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Bertil Nlend

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**THÈSE DE DOCTORAT EN COTUTELLE INTERNATIONALE PRÉPARÉE A
L'UNIVERSITÉ DE BOURGOGNE FRANCHE-COMTÉ**

École doctorale n°554
Environnement-Santé

Doctorat de géologie - Structure et évolution de la Terre

Par

M. Bertil NLEND

**Processus hydrologiques dans une zone côtière hyper-
humide sous forte influence anthropique (Douala,
Cameroun). Une étude géochimique de la dynamique
de l'eau de l'atmosphère au sous-sol.**

Thèse présentée et soutenue à Besançon, le 10 septembre 2019

devant le jury composé de :

M. HUNEAU Frédéric	Professeur à l'Université de Corse - Pascal Paoli	Président
M. Stephen FOSTER	Professeur à l'University College of London	Rapporteur
M. Philippe LE COUSTUMER	MCU HDR à l'Université de Bordeaux 1	Rapporteur
Mme. Camille RISI	Chargé de Recherche HDR à l'Université Paris Sorbone	Examineur
M. Benjamin POHL	Chargé de Recherche HDR à l'UBFC	Examineur
M. Guillaume BERTRAND	MCU à l'UBFC	Examineur
Mme. Hélène CELLE-JEANTON	Professeur à l'UBFC	Directrice de thèse
M. Jacques ETAME	Professeur à l'Université de Douala	Co-directeur de thèse
M. Marc STEINMANN	MCU HDR à l'UBFC	Invité



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« Je me suis toujours posé des questions sur les gouttes de pluie. Je me demande comment elles tombent en trébuchant les unes sur les autres, en se brisant les jambes et en oubliant leur parachute quand elles dégringolent direct du ciel vers une fin incertaine. »

“I always wondered about the raindrops. I wonder how they fall stumbling over each other, breaking their legs and forgetting their parachute when they tumble down from the sky towards an uncertain end.”

Insaisissable, tome 1 : Ne me touche pas de Tahereh Mafi

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Tout au début de cette belle aventure qu'est la thèse se trouve une femme qui avait dédié la majeure partie de sa vie de sciences à l'hydrogéologie du bassin de Douala. **Béatrice Ketchemen-Tandia** est celle qui a guidé mes premiers pas dans la recherche en dirigeant mes travaux de Master sur la signature isotopique des pluies à Douala. C'est elle qui très tôt m'a mis à l'école des articles ; elle m'a mis le pied à l'étrier et m'a aidé à développer ma passion pour les isotopes. Je n'oublierai jamais toute la peine qu'elle a prise lors de la constitution de mon dossier pour l'obtention de la bourse de doctorat que j'aurai finalement eue. Je n'oublierai jamais son implication financière et matérielle lors de mes campagnes de terrain. Bien plus qu'une encadrante, Béatrice a été pour moi comme une mère. J'aurais aimé la compter parmi les membres du jury ce 10/09/2019 jour de ma soutenance, mais le ciel en a décidé autrement. De là où elle se trouve j'espère qu'elle est fière de moi et je lui fais la promesse d'être un bon hydrogéologue pour mon pays comme elle l'a toujours souhaité.

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Chapter I

General introduction

Global context: the dynamic environment of the humid tropics

Humid tropics represent the most dynamic environment in the world (Wohl et al. 2012). Convergence of surface trade-wind easterlies and equatorial westerlies within the humid tropics creates deep convection and often cyclonic vorticity conducive to tropical cyclogenesis. Compared with humid temperate zones, the humid tropics are characterized by greater energy inputs in the form of fluxes of water vapour from the mid-latitudes, more intense precipitation, rapid weathering of inorganic and organic materials, and rapid introduction of large volumes of water and sediments (Stallard & Edmond 1983; Liu & Zipser 2008). These regions produce the greatest amount of runoff (Feteke et al. 2002). According to Fosberg et al (1961), they correspond strictly to areas where (i) the mean monthly temperature for at least eight months of the year equals or exceeds 68°F (20°C.); (ii) the vapor pressure and relative humidity for at least 6 months of the year average ~20 millibars and 65% respectively; (iii) the mean annual rainfall exceeds or ranges from 1500 to 2500 mm and; (iv) rain falling all year with at least six months having precipitation ≥ 75 mm each month. In addition, Salati et al (1983) and Lugo and Brown (1991) mentioned that humid tropics are regions where rainfall exceeds evapotranspiration for at least 270 days in a year.

This dynamic is increasing sharply in coastal environments. Indeed, coastal zones are constantly subjected to the effects of energy flows (from tides, waves and swells, wind, solar radiation and rivers) and receive inputs of organic and mineral matter issued from the land and marine ecosystems around it. Moreover, recently, scientific community, politics authorities and non-governmental organizations recognized that coastal areas in the world suffer from sea level rise (Grip 2017).

This description of humid coastal areas dynamics is incomplete without taking into account the human factor. Indeed, humid tropics cover one-fifth of the global land surface and nearly two-thirds of the human population lives and works within 150 km of a coastline (Hinrichsen 1999), placing substantial pressure on coastal areas. Population pressure in developing and low-income countries has led to increasing fragmentation of land cover (through forest cuttings, urbanization and industrialization), with consequent effects on hydrological fluxes (Hansen et al. 2008) from deep groundwater to the troposphere (Wohl et al. 2012). Of particular concern are groundwater system which is an integral element in humid tropical ecosystem (animal-plant-soil-surface water), because of the intimate relationship between

surface and groundwater and the frequently shallow groundwater table with abundant phreatophytic vegetation in such environments (Foster & Chilton 1993).

Local context: the region of Douala, a hyper-humid coastal site

The region of Douala (Cameroon, Western Central Africa) concentrates all the features presented above. It is a coastal site near the equator (Figure 1), a port city, a megacity with exponential demographic rate in Western Central Africa, the economic capital of Cameroon with several industries (textile, agro-food, chemistry, glass, cement, wood, fertilizer, etc) and it has one of the highest yearly rainfall amount (~ 4m) in the world.

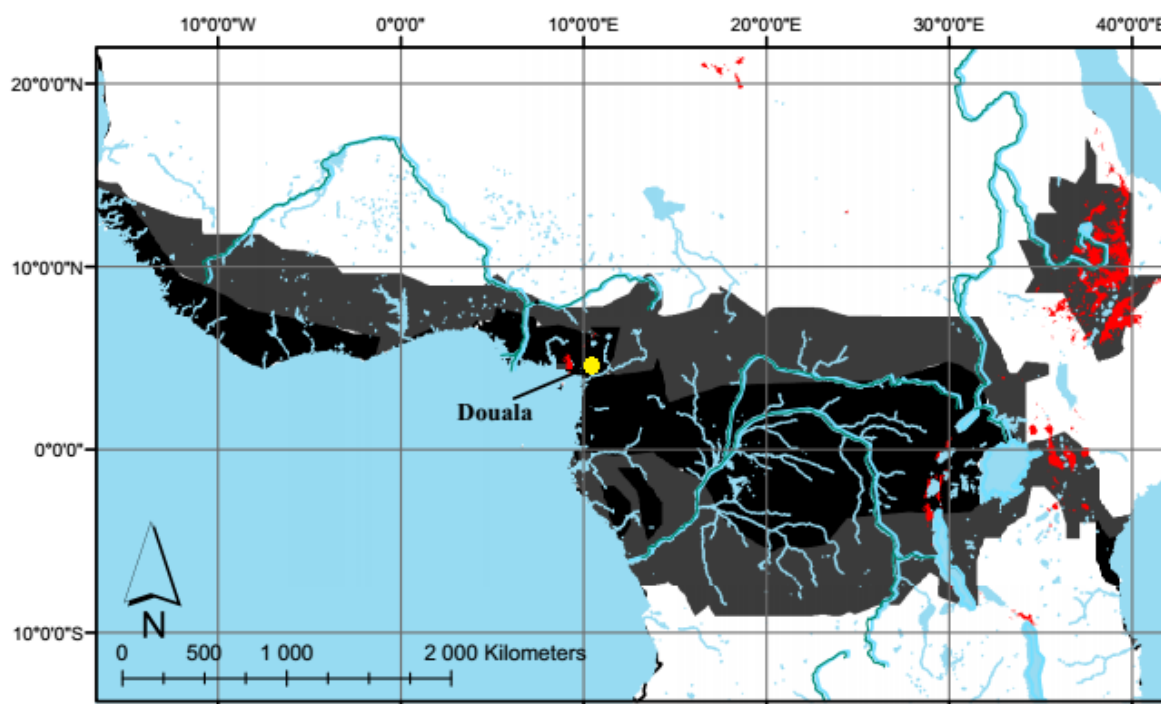


Figure 1: delimitation of humid tropical areas in Africa (Fosberg et al. 1961; modified). The red surfaces represent mountains which have an elevation of more than 2,000 m. Areas in black colour are characterised by permanent high humidity (dry periods are almost non-existent) while in regions displayed in grey colour there is a contrast between a drier and a wetter season. The location of Douala (yellow point) is also plotted.

In this context of population growth, of urbanization and industrialization, access to water is a major challenge for government despite abundant water resources. To cope with the growing demand for drinking water, public authorities of Douala have progressively turned to aquifers (Table 1) which are more protected from surface pollution and require thus less treatment processes. Thus, groundwater accounts nowadays for about 49% (22% and 27% respectively from Paleocene and Mio-Pliocene aquifers) of the total volume of water distributed by the Camwater (Cameroon Water Utilities Corporation) while 51% corresponds to surface water exploitation (Dibamba and Mungo Rives). The Table 1 well summarizes all these information on public water supply at Douala.

Table 1: public water supply at Douala. Data sources: Leutou (2010); Ketchemen-Tandia (2011) and INSIGHT BDS (2013).

Exploited water		volume of water dispensed (m ³ /day)	Percentage in the global water supply	Start of operation
Surface water	Dibamba River	65,000	29	1950
	Moungo River	50,000	22	2010
Groundwater	Paleocene aquifer	50,000	22	1984
	Mio-Pliocene aquifer	60,000	27	1998
Total		225,000	100	

However, more than 50% of the population in the Douala region is not registered to the Camwater and therefore is not considered in the public water supply. This part of the population use waters from springs, hand-dug wells and/or private boreholes tapping the Mio-Pliocene. The number of private boreholes and private hand-dug wells is constantly increasing. For instance, [Ketchemen-Tandia \(2011\)](#) revealed that the number of private boreholes in Douala, accounting for 300 in 1996, has been multiplied by ten during the last decade showing firstly the increasing interest on groundwater potential and secondly the increase of water demand due to population growth.

Issue

Since in these humid areas, groundwater is strongly exploited for -and possibly degraded by- human activities, there is an urgent need to increase the knowledge of aquifers functioning. This was pointed out by the scientific community since 1989 and 1999 ([UNESCO 1990, 2000](#)) at the first and second International Symposium on Hydrology and Water Resources Management in the Humid Tropics but is still of a great concern. To conduct a sustainable water management, we have to know if the aquifer potential is maintained in terms of quantity and quality, regarding the inadequately controlled exploitation and the poor sanitation network (characteristic of sub-saharan countries, see [Banerjee & Morella 2011](#)) in the study region. Moreover, as recharge of aquifers may oper all the year long in such tropical humid regions, this knowledge should include a comprehensive understanding of water fluxes from atmosphere to groundwater and vice versa.

Objectives

Then the main goal of this thesis is, with the help of chemical and isotopical tools, to determine the hydrological and hydrochemical processes that affect water fluxes through the critical zone (land-atmosphere-subsurface continuum) in the hyper-humid context of Douala with particular focus on:

- meteorological factors controlling rainfalls within Western Central Africa and more peculiarly at Douala;

- mode, time and rate of groundwater recharge;
- hydrodynamical or hydrogeological conditions of groundwater flow (confined/unconfined, velocity, groundwater flow paths and mixing);
- discharge area of groundwater
- Mio-Pliocene aquifer's vulnerability (quantitatively and qualitatively) to human activities

Document outline

This thesis is organized in 6 chapters. Following this one, the chapter 2 presents the water sampling strategy and the data obtained or collected for this project. In chapter 3, we study the atmosphere dynamic through identification of processes controlling the rainwater isotopic composition. In chapter 4, thanks to information on the input signal, we focus on the hydrogeological functioning of groundwater. Then in chapter 5, we evaluate the groundwater response to human induced changes.

Chapter II

Water sampling strategy, data and analytical methods

The general objective of our study is to characterize the hydrological processes that affect the critical zone of a hyper-humid tropical region. Then we decide to study both the atmospheric and groundwater cycles by using water stable isotopes (^{18}O and ^2H) and major ions (Cl^- , SO_4^{2-} , NO_3^- , HCO_3^- , Na^+ , K^+ , Mg^{2+} and Ca^{2+}). Coupling with atmospheric and hydrological data; the effectiveness of these natural tracers is nowadays well recognized by the scientific community. This chapter is dedicated to present the strategy deployed for the sampling and analysis of rainwater and groundwater in order to answer the main goal of the study.

The atmospheric water cycle was studied using the stable isotopic composition of water vapour and rainwater. We were greatly inspired by the work of Camille Risi (Risi 2009, 2017) and Françoise Vimeux (Vimeux 2011) who used stable isotopes to understand atmospheric processes in various regions in the tropics. Sub-surface hydrology was addressed using isotopic and chemical composition of groundwater in addition to a precise hydrogeological characterisation and water level and flow measurements.

Since a clear description of the methodology will contribute to validate the approach and interpretations developed throughout the manuscript, we present below a description of rainwater and groundwater sampling networks which have been set up or used during the study, sampling and measurements protocols and additional data such as satellite information and hydrological data used for interpretation.

1. Atmospheric water investigation

1.1. Rainwater sampling sites

In order to characterize the isotopic signal of rainwater, we firstly relied on monthly data of the GNIP (Global Network of Isotopes in Precipitation) station of Douala (Table 2). This latter was installed in June 2006 by the hydrogeology team of the Earth sciences Department (University of Douala, Cameroon). The isotopes measured at this station are oxygen-18 (^{18}O) and deuterium (^2H) of the water molecule. Nowadays, it is the oldest existing GNIP station in Central Africa with more than ten years of continuous isotopic record. In this thesis, we use monthly data from June 2006 to December 2016 (which were available at the beginning of this project).

Table 2: location and sampling periods for the different sampling sites at Douala.

Stations	Longitude (E)	Latitude (N)	Elevation (m)	Sampling periods
Douala GNIP-Station	9.7342 E	4.0367 N	40	2006-2016
Douala-University	9.7461 E	4.062 N	20	March 2017 – August 2017

Regarding its position at the centre of Douala (Figure 2), and its altitude (Table 2) close to the mean altitude of the study area (38 m), the GNIP station of Douala can be considered as representative of the study region.

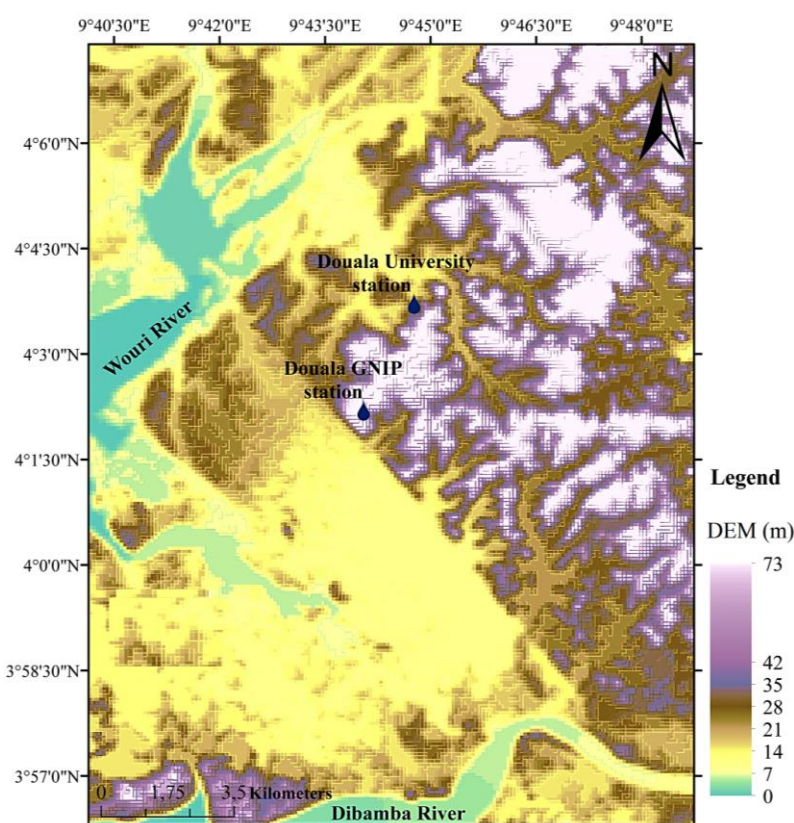
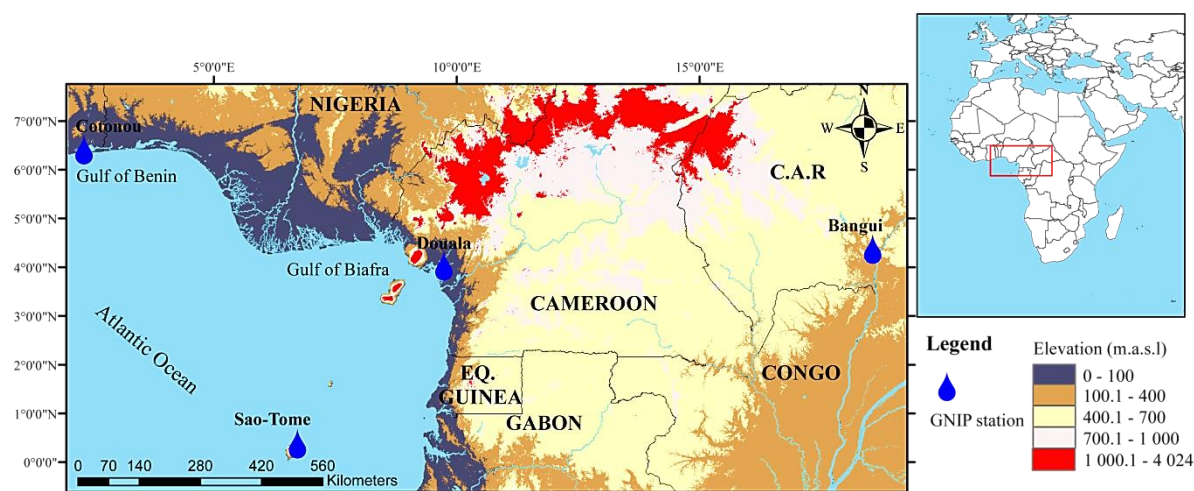


Figure 2: location of rainwater sampling sites with DEM (digital elevation model) on background.

We also used data from other GNIP stations (Table 3) to compare their main features to the ones of Douala and to link their behaviour on a climatological and meteorological point of view, to the regional atmospheric circulation. We selected stations localised either along the western Africa coastline or in the tropical forest region of Central Africa closed to Douala, with an isotopic chronicle, sufficiently long. The three stations indicated in Table 3 match these requirements: Cotonou, Sao-Tome and Bangui (Table 3, Figure 3).

Table 3: GNIP stations used in this study in complement to data from the Douala-GNIP station.

Stations	Longitude (E)	Latitude (N)	Elevation (m)	Sampling periods
Cotonou	2.3293	6.4172	14	2005-2012
Bangui Université	18.5625	4.3771	363	2009-2016
Sao-Tome	6.72	0.38	8	1962-1976

**Figure 3:** Location of GNIP stations of Cotonou, Bangui, Douala and Sao-Tome.

As for the GNIP station of Douala, the stable isotopes of the water molecule are measured at these stations on a monthly basis. The meteorological settings such as rainfall amount, air temperatures relative humidity and vapour pressure are obtained at the national meteorological centre of each country.

Since individual meteorological events are hidden at a monthly scale, we complete the monitoring network by a specific station dedicated to daily measurements. This station called Douala-University is located 3.5 km NNW to Douala-GNIP (Figure 2), closed to our research building in the University campus in order to monitor it more easily. Measurements begin in March 2017 and last till August 2017 in order to sample the major rainy events for one year.

Douala-GNIP and Douala-University stations have been set far away from trees (precisely at a distance corresponding to the double of height of surrounding trees), roads, buildings etc. to avoid influence of these elements.

1.2. Rainwater sampling protocols

Monthly scale

Monthly samplings achieved in the GNIP stations follow the standard protocols of the International Atomic Energy Agency (IAEA 2012). At Douala-GNIP, samples were collected by using a rain gauge which consists of a plastic funnel coupled with a filter mesh to prevent debris contamination (Figure 4). Approximately 0.5 cm layer of light paraffin oil (available in all chemistries) has been systematically added into the rain collector. Paraffin oil floats on the water sample in the collector and prevents sample evaporation.



Figure 4: Douala GNIP station.

Samples are taken regularly (every week during the dry season and almost every day during the rainy period), so that a GNIP sample represents the total natural precipitation of a calendar month. Each monthly sample was stored in a totalizer and kept at 4°C before being transferred in 50 ml amber glasses bottles tightly capped (Figure 5).

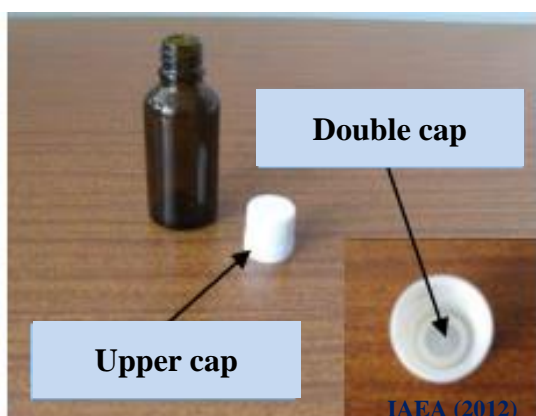


Figure 5a: Borosilicate glass flask.



Figure 5b: Twelve rainwater samples of one year ready to be sent to the laboratory.

It is this aliquot part of rainwater which is sent to the International Atomic Energy Agency (IAEA) laboratory, Vienna, Austria for stable isotopes (^{18}O and ^2H) determination. We careful mark on the bottle the presence of paraffin oil and at the laboratory, before analyses, removal paraffin oil is proceeded.

The number of samples collected and analysed along the sampling period is presented in **Table 4** as well as those of Cotonou, Bangui and Sao-Tome involved in this study. For these stations, the data are available on the GNIP database at: <https://nucleus.iaea.org/wiser>.

Table 4: Number of samples for each sation.

Stations	Sampling period	Number of samples
Cotonou	2005 - 2012	95
Bangui	2009 - 2016	81
Douala	2006 - 2016	106
Sao-Tome	1962 - 1976	123

Daily scale

Daily samples were collected at Douala-University every rainy day as soon as possible after the rain-event by using a Palmex rain gauge (**Figure 6**) that presents the advantage to avoid evaporation without using medicinal paraffin oil (Gröning et al. 2012).

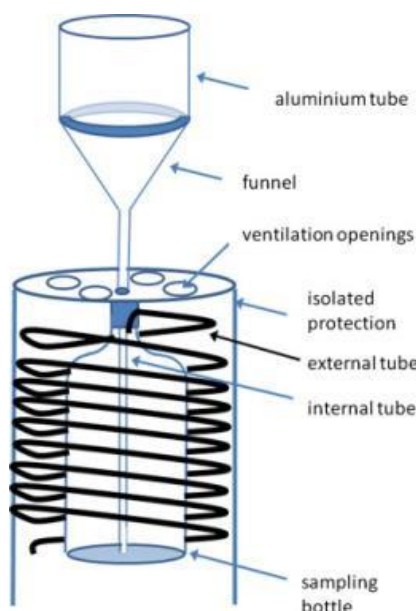


Figure 6: Scheme of the daily precipitation water sampler (Gröning et al. 2012). Marked in black, the external plastic tubing around the sampling bottle is dedicated to pressure equilibration and avoids evaporation.

Samples are taken in 50 ml amber glasses bottles (presented above) that have been sent after the 6 months campaign to the hydrogeology Department, UMR 6134 SPE of the University of Corsica for isotopes determination.

It should be noted that monthly and daily sampling strategies presents both advantages and disadvantages described in **Table 5**.

Table 5: Rainfall monthly monitoring: advantages and disadvantages.

	Monthly sampling	Daily sampling
Advantages	<ul style="list-style-type: none"> • Sufficient temporal resolution for groundwater and catchment hydrology • Compliant with any other monthly averaged data • Lower analytical effort and cost (maximum of 12 samples / year / station) 	<ul style="list-style-type: none"> • Allows obtaining data at high temporal resolution • Is an appropriate method in hyper-humid area where convective activity is intense (risk of not seeing extreme events is high when accumulating).
Disadvantages	<ul style="list-style-type: none"> • Can blur significant rainfall events (which may have distinctive isotope values) • Risk of sample evaporation during totalized collection or long storage 	<ul style="list-style-type: none"> • Needs permanent observer or highly sophisticated sampling equipment, high cost • Higher analytical effort and cost (considerable number of samples per year/station)

In parallel to isotopic investigation, meteorological data (rainfall amount, air temperatures, vapour pressure, relative humidity and evaporation), at monthly and daily scales (only for 2017) are continuously collected at the meteorological service of Douala from the station which present the followed coordinates: 04°01'N, 09°42'E and an altitude of 25m. Thanks to this data collection, we have 65 years of monthly rainfall amount data (between 1951 and 2016), 45 Years (1971-2016) of data on monthly air temperatures and more than 20 years of vapour pressure, relative humidity and evaporation data.

1.3. Satellite dataset

In addition to field measurements, data from satellite have been integrated in this project. The combination of these different dataset aims to make our study robust and will be helpful for the understanding of the regional atmospheric circulation since information provided by satellite cover generally a large area.

TES (Tropospheric Emission Spectrometer): measurements of water vapour isotopic content

With the advent of new technology in stable water isotopes, it has become easier to analyze isotopic composition of water vapor from measurements within satellite (Aemisegger et al. 2012). Thus, TES instrument on board on the Aura satellite is a nadir-viewing infrared Fourier transform spectrometer from which the deuterium content of water vapor (δD_v) can

be retrieved (Worden et al. 2006; Worden et al 2007). In this project, we used δD values acquired at 900 hPa (closest data from the soil/sea surfaces) from 2004 to 2008, period in which both isotopic and TES data (covering the study area) are available. More details can be found in the section 3 of chapter III.

GPCP and SAFNWC products: information on intensity and organization of convection

Convective activity prevails in the tropics and impacts isotopes variation in rainwater. Its effects have been analysed using the Global Precipitation Climate Project (GPCP; Huffman et al. 2001) data and cloud type (CT) products issued from geostationary MSG (Meteosat Second generation; Derrien & Le Gléau 2005).

GPCP data were retrieved from the National Oceanic and Atmospheric Administration (NOAA) website (<https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>). These data used both for monthly and daily analyses, allows the evaluation of convection intensity and its control on rainfall isotopes.

The organization of convection in the region (and its influence on precipitation isotopes), have been assessed by using CT products developed by SAFNWC (Satellite application facilities in support to nowcasting) /MSG algorithms (for more information see <http://www.nwcsaf.org/web/guest/scientific-documentation>).

More details concerning these datasets are presented in the section 3 of chapter III.

1.4. Representativeness of the study period

Since the measurement period is different from one station to another, to validate our interpretations and to generalize them, we must evaluate the representativeness of these periods in relation to the normal ones. (Figure 7). The difference between the normal (3846.7 mm) and the mean rainfall (3717.1 mm) amount recorded during the GNIP sampling period do not exceed 3.5% at Douala. This low value highlights the great representativeness of the GNIP sampling period at Douala for climate study and therefore, interpretations that we will formulate below, will not be limited to a restricted timescale. However, at Cotonou, Bangui and Sao-Tome, a large difference of respectively 9.3%, 22.1% and 12% exists between the normal and the mean rainfall amount over the GNIP sampling periods. Thus for these stations, interpretations should be reported to the study period and any extrapolation to a larger period should take into account this lack of representativeness of the meteorological parameters.

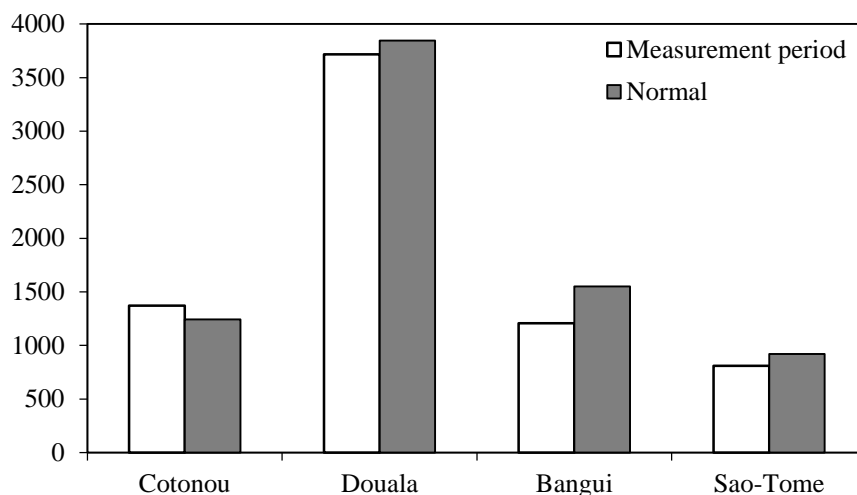


Figure 7: Average annual rainfall for each station compared to normal (over 30 years).

We also checked the representativeness of monthly GNIP measurements at Douala month by month. Monthly precipitations recorded during the GNIP monitoring from June 2006 to December 2016 are mostly in the range of $\pm 5\%$ relative to the normal (Table 6). Only the months of January, May and July show a deficit of 29, 15 and 17% (Table 6). This can be explained by the low number of samples in January and by relative dry conditions in May and July compared to the normal conditions. However, in November and February, up to 24% more precipitation is observed (Table 6). Finally, for the majority of months, the gap between the normal and measured rainfall amount is weak. For a study at a seasonal scale, we can consider that the data covering the study period are representative of the climate context at Douala.

Table 6: comparison of normal (over 30 years) and measured rainfall amount during the study period from June 2006 to December 2016. The gap is the difference between the two measures and n is the number of GNIP samples collected.

	1	2	3	4	5	6	7	8	9	10	11	12
Monthly normal (mm)	41	66	173	242	280	445	668	742	618	400	144	34
Mean monthly GNIP precipitation (mm)	29	82	170	240	237	463	556	716	633	383	178	33
Gap (%)	-29	+24	-1.7	-0.8	-15	+4	-17	-3.5	+2.4	-4	+24	-3
n	4	6	7	9	10	11	11	11	10	10	10	7

Furthermore, we note that the number of samples often varies from one month to another (Table 6). This is due to the lack of rain during certain periods. Moreover, samples which have been subject to evaporation (resulting of sampling or rainwater storage which does not respect the protocol) have not been considered.

Concerning the daily data, the 70 samples collected between March 2017 and August 2017 give a total rainfall amount of 2054 mm which account for about 55 % of the annual average rainfall recorded during the 11 years monthly monitoring at Douala GNIP station attesting the representativeness of this sampling period.

2. Groundwater investigation

2.1. Choice and description of sampling points

Sampling points were at first selected to obtain a relative good distribution throughout the Douala region. Sampling points are however concentrated in the urban centre of Douala (Figure 8) where there is the maximum of wells used by households and industries. The following criteria were considered for the choice of points:

- we ensure that the identified well (hand-dug well or borehole) taps the target aquifer for this study
- accessibility of wells (hand-dug wells and boreholes),
- existence of protective measures against surface pollution and the fact that the well is used by the local population,
- boreholes must have basic information such as drilling log.

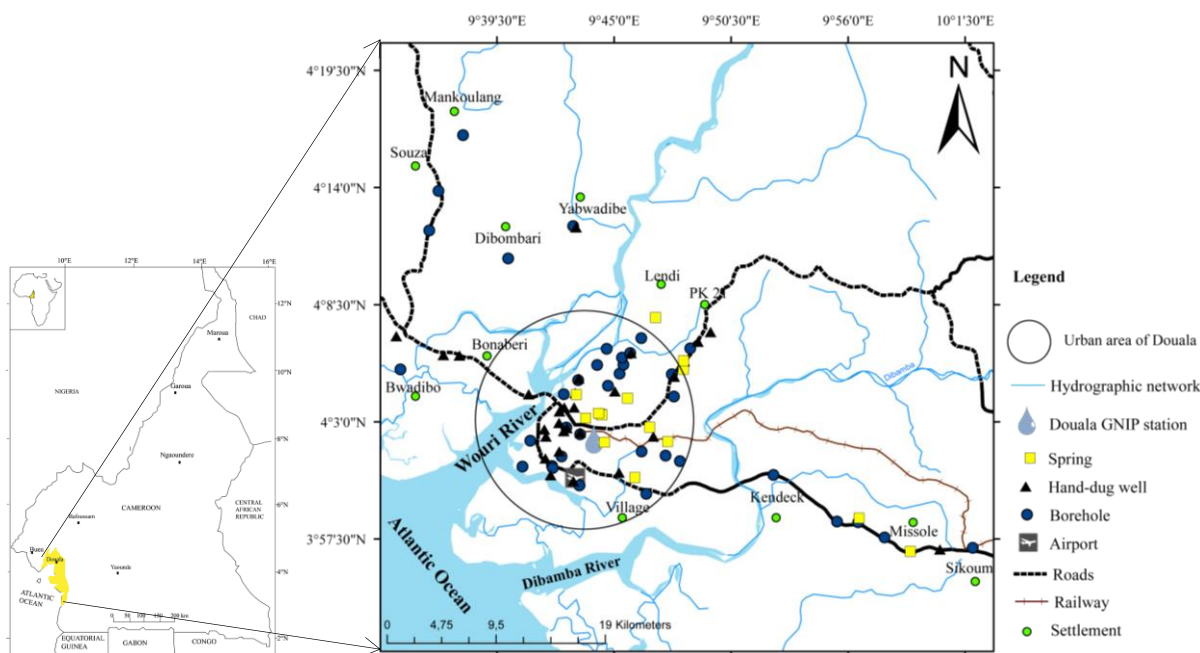


Figure 8: sampling map.

In addition, we made the effort to have one sample per neighbourhood. So by applying all these criteria, we sampled water in 48 wells (28 boreholes and 20 hand-dug wells) and 10 springs. Unlike many previous works, we selected bore wells with water table as far away to the soil surface in order to avoid eventual influence of surface pollution and capture the natural geochemical background of water.

Borehole

Boreholes in the study area are often equipped with foot, hand pumps or directly connected to a faucet (**Figure 9**). They are used by industries and population for drinking water and domestic uses. The depth of sampled boreholes varies from 45 m to 140 m. The only disadvantage of this engineering structure in Douala is that they are most of the time screened at several depths. This can complicate the understanding of groundwater flow and hydrochemical processes which take place within the aquifer.



Figure 9: some types of boreholes in the region of Douala.

Hand-dug wells

They are usually called traditional wells and have depths varying between 1 and 17 m. People generally use it only for domestic uses (e.g. laundry and housework). The types of hand-dug wells encountered at Douala are presented on **Figure 10**. The well-coping (cemented, made of sheets metals or wheels of trucks) when they exist often reach 0.5 m. There are no protection zones but wells openings have lids to protect water from occasional pollution from external sources. The great disadvantage of hand-dug wells lies in their maintenance. The walls of these wells are poorly cemented, so that they crumble easily, under the action of infiltration of runoff water. Moreover, we often found in the wells the presence of tree roots.



Figure 10: types of hand-dug wells in Douala.

Springs

Springs encountered at Douala are located at the bottom of steep slopes, bordering important marshy areas. These emergences called overflow sources (GRET 1987) are due to the intersection of the upper surface of an impermeable layer with the topographic surface. A conceptual scheme is presented in Figure 11 and we can see on Figure 12 some pictures of sources in Douala. These latter are arranged in a simple way using a pipe through which water flows (Figure 12).

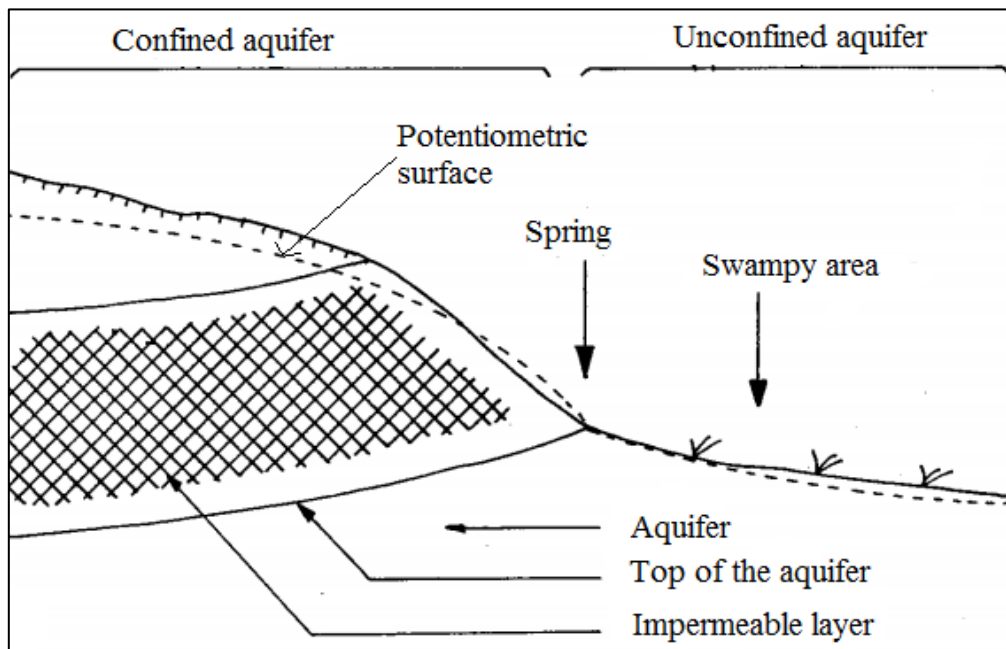


Figure 11: conceptual scheme of an overflow spring (modified from GRET 1987).



Figure 12: Springs in Douala.

Despite their general difficult accessibility, water from springs is used in Douala both for domestic uses and drinking water.

2.2. Sampling protocols

Sampling has been carried out in February 2017 during 12 days. We choose to perform the sampling at this time corresponding to the “dry season” in Douala, because

- (i) the study region undergoes almost continuous rainfall during the year. The existing dry season is not strong (more details in Chapter III) and therefore we supposed that the groundwater is recharged along the year;
- (ii) we expected to observe the real geochemical signature of groundwater without external influences at this time period. Indeed, Douala is submitted to a very long rainy season lasting from March to November (see chapter 3) with a peak in July-August. During this period of July-August, rainfall amount is higher than 1 m, groundwater table is close to the soil surface, blending with runoff and renewal of groundwater corresponds to a mixing with various leachates mobilized by the important water fluxes. Therefore, we estimated that the water sampled at this time would not be representative of the aquifer itself. This second fact motivated us to make one sampling campaign instead of two as usually done in hydrogeology studies;
- (iii) many authors in similar climate contexts previously show that there is no significant difference in groundwater geochemical signature between the dry and the rainy season (e.g. [Djebebe 2014](#), [Ngo Boum et al. 2015](#) and [Emvoutou 2018](#)).

A sampling day was conducted from morning (~08 AM) to early evening (~05 PM) with temperatures ranging from 23.5 ° C to 34.8 ° C.

All the different field measurements can be summarized in the following way for each sampling point:

- (i) *Well purging* (for wells)
This procedure concerns both boreholes and hand-dug wells. The purging allows draining the stagnant water from the well to obtain a sample that represents groundwater from the aquifer. However, assuming the fact that wells in Douala are daily used for domestic supply, it was considered that there is no stagnant water within the well and that their purge is already achieved.
- (ii) *Taking geographical coordinates*
By using a Garmin GPS, longitude and latitude has been recorded. The altitude (Z) was determined further on Arc Gis, software dedicated to cartography.
- (iii) *Measurement of groundwater table*
The depth of water in the well relative to the soil surface *i.e* groundwater table (h) has been measured by using a potentiometric probe ([Figure 13](#)). Thanks to this measure, the potentiometric surface (H) has been calculated through the equation 1.

$$H = Z - h \quad (1)$$



Figure 13: measurement of water table in a hand-dug well.

- (iv) *Measurement of physicochemical settings (pH, Electrical Conductivity, Temperature and Dissolved Oxygen)*

It was performed by using a WTW 2FD46G multi-parameter kit. These measurements have been carried out for non-stagnant water in a beaker. They have been validated only after all the in situ parameters reached the stability for three consecutive measurements separated by 5-minute intervals.

- (v) *Rinsing of sampling bottles* (for chemical and isotopic analyses) with water to sample (3 to 4 times)

- (vi) *Filling two polyethylene bottles* of 30 ml dedicated to cations and anions analyses through 0.45 μ m syringe filters (Figure 14). Samples for cations were acidified with ultra-pure nitric acid (HNO₃)

- (vii) *Filling amber glass bottles* (presented above in rainwater sampling) without filtration for stable isotopes analyses.

- (viii) *Bicarbonates measurement*

Here we used the method of titration with sulfuric acid solution and coloured indicator (bromocresol). This latter is added in 100 ml of water. The titration by H₂SO₄ is then done gradually and HCO₃⁻ content is determined when the sampled water turns from green to pink colour. The detection threshold for this method is 0.1 mg/l CaCO₃ (Stumm & Morgan 1996).



Figure 14: water filtration during sampling;

Figure 15 summarizes all the equipment deployed for this fieldwork.

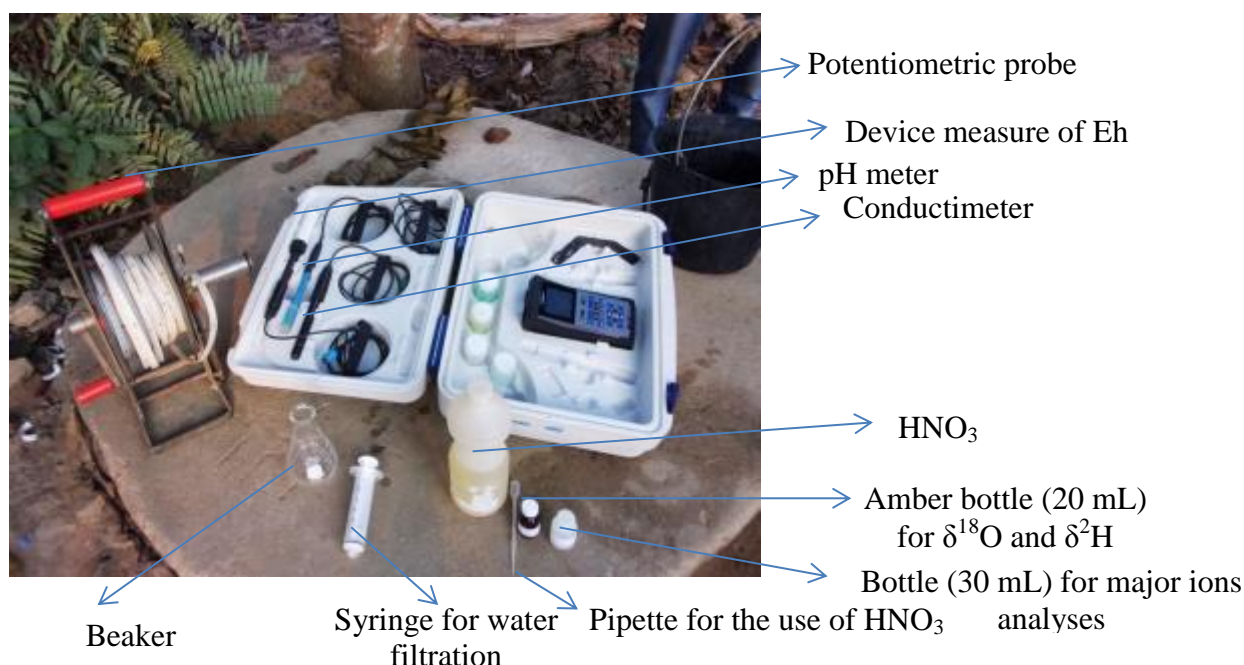


Figure 15: Field equipment.

At the end of the measurements and sampling, the samples were kept cool in ice boxes before shipment to the laboratory for analyses of major ions and stable isotopes.

2.3. Database

Figure 16 well summarizes the methodology developed for groundwater investigation. Long-term monthly meteorological data (monthly rainfall, air temperature and evaporation rate) acquired at the meteorological service of Douala (Cameroon) and GNIP dataset represent the input of the database which has been constructed in order to understand subsurface hydrology of the study region.

Data concerning the base flow (such as runoff) and the soils properties was compiled from previous works (Ndome 2010; Emvoutou 2018).

Drilling logs and hydrodynamics parameters (transmissivity, discharge flow, permeability and storage coefficient) which are collected from drilling companies by the hydrogeology team of the Earth Sciences Department (University of Douala) since several years constitute the third element of our database for this project.

Chemical data on aquifers (and more or less from surface water) compiled from studies on groundwater quality (Eneke et al. 2010; Kopa et al. 2012; Ngo Boum et al. 2015; Fantong et al. 2016; Tatou et al. 2017; Ketchemen-Tandia et al. 2017 and Wirmvem et al. 2017) have also been integrated firstly to have an overview of issues on groundwater resource in Douala and secondly to identify an evolutionary trend in some chemical species.

Coupled with measurements carried out in February 2017 in the framework of this thesis, all this dataset will provide insights on hydrogeology of Douala.

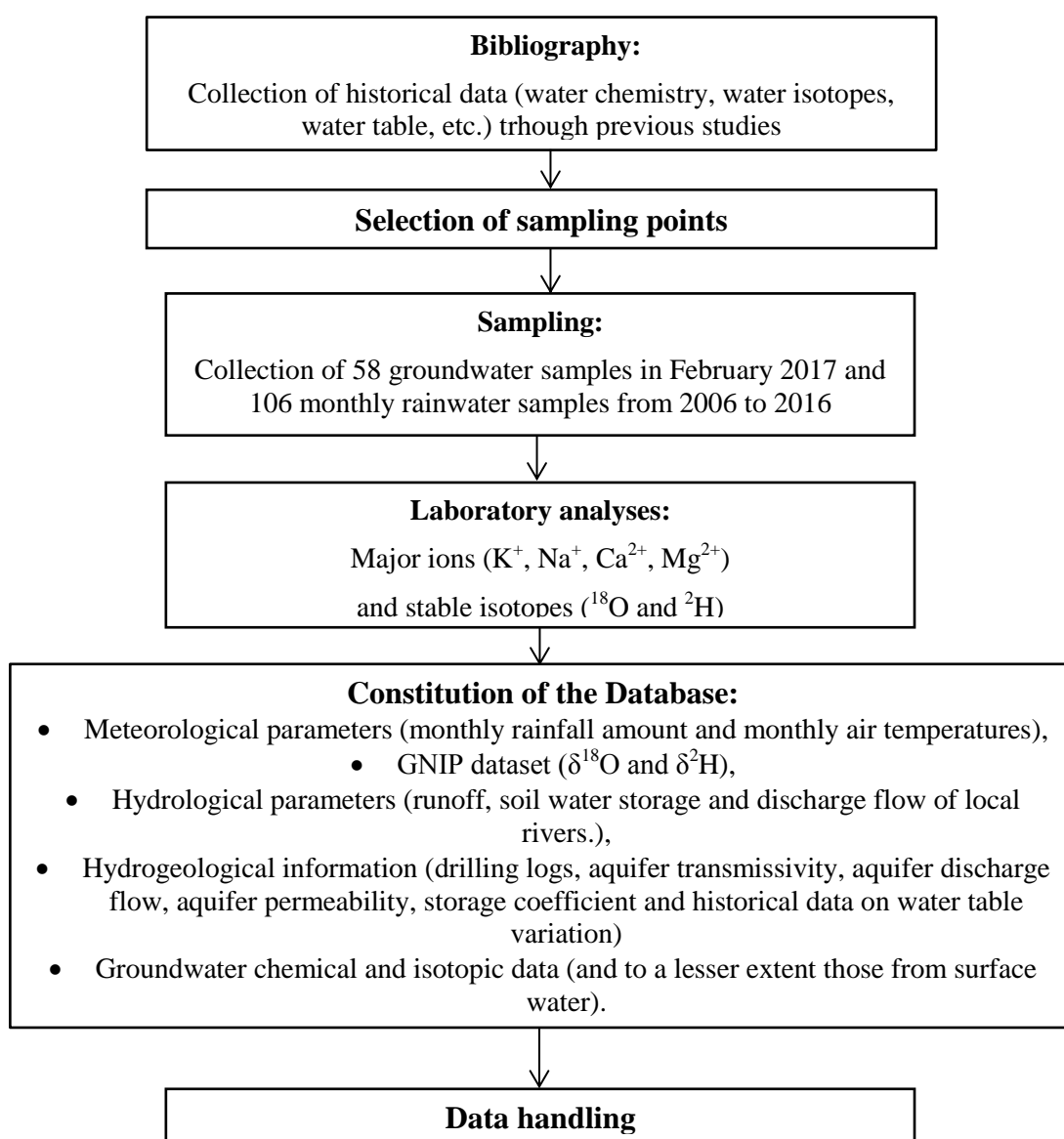


Figure 16: hydrogeological work's structuration.

3. Analytical methods

3.1. Isotopic Analyses

Analyses have been performed at the isotope hydrology laboratory of IAEA in Vienna (Austria) for monthly rainwater and at the hydrogeology department, UMR 6134 SPE of the University of Corsica (France) for daily rainfall and groundwater samples.

Delta (δ) and standard concepts

The isotopic composition of water is given by the ratio (R) of the heavy isotope on the light isotope (equation 2). Since the heavy isotope is very rare, this ratio is very small. The isotopic ratios of the water molecule are compared to the isotopic ratio of a standard water of known isotopic ratio (equation 3). The Vienna Standard Mean Ocean Water (VSMOW) is the most widely used standard

Thus, measurements in stable isotopes are usually done differentially using abundance ratio R (equation 2) compared to a standard (equation 3). Finally, in order to facilitate calculations, isotopic abundances are expressed in δ per mil (‰).

$$R = {}^{18}\text{O}/{}^{16}\text{O} \text{ or } R = {}^2\text{H}/{}^1\text{H} \quad (2)$$

$$\delta = [(R_{\text{sample}}/R_{\text{VSMOW}}) - 1] * 1000 \quad (3)$$

Analytical protocol

Isotopic contents have been determined using a Los Gatos DLT-100 laser isotope analyser following the method described by Aggarwal et al (2006) and Penna et al. (2010). The fourth generation off-axis ICOS (Integrated Cavity Output Spectroscopy) technology incorporated in this equipment yielded higher precision and reduced measurement time compared to conventional cavity ring down spectroscopy (CRDS; Aggarwal et al. 2006). The quality of the isotopic analysis was checked using a standard deviation condition up to 1‰ for $\delta^2\text{H}$ and up to 0.1‰ for $\delta^{18}\text{O}$.

3.2. Chemical analyses

These measurements were conducted at the Hydrogeology Department, UMR 6134 SPE of the University of Corsica, France. The contents of ions: anions (Cl^- , SO_4^{2-} , NO_3^-) and cations (Na^+ , K^+ , Mg^{2+} and Ca^{2+}) concentrations were determined by ionic chromatography using a Dionex ICS 1100 chromatograph. The quality of the chemical analysis was checked by calculating the ionic balance error. Analyses were rejected if the ionic balance error was greater than 5 %.

Chapter III

Atmospheric water cycle in the coastal hyper-humid region of Douala: isotopic study of rainfall at different time-scales

Wohl et al (2012) reported that in the context of land use and climate changes, the processes that operate within the hydrological cycle are expected to accelerate as temperatures rise and the capacity of the air to carry moisture increases. By having greater energy inputs and faster rates of change this fact is most relevant in humid tropics (Wohl et al. 2012). Unfortunately, the understanding of hydrological cycle is still limited in these areas and peculiarly in humid regions of West Africa -while during the last decades we recorded a lot of works in arid or semi-arid region (e.g., Celle-Jeanton et al. 2001; Risi et al 2008b, 2010 and Tremoy et al 2012) - and relies heavily on model-based scenarios rather than observations (e.g., d'Orgeval et al. 2008; Stanzel et al. 2018). Of particular concern when we talk about hydrological cycle are the processes involved in the atmosphere. The atmosphere is an essential hydrological environment; the major place regulating the transfers and exchanges for the global functioning of the Earth system.

The use of water stable isotopes, both δD and $\delta^{18}O$ has provided insights in the study of atmospheric water cycle (e.g., Rozanski et al. 1993, Araguas-Araguas et al. 2000, Celle-Jeanton et al. 2004). Precipitation stable isotopes are efficient tools to determine the origin of water vapour, identify the evaporation processes, the incorporation of recycled atmospheric moisture, and/or the possible mixing between isotopically distinct reservoirs. Moreover, efforts have been made recently to measure the composition of atmospheric water vapour by satellite (Worden et al 2012).

Thus, thanks to isotopic monitoring of rainwater at different timescales and isotopic data from satellites on water vapour, this study aims to investigate the processes involved in the atmospheric water cycle in the Western Central Africa region with a specific focus on Douala (Cameroon). The chapter firstly begins with a clear description of the atmospheric circulation in Western Africa and then presents the meteorological parameters measured at Douala in order to give the context of the results submitted in *Journal of Hydrology* in 2019.

1. Physical framework of the West African Monsoon (WAM)

1.1. Location

West Africa belongs to the intertropical domain and can be defined as being situated in latitude, between the equator and the southern fringe of the Sahara (about 20°N), and, in longitude, between 18°W and 20°E (eastern border of Lake Chad; [Figure 17](#)). This region appears as an important continental incursion into the tropical Atlantic ([Figure 17](#)). Since the mainland has the ability to heat up and cool faster than the ocean, there is then, on the spindle 18°W-10°E, a contrast between continental and oceanic surfaces. This meridian land / sea asymmetry has an important consequence on precipitation regimes and the distribution of atmospheric and oceanic fields (Chapter III sections 2 and 3.1).

1.2. Topography

The West African relief is quite simple ([Figure 17](#)). The topography is composed of plateaus, mountainous massifs, large plains and tabular spaces of low altitude (about 200 m). Plains characterize the littoral border, whereas, inland is mainly dominated by tabular spaces. The mid-altitude plateaus and mountains are located at the south-west, south-east and north-east margins of the region. The highest mountain ranges of Western Africa are: the Hoggar massif (> 2900 m), the Tibesti chains (> 3400 m) and the Mount Cameroon (> 4000 m at 70 km SW of Douala). This simplified topography explains, to a large extent, the meridian arrangement of precipitation ([Figure 18](#)). However, it is not excluded that despite its low relief (average altitude of 400 m) compared to other monsoon regions (e.g. Himalaya), the West African orography has an impact on regional atmospheric circulation. [Drobinski et al. \(2005\)](#) showed, for example, the role of the Hoggar Massif (7.5°E 25°N) in triggering the African monsoon. In the Gulf of Guinea, [Suchel \(1988\)](#) underlined the role of the Mount Cameroon (>4000 m) as a pluviogenesis factor by promoting air mass elevations and thunderstorm activity in the region.

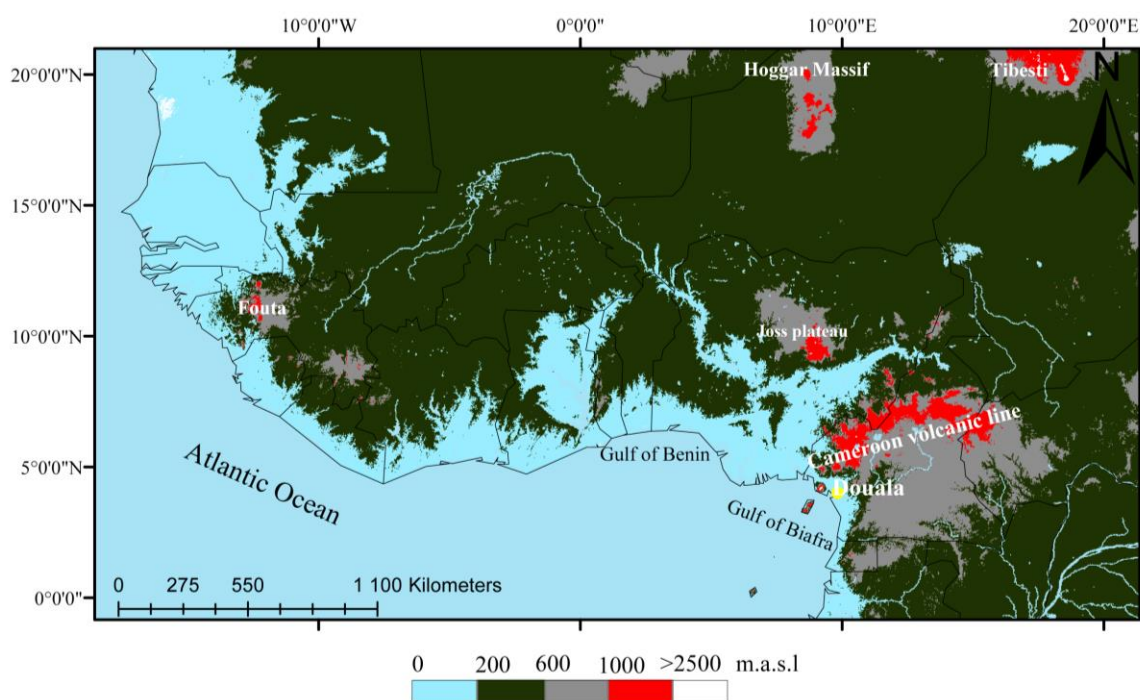


Figure 17: Topography of West Africa. The location of Douala (represented by the yellow point) and the mains massifs is highlighted.

1.3.Spatial distribution of rainfall

On a large scale, the rainfall gradient increases in a N-S direction. Sub-Saharan West Africa has a strong annual precipitation gradient with cumulative rainfall ranging from about 100 mm (northern fringe of the Sahelian zone) to more than 2500 mm in the SW part of the region close to the Mount Cameroon (Figure 18). Indeed, in this region, we record exceptional annual rainfall amount. Territories on the western slope of the mountain receive between 6000 and 11000 mm of rainfall per year while those on the eastern slope (including Douala) record only 2500 to 6000 m (Suchel 1988). Indeed, the humidity transported from the equatorial Atlantic, via the monsoon flow, makes that the part of the relief facing the winds is very watered.

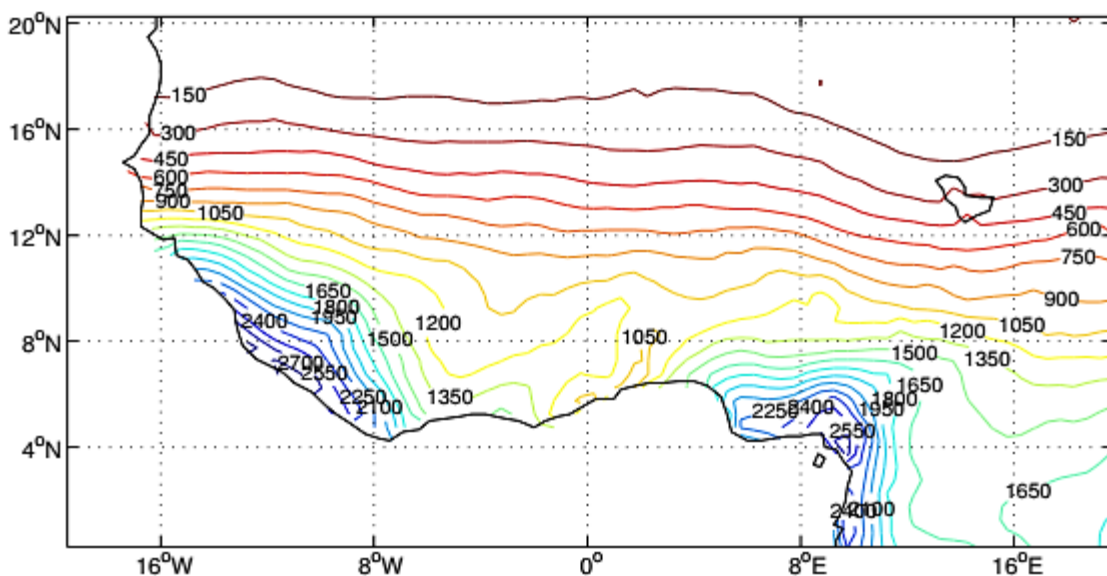


Figure 18: Spatial distribution of average annual rainfall amount (in mm) in West Africa over the period 1968-2002. This map was established by Louvet (2008) from monthly CRU (Climate Research Unit) data ($0.5^\circ \times 0.5^\circ$).

2. Regional atmospheric circulation

Atmospheric circulation in West African coast is organized around some key elements (Figure 19), notably in low layers: sea surface temperatures (SSTs) and the convergence between Monsoon flow (South-West) and Harmattan (North-East).

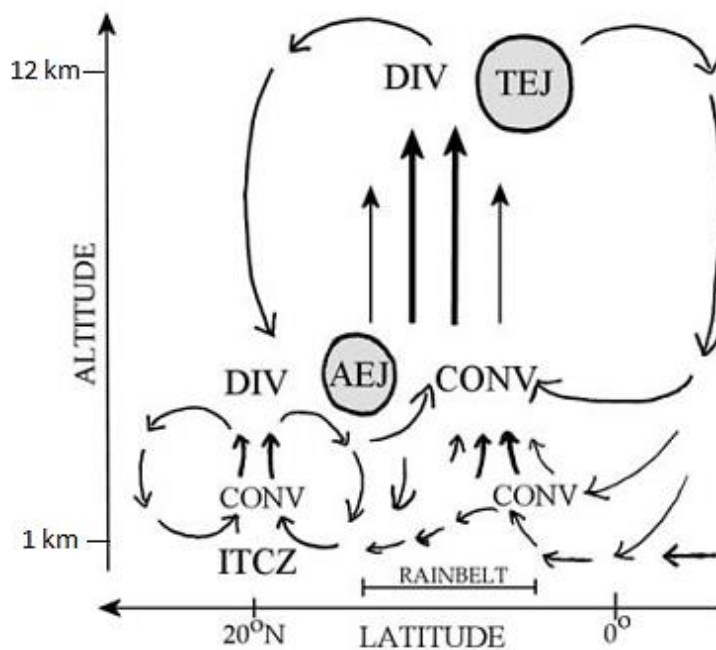


Figure 19: Schematic illustration of the West African monsoon (Nicholson 2009).

2.1. Monsoon and harmattan flows

The anticyclones of Azores in the northern hemisphere and Saint-Helen in the southern hemisphere are the two belts that affect directly the atmospheric dynamic and tropical climates in West Africa, with the first largely overrunning during the boreal winter (Figure 20). The northern high pressure cell tends then to disappear over West African coast areas especially during the summer season, although it remains in altitude between 500 hpa and 700 hpa above the Sahara Desert. It has the characteristics of being a cell of subsidence and divergence with remarkable dryness (Laing and Evans 2011). The surface of the northern circulation cell flows generally from NE and tends to curve to the west, responding to the anticyclone curvature (Figure 20). This northeast trade wind is a continental air mass called harmattan. Above the Atlantic Ocean it is generally stratified with a slightly lower wet and cool layer. During the boreal spring, the wet layer becomes thicker over the ocean, with decreasing stability in the atmosphere and increasing intensity and frequency of rainfall. A major thermal gradient directed towards the north then takes place and is accompanied on the continent by the migration of a thermal depression which is positioned above the superheated low levels. The SE trade winds coming from the southern hemisphere are then strengthened enough to reach the northern hemisphere. Once the equator is crossed, these moisture laden winds are deflected by the horizontal component of the Coriolis force to form the southwestern "monsoon flow". This flow brings moistured air to the continent, what is necessary for cloud convection. It is the main cause of precipitation, development of cumulonimbus with strong vertical development and convection. Further, the intensity and the energy of the monsoon flow will be decisive for its positioning on the continent.

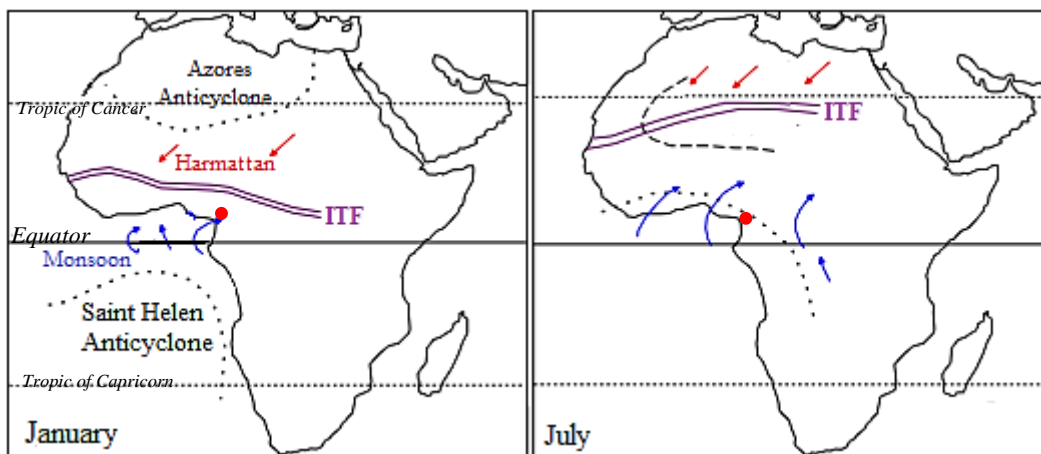


Figure 20: position of the ITF in Africa for January and July (Olivry 1986). The location of Douala is represented here by the red point.

2.2. African “ITCZ”

The convergence between Harmattan and monsoon flows marks the location of the InterTropical Front (ITF, Adefolalu 1983) which represents the ground track of the ITCZ. This dynamic system corresponds to a vertical upward flow and is characterized by a low intertropical atmospheric pressure derived from the trade wind convergence (Figure 20).

Since dry air from the north and humid air from the south meet, it is an area of conflict between north-eastward continental and south-eastward oceanic wind flows, and therefore a region of major turbulence. The ITCZ is responsible for the zonal organization of annual rainfall in West Africa (Figure 18). Its annual movement follows the sun's zenith. Between April and the end of June, the ITCZ is positioned above the Guinean coast ($\sim 5^{\circ}\text{N}$), resulting to the first rainy season in this region. Then, during the first half of July, it moves rapidly to the north and reaches relatively $\sim 11^{\circ}\text{N}$, corresponding to the establishment of the rainy season in the Sahelian regions. ITCZ stays on this latitude until the end of August, and then descends gradually to the south, crossing over the Guinean coast and resulting in another rainy season in this region. In consequence, the northern semi-arid regions experiences precipitation only during summer while the coastal guinea areas present two rainy seasons in spring and autumn. The abrupt rise of the ITCZ to the north contrasts with its withdrawal, which appears to have a more steady progression southward.

Figure 20 provides positions of ITF and Harmattan/monsoon flows in January (southernmost position) and July (when it tends to reach its northernmost location).

2.3. Oceanic surface

The eastern equatorial Atlantic has a very marked seasonal cycle (Wauthy 1983), having an influence on Western Africa rainfall regime (Mitchell and Wallace 1992; Gu and Aldler 2004). Figure 21 shows the monthly sea surface temperatures (SSTs) variation at 5°W . Generally, SSTs are warmer in March-April from 50°W to 10°E . The transition from warm to cold temperatures takes place from May to June with a more intense cooling from June to August. Indeed, SST decreases by 5°C to 7°C at this period and the minimum values are located between 1°E - 5°E and roughly 4°S - 1°N (Marin et al. 2009; de Coëtlogon et al. 2010; Giordani et al. 2013; Figure 21). From August to December, the ocean warms up again. Warm SSTs correspond to spring and autumn rainfall periods in Gulf of Guinea. The onset of the cooling developed southerly to the equator is well correlated to the abrupt northward shift of the ITCZ in July (Picaut 1983; Colin 1989; Waliser and Gautier 1993). The intensification of the “cold tongue” in the Atlantic Ocean increases the contrast of air temperature between the Gulf of Guinea and the Sahel, which in turn accelerates, onshore, south-to-north near-surface winds. Indeed, the recent trends of Sahel drought are attributed to high SSTs, which favours the establishment of a deep convection zone over the ocean and weakens the convergence of the monsoon flux over the continent (Giannini et al. 2003). On the other hand, the cold tongue drives the convection zone northward and inhibits Western African precipitation in almost part of Gulf of Guinea (Okumura and Xie 2004). However, in the Gulf of Biafra (Figure 17), between 2°N and 4°N and 5°E - 10°E , SSTs remain sufficiently high to maintain convection in Douala (Figure 21).

SSTs variations are due to the formation of equatorial upwelling (Merle et al. 1980; Picaut 1983; Weingartner and Weisberg 1991). The origin of this equatorial upwelling is generally attributed to the divergence of ocean's currents along the equator (Philander 1990). However, the upwelling can also be explained by a vertical oceanic mixing (Peter et al. 2006) or Kelvin equatorial waves (McCreary et al. 1984).

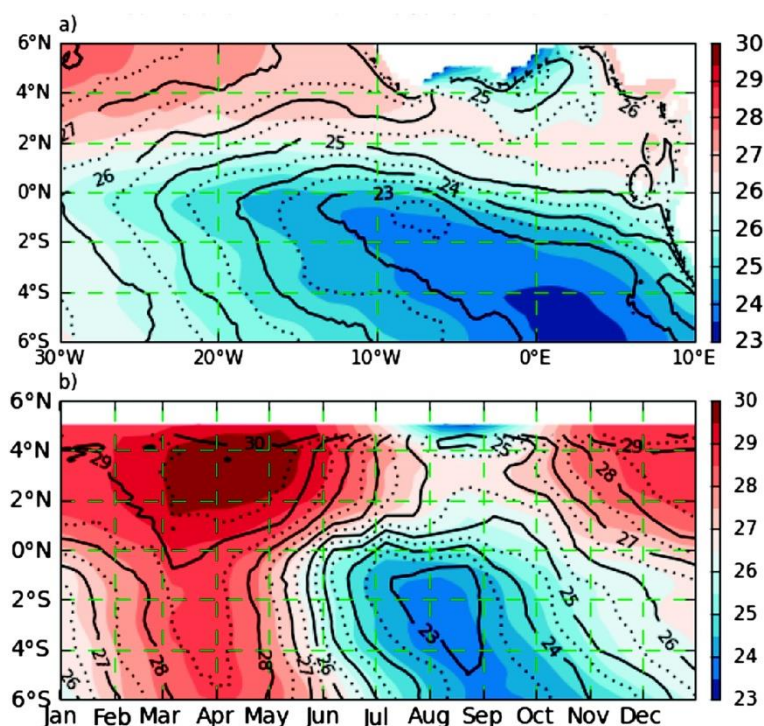


Figure 21: Mean climatological SSTs (°C) from 2001 to 2006 (Jouanno 2011): (a) horizontal distribution in August and (b) time–latitude distribution at 5°W.

3. Meteorological features of Douala

3.1. Precipitation

Rainfall regime

Douala is the wateriest urban centre after Monrovia (Liberia) in Western Africa. It receives exactly on average, 3854.3 mm of rain per year (standard deviation = 464.4 mm; weather data from 1951-2016).

According to the ombrothermal diagram presented in Figure 22, the megacity of Douala has a long rainy season from March to November, and a lesser wet season from December to February. Compared with other humid areas in the region of the Western and Central Africa such as Cotonou (Benin), Bangui (Central African Republic), and Sao-Tome (Sao-Tome and Principe), which present a relative long dry period respectively of 5, 7 and 8 months, Douala appears as a hyper-humid region.

The unimodal rainfall regime observed in Douala, is also atypical. In the whole part of the Gulf of Guinea, the bimodal regime is a more common feature (see for example at Sao-Tome and Cotonou; Figure 22). This particularity of Douala is related to the interaction between the southwestern African monsoon wind (SW monsoon) and the geography/topography of the region. Firstly, the concave shape of the Cameroonian coast at Douala, perpendicular to the southwestern monsoon winds, induces a convergence of these winds. The same pattern is observed on the Liberian coast.

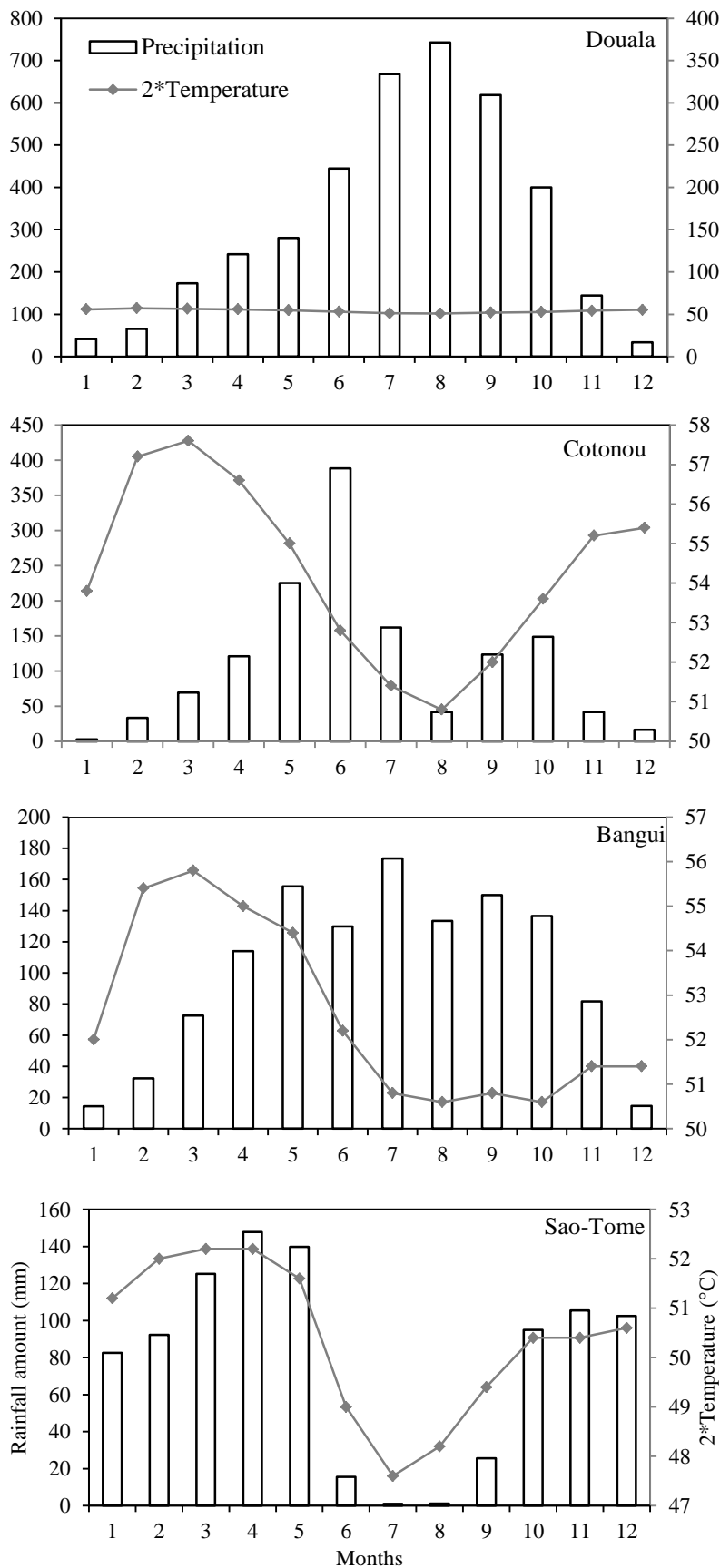


Figure 22: Ombrothermal diagram of Douala (Meteorological data are ranged from 1951 to 2016 (1971-2016) for rainfall (temperatures). We also provide those of Cotonou (Benin), Bangui (Central African Republic), and Sao-Tome (Sao-Tome and Principe).

Secondly, the Mount Cameroon (~ 4000 m; ~70 km at the southwest of Douala) constitutes an obstacle to the southwestern winds precipitated and induces orographic ascents of an extremely hot, humid and therefore unstable air. These air mass convergence and orographic airlift are more significant if the monsoon flow is intense and thick as it is the case during the summer monsoon season, when the ITCZ is far up to North and the monsoon is well developed. This contributes to explain the unimodal nature of the rains at Douala.

In summary, the specificity of the Douala's climate is linked to: (i) SSTs that remain sufficiently high during the summer in the Gulf of Biafra (Figure 21) favouring atmospheric convection; (ii) the concave shape of the Cameroonian coast at Douala, perpendicular to southwesterly monsoon winds (Figure 20) and (iii) the influence of the Mount Cameroon (Figure 17).

The specificity of rainfall distribution is also reflected by a significant occurrence of rainfalls during the night (Tsalefac et al. 2003). According to Vondou et al (2018), this could be due to the propagation of convective systems that are generated on the continent, during the afternoon. However, it could also be associated to the strengthening of convergence on the sea and the coast, at night, due to the replacement of sea breezes by land breezes (Leduc-Leballeur 2012).

Inter-annual precipitations

The inter-annual evolution of precipitation between 1951 and 2016 (Figure 23) shows a strong variation with a general downward trend. We observe a wet phase (average of 4157.6 mm) from 1951 to 1981 characterized by rainfall above the inter-annual mean (3854 mm) and a less humid or "deficit" phase from 1982 to 2016 (average of 3570.5 mm), marking a long period with precipitation below the average inter-annual value.

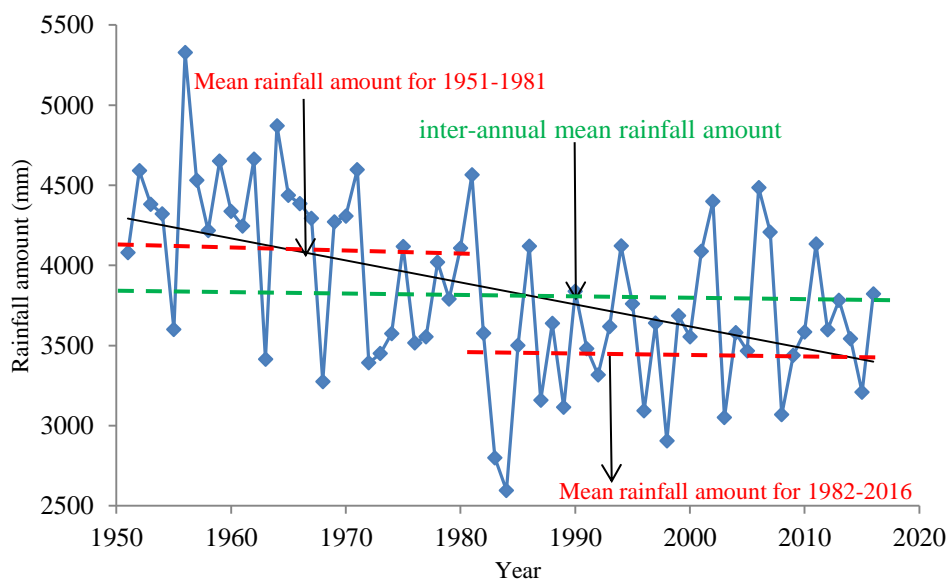


Figure 23: inter-annual evolution of rainfall (mm) in Douala (1951 to 2016).

3.2. Temperatures

The monthly temperature distribution is relatively uniform at Douala. The annual average over 44 years is 27°C (standard deviation = 0.3), with a minima of 25.4°C in August and a maxima of 28.6°C in February (Figure 24); giving a thermal amplitude of 3.2°C on average.

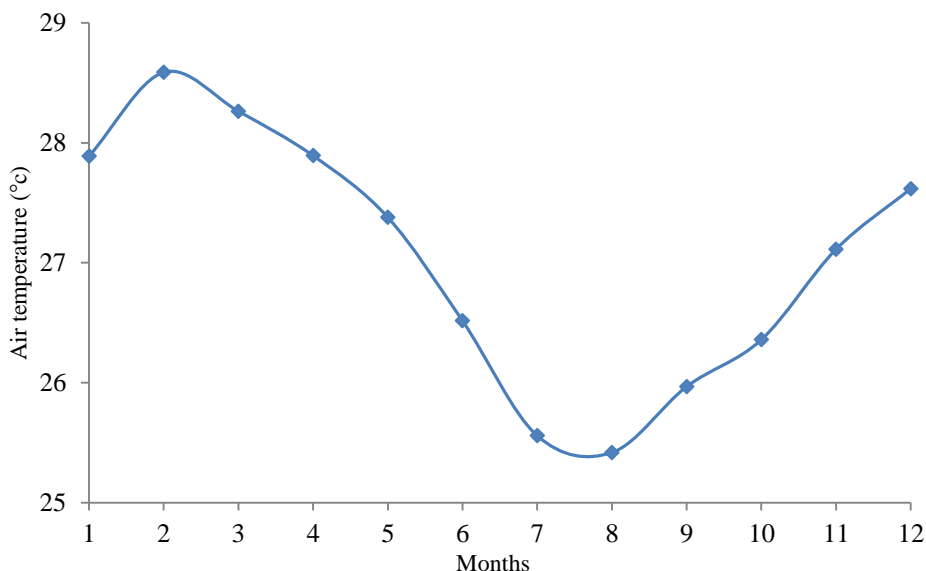


Figure 24: average monthly temperatures (°C) in Douala (1971-2016)

Between 1971 and 2016, there is a slight increase in annual average temperatures (Figure 25) corresponding to approximately +0.02°C/year.

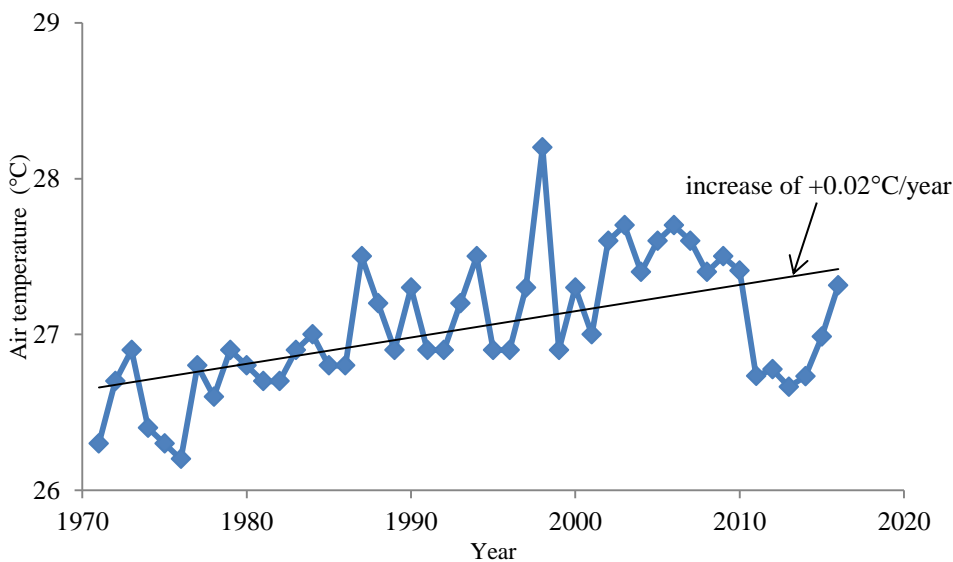


Figure 25: inter-annual evolution of temperatures (°C) in Douala (1971 to 2016).

3.3. Other parameters

Relative humidity

The abundance of rainfall in the region involves a high cloudiness that maintains a constantly high humidity. The monthly variation in humidity is parallel to that of precipitation and is anti-correlated to that of temperatures. Monthly average values range between 79% and 90% during the rainy season (March to November) and between 77% and 81% during the less wet season (December to February), with an average annual relative humidity of 85% (meteorological data from 1971 to 2009).

Evaporation / evapotranspiration

Evaporation data obtained at the meteorological centre of Douala are ranged from 1992 to 2016. They show that strong evaporation occurs on average in February (58.3 mm) while the lowest rate is observed in August (27 mm). This monthly variation of evaporation is therefore similar to that of temperatures (**Figure 24**). Annual evaporation rate (and actual evapotranspiration) is always lower than 600 (and 1000 mm). These rates significantly lower than the rainfall amount indicate once again the hyper-humid character of Douala and the fact that these latter parameters must have a weak influence on the global hydrology of the study region.

The main climatic or/and meteorological features of Western Central Africa and peculiarly those of Douala being presented, in the next section we will investigate -thanks to rainfall isotopes, water vapor isotopic composition, GPCP precipitation and clouds types products- the processes controlling the atmospheric circulation in the study region.

4. Article: Identification of the processes that control the stable isotope composition of rainwater in the humid tropical Western and Central Africa

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Article Type: Research paper

Keywords: $\delta^{18}\text{O}$; water vapor; convective activity; GPCP precipitation; air back trajectory.

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Abstract

This study interprets 11 years (2006 to 2016) and 6 months (March to August in 2017) of respectively monthly and daily isotopic (δD and $\delta^{18}O$) monitoring of rain at Douala (Cameroon), a humid tropical station in Western Africa. The main scope is to analyze the climate controls on precipitation isotopes at different timescales. Firstly, we examine the annual cycles of $\delta^{18}O$. Over the 11 years of survey, the annual cycle exhibits a W shape that is quite reproducible from year to year, with two minima in spring and autumn periods. Based on back trajectory calculations and remote sensing observations of water vapor isotopic composition, we show that the observed depletion in spring and autumn is due to strong convective activity along air mass trajectories. The same effect of convective activity can be observed at the daily timescale. At seasonal and daily time scales, the isotopic composition is also strongly tied to the convective organization and cloud types. More depleted precipitation is associated with larger areas of high clouds. Very low to low clouds are observed in July-August, mid-level to high clouds are dominant in June and high to very high clouds characterize March-April-May, thus explaining the enriched (depleted) values in summer (spring). Finally, this paper highlights the importance of large scale meteorological conditions controls on precipitation stable isotope composition in the Gulf of Guinea.

Keywords: $\delta^{18}O$, water vapor, convective activity, GPCP precipitation, air back trajectory.

1. Introduction

The atmosphere is an essential hydrological environment. It contains all the water vapor (0.001% of all the water of the Earth; Delmas et al. 2005) that forms the clouds by condensation which can then generate precipitations (liquid/solid) as a function of air temperature. The atmosphere is also an essential place of transfer and exchange for the global functioning of the Earth system. Its multiple interactions with the oceans, the continent and the biosphere make it an important study environment for understanding global changes. According to IPCC (1998), these global changes must affect tropical regions which are among the most vulnerable to possible anthropogenically induced climatic changes.

During the last decade, the scientific community, environmental institutions, governments, and local communities have increased their awareness of the importance of current tropical climate variability, based on the premise that, under increasing anthropogenic influence on the climate, changes in regional and global circulation may lead to an intensification of extreme events (i.e. floods or severe droughts: e.g., Pohl et al. 2017). In parallel, the use of stable isotopes of water, both δD and $\delta^{18}O$ has provided insights in the study of atmospheric water cycle (e.g., Rozanski et al. 1993, Araguas - Araguas et al. 2000, Celle-Jeanton et al. 2004); the key to understand the future climate changes or global changes. Relationship between δD and $\delta^{18}O$ in natural meteoric waters serves as a foundational reference to determine regional and local deviations from equilibrium processes and the potential origin of the water vapor. Moreover, water losses due to evaporation, incorporation of recycled atmospheric moisture, and/or mixing between isotopically distinct reservoirs leave a unique water fingerprint that can be used for climate-reconstructions (Moerman et al. 2013). Recently, isotopic composition of tropical meteoric water has also proven its usefulness as an indicator of modern climate variability (Vuille and Werner 2005; Ishizaki et al. 2012; Sanchez-Murillo 2015).

While in extra-tropical climates, stable isotope variations in meteoric waters have been successfully explained by air temperature variability (Dansgaard 1964; Rozanski et al. 1993), the case of tropical humid regions proved to be very much complex since temperature variability is much weaker. The amount effect occurs as a result of convective precipitation and can be nonlocal (Vimeux et al. 2005; He et al. 2015). The degree of organization of convective systems has been shown to impact the atmospheric conditions at the large-scale (Tobin et al. 2012; Wing et al. 2017). Consistently, it also impacts the isotopic composition of water vapor and precipitation. Many additional factors can potentially play a role, such as orographic effects, continental recycling or moisture origin combined with complex microclimates (Rozanski et al. 1993, Lachniet and Paterson 2009).

These problematics are of major importance for the paper. What are the key factors controlling stable isotope ratios of meteoric waters in humid tropical areas of West and Central Africa? Answers to this question will contribute to the understanding of atmospheric processes in the study region. Unlike arid and semi-arid African areas, where isotopic variability has already been assessed in previous work (e.g; Taupin et al. 1997, Celle-Jeanton et al. 2001; Risi et al. 2008b, 2010; Lutz et al. 2011, Tremoy 2012; Tremoy et al. 2014), the

Gulf of Guinea (GOG) region and tropical humid areas in Central Africa (Figure 1) are still under-documented in isotopic data. There, the atmospheric cycle of water remains poorly documented and isotopic data may help improve their knowledge. Indirectly, the paper will help to understand rainfall variability in Douala and the origin of precipitated water through isotopic analysis. In this objective, we took advantage of the long term monthly monitoring set up in Douala, Cameroon (Figure 1) as part of the Global Network for Isotopes in Precipitation (GNIP) framework (IAEA/WMO 2018) from 2006. In parallel, a daily sampling has been carried out in 2017. This article represents the first valuation of precipitation isotope data in the region. Datasets of other GNIP stations in the GOG and Central Africa (Figure 1) are also integrated in this study, together with remote sensing data that document water vapor isotopic composition, convective activity and cloud properties.

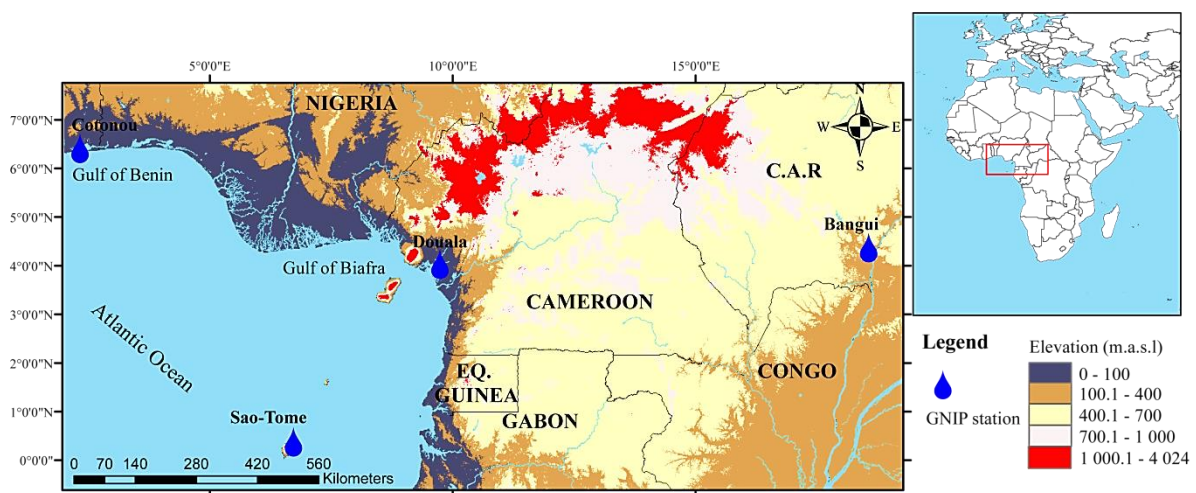


Figure 1. Map of the study area (Western Central Africa) with the location of GNIP stations of Cotonou, Bangui, Douala and Sao-Tome.

2. Regional climate: the West African Monsoon (WAM) dynamic

Seasonality in the tropics is mostly determined by the seasonal migrations of the Inter Tropical Convergence Zone (ITCZ, Preston-White and Tyson 1988; Schott et al. 2003), a highly energetic feature of earth climate that is associated with deep convection. The ITCZ or meteorological equator in Africa is the result of convergence between the Harmattan (northeasterly dry wind) and Monsoon (southwesterly wet wind) in low levels of the atmosphere (Sultan and Janicot 2000, Fink et al. 2018). Nicholson and Grist (2003) have shown that the rain belt over Western and Central Africa is positively correlated with the migration of the ITCZ. During the boreal spring (Mar-Apr-May), ITCZ holds a position of about 5°N; half of the rain belt is located over the continent and the other one on the ocean (Waliser and Gautier 1993). The mean rainfall amount calculated for this period, according to GNIP measurements, is 232 mm for Douala, 138.4 mm for Cotonou, 137.7 mm for Sao-Tome and 114.1 mm for Bangui. The relative humidity increases significantly over the continent and sea surface temperatures (SST) present their annual peak (>27°C) during this period

(Dezfuli and Nicholson 2013). Then, ITCZ abruptly shifts from 5°N to 10°N in June-July (Sultan and Janicot 2003). The so-called monsoon jump causes a subsidence in the southern part of the GOG and the development of a cold tongue complex (Gu and Adler 2004). Low SSTs suppress then partly or totally rainfall as e.g. in Sao-Tome (Figure 3). However, in the Gulf of Biafra (Figure 1), SSTs remain high enough (>26°C) to partly maintain convection (Odekunle and Eludoyin 2008). Moisture increases over land and enhances rainfall there. Simultaneously, convective activity migrates to the North, and the monsoon flow crosses the Equator from South (GOG) to North (Guinean and then Sahelian Africa). At this time of the year (Jun-Jul-Aug), a rainfall peak is observed (Figure 3) in Douala (618.3 mm) and Bangui (145.5 mm). In Cotonou, Ogu et al. (2016) have also shown a good correlation between SSTs and precipitation, connecting rainfall amount in June to anomalously warm waters of the Gulf of Benin.

The abruptness of the northward progression of the ITCZ is in sharp contrast to its withdrawal, which appears as a more progressive southward progression. Like most regions in the equatorial latitudes, the Guinean Coast/Central Africa thus benefits from a double passage of the ITCZ in spring and in autumn.

The unimodal distribution and the highest rainfall amount (~ 4000 mm/year) observed in Douala (Figure 3) is very particular as the whole region is generally characterized by a bimodal distribution with two precipitation maxima in April-May (or May-June) and October-November (or September-October), with a total amount lower than 2000 mm/year. The concave shape of the Gulf of Biafra may induce a convergence of southwesterly winds and topographic ascents forced by the relief of Mount Cameroon (> 4000 m, Figure. 1). This mesoscale convergence and orographic influence (Vondou et al. 2017) are all the more marked if the monsoon flow is intense and thick, which is the case in the core of the summer monsoon, when the ITCZ is far to the North. These regional features can explain the unimodal regime observed at Douala while further west (in Cotonou), and in southern hemisphere (Sao-Tome), the annual cycle is bimodal.

3. Data and methods

3.1. Rainfall sampling and isotopes analyses

This paper makes use of the 106 monthly samples of rainwater that have been collected from July 2006 to December 2016 at the GNIP station of Douala (see details of the GNIP stations in Table 1 and Figure 1). The sampling followed the standard protocols (IAEA 2012). Samples were collected by using a rain gauge which consists of a plastic funnel (diameter = 10 cm) coupled with a filter mesh to prevent contaminations by debris. A 5 cm layer of mineral oil has been systematically added into the rain collector to avoid fractionation of the collected rainwater. For each month, total rainfall was collected. Samples were taken regularly, stored in a totalizer and kept at 4°C before being transferred in 50 ml amber glass

bottles, tightly capped and sent to the International Atomic Energy Agency (IAEA) laboratory in Vienna, Austria for stable isotopes determinations. Stable isotopes of hydrogen and oxygen were then analyzed by laser absorption spectroscopy following the method described by Penna et al. (2010).

Table 1. Characteristics of GNIP sampling sites in GOG and Central African regions. Data from Cotonou, Bangui and Sao-Tome have been obtained online from the GNIP database (AIEA/OMM 2018).

Site	Country	Sampling period	Elevation (m.a.s.l)	Mean annual precip*(mm)	Vapor Pressure (hPa)	Mean annual T* (°C)
Cotonou	Benin	2005 - 2012	14	1395	28.3	27.1
Bangui	CAR*	2009 - 2015	363	1208	25.7	26.3
Douala	Cameroon	2006 - 2016	18	3720	30.5	27
Sao-Tome	Sao-Tome and Principe	1962- 1976	8	933.7	26.2	25.2

* Precip. = Precipitation, T = temperatures; CAR= Central African Republic; dec. deg = decimal degrees

The rainwater daily survey was conducted from March to August 2017 at the campus of the University of Douala (X= 9.7461; Y= 4.062; Z= 17 m.a.s.l.), approximately at 7 km from the GNIP station. Seventy samples were collected using a Palmex rain gauge that presents the advantage to avoid evaporation without using medicinal paraffin oil (Gröning et al. 2012). Daily samples were stored using the same protocols as for monthly rainfall. Isotopes analyses were performed at the Hydrogeology Department of the University of Corsica, France, by using a liquid-water stable isotope analyzer DLT-100 Los Gatos Research (Aggarwal et al. 2006; Penna et al. 2010).

Ratios of $\delta^{18}\text{O}/\delta^{16}\text{O}$ and $\delta^2\text{H}/\delta^1\text{H}$ are expressed in delta units (‰, parts per mil) relative to Vienna Standard Mean Ocean Water (V-SMOW). The analytical precision is $\pm 0.1\text{‰}$ for oxygen-18 and $\pm 1\text{‰}$ for deuterium.

Local meteorological settings (precipitation amount and duration, air temperatures, vapor pressure) were provided by the National Weather Direction of Cameroon.

3.2. Tropospheric Emission Spectrometer (TES) data

With the advent of new technology in stable water isotopes, such as spectrometer on-board satellite, it has become easier to analyze isotopic composition of water vapor based on indirect laser measurement (Aemisegger et al. 2012). TES instrument on board on the Aura satellite is a nadir-viewing infrared Fourier transform spectrometer from which the deuterium content of water vapor (δD_v) can be retrieved (Worden et al. 2006; Worden et al 2007). The

sensitivity of the retrieval is typically larger between 900 hPa and 400 hPa with a peak at 700 hPa. On average, δD_v retrieved over these levels has a precision of 1.5% or about 15 parts per thousand (per mile) relative to Standard Mean Ocean Water. Uncertainties are reduced by averaging several measurements (Worden et al. 2006; Risi et al. 2013). Then the precision is sufficient for characterizing the global distribution of evaporation and condensation processes (Worden et al. 2006).

There is on average 1.8 degrees of freedom for δD_v retrievals in the tropics (Worden et al. 2012), meaning that vertical profiles bear information on more than one level. To ensure good data quality, we selected only the measurements for which the quality flag is set to unity and for which the degree of freedom of the signal is higher than 0.5 (Risi et al. 2013). Here, to document the water vapor composition as close as possible to the surface, we use the δD values retrieved by TES at 900 hPa from 2004-2008 at a monthly scale and we focus on a multi-year mean seasonal cycle and temporal variations rather than absolute values.

3.3. Convection and cloud datasets

Convective activity associated with the West African Monsoon (WAM) was analyzed using the Global Precipitation Climate Project one degree daily (GPCP-1dd; Huffman et al. 2001) data. The same dataset is used for both monthly and daily analyses. Data were retrieved from the National Oceanic and Atmospheric Administration (NOAA) website (<https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>). The robustness of GPCP products has been demonstrated in many studies (e.g.; Huffman et al. 1995, 1997; Lekshmy et al. 2014; Adler et al. 2017) through a comparison with other proxies of convection or by multi-proxy studies: OLR (Outgoing Longwave Radiation) and TRMM (Tropical Rainfall Measurement Mission). GPCP products are a combination of precipitation data provided by a multiple sources of satellite-gauge (SG). They are obtained by optimally merging precipitation estimates computed from microwave, infrared, sounder data observed by the international constellation of precipitation-related satellites, and rain gauge analyses, taking advantage of the strengths of each data type. Mean SG products are computed by combining multi-satellite estimates with rain gauge analysis (Huffman et al. 2001). In this study, we use the GPCP-1dd (1-degree grid over the entire globe at 1-day) both for monthly and daily analyses. These data were retrieved from the National Oceanic and Atmospheric Administration (NOAA) website (<https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>).

To document the cloud types and convection organization in Western Central Africa, we use a cloud type (CT) product issued from geostationary MSG (Meteosat Second generation) satellite data and developed by SAFNWC (Satellite application facilities in support to nowcasting) /MSG algorithms (for more information see <http://www.nwcsaf.org/web/guest/scientific-documentation>). Clouds types are determined from their top temperature or pressure and, for high level clouds from their opacity (Dommo et al. 2018; Seze 2015). The SAFNWC CT offers a classification of clouds into 12 classes: free land, free sea, very low clouds, low clouds, medium clouds, high clouds, very high

clouds, thin cirrus, medium cirrus, thick cirrus, fractional clouds and semi-transparent above low or medium clouds, at 3-km spatial resolution for regions close to MSG sub-satellite point (0N, 0E) and a time step of 15-min. For our study purposes, focus is given to the altitude of clouds (low, medium, high, etc.) and their organization (as measured by the spatial extent of connected cloud pixels) to seek links with the isotopic contents of rainfall. Data are extracted for the region bounded by latitudes 10S–10N and longitudes 0E–20E, for the period from March to June 2017.

Based on these images, very high clouds areas (corresponding to very organized convective system) around Douala were calculated for each event using ArcGis mapping software, through the tool “measure”. Indeed, since the contours of cloud masses are approximated to geometric forms (circle, rectangular, trapezoidal shape, etc.), the areas were calculated based on these forms. For events with duration of more than 15 min, we have taken the maximum cloud area throughout the duration of rainfall.

3.4. Back trajectories

In order to assess the influence of air masses pathways on the isotopic composition of precipitation, and the importance of the location of convective activity in the region, we compute air back trajectories at 6h time steps, 10 days prior to arrival in the sampling site. This operation was performed for monthly and daily scales when isotopic data is available. Winds (at 900 hPa) were simulated by using the general circulation model LMDZ5A (Hourdin et al. 2013) guided by reanalysis products (ERA-Interim, Dee et al. 2011) of the European Centre for Medium-Range Weather Forecasts (ECMWF). Back trajectories (speed and direction) were then computed with a 2D algorithm (similar to Vimeux et al. 2005) in order to approximate the moisture transport near the ground surface.

4. Results and discussion

4.1. Annual cycles of isotopes (δ) in precipitation of Douala

Figure 2 presents the seasonal variations of $\delta^{18}\text{O}$ from 2006 to 2016. The annual cycle of δ is quite reproducible from year to year. It exhibits a W shape most of the time, with minima in spring and autumn periods. Because of this rather good reproducibility of $\delta^{18}\text{O}$ seasonal cycle from year to year; we further consider a multi-year mean seasonal cycle in the section 4.2, and investigate the factors associated with this W cycle of δ .

However, the magnitude varies widely from one year to another for a given month. Such inter-annual variability could either reflect variations (i) in the climate seasonal background, or (ii) in synoptic / intra-seasonal variability, which could modify seasonal mean fields through upscaling processes, and eventually affect isotopic variations. These hypotheses are tested and discussed below.

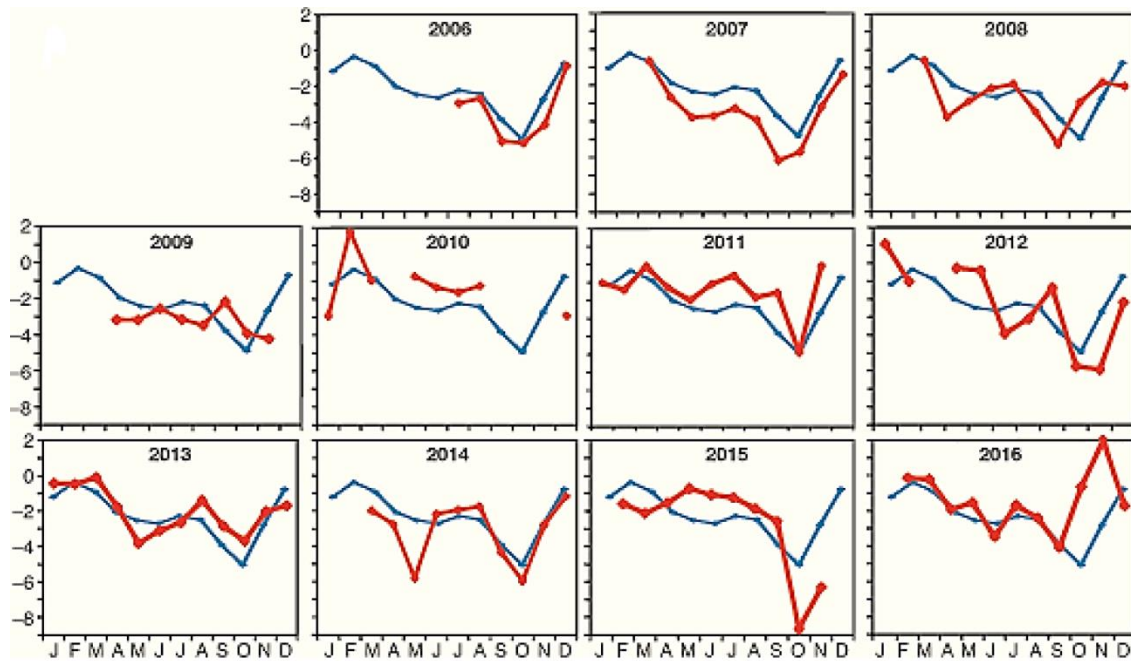


Figure 2. Annual cycles of $\delta^{18}\text{O}$ from 2006 to 2016. The blue line represents the weighted mean seasonal cycle while the red line corresponds to a given year

4.2. Factors responsible for δ variations at seasonal scale

4.2.1. Highlighting of a regional context

Seasonal variations of $\delta^{18}\text{O}$ and precipitation amount for GNIP stations in GOG and Central Africa region are presented in [Figure 3](#).

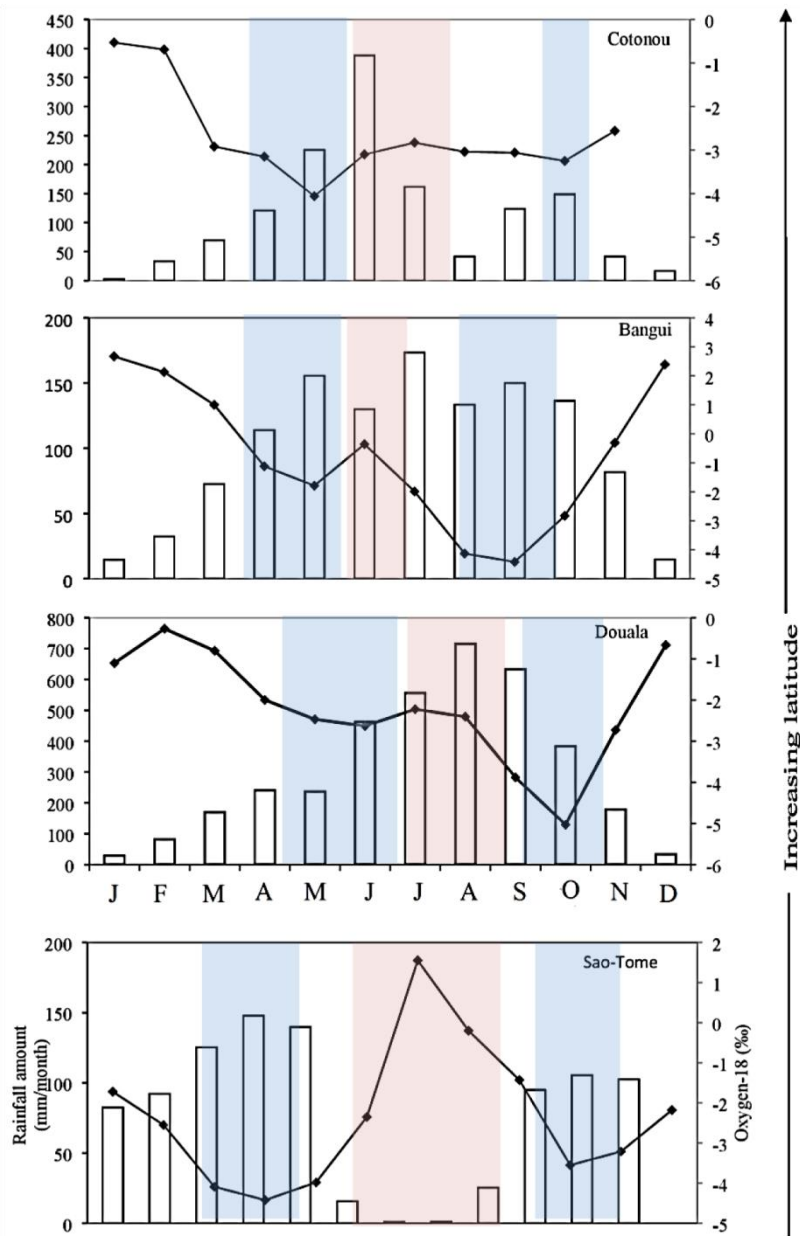


Figure 3. Monthly mean for $\delta^{18}\text{O}$ (black line) and precipitation amounts (bars) at the GNIP stations of Cotonou (2005-2012), Bangui (2009-2015), Douala (2006-2016) and Sao-Tome (1962-1976). Summer enrichment phase are highlighted in pink and depletion phases in spring and autumn are underlined in blue.

Similarities can be observed in the seasonal evolution of $\delta^{18}\text{O}$ at Cotonou, Bangui, Douala and Sao-Tome (Figure 3): (i) from January-February to April-May, $\delta^{18}\text{O}$ decreases; (ii) an enrichment in isotopic content is observed in summer (in June, July or August depending on the station); (iii) isotope contents then decrease until September or October and (iv) a new increase occurs until December. This relative homogeneity suggests that isotopic seasonality is controlled by mechanisms of, at least, regional scale.

Correlation coefficients between $\delta^{18}\text{O}$, precipitation and temperature are very low for all the stations (Table 2). The weak correlation between $\delta^{18}\text{O}$ and air temperature (Table 2)

highlights the lack of temperature effect in the GOG and Central Africa regions. Despite the fact that, in tropical maritime stations, a local amount effect is often observed (Rozanski et al. 1993), the poor correlation between $\delta^{18}\text{O}$ and local precipitation amount shows that this effect does not dominate the isotopic seasonality in Central Western Africa. Therefore, it is clear that, the local climate parameters do not control the seasonal variation of δ in precipitation. Thus we hypothesize that convective activity at the regional scale could be involved. In the next section, this hypothesis is tested for the Douala station.

Table 2. Coefficient of determination (r^2) between $\delta^{18}\text{O}$ and local meteorological settings (precipitation (P) and temperature (T)) for monthly GNIP stations of Cotonou, Bangui, Douala and Sao-Tome, at different sampling periods.

Stations	Sampling period	$r^2 \delta^{18}\text{O}/\text{P}$	$r^2 \delta^{18}\text{O}/\text{T}$
Cotonou (n=95)	2005 - 2012	0.05	0.13
Bangui (n=81)	2009 - 2016	0.24	0.04
Douala (n=106)	2006 - 2016	0.12	0.09
Sao-Tome (n=123)	1962 - 1976	0.19	0.20

4.2.2. Influence of regional convective activity

Many studies in China (e.g., Gao et al. 2013; He et al. 2015, Yu et al. 2016; Guo et al. 2017; Shao et al. 2017; Gao et al. 2018), India and Indo-Pacific region (Chakraborty et al. 2015; Rahul and Gosh 2016; Cai et al. 2016; He et al. 2018), South America (e.g., Hoffmann et al. 2003, Vimeux et al. 2005, Villacis et al. 2008, Samuels-Crow et al. 2014) and Sahelian Africa (e.g., Risi et al. 2008b, Risi et al. 2010b, Tremoy et al. 2012b) based on both observations and models, have shown that convective activity, that occurs upstream the pathway of air parcels, is a major control of rainwater isotope composition in the tropics at daily, seasonal and inter-annual timescales.

Convective activity is known to deplete water vapor through 3 main processes: i) precipitating downdrafts, either at the convective-scale or at the meso-scale (Risi et al. 2008a, Kurita 2013), bring down depleted water vapor from the mid-troposphere to the boundary layer; ii) rain evaporation, when concerning a small proportion of each raindrop, adds depleted water vapor to the lower troposphere (Worden et al. 2007, Risi et al. 2010); iii) rain-vapor diffusive exchanges in a saturated atmosphere can also deplete the water vapor (Lawrence et al. 2004). GPCP precipitations are used to examine convective activity upstream the sampling site of Douala. Figure 4 presents monthly mean precipitation and back trajectories calculated for

each month. As expected, trajectories come from the Atlantic Ocean most of the time and precipitation, at this timescale, is entirely controlled by the seasonal migration of the ITCZ. In November and December, trajectories come from the North-East without undergoing any convection. From December to January, they abruptly shift from North-Easterly to South-Westerly, in line with the beginning of long northward migration of the ITCZ. From March to May (spring season), trajectories undergo strong convective activity over the Gulf of Guinea. From June to August, trajectories still travel over the Gulf of Guinea, but air masses undergo a weak convective activity because the ITCZ has shifted further north over the sahel. From September to October (autumn period), the ITCZ retreats to the South so that air masses undergo strong convective activity once again. The shift between October and November trajectories marks the transition to the dry season when the monsoon winds become less influent.

Figure 5 presents the variability of monthly mean GPCP precipitation along the back trajectory over time (in hours), towards Douala station for May (spring period), August (summer period), October (autumn period) and January (winter period). This analysis reveals where, along the trajectories, convective activity becomes higher and thus impacts $\delta^{18}\text{O}$ of Douala rainfall. Overall, GPCP precipitation increases from the Southern Atlantic to Douala. Along the air back trajectories, at 7 days (168 hours) to the sampling site, precipitation is higher (and similar) in August and May. First significant changes are observable at 120 hours, when a decrease (increase) of GPCP precipitation occurs in January (October). It substantially increases in May and August. At 3 days (72 hours) before Douala, convective activity is stronger in October (and to a lesser extent in May) than August and January. Since rainfall is most depleted in spring and autumn (Figures 2-3), $\delta^{18}\text{O}$ seems to be mostly sensitive to convective activity only in the past few days before reaching Douala. This is consistent with the “memory” of convection in the isotopic composition of water as discussed by [Risi et al \(2008a\)](#), [Tuinenburg et al \(2015\)](#) and [Gao et al \(2013\)](#). Stable isotopes are imprint of convection along air parcel trajectories, and in the case of Douala, precipitation seems to acquire its signature on average 72h before reaching the station. **Figure 6** shows the precipitation averaged over the past 72h (3 days) along the backward trajectories, for each month. The precipitation $\delta^{18}\text{O}$ is significantly anti-correlated with this average precipitation ($r^2=0.60$). This supports our hypothesis that convective activity along trajectories significantly controls the seasonality of precipitation $\delta^{18}\text{O}$ in Douala.

In summary, the moisture “source” at Douala is most of the year in the GOG. Two seasonal precipitation maxima along the trajectories (**Figure 6**) are related to the seasonal migration of the ITCZ. Thus, even if precipitation in Douala shows a unimodal regime with a rainfall peak in August, $\delta^{18}\text{O}$ records bimodal cycle as in the “source” area. This suggests that the regional convective activity is the main control of the isotopic composition of precipitation in Douala. In the following section, we use the isotopic information of the water vapor to provide additional insights about the main processes controlling the isotopic composition of precipitation.

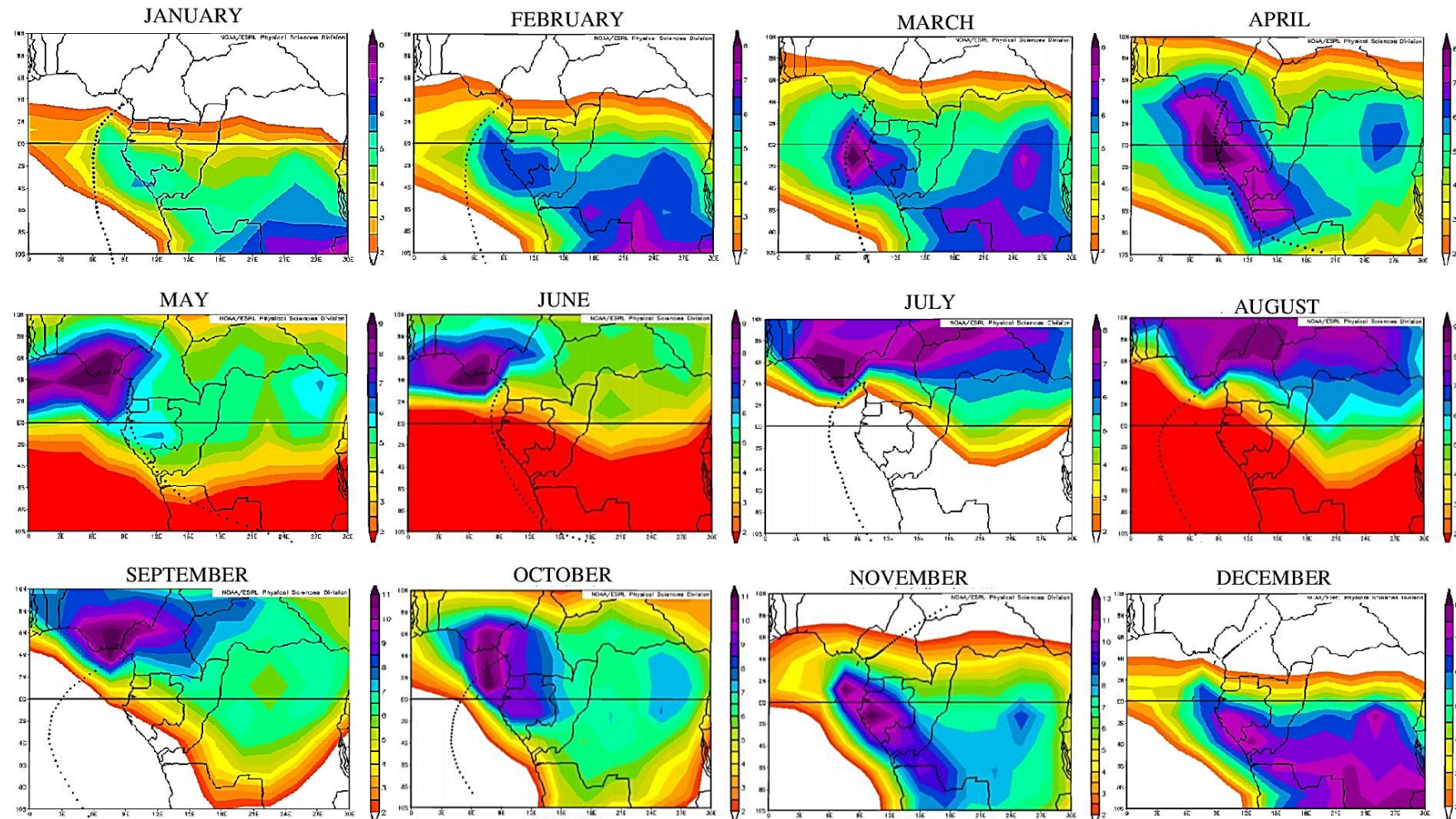


Figure 4. GPCP monthly mean precipitations (mm/day) distributions (colors) and back-trajectories (dotted curves) during the period of 2006 to 2016. White color characterizes an absence of precipitation. Monthly trajectories were calculated using monthly average mean ERA-Interim reanalysis

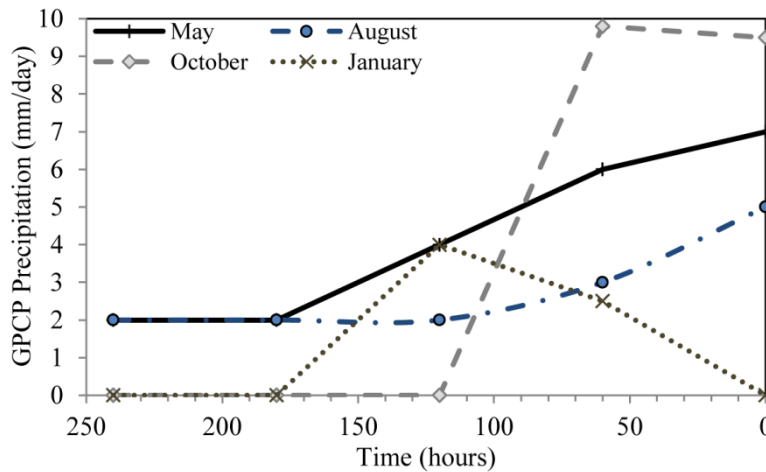


Figure 5. Evolution of monthly mean GPCP precipitations (mm/day) along the back trajectories over time (in hours) towards the Douala GNIP station in May, August, October and January for the 2006-2016 period.

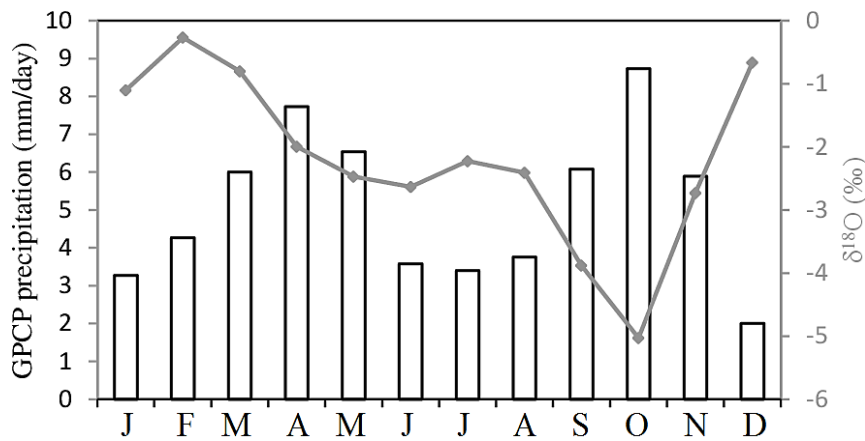


Figure 6. Monthly mean variations of $\delta^{18}\text{O}$ (grey line) and average GPCP precipitations (bars) recorded over the past 72h along the back trajectories for the 2006-2016 period.

4.2.3. Information from the isotopic composition of water vapor (δv)

The isotopic composition of the water vapor given by the TES instrument can help to understand the variation of δ in precipitation: it allows separating the relative effect of processes acting along trajectories on water vapor (δD_v) and local post-condensational processes ($\delta D_p - \delta D_v$) following the equation below:

$$\delta D_p = \delta D_v + (\delta D_p - \delta D_v) \quad (1).$$

δD_v and δD_p (Figure 7a) show a similar seasonality ($r^2 = 0.57$). Both δD_v and δD_p present depleted values in April-May and September-October (Figure 7a), corresponding to more active convection in the GOG. Thus, the isotopic information on the advected water vapor is preserved in the isotopic composition of the rain.

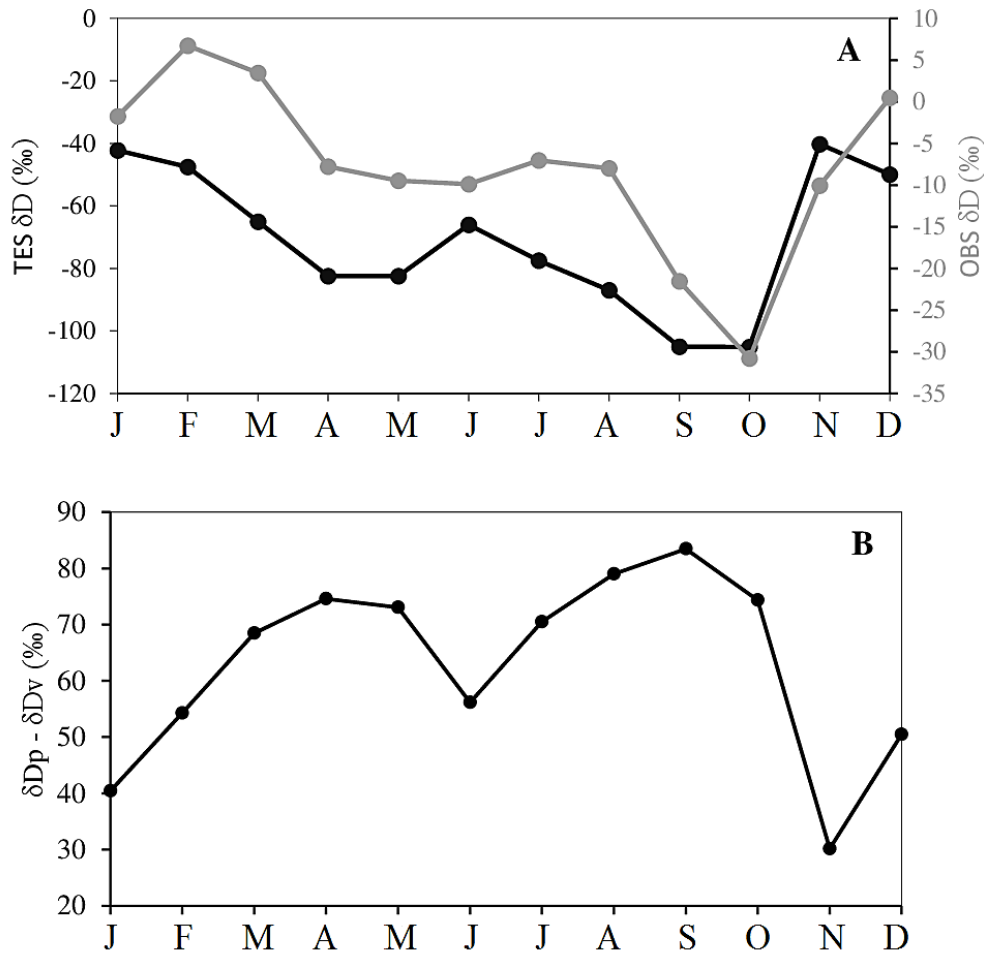


Figure 7. Mean seasonal variations of (A) δD in precipitation (in grey) and in water vapor (in black) at 900 hPa over Douala as observed at the GNIP station (2006 to 2016) and by the TES instrument (2004 to 2008) respectively; (B) $\delta D_p - \delta D_v$ over Douala

However, absolute values of δD_p and TES δD_v should not be directly compared. TES was calibrated using in-situ measurements on local sites (Worden et al 2012) but not specifically in West Africa. In addition, TES data at 900hPa represent an average over several vertical levels in the lower troposphere, and there is no reason for the precipitation to be in equilibrium with this vapor. Therefore, focus is given instead to temporal variability. Yet, assuming that the vertical δD gradient between 1000 and 900hPa is constant, $\delta D_p - \delta D_v$ variations can be interpreted as variations in the rain-water vapor interaction processes.

The regression between δD_p and δD_v gives a slope of $a_1 = 1.68$; $r^2 = 0.57$ whereas the values for δD_p and $\delta D_p - \delta D_v$ are $a_2 = -0.68$ and $r^2 = 0.18$. This insignificant r^2 attests that the rain-water vapor interaction processes do not control the δD_p variations. Based on the slope a_1 , δD_v accounts for more than 100% of the δD_p variability. This confirms that the seasonal variability of the isotopic composition of rainfall is predominantly influenced by δD_v , i.e. by

the processes that affect water vapor along the trajectories. This means that the variability of $\delta D_p - \delta D_v$ acts only to dampen and to blur the variability of δD_p . For instance, the evolution of $\delta D_p - \delta D_v$ presents a maximum in spring (Figure 7b) and autumn, when δD_v is most depleted.

4.3. Main controls of precipitation isotopic composition at daily scale

4.3.1. Temporal evolution of δ and link with upstream convection

Daily $\delta^{18}O$ in Douala varies from -0.3‰ to -7.4‰, with a mean of -3.0‰ close to the monthly weighted mean of -2.8‰ calculated for the 2006-2016 period. These daily data appear then to be representative of the 2006-2016 mean seasonal cycles. Moreover, as for the seasonal scale, daily rainwater (Figure 8) is most depleted in spring (April-May) and more enriched in summer (July-August).

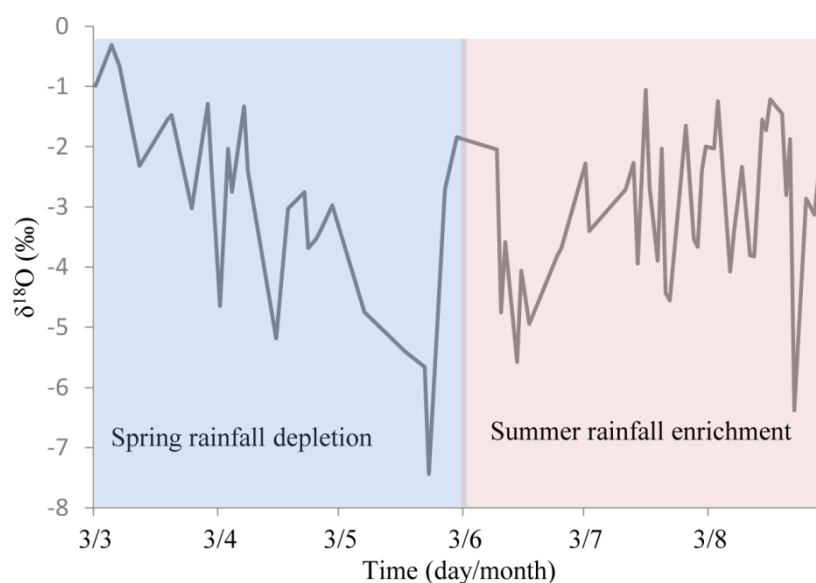


Figure 8. $\delta^{18}O$ in daily rainfall at Douala from March 2017 to August 2017.

In order to investigate upstream convection effects, we calculated the correlation between the $\delta^{18}O$ of rainfall and the precipitation recorded at 1 to 3 days earlier, along back trajectories (Table 3). In March, April and August, the correlations are significant ($\geq 95\%$), suggesting that, like for the seasonal timescale, the daily evolution is driven by convection along trajectories. Yet, this mechanism is insufficient to explain completely the variability of δ in daily precipitation, especially in May, June and July.

Table 3. Coefficient of determination (r^2) between $\delta^{18}\text{O}$ and average GPCP precipitation in average over the first day, two first days and three first days along the air parcel trajectory before rainfall in Douala. Correlation coefficients $\geq 95\%$ are highlighted in bold and underlined.

		March (n=08)	April (n=12)	May (n=07)	June (n=09)	July (n=14)	August (n=20)
$\delta^{18}\text{O}$ Vs GPCP Precipitation	One day before	<u>0.53</u>	<u>0.43</u>	0.40	0.03	0.14	0.15
	Two days before	<u>0.55</u>	0.23	0.28	0.14	0.03	<u>0.23</u>
	Three days before	<u>0.64</u>	0.16	0.44	0.00	0.11	<u>0.23</u>

4.3.2. Factors besides the upstream convection intensity: continental recycling and organization of convective systems

Continental recycling?

The goal of this section is to test whether continental recycling has significant influence on $\delta^{18}\text{O}$ at the daily time scale. To that end, we calculated the percentage of time of the air parcel over the continent during the last 3 days along the trajectory, hereafter F_{land} . In June, July and August, F_{land} is 0% for all rainy days (except on June 11th when $F_{\text{land}} = 25\%$). Table 4 presents the detailed results for spring period and shows an anti-correlation between $\delta^{18}\text{O}$ and F_{land} . Precipitation are thus more depleted, when the transit time of air parcels over the continent is long, during the last 3 days along the back trajectory. This is in contradiction with the expected effect of a continental recycling.

Table 4. F_{land} statistics during the last 3 days along the air parcels trajectories for the months of March, April and May. Relationship (r^2) between F_{land} , $\delta^{18}\text{O}$, and upstream GPCP precipitation. For the summer period, F_{land} corresponds to 0% for almost all rainy days. Correlation coefficients $\geq 95\%$ are in bold and underlined.

	March	April	May
F_{land} (%)	0	0	25
Minimum			
F_{land} (%)	100	100	100
Maximum			
F_{land} (%)	25	69.45	70.83
Mean			
F_{land} (%)	0	83.34	79.17
Median			
r^2 (F_{land} vs $\delta^{18}\text{O}$)	0.23	<u>0.33</u>	0.28
r^2 (F_{land} vs GPCP precip.)	0.51	0.42	0.85

Since δ is controlled in spring by a convection upstream the sampling site, the fact that $\delta^{18}\text{O}$ is more depleted with the increase of F_{land} , suggests significant influence of convection intensity over the continent. Indeed, [Xu and Zipser \(2012\)](#) demonstrated that convection is generally more intense over the land than over the ocean. The more intense the convection along trajectories, the more depleted the water vapor. Therefore, moisture origin has only an indirect effect on isotopic composition of precipitation, depending on whether air mass goes through regions of a strong convection. The positive and significant correlation between F_{land} and GPCP precipitation confirms this mechanism.

Therefore, we suggest that, δ variations at a daily timescale are partly controlled by the intensity of the convection along air parcel trajectories and that continental recycling is not involved.

Influence of the organization of convective systems?

Several studies have shown that convective systems deplete the low-level water vapor more efficiently when they are more organized ([Lawrence et al. 2004](#), [Risi et al. 2008](#), [Tremoy et al 2014](#)), probably because moister air in larger systems allows for more efficient rain-vapour diffusive exchanges ([Risi et al. 2008a](#)). In addition, convective systems deplete more vapor as they extend to the upper troposphere ([Lacour et al 2018](#)) and as the extent of their anvils (measured by the fraction of stratiform clouds) is large ([Aggarwal et al. 2016](#)). These features are typically associated with higher degrees of organization.

Here, we test whether the type of convective organization has a significant impact on the $\delta^{18}\text{O}$ observed at Douala. By using satellite image from the SAF classification, we define 3 classes of clouds in the region from March to August according to their altitude: (i) very low to low; (ii) medium to high and (iii) very high clouds. The low cloud class is mostly observed in July-August ([Table 5](#) and [Figure 9](#)). The mid-level to high cloud class is dominant in June and the very high clouds are mostly present in spring ([Figure 9](#)). The area of cloud systems increases throughout spring, reaching a maximum in May, and decreases again from June. In July-August, the areas are too small to be calculated.

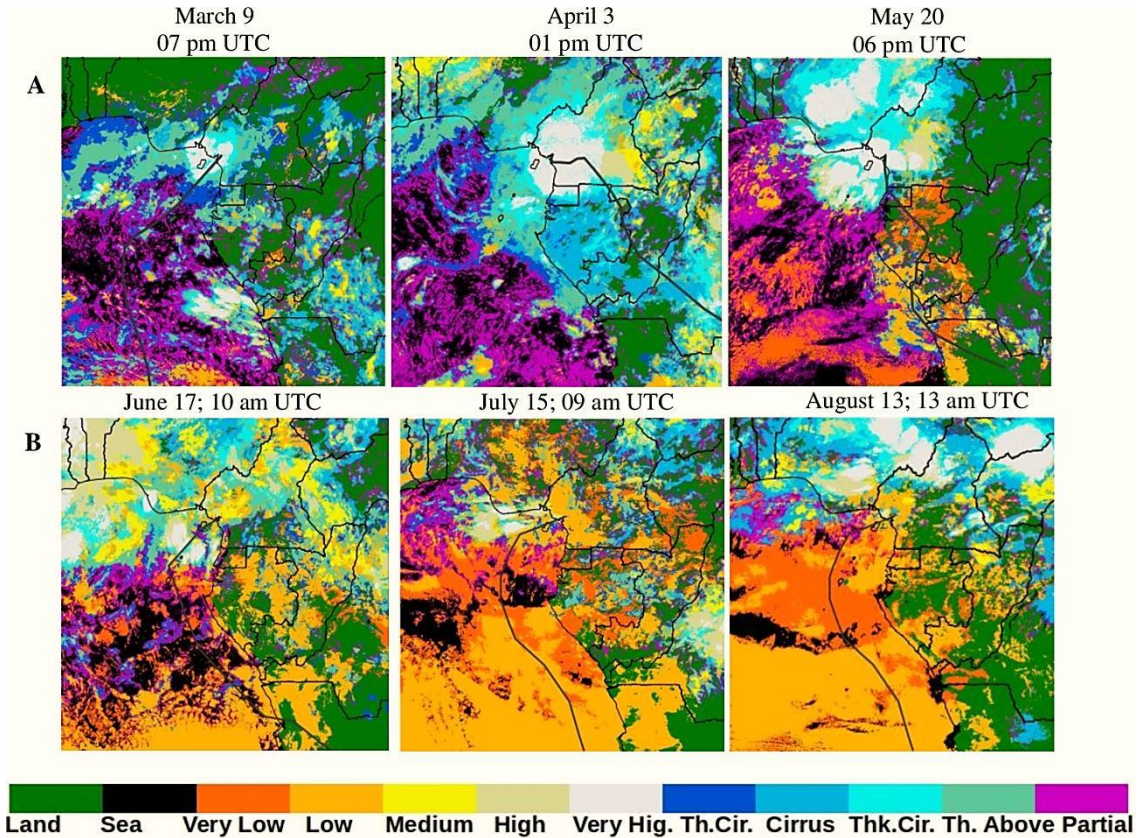


Figure 9. Example of meteorological situations in the study region in 2017 (based on the SAFNWC cloud classification) during (A) spring and (B) summer periods. The backward trajectories (grey line) are plotted for each event.

Spatial organization of convective systems also determines rainfall event duration. The latter increases globally from March to August (Figure 10). It ranges from 12 minutes to 1278 min (i.e. more than 21 hours).

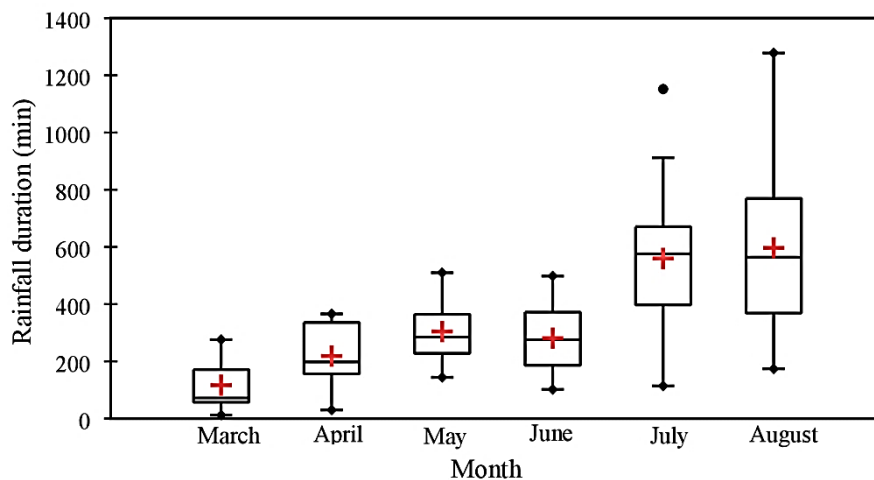


Figure 10. Statistical distribution of daily rainfall duration at Douala as shown by box-and-whisker representation. The boxes have lines at the lower, median and upper quartile values.

The whiskers are lines extending from each end of the box to 1.5 interquartile range. Red cross represents the mean and outliers are represented by black points above the maximum

Combining this information on cloud altitude, cloud area and rainfall duration, we can infer that in March-April, most convective systems are deep meso-scale convective systems (MCS; Mapes and Houze 1993; Laing and Fritsch 1997; Mathon et al. 2001; Fink et al. 2006; Tremoy et al. 2014). In May-June, convective systems are MCS that become even larger and organized, but extend less deep in altitude (in June). In contrast, in July-August, convective systems are isolated; characterized by small cumulonimbus in the middle of low-to-medium clouds (Figure 9b) that follow one another throughout the day, explaining the apparent long durations of rain events.

The type of convective organization emerges then as an important control on the precipitation isotopic composition. Cloud surface shows a significant negative correlation with precipitation $\delta^{18}\text{O}$ from March to June (Table 5). The larger the cloud area, the more depleted the precipitation. In addition, the more the convective system is organized, the longer is the duration of the event (Laurent and Machado 2002, Fiolleau et al. 2013). Consistently, event-scale $\delta^{18}\text{O}$ is anti-correlated with event duration in March ($r^2 = 0.44$), April ($r^2 = 0.54$), May ($r^2 = 0.64$) and more weakly in June ($r^2 = 0.34$). The longer is the convective system, the more depleted is the precipitation.

These different types of convective organization can also explain the isotopic evolution at the seasonal scale. In spring, the organized, deep MCS deplete the water vapor efficiently, leading to the observed precipitation $\delta^{18}\text{O}$ minimum. In contrast, in July-August, the shallower, small isolated cumulonimbus clouds deplete the water vapor less efficiently, leading to the observed precipitation $\delta^{18}\text{O}$ maximum in spite of the local precipitation maximum observed at Douala.

Surprisingly, the r^2 between cloud area and $\delta^{18}\text{O}$ are close and even higher (in May and June) than that observed between $\delta^{18}\text{O}$ and upstream precipitation (Table 3). After verifying that upstream convection (GPCP precipitation recorded at 72h to Douala along the trajectory) and cloud area are uncorrelated (Table 5), we can assert that two independent parameters control $\delta^{18}\text{O}$: upstream convection intensity and the size of the convective system (both at local scale and at upstream, see the Table 5).

Table 5. Information on the organization of convection (cloud types, cloud area and local/upstream) and its influence on the isotopic composition of daily rainfall over the period from March 2017 to August 2017. Cloud areas were only calculated for very high classes. Correlation coefficients significant $\geq 95\%$ are in bold and underlined.

	March	April	May	June	July	August
Very low to low clouds (%)	0	0	0	0	71.43	54
Medium to high clouds (%)	0	0	18.18	72.73	21.43	40.5
Very high clouds (%)	100	100	81.82	27.27	7.14	5.5
Local without upstream convection (%)	75	27.27	0	22.29	7.14	0
Upstream and local convection (%)	25	72.73	100	77.71	92.86	100
Minimum cloud area (km²)	5300 ± 100	4500 ± 100	63400 ± 100	2400 ± 100		-
Maximum cloud area (km²)	35300 ± 100	158100 ± 100	285600 ± 100	280000 ± 100	3077 ± 100	615 ± 100
Mean cloud area (km²)	17800 ± 100	73700 ± 100	225100 ± 100	138500 ± 100	-	-
r² Clouds area Vs rainfall duration	<u>0.54</u>	<u>0.63</u>	<u>0.51</u>	0.34	-	-
r² Clouds area Vs $\delta^{18}\text{O}$	<u>0.44</u>	<u>0.55</u>	<u>0.97</u>	<u>0.90</u>	-	-
r² Clouds area Vs GPCP precipitation	0.30**	0.10**	0.01**	0.46**		
r² Rainfall duration Vs $\delta^{18}\text{O}$	<u>0.44</u>	<u>0.54</u>	<u>0.64</u>	0.24	0.00	0.07

**Anti-correlation

5. Conclusion and outlook

This study aims at investigating the processes controlling the year-to-year (inter-annual), month-to-month (seasonality) and day-to-day (intra-seasonal) variability of rainfall isotopic composition in the Gulf of Guinea (GOG) region and especially in Douala (Cameroon). We observed that the annual cycle of δ is quite reproducible. Most years presents a W shape with minima in spring and autumn. $\delta^{18}\text{O}$ and δD_v appear to be mainly controlled by upstream convection and by the size of convective systems. We identified that the continental recycling doesn't impact the rainwater isotopes in the humid tropical area of the GOG. In particular, the $\delta^{18}\text{O}$ minima in spring and autumn are associated with strong convective activity in the GOG and large, long-lived and deep meso-scale convective systems, whereas the $\delta^{18}\text{O}$ maximum in July-August is associated with reduced convective activity in the GOG and isolated shallow convective systems. The importance of upstream convective activity in controlling the $\delta^{18}\text{O}$ of precipitation at various time scales is in line with a large body of recent research in different tropical regions influenced by a monsoon system. The importance of the type of convective system (size, organization, vertical extension) is also consistent with a growing number of recent studies but this is the first time that it is demonstrated through a detailed analysis of such a large number of individual convective systems. The findings of this study (obtained by integrating in situ and satellite measurements) advance our understanding of the temporal variation of precipitation stable isotopes in humid tropical area such as Douala, and shed a new light on the importance of large scale meteorological conditions controls on precipitation stable isotope composition in the GOG.

Notwithstanding, numerical climate modelling could be a useful complementary approach to further analyse the factors controlling rainfall isotopic composition in and around Douala. Moreover, the climate in Douala being representative of a small area with monomodal rainfall regime surrounded by area with bimodal rainfall, high resolution modelling is necessary to correctly capture such particularity. More robust conclusions could be obtained with larger samples, which could be obtained by extending the length of the record. To better understand the role of convective organization on the isotopic composition, sampling at the intra-event scale is necessary. Finally, measuring the isotopic composition in the water vapor in addition to precipitation would be useful to isolate the post-condensation effects.

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5. Synthesis and final discussion

This chapter demonstrates the usefulness of isotope hydrology for the study of atmospheric processes in addition to conventional meteorological measurements. This research gives important insights on the factors controlling the isotopes variations at different timescales in the humid Western Central Africa region and peculiarly in Douala.

The main highlights of this work are:

- a good reproducibility of $\delta^{18}\text{O}$ annual variation from year to year with a W shape; the lowest values of δ are quoted in spring and autumn due to intense convective activity;
- a strong influence of regional convective activity on rainfall isotopes whereas local meteorological parameters seems to have no influence;
- The elevation and size of convective systems lead to a modification of the isotopic content of precipitation.

In detail, we show that the isotopic composition of rainwater is more related at first order to regional (and not local) precipitation via the history or trajectory of the air mass. This is the influence of upstream convection. The W shape observed on the annual cycles of $\delta^{18}\text{O}$ reflects the bimodal cycle of rainfall in the “source” region of Gulf of Guinea although Douala displays a unimodal mode with a maximum rainfall amount in August. This kind of control also observed in South America (e.g., [Vimeux et al. 2005](#); [Villacís et al. 2008](#)), Southeast Asia (e.g., [He et al. 2015](#), [Chakraborty et al. 2015](#)) is then one of the main characteristics of humid tropical regions.

The isotopic signal of the water vapor appears to be similar to that of rainfall, suggesting a weak influence of post-condensation processes. Thus, the signal in the vapor reflects the history of the air mass and is not altered during the rainfall.

We demonstrate also that there is no continental recycling in the studied region. This confirms the results of [Njitchoua et al \(1999\)](#); [Peng et al \(2011\)](#) and [Risi et al \(2013\)](#) who show that in coastal regions, the intra-seasonal variability of moisture is mainly driven by the variability in oceanic moisture convergence. Instead of continental recycling process, we observed that the convection type of tropical rainfall in Douala is divided into two archetypical regimes: continental and maritime. Active monsoon convection (July-August) is more maritime-like, while the break periods (spring and autumn periods) are often closer to continental convection in agreement with the work of [Xu and Zipser \(2012\)](#). By comparison, we note that, if the summer monsoon which corresponds to the peak of the rainy season, is characterized by squall lines with very intense convection in the northern portion of the Western African region, at Douala the convective systems at this time appear disaggregated, characterized by small cumulonimbus that follow one another throughout a day.

At a daily scale, information obtained by satellite images of clouds is very valuable in our investigations. The importance of the type of convective system (size, organization, depth) is consistent with a growing number of recent studies ([Lawrence et al. 2004](#), [Risi et al.](#)

2008a, Tremoy et al. 2014, Aggarwal et al. 2016, Lacour et al. 2018). Nevertheless, it is the first time that it is clearly demonstrated through a detailed analysis of such a large number of individual convective systems.

Finally, in this chapter, we have shown the contribution of isotopes to a better understanding of convective/hydrological processes in the atmosphere. This is essential in the context of surface and subsurface hydrological studies as precipitation constitutes the input signal of groundwater. Atmospheric processes modifying the isotopic contents of rainwater along the year can be useful to trace the transfer of continental waters through the critical zone, notably with regard to the conditions and timing of groundwater recharge (Gonfiantini 1996).

Chapter IV

From rainwater to groundwater. Characterization of subsurface flow by coupled hydrology-geochemistry approach.

Following the previous chapter, which presented the processes involved in the circulation of atmospheric water in the hyper-humid region of Douala, this chapter deals with the transfer from the atmosphere to the saturated zone. This study focuses on the Mio-Pliocene aquifer and was carried out by using potentiometric data, major ions and stable isotopes. In a first step, natural features of Douala (in addition to meteorological settings presented in the previous chapter) such as: the relief, the hydrography, and the types of soils have been defined since these parameters control the rainwater infiltration into the sub-surface. Secondly, the geology (lithology and structural elements) which constitutes the key control of water circulation within the aquifers has been described. Finally, thanks to hydrogeological approach and geochemical tools, this study will present the processes which affect the water molecule within the subsurface. By depicting the aquifer functioning, it will contribute to a better management of water resource in the study region.

1. Geomorphology, hydrography and soils

1.1. Geomorphological context

The coastal surface where the region of Douala lies extends from the ocean towards inland about 150 km to the East and 200 km to the North. The Digital Elevation Model (DEM) shows for Douala, a very weakly contrasted topography, characteristic of flattened surfaces as described behind, with altitudes varying between 0 and 73 m.a.s.l (Figure 26). However, two large areas separated by an escarpment can be observed on the DEM (Figure 26): the coastal plain *sensu stricto* and the inner plateau.

The coastal plain

It is bounded on the NW by the Wouri estuary and on the NE by the escarpment line (Figure 26). The coastal plain represents more than half of the city of Douala. The reliefs are flat and monotonous, with slopes varying between 0° and 3° but in some places there are hills exceeding 34 m a.s.l.

The inner plateau

It covers the eastern districts of Douala. It is the most incised area with sometimes steep slopes reaching 9°. Its average altitude is approximately 50 m.a.s.l with a minimum and maximum corresponding respectively to 28 and 73 m.a.s.l approximately. The relief has several peaks and the surface is strongly dissected by a dense hydrographic network.

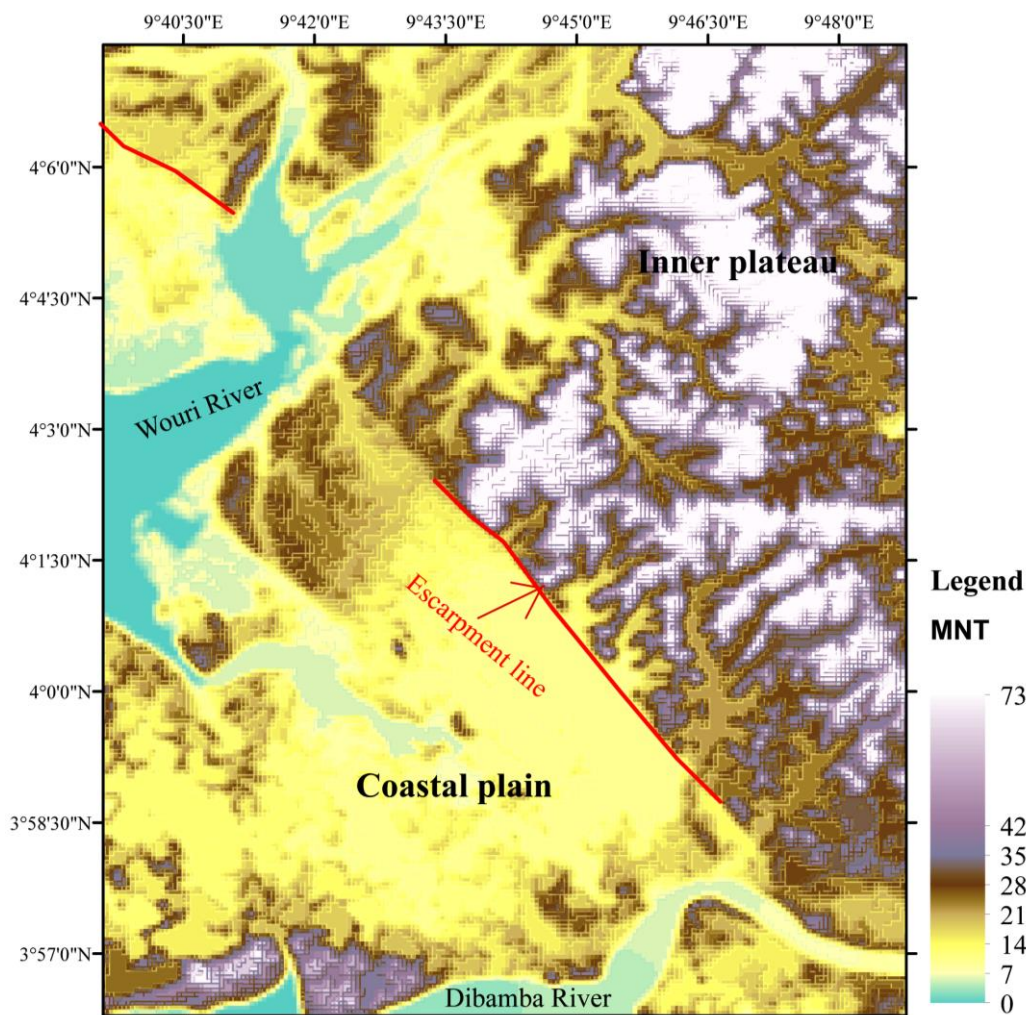


Figure 26: Digital Elevation Model (DEM) of the city of Douala, extracted from SRTM data.

1.2. Hydrographic network and hydrology

The hyper-humid conditions characterizing the region of Douala are responsible for large surface water masses. Two principal rivers can be identified: the Wouri and the Dibamba, with several tributaries (Figures 26 and 27). Surface water flow NE to SE following the topography. In the NE side of the study region, where the altitudes are highest (Figure 26), the hydrographic network is most incised while in lowland areas it is more related to swamps. The weak slopes at Douala lead to a meandering network (Figure 27) which is classic in the alluvial plains (Bettes & White 1983).

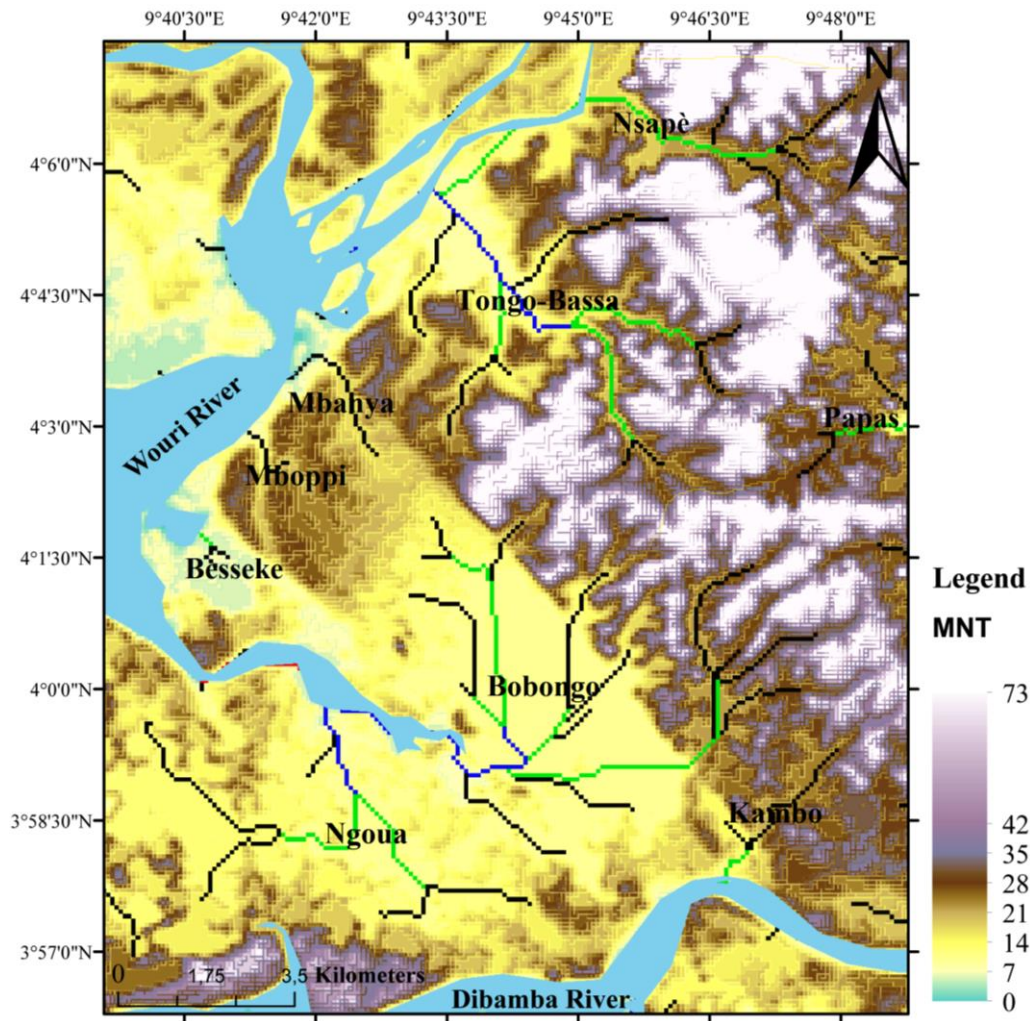


Figure 27: hydrographic network of the region of Douala with Digital Elevation Model (DEM) on background. The names of different sub-basins are indicated.

The Wouri watershed

It has a total area of 11700 Km² with 2% in the Douala meagacity where it occupies the greatest part compared to the Dibamba one. The Wouri River has 7 tributaries corresponding to 7 sub-basins at Douala: Ngoua, Bobongo, Bessekè, Mboppi, Mbanya Tongo Bassa and Nsapè (Figure 27).

Tongo Bassa, Nsapè, Bobongo and Ngoua Rivers are among the largest collectors of water (Figure 27). They are also the most meandering rivers with lengths of 9 km for Tongo-Bassa, 8 km for Nsapè, 13 km for Bobongo and 9 km for Ngoua, between the source and the confluence with the Wouri River. These lengths are associated with coefficients of sinuosity (λ) greater than 1.5, thus confirming the meandering character of the rivers (Brice 1974). λ corresponds to 7, 10, 17 and 13 at Tongo-Bassa, Nsapè, Bobongo and Ngoua. The altitude difference between the source and the lowest point for these rivers corresponds respectively to 21 m, 34 m and 24 m respectively. This reflects a flow from the inner plateau to the coastal plain.

The hydrology of the Wouri River is well known thanks to [Olivry \(1986\)](#) who carried out measurements from 1951 to 1977 at a station located approximatively at 90 km NE of Douala in order to avoid tides influences. The hydrological regime of the river is similar to that of precipitation ([Figure 28](#)).

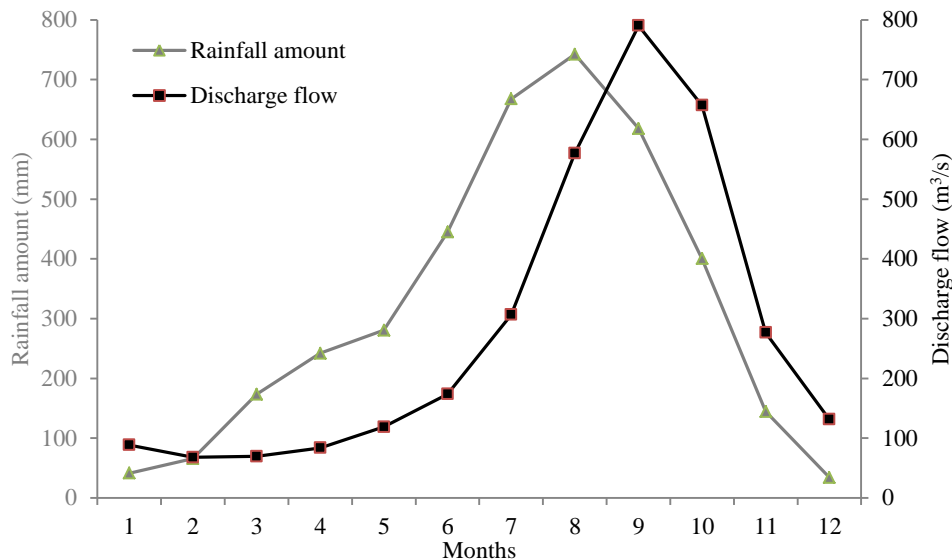


Figure 28: Monthly variations of rainfall amount (data from 1951 to 2016) and discharge flow of the Wouri River (data from 1951 to 1977).

From December to June, discharge flows are low. The resumption of rainfall in March does not lead to a significant increase in discharge. This latter increases rapidly from June-July to reach maximums in August-September and October, related to maximum rainfall amount. This lag time between the increase of precipitation and the river's response from March-April to May-June is due to the replenishment of groundwater and soil reserves which had dried up in the period of December-February. However, in the core of the rainy season (July-August), surface water responds rapidly to rainfall and from a discharge of $900 \text{ m}^3/\text{s}$ ([Olivry 1986](#)), floods generally occur in the Douala region, favored by weak slopes. This case often occurs from August to October.

The Dibamba watershed

It covers an area of $2,400 \text{ km}^2$ with a little part (2.8%) in the Douala region. The 150 km long Dibamba River enters the study region on its southeast side (in the district of Japoma), and then flows towards the Wouri estuary. It corresponds at Douala to the Kambo watershed ([Figure 27](#)). The first-order, second-order and third-order watercourses which constitute the sub-watershed of Papas, at the east of Douala ([Figure 27](#)), would also throw in. The Dibamba is influenced by tides over a length of about 68 km ([Olivry 1986](#)). Unlike to the Wouri River, the Dibamba never undergoes a long monitoring period. Nevertheless, [Olivry \(1974\)](#) thanks to one year measurements reported that the lowest and flood discharges are respectively of $10 \text{ m}^3/\text{s}$ and $420 \text{ m}^3/\text{s}$ with an annual mean of $125 \text{ m}^3/\text{s}$.

In summary, the hydro-geomorphology of the city of Douala is marked by:

- (i) an upstream zone (eastern part of the city) where the slopes are more marked and the streams beds are well individualized;
- (ii) a downstream zone with more weaker slopes constituting a flood-spreading area in a larger and swampy bed.

1.3. Soils

Douala has two types of soils: ferralitic soils and hydromorphic soils (Segalen 1967; Zogning 1987 and Ndomé 2010). In both cases, the authors identified a large proportion of fine and coarse sands (45 to 80%), and clays (10 to 50%). The proportions of kaolinite (50-60%) are the most important while goethite (35-42%) is significant and gibbsite (2-10%) is negligible.

Ferralitic and hydromorphic soils occupy respectively 80% and 20% of the study region. The latter are mainly observed in alluvial plains and valley bottoms.

The Soils are mostly occupied by urban areas (35%) and vegetation (48%) which respectively spread and decrease overtime due to human activities. Farmlands and surface water cover respectively 8% and 9% of the study region (Emvoutou 2018).

2. Geological framework

2.1. The Douala basin: geodynamic evolution from the Pangea to the present

Global features at earth scale

The Hercynian orogeny assembles the Pangea Supercontinent in the Permian. However Pangea begins to fracture very soon after (Figure 29). The Paleo-ocean Tethys opens from East to West from the Upper Permian to the Middle Jurassic, separating the Pangea in two continents: Gondwana to the South and Laurasia to the North (Figure 29). The Tethys ends in the West by the separation of the current Southern Europe and the present North Africa.

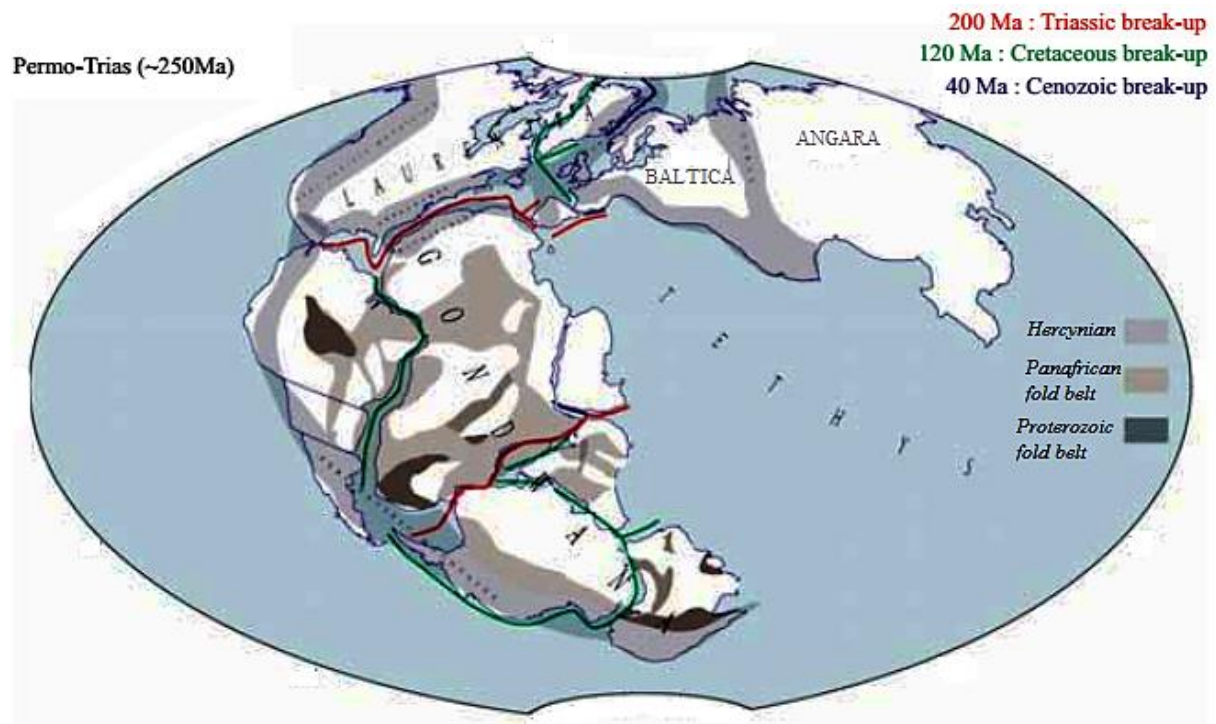


Figure 29. Permo-Triassic reconstruction (~ 250 Ma), just before the dislocation of the Pangea. (Olivet et Aslanian, pers. comm. in Moulin et al. 2003).

At the same time, at the end of the Triassic, about 200 Ma, the super-continent Pangea also undergoes several ruptures (red and green lines, **Figure 29**) giving birth to two oceans :

- Atlantic Ocean:

The Atlantic separates the Gondwana in two blocks: the current South American and African continents. The south-eastern part of the Atlantic will correspond to the West African passive margin from which the Douala sedimentary basin.

- Indian Ocean:

Part of the future Indian Ocean begins its stretch about 220 Ma within Gondwana continent. In the Upper Jurassic, about 160 Ma, a rift thus separates Africa from India.

At the opening of the Atlantic Ocean, the Americas and Africa gradually moved away. The mid-oceanic ridge thus divides the Atlantic Ocean from North to South in an American part in the West and Africa at the East. The physiographic elements of the Atlantic Ocean describe five main "super-basins" (**Figure 30**) on the West African margin whose dimensions are of the order of a few million km² of surface. We distinguish:

- the super-basin of the margin of Morocco composed of the basins of *Rharb-Mamora*, *Doukkala*, *Essaouira-Agadir*, *Tarfaya-Laâyoune* and *Dakhla*

- the super-basin of the margin of Mauritania – Senegal – Guinea Bissau - Guinea Conakry which includes the basins of *Mauritania*, *Senegal*, *Gambia – Casamance* - *Guinea Bissau-Guinea Conakry* and *Sierra Leone - Liberia*

- the super-basin of the Gulf of Guinea northern margin represented by the basins of *San Pedro, Abidjan, Ghana – Togo - Bénin* and *Nigéria*
- the super-basin of the Gulf of Guinea southern margin made of basins of *Douala, Kribi-Campo, Rio-Muni, Gabon, Cabinda/Bas-Congo, Kwanza, Benguela* and *Moçamedes*
- the super-basin of the margin of Namibia – South Africa including the basins of *Walvis, Luderitz* and *Orange*.

Before going further, it is important to note that the formation of a passive margin taking place via two major processes intimately linked: rifting and ocean formation. Rifting is the process of dislocation of a continental crust following stretching and thinning of the lithosphere. It results in the creation of normal faults, tilted blocks and highly subsistent grabens. Oceanization is a process leading to the formation of a new oceanic crust. Indeed, following intense stretching and maximum thinning of the continental crust, the lithosphere breaks and the two parts of the continental lithosphere separate and progressively move away from each other, and then the oceanic crust is formed. This continental separation step is called "break-up". A narrow ocean set up and the rift sinks below the sea level. Submarine volcanism then forms a first basaltic ocean floor (oceanic crust): it is the linear sea. Ocean floor expansion is provided by volcanic activity that ejects materials on both sides of the shore. When the floor is big enough, you get a well-structured full margin (for more information, see [Mvondo 2010](#)).

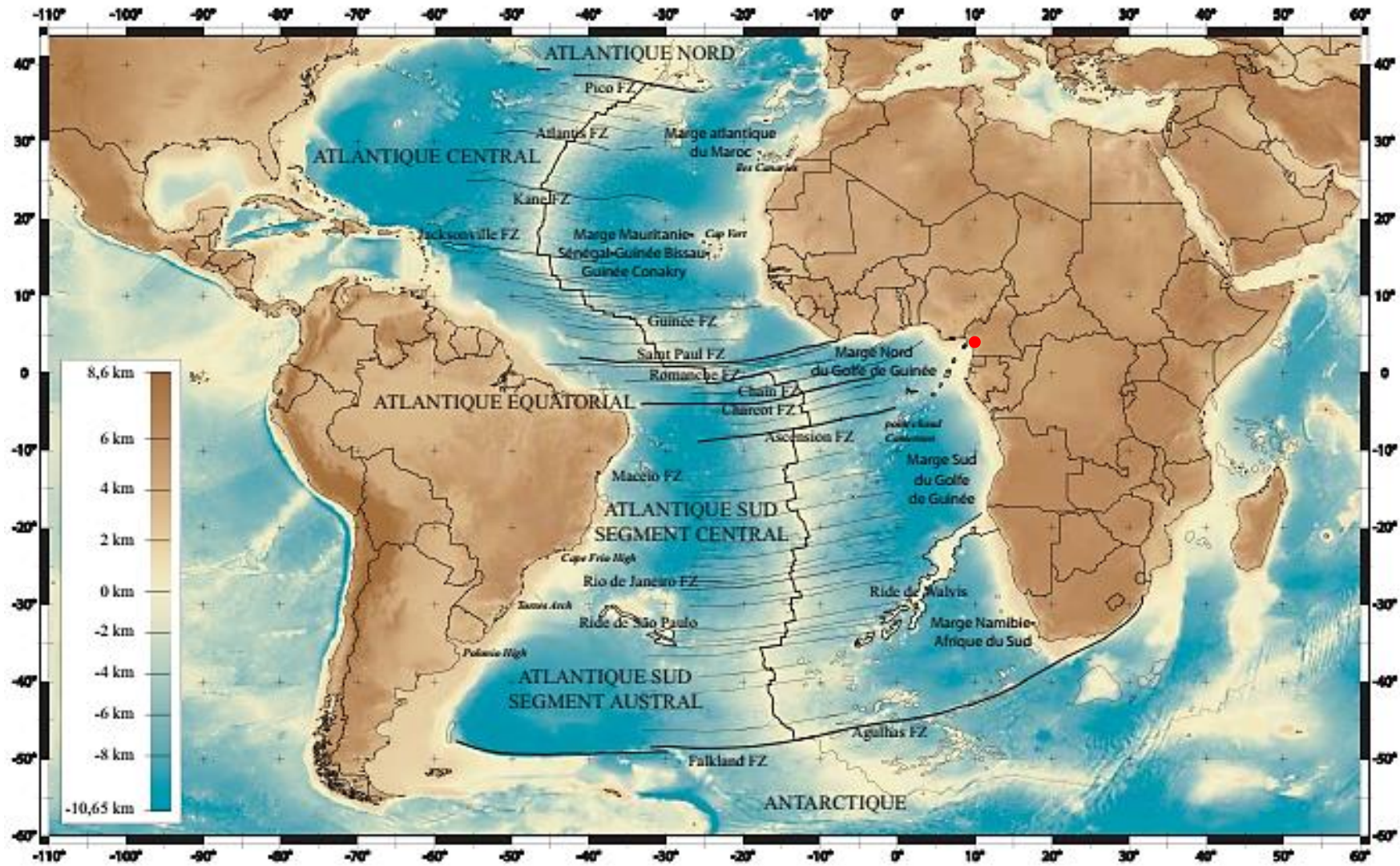


Figure 30: Map of sedimentary basins of the West African passive margin (Helm 2009). The red point represents the location of the Douala region.

Specific features at the Douala basin scale

In the following paragraphs, we will only focus on the evolution of the southern margin of the Gulf of Guinea and more specifically to that of the Douala basin in Cameroon.

The pre-rift stage, between the Upper Proterozoic and the Ordovician, is characterized by the Pan-African orogeny that will become the base of the passive margin of the South Atlantic. An important gap overcomes it between the Silurian and the Jurassic in its central segment.

Then the rifting spreads in the lower Cretaceous from South to North. According to [Coward et al \(1999\)](#), the ages that can be retained for the beginning of the rifting in the Douala basin are closed to Intra-tithonian (~150 Ma). These ages need however to be relativized since an uncertainty up to 20 Ma is given by [Helm \(2009\)](#). According to [Davison and Bate \(2004\)](#), there are two stages in the rifting process within the southern margin of the Gulf of Guinea: (i) during the Tithonian, the separation of South America and Africa results in the formation of small NW-SE intra-cratonic basins that are filled with coarse continental terrigenous sediments sometimes interspersed with volcanic rocks; (ii) then, a major erosion surface, interpreted as break-up unconformity, marks the end of the syn-rift stage between the Barremian (125 Ma) and the Lower Aptian, depending on the sub-basins.

After the rifting, between the Middle Aptian and the Upper Aptian, layers of evaporates (700 to 1500 m of thickness) are deposited ([Stark et al. 1991](#)). This period corresponding to the beginning of the passive margin stage, is followed by a period of sedimentation linked to a generalized thermal subsidence that extends on the entire margin.

The geology of the Douala basin will then be affected by a gravity subsidence at the Albian, an angular offset that erodes syn-rift sediments during the Cenomanian, a regional tectonic phase from the Upper Santonian to the Lower Campanian creating a transgression in the Central Africa zone while the Oligocene is marked by regressions and erosions. We also note an increase in bathymetry to the seaward from the Turonian to the present. During the Neogene, the basins continue to sink with a subsidence punctuated by several tectonic episodes and the upper Miocene is affected by regional uplift of the West African margin. This uprising causes a considerable erosion of part of the Douala basin. The escarpment between the coastal plain and the inner plateau ([Figure 26](#)) would then be dated from the Miocene? The Quaternary for its part shows little evidence of deformation. Most of tilts and uplifts seem to have been completed in the Pliocene.

2.2. Some tectonic elements of the Douala basin

From a strict structural point of view, the Douala basin results from the E-W extension of the South Atlantic rift, where the NE-SW to ENE-WSW direction of the Cameroon volcanic line is superimposed. The evolution of the Douala basin seems to be deeply influenced by these two structural elements. The mainland basin is characterized by a half graben affected by NE-SW lineaments. The offshore part presents faults related to pre- and syn-rift structures.

A second fracture system is formed by N 60 ° E transverse faults superimposed to NE-SW lineaments.

In summary, the rifting phases fractured the basement and it is on one half-graben that sediments were deposited following a monoclinical structure (Figure 31). These deposits, continental to the east, are progressively moving westward to coastal plain, marginal sea, continental shelf and deep seabed environments.

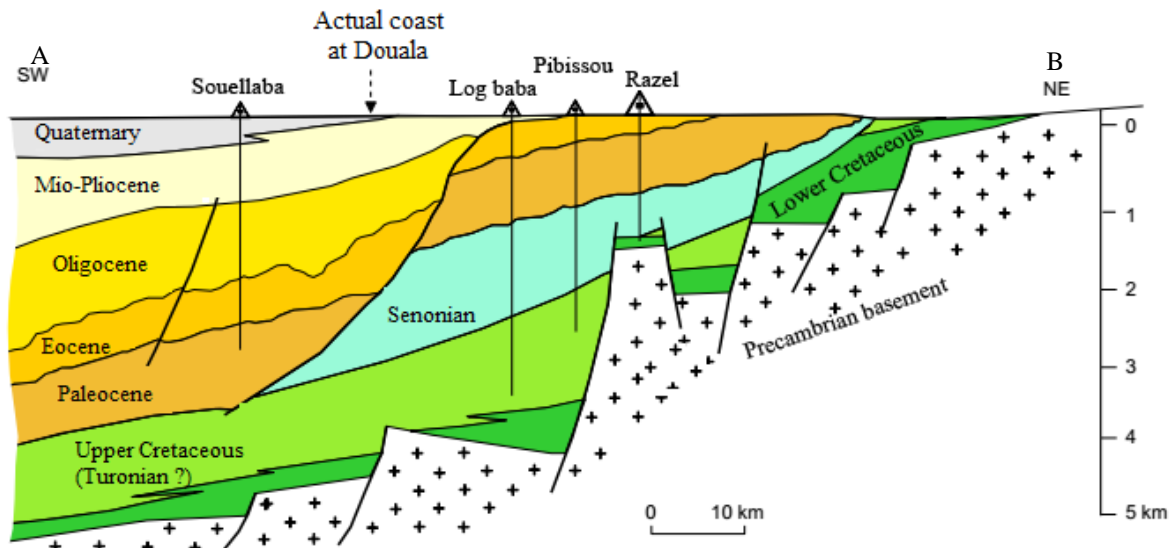


Figure 31: geological cross section of the Douala basin (Regnault 1986).

2.3. Litho-stratigraphy and palaeoenvironments of the Douala basin

The Douala basin is characterized by successive deposits similar to other basins of the West African margin (Figure 31). It is composed of 7 geological formations that are, from the bottom to the top (from the oldest to the youngest): Mundeck, Logbadjeck, Logbaba, N'kapa, Souellaba, Matanda and Wouri (Figures 31 and 32). These formations are relatively well known thanks to the previous studies of Dumort (1968), Njike Ngaha (1984), Regnault (1986), Nguene et al (1992), SNH/UD (2005), Manga 2008, Djomeni et al (2011), Ngon Ngon et al (2012), Njoh et al (2014), Njoh and Petters (2014), Ngon Ngon et al (2014), Chavom et al (2014), Mbesse (2014), Njike Ngaha et al (2014).

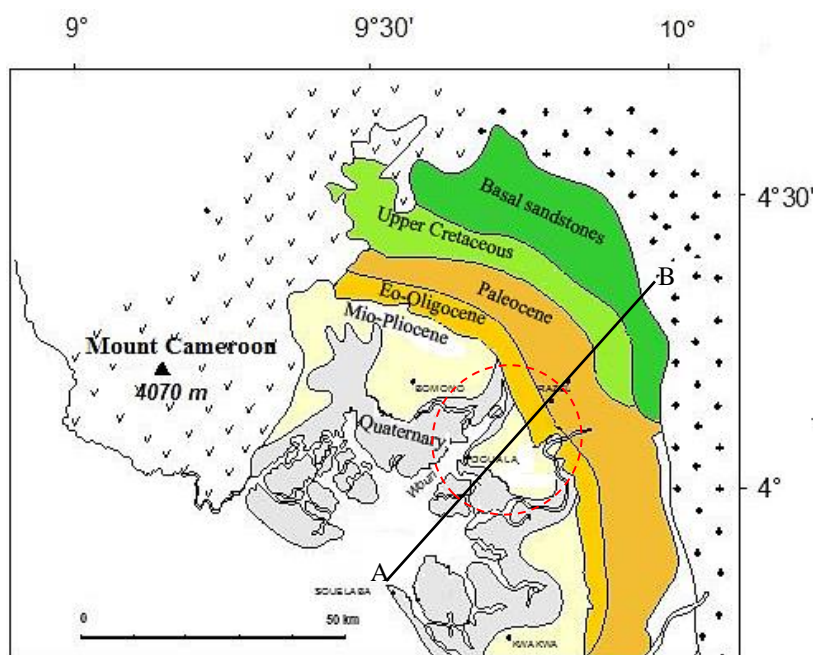


Figure 32: Geological map of the Douala basin (Regnoul 1986). The red circle highlights the Douala region.

The Mundeck or "basal sandstone" (Aptian-Albian)

The erosion of the basement by the rivers resulted in accumulation, over several hundred meters, of various elements with variable sizes. Silicate rocks more resistant have therefore evolved in sandstones, sands and clays. The Mundeck thus consists from the bottom to the top in a conglomerate of friable kaolinized sandstones followed by clays (Bourgeois 1977). This formation is observed under the lateritic cover at Mbanga, Muyuka (71 km, 90 km NW to Douala) and near Edea (at 64 km SE of Douala) where they rest unconformably on the crystalline basement.

Continental sandstones (Apto-Albian) are the first evidence of rifting and oceanization phenomena. They would go up to the Cenomanian at the NW of Douala, where their thickness would vary between 650 and 700 m and even to the Senonian, at the SE of Douala with a thickness reduced to about fifteen meters (Bourgeois 1977). The dominant presence of gymnosperms at the Aptian indicates xeric climatic conditions at this time and would then explain the slight salt deposits observed (Nguene et al. 1992). During the Albian, the microflora changes with appearance of species indicating wetter conditions due to the marine influence.

Log Badjeck or Mungo formations (upper Turonian– lower Campanian)

The formation of Log Badjeck outcrops on the banks of the Mungo River at 20-25 km NW of Douala and at 27 km ESE of Douala in the locality of Loungahe. It has been well described in the first and the second cases respectively by Bourgeois (1977) and Njike Ngaha et al (2014).

Bourgeois (1977) revealed that Log Badjeck consists of:

- (i) sandstones and sandy clays with rare calcareous intercalations at the base;
- (ii) clays and limestones at the middle with a maximum thickness of 15m;
- (iii) fine sandstones surmounted by micaceous clay with intercalations of lumachellic limestones at the top.

In the locality of Loungahe, several lithofacies has been described by Njike Ngaha et al (2014). They identified from the base to the top:

- (i) a conglomerate facies resulting from alluvial cone accumulation in response to uplift and erosion of the rift edges;
- (ii) a sandstone facies with ferruginous matrix and massive structures indicating deposit in an agitated environment;
- (iii) a silty facies with a thickness less than 1 m. The presence of laminar structures and some traces of bioturbation indicates floodplain deposits;
- (iv) a grey to black clay facies with traces of bioturbation. The presence of organic matter and marine fossils suggests a relatively anoxic shallow marine environment;
- (v) a grey to black limestone facies containing bivalve fragments associated to black clays. These limestones have been deposited in a shallow and highly turbulent marine environment with a continental influence attested by the presence of sub-rounded to rounded quartz fragments.

Log Baba formation (Upper Campanian - Maastrichtian)

The Log Baba formation is dominated by marine clays; the presence of marl is also reported. Sediments were deposited on a shallow continental shelf, with rapid deepening to the west in a developing oceanic basin. The existence of a Maastrichtian flora consisting of a large number of algae confirms a predominance of marine elements. This palyno-stratigraphic information is in agreement with the data of Manga (2008) who shows an overall trend towards progradation up to Maastrichtian. The best possible observation of this formation is along the Mungo River.

N'kapa Formation (Paleocene - Eocene)

Paleocene sediments were deposited directly after the Cretaceous formations and can be observed on 3 sites: (i) on the right bank of the Mungo River where they form clay-limestone shales with gastropods and bivalves, (ii) at the SE of Douala on the right bank of the Sanaga River (38 km to Douala) where they consist of 150 to 300 m of sands, sandstones and clays covering the Campanian clays, and (iii) on the banks of the Bongué River, near Kompina (54 km NW to Douala), constituting 230 m of sandstone surmounted by 100 m of marl and 40 m of coarse sandstone (Bourgeois 1977). Pollen grains associated with marine micro-plankton algae increase as the number of algae decreases and the climate is tropical to subtropical.

The Eocene is outcropping in the NW side of Douala, on the left bank of the Wouri River (Figure 32). It consists of calcareous sandstones, limestones and marls. The presence of cuticles, freshwater algae (*Pediastrum* and *Scenedesmus*) and the decrease of micro-plankton in this period suggest that these sediments are mainly continental. The Eocene flora also

shows an association of varied grasses and dicotyledons, which demonstrates the coexistence of dry and wet forest plants under a warm climate.

However, it is worthwhile noting that the N'kapa Formation has been completely eroded in the East and Southeast parts of the basin.

Souellaba formation (Oligocene – lower Miocene)

The Souellaba formation is prograding and diachronous. The base is very clayey with very thin and rare the sandy beds. In the upper part, the sandy episodes appear much more frequently and are marked by passages of lignite. This formation is recognized at the outcrop in the Missellele River near Tiko (55 km W to Douala), in the form of yellow sands and clays with interbedded basalts. The sediments are fluvatile although they contain some forms of marine micro-plankton. This contribution of continental material is maintained in the Miocene.

In summary, from the Maastrichtian period to the early Miocene, there has been a gradual replacement of xeric vegetation by a more luxuriant and varied vegetation adapted to a warm and humid climate announcing the current environment in the Douala region.

Matanda formation (Burdigalian? – Tortonian?)

Unconformably layed on Souellaba formation, Matanda corresponds to prograding sequences with thickness exceeding 600 m. It is composed of clays with interbanks of sands and gravels. Towards the top, the clays are slightly silty and calcareous, rich in bioclasts and glauconite. The sandy sequences appear more developed at the NW of Douala where their thickness exceeds 200 m.

Wouri Formation (Messinian? - Present)

The most recent sediments are localised in the southern part of the Douala Basin and constitute the Wouri Formation, which generally represents the first 300 to 400 meters (**Figure 31**). They also constitute a prograding sequence set up thanks to the estuarine sedimentation of Wouri and Dibamba Rivers. Studies of Nguetchoua (1996) and Eneke et al (2011) show that the mineralogy consists mainly of clays (mostly represented by kaolinite), quartz and feldspars.

With an average thickness of 50 to 70 m under Douala, the Wouri formation is represented by an alternation of sand, gravel, clayey-sand with predominance of clayey formations in the base. It bevels in the west and east on the Matanda formation and in some places in the NNW of Douala on the Eo-Oligocene formations (**Figures 31 and 32**).

Table 6 well summarizes the lithostratigraphy presented above by giving the main lithology of each formation, the paleo-environments and paleoclimates conditions, and finally the places where each sedimentary formation outcrops. In this thesis, the ages used come from the most recent stratigraphy and palynostratigraphy works of Manga (2008), Mvondo (2010) and Salard-Cheboldaeff (1981, 1990) respectively. Each author proposes according to its results his own charter (**Table 7**).

Table 6: summary of the lithostratigraphy, paleoenvironments and outcrops areas of the Douala basin.

Formation	Main Lithology	Paleoclimate	Paleoenvironment	Outcrop area
Mundeck (Aptian-Albian)	Sandstones and clays	Xeric at the Aptian and wet during the Albian	Continental deposits	Mbanga, Muyuka (71 km, 90 km NW to Douala) and at (at 64 km SE of Douala)
Log Badjeck (upper Turonian–lower Campanian)	Limestones, sandstones, sandy-clays, and clays	Wet conditions	Shallow marine environment	On the banks of the Mungo River (20-25 km NW to Douala) and at Loungahe (27 km ESE to Douala)
Log Baba (upper Campanian – Maastrichtian)	Clays and marls	Wet conditions	Marine environment	Along the Mungo River
N’Kapa (Paleocene)	shales, clays, sands, sandstones and marls	Warm climate	Continental deposits	In the right bank of the Mungo River, at 38 km to Douala along the Sanaga River and at Kompina (54 km NW to Douala)
N’Kapa (Eocene)	Calcareous sandstones, limestones and marls	Hot and humid	Continental deposits	In the NW of Douala
Souellaba (Oligocene-lower Miocene)	Clays and sands	Hot and humid	Continental deposits	At Tiko (55 km W to Douala)
Matanda (Burdigalien ?-Tortonien ?)	Clays, sands and gravels	Hot and humid	Continental deposits	In almost the whole city of Douala
Wouri (Messinian? – Present)	Sands, gravels and clayey-sand	Hot and humid	Continental deposits	In the South of Douala

Table 7: stratigraphic chart of the Douala Basin according to different authors.

Age	Nguene et al. (1992)	Schlumberger (1983) in Dickson et al. (2003)	Manga (2008)	Mvondo (2009)	Njoh & Petters (2014)
Quaternary ▪ Pleistocene			Wouri		Wouri
Tertiary ▪ Pliocene ▪ Miocene • Messinian • Tortonian • Serravallian • Langhian • Burdigalian • Aquitania ▪ Oligocene ▪ Eocene ▪ Paléocene	Wouri Matanda Souellaba N’Kapa	Matanda N’Kapa	Matanda Souellaba N’Kapa	Wouri Matanda Souellaba N’Kapa	Matanda Souellaba N’Kapa
Upper Cretaceous ▪ Maastrichtian ▪ Campanian • upper • lower ▪ Santonian ▪ Coniacian ▪ Turonian ▪ Cenomanian	Log Baba Mungo	Log Baba Mungo	Logbaba Mungo	Log Baba Mungo	Log Baba
Lower Cretaceous ▪ Albian ▪ Aptian ▪ Barremian	Mundeck	Basal sandstones	Mundek	Mundeck	Mundeck
Precambrian	Basement	Basement	Basement	Basement	Basement

3. Hydrogeological framework

3.1. The main aquifers of the Douala basin

Just as surface waters that are sensitive to weather, the hydrologic function and distribution of groundwater are also highly correlated to rainfall amount (Braune and Xu 2009). However, groundwater resources are not only influenced by the precipitation height but they also vary substantially according to the geological features of the area. In this way, Martin (1979) distinguishes four main aquifers in the Douala Basin: the basal sandstones of the Upper Cretaceous; the Palaeocene sands; the Mio-Pliocene sands and finally, the Quaternary sands and alluvium. However, Envoutou (2018) proposed a revised picture of this general hydrogeological frame by including an Eo-Oligocene hydrosystem between the Palaeocene and the Mio-Pliocene permeable layers. In our study, we use this updated scheme since there are many boreholes and hand-dug wells tapping the Eo-Oligocene formation and currently exploited in the NE and eastern sides of Douala.

Basal sandstones aquifer (Upper Cretaceous)

The average thickness of the basal sandstones varies from 200 to 300 meters. This formation contains water exploited through boreholes, hand-dug wells and springs. It is notably tapped by Tangui, an industry of mineral water. The well log (Figure 33) of Tangui highlights the extension of the permeable layer from 152 m.a.s.l. to 32.5 m.a.s.l, overlaid by 20 m of clay and clayey sands that confine the aquifer.

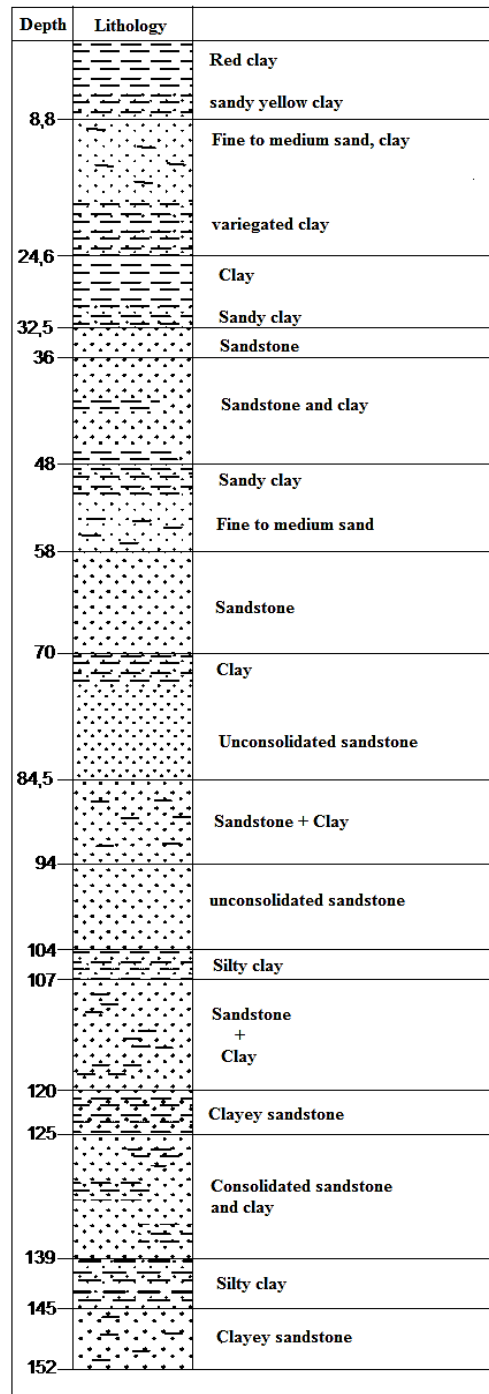


Figure 33: well log in the basal sandstones. Source: Ketchemen-Tandia (2011).

The basal sandstones are likely to provide discharge of more than $10 \text{ m}^3/\text{h}$ with a transmissivity in the order of $2 \cdot 10^{-4} \text{ m}^2/\text{s}$.

Paleocene sands aquifer

Like the basal sandstones, the palaeocene outcrops in an arc (Figure 32); covering an area of approximately 500 to 15000 km^2 . This vast reservoir with an average thickness of 200 m, under 70 to 100 m of clay deposits, represents, according to Martin (1979), the best aquifer of the Douala basin. Lithological correlations made on the basis of wells logs from oil drilling (see Ketchemen-Tandia 2011) indicate a monoclinical arrangement of deposits and the existence of lateral variations in the south: continental deposits passing to clay marine facies (Figure 34). Piezometric measurements carried out by Martin (1979) suggest that groundwater flows laterally to the streams that drain it into the outcrop area. The transmissivities values are about $4 \cdot 10^{-3} \text{ m}^2/\text{s}$ while the storage coefficient ranges from $3 \cdot 10^{-4}$ to $4 \cdot 10^{-4}$ and the discharge of some boreholes reaches $250 \text{ m}^3/\text{h}$.

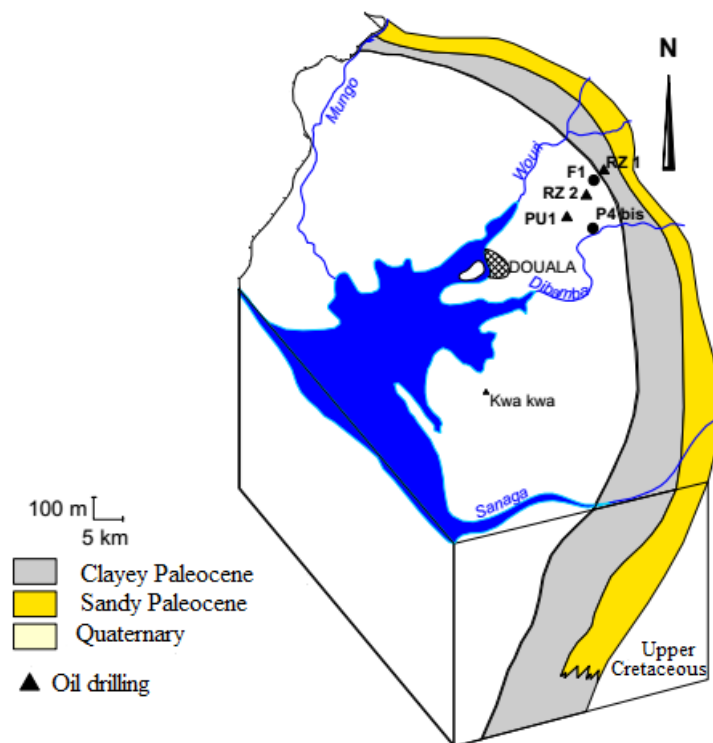


Figure 34: 3D schematic block diagram of Palaeocene (Martin 1979 in Ketchemen-Tandia 2011)

Eo-Oligocene aquifer

It outcrops in the N, NE and E of the study area (Figure 32) with a maximum thickness of 210 m (Emvoutou 2018). Examination of some logs (Figure 35) from wells tapping this formation reveals several lateral variations in lithology. The clayed beds can reach 70 m while the sandy layers are thin with a maximum thickness of 8 m. Wells discharges vary between 27 and 37 m^3/h with an average transmissivity of $3.9 \times 10^{-4} \text{ m}^2/\text{s}$.

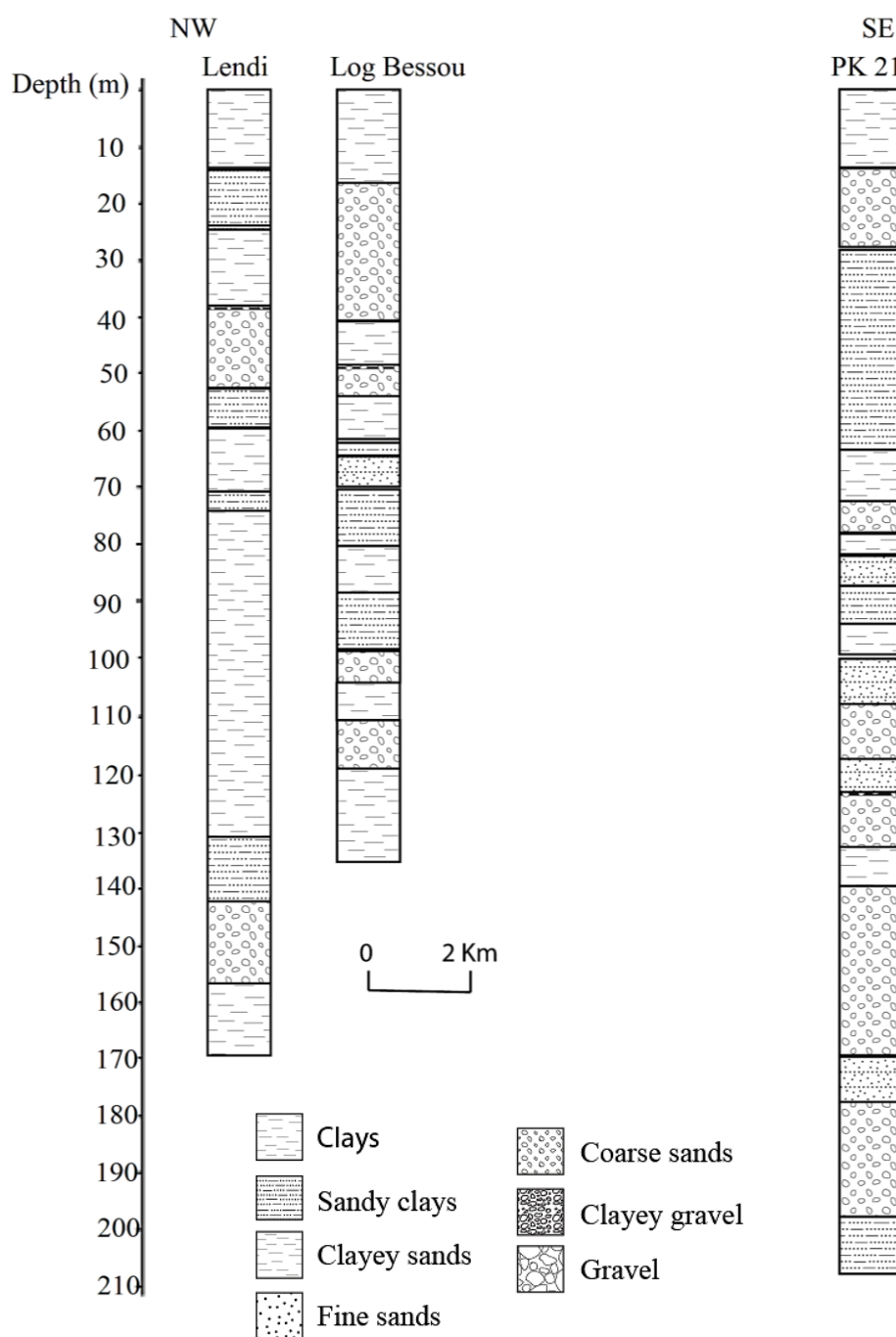


Figure 35: wells logs in the Eo-Oligocene aquifer

Mio-Pliocene (MP) sands aquifer

This aquifer is heavily exploited in Douala through private boreholes, private hand-dug wells and by the Cameroon Water Utilities Corporation (Camwater) for the city's drinking water supply. The Mio-Pliocene formation abuts at the North-East on the Eo-Oligocene sediments and is framed in the South by those of the Quaternary (Figure 32). As for the E-Oligocene, observation of wells logs shows a great variability in geological facies (Figure 36).

However, according to the vertical distribution of sediments, a horizontal lenticular extension of sediments layers can be envisaged and the Mio-Pliocene formation then appears as a multilayered aquifer with clays materials constituting the first 10 to 15 meters representing the top of the aquifer. Below, the vertical and lateral facies and the thickness of aquifer are very variable.

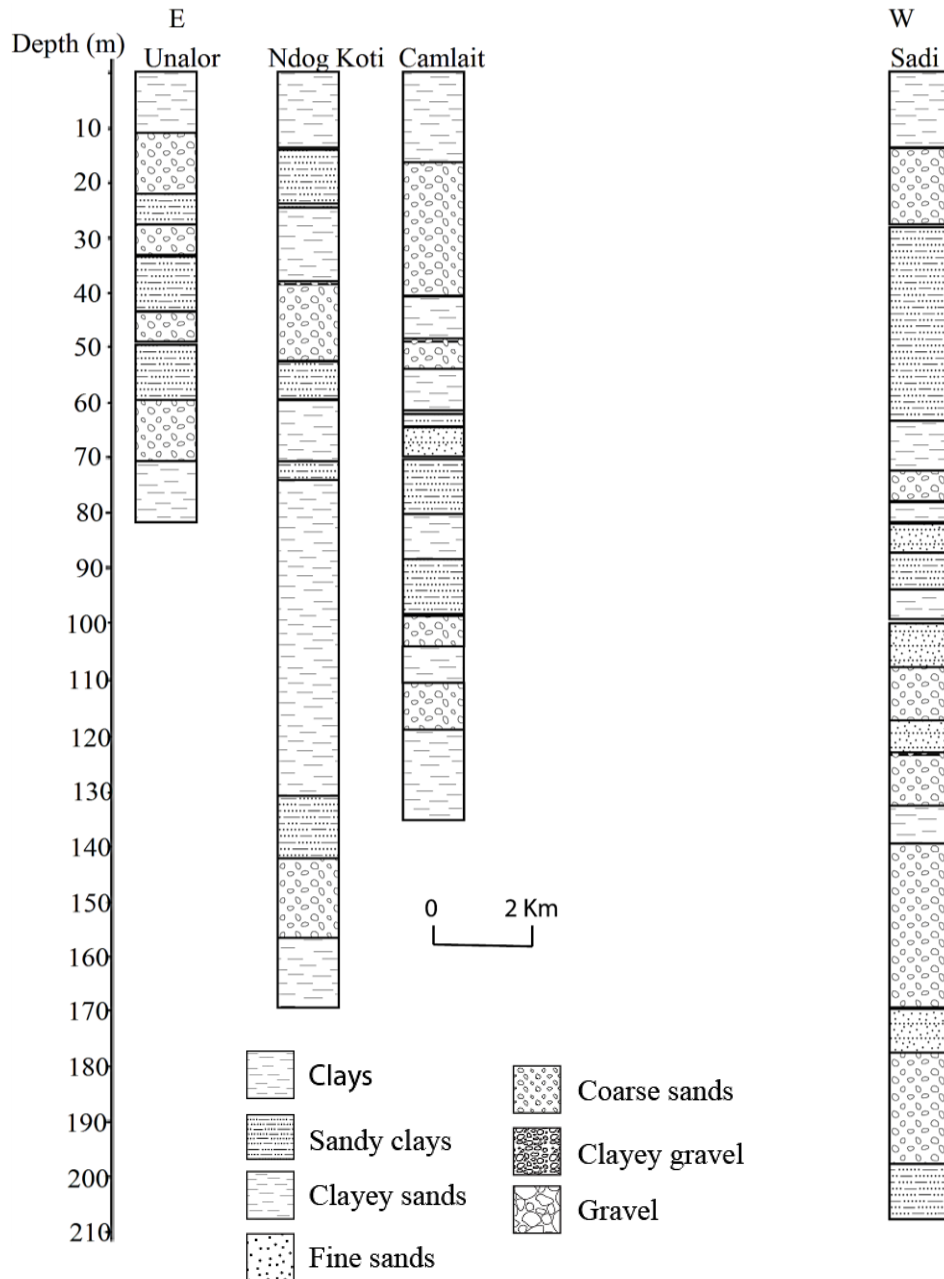


Figure 36: wells logs in the Mio-Pliocene aquifer system. The vertical scale is in meters.

Aquifer of Quaternary sands and alluvium

The Quaternary formation is located around the estuary, along the Wouri, Dibamba and Mungo Rivers. Like the Mio-Pliocene aquifer, the Quaternary hydrosystem is a multilayered aquifer with significant lateral variations of lithological facies. The first 5 meters are marked

by a top clay layer that is not generalized in the entire Douala basin. Between 15 and 70 m deep, there is a vertical alternation of sandy and gravelly beds with at the base a second clay layer that seems to mark the end of the Quaternary period (Figure 37).

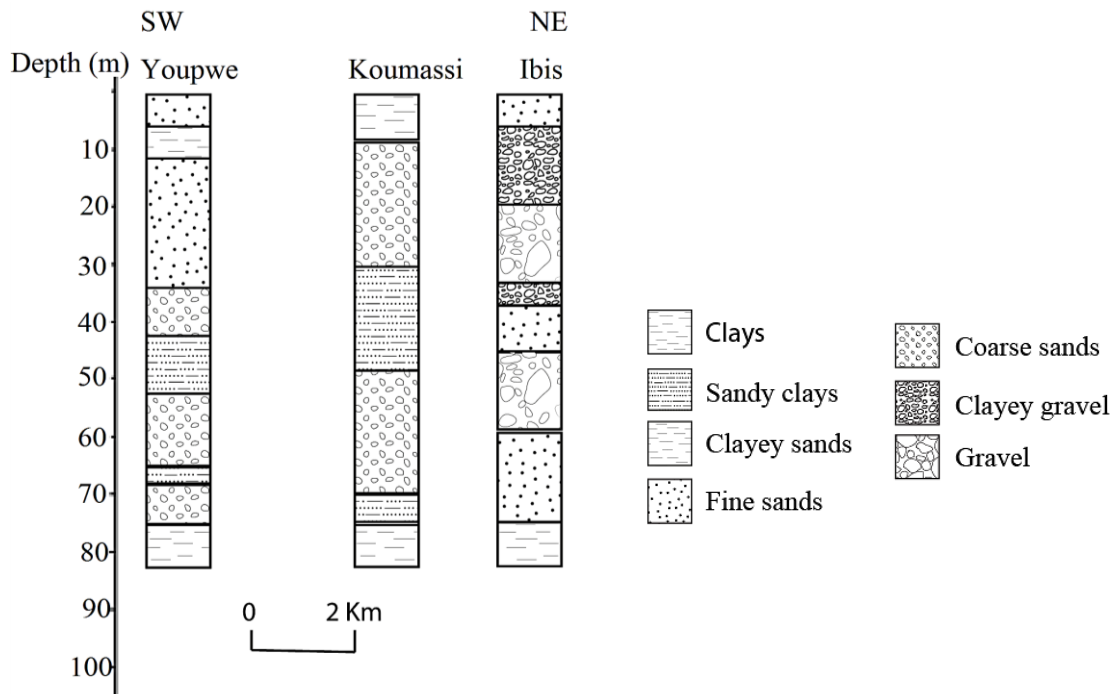


Figure 37: wells logs in the Quaternary aquifer system.

Compared to the Mio-Pliocene sandy aquifer, Quaternary sands have lower transmissivities (average of $0.2 \text{ m}^2/\text{s}$), lower discharge rate (around $18.2 \text{ m}^3/\text{h}$) ranging from 4.7 à $51.4 \text{ m}^3/\text{h}$.

The Paleocene, Eo-Oligocene, Mio-Pliocene and Quaternary formations outcrop everyone in the megacity of Douala (Figure 38). However, since the MP aquifer covers the largest area (Figures 32 and 38), and due to the fact that it is the most exploited resource in the study region, we therefore focus only on this aquifer. The next section thus presents a detailed hydrogeological synthesis of this aquifer.

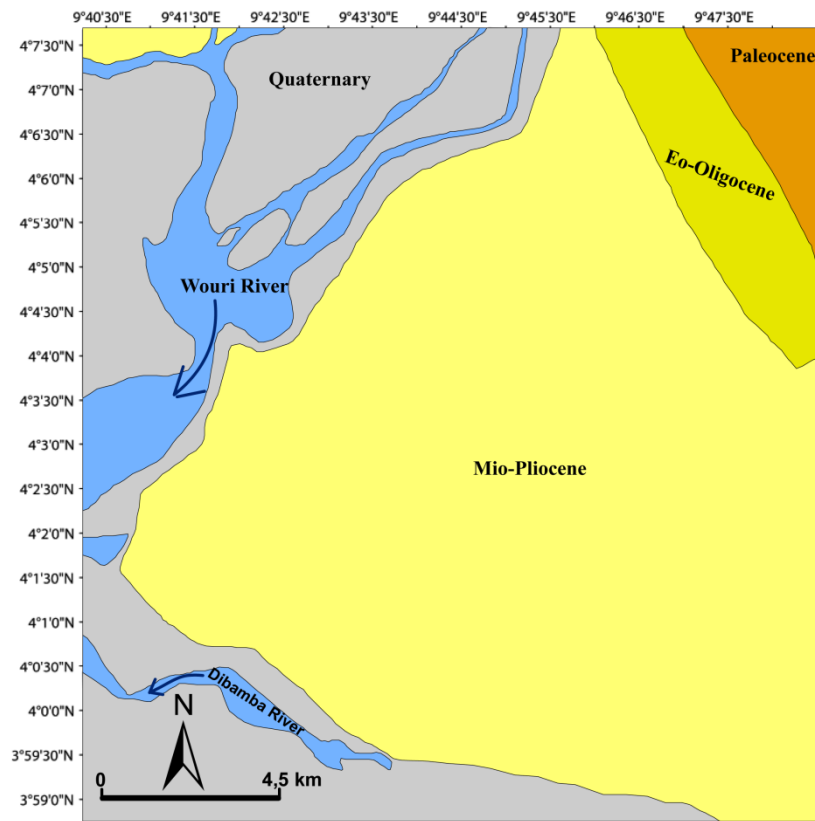


Figure 38: geological formations corresponding to aquifers domains in Douala basin.

3.2. Detailed hydrogeological synthesis of Mio-Pliocene aquifer

Thanks to data collected from existing boreholes in Douala, spatial maps of aquifer thickness (e, [Figure 39](#)), transmissivity (T, [Figure 40](#)), and hydraulic conductivity (K, [Figure 41](#)) variations have been drawn.

Aquifer thickness (Figure 39)

The MP layer's thickness increases from West to East, ranging from 4 to 35 m. Since the deposits are continental, it is possible that these higher thicknesses in the inner plateau are linked to erosion of bedrocks thanks to the meandering rivers while in the coastal plain there is a dominance of alluvium.

Transmissivity (Figure 40)

The transmissivity (T) of an aquifer represents its ability to mobilize the water it contains. It is a hydrodynamic parameter determined during pumping tests based on the equation (4):

$$T = K \times e \quad (4)$$

With K: hydraulic conductivity and e: aquifer thickness

The distribution of transmissivity at Douala is roughly similar to that of aquifer thickness. The highest transmissivities values are observed in the NE side of the Douala region due probably to the thick permeable layers leading to better hydrogeological conditions. Finally, according to Mabilot (1980) the MP aquifer is less productive at the center of the Douala region since $T < 10^{-1} \text{ m}^2/\text{s}$.

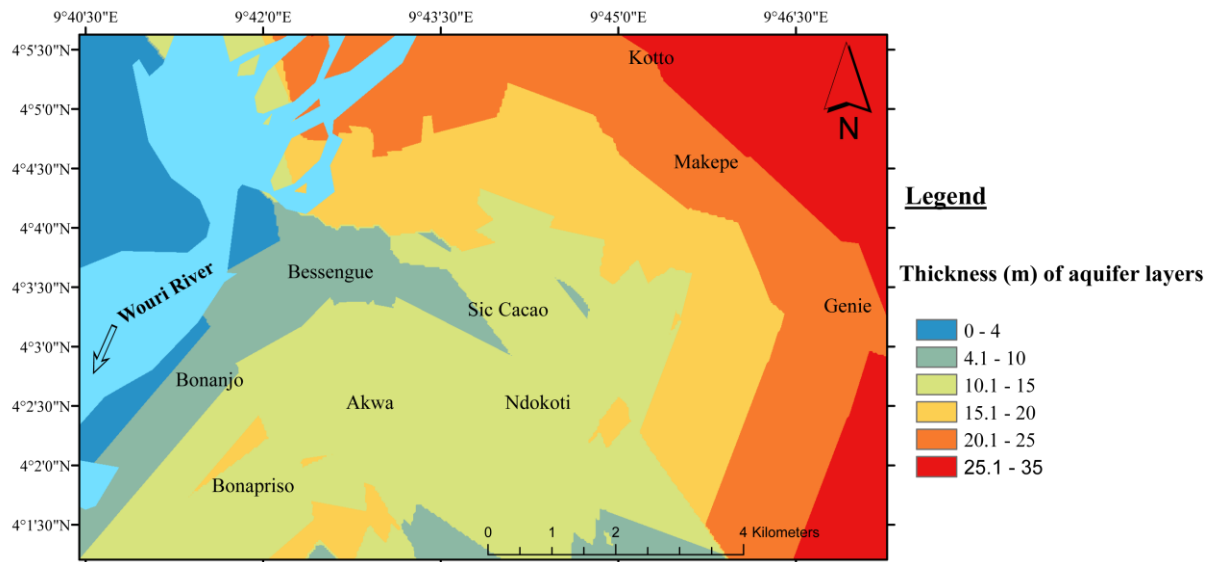


Figure 39: spatial variation of the thickness of MP layer in the city of Douala.

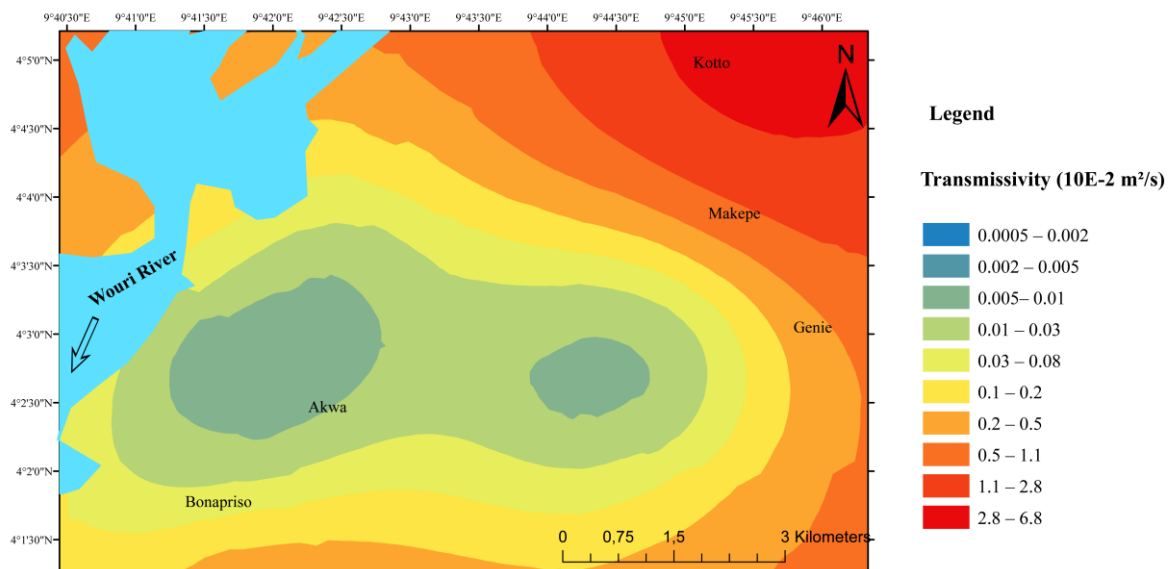


Figure 40: spatial variation of the transmissivity in the Mio-Pliocene aquifer in the Douala region.

- Hydraulic conductivity (Figure 41)

Hydraulic conductivity indicates the ease with which water can move through pore spaces or fractures. It is generally determined by (i) empirical approach through correlation with soil properties, or (ii) from hydraulic experiments using Darcy's law.

Hydraulic conductivity (K) values in the study region were compiled from hydraulics experiments carried out during drillings. Values are homogeneous, varying in majority between $0.01 \cdot 10^{-3}$ m/s and $0.03 \cdot 10^{-3}$ m/s. This homogeneity in K implies that the MP aquifer is homogeneous. Sands layers at different depths seem to present the same properties. Furthermore, this confirms that K does not have a significant influence on T which is more controlled by the aquifer thickness. However, it is worthwhile noting that these values of K for the MP aquifer are significant and in the range of values (10^{-2} to 10^{-5}) reported by Castany & Margat (1977) for sands. It may involve an important groundwater velocity (V).

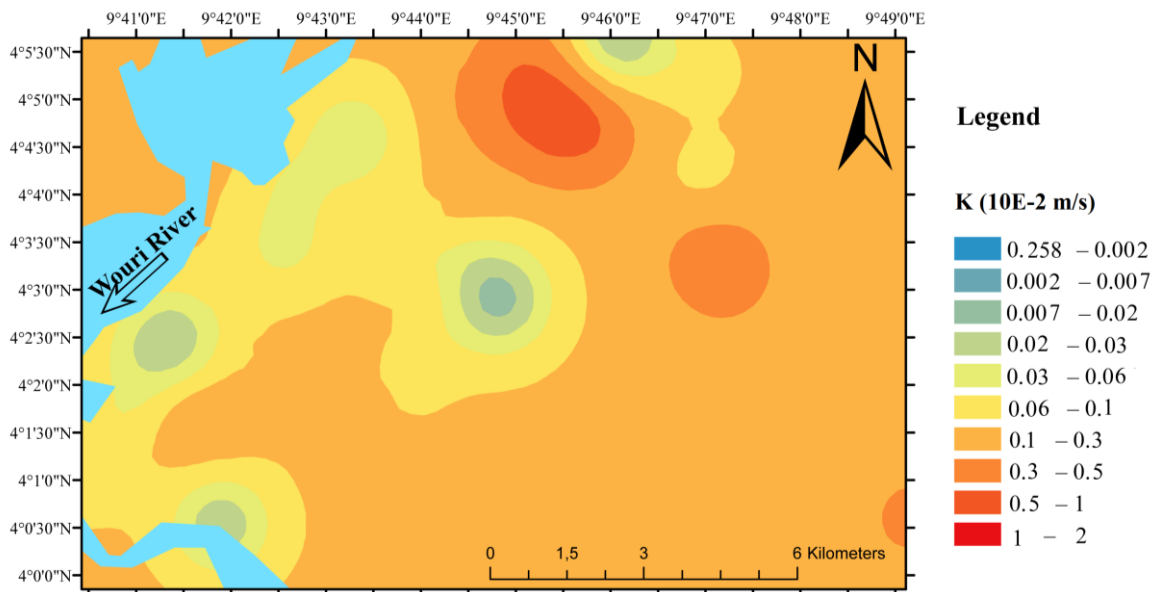


Figure 41: spatial variation of the hydraulic conductivity of the MP aquifer in the city of Douala

Water table of the MP aquifer fluctuations within time

Water levels were measured in the dry and wets seasons of 2004 (Ketchemen-Tandia 2011) and 2014 (Emvoutou 2018) in order to image the hydrodynamic of the MP aquifer and the fluctuation of water table during the year. The measurements have been carried out in the same wells from one season to another. On average, in 2004, water levels measured in March (end of the dry season) and November (end of the rainy season) are respectively 3.1 m and 2.1 m. In 2014, the average values of water levels vary between 2.37 m and 1.44 m. Thus, the water level variation is not significant between the seasons in Douala (1 m in 2004 and 0.93 m in 2014). This is in agreement with the climate context of Douala which has a poor dry season (see the section 2 in chapter III). Figure 42 shows the results of monitoring performed by Emvotou (2018). In the same hand-dug wells which have been sampled in March and November, we see that the water table does not record any changes. Groundwater table is flush to sub-flush all the time, especially in the low lying zones of the Douala region.

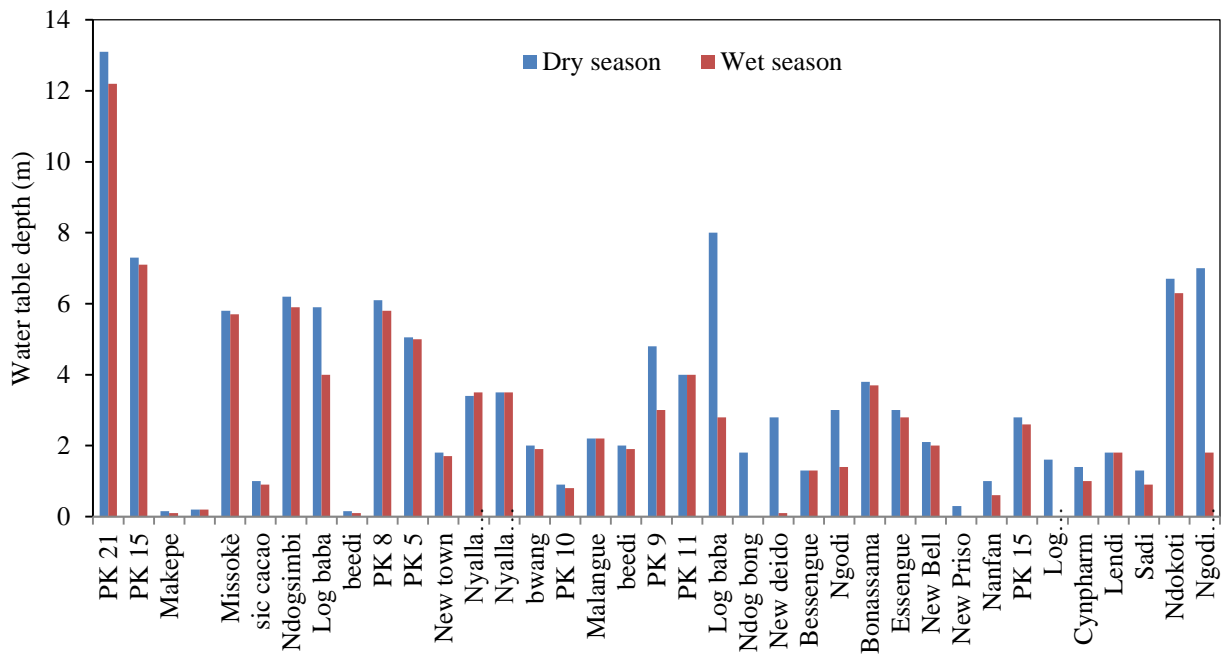


Figure 42: Seasonal variation of MP water table depth based on monitoring of hand-dug wells at different settlements in Doula during the year 2014 (Emvoutou 2018).

4. Article: Behaviour of a shallow urban aquifer under hyper recharge equatorial conditions and strong anthropogenic constrains. The example of the Mio-Pliocene aquifer in the coastal region of Douala (Western Central Africa).

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Title: *Behaviour of a shallow urban aquifer under hyper recharge equatorial conditions and strong anthropogenic constrains. The*

example of the Mio-Pliocene aquifer in the coastal region of Douala (Western Central Africa). Article Type: Research paper

Keywords: shallow aquifer, urban aquifer, recharge, rainfall, runoff, stable isotopes.

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Abstract

This study brings out the detailed hydrogeological features that characterize aquifers in hyper-humid region. It focuses on the Mio-Pliocene aquifer of Douala Megapole (Western Central Africa region) which is the rainiest city on the West African coast (4m/year). Groundwater recharge, approached through Penman-Grindley and Water Table Fluctuation methods, corresponds to 26-27% of annual rainfall amount. Hyper-rainy conditions lead to a hyper recharge which occurs almost all year long. Groundwater pathways have then be examined thanks to potentiometric data and showed that the Mio-Pliocene aquifer is characterized by a multi-directional flow toward the estuary with an average Darcy velocity of 2 m/day. Then, coupled with water chemistry, isotopes provide insights on the global functioning and allow defining three flow paths with strong hydraulic connections between each other. The shallower flow path is relatively homogenous in term of isotope content -reflecting a single origin of recharge- but heterogeneous in term of water chemistry due to various inputs on this shallower system. The chemistry becomes more homogeneous along the vertical flow. Water from deep flow paths records the most depleted contents in isotopes with lowest values in tritium (< 1 TU) and higher chemical contents suggesting a relatively long residence time and higher water rocks interactions. These latter factors coupled with hyper-rainy conditions (leading a dilution effect) are the two natural controls of groundwater chemistry.

Keywords: shallow aquifer, urban aquifer, recharge, rainfall, runoff, stable isotopes.

1. Introduction

While many works have been published on recharge, functioning and management of aquifers in arid or semi-arid areas (e.g., Sami 1992; Allison et al. 1994, Scanlon et al. 2006, Rahmani et al. 2017), there is still very little knowledge about groundwater conditions in humid tropical regions and papers on humid tropics hydrogeology remain rare. These areas are characterized by: (i) a monthly temperature equaling or exceeding 20°C for at least eight months of the year; (ii) a vapor pressure and a relative humidity average ~20 millibars and 65%, respectively, for at least 6 months of the year; (iii) an annual rainfall exceeding 1500 mm and; (iv) rain falling all year with at least six months having precipitation ≥ 75 mm / month. (Fosberg et al. 1961). They represent approximately 22% of the earth's surface (UNESCO 1990). They house a lot of developing countries which present the highest demographic growth rate and whose population is expected to exceed 50% of the world population by the end of this century (UNESCO 2000). Moreover, Wohl et al (2012) reported that humid tropics are dynamic environments where freshwater is under pressure from population growth, land use and climate change. A particular interest should be paid to unconfined or semi-confined groundwaters which have become increasingly important as an economical source of high-quality water supply for many countries in humid tropical areas. In addition to their importance in water supply, these hydrosystems are a key factor in the preservation of humid tropical ecosystems (animal-plant-soil-water), because of the intimate relationship between surface and groundwater and the frequently shallow groundwater table with abundant phreatophytic vegetation in such environments (Foster & Chilton 1993). Regarding all these aspects, the scientific community pointed out, at the first (UNESCO 1990) and second (UNESCO 2000) International Symposium on Hydrology and Water Resources Management in the Humid Tropics, the urgent need to increase the knowledge in aquifers functioning in humid tropical areas.

Douala Megapole (Cameroon, Western Central Africa; Fig. 1) constitutes a perfect example of such tropical region with approximately 4000 mm/yr, 230 rainy days/yr, a mean air temperature of 27°C (Tchiadeu and Olinga 2012) and a rapid urbanization process due to a demographic boom that begins in the early 80's (Nlend et al. 2018). The Mio-Pliocene (MP) aquifer is the most exploited resource for domestic uses, drinking water supply industries and to a lesser extent for agriculture (Mafany 1999) in Douala. Previous studies on the MP aquifer have mainly dwell long on groundwater quality (Takem et al. 2010; Kopa et al. 2012; Ngo Boum et al. 2015; Fantong et al. 2016; Tatou et al. 2017; Ketchemen-Tandia et al. 2017 and Wirmvem et al. 2017). This paper is a first attempt to describe the hydrogeological functioning by using a combination of various methods from hydrodynamic to isotope hydrology. It also aims at studying how the groundwater acquired its mineralization along a flow path, which processes are associated to this evolution and if the hyper-humid conditions of Douala affect the water chemistry. All the results have then summarized in a conceptual scheme describing the hydrogeological structure and functioning of Mio-Pliocene aquifer in Douala that can be used as a reference for porous aquifers in humid tropical areas and in the establishment of water management strategies in such areas.

2. Study site

2.1. Location and additional information

The Douala region ($03^{\circ}45'N - 04^{\circ}20'N$, $09^{\circ}34'E - 10^{\circ}00'E$) is a coastal site (~ 33 km to the ocean) on the Gulf of Guinea, in Cameroon (Fig. 1).

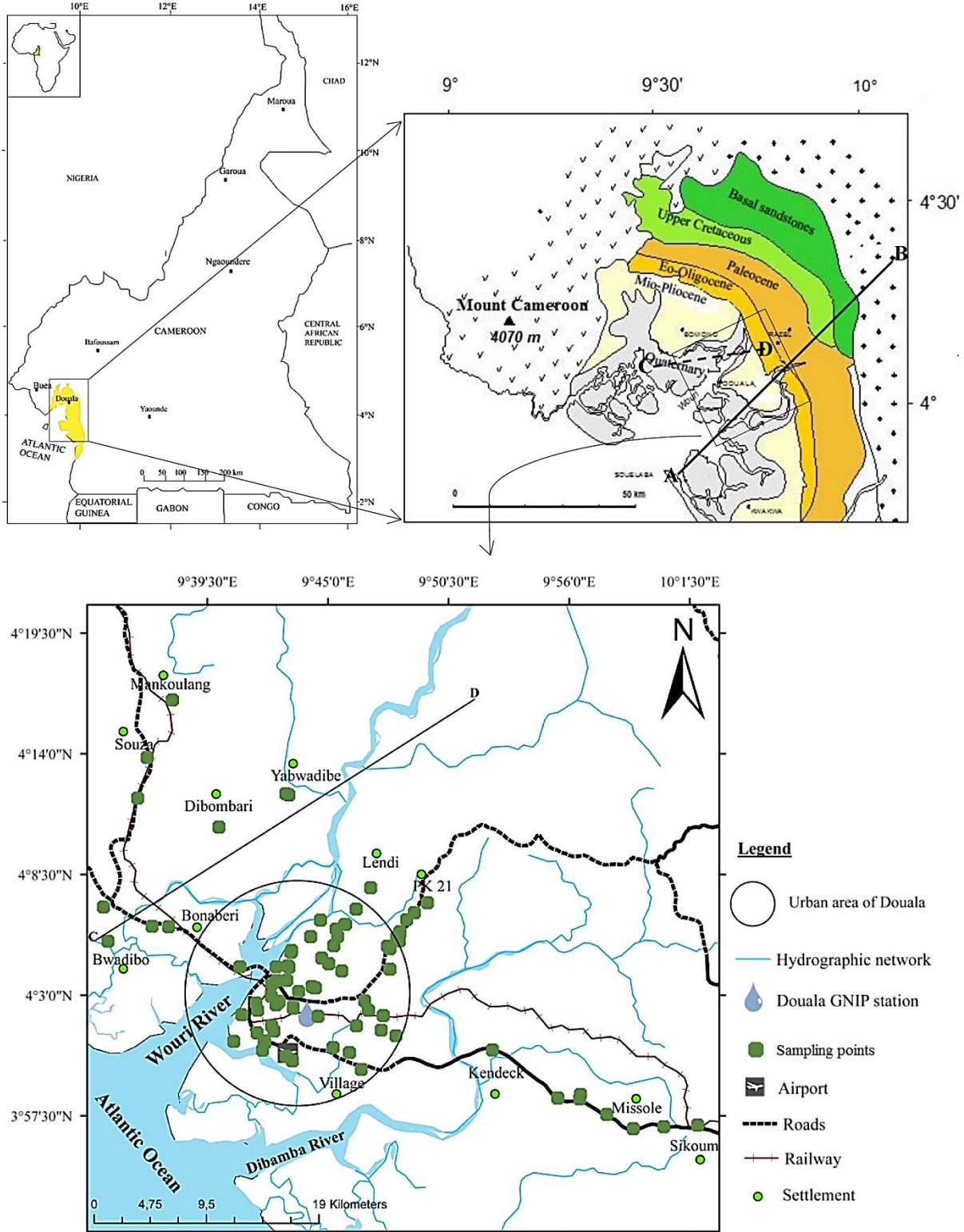


Fig. 1 Location of the study area showing the sampling points for water chemistry. The cut lines A-B and C-D refer respectively to geological cross sections within the Douala basin.

It is located approximately at 70 km southwest to the Mount Cameroon (~ 4100 m). The relief is weakly contrasted with altitudes varying between 3 m on the estuary zone to about 80 m in the eastern side of the region. Douala megacity is the most populated city of Cameroon with nearly 4 million of inhabitants corresponding to ~ 16% of the national population (Habitat III 2016). It covers an area of more than 300 km² and thanks to the port traffic which fosters the presence of various industries (cement, textile, agro-food wood, fertilizer, glassware, etc.); Douala is considered as the economic capital of Cameroon.

Due to its geographical position, the climate of Douala is characterized by marine influences (Olivry 1986). The annual rainfall regime is unimodal with a long rainy season from March to November and a short (more) dry season in December–February (Fig. 2). This latter with a total rainfall amount of 137 mm, is however less marked than the one in the Sudanese-Sahel zone (Mertz et al. 2012). Considering the 65 years (1951–2016) of rainfall height recorded at Douala meteo-station (04°01'N, 09°42'E), the maximum and minimum monthly amounts are respectively measured in August (742.4 mm) and December (34 mm). This continuous rainfall over the year makes Douala to be considered as a singular hyper-rainy city.

2.2. Climate

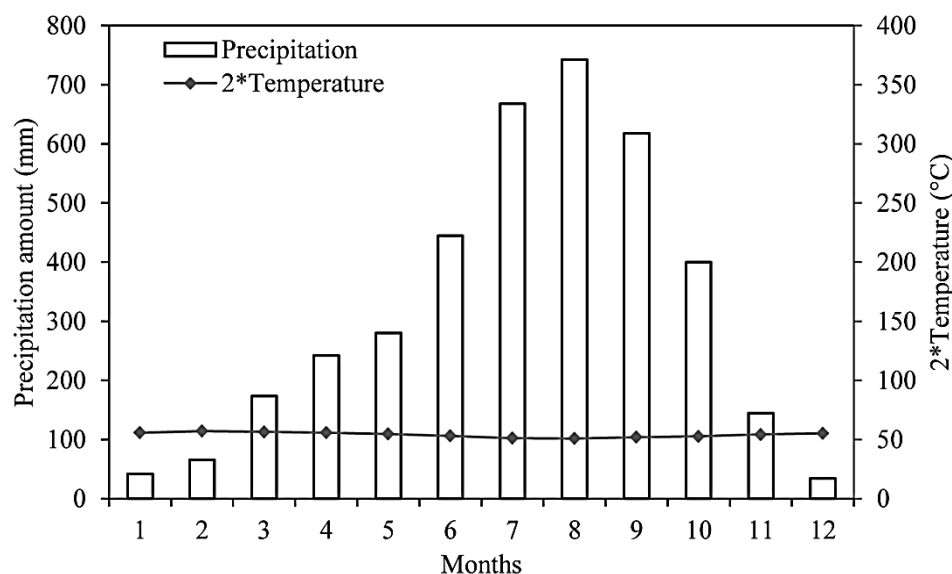


Fig. 2 Ombrothermal diagram of the region of Douala. Averages of rainfall amount (3854.3 ± 464 mm/year) and temperatures ($27 \pm 0.4^\circ\text{C}$) are respectively calculated thanks to 1951-2016 and 1971-2016 chronicles recorded at the meteo-station of Douala.

The unimodal distribution and the high rainfall amount are very particular as the Guinean Gulf is generally characterized by a bimodal distribution with two precipitation maxima in spring and autumn periods and a total amount lower than 2000 mm/year (Nlend et al. 2018). This climate specificity is linked to (i) the concave shape of the coast at Douala which induces a convergence of south-westerly winds and (ii) topographical ascents forced by the relief of Mount Cameroon. These mesoscale convergence and orographic influence (Vondou et al. 2017) are all the more

marked when the monsoon flow is intense and thick as it is the case during the summer period (Sultan and Janicot 2000).

The peculiar climate of Douala is also linked to the relative uniformity of air temperature. Thanks to the long-term record at the meteo-station of Douala (1971 to 2016), we observe that monthly mean values of temperature vary between 25.4 °C in August and 28.6 °C in February, giving low thermal amplitude of 3.2 °C. The data on relative humidity (records of 1971-2009) show that Douala is wet all the time: monthly averages range between 79% and 90% during the rainy season (March to November) and between 77% and 81% during the dry season (December to February), with an annual mean of 85%. Indeed, abundance of rainfall involves a high cloudiness and therefore an important humidity.

2.3. Hydrography

The wet conditions described above are reflected at the ground surface by a dense hydrographic network confirming the observations of Braune and Xu (2009) in this region of Africa. Apart swamps that cover some parts of the Douala region, two main watercourses can be quoted: the Wouri and the Dibamba Rivers that present dense networks with a lot of tributaries (Fig. 1). Hydrological measurements carried out from 1951 to 1977 at the Wouri hydrometric station (90 km NE of Douala) show on average that from December to June, discharge values are low (<200 m³/s) and then rapidly increase from July to October with a maximum value recorded in September (up to 900 m³/s, Olivry 1986). Concerning the Dibamba River, there are unfortunately no hydrological measurements. Both the Wouri and the Dibamba dendritic drainage basins discharge into the Atlantic Ocean where tides entering the estuaries make them vulnerable to seawater intrusion (Onguene et al. 2015). Sometimes, during the rainy season, due to high rainfall amount and intensity, the soil often becomes saturated and the streams overflow their channels causing floods in the region favoured by weak slopes.

2.4. Soils

Segalen (1967) and Zogning (1987) identified hydromorphic and ferrallitic soils (80% of the study region) in Douala. Hydromorphic soils, composed by sands, clayey-sands, vases and peats are dominant in valleys and along the Rivers (Zogning 1987). They are mostly occupied by urban areas (35%) and vegetation (48%) which respectively spread and decrease overtime due to human activities. Farmlands and surface waters cover respectively 8% and 9% of the study region (Emvoutou 2018).

2.5. Geology and hydrogeology : emphasis on Mio-Pliocene formation

The Douala region is constructed on a 5 km-thick sequence of unconsolidated to semi-consolidated sedimentary rocks that range from Pleistocene to Aptian (Fig. 3; Regnault 1986). These sediments are associated to tectono-sedimentary dynamics which prevailed during the opening of the South Atlantic and the formation of West African passive margin (Moulin et al. 2003; Helm 2009). Continental in the eastern part of the basin, sediments progressively move westward to marginal sea, continental shelf and deep seabed environments. They can be divided into seven formations from the bottom to the top (Fig. 3): 1) Mundeck's

conglomerates and sandstones (Apto-Albian), 2) Logbadjeck's conglomerates, sandstones and limestones (Turonian-Santonian), 3) Logbaba's sands, sandstones and clays (Campanian-Maastrichtian), 4) Nkapa's limestone, sandstone, marl and shales (Paleocene-Eocene), 5) Souellaba's clays and sands (Oligocene-Lower Miocene), 6) Matanda's clays, sands and gravels (Upper Miocene-Pliocene) and 7) Wouri layers (Quaternary) consisting of clays, sands and gravels (Dumort 1968; Njike Ngaha 1984; Regnault 1986; Nguene et al. 1992; SNH/UD 2005; Manga 2008; Njoh et al. 2014; Njoh and Petters 2014; Njike Ngaha et al. 2014).

The Mio-Pliocene aquifer is represented by Souellaba and Matanda formations, overlying the Eocene-Oligocene and covered, in some places by the Quaternary sediments 20 to 70 m thick (Feumba 2015). It consists in a multi-layered aquifer separated from more superficial and deeper aquifers by discontinuous clay layers. Its thickness globally increases NE to SW (Fig. 3). Although many lithological lateral variations (Fig. 4), the global structure of the MP aquifer from the bottom to the top can be described as follows by using well logs and previous works on geology (Bourgeois 1977; Martin 1979 and Ketchemen-Tandia 2011):

- (i) the Lower Miocene formation is made up of cross-bedded lower Miocene Sands and are marked by some passages of lignite and limestone;
- (ii) the Upper Miocene consists of coarse grained sand with gravel intercalations. Sandy sequences, slightly silty and calcareous, appear well developed at the NW of Douala where their thickness exceeds 200 m (Bourgeois 1977);
- (iii) The Pliocene is clayey, clayey-sandy and sandy-clayey. When it outcrops, its depth does not exceed 40 m.

The global mineralogy is mainly marked by silicate minerals such as quartz, feldspar and kaolinite (Ngueutchoua 1996).

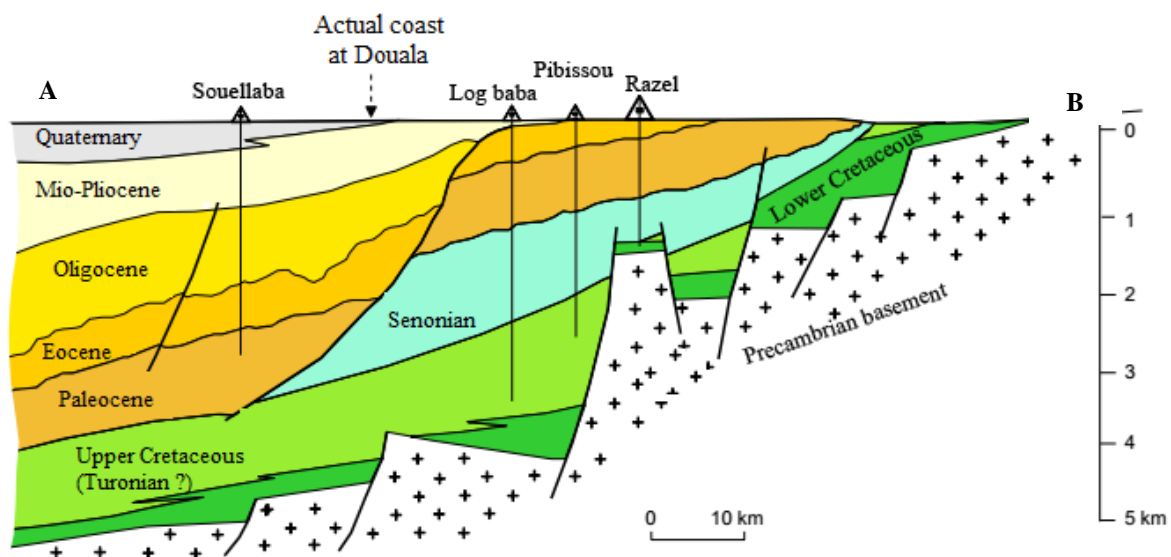


Fig. 3 Geological cross section through the Douala sedimentary basin (Regnault 1986). The corresponding cut line A-B is plotted on Figure 1.

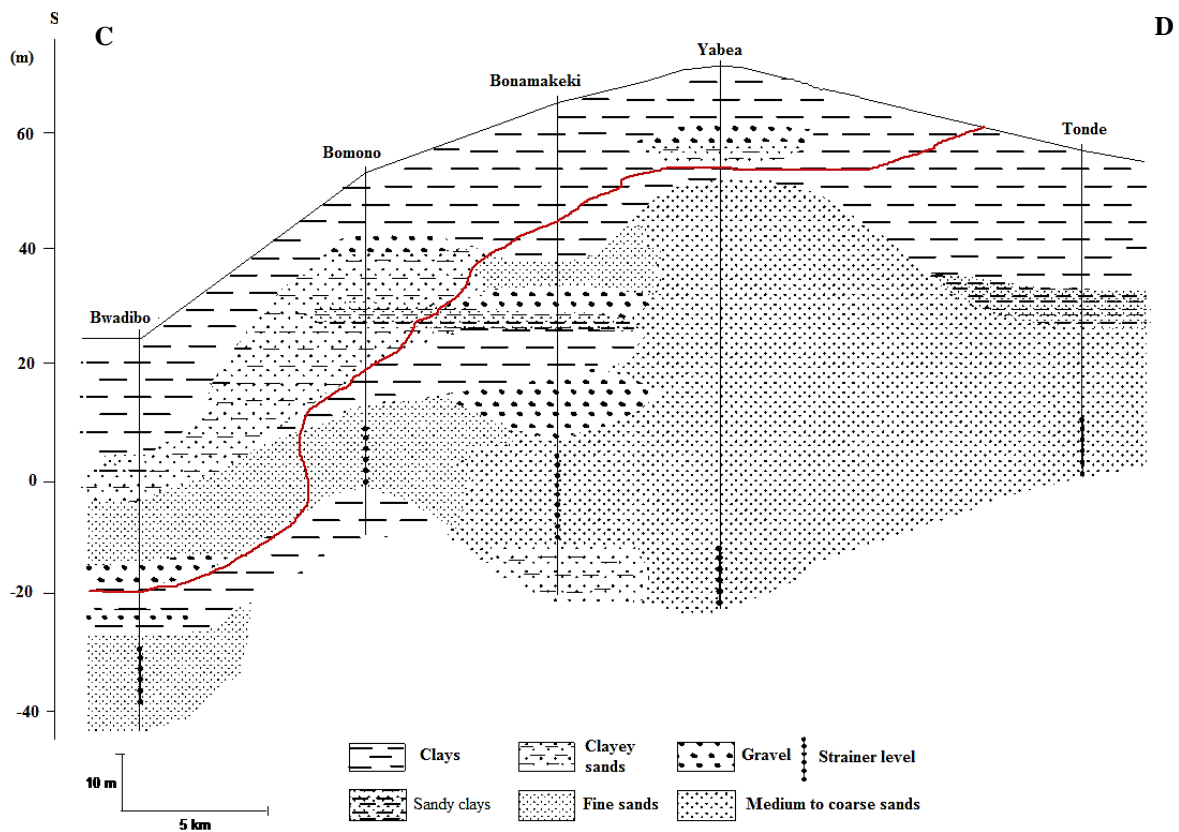


Fig. 4 Cross section of the Mio-Pliocene multi-layered aquifer (see the cut line C-D on Figure 1) at Douala based on well logs correlations. The red line represents the Quaternary boundary.

Table 1 presents this hydro-stratigraphy associated with hydrogeological characteristics and Table 2 highlights the global hydrodynamic parameters of the Mio-pliocene aquifer. Data were obtained from historical records of drillings for water wells.

Table 1 Hydro-stratigraphy of the Mio-Pliocene aquifer.

Age	Lithology	Thickness	Hydrogeological characteristic
Pliocene	Clay, sandy-clay, clayey-sands	0 - 40 m	Aquiclude/aquitard
Lower Miocene	Cross-bedded sands with passages of lignite and limestone	>220 m	Aquifer
Upper Miocene	Coarse grained sand (slightly silty and calcareous) Gravel		

Table 2 Hydrodynamics settings of the Mio-Pliocene aquifer in Douala. Data were collected from historical records of drillings for water wells.

	Mean	Minimum	Maximum	Standard deviation
Transmissivity (m²/s)	5.6 x 10 ⁻³	4.6 x 10 ⁻⁴	6.8 x 10 ⁻²	6.1 x 10 ⁻³
Hydraulic conductivity (m/s)	1.5×10 ⁻³	2.6 x 10 ⁻⁵ m/s	0.2 m/s	0.03
Thickness of permeable layers (m)	14	35	4	8.1

High values of standard deviation over averages (Table 2) suggest an important anisotropy of the MP aquifer. This hydrodynamic heterogeneity is in agreement with the strong lateral and vertical variations observed in lithology.

3. Methods of investigation

3.1. Inventory of sampling points

Wells logs and results from hydraulic testing, when available, have been compiled from previous projects in the study area. Indeed, priority has been given to wells having this enough basic information and which are still used currently by local populations. In addition to this inventory, a field campaign was conducted to target springs in the study area. A total of 58 sampling points, including 43 wells and 15 springs, have been selected according their distribution over the Douala region.

3.2. Field measurements and sampling for chemical and isotopic analysis

Groundwater sampling and *in situ* measurements (water levels and physicochemical) were carried out in February 2017. Assuming the fact that wells in Douala are daily used for domestic supply, it was considered that there is no stagnant water within wells and that their purge is already achieved. The depth of water in the well relative to the soil surface *i.e* water table (h) was measured by using a potentiometric probe. Thanks to this measure, the potentiometric surface (H) has been calculated knowing the altitude of the sampling site. Water levels are expressed in meters above sea level (m.a.s.l).

Physicochemical parameters (pH, electrical conductivity, water temperature and dissolved oxygen) were measured using a WTW 2FD46G multi-parameter. Measurements have been validated only after all of the *in situ* parameters reached the stability criteria (Rey et al. 2017) for three consecutive measurements separated by 5-minute intervals. Alkalinity measurements were performed using a digital titrator (HACH). The detection threshold for this method is 0.1 mg/l CaCO₃ (Stumm and Morgan 1996). Samples for major ions analysis (Cl⁻, NO₃⁻, SO₄²⁻, HCO₃⁻,

Na^+ , K^+ , Mg^{2+} and Ca^{2+}) were collected in two 30 mL polyethylene bottles after filtration through 0.45 μm nitrocellulose membranes. Samples for cations analysis were acidified with ultrapure HNO_3^- at 70%. Bottles were filled to the top with no headspace and kept at 4°C until analyses. Chemical analyses were achieved at the Hydrogeology Department of the University of Corsica, France by ionic chromatography using a Dionex ICS 1100 chromatograph. The quality of the chemical analysis was checked by calculating the ionic balance error: analyses were rejected if the ionic balance error was greater than 5%.

Samples for stable isotopes of the water molecule were stored in 20 mL amber glasses bottles. All care was taken to avoid evaporation by taking water directly in the well. As for chemistry, bottles were filled to the top with no headspace and samples were kept cool until being transferred to the laboratory of the Hydrogeology Department of the University of Corsica, France. Measurements were performed using a liquid–water stable isotope analyzer DLT-100 (Los Gatos Research) according to the analytical scheme recommended by the IAEA (Penna et al. 2010). The quality of the isotopic analysis was checked using a standard deviation up to 1‰ for $\delta^2\text{H}$ and up to 0.1‰ for $\delta^{18}\text{O}$. Values are reported in per mil units (‰) compared to Vienna Standard Mean Ocean Water standard (VSMOW).

3.3. Methods for estimating Recharge

Techniques that require hydraulic-conductivity data, such as Darcy methods, unsaturated- and saturated-zone models, could not be applied here because hydraulic conductivity can vary over several orders of magnitude for the aquifer is strongly heterogeneous regarding the horizontal or lateral extension. Thus, to avoid strong uncertainties in recharge calculation, we choose to apply the Penman-Grindley (Penman 1950; Grindley 1967) and the water table fluctuation (WTF; Healy and Cook 2002) approaches which are more adequate in the humid context of Douala and easy to implement. Indeed, these two methods are based on areal parameters (hydro-meteorological and hydrogeological) which proved to be more suitable in humid climate (Knutsson 1988; Scanlon et al. 2002; Chung et al. 2016).

Penman-Grindley water balance

Knutsson (1988) shows that in humid climates, where the precipitation is always higher than the evapotranspiration, water balance method is more suitable than in arid climates. Among water balance methods, we choose the Penman-Grindley approach that appears to be more efficient in areas with well-developed soils that never dry completely during the year (Lerner 1997, 2002), as it is the case in Douala. The concept is that water stored in the unsaturated zone, can increase with rainfall and be depleted by evapotranspiration. Groundwater recharge then occurs by percolation through the unsaturated zone more or less continuously. When the field capacity is attained, excess rainfall is routed to surficial runoff. The recharge calculation is then defined by the following equations:

$$P = R + E_a + \Delta\text{SWS} + I_{\text{eff}} \quad (1)$$

$$I_{\text{eff}} = P - (R + E_a + \Delta\text{SWS}) \quad (2)$$

where P is rainfall amount, E_a is the evapotranspiration; ΔSWS is the variation in soil water storage, R is the runoff and I_{eff} is the effective infiltration or recharge.

The accuracy of this method relies on the accuracy of the initial data. Thus, climatic data was obtained from long-term monitoring at the meteorological station of Douala (temperature, precipitation, relative humidity and wind velocity) and it allowed to determine E_A and potential evapotranspiration (PET) using Penman formulae (Penman 1948). Runoff data come from Emvoutou (2018) who used a water budget program (Willmott 1977) while those on SWS are provided by the results of soils analysis carried out by Ndome (2010).

Water table fluctuation (WTF) method

The water table fluctuation method for estimating groundwater recharge is based on the premise that rises in groundwater levels in shallow aquifers are due to recharge water arriving at the water table and going immediately into storage (Healy & Cook 2002). The recharge rate can be obtained by applying the following equation:

$$I_{\text{eff}} = S_y \frac{\Delta h}{\Delta t} \quad (3)$$

where S_y is the specific yield, h is the water table height and t is time.

Eq. (3) assumes that water that reaches the saturated zone is immediately stored and the other components of the subsoil water balance (underground evapotranspiration, base flow, inflow and outflow) are zero during the period of recharge.

The specific yield is approximately equal to the storage coefficient. It is the volume of water released from a unit volume of saturated aquifer material (Maréchal et al. 2006). In this paper, we used the empirical value provided by Healy and Cook (2002) for medium sands which constitute the MP aquifer, while values of h come from the monthly monitoring carried out by Feumba et al (2011) in Douala.

The advantages of this method include its simplicity and sensibility to the water movement across the unsaturated zone (Healy and Cook 2002). It can be used at local (watershed, basin) and temporal scale going from day to years (Chung et al. 2016). The WTF is among the most widely used methods to determine groundwater recharge rate and has already been well applied in both arid (e.g., Leduc et al. 1997; Sibanda et al. 2009) and humid (e.g., Pavelic et al. 2012; Kotchoni et al. 2018) environments.

4. Results and discussion

4.1. Estimation of recharge

Water balance calculation based on Penman-Grindley method

The results of this calculation are presented month by month in Table 3.

Table 3 Monthly water budget (in mm) at Douala.

P precipitation; *PET* potential evapotranspiration; *RET* real evapotranspiration; *SWS* soil water storage; *R* runoff; *I_{eff}* effective infiltration; *WD* water deficit.

	1	2	3	4	5	6	7	8	9	10	11	12	Total
P	41.5	65.6	173.5	241.9	280.4	444.7	667.7	742.4	618	400.2	144.4	34	3854.3
PET	94.4	100.6	96.4	90.5	79.9	77.6	72.5	70.8	74.1	81.2	84.7	92.4	1015.1
E_a	31.2	19.6	47.4	73.2	69.7	77.6	72.5	70.8	74.1	81.2	84.7	71.1	773.1
WD	63.2	81	49	17.3	10.2	0	0	0	0	0	0	21.3	242
ΔSWS	29	0	0	0	0	10.1	33	55.9	-121	-125	-17	28.1	156.4
R	31	39	84.5	117.9	136.6	216.6	325.2	519.7	432.6	280.1	70.3	23.8	1875
I_{eff}	0	7	41.6	50.8	74.1	140.5	237	96	232.3	164.1	6.4	0	1049.8

Potential EvapoTranspiration (PET) has been calculated from the empirical formula of Penman (1948):

$$PET = 16 \frac{10 T_i}{I} F(\lambda) \quad (4)$$

where T_i is the monthly temperature; I the annual thermal index; i the monthly thermal index; $F(\lambda)$ correction factor depending on the latitude and $a = (492390 + 17920 * I - 771 * I^2 + 0.675 * I^3) * 10^{-6}$.

Results show that PET ranges from 70.8 mm (in August) to 100.6 mm (in February) with an annual amount of 1015.1 mm. From June to November, there is no difference between PET and E_A , meaning an absence of water deficit (WD). As expected for this kind of humid area, E_A is always lower than the monthly precipitation amount, with an annual amount corresponding to 20.1% of the annual rainfall. ΔSWS is more important during the peak of the rainy season and the beginning of the dry period. Increase in SWS tends to limit the infiltration of rainwater. For instance, I_{eff} decreases from July to August due to the oversaturation of soil during this period (Table 3) that generates runoff instead of percolation.

Recharge was calculated by using the equation 2. Results show that, the recharge of the Mio-Pliocene groundwater varies from 0 to 237 mm (Table 3) with a total amount of 1049.8 mm per year that corresponds to 27.2% of the annual rainfall. The aquifer is continuously recharged along the year from February (14.1 mm) to October (13.43 mm) with a maximum in July (237 mm) and September (223.2 mm).

WTF approach

In the study area, observation of groundwater levels from 2004 to 2007 and in 2014 was conducted by Ketchemen-Tandia (2011) and Emvoutou (2018) at the ends of the dry and rainy seasons in March and November, respectively. They show that the aquifer displays a slight water-level fluctuation (< 1m) along the year. Water table rises during rainy season, due to percolation of water through the unsaturated zone, and then drops during dry season. Feumba et al (2011) through a monthly monitoring in some wells, provided information on water level fluctuations

month by month. They reported that the lowest water table (0 m) is observed in August while the highest one is in December (5.8 m). Therefore, the fluctuation of water table is ranging between 0.00 and 5.80 m thus giving $\Delta h = 5.8$ m.

The specific yield of the Mio-Pliocene sands was estimated to be equal to 0.161 in agreement with aquifer tests carried out by Healy and Cook (2002). This value of S_y has also been used for Quaternary sands at Cotonou (Kotchoni et al. 2018) and in similar beach sands in India (Vouillamoz et al. 2012). The relative high value of S_y is consistent with the significant values of transmissivity of the aquifer as mentioned above.

Recharge is then calculated from January 2010 and December 2010 by using Eq. 3. An average value of 933.8 mm has been obtained. Since the annual rainfall amount recorded in 2010 is 3585.2 mm, a recharge coefficient (I_{eff}/P) is approximately equal to 26%. The Penman-Grindley method applied on this period gives a similar result of 959.7 mm.

Therefore, we can assert that MP groundwater recharge vary around 26‰ and 27% of annual precipitation in Douala. As comparison with semi-arid/arid contexts, we show that groundwater recharge in hyper-humid Central Africa is more than the double of that observed in the Sahel region (Leduc et al 1997). The groundwater recharge rate in Douala is similar to that obtained at a global scale through model analysis by Mohan et al (2018) in Amazonia, Papua New Guinea and Japan which present the highest recharge rates in the world.

4.2. Analysis of groundwater flow

Piezometric pattern

The potentiometric map of the MP aquifer is presented on Fig. 5. It shows that the groundwater globally moves from the eastern side of the study region toward the discharge area in the Wouri estuary zone. We identify on this map, two piezometric domes in Ndogpassi – Nyalla (SE) and Kotto (NE), which can be considered as the focused recharge areas of the aquifer at Douala. In these sectors, the infiltration is more concentrated, more active or easier, probably related to the topography. Indeed, the piezometric structure of the aquifer follows the topography of the region as described in section 2.1. However, the variable groundwater flow directions and the variability of the spaces between the potentiometric surface contours (Fig. 5) characterize a non-uniform flow regime. Potentiometric surface contours become more and more distant from the recharge area to the discharge one, indicating a dominance of permeable formations towards the estuary in agreement with geological/hydrogeological description. Moreover, the general shape of the potentiometric surface is convex, showing a radial aquifer with divergent streamlines contrary to semi-arid and arid regions where convergent streamlines towards the water course axis are generally observed (e.g., Ouali et al. 1999; Lienou et al. 1999).

The discharge area of the MP aquifer is characterized by a complex hydrosystem composed by Quaternary aquifer and Wouri River (Fig. 5). It can be suspected that when there are superimposed, a natural upward water flux from the MP to the Quaternary aquifers should occur. Moreover, in this discharge zone, groundwater can also be influenced by ocean tides. However, regarding the geographical position of the aquifers (Fig. 5), Quaternary sands seem to be more vulnerable to saline intrusions than Mio-Pliocene formation. Finally, it is worthwhile noting that

groundwater discharge also occurs at numerous springs in the study area due to very local topographic control.

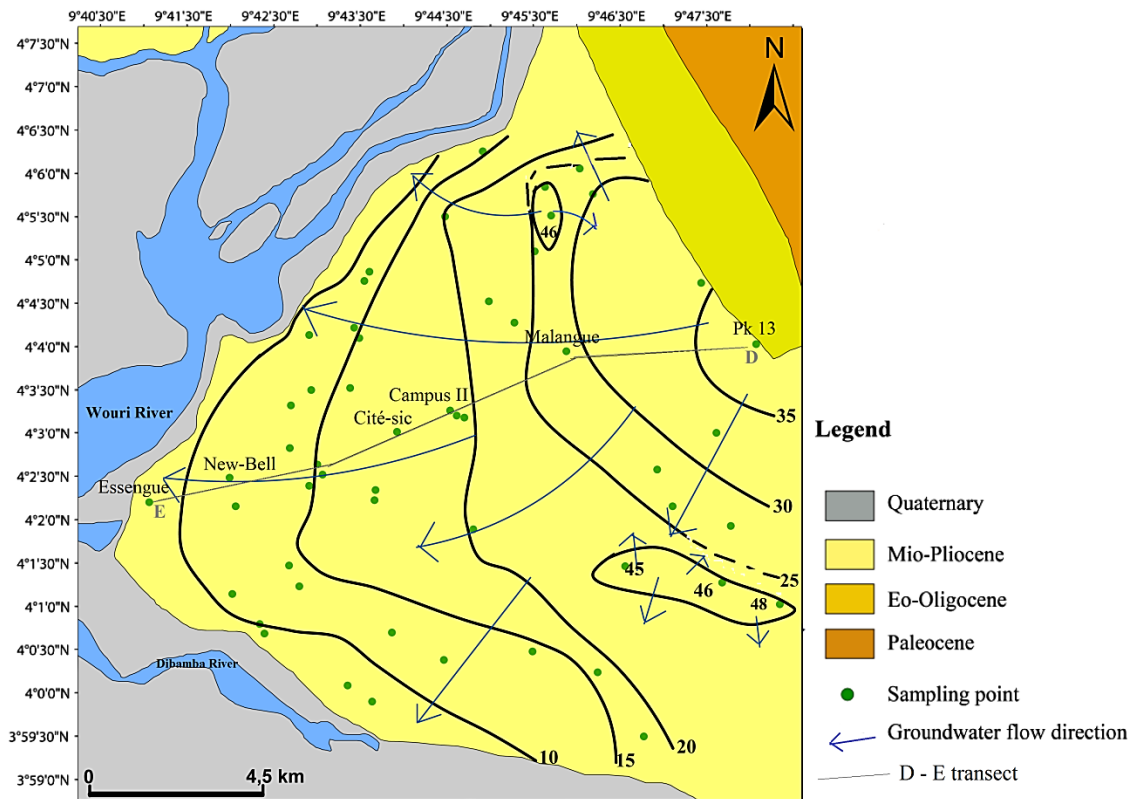


Fig. 5 Potentiometric map of the Mio-Pliocene aquifer in Douala (Cameroon) in February 2017.

Hydraulic gradient

Hydraulic gradients from upstream to downstream, through a transect line D-E (Fig. 5) are shown in Table 4. There is a progressive decrease in hydraulic gradient suggesting a progressive evolution from unconfined to semi-confined conditions. By contrast, in the discharge area, in the settlement of Essengue, we observe an upward gradient due either to unconfined conditions or by natural upwards of deep groundwater. The low altitudes observed in this sector may also play a role. This variation of hydraulic gradient along the D-E flow path tends to characterize in spite of multi-directional flow the relative homogeneity of the Mio-Pliocene aquifer.

On average, hydraulic gradient of the MP aquifer can be estimated to 2.3‰; that value is characteristic of unconfined aquifers.

Table 4 Hydraulic gradients along the D-E flow path in the MP aquifer

Sample ID along the D-E flowpath	Settlement	Region	Easting	Northing	Potentiometric level (m)	i = dH/Dl (%)
BD 5	Pk 13	Recharge area	9.796944	4.069722	41	3.5
BD 45	Malangue	Flow path at the center	9.760497	4.068436	27	
BD 16	Campus II	Flow path at the center	9.739527	4.055722	18	3.3
BD 18	Cité-sic	Flow path at the center	9.72775	4.052888	15	2.1
BD 56	New-bell	Flow path close to the discharge area	9.708944	4.022833	14.8	5.42*10 ⁻²
BD 33	Essengue	Near the discharge area	9.678361	4.014972	6.8	2.3

Groundwater velocity

An accurate estimate of groundwater velocity has been calculated using Darcy's Law:

$$V = K \frac{I}{n} \quad (5)$$

In this formula, V stands for "groundwater velocity," K corresponds to the "horizontal hydraulic conductivity," I is the "horizontal hydraulic gradient," and n is the "effective porosity." Assuming a porosity of 0.15 (from laboratory experiments of Stephen et al. 1998) and an average hydraulic conductivity of 1.5×10^{-3} for the Mio-Pliocene sands, groundwater velocity can be estimated to 2.3×10^{-5} m/s or 2 m/day. Therefore, it would take 28 years for water to travel from the upstream zone (at PK 13) to the estuary area (Fig. 5).

4.3. Functional information from the isotopic investigations

Groundwater origin

The isotope ratios of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ from the aquifer are plotted on Fig. 6 with respect to the global meteoric water line (GMWL) and the local meteoric water line (LMWL) derived from the GNIP data at the Douala station. The weighted mean values of rainfall are respectively -2.8‰ and -12.2‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$. MP groundwaters range from -5.1‰ to -3.1‰ $\delta^{18}\text{O}$ and -25.7‰ to -9‰ $\delta^2\text{H}$, well plotted on the LMWL confirming a local recharge by the rainwater (Fig. 6). Surface waters are more enriched than groundwater suggesting evaporation processes. This tends to confirm the piezometric structure. In addition, the homogeneity of groundwater isotope signature reflects a single origin of groundwater recharge by rainwater.

In summary, all these features reflect a recharge of the MP aquifer by rainwater without any evaporation impacts. Indeed, the higher is the humidity in the Douala region, the lower is the evaporation rate. It has to be quoted that the most depleted sample of the MP samples ($\delta^{18}\text{O} = -$

5.1‰ and $\delta^2\text{H} = -25.7\text{‰}$) should reflect a relatively “old” water and may involve different flow paths within the MP aquifer.

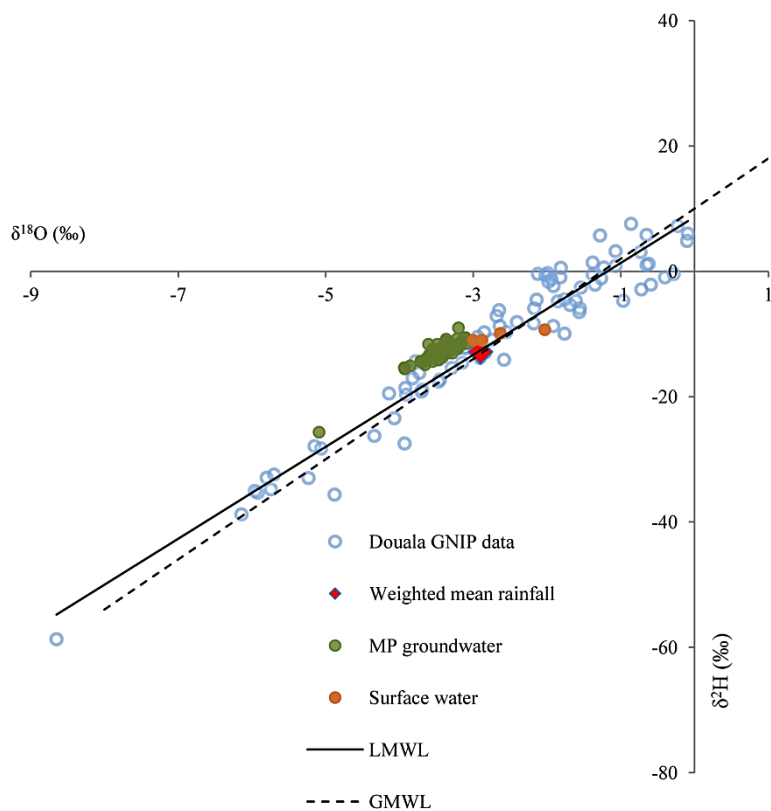


Fig. 6 Plots of Mio-Pliocene (MP) isotopic values with respect to Douala local meteoric water line (LMWL: $\delta^2\text{H} = 7.3 \delta^{18}\text{O} + 8.7$; $r^2 = 0.93$) and global meteoric water line (GMWL: $\delta^2\text{H} = 8 \delta^{18}\text{O} + 10$). The weighted mean rainfall and some surface water samples (Emvoutou et al. 2018) are also plotted.

Timing of groundwater recharge

Analysis of monthly rainfall data from the Douala GNIP station reveals a dominance of recharge from April to August and November; as precipitation isotopic signatures during these times are similar to sampled groundwater in the MP aquifer (Fig. 7). The months from December to March show precipitation highly enriched and this signature is not reported in groundwater. It can be hypothesized that infiltrated rainwater of these months is lost through evapotranspiration (ET), as ET is greater than effective rainfall during this relative dry period (Table 3). However, isotopes reveal that there is no recharge in September and October (Fig. 7). From September to October, the vadose zone of the soil is likely saturated with rainfalls from April to August. Then heavy rainfalls rather contribute to run-off and recurrent floods in the city. Whereas in November, the soil is relatively dry and the aquifer can be recharged. Similar inferences of negligible recharge by the heaviest and the most depleted rains have been recognized elsewhere in the tropics

(Mbonu and Travi 1994 in Nigeria, Oga et al. 2008 in Ivory Coast, Wirmvem et al. 2015 in Northwest Cameroon).

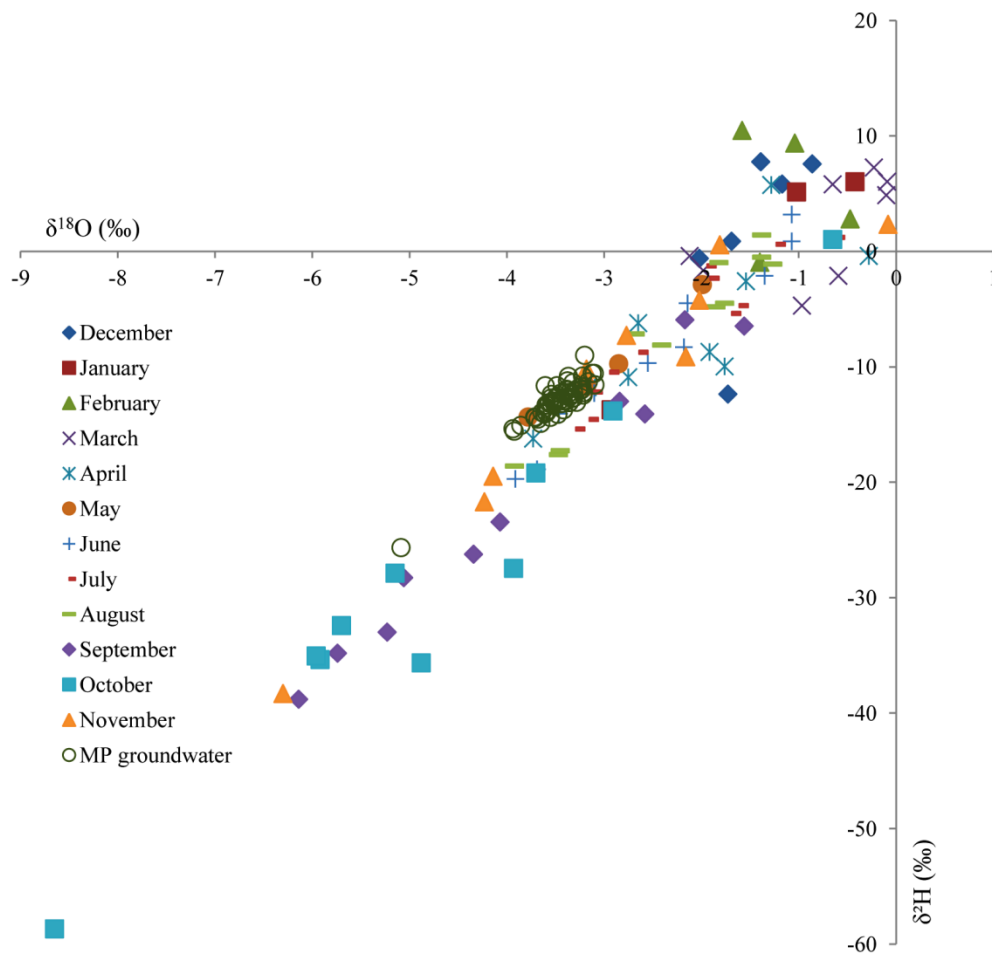


Fig. 7 GNIP stable isotope composition of precipitation depicting months whose signatures are observed in MP sampled groundwater.

In addition, the greater similarity between the LMWL obtained for rainwater from April to August and November ($\delta^2\text{H} = 6.6 \delta^{18}\text{O} + 7.6$; $r^2 = 0.91$) and the MP water line ($\delta^2\text{H} = 6.8 \delta^{18}\text{O} + 10.7$; $r^2 = 0.87$) supports once again a preferential recharge of the aquifer during these months.

MP aquifer functioning

The main causes of variations in the groundwater stable-isotope signature are natural variations in the isotopic composition of rainfall, mixing with pre-existing waters, and evaporation during percolation through soil and/or the unsaturated zone (Barnes and Allisson 1988). However, in the previous paragraphs, the absence of evaporation effect in the aquifer system was clearly highlighted. The depth to water table relationship with $\delta^{18}\text{O}$ (Fig. 8) can be useful to identify a mixing of water within the system (Oiro et al. 2018). The stable isotope composition of MP groundwater plotted against the depth to water table does not yield any relationship. Nevertheless, two clusters can be identified: (i) samples from low water table depth corresponding to shallower aquifer system and (ii) samples from important water table depth

standing as intermediate to deep flow path. The Mio-Pliocene shallow water presents a great homogeneity with a short range of $\delta^{18}\text{O}$ values (-3.9 ‰ to -2.8‰) while water from deep to shallow flow paths are well differentiated with depleted signatures. This observation is in contradiction with the expected anti-correlation between these two parameters since higher water table must be affected by evaporation or must enable an effective evapotranspiration process which should modify the composition of the stable isotopes (Oiro et al. 2018). This homogeneity in shallower flow path is related to uniform origin of the recharge (as presented above) and/or to a mixing between shallower, intermediate and deep flow paths. There is likely also a mixing between deep and intermediate flow paths according to an upward flux process of water.

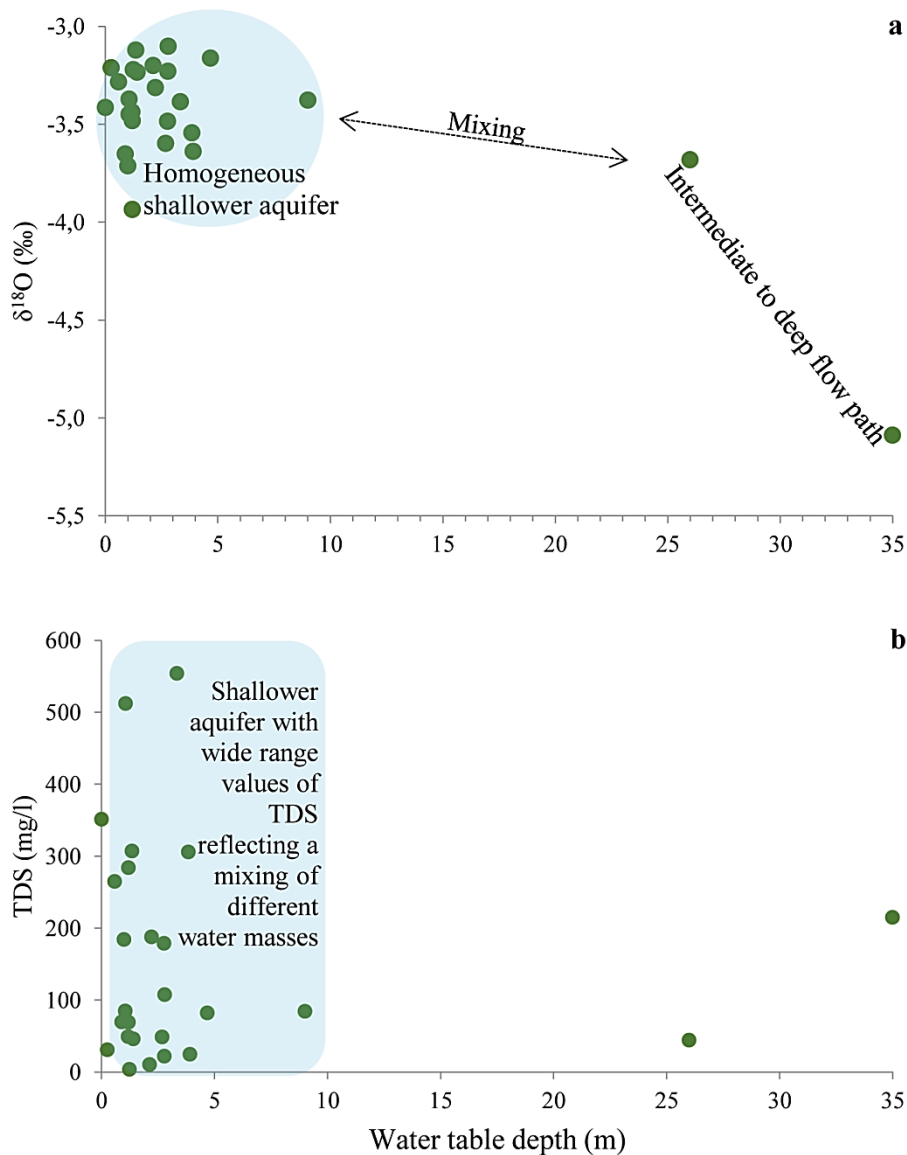


Fig. 8 Plots of a) $\delta^{18}\text{O}$ and b) TDS *versus* water table depth of sampling wells.

The existence of deep flow path with depleted water in heavy isotopes (Fig. 8a) corroborates the results of Ketchemen-Tandia (2011) and Ketchemen-Tandia et al. (2017) which have shown that boreholes tapping the most confined part of the aquifer exhibit depleted isotope values and

tritium contents from below the detection limit (< 0.7 TU) to 1.3 TU. These tritium values indicate that the groundwater had received recharge prior to the atmospheric bomb tests (i.e. before 1953; Fontes 1983) but there has been locally mixing with more recent water, probably (i) through leakage due to annular spaces around the casing of poorly-constructed boreholes tapping the aquifers in Douala and /or (ii) through a natural upward flux of water from deep to shallower flow path.

Thus, shallow groundwater in the Douala basin is indicative of a good mixing of waters from different recharge episodes (going up to or more than 70 years) and ambient groundwater. Oga et al (2008) and Ndembo (2009) working in porous aquifers of Abidjan and Kinshasa, have made very close observation in these others humid tropical areas.

4.4. Controls on water chemistry

Main features of groundwater chemistry

Groundwater temperatures (27.2°C to 31.5°C with a mean of 28.6°C) are close to that of air temperatures (26.9°C to 30.5°C with a mean of 28.6°C) in February when the field measurements were carried out. This reflects the shallow character of groundwater in Douala. The pH ranges from 3.9 to 7.3 with almost samples displaying pH values below 7. These acidic conditions may reflect the acidic character of rainwater which then evolves in silicate environment. The electrical conductivity ranges from 13.6 to $1632 \mu\text{S}/\text{cm}$ (Table 4). The lowest EC ($< 200 \mu\text{S}/\text{cm}$) are mainly observed in groundwater from the NE part of the study region whereas the highest EC ($> 500 \mu\text{S}/\text{cm}$) are most observed downstream near the estuary, in low-lying areas. The plot of EC *versus* potentiometric level of groundwater (Fig. 9a) shows that there is no clear relationship between the two parameters. The shallower aquifer system (potentiometric level < 20 m) presents a great variability in EC (Fig. 9a), due to various inputs entering the system: rainwater, various types of effluents, water from pit latrines, leaking of solid waste, and mixing with deeper groundwater. With the increase in depth, along the flow path, EC tends to decrease and becomes more homogeneous. The deep part of the aquifer thus present values ranging from 13 to $187.8 \mu\text{S}/\text{cm}$.

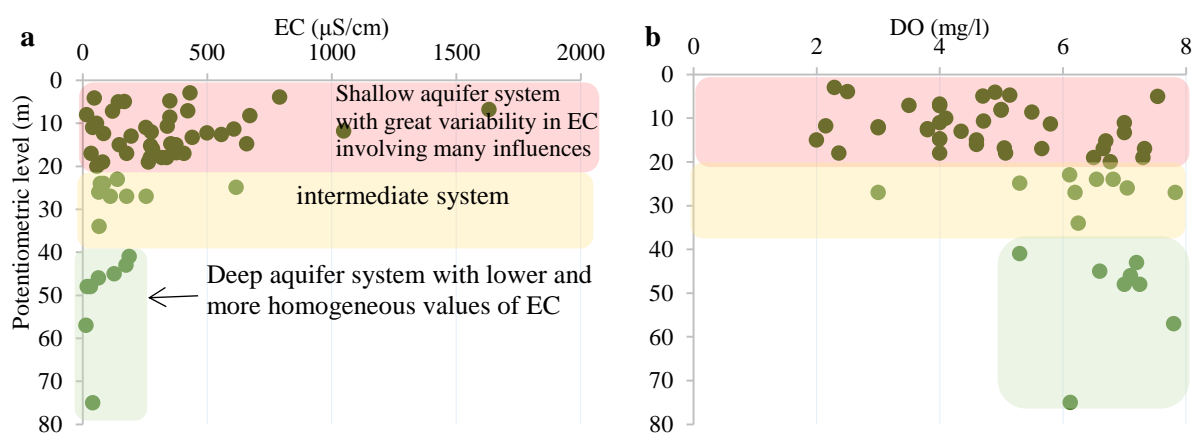


Fig. 9 Plots of a) Electrical Conductivity and b) Dissolved Oxygen *versus* Potentiometric levels of Mio-Pliocene groundwater.

Dissolved oxygen (DO) concentration ranges between 2 mg/l to 7.8 mg/l with an average of 5.2 mg/l and a standard deviation of 0.6. As for EC, there is no relationship between dissolved oxygen (DO) and potentiometric levels (Fig. 9b). Shallower and intermediate flow paths previously identified present a wide range of values from 2 mg/l to 7.8 mg/l thus presenting enriched and depleted water in oxygen suggesting a mixing of different water masses and/or changes in the confinement conditions of the aquifer. Groundwater from the deep flow paths are more homogeneous and present the highest value in DO from 5.3 to 7.8 mg/l. These high values in DO are in contradiction with what is generally observed. Indeed, it was expected that DO decreases with the increase in water table depth or potentiometric level. This vertical distribution of DO can be explained by the fact that the water from the shallower flow path are much enriched in organic matter and the oxygen is often consumed by bacteria activity. As the aquifer depth increases, the organic matter decreases, and the environment becomes more mineralized. It is therefore possible to find oxygen at significant water table depth. This atypical case was already described by Ayraud (2005). Another reason which can be mentioned is the fact that shallower groundwater rich in oxygen may recharge deep water thanks to erosion of impermeable or semi-impermeable layer between the different flow paths or thanks to lateral variations of lithology. This second case was observed for instance by Klopmann et al (1996) in the chalk aquifer of Paris basin.

Concerning the major ions chemistry, the order of abundance of ions in MP water is $\text{Na}^+ > \text{Ca}^{2+} > \text{K}^+ > \text{Mg}^{2+}$ for cations and $\text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ for anions (Table 5).

Table 5 Descriptive statistics of chemical parameters from rainwater to groundwater in the Douala basin.

All values are in mg/l except EC ($\mu\text{s}/\text{cm}$)

Min. minimum; *Max.* maximum; *St. dev.* Standard deviation.

Parameters	EC	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}
WHO limit	1000	300	250	250	50	200	100	<200	<200
Rainwater (n = 3; Eneke et al. 2010)									
Mean	14.3	0.7	0.9	1.4	1.1	0.8	0.9	0.9	0.1
Median	17.8	0.7	0.9	1.4	1.1	0.7	0.9	0.9	0.1
Min.	4.6	0.4	0.5	0.8	1	0.6	0.6	0.7	0
Max.	20.4	0.9	1.4	1.9	1.3	1.1	1.1	1.2	0.1
St. dev.	8.5	0.3	0.5	0.6	0.2	0.3	0.3	0.3	0.1
Mio-Pliocene groundwater (n = 58)									
Mean	287.4	11.5	31.3	17.4	48.5	25	7.7	12.2	1.9
Median	224.7	0	25.4	5.4	42.1	21.5	5.7	5	0.9
Min.	13.6	0	1.6	0.5	1.1	0.03	0.1	0.2	0.1
Max.	1632	222.2	131.1	90.5	245.6	87	41	81.1	21.4
St. dev.	284	38.8	31.2	22.3	43.8	19.9	7.9	16.1	3.5

This order of abundance of ions justifies the different water types observed on the Chadha diagram (Chadha 1999; Fig. 10).

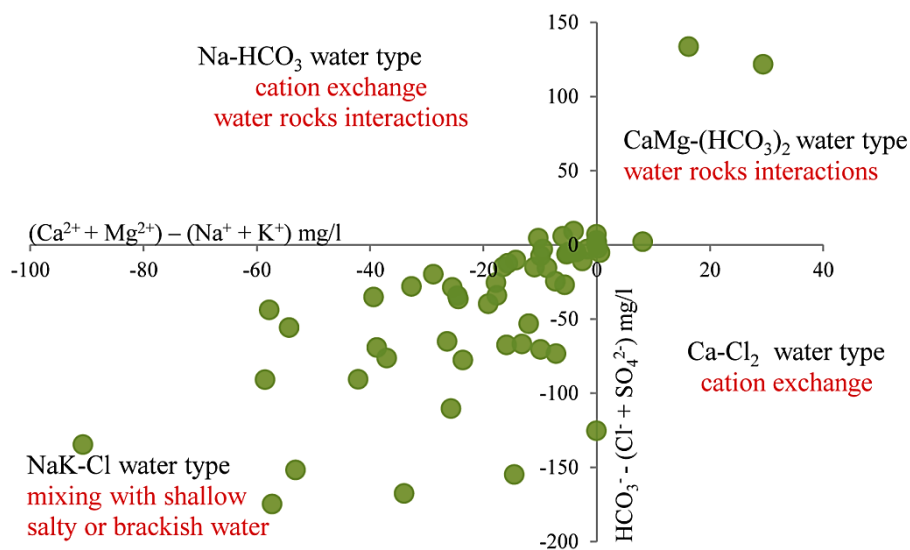


Fig. 10 Chadha diagram of Mio-Pliocene groundwater in the Douala region (Cameroon). The main processes which are supposed to be involved for each water types are mentioned in red.

The evolution of concentrations in major ions along the flow path (D-E transect; Fig. 5) is presented in Figure 11. The samples, which are concerned are located in the settlements of Pk 13, Malangue, Campus II, cite sic, New-Bell and Essengue located respectively at 19, 14, 10, 9, 6.5 and 2 km to the sea. Concentrations in ions show an overall increase trend along the flow path (with EC ranging from 187.8 to 1632 μ S/cm). An abrupt augmentation in Ca^{2+} , K^{+} and SO_4^{2-} is observed at New-bell (Fig. 11). Since the nitrates concentrations are high (78.1 mg/l) at this point, a such increase can be linked to local pollution when effluents from latrines or elsewhere are mixed with freshwater (Lapworth et al. 2017). This hypothesis is supported by the fact that this settlement is one of the most populated in Douala and the observations of Ketchemen-Tandia et al (2017) that showed that densely populated and low-lying areas present the worst groundwater quality in the study region. The variation in NO_3^{-} content is not linear, reflecting the great influence of anthropogenic activities on this element.

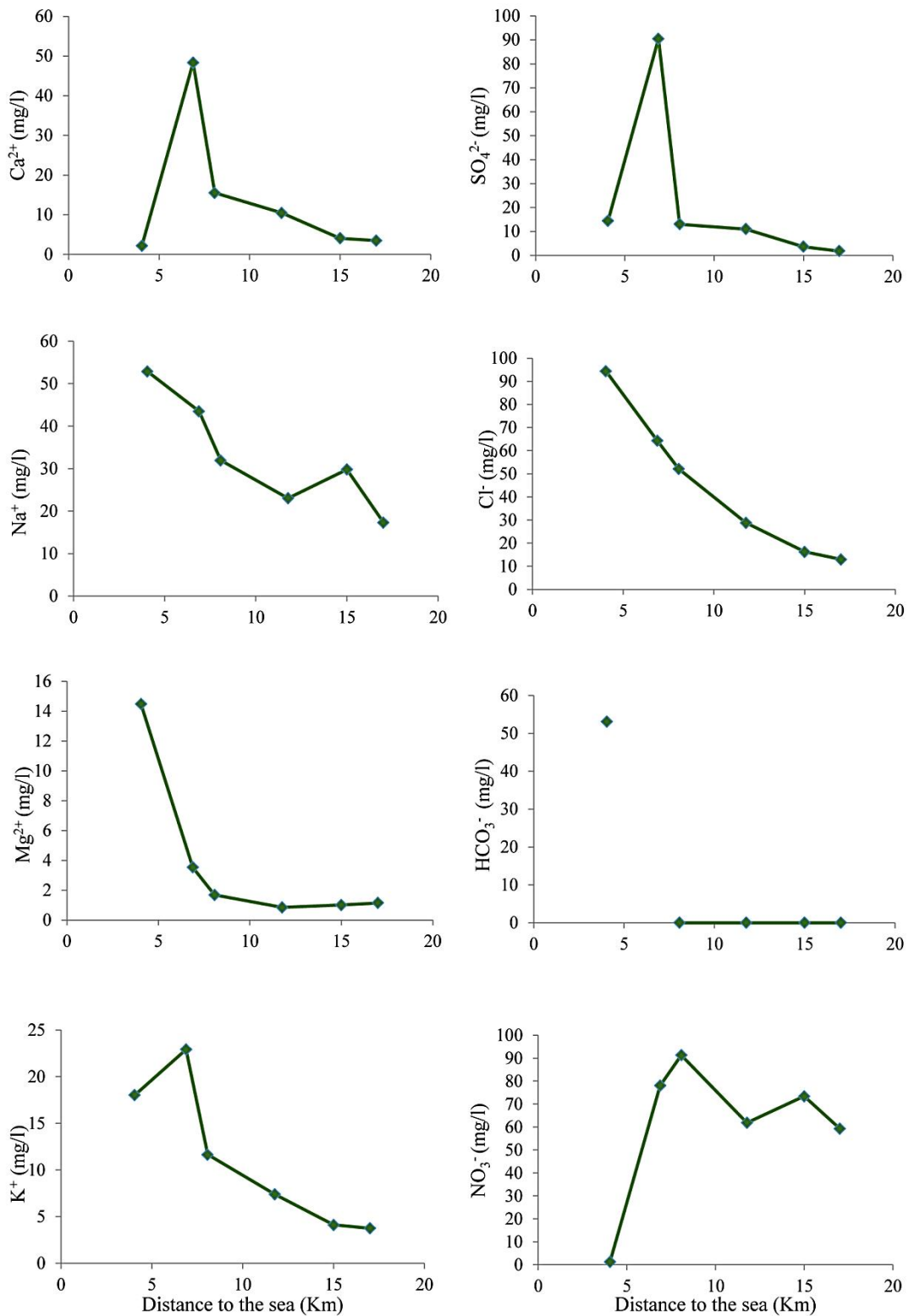


Fig. 11 Major ions evolution along a D-E flow path from PK 13 (upstream) to Essengue (downstream).

This overall increase in ions contents upstream to downstream does not correspond to an increase in water mineralization with the depth of the system as TDS varies independently of the water table (Fig. 8b). As it has been shown with stable isotopes, within the MP aquifer there is a mixing of water circulating at different depths (shallower, intermediate and deep). Nevertheless, high mineralized water can be attributed to shallower flow path which are more vulnerable to pollution; while low mineralized water with depleted values in stable isotope correspond to the deep circulations within the aquifer (Fig. 8b).

Geological controls

CaMg-(HCO₃)₂ and Na-HCO₃ water types are observed for the recharge area and correspond to the piezometric domes identified on the Fig. 5. It can be thus hypothesized that infiltration of acidic rainwater in the Douala area leads to a total congruent dissolution of silicate minerals according to the local geology. Under these conditions, the weathering of unstable minerals in soil (olivine, Ca-feldspar, K-feldspar, albite, pyroxene) is likely to release Ca, Mg, and Na/K (Goldich 1938) into solution that would lead to groundwater with a chemical composition dominated by Ca–CaMg-(HCO₃)₂ or CaMg-(HCO₃)₂. The presence of bicarbonate in silicate environment such as Douala may be linked to enrichment in CO₂ following the equations (6) and (7):



The silicate weathering is indicated by many chemical features: 1) a positive correlation between Mg and Ca (R=0.28; Table 6) with 69% of samples presenting a Ca/Mg ratio above 2 (Reddy and Kumar 2010), 2) a Mg/[Mg+Ca] ratio above 0.5 (Drever 1997) for 66% of the samples, 3) a Na/Cl ratio above 1 for 46% of the samples indicating that Na⁺ is partly released from silicate weathering (plagioclase, feldspar minerals; Meybeck 1987), 4) a positive correlations between K, EC, Ca and Mg (Table 6) meaning that K is influenced by chemical weathering of silicate minerals such as orthoclase (KAlSi₃O₈). These findings are in agreement with those of Emvoutou (2018) who highlighted through diverse binary diagrams the silicate weathering in the Douala region is greatly responsible of the release of K⁺, Na⁺, Ca²⁺, Mg²⁺ and even HCO₃⁻ in the solution.

Table 6 Correlation matrix for chemical elements. The significant relationships are underlined and bolded.

	EC	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SO ₄ ²⁻	NO ₃ ⁻	Cl ⁻	HCO ₃ ⁻
EC	1	0.49	<u>0.58</u>	<u>0.72</u>	<u>0.76</u>	0.46	0.38	<u>0.78</u>	0.35
Ca ²⁺		1	0.28	<u>0.60</u>	<u>0.68</u>	<u>0.75</u>	0.36	0.48	<u>0.58</u>
Mg ²⁺			1	0.26	0.37	0.12	0.00	0.27	<u>0.64</u>
Na ⁺				1	<u>0.86</u>	0.55	<u>0.56</u>	0.90	0.12
K ⁺					1	<u>0.57</u>	<u>0.67</u>	<u>0.77</u>	0.23
SO ₄ ²⁻						1	0.34	<u>0.61</u>	0.00
NO ₃ ⁻							1	0.45	0.00
Cl ⁻								1	0.00
HCO ₃ ⁻									1

Finally, Gibbs plot (Gibbs 1970, Fig. 12) has been used to help to understand hydrochemical trends in the aquifer. The diagram is divided into zones based on the contribution of recharging precipitation, rock/mineral weathering and evaporation/crystallization on the hydrochemistry. The discretization is based on the concentration of the Na⁺ ion relative to the sum of the concentrations of the Na⁺ and Ca²⁺ ions in the hydrochemistry and the TDS content of the water. Waters affected by high evaporative effects are generally expected to present high TDS and Na/Ca + Na ratios. When the hydrochemistry is controlled mainly by mineral weathering processes, the TDS is moderate, and the Na/Ca + Na is also moderate. For waters influenced mostly by the hydrochemistry of precipitation, the TDS is low but the Na/Ca + Na ratio is moderate to high. In this study, the Gibbs diagram firstly confirms that there is no evaporation process in the aquifer. Most of the samples plot in the rock dominance field and their mineralization is mainly due to water/rock interaction.

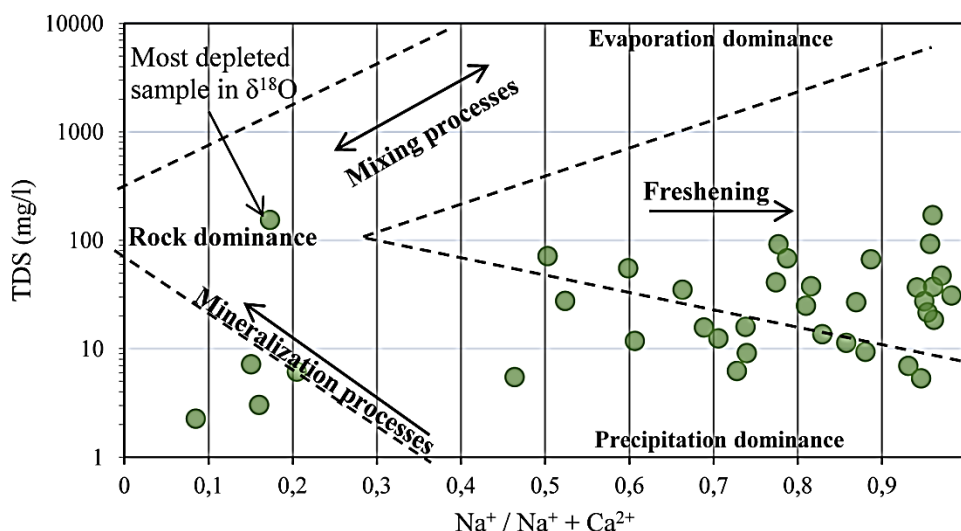


Fig. 12 Gibbs diagrams showing the main natural processes controlling the mineralization of the Mio-Pliocene aquifer in Douala (Cameroon).

Influence of climate

It is worthwhile noting that the silicate weathering through hydrolysis reactions is favored at Douala by the relative high temperatures and low thermal amplitude according to Segalen (1965) who showed that hydrolysis reactions are more intense and faster in humid tropical regions. Thanks to the constantly high temperature, the presence of H^+ ions in the subsurface water allows a chemical decomposition of the minerals of the rocks. The hyper-rainy character of Douala, which enables significant drainage, also plays an important role in promoting the solutionizing of the elements (Helgeson et al. 1984) and dilution (Foster (1993). To check the influence of this phenomenon on the Mio-Pliocene aquifer of Douala, we compiled historical data on nitrate concentrations of 2011 (Fantong et al. 2016), 2014 (Emvoutou 2018), 2015 (Wirmvem et al. 2017) and 2017 (this study). Nitrates generally well reflect the impact of human activities on the water resource. Thus, regarding the urbanization trend in Douala, the increase in population and inhabitants' density (see Nlend et al. 2018 for more details), we expect that NO_3^- content in groundwater would increase overtime. It is the case for the 2011-2017 period; maximum values

increased from 70 mg/l to 245.6 mg/l; median values evolve from 6 to 29.3 mg/l (Fig. 13). These latter values are however under the standard limit for drinking water supply (WHO 2006). They are similar to that observed in contexts with less anthropogenic constrains (e.g., Stadler et al. 2008; Huneau et al. 2011; Adimalla et al. 2018).

Thus, it is possible that the increase in NO_3^- is moderated by the dilution effect due to the groundwater hyper-recharge in Douala. For these reasons, dilution can be considered as a key factor in determining groundwater contamination in humid region as it plays an important role in lowering contamination levels. This fact has already been shown in different parts of the world (Foster 1993; Stigter et al. 2006; Lasagna and De Luca 2006, Lasagna et al. 2013; Farooq et al. 2011).

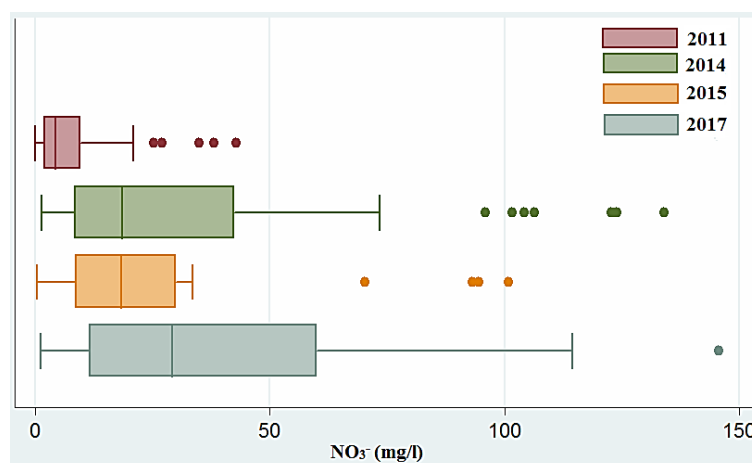


Fig. 13 Box whisker plot illustrating the temporal moderate evolution of NO_3^- due to dilution effect in the Mio-Pliocene aquifer.

Residence time

CaMg-(HCO₃)₂ and Na-HCO₃ water types observed in recharge areas, also correspond to samples which have the lowest δ¹⁸O values. Since these water types are only associated to water-rocks

interactions, it is possible that association of CaMg-(HCO₃)₂ water type with depleted value of δ¹⁸O must be related to a relative long residence time of this water and therefore, a significant water-rock interactions time (Huneau et al. 2011). This hypothesis is in agreement with the work of Santoni et al (2016) who clearly showed that the lower the ratio of young water, the greater is the concentration in Ca²⁺, HCO₃⁻ and SiO₂. On the Gibbs diagram, we observe especially that the sample which has the lowest value in δ¹⁸O is located at the extreme end of this category with a TDS of 153.6 mg/l and Na/Ca + Na ratio of 0.17. Higher TDS associated to low Na/Ca + Na (low Na⁺ meaning a non-influence of shallow polluted water rich in salts) ratios must reflect an important mineralization of water in relation to a long residence time within the aquifer. The identified sample (δ¹⁸O = -3.9‰) of intermediate flow path (Fig. 8) has however Na/Ca + Na ratio of 0.9 and a TDS of 169.6 mg/l. This important value of TDS and more important value in Na⁺ confirm an influence of pollution at this depth of the aquifer.

As presented above, the influence of groundwater long residence time is strongly supported by low tritium contents revealed for this aquifer by Ketchemen-Tandia (2011) and Emvoutou et al

(2018). Indeed, Ketchemen-Tandia (2011) has shown that most of boreholes tapping the Mio-Pliocene aquifer exhibit tritium concentrations lower than 2 TU. Emvoutou et al (2018) found similar results. They observed that measured tritium values phreatic aquifer ranged from 0.9 to 2.3 TU (mean 1.3 TU).

5. Synthesis: hydrogeological scheme of the Mio-Pliocene aquifer

A conceptual scheme, detailed below, combines the results from the multi-disciplinary approach developed in this study.

Hydrogeological structure

We were able to identify three flow paths within the large MP aquifer: the shallower, the intermediate and the deep which are probably separated from each other by semi-permeable layers.

(i) The shallow flow path

It represents the upper part of the aquifer which are mostly unconfined or under a thin layer of clays. Groundwater here is characterized by a potentiometric surface lower than 20 m. The fast infiltration (no evaporation) and the low water-rock interaction process show a rapid renewal of the water. The high mineralization resulting of anthropogenic input shows a strong impact of poor sanitation system or human activities.

(ii) The intermediate flow path

It presents strong interconnection with groundwater from shallow flow path. Anthropogenic impact, even though significant locally, is buffered. The potentiometric levels range approximately between 20 and 40m. The hydraulic gradient is much lower and water renewal is then slower than in the top part of the aquifer.

(iii) The deep flow path

It refers to the confined layers of the aquifer with potentiometric levels > 40m and the lowest hydraulic gradient ~ 0.002. Water is geochemically and isotopically distinct compared to the others and there is no anthropogenic impact.

Hydrogeological functioning

The semi-permeable layers existing between the identified flows paths within the aquifer do not prevent vertical transfers. In addition, the progressive difference in hydraulic gradient along the flow path (Table 4) suggests that there is hydraulic connection between the different flow paths. Nevertheless, the low permeability layers between the different sub-aquifers may be enough to limit infiltration from the shallow flow path towards the underlying intermediate and deep ones. The absence of reverse hydraulic gradient confirms this structural scheme which has also been observed for instance in an insular tropical humid volcanic watershed by Charlier et al (2011). Groundwater moves progressively from unconfined conditions in upstream to confined hydrogeological conditions and in the discharge area the aquifer becomes again unconfined (see hydraulic gradients in Table 4). A vertical transfer occurs from the deeper part of the MP aquifer

to the shallow one which is finally drained by the Wouri River. In the discharge area of the basin, Quaternary and Mio-Pliocene aquifers are directly in contact (Fig. 5) and therefore interact hydraulically together. A third component can be quoted with the ocean tides.

Aquifer homogeneity

The homogeneity of the shallower MP aquifer is supported by isotopes data (Fig. 6 and 7) which present a low range of variation indicating a uniform recharge from rainwater. Further, this homogeneity reflects a mixing between different flow paths. When we refer to Ketchem-Tandia (2011) and Emvoutou et al (2018) who measured tritium in MP groundwater and obtained for many samples a tritium content lower than 1 TU or below the detection limit, it is therefore possible that deep flow path of the Mio-Pliocene was recharged by rainfall prior to the atmospheric bomb tests (Fontes 1983; IAEA 2000). Therefore, it is clear that the large multi-layer MP aquifer can gather “paleo-water”

The homogeneity of the shallower aquifer is however contrasted when looking to the chemical data which show water-rock interaction processes and many influences of human practices. The chemistry becomes more homogeneous along the vertical flow. The deeper is the water, the less vulnerable to pollution it is and the more homogeneous is the water chemistry.

The aquifer homogeneity is also underlined by a same lithology within the aquifer no matter the depth and by the absence of faults or any tectonic structures during the Mio-Pliocene. These

homogeneity factors allow the absence of vertical hydraulic separations within the aquifer as observed in basement and volcanic contexts (Santoni et al. 2016; Charlier et al. 2011).

A conceptual model of the aquifer functioning in terms of groundwater origin, mineralization flow paths and mixing is thus proposed in Fig. 14.

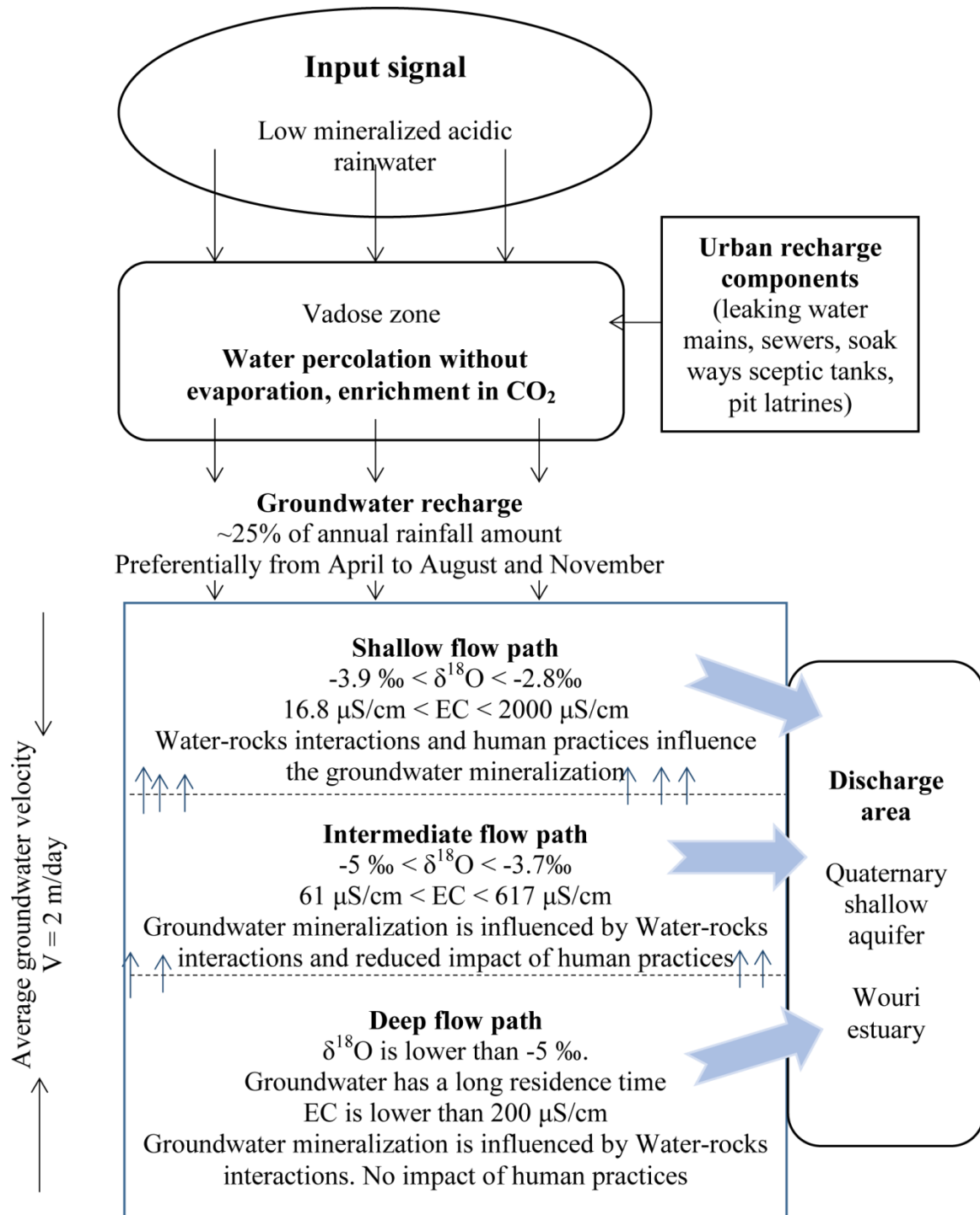


Fig. 14 Conceptual scheme of the hydrogeology of Mio-Pliocene aquifer (Douala, Cameroon).
The big blue arrows represent the discharge of groundwater in the estuary system.

6. Concluding remarks

The present study brings out the detailed hydrogeological features characterizing an aquifer in hyper-humid region. For sustainable groundwater management, substantial information on

groundwater recharge and groundwater flow conditions (flow directions, velocity, and identification of different flow paths) is necessary. The approach used involves hydro-climatic data, measures of potentiometric levels, hydrochemistry and stable isotopes. It is the first time that such kind of study is achieved in the Central Africa tropical humid region.

By applying Penman-Grindley and water table fluctuation methods, we estimated that the Mio-Pliocene groundwater recharge rate varies between 26 and 27 % of rainfall amount. Further, the stable isotopes allow us to determine the recharge conditions and timing (at monthly scale).

The combination of several tools: geological, hydrodynamic (piezometry) and hydrochemical (major ion chemistry and water isotopes), allows for the design of the hydrogeological structure and functioning of the aquifer system. Three flow paths have been identified. The shallower one is homogeneous in term of isotopes but heterogeneous in term of major ions chemistry thus reflecting various influences on this upper part of the aquifer. Shallower MP is a mixing of water from the different flow paths. The intermediate and deep flow paths are more depleted in stable isotopes and more homogeneous in term of chemistry. Water from the deepest part of the aquifer seems to have a relatively long residence time. The depleted value in $\delta^{18}\text{O}$ ($\sim -5\%$) and low tritium contents (< 1 TU) observed from this groundwater flow path suggests the presence of old water (over 70 years) in the aquifer system. Thus, Mio-Pliocene aquifer gathers water recharged recently and older ones.

Another key result of this paper is the great influence of climate on water chemistry. The relative high temperatures and low thermal amplitude recorded at Douala are factors which accelerate hydrolysis silicate reactions. In addition, the hyper-rainy conditions observed controls the ions contents through dilution effect.

All of these conclusions help in the understanding of hydrology in humid tropics. As these regions have abundant resources with greater energy inputs, efforts must be emphasized to quantify the water fluxes and hydrological interactions in order to implement easily a global approach in water management. On the other hand, in the urban context of Douala, the results of this work will be useful for the establishment of a new water supply scheme. For instance, the three groundwater flow paths highlighted in this paper must be considered in the management and the distribution of groundwater resource. It is not realistic to attempt to protect the shallow aquifer because it is already deteriorated by human activities. However, it will be prudent to identify those activities which through effluents threaten groundwater quality overall. Only water from deep flow path is suitable for drinking water supply. Finally, effective urban groundwater management has to be active through an institutional framework involving each stakeholder with regulatory measures.

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5. Synthesis and final discussion

The study of rainwater, groundwater and more or less that of rivers on the basis of chemistry and stable isotopes allows us to conclude that the aquifers in the study area are recharged by precipitation and the rivers by shallow groundwater. Rainwater infiltrates the soil, percolates into the vadose zone and reaches the saturated zone without evaporation.

By using the Penman-Grindley method, we estimated the water budget in Douala (Table 8).

Table 8: how rainwater is distributed on the soil surface at Douala.

Hydrological processes or components	Budget (in %) relative to rainwater
Groundwater recharge	27.2%
Actual evapotranspiration (E_A)	20.1%
Runoff	48.7%
Soil water storage	4%

As expected, the runoff consumes the greatest part of the water budget. Indeed Wohl et al (2012) reported that the humid tropics produce the greatest amount of runoff in the world. Flows of water on the soil are tightly bound to the amount of rainfall. The more the precipitation amount increases, the more the runoff becomes important. This greatest runoff must also be linked to urbanization phenomenon which tends to provoke a waterproofing of soils. However, in the hydromorphic soils of the valley floors, normally porous soils must become impermeable in the height of the rainy season when the groundwater rises to the surface so that, although runoff is significant, it is mistaken for overflowing groundwater following severe storms. This case have been mentioned for instance on the freely drained soils under savanna at the edge of the forest (central Ivory Coast, 1200 mm annual rainfall; Dubreuil 1985). It marks the dynamic character of water fluxes in humid tropics watersheds.

Concerning the evapotranspiration (E_A), the rate observed at Douala is very lower compared to that reported in Amazonia due to the presence of tropical rainforests. Indeed, it was estimated that 50% of the incident precipitation in this area is recycled as precipitation. (e.g. Shuttleworth et al. 1984; Shuttleworth 1988; Hodnett et al. 1995; Grace et al. 1995; Malhi et al. 2002; Vourlitis et al. 2002). The low rate of E_A at Douala can be attributed to the the absence of strong dry period as it exists in other West African areas. Douala undergoes a permanent influence of monsoon flow from the Atlantic Ocean. This case is rather similar to that of the Southeast Asian maritime environments which do not have phase-locked dry periods because their climate is the combined result of a summer monsoon from the Indian Ocean, a winter monsoon from the Pacific Ocean and South China Sea, and the Madden and Julian Oscillation (Kumagai et al. 2005).

Thus, according to these results from water balance analysis, the groundwater recharge is not mainly controlled by evapotranspiration (which is very limited by climatic conditions in this

hyper-humid area) but by the soil hydraulic conductivity. As a point of comparison, the groundwater recharge rate at Douala (~ 1000 mm/year) is one the highest in the world (Jasechko and Taylor 2015; Mohan et al. 2018). Regarding the results from water balance calculation and information from water stable isotopes, the relation between monthly rainfall and monthly groundwater recharge is not linear. The means by which subsurface stormflow is delivered to streams can be viewed as routing through the soil matrix (matrix flow), macropore flow and pipeflow. Moreover, as stable isotopes revealed a great mixing of water within the aquifer, we can hypothesize a connectivity of macropores and pipes in the downslope direction. More specifically, water stable isotopes helped to identify groundwater from different episodes. Thus “old” water represent the deeper flow path and recent water the shallower flow path which however consists of a mixing between shallower, intermediate and deep flow paths. Major ions chemistry show that groundwater mineralization increases from the recharge area to discharge zone in the estuary. This mineralization is mainly controlled by water-rocks interactions, groundwater residence time and dilution effect due to high rainfall amounts. The dilution effect tends to stabilize or to decrease the contents in chemical elements. However, the effects of human activities on aquifer are already visible. For instance, the maximum and median values of nitrates increase overtime and water from the identified shallower flow path present the highest TDS values suggesting an anthropogenic input.

Regarding this latter aspect and the dynamic character of the megapole Douala region, we carried out a study (Chapter V) in order to understand the impact of human activities on groundwater system. Since the human pressure involves an urbanization phenomenon and therefore land use changes/climate changes, we wanted to know how the hydrological components are/will be affected.

Chapter V

How global changes impact hydrological processes and especially groundwater resources in the humid region of Gulf of guinea and peculiarly in the megacity of Douala?

In the two previous chapters we have shown how the water molecule evolves from rainwater to aquifer and what are the processes controlling the groundwater flow and chemical contents. We have thus gained a relative comprehension of the dominant hydrological features of hydrological system on the hyper-humid areas such as Douala. In the present chapter, we aim to investigate how global environmental changes modify these processes, the intensity with which they take place and therefore how global changes affect transfers of water from one hydrological compartment to another.

Global changes can be defined as a set of changes that affect the earth system and are directly caused by human activities (Vitousek 1994). In the context of West African coast, global changes will consist in: increasing population, urbanization process, industrialization and economic development which contribute to accelerate climate changes and can be considered as the main drivers for an ever-increasing demand for water worldwide. This can lead, if groundwater abstraction exceeds its recharge for extensive areas and for a long time to an overexploitation and apersistent groundwater depletion can occur (Gleeson et al. 2010). The resulting lowering of groundwater levels can have devastating effects on natural streamflow, wetlands and their related ecosystems. Groundwater depletion in coastal areas may generate salty water intrusions that may contaminate aquifers for decades. However, unfortunately, as concluded by the Inter-governmental Panel on Climate Change (IPCC) in both their 3rd (2001) and 4th (2007) assessment reports: “*groundwater is the major source of drinking water across much of the world ... but there has been very little research on the potential effects of climate change*”. This chapter presents a review of the large-scale impacts of changing climate and anthropogenic land-use on MP groundwater resources, in terms of quantity and quality at a regional scale including other humid tropical megacities of the Western African coast. The chapter is dedicated to climatologists, hydrogeologists, hydrologists, and water managers to draw attention to insights concerning human-induced changes on tropical hydrology in Africa. We firstly present an overview of socio-environmental issues in West African coast or gulf of guinea, and then the impact of urbanization on groundwater and finally we review the potential effects of climate changes in the study area.

1. West African coast: key socio-environmental problems

Weak access to safe drinking water

Despite the fact that the Western African coast is endowed with abundant water resources (important rainfall amount, big rivers, large lakes, vast wetlands and widespread groundwater), access to basic water supply is highly inadequate in this region. In urban areas, it is estimated that 43 percent of population does not have access to adequate water (Banerjee & Morella 2011). For instance, in Abidjan, 45.7% of households buy their water from retailers (Figure 43) and the same is true for Douala where only more than 40% of population are connected to the public network. Access to water is also a challenge in Lagos and Cotonou according to the fact that 80% and 20%, respectively, of local population use private hand-dug wells or boreholes (Nlend et al. 2018). Therefore, hand dug wells and boreholes are by far the fastest-growing exploited source of water, thus underlying the widespread exploitation of aquifer in urban areas of the Western African coast.

Moreover, distribution of water by the public services is often the subject of inadvertent cuts which can last from minutes to days causing real inconveniences to populations.

At last, the poor access figures are likely to be compounded by an exponential population growth (at 5% per annum over the last 30 years at Douala for example) in the region.



Figure 43: water seller in Abidjan (Photo: N’Kongo 2018).

A non-existent or poorly managed sanitation system

Adequate sanitation is defined as any private or shared, but not public, facility that guarantees that waste is hygienically separated from human contact (JMP 2000). However, this is often not the case in urban areas of sub-Saharan Africa (SSA). According to JMP (2000), 37% of the world’s population with unimproved sanitation lives in SSA. In Accra (Ghana) for example, Mariwah et al (2017) reported that only 14% of the households are covered by

adequate sanitation system. Traditional pit latrines are by far the most common facility (Banerjee & Morella 2011). Households are equipped with latrines in 70% of cases in Douala (Ketchemen-Tandia 2011), 58.8% in Abidjan (UNICEF 2000), more than 45% in Lagos (Olajide 2010) and 40% in Cotonou (Ecoloodi 2015). Domestic waste is most often released at the surface while sanitation is absent in some settlements (Figure 44). Natural drains are often invaded by grass as well as indiscriminate waste disposals from industries and households (Figure 44). When they exist, sanitation networks are also poorly managed (Figure 44). These effluents observable at the surface of all the coastal large cities (Figure 44) in Western Africa represent serious potential sources of groundwater pollution and can explain why we have several cases of waterborne diseases in SSA (Lapworth et al. 2017).



Figure 44: Inadequate sanitation systems in some cities of the West African coast. “a)” correspond to Douala (photo: Ketchemen-Tandia 2011) “b)” and “c)” correspond to Abidjan (photos credit: M. Marteau 2019) and “d)” to Cotonou (photo: Ecoloodi 2015).

Indeed, due to this insalubrity and poor drinking water supply systems, several cases of cholera have been revealed for example in Douala in 2004 (Guevart et al. 2006) and 2012 (Ketchemen-Tandia and Banton 2012).

Waterborne sewerage systems are rare in Africa. Little more than half of the households with piped water also have flush toilets, which are often connected to septic tanks rather than to sewers. In the Western African coast, only Senegal does some of the utilities covering the largest cities provide universal sewerage coverage (Banerjee & Morella 2011).

Furthermore, the sanitation sector is still institutionally fragmented in all the cities mentioned above between the central government, the ministries, national water companies, cities authorities and municipalities. This does not contribute to coordinate actions.

Air, soil and water pollution

Poor sanitation networks and uncontrolled urbanization lead to environmental pollution as streams and soils are generally invaded by effluents or solid waste. Quality of shallow groundwater is thus generally affected by contaminants. Moreover, emissions from vehicles, industrial processes, liquid and solid waste, pesticides and chemical fertilizers for agricultural and domestic purposes release toxic substances into the air and return obviously into the soils and waterbodies thereby affecting aquatic systems in the environment.

Air pollution in fast-growing West African cities is reaching dangerous levels (Kuo 2015) but the worst part, according to Knippertz et al (2015), is that we almost know nothing about the pollutants emerging from these new urban centers and their impact on weather systems, on agriculture, and more generally on public health. There's little or no monitoring of pollution and no emissions inventories while for instance, as much as 94% of Nigeria's population is exposed to levels of air pollution that exceed what the World Health Organization deems as safe (Kuo 2015). The sources of pollution are many: car exhaust, wood burning, garbage burning, cooking indoors with fuel stoves, the use of diesel electricity generators, petrochemical plants, etc. This results to a release of carbon dioxide into the atmosphere, which is a toxic pollutant. Knippertz et al (2015) found that these emissions may even be altering the climate along the coast of West Africa, leading to changes in the clouds and so potentially to rainfall with devastating effects (scientists have previously linked aerosols to changing rainfall patterns in Asia and the Atlantic Ocean; e.g., Lau et al. 2006, Booth et al. 2012). Indeed, anthropogenic emissions of aerosols and other gases have grown quickly and are projected to double and possibly quadruple by 2030 in cities along the Guinean Coast (Knippertz et al. 2015).

Loss of wildlife habitats and biodiversity

Water pollution is one of the prime reasons for the loss of aquatic genetic diversity. On the other hand, forest areas such as mangroves also decrease due to expanding urban agriculture and conversion into farmlands. Nowadays, in several Sub-Saharan African countries, the rate of deforestation exceeded the global annual average of 0.8% (Agyei 1997). The region, located primarily near the equator on the western side of the continent extending from the Congo River basin along the Ivory Coast, is the most concerned (Werth and Avissar 2005). Deforestation for agricultural expansion is expected to lead an increase in levels of runoff and greater sediment loads in rivers systems, with subsequent impacts on freshwater species and habitats. Finally, it is worthwhile noting that as population grows in large coastal cities, there is an urban sprawl and therefore natural spaces decrease while the number of buildings increases.

Coastal erosion

Coastal erosion is the weathering of a way of land or the removal of beach or dune sediments by wave action, tidal or wave currents. According to [Hinrichsen \(1990\)](#), it is probably the most serious environmental problem facing Western African coast. This phenomenon is particularly more pronounced in Cote d'Ivoire, Ghana, Togo, Benin and Nigeria. It has been linked to climate change, and in turn to rising sea levels ([IRIN 2019](#)). In Benin for instance, remote sensing and maps of eastern Cotonou, show that the shoreline has receded over 400 meters from 1963 to 2000 ([IRIN 2019](#)). The effects of coastal erosion are numerous: vegetation at the shore of the coast is washed away, reduction of the beach size, destruction of the habitat of some organisms, etc.

Table 9 below outlines the major threats by broad ecosystem type. We see globally the influence of land use and climate changes. Poverty, rapid increase in population and urbanization magnify the trends of some of problems. Unfortunately, continuous monitoring mechanisms of water resources are not in place.

Table 9: direct threats on Western African coastal ecosystems

Natural Ecosystem	Threats
Tropical moist forests	<ul style="list-style-type: none"> • Deforestation for agriculture and plantation tree crops • Urbanization • Climate change
Groundwater, rivers and wetlands	<ul style="list-style-type: none"> • Pollution of water resources (e.g. effluent from households, agriculture, dumping of industrial and municipal solid and liquid waste in watersheds and in sources) • Over-exploitation of groundwater • Conversion of wetlands/swamps in human habitats • Climate change • Invasive species (e.g. water hyacinth proliferation)
Coastal estuaries and mangroves	<ul style="list-style-type: none"> • Infrastructure development (e.g. building of roads, houses and on-shore oil and gas infrastructure) • Pollution (dumping of untreated sewage and other liquid and solid waste) • Climate change (especially as it impacts flows and flushes of fresh water) • Over-exploitation of mangrove resources (e.g. harvesting of mangroves for firewood and over-fishing using fine mesh nets) • Beach sand mining (e.g. extraction of sand for the building industry)

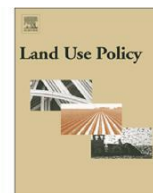
2. Article: Impact of urbanization on groundwater resources



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The impact of urban development on aquifers in large coastal cities of West Africa: Present status and future challenges



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ABSTRACT

This paper investigates the coastal cities of Abidjan, Cotonou, Lagos and Douala in West Africa. Published data on these areas were aggregated in order to compare the urban development of some African huge cities and assess their impacts on groundwater. Those urban centers have experienced an exponential demographic expansion since the 1950s, with increased population densities and a geographical coverage expansion as well. The Continental Terminal aquifer, major groundwater resource tapped in this region by the national water companies and local populations, shows a continuous downward trend in piezometric levels. Concerning water quality, the evolution up to the current state (saline intrusion, nitrate pollution) and the natural geochemical process (dilution, redox reactions) affecting the aquifer have been highlighted. The results confirm the urgent need to consider groundwater development relatively to demographic and economic growth. Some management approaches have been proposed including monitoring of contamination, protection of the resource and the use of shallow large-diameter wells, which have proved to be less saline and more sustainable than deeper small-diameter boreholes. The results and discussion of this paper have provided a considerable new insight of West African coastal cities. This will help stakeholders involved in local development to face the urban pressure.

1. Introduction

Millions of big cities inhabitants around the world depend on groundwater for drinking water supplies either as exclusive public water supply or as alternatives for the limited surface water resources. However, it is increasingly reported that aquifers in urban areas are deteriorating in water quality (Chilton, 2005; Morris et al., 2003; Lerner, 2014; Costa et al., 2016). There is no predefined strategy, set to handle the growing problem. Nowadays, more people in the world live in urban areas (54% in 2014) than in rural areas (United Nations, 2014). This percentage was 30% in 1950 and is expected to reach 66% by 2050, with nearly 90% of the increase to take place in the urban areas of Africa and Asia (Floater et al., 2014; United Nations, 2014). As the world continues to urbanize, sustainable development challenges will be increasingly concentrated in cities, particularly in the lower-middle-income countries where the pace of urbanization is the fastest (United Nations, 2014). African cities particularly constitute a good example of this evolution. However, the incomes are much lower in these cities than

in other developing regions with similar urbanization levels. Also the capital investment in these cities' infrastructure, industrial, and commercial structures remains relatively low (Vinay et al., 2017) and key population facilities such as water supply, sanitation and drainage networks come later in this urbanization process. One region that combines all of these features is the Gulf of Guinea.

The Gulf of Guinea, widely considered as one of the most dynamic regions in sub-Saharan Africa in the global energy sector, is of critical importance for the economic development of much of the Atlantic Coast of Africa (Jenkins and Edwards 2006). This dynamism is demographically characterized by a growth of rare magnitude (on average 2.2–4% per year over the last three decades) expressed by a large movement of people from the countryside to the coastal cities due to economic reasons. Given their geographical position, cities of the Guinean coast ensure the transit of goods from the rest of the world to several Sahelo-Saharan countries (e.g., Burkina Faso, Mali, etc.) and fuel the growth of landlocked countries (e.g., Central African Republic, Chad, etc.).

The coastal cities of the Gulf of Guinea region experiences a humid tropical climate characterized by high rainfall, mostly higher than other parts of Africa, responsible for large surface water masses. Braune and Xu (2009) show that in terms of the present conditions, the hydrologic function and distribution of groundwater are also highly correlated with rainfall patterns in this region. However, groundwater resources are not only influenced by the precipitation height but they also vary substantially according to the geological features of the area, which mainly comprise crystalline basement rock (40%), consolidated sedi-mentary rocks (32%), unconsolidated sediments (22%), and volcanic rocks (6%) (Mac Donald and Davies, 2000).

Unconsolidated and consolidated sediments found in the study area contain substantial shallow groundwater (often in unconfined condi-tions) that is commonly used by the local population as the primary resource for water supply. Despite the apparent abundance of water in this humid tropical region of Africa, access to potable water by the population remains difficult, paradoxically making this area looking like a damp desert. It was estimated in 2014 that more than 1/3 of Abidjan and Cotonou populations did not have access to good water quality (AFRIMAG, 2014). These statistics are even more alarming in Lagos and Douala where this proportion reaches more than half of the population (INSIGHT BDS, 2013). Hydric diseases linked to preferential uses of surface or shallow groundwater are often declared (UNICEF d'Ivoire, 2007; Odoulami, 2009; Guevart et al., 2006). Thus, deep aquifers appear to be of a major interest for their protection from sur-face pollution and their natural protection that make them easier for treatment processes. An example of this increasing interest on this groundwater potential, the number of boreholes in Douala, accounting for 300 in 1996, has been multiplied by ten during the last decade (Ketchemen-Tandia 2011).

In addition, urbanization has hydrological impacts including in-creases in peak runoffs (caused by increased urban fringe imperme-ability), deterioration in the quality of both surface and groundwater resources, and changes in frequency and volume of groundwater re-charge (Foster, 1999). Added to these features, the increase in the number of inhabitants leads to an over-exploitation that in turn en-hances the vulnerability of groundwater. Inadequately controlled groundwater exploitation is well known to result in an increase in the scarcity of water resources, which may largely contribute to the esca-lation of water supplies costs (Morris et al., 1997) and lead to potential conflicts (Foster et al., 2003). Moreover, over-exploitation can generate

quality problems due to the contamination of good quality groundwater masses by seawater in coastal cities, or by superficial aquifers and/or surface waters suffering from an anthropogenic pollution.

This paper focuses on the impacts of urban development on aquifers in coastal large cities of West Africa located around the Gulf of Guinea: Abidjan, Cotonou Lagos and Douala (Fig. 1). All of these cities are economic capitals occupying a strategic position in the sub-regions of western and central Africa, concentrating more than 2/3 of national industrial production and the greatest part of the population of Côte d'Ivoire, Benin, Nigeria and Cameroon, respectively (Kouakou Yao et al., 2010; Mairie de Cotonou, 2008; Opoko and Oluwatayo, INS, 2011). These cities have been selected in this work according to their fast urbanization and wide range of available data (environmental, societal and hydrogeochemical).

The objective of this paper is to describe the importance of groundwater in the water supply of these four major cities in sub-Saharan Africa and to examine the impact of urbanization on quality and quantity of groundwater. The history of urban development, cur-rent groundwater management practices, policy implications and future challenges are also discussed as well as the evolution of climatic parameters and their possible impact on the resource.

2. Studies areas – overview

2.1. Location, climatology and hydrography

The Gulf of Guinea is the north easternmost part of the tropical Atlantic between Cape Lopez in Gabon and Cape Palmas in Liberia. The location of the four studied sites with mean monthly precipitation is illustrated in Fig. 1.

Although some differences in environment resources and economy, those four cities present some similarities. Indeed, the mean annual temperatures are the same with a value of about 27 °C. The moisture inputs in the region originate directly from the Atlantic Ocean. Recordings of rainfall amounts over more than five decades vary from 1 330 mm in Cotonou to ~ 4000 mm in Douala, with intermediate values of 1 920 mm in Abidjan and 1 515 mm in Lagos. The precipitation decreases in the west-northwest direction from the Cameroon coast to Accra (semi-arid coast) then increases to Liberia, where rainfall reach 5000 m/year in Free Town.

The regional hydrography is shaped by many rivers flowing to the

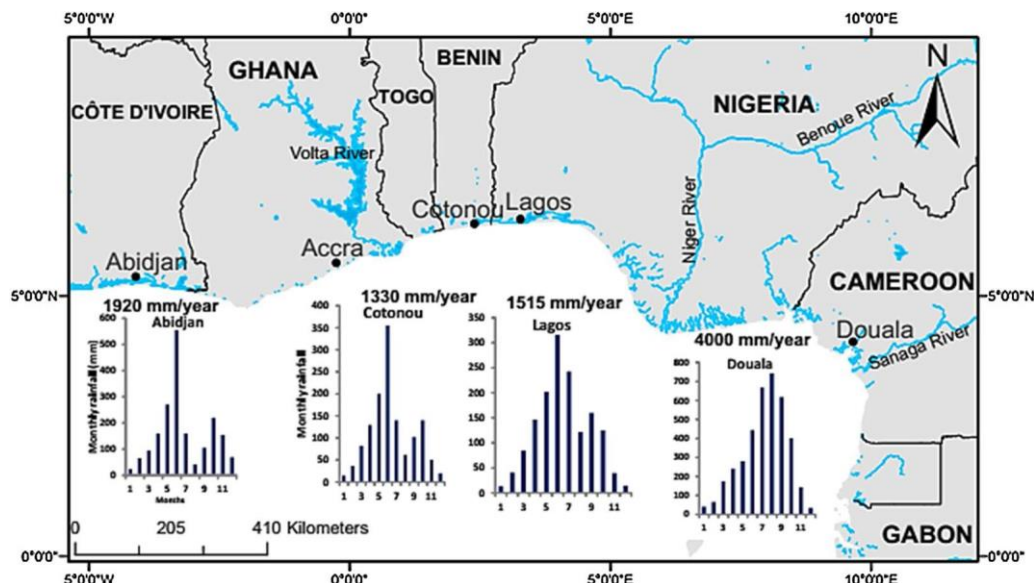


Fig. 1. Location of the four study sites (Abidjan, Cotonou, Lagos, and Douala) in the Guinean coastal area. The monthly rainfall distribution of each site is also presented.

Atlantic Ocean. From north to south, we distinguish Cavally River (crossing Liberia and Cote d'Ivoire), Sassandra River (Cote d'Ivoire), Bandama River (Cote d'Ivoire), Volta River (Ghana), Mono River (crossing Togo and Benin), Niger River (Crossing Sierra Leone, Mali, Niger and Nigeria) which is the most important river in Africa after Nile and Congo; Wouri and Sanaga Rivers (Cameroon), Ogoue River (Gabon). Furthermore, Abidjan, Cotonou, Lagos and Douala, the most important surface water are respectively: Ebrie lagoon (extends 140 km long and covers an area of 523 km²), Lake Nokoue (150 km² of surface area), Lagos lagoon (extends 50 km long and covers an area of 6355 km²) and Wouri River (160 km long, watershed area of 11,700 km² and discharge varying from 68 to 790 m³/s).

2.2. Geology and hydrogeology

The Gulf of Guinea coast corresponds to the largest West African coastal sedimentary basin. It is composed of a set of sub-basins generated by the opening of the Atlantic Ocean. The geological history of these basins starts with the dislocation of the super-continent Pangea in the Jurassic period (Moulin, 2003) and ends with the sedimentary deposits in the Pliocene-Quaternary period. These deposits have a monoclinical structure characterized by a growing differential subsidence towards the Atlantic Ocean (Regnault 1986; d'Almeida et al., 2016).

Four major aquifers can be distinguished within this large sedimentary basin:

- The Lower Cretaceous (LC) formation, mainly constituted of sands and conglomerate sandstones, appears in Côte d'Ivoire, Nigeria and Cameroon.
- The Maastrichtian to Paleocene sands aquifer observed in Côte d'Ivoire, Benin and Douala sub-basins.
- The Mio-Pliocene to Pleistocene deposits which are referred to herein as Continental Terminal (CT), mainly constituted of sands, clays and indurate lateritic layers. It is a multi-layered aquifer, which appears in Abidjan, Benin, Lagos and Douala.
- The shallow sediments from the Pleistocene to the present distinguished in Abidjan, Cotonou, Lagos and Douala.

Due to its relevance as drinking water supply and its use by public authorities of Abidjan, Cotonou, Lagos and Douala regions, only the CT aquifer has been considered in this study. Table 1 summarizes the hydrodynamic data of CT aquifer in the different sub-basins.

2.3. Socio-environmental aspects

Abidjan, Cotonou, Lagos and Douala account for ~23 million people which represent ~2% of the African population (United Nations, 2014). Despite the urban development prevailing in those territories, access to water and sanitation remains a challenge for public authorities. In 2005, the FAO, following an investigation, reported that the average water availability was 4853 m³ yr⁻¹. This value is above the physical limit of water scarcity of about 1076 m³ yr⁻¹ and below the world average which is approximately 8500 m³ yr⁻¹ (Droogers et al., 2012). The major constraints associated with urban water supply

in the region have been reported by Adelana et al. (2004), Ketchemen-Tandia (2011), WHO (2013), Balogun et al. (2017). These includes:

- An insufficient funding: funds for operation, maintenance and network expansion are not always available. As a result, water supply facilities are poorly kept up, thus creating a situation that accelerates deterioration.
- Water leakages: most of the urban water distribution systems are heavily leaking (up to 50%), primarily due to outdated equipment.
- Inadequate working tools and equipment: Water authorities do not have sufficient funds to purchase enough tools and equipment for the daily operation and maintenance of water facilities. This contributes to poor work output and therefore reduced system efficiency
- Limited production and distribution capacity: Inadequate pumping facilities, conveyance, storage and distribution capabilities hamper the ability to meet water needs relative to the fast population increase within urban centers.

The management of pumping stations and the distribution systems of water is the responsibility of public enterprises: SODECI (Société de Distribution d'Eau de la Cote d'Ivoire), SONEB (Société Nationale des Eaux du Bénin), LWC (Lagos Water Corporation) and the Camwater (Cameroon Water Utilities) partnership. In Abidjan and Cotonou, water supply is exclusively performed by pumping the CT aquifer. In Lagos, 17% of the water used by the LWC derives from the CT coastal plain sands; the rest is supplied by surface water (Adiyan, Iju, and Ishashi Rivers). In Douala, the CAMWATER-CDE partnership provides water coming from rivers (51.1%), Paleocene sands (22.2%) and CT (26.7%). Only 20% of the population in Lagos is connected to the LWC while more people (80%) depend on groundwater through the use of private hand dug well/boreholes (Erinosho, 2013). In Douala, Abidjan and Cotonou, the percentage of population connected to the public network is respectively estimated to 40% (INSIGHT BDS, 2013), 70% (Koffi et al., 2016) and 80% (SONEB 2013). To the individual consumers, industries and administrations consumption have to be considered. The whole uses represent about 93.3% and the losses amount to 6.4%.

In all the studied cities, sanitation system is very poor. Natural drains which constitute the first network may be invaded by grass as well as indiscriminate waste disposals. Households are equipped with latrines in 70% of cases in Douala (Ketchemen-Tandia 2011), 58.8% in Abidjan (UNICEF 2000), more than 45% in Lagos (Olajide, 2010) and 40% in Cotonou (Ecoloodi, 2015). Industrial water waste is most often discharged into the primary or secondary networks described above. Therefore, these effluents are potential sources of water pollution in shallow wells and streams.

3. Datasets, methods and analysis

Data were collected from published articles, online journals, public and unpublished reports. Given the various sources, priority was given to data from scientific articles and technical reports. We then compiled data for each city, followed by statistical processing and comparison between respective datasets. Data collected comprised socio-

Table 1. Hydrodynamics data of CT aquifer in the coastal basin of West Africa.

Location	Lithology	Thickness (m)	Transmissivity (m ² /s)	Permeability (m/s)	Static level (m)	Storage (%)	Discharge (m ³ /h)	References
Abidjan	sands/sandstones	70 to 200	30.10 ⁻² –20.10 ⁻²	10 ⁻⁶ –10 ⁻³	5–80	0,05–0,2	7,2–338	Jourda (1987)
Cotonou	sands/ conglomerates	60 to 200	2.10 ⁻⁴ –1,01.10 ⁻²	10 ⁻⁴ –10 ⁻²	< 15–> 50	2.10 ⁻⁴ –1,92.10 ⁻²	20–300	Bouzid (1967), Boukari et al. (1996)
Lagos	sands	10 to 280	1,05.10 ⁻² –11,3.10 ⁻²	7.10 ⁻⁶ –1,7.10 ⁻⁴	4,6–71	1,07.10 ⁻⁴ –4,5.10 ⁻⁴	24,8–336	Longe (2011)
Douala	sands	0 to 220	4,6.10 ⁻⁴ –6,8.10 ⁻²	2,6.10 ⁻⁵ –0,195	0–41		1–250	Ketchemen-Tandia (2011)

demographic, socio-environmental, climatic settings, hydrodynamic and geochemical data of groundwater.

Demographic data cover a period of almost a century. The preferred source for this information is the national population census for each country concern (e.g. N'Guessan et al., 2010; INSAE, 2016 for Cotonou; National Population Census, 1997, 2017; National Bureau of Statistics, 2007 for Lagos; BUCREP, 2005 for Douala). Data from projections of miscellaneous studies were used when the last census or data gap between censuses was too old (Duchemin and Trouchaud, 1969; Mainet, 1985, 2005; Antoine et al., 1987; Guingido Gaye 1992; UNCHS, 1996; Aniah, 2001; Global Archiconsult, 2008; United Nations, 2008; N'Guessan et al., 2010; George, 2010; Ilesanmi 2010; INSC 2010; Yengoh et al., 2016). Projections calculations were made using the equation given by Keyfitz and Caswell (2005):

$$A = P(1 + r)^n \quad (1)$$

where A = Forecasted future population in n years' time; P = Baseline population of 2015; r = annual population growth rate; n = number of years from the baseline population year to the future population year, which was 5, 15, 25 and 35 years for 2020, 2030, 2040 and 2050 respectively. Three growth rates were used: 2.2% lower growth rate (LGR) (Global Archiconsult, 2008; Pitts, 2012), 3.7% medium growth rate (MGR) given by N'Guessan et al. (2010), INSC (2010), Lagos Water Corporation (2016), 5.6% high-growth rate (HGR) (George, 2010; United Nations Centre for Human Settlements, 1996). Nonetheless, Balogun et al. (2017) have reported a growth rate of 8% for Lagos. However, regarding the consistency of the interpretations concerning the four cities, we will use LGR, MGR and HGR defined above. It is assumed that growth rate remains constant over the projected time-frame.

Socio-environmental data used in this work are linked to the extension of respective study sites, changes of land uses and water production. These data, unreleased for the concerned cities, have been compiled based on several reports and articles (Saint-Vil, 1983; Odoulami, 2009; Meva'a Abomo, 2006; Oteri and Ayeni, 2016; Odoulami, 2009; Ayeni et al., 2016; Silliman et al., 2010; SODECL, 2011; Oyegoke et al., 2012; Camwater, 2014; Ettien Boni, 2010; Koffi et al., 2016). To see the groundwater consumption evolution in the four areas, calculations for Lagos and Douala took into account the percentage of groundwater used in production and the increasing number of subscribers in the different public network. The gaps in the data timeline were filled by considering that the consumption of a city dweller in less developed countries is estimated at about 1200 m³/year (Droogers et al., 2012).

Rainfall amount (provided by meteorological stations), piezometrics levels, concentrations in major ions of groundwater were also collected for each city.

4. Results and discussion

4.1. Climate change

Fig. 2 presents long-term annual variability of rainfall for the four sites with a trend line indicating a decrease of 112 mm/10 years in Abidjan (4 decades), 41 mm/10 years in Lagos (3 decades) and 137 mm/10 years in Douala (5 decades). The Intergovernmental Panel on Climate Change report (2007) has confirmed this important diminution of rainfall in Douala. Climate change in this equatorial area leads to a drop in the precipitation accompanied by a proliferation of extreme events that may cause floods. Cotonou exposes different feature with an upward trend of 89 mm/10 years (over more than 30 years). Amoussou et al. (2016) confirmed this tendency and published an increase of 7% from 1951 to 2010. This rainfall increase has also been observed in Accra by Nyatuame et al. (2014) while in Lomé (Togo), Adewi et al. (2010) observe no trend in precipitation over more

than 4 decades. Thus in the semi-arid Guinean coast, evolution of an-annual rainfall amount shows a different scheme from that observed in coastal humid zones.

On the other hand, annual average temperature has increased by +1.64 °C in Abidjan (Ringard et al., 2004) and +1.8 °C in Cotonou (Roko, 2007), between 1950 and 2010. In Douala, data reveal an increase trend of about 0.17 °C/10 years over the last 45 years. This value is close to that observed in Accra, found by Amoussou et al. (2016) in Benin coast, and can be used to characterize the average annual temperature change in the study area. This significant increase in temperature in the Gulf of Guinea may result in a high potential evapo-transpiration, which is detrimental to water resources.

4.2. Socio-economical changes

4.2.1. Demographic changes

The analyses showed that the population has grown rapidly at different intensities in each site (Fig. 3). Africa presents a growth in population rate of 2.7% per year, which is above the world average of 1% per year. Lagos, Abidjan and Douala show higher rates than these numbers. Lagos is the fastest-growing city in the world, with an annual growth rate varying from 4.4 to 8% (UNCHS, 1996). In Abidjan, the number of inhabitants over-doubled during the last 25 years with a growing rate varying from 3.7 to 5.6% per year over the past 40 years. This increase in population made Abidjan to be the second most populous French-speaking city after Kinshasa. Douala displays a growth rate estimated at 5% over the last 30 years, above the national rate, estimated at 2.8% (INSC, 2010). In this city, the population has over-quadrupled during the last 25 years' period. At last, with a population smaller than 1 million, the demographic growth rate of Cotonou is of 2.2%. However, this rate, used to be 4.05% around 1979–1991 before dropping and plateauing (or became stable) (Fig. 3). Despite displaying the lowest growth rate of the study area, Cotonou population increased by 65% over the last 24 years from 1991 to 2015.

The results from projection calculations are alarming (Fig. 3B). Concerning Lagos, the projection towards 2030 is in accordance with the growth rate of 3.7% found by Opoko and Oluwatayo (2014). The projected result towards 2020 is also similar to the one obtained by Nwokoro and Dekolo (2012) with the LGR scenario. At a HGR, population of Lagos will exceed 50 million. We have decided not to represent it on this graph especially for stylistic issues. Values obtained for Douala are similar to those of Institut National de la Statistique Cameroun (2010). Thus, whatever the considered scenario, Abidjan and Douala will certainly join Lagos as having Megacity status (more than 10 million inhabitants; UNCHS, 1996) after 2050. While it also creates many opportunities for Governments in the region and private sector (in terms of businesses and investments), this kind of population size constitutes a huge challenge. Therefore, strategic planning should be necessary adopted to meet the state's infrastructural needs, water for instance, in order to sustain the quality of life and the availability of the resource.

4.2.2. Urbanization rates and land use changes

The city's spatial extent follows the demographic progression. It was in the early 1960s, during the period of independence, that towns began to expand in the region. In Cotonou and Abidjan, expansions move from the top of the coastal sand cordons, marsh and lowland areas to inland while Douala and Lagos cities increase from the estuary and island to the mainland. Following such rapid urban expansion and demography, the density of population has also increased in the study area (Table 2). Hence, urban and peri-urban agricultural lands are under intense pressure and a reduction of agricultural areas in favor of housing is affecting most of the major cities in this part of Africa. From 2004 to 2007, agricultural fields have reduced of 41% in Abidjan. This decrease also involves Lagos, where a drop of 5% of the cultivated farmland is observed. This

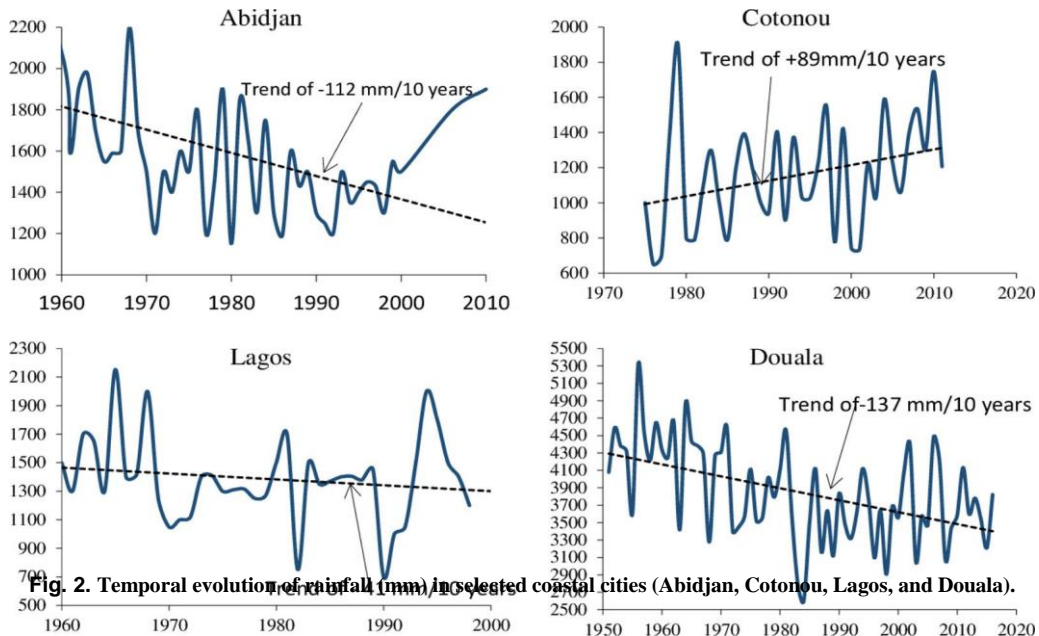


Fig. 2. Temporal evolution of rainfall (mm) in selected coastal cities (Abidjan, Cotonou, Lagos, and Douala).

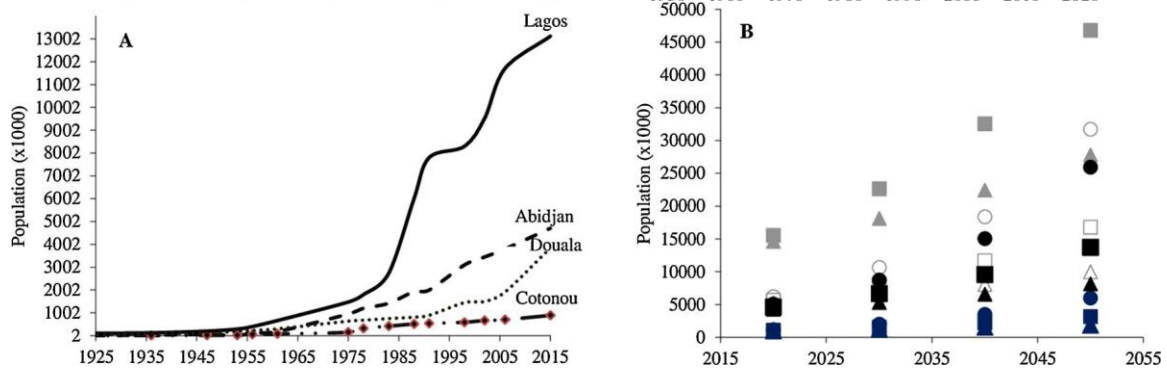


Fig. 3. Evolution of demography in four major cities of the Gulf of Guinea region: Abidjan, Cotonou, Lagos and Douala. A) Population growth observed in almost one century; B) Projected population. The grey, white, black and blue colors represent Lagos, Abidjan, Douala and Cotonou respectively. The LGR, MGR and HGR correspond to triangle, square and circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2. Urban extension and evolution of population density in the study sectors.

Cities	Years	Area (km ²)	Density (inhabitants/km ²)	References
Abidjan	< 1960	167	350	Agbo (1985), Kouakou
	1960–1970	350	1475	Yao et al. (2010)
	1970–1990	–	–	
	1990–Present	422	> 14,000	
Cotonou	1960	9,5	1000	Mairie de Cotonou (2008)
	2015	79	11,276	
Lagos	2011	999	12,095	Nwokoro and Dekolo (2012), Opoko and Oluwatoyo (2014), Ayeni et al. (2016), National Population Commission Nigeria (2017)
	2016	1183	15,854	
	Present	–	–	
Douala	1980	65	> 50	Mainet (1981), Olinga (2012), Yengoh et al. (2016)
	2000	189	200	
	Present	300	2800	

regressive dynamic also affects the forest. In 1955, the dense forest in Abidjan covered approximately 5462 ha and the secondary forest occupied an area of 9220 ha. By 2015, less than 3000 ha of native forest and 400 ha of forest

plantations remain. Forest lands in Lagos have reduced by approximately 20% from 1990 to 2008 in order to accommodate for the rapid growth of urban developments. According to Douala City Council, about 16,300 ha of land have been urbanized since the 1960s, averaging 326 ha per year; this leads the reduction of the mangrove space. Approximately 64% of the urban area is occupied by dwellings, of which approximately 24% are unplanned (Yengoh et al., 2016). Global land use changes are also linked to water bodies and marshy lands. The mangroves destruction, the scarcity of green space and the lack of urban forest contribute to the increase in temperatures as observed above.

4.2.3. Evolution of water uses and demand

The demographic boom has resulted in high increase of water production (Fig. 4) and the number of subscribers to the water supply companies. For example, the number of subscribers to the SODECI has increased from 3947 (1960) to 29,902 (1972) (Tia and Seka, 2015). Based on the current growth rate, Lagos needs in water is expected to increase to about 2,418,900 m³/day in 2026. In Douala, groundwater has been progressively required since the beginning of the 1980s to deal with the growing demand.

Table 3 presents the terms and results of the water balance of the Miocene sands of Abidjan, Cotonou, and Douala.

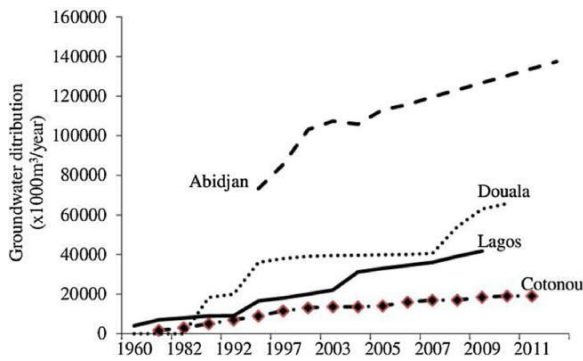


Fig. 4. Evolution of national groundwater distribution in Abidjan, Cotonou, Lagos and Douala.

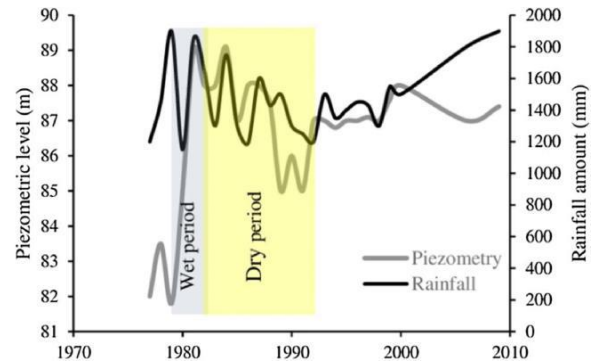


Fig. 5. Annual evolution of the piezometric level in CT aquifer, Filtissac pie-zometer, center of Abidjan. Data are coming from Saley et al., 2009

Evapotranspiration is obtained from the water balance calculated by the Thornthwaite method. The runoff values were collected from the following previous works: Sighomnou (1983) in Abidjan, Le Barbé et al. (1993) in Cotonou (Godomey); and Feumba et al. (2011) in Douala. Unfortunately, no datum could be obtained in the case of Lagos. The effective infiltration was then determined according to the principle of the hydrological balance whose simplified equation is written as follows:

$$P = RET + R + I \quad (2)$$

Where P is precipitation, RET, the real evapotranspiration, R, the runoff and I, the infiltration. Pumping flow rates were converted in height of water (mm) over the area of each city (Yao et al., 2015).

Drinking water supply is the main cause of water abstraction with more than 90% of all water pumped in Abidjan and Cotonou and almost 75% in Douala. Industrial requirements constitute the second type of groundwater use.

RA: Rainfall Amount; Rf: Runoff; RET: Real Evapotranspiration, SW: surface water, EI: Effective Infiltration.

In the case of Cotonou, input and output data for the Lake Nokoue (SW) are coming from Boukari et al. (1996).

Sometimes, this exploitation of groundwater is higher than the potential recharge, as in the case of Cotonou, where the balance is negative. Runoff is particularly high in Douala compared to the other sites. This could be the consequence of urbanization (increase of building) which generally leads to the waterproofing of soils, a decrease in recharge to aquifers and causes a leaching of pollutants from urban and industrial wastes disposed on the land surface (Foster, 1999; Goldshleger et al., 2012).

4.3. Groundwater response

It is well known that groundwater is a vulnerable and fragile resource. Over the past few decades, the field of urban hydrology has gained a better understanding of some impacts of urban development on aquifers. Despite this, in humid tropical areas, the response of aquifer system to urbanization—as described above—is complex and

our knowledge still limited comparing to temperate or arid regions. This section assesses degradation of CT aquifer in terms of quantity and quality. The quantity evolution of the aquifer is characterized by using the water table records existing in the study region. Chemical indicators of groundwater contamination will allow us to evaluate the impact of urbanization on groundwater quality. This part of the paper provides insights regarding pollution sources, risk factors and natural geochemical processes prevailing at each site.

4.3.1. Decrease in the resource?

All groundwater exploitation results in some decline in aquifer water level (water table or piezometric surface) over a certain area. Hence, if overall abstraction from part or all of an aquifer system exceeds the long-term average rate of replenishment, there will be a continuous decline in water level, overdraft of aquifer storage and consumption of aquifer reserves.

Unfortunately, there is no groundwater quantity monitoring in the Gulf of Guinea region. Thus piezometric data are scarce, neither measured nor accessible. As an example, piezometric evolution of the CT aquifer in Abidjan has been reconstructed from 1976 to 2009 (Saley et al., 2009) in this paper. Fig. 5 shows an increase in piezometric level from the late 1970s to the early 1980s and then a significant decline until 1991. These two periods correspond respectively to the large wet and dry periods affecting the study region. From 1997 (H = 87.5 m) to 2008 (H = 86.9 m), another decline is observed. Nevertheless some short and weak recharge periods can be noticed (Fig. 6). This recent decline in groundwater level is not related to the apparent resumption of precipitation in this area and indicate an influence of intensive and uncontrolled pumping on the aquifer.

Onwuka and Adekile (1986) studied the coastal plain sands aquifer in Lagos and revealed a decrease in the piezometric levels, especially in Ikeja (the densely populated industrial center of Lagos). This decreasing water level at Ikeja and in some other parts of the Lagos metropolis is linked to over-abstraction. The water level is declining, as the rate of abstraction is greater than the rate of recharge (even though Lagos has a high annual rainfall amount).

Table 3. Water balance for Miocene-Pliocene sands in Abidjan, Cotonou and Douala.

	Inputs (mm)			Outputs (mm)						
	RA (mm)	RET (mm)	Rf (mm)	EI (mm)	SW	Extraction from public network	Private wells	Industries	SW	Balance
Abidjan	1920	1000	230	690	–	279.5	83.9	20	–	306.6
Cotonou	1330	829.8	200	283.2	63.6	156.6	218.5	–	14.2	–25.5
Douala	3846.7	1300	1875	671.7	–	160.7	140.5	160	–	210.5
Lagos	1515	–	–	–	–	–	–	–	–	–

RA: Rainfall Amount; Rf: Runoff; RET: Real Evapotranspiration, SW: surface water, EI: Effective Infiltration. In the case of Cotonou, input and output data for the Lake Nokoue (SW) are coming from Boukari et al (2000).

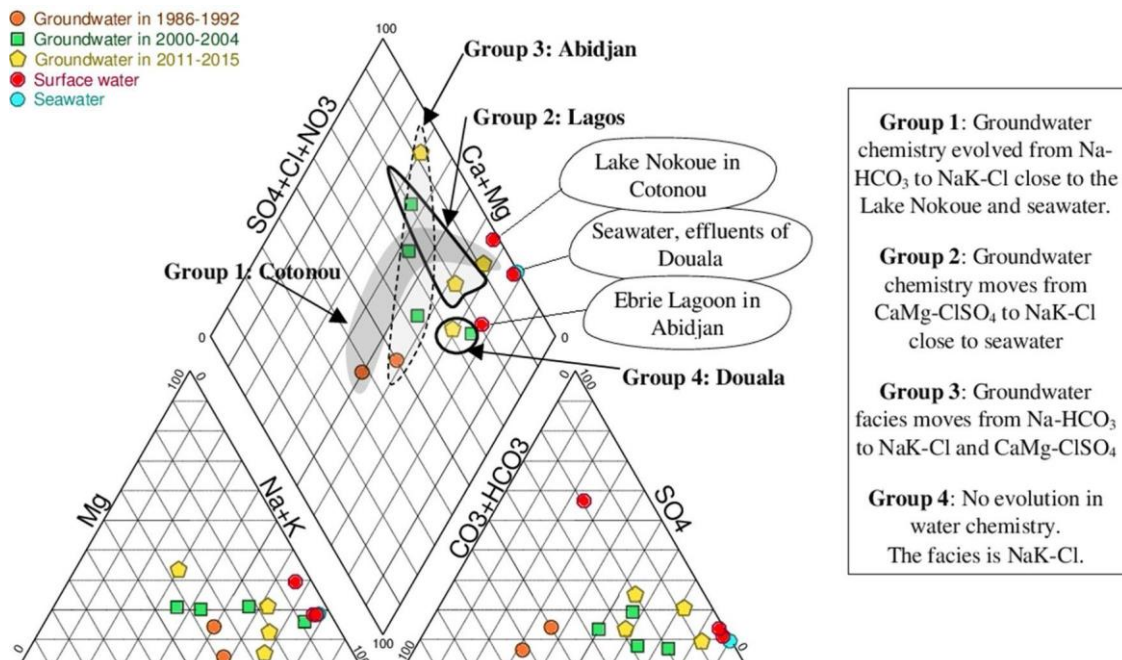


Fig. 6. Piper diagram showing chemical evolution of CT aquifer through several years in Abidjan, Cotonou, Lagos and Douala. Chemical data for Abidjan coming from Jourda (1987) ($n > 100$), Ahoussi et al. (2011) ($n = 30$) and Yapo et al. (2010) ($n = 25$). Those for Cotonou are the results of Maliki (1993) ($n = 159$), Totin et al. (2010) and Alassane et al. (2015) ($n = 95$). In the case of Lagos, data coming from the published works of Seifu (2007) and Akoteyon (2013). Chemical data used for Douala are the results of Ketchemen-Tandia (2011) ($n = 452$), Takem et al. (2010) ($n = 78$) and Wirmvem et al. (2017) ($n = 52$). Sample of seawater (Hem, 1970), Ebrie Lagoon (Jourda, 1987), lake Nokoue (Alassane et al. (2015) and Effluents of Douala (Fantong et al., 2016) are plotted for comparison

This decline in aquifer water level often results in some areas, in an irreversible side effect, which involves the encroachment of saline water (if coastal hydraulic gradients are reduced or reversed). This effect is quasi-irreversible, because the saline water invades macropores and diffuses rapidly into the porous aquifer matrix under the prevailing high salinity gradients and later takes decades to be flushed out even after the flow of freshwater has been re-established (Foster et al., 2003).

4.3.2. Contamination by seawater intrusion

The increase in the volume of water pumped, the decrease in pie-zometric surface as observed in Abidjan and reported in Lagos (even though a high rainfall amounts), and particularly the negative balance recorded in Cotonou (Table 4) encourage us to consider the possibility of a marine intrusion into the focused cities in this study. The Piper diagram (Fig. 6) clearly shows a temporal evolution of groundwater chemistry. Cotonou and Lagos move from HCO₃-Na to NaK-Cl and ClSO₄NO₃-CaMg to NaCl water types respectively, in the seawater field (Fig. 6). They present the strongest mineralized waters in the region. As described above, the Cl⁻ content (primary indicator of seawater

intrusion into the coastal groundwater system) increases in Cotonou from 23.6 (in 1991) to 160 mg/l (in 2011). This increase is parallel to sulphate concentrations evolution from 6.4 to 25.7 mg/l over the same period (Fig. 7). The case of Lagos is similar but the sulphate contents are more important (~100 mg/l). Alassane et al. (2015) have shown that Cl⁻ are well correlated with Na⁺ ($r^2 = 0.95$) and SO₄²⁻ ($r^2 = 0.54$) in groundwater of Cotonou, indicating that they most likely derive from the same source of saline water. In Lagos, Sanyaolu and Mbega (2010) also found a good relation between Na⁺ and Cl⁻ ($r^2 > 0.9$). Finally, the evolution of Na/Cl molar ratio also confirms the marine influence of the salt in the case of Benin coast with the Na/Cl molar ratio of 0.52 close to that of Atlantic ocean (0.55), while in Lagos, the Na/Cl ratio (0.71) of groundwater is close to that of the lagoon water (0.72) (Table 4). This hydrochemical vision is in agreement with the results obtained by Oladapo et al. (2014) using geophysical methods. It is estimated that the whole coastline (1000 km) of Nigeria and the Gulf of benin have been affected by seawater intrusion, although marine sediments should not be excluded from affecting the groundwater quality (Oteri and Atolagbe, 2003; Adepelumi et al., 2008).

Table 4

Evolution of Na/Cl ratios in the groundwater of Abidjan, Cotonou and Lagos. The ratios for Lake Nokoue, Lagos Lagoon, Effluents in Douala, and Atlantic Ocean are also highlighted (Alassane et al., 2015; Odukoya et al., 2013; Fantong et al., 2016; Hem, 1970).

Location and times	Na/cl ratio in groundwater	Na/cl ratio in Lagos Lagoon	Na/Cl ratio in the Lake Nokoue	Na/cl ratio in the Atlantic ocean	Na/Cl ration of Effluents in Douala	References
Cotonou (1991)	1.94			0.55		Maliki (1993), Alassane et al. (2015)
Cotonou (2011)	0.52					
Lagos (2004)	1.23	0,71				Seifu (2007), Akoteyon (2013)
Lagos (2012)	0.72					
Abidjan (1986)	0.09					Jourda (1987), Ahoussi et al. (2011)
Abidjan (2011)	1.01					
Douala (2003)	1.42				0.68	Ketchemen-Tandia (2011), Wirmvem et al. (2017)
Douala (2015)	1.12					

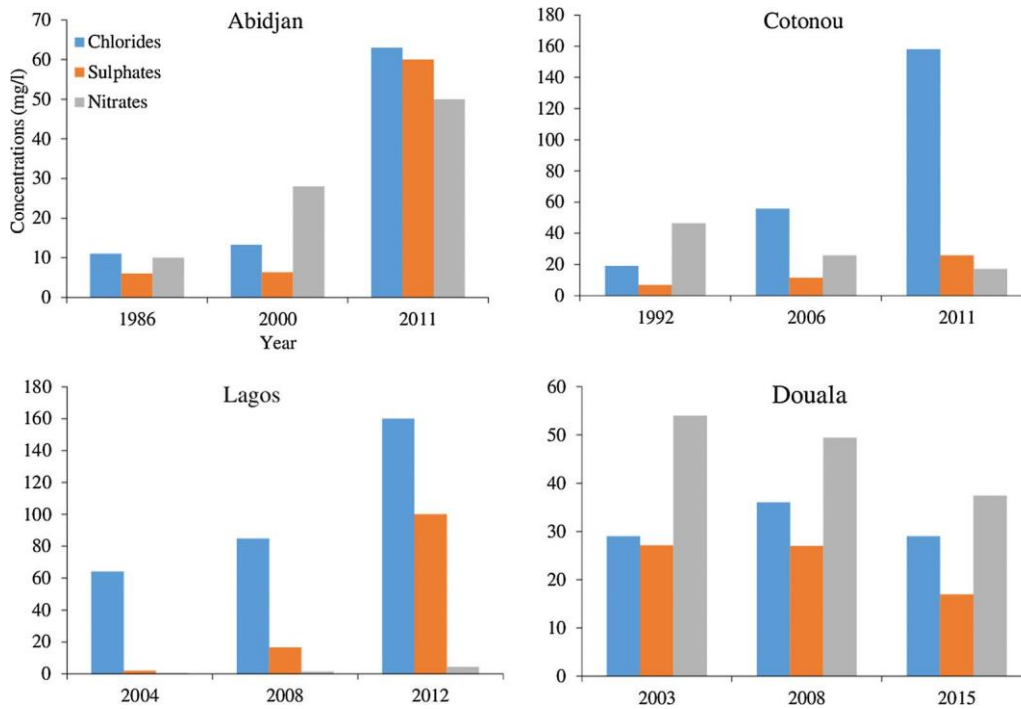


Fig. 7. Temporal evolution of Cl-, SO₄²⁻ and NO₃⁻ in CT aquifer of Abidjan, Cotonou, Lagos and Douala.

Regarding Douala and Abidjan, the two other studied sites considered by this paper, their water chemistry does not seem to be affected by salt intrusion. However, Na/Cl ratio of groundwater in Douala have decreased between 2003 and 2015. Some authors (e.g. Steyl and Dennis, 2009) revealed that coastal aquifer in Cameroon is under threat due to sea level rise, causing seawater to permeate the groundwater resource in this part of the Guinean coast.

4.3.3. Widespread degradation caused by anthropogenic activities

Urbanization, coupled with its associated industrial development has profound impacts on hydrological cycle and groundwater quality. According to Foster et al. (2003), more insidious and persistent problems are linked to sanitation system, industrial effluents and agri-cultural cultivation.

Most of the industries generate liquid effluents, which are often directly discharged on the land surface and represent serious long-term threat to groundwater quality. Inadequate sanitation design (septic tanks, cesspool and latrines) is an important source of water quality deterioration as a result of increasing concentrations in nitrate, generally associated with high concentrations of chloride (mostly from excreta), sulphate and borate (from detergents)-, organic carbon (which can lead to enhanced mobilization of Fe and/or Mn) and a localized contamination by fecal pathogens (Lapworth et al., 2017).

Among the four studied sites, Abidjan shows the worst case with a simultaneous sharp rise in Cl, SO₄²⁻, NO₃⁻ (Fig. 7). Groundwater facies move from Na-HCO₃ in 1986 to NaK-Cl in 2000 and to CaMg-ClSO₄ in 2011 (Fig. 6). According to Abderamane (2012), the evolution towards the Cl-SO₄ pole as is the case in Abidjan should be linked to anthropogenic pollution in addition to natural phenomena.

Simultaneous increase in nitrates, chlorides and sulphates concentrations at similar levels is due to a failure of sanitation systems (major), the disposal or leakage of industrial wastewater (minor to major), leaking sewers (minor) and seepage from canals and rivers (minor to major) (Foster, 2001; Morris et al., 2003; Huneau et al., 2011). Probably the most serious source of groundwater pollution in

Abidjan is sewage handling (treatment and/or disposal) as mentioned above, regarding the percentage of population using pit latrines and septic tanks for sanitation. Another source of groundwater pollution arises from the disposal of wastes linked to population density. Many people live in unplanned (squatter) areas, where there is a few or no infrastructure service for waste collection. Due to increased urban population, the quantities of waste to be collected and transported for disposal have also increased tremendously in recent years. For example, the solid waste generated, increased from 994,043.30 tons/day in 1998–1,438,778.74 tons/day in 2005 with 548,684 tons of uncollected waste during this year (Soro et al., 2010). The results of this paper are in agreement with those of Oga et al. (2010) who have shown that groundwater contamination in Abidjan originates from septic system effluents and human waste (e.g. detergents), using ¹⁸O and ¹⁵N iso-topes.

Despite the highest density of population and equivalent characteristics compared to Abidjan in terms of socio-environmental characteristics and industry contexts, Lagos surprisingly displays low contents in NO₃⁻. Vulnerability to pollution is a function of (i), the ease for water and pollutants to move to the underlying groundwater, and (ii) the attenuation capacity of the material (Schmoll et al., 2006). These parameters are both determined by the characteristics and properties of soil and aquifer, as described by Vrba (2002) and Foster et al. (2003), and vary with hydrogeological settings. Morris et al. (2003) demonstrated that coastal plain sediments (identified in Lagos) present a high to moderate attenuation potential and a low to moderate vulnerability to pollution. On the contrary, consolidated sedimentary aquifers (porous sandstone) in Abidjan display a low to moderate attenuation potential and an extreme to high vulnerability to pollution. However, Adelana et al. (2004) observed nitrate concentrations above the WHO guideline of 50 mg/l in some hand-dug wells tapped the unconfined Quaternary aquifer.

In Cotonou, the slight decrease in NO₃⁻ (Fig. 7) could also be related to the lack of hygiene and sanitation leading to heavy metal pollution due to redox conditions in the superficial layers of the

Continental Terminal. [Dovonou et al. \(2015\)](#) did the same interpretation after observing an increase in iron, zinc and copper in the SONEB wellfield. This denitrification process can explain why sulphates concentrations are very lower (despite the salt intrusion) compared to those in Lagos. Nitrate reduction can also be explained by the dilution process, which is frequently observed in humid environment ([Djebebe-Ndjiguim et al., 2013](#)).

The case of Douala is more particular. The Piper diagram ([Fig. 6](#)) does not show an evolution of the chemistry. The water types remain NaK-Cl between 2003 and 2015. There is no particularly evolutionary trend in Cl^- contents. However, concentrations in SO_4^{2-} and NO_3^- decrease indicating a denitrification process already reported by [Ketchemen-Tandia \(2011\)](#) and [Wirmvem et al. \(2017\)](#). A progressive decline in redox potential, leads the removal of nitrate by denitrification, mobilization of manganese and iron and the reduction of sulphate ([Rivett et al., 2008](#)). This is alarming when we know that Paleocene water of the Douala basin is already polluted by hydrogen sulphide, iron and manganese.

Compared to the other sites, Cl^- content is the lowest in Douala. Despite the downward trend, NO_3^- concentrations are important (37.4 mg/l in 2015) and not far from those observed in Dug wells of Yaounde (mean of 43.4 mg/l), (the second big city of Cameroon) ([Kringel et al., 2016](#)). This is probably resulting from a mixing process of anthropogenic pollution and natural redox conditions that influence the chemistry of the CT aquifer in Douala.

In general, the high precipitation rates in the humid tropics cause rapid leaching of pollutants from urban and industrial wastes disposed in (or on) the land surface resulting in significant pollution risk for vulnerable aquifers ([Pitts, 2012](#); [Villanueva et al., 2015](#)). In relation to the sanitary aspects of waste disposal, it should be noted that pathogens are likely to be more persistent in aquifers of tropical regions because of higher ambient groundwater temperatures (normally in excess of 25 °C).

With regard to this hydrogeochemical synthesis, there is some evidence to suggest that urban agricultural practices (not developed in the study area) have no or little impact (or is made invisible by other dominant factors (mailmen) such as industrial effluents and poorly sanitation) on groundwater quality, partly because of a large dilution offered by high rates of annual infiltration.

An overall classification of groundwater quality problems and causes in each studied site are summarized in the [Table 5](#). According to [Foster \(1993\)](#) in the humid tropics, three processes control the natural groundwater chemistry in the region:

- (i) Relatively rapid dissolution of minerals, associated with the high rates of circulation of infiltrating meteoric water
- (ii) Very large dilution and low levels of salts concentrated in the soil by transpiration (such as NaCl and CaSO₄) as a result of high groundwater rates
- (iii) The redox conditions that determine the nitrogen compounds in groundwater system (NH₄, NO₃, ...)

5. Conclusion and prospect

This paper has presented the status of the regional aquifer of Continental Terminal, major and most exploited groundwater resource in Western African coast. The urbanization process that affects the region is characterized by a population increase and population density. Furthermore, the expansion of the cities is associated with deforestation and a reduction of cultivated areas for buildings purpose. Strong similarities and noticeable differences have been highlighted at each site as follows:

- Groundwater resources are important and used by population through private boreholes/hand-dug well and spring or direct supply from the national water companies for domestic, industrial and agricultural needs. Out of total volume distributed by these national companies, water from the CT aquifer represent 100%, in Abidjan and Cotonou, 17% in Lagos and 26.7% in Douala.
- Downward trend of annual rainfall amount in most areas, which implies a potential decrease in the recharge of the aquifer.
- The observed population increase (at different average annual rates) from 2.2% (Cotonou) to 8% (Lagos) leads to an increase in demand, causing an over-exploitation of the resource. This overexploitation is responsible for the intrusion of saline water in Cotonou and Lagos.
- Groundwater deterioration is also observed since urbanization process in the region was undertaken regardless of sanitation infra-structures or an innovation about waste management. Thus, in Abidjan we observe an increase in nitrates, chlorides and sulphates. Regarding Douala and Cotonou, there is a denitrification process which could be linked to anthropogenic pollution or natural processes particularly in the case of wet soils that are generally deprived of oxygen.

A global synthesis showing the impact of urbanization on coastal aquifers in sub-Saharan Africa is proposed in [Fig. 8](#).

The study confirms the fundamental importance of coastal

Table 5; Classification of groundwater quality problems in the four studied cities.

City	Groundwater quality problems	Underlying cause	Parameters of concern
Abidjan	Anthropogenic pollution	- Industrial effluents	Pathogens, NO ₃ Cl, SO ₄ , B, heavy metals, DOC,
		- Waste disposal	
		- Use of pit latrines and septic tanks - Inadequate protection of aquifer	
Cotonou	Salinization process due to seawater intrusion	Inadequately controlled groundwater abstraction	Electrical Conductivity, Na, Cl, SO ₄ , Br and sometimes F
	Anthropogenic pollution	- Industrial effluents - Inadequate protection of aquifer	NO ₃ , NH ₄ , heavy metals
	Naturally occurring contamination	Related to dilution effect, to pH-Eh evolution of groundwater or to the confinement of the aquifer	NO ₃ , NH ₄ , heavy metals
Lagos	Salinization process due to intrusion of lagoon water	Inadequately controlled groundwater abstraction	Electrical Conductivity, Na, Cl, SO ₄ , Br and sometimes F
Douala	Anthropogenic pollution	- Industrial effluents	Pathogens, NO ₃ Cl, SO ₄ , B, heavy metals, DOC, NO ₃ , NH ₄ , heavy metals (mainly Fe and Mn)
		- Waste disposal	
		- Use of pit latrines and septic tanks - Inadequate protection of aquifer	
Naturally occurring contamination	Related to dilution effect, to pH-Eh evolution of groundwater or to the confinement of the aquifer	NO ₃ Cl, SO ₄ , B, heavy metals, DOC, NO ₃ , NH ₄ , heavy metals (mainly Fe and Mn)	

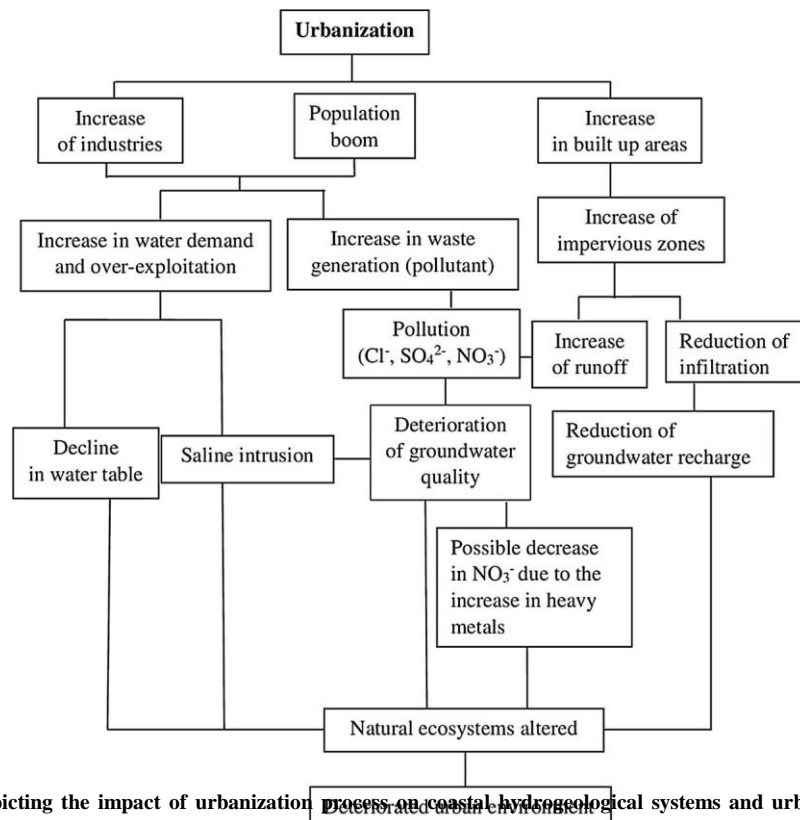


Fig. 8. Conceptual model depicting the impact of urbanization process on coastal hydrogeological systems and urban environment quality in sub-Saharan Africa. Modified from Suresh, 1999 as quoted in Mato, 2002

groundwater resources for the development of the region and the urgent need to correlate the rate of water development with the rate of demographic change, including urban expansion and economic growth. In order to make progress, some management requirements should be followed: first, the reservation of good quality (deeper) water for sensitive uses and shallow water (poor-quality) for non-sensitive uses, then, the definition of protection zones for priority control of contaminant load and finally the planning of wastewater treatment/disposal. Besides, the public awakening of national and inter-African consciousness and leadership with regard to water development must be accompanied by the awareness of the fundamental importance of implementing coastal groundwater development strategies, different from other physical scheme where borehole productivity is the target.

Conflict of interest statement

None.

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Chapter V: How global changes impact hydrological processes and especially groundwater resources in the humid region of Gulf of guinea and peculiarly in the megacity of Douala?

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3. Review of the potential impacts of climate changes on groundwater resources at Douala

Since climate changes affect the components of water cycle such as evaporation, temperature, evapotranspiration and precipitation, it is clear that the effects on subsurface water will be reflected by changes on recharge and discharge rates, changes in quantity and quality of water in aquifers.

3.1. Analyses of climate changes effects on groundwater quality: emphasis on the possible changes on the Mio-Pliocene aquifer of Douala

Temperature changes

Sylla et al. (2016) show a clear warming trend in Western Africa, ranging from 0.1°C to more than 0.5°C per decade from 1983 to 2010 consistently with the IPCC report (IPCC 2013) and with the results highlighted in the previous section (Nlend et al. 2018). This present-day warming is likely to be exacerbated in future climate. At the end of the XXI century, possible warming over Western Africa ranges from +1.5 to +6.5°C according to the RCP4.5¹ (midlevel forcing scenario) and RCP8.5¹ (high level forcing scenario), respectively.

General effect of temperature increase on groundwater

This warming will likely cause a rapid increase in the temperature of shallow groundwater reservoirs. However, subsurface temperature change might have potential effects on groundwater quality through changes in physical, chemical, and microbial processes. Higher temperatures might affect groundwater quality directly by accelerating geochemical processes (e.g., the dissolution of salts). Hence, the mineralization in groundwater will increase and water will become more saline (e.g., Adham et al. 2011). Indirectly, higher temperatures will cause increasing microbial respiration rates (Chapelle 1993). The effect of which can be positive or negative. Enhanced microbial activity favors the degradation of pollutants in groundwater (Sprenger et al. 2011) and the removal of pathogens (Schijven & de Roda Husman 2005), but might also lead to the formation of unwanted byproducts by reducing dissolved oxygen (DO) concentration and altering redox conditions. The reduction process can further allow the presence of iron and manganese into the solution.

¹ Representative Concentration Pathway (RCP) is a greenhouse gas (GHG) concentration trajectory adopted by the IPCC for its 5th Assessment Report (AR5) in 2014 (IPCC 2013). Four pathways have been selected for climate modeling and research, describing different climate futures scenarios. All of them are considered possible, depending on how much GHG are emitted in the years to come. The four RCPs, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, are labelled after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m², respectively)

Possible effect of temperature increase on Mio-Pliocene groundwater at Douala

The shallow and intermediate flow paths of Mio-Pliocene groundwater (studied in Chapter IV) are particularly susceptible to changes in redox conditions as it records directly air temperature. Higher temperature will foster the microbial activity. This latter will contribute to the increase of pathogens in groundwater according to the fact that microbial species are more able to leave in hot humid tropical areas than in temperate climate (Foster & Chilton 1993; Lapworth et al. 2017). On the other hand, in the presence of bacteria consuming oxygen, the shallow aquifer water will become a reducing media, leading to the formation of copper, iron and manganese in the water. Furthermore, anoxic conditions have been documented for the Paleocene aquifer in Douala (Martin 1979).

In summary, no matter the situation, the increase of air temperature will make the shallow MP groundwater unsuitable for drinking.

Impact of CO₂ emission on groundwater

Important emissions of greenhouse gases (GHG) in particular carbon dioxide (CO₂), will contribute to lower the pH of water-bodies (Solomon et al. 2009). Furthermore, an acidification trend of shallow groundwater has been already revealed by Takem et al (2015) in the shallower flow path of MP groundwater. This acidification is manifested by depletion in HCO₃ and increase in SO₄ concentrations.

Rise of sea level (Table 10)

Due to global warming and glacial melt spurred by fossil fuel burning, oceans are now rising at their fastest rates in 10,000 years. As a result, many coastal towns and cities around the world are under increasing threat of flooding. In West Africa, Fagotto (2016) paints a picture of broadening inundation. Indeed, since 1990, the sea level has increased by 3 mm per year in Gulf of Guinea region (Church et al. 2004). Nicholls et al. (2011) estimate that for an overall increase of 4°C in average in 2100, sea level could rise from 0.5 to 2 meters.

Table 10: projected increase of temperature and sea level in Douala, in the case of high level forcing scenario (RCP8.5) according to the works of IPCC (2001), IPCC (2013) Noubissi Domguia (2016) and Sylla et al. (2016). Intervals are given taking as a reference the year 2008.

Scenarios	Temperatures increase		Sea level rise	
	2050	2100	2050	2100
RCP8.5	6.7% - 8%	18% - 21.2%	25% - 47%	68% - 104%

Impact of sea level rise on groundwater

The sea-level rise is projected to extend areas of salinization over the estuaries, resulting in a decrease of freshwater availability for humans and ecosystems in coastal areas (Bates et al. 2008). This phenomenon already observed at Cotonou, as highlighted in the previous section (Nlend et al. 2018), will be exacerbated because of uncontrolled groundwater abstraction.

Changes in precipitation amount

Concerning precipitation trends, using various sets of data (from 1983 to 2010) and IPCC findings, Sylla et al (2016) highlighted that small part of Gulf of Guinea (including Douala) recorded drier conditions in recent years while most of the region experiences no changes. These results are consistent with our investigations presented in section 2 (Nlend et al. 2018). However, it is worth mentioning that a few precipitation increasing (5–10 %) are projected but to a lesser extent in some small areas in the Gulf of Guinea, covering Sierra Leone, Liberia and Cote d'Ivoire, according to RCP4.5 and RCP8.5 scenarios (Sylla et al. 2016) for the early (2036–2065) and the late (2071–2100) 21st Century.

Potential impact of change in precipitation amount on MP groundwater

Since climate scenarios reveal neither an increase nor decrease in rainfall amount in the Douala area at a long-term, it is clear that there will not be an increase in floods or actual runoff rate in this zone. Indeed, Roudier et al (2014) show that future tendency in runoff developments is overall very uncertain in Western Africa. They highlight a link ($R = 0.49$) between runoff and rainfall changes. Finally, this will tend to preserve the MP groundwater quality as greater runoff results generally in greater loads of salts, fecal coliforms, pathogens and heavy metals (Arnell 1999) that can seep into the aquifer.

3.2. Analyses of climate changes effects on groundwater quantity: emphasis on the possible changes on the Mio-Pliocene aquifer of Douala

Precipitation is the primary climatic driver for groundwater recharge. However, recharge is not only influenced by the magnitude of precipitation, but also by its intensity and seasonality. (e.g., Barron et al. 2010; Zhang et al. 2016). Temperature and CO₂ concentrations are also important since they affect evapotranspiration and thus the portion of precipitation that may flows through the soil profile toward the aquifers. Taylor et al (2013) assert that under higher atmospheric CO₂ concentrations, terrestrial plants open their stomata less; and this response is projected to reduce evapotranspiration and increase continental runoff. Indeed, (i) a greater plant growth (and consequently greater leaf area) can offset reductions in evapotranspiration through stomatal closure and a (ii) reduced leaf area due to unfavourable climate conditions can result in an increase of groundwater recharge even with slightly decreased rainfall. Changes in evapotranspiration driven by any of several potential climate changes can affect

the amount of groundwater recharge by changing the consumption of water at the land surface, from the unsaturated zone.

Groundwater quantity may also be affected by change in precipitation timing. IPCC (2013) along with previous studies using either Global Circulation Models (GCMs) or RCMs (e.g. Sylla et al. 2010) reported an increase in dry spell length² and an intensification of extremes wet events² as a response to future climate change. These two cases will probably affect groundwater recharge in term of timing.

Finally, the study of Döll (2009) on projected impact of climate change on groundwater recharge by 2050 showed that all scenarios agree broadly in that groundwater recharge will increase in northern latitudes, but will decrease strongly, by 30-70% or even more than 70%, in some currently semi-arid zones, including the Mediterranean, north-eastern Brazil and southwestern Africa (Figure 45). However, the Gulf of Guinea including the megacity of Douala is expected to record quite no change or only a slight increase in groundwater recharge. This is in agreement with detailed studies presented above which reveal that annual precipitation amount will not undergo any change in the study region.

Regarding the discussion above, Figure 46 tries to present a global synthesis of potential climate changes effects on MP coastal groundwater in Douala in the 2050s, both in terms of quantity and quality.

² The dry spell length is calculated as the maximum number of consecutive dry days (i.e., days with precipitation lower than 1 mm). Extreme precipitations refer to wet days above the 95th percentile. While the dry spell length index measures drought occurrence (WMO 1986), total precipitation intensity of very wet days provides an indication of high intensity precipitation

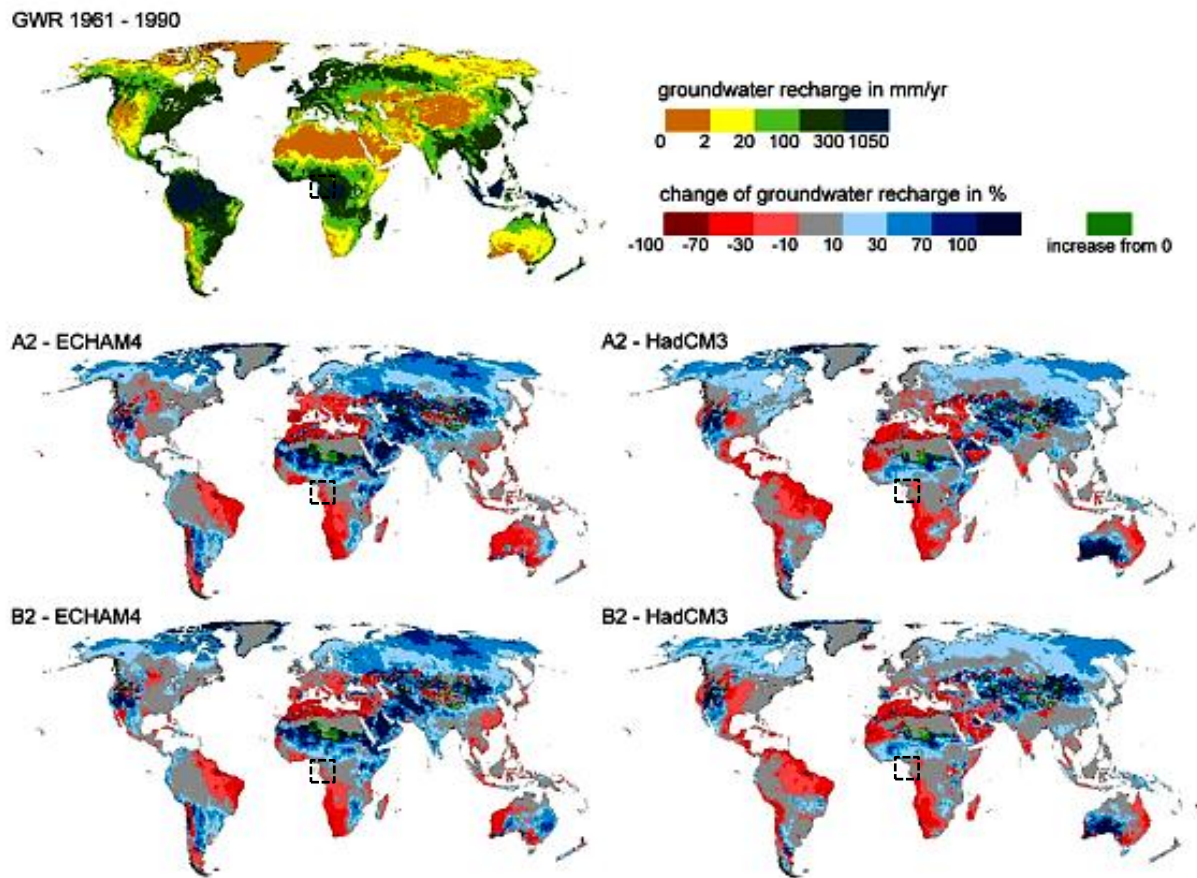


Figure 45: Impact of climate change on long-term average groundwater recharge (GWR) in the 2050s with the reference period of 1961–1990 (Döll (2009)). Calculations were made using ECHAM4³ and HadCM3³ climate models. The black box represents the western central African region where lies the city of Douala (Cameroon).

³ A2 and B2 are scenarios discussed in the IPCC's Third Assessment Report (IPCC 2001). A2 scenario considers the world as heterogeneous and it is characterized by continuously increasing population and economic development. B2 scenario refers to a world more divided, but more ecologically friendly. This scenario is characterized by continuously increasing population, but at a slower rate than in A2.

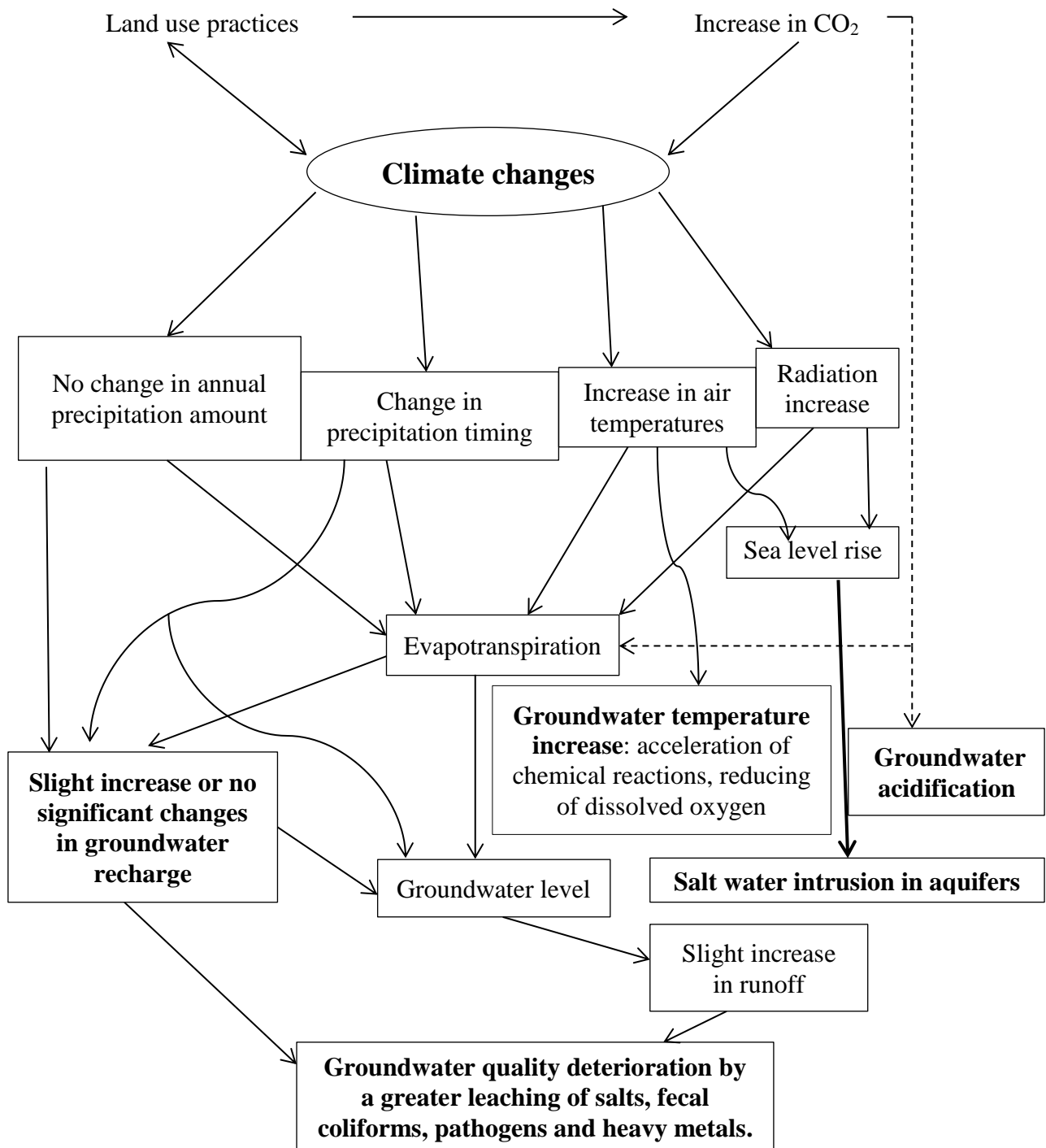


Figure 46: Global synthesis of climate changes impacts on coastal groundwater (in bold character) at Douala, in the 2050s according to RCP4.5 and RCP8.5 scenarios. External factors such as population growth, groundwater abstraction and water demand are not considered here.

4. Synthesis and final discussion

Groundwater in the Gulf of Guinea and more especially in Douala represents the most exploited fresh water for drinking, domestic, industrial and -to lesser extent-, agricultural uses. However, the situation in large coastal cities is worrying. There is an exponential demographic growth, urbanization is uncontrolled and the water demand is in increase. All these features affect the sustainability of regional aquifers. In some sites groundwater levels decrease, in spite of meteorological conditions which remain favorable, as consequence of uncontrolled withdrawals. Increase in the volume of water pumped and decrease in potentiometric surface lead to salty water intrusion, already visible in the cities of Cotonou and Lagos. In general there is a widespread degradation of groundwater quality due to anthropogenic activities.

This groundwater deterioration tends to be emphasized in the context of climate change. This latter will affect the study area through an increase in CO₂, increase in air temperatures and eventually slight increase in precipitation amount with changes in rainfall timing. The impacts on groundwater are likely to be major even for unconfined aquifer systems, which may respond rapidly to surface changes. If the groundwater recharge and quantitative aspect of aquifer in Douala do not show any negative response to climate changes, it is not the case for water quality.

In summary, the climate change impacts in Douala are likely to be insignificant, though uncertain in magnitude, while the direct and indirect impacts of demographic change on both water resources and water demand are not only known with far greater certainty, but are also likely to be much larger. The expanding population will place ever-increasing demands on water resources. Therefore, according to [Carter and Parker \(2009\)](#) population growth in Africa will indirectly impact on water resources, in ways that are not yet fully understood. The coastal cities where environments are already being deteriorated (shoreline erosion, higher water table, mangrove destruction, etc.) are much concerned ([Nicholls 1995](#)).

Chapter VI

Conclusion, outlook and recommendations.

The general objective of this thesis was to describe the key hydrological processes in the hyper-humid context of Douala megacity which already undergoes strong anthropogenic influences. We thus performed a research on the critical zone (land–atmosphere–subsurface continuum) by using water stable isotopes and major ions from water vapour, rainwater and groundwater. Thanks to this investigation we have been able to highlight the major processes involved in the local hydrological cycle step by step (Figure 47):

- (i) Water vapour to rainwater: weak influence of post-condensational effects. Indeed, as explained by Dansgaard (1964) and Risi et al (2008a), The evaporative enrichment is reduced at higher precipitation rates by the fact that the fractionation during reevaporation is less efficient for high relative humidity such as observed at Douala. The diffusive exchanges (less fractionating) which are well known to dominate in very high precipitation rates (Risi et al. 2008a) have also poor control on δp . This finding is very important in the understanding of atmospheric water cycle. Thus it could be hypothesize that in the area of Douala, when raindrops agglomerate and begin to fall toward the ground in contact with the rising air, the exchanges between the liquid and gaseous phases are limited. However, this depends of the intensity of precipitation and the size of the drops. According to Salati et al (1979) this case corresponds to heavy tropical rains, associated to the ITCZ and its clouds with great vertical extension.
- (ii) Rainwater to groundsurface: dominance of runoff followed by infiltration. This finding is consistant with the work of Wohl et al (2012) who shown that the runoff consummes the greatest part of water budget in tropical hydrology.
- (iii) Rainwater to groundwater: absence of evaporation, water-rocks interactions, dilution effect on ion contents and mixing with salt water from effluents.
- (iv) Groundwater to surface water: increase of mineralization and water mixing from different flow paths
- (v) Surface water to the estuary : evaporation

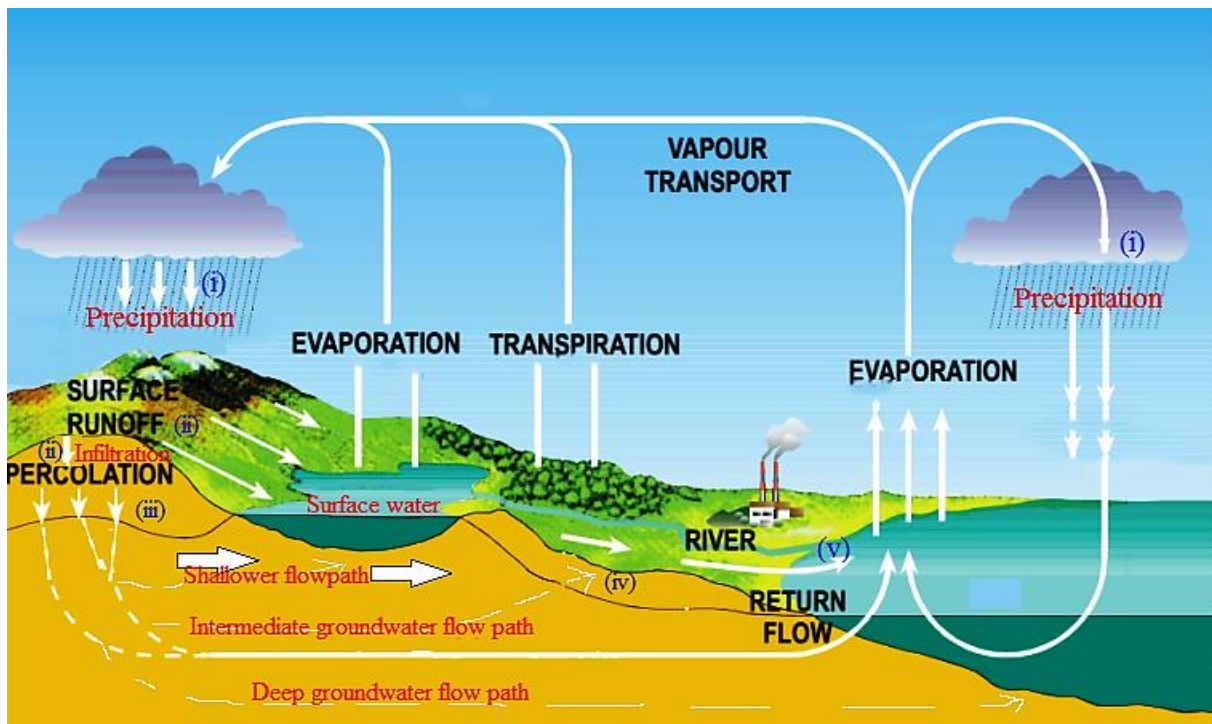


Figure 47: Schematic view of the hydrological cycle with processes and water fluxes involved in the region of Douala (adapted from IAEA 2000).

1. Summary of results

From the water vapour to the rainwater, we observe that the isotopic signal is mostly conserved. This suggests a lack of post-condensational effects such as diffusive exchanges or evaporation. The isotopic composition (δ) of rainwater and water vapour are strongly affected by upstream convective activity in the Gulf of Guinea (GOG). The convection also plays a role through the organization of convective systems both upstream and locally. The more they are large, long-lived and developed in altitude; the more the precipitation is depleted in heavy isotopes. The amount effect in Douala is non-local but regional reflecting the influence of large scale meteorological conditions on local climate. Moreover, we found that the isotopic content of rainfall is not influenced by interactions between the continent and the atmosphere. For instance, we have not identified a clear impact of continental recycling.

From rainwater to groundwater, there is no fractionation process. By coupling the isotopic signal of meteoric water with that of groundwater, we show that the Mio-Pliocene aquifer (which covers almost all the study region) is locally recharged by rainwater and that this recharge occurs preferentially from April to August and November. Groundwater stable isotopes coupled with groundwater chemistry allow the identification of different flow paths and water mixing within MP aquifer. To answer the question of whether the hyper-humid conditions at Douala correspond to a hyper-recharge of the aquifer, we used the Penman-Grindley and Water Table Fluctuation methods. The results obtained show that the recharge rate corresponds on average to ~ 1000 mm/year, value similar to the ones estimated in the wettest areas of the world (e.g., Amazonia, Papua New Guinea). The most important part of

the hydrological cycle at Douala is however consumed by the runoff (48.7% of annual precipitation amount). Rainwater infiltrates at high altitudes, that constitutes the main recharge areas, and flows underground with a velocity around 2m/day, before reaching the estuary (main discharge area). This relatively high velocity of groundwater flow must be attributed to the high permeability of Mio-Pliocene sands. Along the flow, the mineralization of water increases due mainly to interactions with rocks. Nonetheless, highest rainfall amount can lead to a dilution of concentrations and human activities can contaminate natural waters. Indeed, it is clear that the urbanization process (population increase, expansion of large coastal cities, deforestation for buildings purpose, etc.) already has an impact on groundwater. Due to industrial effluents, waste disposal, use of pit latrines and septic tanks, we observe higher concentrations in NO_3^- , Cl^- and SO_4^{2-} . This groundwater quality deterioration should be exacerbating in the future, through climate change that provokes an increase in CO_2 , an increase in air temperatures and eventually a slight increase runoff. Nevertheless, we show that the population growth and the uncontrolled urbanization may have a more significant and large impact on water resources than climate changes in the study region.

Finally, the results obtained provide important information for the management of water resources. This thesis shows that the implementation of a multi-tracer approach can deliver useful information on water dynamics in complex environments such as Douala (Cameroon, West Africa). It opens new opportunities for the critical zone observations in humid tropical area.

2. Outlook

Further investigation on the life of a convective system

To understand the life of a convective system in the hyper-humid area of Douala, we plan to carry out a rainwater sampling at a much shorter time-scale (event scale). In addition with various satellite data, this approach will be useful to document the isotopic variations associated with different phases of the convective live and with degree of convective organization.

Further investigation on the convective and cloud process

In addition to sampling water at event-scale, we need to set up a monitoring of isotopic composition in the near surface water vapour. Indeed, the vapour is a more direct tracer of water origin and air mass history, whereas complex processes may affect the rain composition as it falls (Bony et al. 2008, Lee and Fung 2008, Risi et al. 2010). So far, measuring water isotopes in the vapour is difficult and costly, but recent measurement of the boundary layer vapour isotopic composition from space at the global scale (Frankenberg et al. 2009) and in-situ using new laser spectrometry (Gupta et al. 2009) will open many new perspectives. To better evaluate the isotopic response to convective and cloud processes, we also need to use a Global Circulation Model (GCMs) which are well known to simulate such kind of microprocesses (rainfall re-evaporation phenomenon, diffusive exchanges, the contribution of

the environment entrained into the convective system and the effect of unsaturated downdraft).

Further investigation on groundwater recharge conditions

Groundwater recharge conditions and processes involved during the infiltration will need to be clearly identified. This approach will be based on the development of investigative tools specific to the vadose zone (e.g., ^{13}C , radioactive and stable isotopes). ^{13}C will be useful to highlight biogeochemical processes, radioactive tracers such as ^3H will provide information on the velocity of water transfer from the unsaturated to the saturated zone while stable isotopes will be helpful to investigate evaporation processes and water mixing within the soils. All these investigations will contribute to a better management of aquifers.

Further investigation on the distribution of groundwater flow path

At short-term, it will be necessary to use CFCs and SF₆, adequate tracers for date young groundwater (few years to few decades). CFCs and SF₆ are very adapted in the context of Douala where groundwater velocity is important and water is renewed in a space of few years. Regarding the hydrometeorological context of Douala, we can expect that these tracers will be efficient. On the other hand it will help to shed a light on complex mixtures scenarios (Jaunat 2012) observed in the studied aquifer. Coupling these dating data with chemical and isotopic measurements will provide accurate and valuable information on the different flow pattern.

Further investigation on the global changes and their impacts on the hydrological fluxes at Douala

There is a need for future research to downscale Global Climate Models (GCM) on a basin scale and couple them with relevant hydrological models (Barron et al. 2010) considering all components of the hydrological cycle and including other factors such as pumping rate. Output of these coupled models will help to see the groundwater response to global changes which already affect the Douala megacity, and in taking appropriate adaptation strategies due to the impact of global changes (land use changes + climate change).

3. Recommendations

Despite the apparent abundance of water in the hyper-humid zone of Douala, access to potable water remains a major issue for many households. This is why Ketchemen-Tandia (2011) asserted that Douala is a “damp desert”. The establishment of a global water resources management is therefore of primary importance for local populations. For this purpose, the understanding of the atmospheric phenomena associated with rainfall and the hydrogeological functioning of the hyper-recharged aquifer system are an essential prerequisite. The obtained results summarized above, allow us to propose some recommendations to water management authorities.

Exploration of new resources of groundwater for drinking water supply

The exploration of new groundwater resources in the region of Douala should be based on the hydrochemical results. The MP aquifer appears already impacted by pollution. Only the groundwater from the deep flow path present good chemical qualities. Alternatively to the abstraction of deep MP water, public authorities have to investigate a new aquifer for water supply. The Eo-Oligocene aquifer located in the NE part of Douala, at more elevated altitudes and covering settlements with low density of inhabitants would be appropriate.

Focus on a better protection of groundwater

The establishment of regulatory protection perimeters around water catchments must be carried out. Hand-dug wells in houses are generally close to latrines, and boreholes in neighbourhoods are often not far from garbage dumps. It is essential to take into account the distance between well and latrine or to position the water catchment upstream of a discharge zone. Moreover, the quality of the resource requires regular maintenance of water catchments. Thus, the development of plants or the deposition of particles at the bottom of the hand-dug wells or boreholes can pose quality problems.

New groundwater governance

Nowadays, there is overlapping jurisdictions and uncoordinated actions between the several actors of groundwater resource. **Table 11** summarizes the multi-layered system management/governance existing in Douala. Since the Douala megacity continues to extend and becomes a metropolis this administrative fragmentation does not favour the implementation of an homogeneous or egalitarian supply network, and can even aggravate the spatial segregation, as it was observed in Rio de Janeiro state (Pilo' 2016) and already reported by Nantchop Tenkap (2015) for the case of Douala.

Table 11: main actors in charge of water management from National level to the municipalities.

Regulatory and institutional agencies	Responsibilities and actions regarding water resources
NATIONAL LEVEL	
Ministry of Water and Energy (MINEE; French abbreviation)	Definition and implementation of the national policy for the governance and management of water resources; establish a legal framework regulating the water sector.
Cameroon Water Utilities Corporation (CAMWATER)	Ensures the urban water supply; looks for financing for the construction and maintenance of hydraulic engineering structures. propose collective solutions (wells and standpipes) for access to drinking water in unserved or very poorly served neighborhoods
CITY LEVEL (Douala)	
Communauté Urbaine de Douala (CUD)	Improve access to drinking water (with collective wells or standpipes) and sanitation. ensures the management and the maintenance of surface waters
MUNICIPAL LEVEL	
Municipalities	Improve access to drinking water and sanitation (with collective wells or standpipes)
Private operators / informal actors	Improve access to drinking water ((with collective wells or standpipes). ensures the development and protection of wells and sources for collective use

All the actors of groundwater in the city of Douala should work in collaboration. The sharing of experience feedback from the various actions carried out would allow collective and coordinated actions and would be a valuable aid for decision-making. Furthermore, groundwater needs to be managed conjunctively with surface water as proposed by Foster & Steenbergen 2011. Appropriate functional linkages are needed with other sectors—land-use, urban, agriculture, environment, mining and energy, together with all users of subsurface space. For this purpose, institutional Leadership is needed to ensure both vertical integration between the national and local levels (Table 11), and horizontal cooperation with the other sectors mentioned.

Finally, we recommend the construction of a numeric file or public database on all boreholes (geographic coordinates, depth, age, lithology log, chemical data, cetc.) operating in the city. This will allow a better monitoring of the resource.

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Titre : Processus hydrologiques dans une zone côtière hyper-humide sous forte influence anthropique (Douala, Cameroun). Une étude géochimique de la dynamique des eaux de l'atmosphère au sous-sol.

Mots clés : Précipitations; aquifère Mio-Pliocène; Isotopes stables; ions majeurs; convection atmosphérique; Activités anthropiques, Zone Critique.

Résumé : Une approche multidisciplinaire a été menée à Douala, mégapole côtière tropicale humide (Cameroun, Afrique de l'Ouest) qui subit déjà certains changements environnementaux dus à la croissance démographique, à l'urbanisation et à l'industrialisation. Nous avons cherché à identifier les processus hydrologiques impliqués dans ce site particulier, qui enregistre environ 4 m de précipitations / an et qui reçoit des pluies en continue tout au long de l'année. De plus, comme il est bien connu que les modifications d'utilisations des sols peuvent influencer profondément sur l'hydrologie, nous devons améliorer notre compréhension des processus hydrologiques clés dans ces zones tropicales humides. Pour répondre à cette problématique, nous nous concentrons sur les flux d'eau à travers la zone critique (continuum surface du sol – atmosphère – sous-sol) au moyen de données isotopiques et chimiques issues de la vapeur d'eau, des précipitations et des eaux souterraines.

En ce qui concerne les flux atmosphériques, les résultats mettent en évidence une influence des conditions météorologiques à grande échelle sur la composition en isotopes stables des précipitations locales. Les processus classiques (thermodépendance, effet de masse, recyclage continental) observés ailleurs ne s'appliquent pas à la région de Douala. L'intensité de la convection en amont et la taille des systèmes convectifs contrôlent les variations mensuelles et journalières des teneurs en isotopes dans les précipitations. Nous avons également mis en évidence que le développement des nuages en altitude, dus à une forte convection, provoque un appauvrissement des pluies en isotopes lourds. Par ailleurs, on note que la signature isotopique des pluies à Douala est similaire à celle de la vapeur d'eau, ce qui signifie un manque d'effets de post-condensation.

En couplant ce signal isotopique des précipitations à celui des eaux souterraines, nous montrons que l'aquifère Mio-Pliocène de Douala est rechargé localement par les eaux de pluie et que cette recharge a lieu préférentiellement d'avril à août et en novembre. Il n'y a pas de processus de fractionnement lors de l'infiltration d'eau de pluie. Les isotopes stables dans les eaux souterraines soulignent l'existence de différents réseaux d'écoulement au sein de cet aquifère multicouches. Les eaux issues du réseau d'écoulement profond semblent correspondre à une eau souterraine avec un temps de séjour plus long comparé à une celle circulant dans les couches superficielles. Les informations obtenues par les isotopes sont similaires à celles fournies par les données hydrométéorologiques et piézométriques. La recharge de l'aquifère varie entre 892,6 mm et 933,6 mm/an. Les eaux de pluie s'infiltrent à haute altitude, puis coulent sous terre avec une vitesse estimée à 1,96 m/jour, avant d'atteindre l'estuaire. Les données sur la chimie viennent renforcer ces résultats. La minéralisation de l'eau augmente clairement le long d'un chemin d'écoulement conduisant l'eau de la zone de recharge (haute altitude) vers la zone de décharge (estuaire). Les concentrations en ions majeurs sont en partie contrôlées par l'intensité des précipitations au travers de l'effet de dilution, les processus d'interaction eau-roche et les activités humaines.

Les impacts de ces activités humaines sur la quantité et la qualité des eaux souterraines, mais aussi, d'une manière plus générale, sur les changements climatiques dans la région, ont ensuite été examinés en profondeur. Les résultats montrent qu'il y a une dégradation généralisée de la qualité des eaux souterraines due aux activités anthropiques, entraînant une intrusion d'eau de mer dans certaines mégapoles côtières de l'Afrique de l'Ouest. Le changement climatique aura tendance à aggraver cette détérioration des eaux souterraines à travers l'augmentation du CO₂, de la température de l'air et les quantités importantes d'eau de ruissellement.

Au regard de tout ce qui précède, cette thèse fournit de nouvelles informations sur l'hydrologie tropicale et des outils pour la gestion globale des ressources en eau de Douala.