters sampled vary respectively from -7.25‰ to 5-.09‰ for $\delta^{18}O$ and from -46.9‰ to -24.7‰ for $\delta^{2}H$. Water form the lakes are more enriched compared to those rivers and groundwater. The diagram $\delta^{18}O$- $\delta^{2}H$ shows that groundwater is recharged from local rainwater but undergoes low evaporation before infiltration. However, the results obtained from the parameters measured in situ show that a lateral recharge of groundwater from the streams feeds the neighboring aquifers. Lakes are fed by run-off during the rainy season.

Keywords: Environmental isotopes, water resources, water supply

Introduction

The upper catchment of Ikopa covers an area of 4190 km^2 approximately, and is bounded on the east by Lake Mantasoa and Lake Tsiazompaniry, on the south by the Ankaratra Massif, and finally on the north by Bevomanga Station (Mandanirina, 2015). In this area, the water supply is based on the exploitation of surface water such as streams or lakes for daily use. The use of surface water has a limit because of its risk from pollution, so it is very difficult to exploit for the supply of drinking water (Ratavilahy, 2007). On the other hand, groundwater plays a very important role for the sustainable management of water resources. They are even less exploited due to insufficient information on the study of the recharge of this water table. The isotopes of the $\delta^{18}O$ and $\delta^{2}H$ environment are tracers used to determine the origin of groundwater, migration paths and mixing of groundwater (Fontes, 1986).

On the other hand, isotopic and geochemical indicators are often used as effective methods to solve multiple problems in hydrology and hydrogeology (Cook and Hreczeg, 1999). These techniques will be widely used to obtain groundwater information such as source, recharge and interaction between surface and groundwater (Yang *et al.,* 2012). The technique with the use of stable isotopes as excellent tracers is widely adopted by many researchers on hydrological cycle studies (Chen *et al.,* 2011). A very broad understanding of the origin and behavior of major ions in groundwater can improve understanding of the geochemical evolution of groundwater (Cook and Herczeg, 1999).

Description of study zone

Localization of the study area

The upper catchment of Ikopa (Fig. 1) covers an area of 4190 km², and is limited to the northeast by Lake Mantasoa, to the southeast by Lake Tsiazompaniry, to the southwest by the Ankaratra Massif. , and finally to the northwest by the Bevomanga station (Mandanirina, 2015). In this zone, the water resource is based on the use of surface water such as rivers or lakes for their domestic needs (Rakotondraibe, 2006). The use of surface water has a limit because it is very sensitive to pollution so it is difficult to exploit it for the supply of drinking water (Ratavilahy, 2007). Moreover, groundwater plays a very important role for the sustainable management of water resources but its use is still under exploited because of the insufficiency of the study concerning the recharge problem to evaluate the potentiality of this resource. The isotopes of the $\delta^{18}O$ and $\delta^{2}H$ environment are excellent tracers for determining the origin of groundwater and widely used to study groundwater recharge, migration routes and mixing of water from different sources (Fontes, 1986). The objective of this research is to use the isotope method to characterize groundwater to determine their origin and recharge process. In addition, the isotopic composition provides information on the interaction between groundwater and surface water.

Geologic and hydrogeologic settings

Geologically, the study area is on the crystalline base of the Antananarivo group. This base is formed by a crystallophyllian complex. The rocks that compose it were

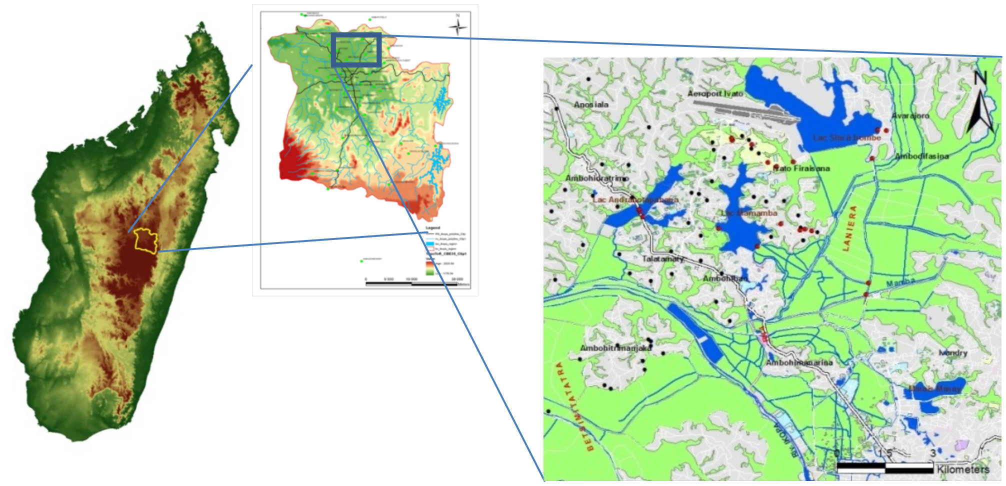

Fig. 1. Localization of the study area

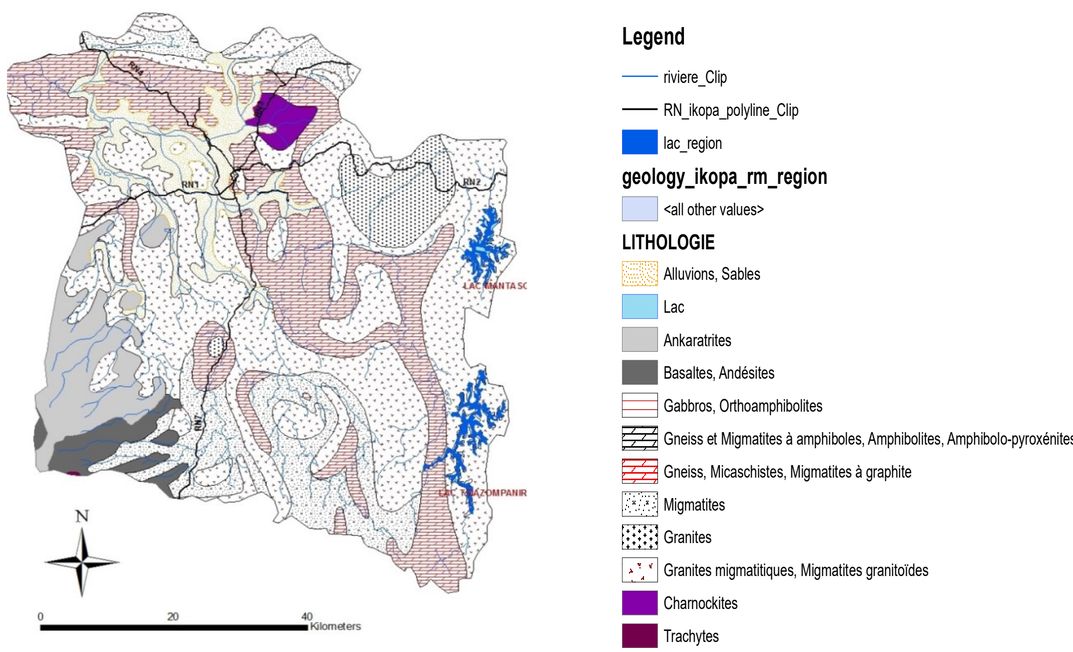

Fig. 2. Geological map of upper catchment Ikopa

grouped into two groups on the basis of lithological, structural and weathering criteria: granitoids and orthogneiss. Orthogneiss are associated with Shamwaian orogeny in the order of 2600 million years. Recent granitization, probably Pan-African, has individualized granitoid units in the Antananarivo region. Most often, the old base is not flush, including the right interfluves where it is present under an alteritic cover that can reach fifty meters thick. The succession of facies of alteration is schematically, from the outcrop to the base:

- a red ferralitic horizon of a few meters;
- alterites (kaolinic alteritic horizon) which correspond to the argilisation zone of the altered materials,
- micaceous arenas, a sand-clay arenitic material,
- the healthy pedestal itself.

From the hydrogeological point of view, the recharge of the alluvial aquifer is mainly ensured in the dry season by the rivers. During the rainy season, the water surplus feeds the water table through infiltration and lateral drainage. The drainage of the sheet is constituted by drains and evapotranspiration. The drainage efficiency is obviously a function of the permeability of the clay-peat cover and the density of the channels.

On the alluvial plain of Antananarivo, there are four types of aquifer (Dussarat B., 1993):

First, a semi-captive arena tablecloth below the clay level to the right of interfluves that surmount everywhere the healthy base.

Second, a sheet of the discontinuous base formed by networks of fissures through the metamorphic bases which are sometimes flush with the surface. It is fed by the layers of arena that surmount it.

Third, a tablecloth in the lowlands which is playing the role of drain.

Finally, an alluvial sheet whose roof is flat with a gradient of average slope towards the north-east of the order of 0.40% continuously fed by surface water.

The alluvial aquifer is fed by three complementary processes:

- Vertically through direct infiltration during precipitation or impoundment of rice fields whose feeding is limited by runoff, evapotranspiration and the clay nature of the outcrop;

- By the underground flows via the basement fracture networks and the altered massifs containing the arena layers;

- Vertically by drainage of the surface hydrographic network. It is controlled by the nature of the material to the right of the minor bed of the watercourse and is all the more important that this material is permeable.

Hydrography

There are three rivers that enter the plain of Antananarivo (Varahina-Ikopa, Mamba, Sisaony), which receive the waters of another river Andromba and its tributary Katsaoka to form the Ikopa downstream of the plain, and which must come out in one place, which moreover is very narrow, namely the threshold of Bevomanga.

Climate

The climate, of tropical type, is characterized by the alternation of a wet season (November - March) and a dry season (from April to October). Located at an average altitude of 1250m, the agglomeration of Antananarivo knows relatively mild temperatures, 13°C on average. In addition, the average insolation is relatively high (2700h / year) and regularly distributed. The average rainfall is 1303mm / year, concentrated almost exclusively during the rainy season, and about 60% during the months of December, January and February.

The rainy events are intense, either stormy type or cyclonic type:

- Stormy rain: very short duration
- Cyclonic rain: short duration, with rework

The decennial rainfall (return period 10 years) is 63mm/h.

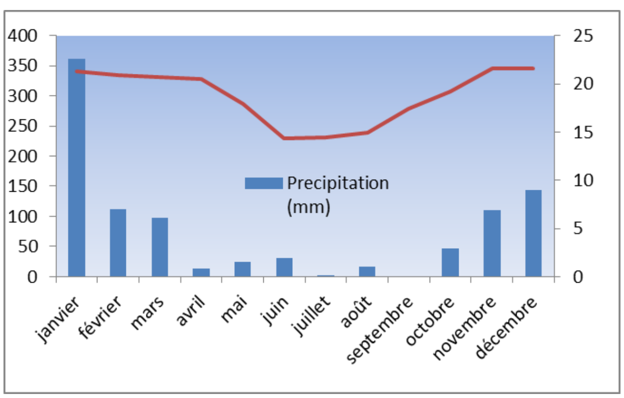

Fig. 3. Précipitation et température mensuelles à Antananarivo

Methodology

We conducted a sampling campaign in October 2017. Fifty (50) water samples were collected from wells, springs, rivers and lakes. Measurements of physical parameters such as pH, temperature, electrical conductivity and dissolved oxygen are made using a multimeter multi 340i. The determination of the alkalinity was made by titration method using a Hach digital titrator. All samples are collected in 50mL polyethylene bottles and stored in the laboratory at a temperature of less than 5°C.

Stable isotope analyzes are performed by PICARRO L-1102i laser spectrometer at the Isotope Hydrology Laboratory of the National Institute of Nuclear Science and Technology (INSTN-Madagascar). The measurement principle is based on the atomic absorption phenomenon using Beer's law. The measurement accuracies are respectively ± 0.15 ‰ and ± 2 ‰ for oxygen and hydrogen.

Results

In situ parameters

The following table shows the values of the different physico-chemical parameters measured on the ground.

Table 1. Values of parameters in situ

Water Types	Temp (°C)	pH	Electrical conductivity (µS/cm)	Alcalinity (mg/L)
Surface waters	21.91±0.49	7.40±0.07	139.28±1.28	·22.57±128.2
Ground waters	20.75±2.98	5.17±0.82	129.23±231.19	41.23±26.02

The average temperature of the surface water and groundwater are respectively 21.91°C and 20.75°C. The surface water temperature is relatively higher than that of the groundwater and they are almost similar because they undergo the same climatic condition.

The pH of the surface waters varies from 6.9 to 8.32 with an average value of 7.4 indicating a basic pH so there is no risk of pollution. In contrast, groundwater has an acidic pH ranging from 3.85 to 6.44 with an average value of 5.17 indicating contamination across the water table.

Surface waters are less mineralized with a mean value of electrical conductivity of 139.28µS/cm. And for groundwater, the average value of electrical conductivity is close to that of surface water, but it varies widely from 21 to 394µS/cm. Therefore, they are more or less mineralized compared to surface waters whose origin could be produced by agricultural and industrial activities.

The alkalinity of surface water samples taken is greater than that of groundwater with mean values of 422.57 mg/L and 141.23 mg/L, respectively. Therefore, surface water is cool compared to groundwater, so it could be fed directly by runoff during the rainy season. The alkalinity of groundwater decreases because of different reactions produced during infiltration.

Chemical facies of groundwater

The concentrations of major ions are plotted in the Piper diagram (Piper, 1944). Hydrochemical facies of waters are classified in three different categories (figure 4). Waters with low electrical conductivity (<100µS/cm) have mainly a Na-Ca-Cl-SO4-NO_3 types. The mineralization of these waters is related on their chemical process and the groundwater recharge. The mineralized waters with electrical conductivity less than 300µS/cm are mixed freshwater and brackish with mixed facies. These are undeveloped waters that are found in the alterite aquifer.

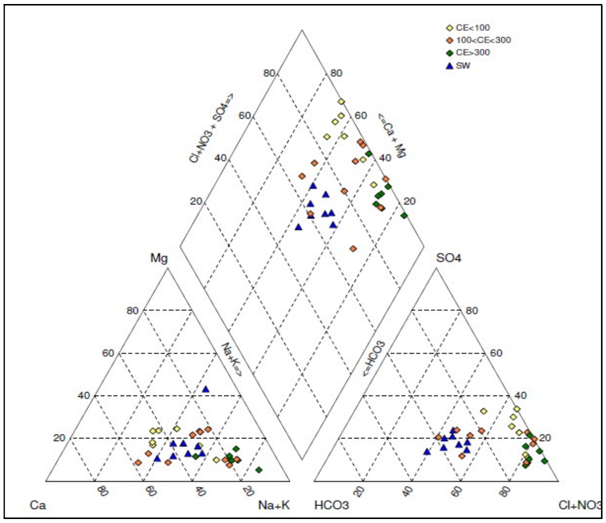

Fig. 4. Piper diagram of plotted samples

Groundwater with electrical conductivity greater than 300µS/cm has Na-NO_3-Cl type chemical facies. These waters are heavily contaminated by man-made chloride and nitrate. Knowing that the water table consists of the sandy alluvium found along the Imamba River, it is very vulnerable to human activity. This high nitrate content can be produced through the use of latrine, wastewater discharges, the use of chemical fertilizers or pesticides for rice cultivation and waste from cattle farming. It can be related to the residence time of the waters in this zone. Surface waters are low mineralized with electrical conductivity values between 29 to 243µS / cm. They have mixed bicarbonate facies that are related to precipitation.

Isotopic composition of waters

The isotopic compositions of the water taken from wells and springs are summarized in Table 2. These values vary respectively from -7.25 ‰ to 4.26 ‰ for δ^{18}O and from -46.9 ‰ to -30.3 ‰ for δ^{2}H. They are therefore depleted compared to river water since their isotopic compositions vary respectively from -6.21‰ to -4.26‰ for δ^{18}O and from -41.3‰ to -30.2‰ for δ^{2}H.

Excess deuterium values for groundwater are similar, however, for surface waters, lakes are more enriched, the excess of deuterium is more negative than river water.

Table 2. Isotopes Composition of all water samples

Types	δ^{18}O (‰)	δ^{2}H (‰)	D_excès (‰)
Puits	-7.25- -4.5	-46.9 - -30.3	11.16
Sources	-6.21 - -4.26	-41.3 - -30.2	8.22
Lacs	2.64 – 5.09	6.6 – 24.7	-15.9
Rivières	-3.85 - -3.57	-27.8- -24.2	3.00

The isotopic signature of groundwater is close to that of local precipitation waters. The groundwater samples plotted along a line which has an equation $\delta^{2}H = 5.94 * \delta^{18}O – 3.19$ (figure 5). The groundwater fall along a trajectory which is consistent with evaporation compared to the local meteoric line.

The isotopic signature of river waters coincides with the line of groundwater but they are more enriched compared to groundwater isotope signature. It is similar for the isotopic signature of lake waters.

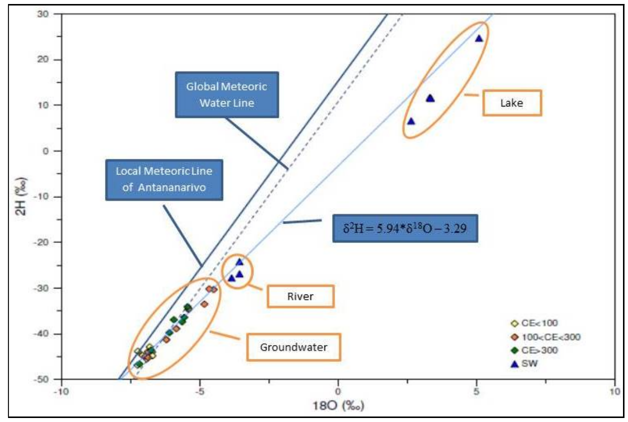

Fig. 5. δ^{18}O- δ^{2}H Diagram

The use of stable isotopes is very important for the evaluation of sources (Fontes, 1976, 1989, Fontes *et al.,* 1986, Gat, 1996, Fritz and Fontes, 1980). The stable isotope composition δ^{18}O and δ^{2}H of the groundwater of an active hydrological cycle are derived from an initial isotopic composition reloading rainwater. The local meteoric line of precipitation at Antananarivo has the equation $\delta^{2}H = 8.22\ \delta^{18}O + 15.3$ according to the IAEA precipitation data from 1960 to 2017. The establishment of the local meteoric water line provides some indication of the origin and process of groundwater recharge. δ^{18}O-δ^{2}H diagram (Craig, 1965) shows that the isotope composition of groundwater with low electrical conductivity is close to the local meteoric line suggesting that these groundwater samples are directly recharged from the rainfall at the summer weather. Moreover, the excess of deuterium for groundwater (d_excess = +11.16‰) is close to the precipitation (d_excess = +13‰) justifies that groundwater recharge is produced from local rainfall during the period of heavy rainfall between December and February. But, the evaporation means that rainfall does not directly infiltrate towards the water table knowing that the geological layer of certain zones is impervious. It is the case of the groundwater recharge at the lateritic aquifer level because runoff is most important.

On other hand, groundwater recharge in the alluvium aquifer at the bottom occurs from a slow infiltration of runoff of by the drainage of rivers.

Isotopic signatures of rivers are relatively enriched compared to groundwater but fall along the same line of evaporation assumes that a connection of surface water and groundwater is present. This assumption must be verified by the results of parameters measured in situ because groundwater and river water have almost the same pH, temperature and electrical conductivity values in some areas.

Regarding the isotope signature of the lakes, they are all more enriched in stable isotopes compared to other waters. Their isotopic compositions coincide with the line of linear interpolation of groundwater. This means that these waters come from rainwater run during the rainy season and undergo strong evaporation because they are closed. This hypothesis is confirmed by the good correlation ($r^2 = 0.996$) that exists between the electrical conductivity and the alkalinity of lake water according to the graph below (Fig. 6). The dissolution of mineral carbonate controls the mineralization of the waters in the lakes.

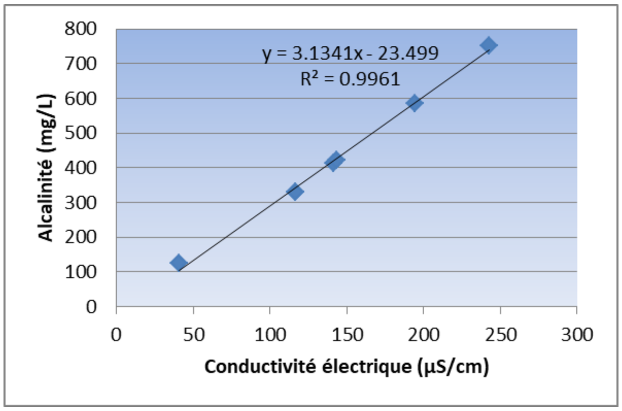

Fig. 6. Relation between alkalinity and electrical conductivity of water lakes

Conclusion

In summary, this study highlights the importance of $\delta^{18}O$ and δ^2H environmental isotopes for determining the origin and mechanism of groundwater recharge in the upper catchment of Ikopa. The diagram $\delta^{18}O$-δ^2H shows that groundwater recharge in this zone is mainly recharged by the local precipitation during the hot and rainy season. The results obtained from the parameters in situ and the isotopic signatures justify an interconnection between the aquifer and the surface waters. Hydrochemical facies of groundwater confirms the chemical evolution and the relation between these waters. Isotopic signatures for the three lakes are similar suggesting that they are supplying from the same process. They are more enriched compared to the groundwater and rivers and their mineralization is controlled by the bicarbonate. It means that they are alimented by the runoff and rainfall during the abundant precipitation.

Acknowledgement

I express my deep gratitude to the Director General of the National Institute of Nuclear Science and Technology-Madagascar for allowing me to carry out analyzes within their laboratory.

My sincere thanks to the Ministry of Water, the Ampandrianomby Meteorological Service and APIPA Antananarivo respectively for the collection of climatic and hydrological data.

References

Baiserie, H, (1970). Geological description of the ancient massif of Madagascar. Volume 6. Le Sud. Doc. Serv. Géol. Tananarive., n°177^e.

Chaperon, P., Danloux, L., and Ferry, L. (1993). Rivers and rivers of Madagascar. P. Orstom (Eds). Hydrological Monographs n°10, 855p.

Chen, J., Liu, X., Wang, C., Rao, W., Tan, H., Dong, H., Sun, X., Wang, Y., and Su, Z. (2011). Isotopic constraints on the origin of groundwater in the Ordos Basin of northern China. *Environmental Earth Sciences,* 66, 505–517.

Cook, P. G., and Herczeg, A. L. (1999). Environmental tracers in subsurface hydrology, Kluwer, Dordrecht.

Craig, H., and Gordon, L. I. (1965). Deuterium and oxygen-18 variations in the ocean and the marine atmosphere, in: Stable Isotopes in Oceanographic Studies and paleotemperatures, edited by: Tongion, E., Laboratorio de geologianucleare, Pisa, 9–130.

Dussarat, B., and Ralaimaro, J. (1993). Hydrogeological characterization of watersheds nested on base altered in tropical areas of elevation : example of the highlands of Madagascar. *Hydrogéologie,* p 53-64.

Fontes, J. C. (1989). Isotopes et ressources en eau. Hydrogéologie 3, 135–142.

Fontes, J. C., Yousfi, M. and Allison, G. B. (1986). Estimation of long term, diffuse groundwater discharge in the northern Sahara using stable isotope profiles in soil water. J. Hydrol. 86, 315–327.

Fontes, J.C. (1976). Environmental Isotopes and Natural Water Cycle: Some Aspects .Ph.D. Thesis, University of Paris VI, 208.

Fritz, P. and Fontes, J. Ch. (1980), Handbook of Environmental Isotope Geochemistry. Elsevier, Amsterdam, p. 21.

Gat, J. R. (1996). Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences,* 24(1), 225-262.

Mandanirina, L. (2015). Evaluation of the ground water potential of the Ikopa plain for the supply of drinking water to the city of Antananarivo and its suburbs. Master memory. University of Antananarivo, 85p.

Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water analysis, Trans. Am. Geophys. Union, Washington, DC. Vol. 25, no.6, pp 914-928.

Rakotondraibe, J. H. (2006). La situation de l'alimentation en eau potable à Madagascar.

Ratavilahy, T. H. (2007). Analysis and diagnosis of drinking water supply, sanitation and hygiene of Grand Tana. Université d'Antananarivo, 81p.

Yang, L., Song, X., Zhang, Y., Han, D., Zhang, B., and Long, D. (2012). Characterizing interactions between surface water and groundwater in the Jialu River basin using major ion chemistry and stable isotopes. *Hydrology and Earth System Sciences,* 16, 4265–4277.