



Characterising groundwater and surface-water interconnections using hydrogeology, hydrochemistry and stable isotopes in the Ouémé Delta, southern Benin

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Abstract

The Mio-Pliocene aquifer of the coastal sedimentary basin of Benin is the most exploited aquifer for water supply to the urbanised region in the southern part of the country. The population explosion is putting increasing pressure on quantitative and qualitative aspects of the groundwater resources. Preventing groundwater contamination caused by surface waters requires a thorough understanding of surface-water/groundwater interactions, especially the interactions between the Mio-Pliocene aquifer and surface waters. This study aimed to investigate the interactions between groundwater and surface waters along the major rivers (Sô River and Ouémé Stream) and brooks in the Ouémé Delta. Field campaigns identified 75 springs located in the valleys which feed the rivers, and thus maintain their base flow. The piezometric results indicated, through flow direction assessment, that the Mio-Pliocene aquifer feeds Ouémé Stream and Sô River. Chemical analyses of groundwater and surface waters show similar chemical facies, and changes in the chemical composition in groundwater are also observed in the surface waters. Moreover, the isotopic signatures of surface waters are similar to those of the groundwater and springs, which led to the identification of potential groundwater discharge areas. As a result of groundwater discharge into surface waters, the fraction of groundwater in the surface water is more than 66% in the brooks, regardless of the season. In the Ouémé Stream and Sô River, the fraction of groundwater is 0–21% between June and September, while from October to March it is 47–100%.

Keywords Groundwater/surface-water relations · Stable isotopes · Benin

Introduction

Climate change along with rapid population growth will probably impact all water resources. Groundwater provides a potential buffer to support adaptation strategies to face climate change. The increasing use of groundwater in coastal

areas is already critical due to a high concentration of humans that exploit groundwater for both small-scale household use and large-scale commercial irrigation, with increased use of motorised borehole pumps for reliable urban water supply (small and larger towns; MacDonald et al. 2011).

Knowledge of the interactions between groundwater and surface water is essential to develop effective water resource management strategies and policies, addressing the following issues (Winter et al. 1998; Ramita et al. 2020):

- Joint and integrated use of groundwater and surface water resources
- Assessment of losses and delays of water released from groundwater reservoirs
- Assessment and mitigation of floods along river valleys
- Assessment and control of contamination of surface water caused by groundwater and vice versa

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Studies related to the interconnection between river water and groundwater are increasingly common in most developing countries. Groundwater/surface-water interactions are quite common in large basins, especially in coastal sedimentary environments, playing a necessary role in maintaining the river basin ecosystem (Kalbus et al. 2006; Ramita et al. 2020). Several studies have been carried out, focusing on the identification of interconnection zones and the presence of exchange flows between surface water and groundwater at regional as well as local scales (Winter et al. 1998; Lee and Kim 2007; Zhang 2016; Alassane 2018; Zhao et al. 2018). Understanding the relationship between groundwater and surface water is therefore crucial for the sustainable use of this precious resource, especially in arid and semiarid areas. Unfortunately, the connectivity between groundwater and surface water remains less known in many areas, as is the case in the Ouémé Delta in southern Benin.

The Ouémé Delta, which is part of the coastal sedimentary basin of Benin (Benin portion of the Keta Basin), has a large representation of groundwater and an important hydrographic network represented essentially by the Stream of Ouémé, the Sô River, and the lagoon complex of Lake Nokoué. This region is the most urbanised and densely populated in Benin, resulting in a heavy mobilisation of the groundwater resource from the Mio-Pliocene aquifer, the major source of freshwater for the population in this basin. Direct exposure of surface waters to pollutants originating from human activities (industrial, domestic and agricultural activities) represents a potential source of groundwater pollution in case groundwater and surface water are hydraulically connected.

Previous research conducted in the coastal sedimentary basin of Benin (e.g., Kpegli et al. 2018 and Dossou et al. 2021) reported the presence of artesian wells that continuously discharge an enormous quantity of groundwater to the surface. Also, it has been demonstrated using isotopic approaches, that near the northern edge of the Coastal Sedimentary Basin, interactions between surface waters (Zou River and Ouémé Stream) and the Turonian-Coniacian aquifer are effective, but such hydraulic connection between surface water and groundwater is progressively lost downward in that northern region of the coastal sedimentary basin (Kpegli et al. 2018; Kpegli 2020). Within the southern region of the Coastal Sedimentary Basin, Alassane (2018) investigated, based on isotopic approaches, the interconnection between groundwater (from the Mio-Pliocene aquifer) and surface water in the Ouémé Delta. A later investigation was carried out at a very local scale, with water samples taken only in the Adjohoun sector, even though the Ouémé Delta has an important surface water network. A few other studies (e.g., Boukari 1998; Alassane 2004; Achidi et al. 2012) based on piezometric observations have indicated that groundwater from the Mio-Pliocene aquifer discharges into surface waters. However, very little information is available in the literature on the contribution of the

Mio-Pliocene aquifer to river flow. Identifying the interaction between groundwater and surface waters in the Ouémé Delta is important to understand the dynamics of exchange and the vulnerability to contamination for integrated water resources management. Thus, the main aim of this study is to map the potential exchange zones between groundwater and surface waters and the dynamics of exchange flow in the Ouémé Delta, based on various methods and techniques including isotopic analyses, characterisation of springs and the groundwater flow direction, and statistical analysis.

Study area

The area covered by this study includes the administrative departments of the Atlantic, Littoral, Oueme and Plateau, with a surface area of ~3,200 km², i.e., 2.8% of the surface area of Benin (Fig. 1). The study area, in southern Benin, is home to several large cities, including Cotonou, Porto-Novo, Abomey-Calavi, Ouidah, Sèmè-Kpodji currently with more than 2,448,804 inhabitants with an annual population growth rate of 4.4% between 2002 and 2013, representing 25% of the country's population (INSAE 2016).

The study area is under a subequatorial climate with two rainy seasons (a longer rainy season occurring from mid-March to July and a smaller rainy season extending from mid-September to November) and two dry seasons occurring from August to mid-September and from December to mid-March, respectively (Achidi et al. 2012). The average annual rainfall recorded from 1986 to 2014 by ASECNA Benin (the Agency for Air Navigation Safety in Africa and Madagascar) is 1,168.5 mm and 1,349.2 mm at the Adjohoun and Cotonou meteorological stations, respectively, with a potential evapotranspiration of about 1,649 mm/year in Cotonou.

The annual mean temperature is 27 °C but can reach to 38 °C in dry seasons and may decrease to 19 °C in rainy seasons (Kpegli et al. 2018). There are two main geomorphological parts:

- The lower valley, alluvial, often marshy and dotted with lakes and lagoon where the elevations are less than or equal to 10 m above sea level (asl)
- Two plateaus, the Allada and Sakété plateaus, with elevations over 20 m asl

The topography (Fig. 1) varies from –10 to about 170 m asl. High elevations are observed in the northern plateaus and low elevations are found in the Ouémé Valley and in the coastal area.

The southern plateaus of the coastal basin are entirely covered by a layer of siderolithic sandy-clay formation crowning the geological formation of Mio-Pliocene strata.

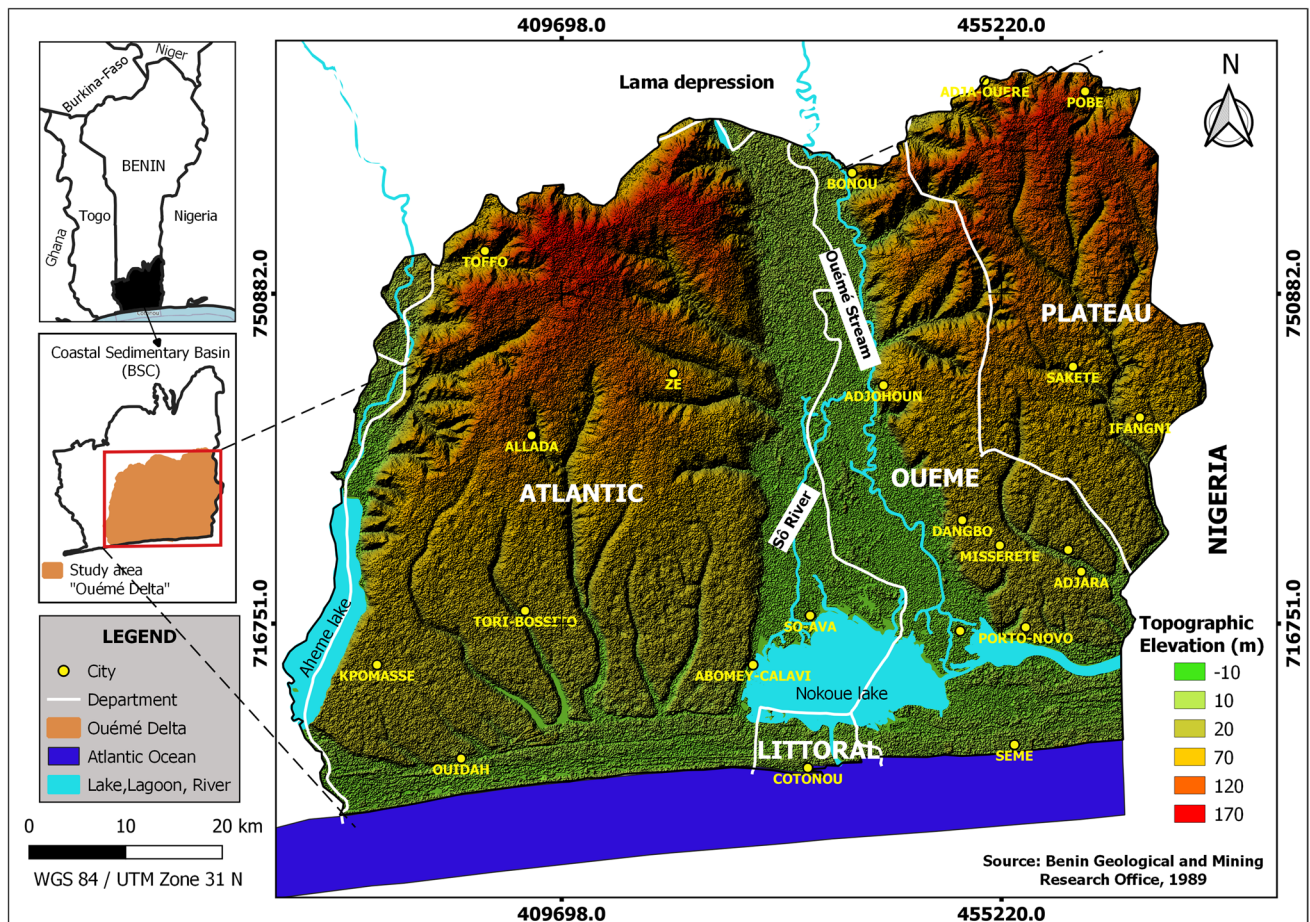


Fig. 1 Location of the study area in Benin: geomorphological map showing the Allada plateau (in the west), the Sakété plateau (in the east) and the Ouémé valley in between these two plateaus. BSC is the coastal sedimentary basin of Benin

This latter Mio-Pliocene formation characterises the surficial geology of the aquifer system. According to Slansky (1968) and IRB (1987), the Mio-Pliocene begins at the base with a fine sandy-clay deposit that lies in angular unconformity with the Lutetian. However, the facies quickly turn into a continental aspect with sandy, sandy-clay, clay and sandstone deposits—Fig. 2 and Fig. S2 in the electronic supplementary material (ESM). Its thickness is not uniform and exceeds about 60 m in the south and decreases towards the north where it is only a few metres thick. There are two aquifers on which the research is based: the Mio-Pliocene sands aquifer and the Quaternary aquifer.

Mio-Pliocene sands aquifer

This is a complex aquifer with a water table under unconfined conditions. It is superficially subdivided into three geomorphological subunits represented from east to west by Sakété, Allada (where the aquifer is thicker, 60 m to more than 140 m thick) and Comé (not included in this work). The Mio-Pliocene aquifer is characterised by relatively

deep static water levels that can reach and even exceed 50 m depth, which makes the distribution of aquifer recharge by surface water and meteoric water somewhat heterogeneous, except for the plateau edge zones where the groundwater levels become more or less superficial. This is particularly the case in the southern edge zones, which are also characterised by a greater thickness of the aquifer; therefore, it offers significant yield (pumping flow rates from boreholes) that can reach 300 m³/h and an average transmissivity value of about 4×10^{-3} m²/s (Boukari 1998).

Groundwater in this aquifer was traditionally tapped using wells, but since the early 1980s, tapping has mainly been done using boreholes equipped either with manual pumps for rural areas, or with motorised pumps to supply drinking water networks in urban or semiurban centres. The oldest intensive wellfield is found at Agonkamey (since 1956), known as the Godomey wellfield, and is located in the extreme south-east of the Allada plateau. Another wellfield, called the Ouèdo wellfield, was created in 2014, located about 20 km west of the Godomey wellfield. These wellfields are used to supply water to the metropolitan area

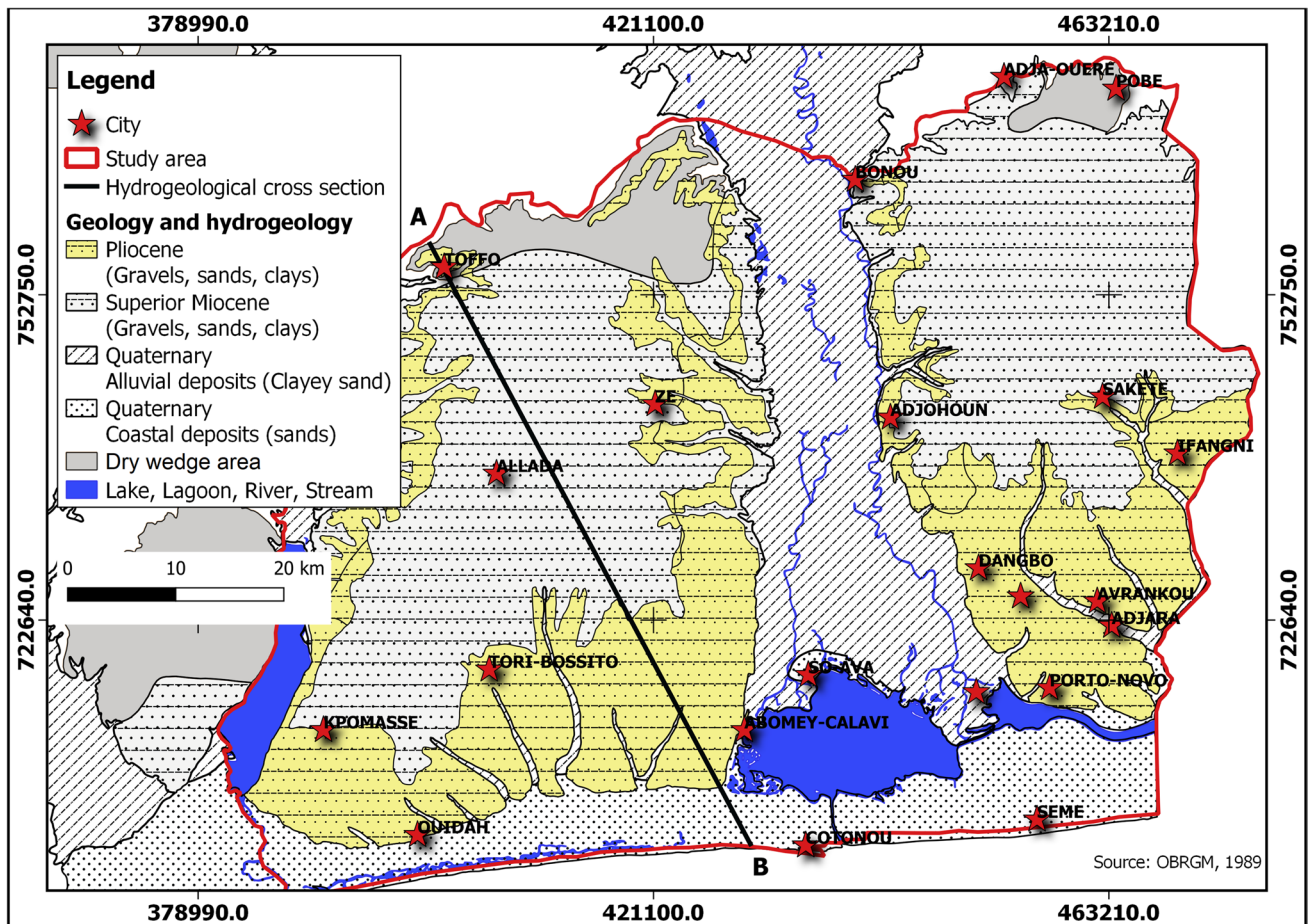


Fig. 2 Geological map of the study area

of Cotonou, the largest city in Benin in terms of population and industry (Boukari 1998).

Quaternary aquifer

The Quaternary aquifer also has a complex structure reminiscent of the Continental Terminal, with alternating sandy or clayey layers that are more or less continuous. In the Benin coastal basin, there are almost always freshwater lenses floating on a saltwater table of marine and/or lagoon origin (Boukari 1998). Below this freshwater/saltwater complex, there is a deep confined aquifer system that extends out under the sea; however, in the east of the basin, this structure of deep and superficial aquifers rather appears as a single aquifer with a free water table. In the alluvial deposits of the great valley of the Ouémé Delta, and probably of the Mono River, the aquifers are often confined under more or less superficial clay layers, resulting in frequent artesian phenomena that occur in the southern part of the valley. The thickness of these alluvial deposits decreases progressively

as one moves upstream, becoming insignificant towards the northern edge of the basin.

The information on groundwater flow direction available on each of the two plateaus indicates that the flow is generally from north to south. However, close to the plateau's edges, the general north–south groundwater flow direction deviates toward the river's valleys and the coastal lagoon, representing the groundwater discharge areas (Boukari 1998; Alassane 2004). It appears that the groundwater head elevation value (m asl) is higher on the Sakété plateau than the Allada plateau, ranging between 85 and about 10 m asl and between 60 and about 5 m asl, respectively.

Materials and methods

In order to achieve the objective of this study, a multi-approach methodology was adopted, involving piezometry, hydrochemistry and isotope analysis. Existing isotopic data were collected from previously reported studies on the lake,

lagoon and Ouémé Stream by Alassane (2018), a study on the springs by Kpégli et al. (2018), and studies on the lake, ocean and rainfall by NOEVA (2019) and AGIRES (2022).

Field activities

Fieldwork was carried out to collect water samples for hydrochemical (major ions) and isotopic (^2H and ^{18}O) analyses. This involved the use of vials, a pH meter, a multiparameter meter, a global positioning system (GPS) device and a groundwater level sounder. The vials were used for samples collection, the pH-meter was to measure water pH, and the multiparameter meter was used to measure in-situ parameters such as electrical conductivity (EC) and temperature. A field campaign to measure the depth to the water table in the wells was also carried out between October and November 2021 to produce a piezometric map. The locations of springs were identified and their flow rates were measured using a graduated container and a stopwatch.

Piezometric surveys

In order to better describe the direction of groundwater flow, static water levels (SWL) were measured in wells of reasonable depth, using an electrical probe (with an accuracy of ± 1 cm). Figure 3 shows the locations of the wells where the static water level measurements took place.

Global positioning system (GPS), Garmin GPS 64S, was used to record the geographical coordinates of the measurement points. The elevations of land surface at the measurement points were extracted from a digital terrain model (DTM) with a geometric resolution of 30 m, using QGIS software. The determined groundwater level head data (see Eq. 1) were used to produce a piezometric contour map of the Mio-Pliocene aquifer, using the SURFER software.

$$h_i = \text{Elv} - \text{SWL} \quad (1)$$

where h_i is groundwater head (m asl), Elv is the land surface elevation (m asl) and SWL is the static water level (m depth).

For the production of the piezometric map, the kriging method was used and the chosen variogram model was validated with the Nash coefficient and the standard observations deviation ratio (RSR), Fig. S3 and Table S1 in the electronic supplementary material (ESM); Moriasi et al. (2007).

Water Sampling

To highlight the interaction between groundwater and surface water, water chemistry is used through analysis of the major ions and the intrinsic isotope composition of the

water molecule (deuterium and oxygen 18; Lee and Kim 2007; Ramita et al. 2020).

Two major water sampling campaigns were carried out, Fig. 3 shows the geographical locations of the sampled points—the first in September to October 2020 (rainy season) and the second in March 2021 (dry season; Fig. 4). These campaigns concerned surface water (river, lagoon and streams) and groundwater (wells, boreholes and springs).

Further sampling was carried out monthly at two strategic points (OU and SO). A total of 136 water samples, including 49 from streams, rivers and brooks, 40 from wells, 26 from boreholes, 12 from springs and 9 from rain catchers, were collected at different times on the two plateaus and along the Sô River, the Ouémé Stream and their tributaries, as well as in the lagoon system.

The applied sampling procedure varied depending on how frequently the wells and boreholes are used by the communities. For rural wells and boreholes that are often pumped during the day, the groundwater samples were taken without any prior purging. Wells and boreholes that are not frequently used by the communities were purged prior to sampling. Purging was considered adequate after stabilisation of in-situ parameters such as temperature, EC and pH. Piezometers were also purged until stabilisation of in-situ parameters—Fig. S4 in the electronic supplementary material (ESM). This ensured that representative samples of the groundwater studied were taken.

Chemical and isotopic analysis

The chemical ions, including cations (Na^+ , K^+ , Ca^{2+} , and Mg^{2+}) and anions (Cl^- , NO_3^- and SO_4^{2-}) were determined by using ion chromatography (Dionex ICS-1000). The bicarbonate ion (HCO_3^-) concentrations were measured by using a titration method (Hach Lange DR 2800) with 0.01N sulfuric acid. The quality of the chemical analyses was checked by running the charge balance error, which was within the $\pm 5\%$ margin.

Stable isotope content ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) analyses were performed on water samples at the Laboratoire de Radio-Analyse et Environnement (LRAE) in Tunisia, using the Laser Absorption Spectrometer LGR DLT 100 with auto sampler (Penna et al. 2010) and mass spectrometry. The abundance of stable isotopes in water indicated by the notation δ is based on isotopic ratios ($^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$) and is expressed in ‰ Eq. (2).

$$\delta^{18}\text{O} \text{ or } \delta^2\text{H} = \left(\frac{R_{\text{Sample}}}{R_{\text{VSMOW}}} - 1 \right) \times 1000 \quad (2)$$

where $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are respectively the ^{18}O and ^2H isotopic signatures. R_{Sample} stands for $^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$ ratio, and R_{VSMOW} stands for the Vienna Standard Mean Ocean

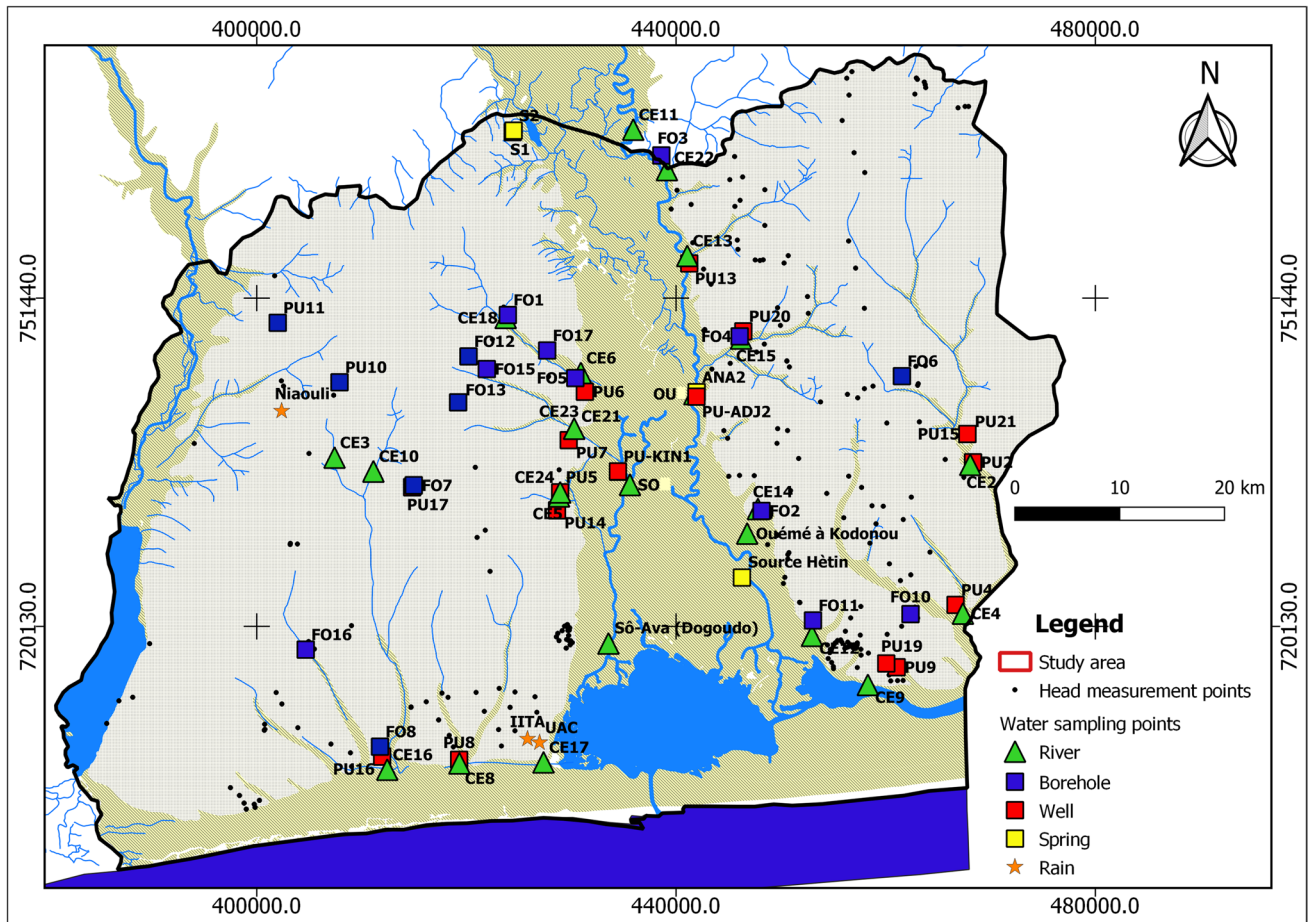


Fig. 3 Locations of water sampling points and groundwater head measurements

Water—absolute VSMOW ratio is $^{18}\text{O}/^{16}\text{O} = 2005.2 \pm 0.45 \times 10^6$ and $^2\text{H}/^1\text{H} = 155.76 \pm 0.05 \times 10^6$ (Klaus and McDonnell 2013). The analytical errors for stable isotopes are ± 0.23 and $\pm 1.00\%$ vs. VSMOW for ^{18}O and ^2H respectively.

To estimate the groundwater discharge into surface water, the following ^{18}O balance equation (Stichler et al. 1986; Mook 2006) was used.

$$\delta^{18}\text{O}_{\text{river}} = X \times \delta^{18}\text{O}_{\text{spring}} + (1 - X) \times \delta^{18}\text{O}_{\text{rain}} \quad (3)$$

Where X is the fraction of groundwater in surface waters and $\delta^{18}\text{O}_{\text{river}}$, $\delta^{18}\text{O}_{\text{spring}}$, $\delta^{18}\text{O}_{\text{rain}}$ are respectively the monthly Oxygen-18 contents in surface water, springs and rainwater, from the same sampling period.

Statistical analysis

Hierarchical cluster analysis (HCA) was used to examine any similarity in chemical composition between surface water and groundwater. Cluster analysis has already proved

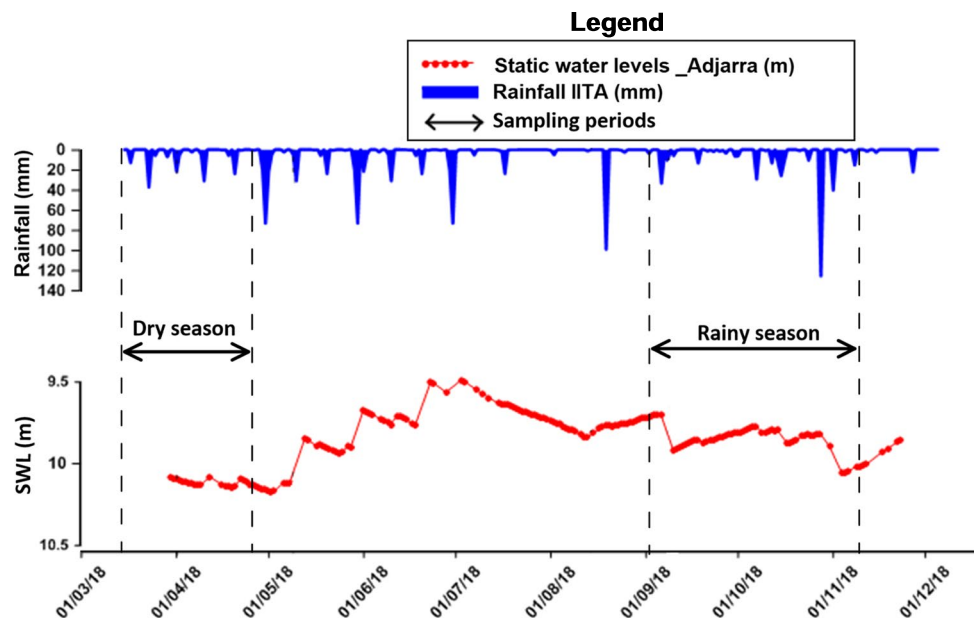
successful in identifying waters with similar chemical or isotopic composition from dissimilar ones (Kumar et al. 2009; Guggenmos et al. 2011; Ganiyu et al. 2018). This approach is based on Ward's linkage method (Ward 1963) with squared Euclidean distances as a measure of similarity between samples (Menció and Mas-Pla 2008; Pathak et al. 2015). The statistical package R version 4.1.2 (2021-11-01) Vienna, Austria, was used for statistical analyses.

Results and discussion

Piezometry

The results from the piezometric survey (October to November 2020) were used to draw the piezometric map of the Mio-Pliocene aquifer (Fig. 5). The piezometric map shows that the groundwater flow direction is generally toward the Ouémé Valley and the south of the study area. In more detail, groundwater flows toward the south and east of the

Fig. 4 Temporal evolution of rainfall at IITA (International Institute of Tropical Agriculture) and static water levels at Adjarra, showing the different sampling periods (NOEVA 2019)



Allada plateau with a hydraulic head of about 64 m asl in the north that significantly decreases to values as low as 4 m asl toward the south and east. The groundwater flow pattern of Sakete plateau is similar to the one of Allada plateau. Hydraulic head is about 96 m asl in the northern part of Sakete plateau and gradually decreases to about 4 m asl in the southern and western parts of the plateau (towards the Ouémé Stream and lagoon).

The piezometric map shows areas of discharge from the Mio-Pliocene aquifer, which is consistent with the location of the springs identified at the borders of the two plateaus linked to the Ouémé Valley. This is an indication that the Mio-Pliocene aquifer discharges in the main rivers of the Ouémé Valley and probably in their tributaries (Achidi et al. 2012; Alassane 2018; Kpégli et al. 2018).

Hydrochemical distribution characteristics

In situ parameters

In situ parameters, namely, temperature, pH and EC in surface waters (collected in the flowing parts of the rivers or streams) and groundwater were measured both in rainy and dry seasons. The temperature of surface waters ranged from 25 to 33.4 °C in the rainy season, while in the dry season the range was 26–34.3 °C. The temperature range of groundwater was 28.2–31.8 °C in the rainy season and 27.2–33.9 °C in the dry season (Table S2 in the electronic supplementary material (ESM)). These values are close to the average atmospheric temperature in southern Benin (about 27 °C) and are an indication of a thermal balance

between groundwater, surface water and the atmosphere (Alassane 2018). EC measured in groundwater ranged from 24 to 548 $\mu\text{S}/\text{cm}$ in the rainy season, and from 27 to 568 $\mu\text{S}/\text{cm}$ in the dry season. Groundwater exhibited higher EC in the dry season compared to the rainy season, except at PU16 (Table S2 in the electronic supplementary material (ESM)). However, in the case of surface waters, the value of EC was low (28–212 $\mu\text{S}/\text{cm}$) in the rainy season, and from 32 to 264 $\mu\text{S}/\text{cm}$ in the dry season. Temperature and EC increase during the dry season in both river water and groundwater while the pH rather decreases.

Hydrochemical type

The main hydrochemical types of the water samples are shown in the Piper diagram (Fig. 6). Five types of chemical facies over the two campaigns are found, with the predominance of Cl-NO₃-Na-K type in the dry season and HCO₃-Ca-Mg in the rainy season. Of the 29 sites where water was sampled in the dry and rainy seasons, the main hydrochemical types are, in order of predominance, Cl-NO₃-Na-K, Cl-NO₃-Ca-Mg, HCO₃-Na-K, SO₄-Ca-Mg and HCO₃-Ca-Mg (dry season) and HCO₃-Ca-Mg, HCO₃-Na-K, Cl-NO₃-Na-K, SO₄-Ca-Mg and Cl-NO₃-Ca-Mg (rainy season). For major anions, chloride (Cl⁻) ranks first in the dry season and bicarbonate (HCO₃⁻) is the most dominant in the rainy season. The main cations are sodium (Na⁺) in the dry season and magnesium (Mg²⁺) in the rainy season.

Several groundwater and surface-water samples show similar hydrochemical types. Also, changes between the two

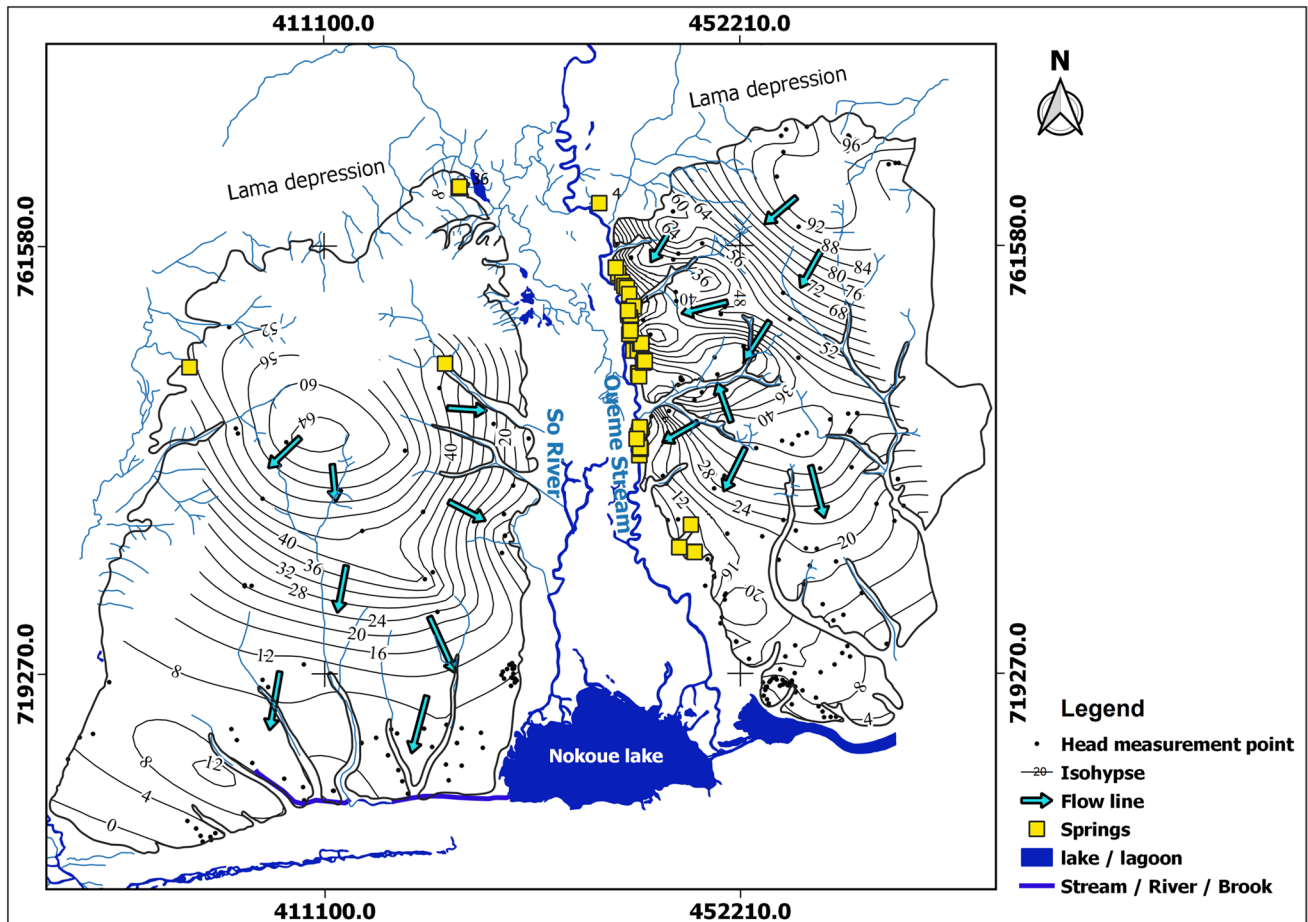


Fig. 5 Piezometric map of the Mio-Pliocene aquifer (October–November 2020); head measurements in m above to sea level (asl)

sampling campaigns were observed. Namely at PU6, PU7, PU13, FO1, FO2, CE2, CE3, CE10 and CE18, a change from $\text{Cl-NO}_3\text{-Na-K}$ in the dry season to $\text{HCO}_3\text{-Ca-Mg}$ in the rainy season occurred. At FO3, FO11, CE4, CE5, CE6 and CE13, a change from $\text{Cl-NO}_3\text{-Ca-Mg}$ in dry season to $\text{HCO}_3\text{-Ca-Mg}$ in the rainy season occurred. At CE12 and FO5, $\text{HCO}_3\text{-Na-K}$ type shifted to $\text{HCO}_3\text{-Ca-Mg}$. At CE11 and FO4, $\text{SO}_4\text{-Ca-Mg}$ type changed to $\text{HCO}_3\text{-Ca-Mg}$. Borehole and river water with a chloride facies (dry season) shifts towards bicarbonate facies (rainy season), indicating a similar change. So, points representing groundwater and surface water are grouped together during the rainy season and similarly during dry season. Hydraulic connectivity could be at the origin of this hydrochemical similarity between groundwater and surface water. However, the previously mentioned changes are not related to the proximity of the groundwater/surface water sites; it could be understood that there is no relationship between hydrochemical change and the distance of the sampled points to the rivers. Some chemical relationships have been used to illustrate this hydrochemical behaviour.

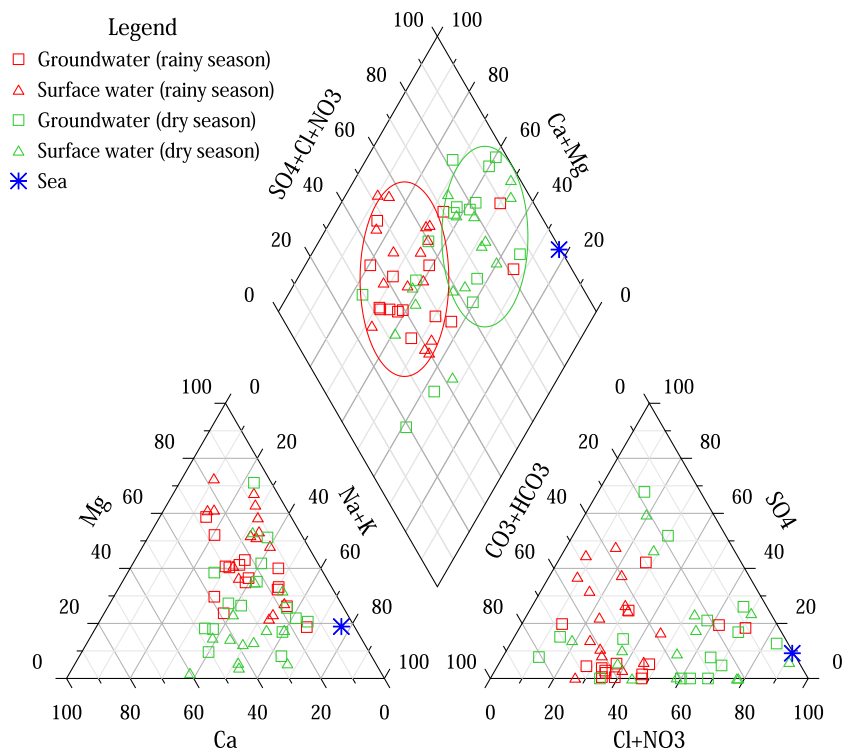
Origins and water mineralisation processes

Clustering of surface water and groundwater samples

For HCA, electrical conductivity (EC), Cl^- , Na^+ , NO_3^- , K^+ , Ca^{2+} , HCO_3^- , pH, Mg^{2+} , and SO_4^{2-} are used as major parameters to identify similarity or interconnection between surface waters and groundwater. All 127 water samples from surface waters, springs and groundwater of both seasons are considered separately for HCA. In the dry season, three clusters, namely 1, 2, and 3, are observed in a dendrogram (Fig. 7a). Cluster 1 consists of the water samples with lower concentrations of Na, K, EC, HCO_3^- , Mg, Cl and Ca. It includes only one borehole site (FO3). Clusters 2 and 3 contain a combination of surface waters and groundwater sites, indicating similarity in selected parameters (Fig. 7a) with higher concentrations of K, HCO_3^- and Na (cluster 2) and lower concentrations of Na, K, EC, HCO_3^- , Mg, Cl and Ca (cluster 3).

Also, three clusters are categorised from the dendrogram of the rainy season (Fig. 7b). Cluster 2 consists only

Fig. 6 Piper diagram showing chemical composition of surface water and groundwater samples in the study area



of surface-water sites (two sites), whereas clusters 1 and 3 contain a combination of surface waters and groundwater sites, indicating similarity in selected parameters (Shrestha and Kazama 2007; Zhong et al. 2018). However, the clusters combining surface waters and groundwater—clusters 1 and 3 from the dry season (Fig. 7a) and clusters 1 and 3 from the rainy season (Fig. 7b), show similarity in selected parameters, indicating interconnection between

surface waters and groundwater (Menció and Mas-Pla 2008; Guggenmos et al. 2011; Huang and Han 2016).

Correlations between chemical elements

The binary correlations between the major ions support the PCA to explain each ion acquisition mechanism.

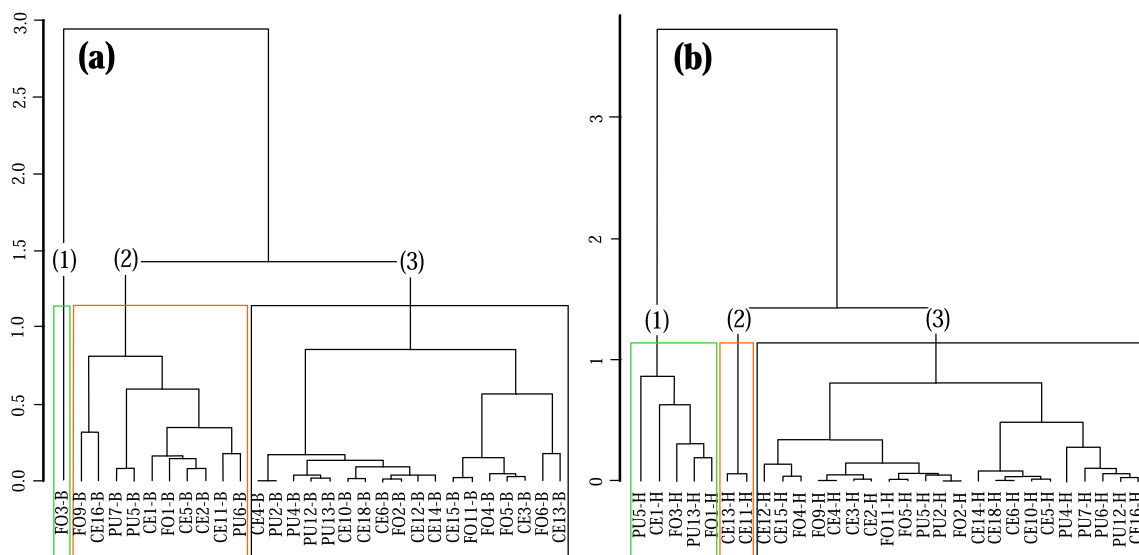


Fig. 7 Dendrogram based on hierarchical clustering (Ward’s method) in **a** dry season and **b** rainy season

Study of the binary correlations allowed the geological and anthropogenic origin of the chemical elements to be determined based on the degree of correlation between them.

Na⁺ vs. Cl⁻ These two chemical elements are often linked to the dissolution of halite (NaCl). The evolution of chloride is studied as a function of sodium content. Figure 8a and b shows an alignment of some points on the halite dissolution line, which is characteristic of halite dissolution in water and confirms the existence of the sodium chloride facies. However, a decrease in the concentration of chloride during rainy season (Fig. 8b) can be observed in both groundwater and surface water.

[Na⁺ + Cl⁻] vs. EC A strong correlation between [Na⁺ + Cl⁻] and EC is observed during both sampling campaigns (Fig. 8e and f). A decrease in [Na⁺ + Cl⁻] is observed in the rainy season in both groundwater and surface water (Fig. 8f). EC increased at some points, while it decreased at others; however, there is a general dilution effect during the rainy season.

[Ca²⁺ + Mg²⁺] vs. [HCO₃⁻ + SO₄²⁻] A slight enrichment of the water in HCO₃⁻ and SO₄²⁻ ions can be observed in the dry season (Fig. 8c). The majority of water samples are more enriched in these ions; otherwise, they

are depleted in Ca²⁺ and magnesium ions in the rainy season (Fig. 8d), at which time ion exchange can be suspected. This phenomenon, already highlighted in other aquifers (Edmund and Cook 1987; Alassane 2018), and observed on the Piper diagram, is the result of an ionic exchange between sodium and potassium. In fact, clays can easily exchange their sodium and potassium ions with the calcium and magnesium of the water. This sodium enrichment can be seen in the Na⁺ vs. Cl⁻ relationship (Fig. 8b).

[(Ca²⁺ + Mg²⁺) - (HCO₃⁻ + SO₄²⁻)] vs. [(Na⁺ + K⁺) - Cl⁻] The base exchange phenomena (Garcia et al. 2001) that takes place in the aquifers is highlighted by the relationship [(Ca²⁺ + Mg²⁺) - (HCO₃⁻ + SO₄²⁻)] versus [(Na⁺ + K⁺) - Cl⁻] as shown in Fig. 8g and h. The subtraction operation carried out between the two parameters ((Ca²⁺ + Mg²⁺) - (HCO₃⁻ + SO₄²⁻)) and [(Na⁺ + K⁺) - Cl⁻], makes it possible to get rid of the ions that may have resulted from other dissolution reactions of carbonate and evaporite minerals. In the absence of these base exchange reactions, all points representing the samples should be near the origin point, according to McLean et al. 2000, as is the case for the major water samples. The calcium deficit and sodium excess characterising a few of the water points sampled during the rainy season can be partly attributed to ion exchange mechanisms. Ca²⁺ ions

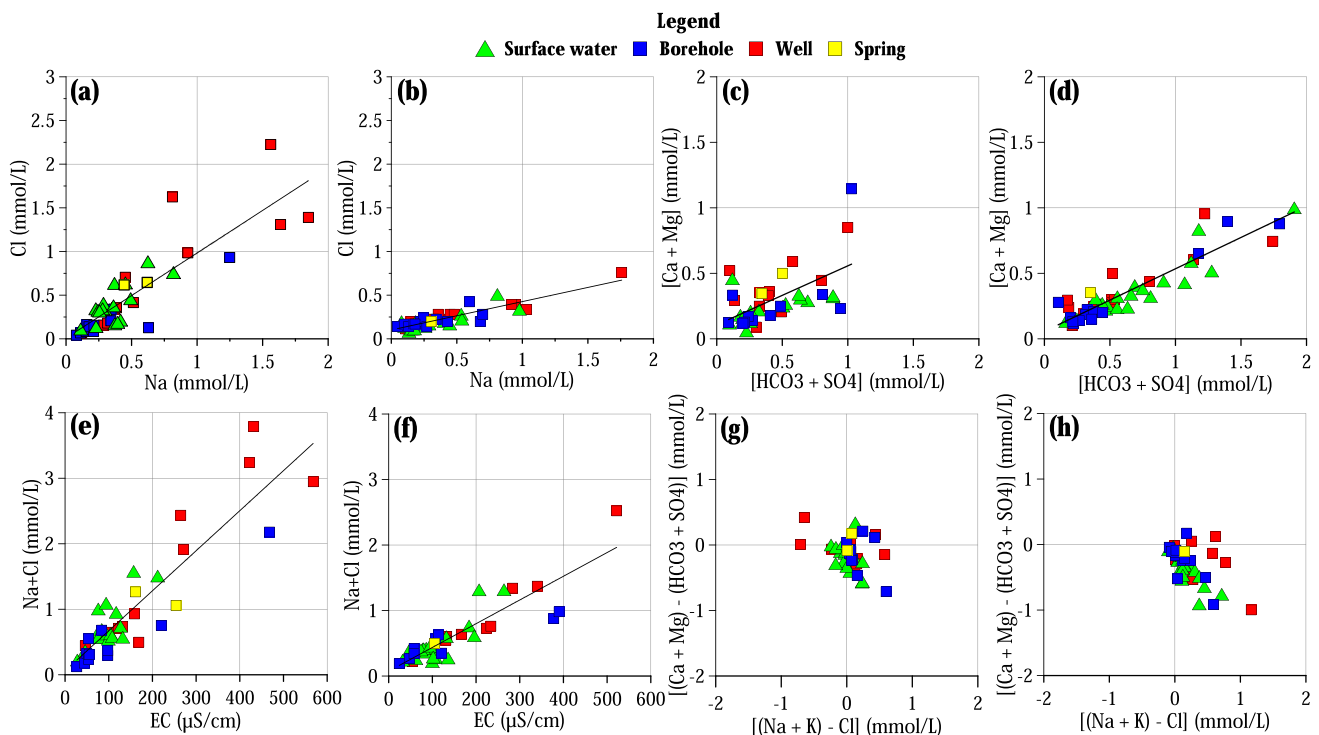


Fig. 8 a–h Binary relationships between chemical elements

are absorbed at the surface of clay minerals against the release of Na^+ ions. This phenomenon could possibly explain the excess of Na^+ ions over Cl^- ions (Fig. 8h).

Stable isotope compositions of hydrogen (δD) and oxygen ($\delta^{18}\text{O}$)

Stables isotopes (^{18}O and ^2H), called the ‘DNA’ of water molecules, do not interact with the aquifer materials (Sidle 1998; Ette et al. 2017). Stables isotopes can help to highlight groundwater/surface-water interactions (Huneau 2000; Kpegli et al. 2015). Therefore, stable isotopes of the water molecule were used in this study to highlight the hydraulic connectivity between groundwater and surface water in the Ouémé Delta. For a better analysis, data from the sampling campaigns are compared with those from previous work—Alassane (2018); Kpegli et al. (2018), NOEVA (2019); AGIRES (2022).

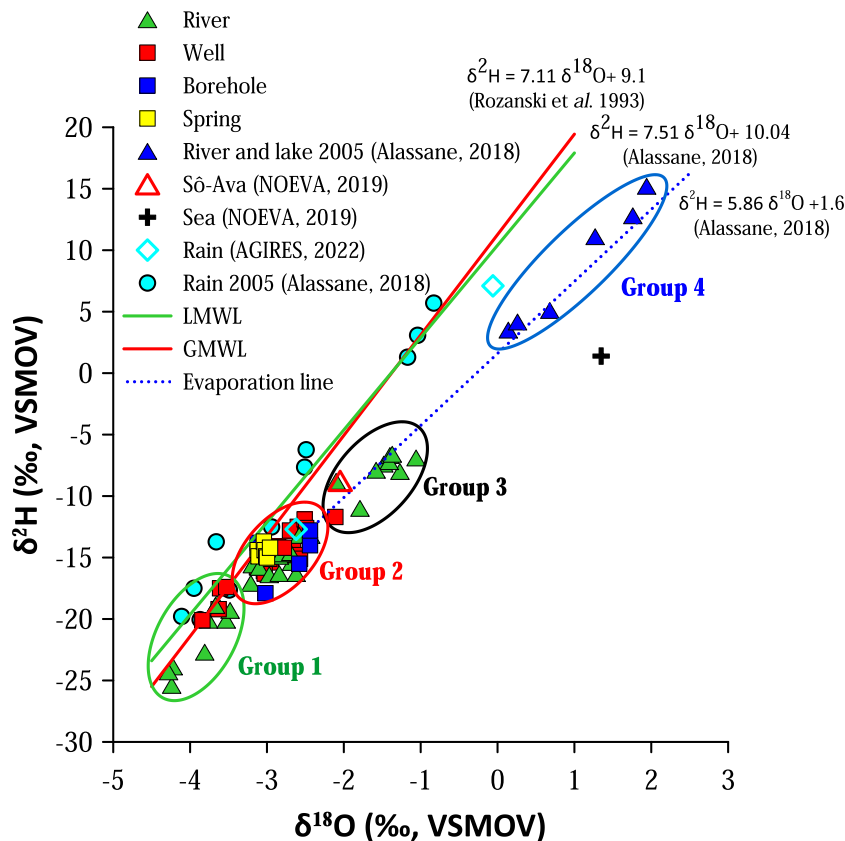
Figure 9 shows the $\delta^{18}\text{O}$ vs. $\delta^2\text{H}$ diagram for groundwater, surface water, spring water and monthly rainfall. It can be seen that the surface waters (lakes and lagoons) sampled in April and May 2005 (dry season, group 4), show highly enriched stable isotope contents compared to rainwater. These months are the months during which evaporation from these water bodies is most intense (Alassane 2018) and this group characterises the isotopic

signature of evaporated water in the Ouémé Delta (contents between -2.05 and 2.48‰ for $\delta^{18}\text{O}$ and between -9.5 and 15.2‰ for $\delta^2\text{H}$).

During this period (dry season), water from the Ouémé Stream, brooks and the Sô River (group 3), in the months of May 2005, December 2020, January and March 2021, are more depleted in ^{18}O and ^2H than the water from the other water bodies mentioned previously. During these same months, low flow rates (5.82 and $3.48\text{ m}^3/\text{s}$) were recorded respectively from the Ouémé Stream and the Sô River (absence of rain). Data from April 2018 (from AGIRES project) show that water from the Sô River (at the north of Lake Nokoué) also presents more depleted contents (-2.05‰ for $\delta^{18}\text{O}$ and -8.77‰ for $\delta^2\text{H}$). However, the points (water from the Ouémé Stream, brooks and the Sô River, group 3) represented on the diagram, are close to the evaporation line, indicating that these waters have been evaporated. Low flow rates recorded and the evaporative effect of the Ouémé Stream waters (Fig. 10a) in this period prove that surface waters are fed by groundwater, which has then undergone evaporation resulting in an enrichment effect.

The groundwater of the Mio-Pliocene aquifer of the Allada and Sakété plateaus, on the other hand, shows relatively homogeneous stable isotope contents (group 2), ranging from -3.13 to -2.44‰ for $\delta^{18}\text{O}$ and from -17.9 to -11.9‰ for $\delta^2\text{H}$. These obtained values are very close to

Fig. 9 Plot of $\delta^2\text{H}$ vs. $\delta^{18}\text{O}$, showing stable isotope signatures of different types of water samples. LMWL = local meteoric water line. GMWL = Global Meteoric Water Line. Reference is given to Rozanski et al. (1993), Alassane (2018), NOEVA (2019) and AGIRES (2022)



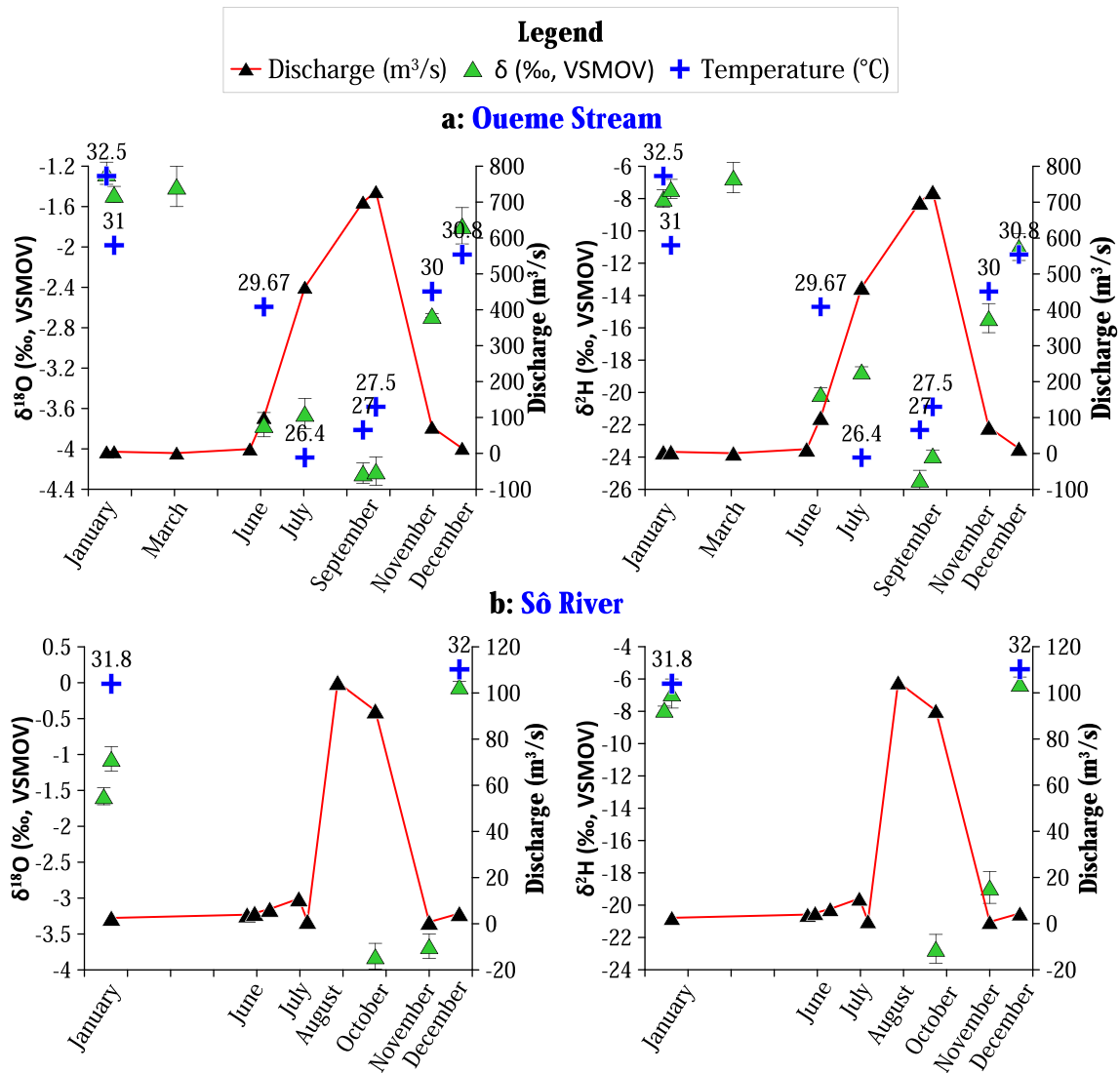


Fig. 10 Relationship between isotopic signatures ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and the flow, **a** Ouémé Stream at Adjohoun and **b** Sô River at Kinto-Oudjra

those obtained in 2005, 2006, 2007, 2008, 2009 and 2010 (Alassane 2018). It is noted that the waters collected from some streams during September, October and November (CE1, CE 2, CE4 CE5, CE6, CE10, CE12, CE14, CE15, CE18, CE21 and OU5), show similar isotopic compositions to those of groundwater collected from wells, boreholes and springs; which could be evidence of groundwater discharging into these streams.

The most isotope-depleted waters are shown in group 1. Two subgroups are identified, namely—Fig. S12 in the electronic supplementary material (ESM):

- Subgroup 1: Includes the waters of the Ouémé Stream (OU3 and OU4), the Sô River (SO1) and the Porto-Novo Lagoon (CE9) sampled in the month of September when

the flows of the Ouémé Stream and Sô River are at their peak (more than 700 and 100 m³/s, respectively), as the floods from the north intervene, as illustrated by Fig. 10, thus it can be said that these surface waters present the signatures of rainwater.

- Subgroup 2: Includes well water (PU-KIN 1, PU-KIN 3, PU-KIN 4 and PU-KIN 5) collected during the months of October, December and January, water from the Ouémé Stream (OU1, OU2, CE11 and CE13) during the months of June, July and October, and water from the Sô River (SO2) collected during the month of November. The well water taken in the dry months has the signature of groundwater. As for the surface water showing similar signatures, one could think of a mixture between groundwater and local rainwater (main rainy season in

May, June and July and short rainy season in September, October and November).

The fraction of groundwater in the Ouémé Stream (see Table 1) ranged from 0 to 21% between June and September (flooding periods for the Ouémé stream, with flow rates ranging from ≈ 100 to $720 \text{ m}^3/\text{s}$, Fig. 10a) and 78–88% between November and December (with lower Ouémé stream flow rates ranging from ≈ 13.99 – $72.93 \text{ m}^3/\text{s}$). The high flow recorded in the rainy months (June–September) is the result of local and northern rainwater, as the groundwater contribution is less than 21% (Table 1). However, from November, up to 78% of the flows recorded come from groundwater, with up to 100% between January and March when there is almost no rainfall (with very lower Ouémé Stream flow rates ranging from ≈ 0.7 to $4.52 \text{ m}^3/\text{s}$). In the Sô River, the proportion of groundwater ranged between 46 to 100% in October, November and December (Table 1). The maximum groundwater discharge into the Sô River occurred in November, when the river had a low flow of $\approx 0.74 \text{ m}^3/\text{s}$ (Fig. 10b), implying that water found in the Sô River during November is totally due to groundwater discharge. The fraction of groundwater in brooks appeared high (66–100%) regardless of the season, revealing that even in the rainy season the surface water found in the

brooks is predominantly due to groundwater discharge (Table 1). The origins of these brooks being located inside the plateaus justify the permanent groundwater discharge from the Mio-Pliocene aquifer through these brooks.

The hydrochemical types, HCA, ion ratios and stable isotope compositions of hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) have been ideal tools in the investigation of groundwater and surface-water interaction. However, the stable isotopes of the water molecule have played a dominant role in this study by the fact that they do not interact with the aquifer materials or human pollution. The hydrochemical parameters also provided good evidence regarding the recognition of the interaction, though it does not seem to correlate well with the stable isotopes. This can be ascribed to the pollution sources, including industrial and agricultural activities in this area, which affect water quality.

The piezometric study is not able to identify the potential areas of interconnection between the groundwater and surface waters, but supports the finding that these intermittent surface waters in the Ouémé Delta would be fed in the dry season by groundwater, because of flow directions indicated by the piezometry map. To sum up, the combination of different methods as in the present case seems to be a good way to study the groundwater/surface-water interactions in this study area and other similar areas.

Table 1 Fraction of groundwater in Ouémé Stream, Sô River and brooks

Parameter	Sampling ID	Sampling month					
		June	July	September	October	November	December
$\delta^{18}\text{O}$ (‰)	Rain	-3.18	-3.79	-4.16	-4.52	0.07	2.43
	Spring	-	-3.12	-3.00	-3.02	-3.04	-3.01
Fraction of groundwater	Oueme Stream (OU)	0	0.21	0	-	0.88	0.78
	Sô River (SO)	-	-	-	0.47	1	0.46
	CE1	-	-	-	0.95	-	-
	CE2	-	-	1	-	-	-
	CE3	-	-	-	1	-	-
	CE4	-	-	1	-	-	-
	CE5	-	-	-	0.87	-	-
	CE6	-	-	-	0.89	-	-
	CE8	-	-	-	1	-	-
	CE10	-	-	-	1	-	-
	CE11	-	-	-	0.66	-	-
	CE12	-	-	-	1	-	-
	CE13	-	-	-	0.69	-	-
	CE14	-	-	-	1	-	-
	CE15	-	-	-	1	-	-
	CE17	-	-	-	1	-	-
	CE18	-	-	-	1	-	-
CE21	-	-	-	1	-	-	

Conclusion

The measurements of hydrochemical parameters (pH, EC, Cl^- , NO_3^- , HCO_3^- , SO_4^{2-} , Na^+ , K^+ , Ca^{2+} and Mg^{2+}) and stable isotopes of the water molecule (^{18}O and ^2H), combined with piezometric measurements, were used to investigate the interconnectivity between surface waters and groundwater along the two river networks (Ouémé Stream and Sô River) in southern Benin. Hydrochemical parameters of surface waters exhibit significant temporal variations compared to groundwater and the results from HCA imply interconnection between surface waters and groundwater in both rainy and dry seasons. Groundwater and surface waters show similar hydrochemical types both in the dry and rainy seasons, and the binary relationships between the different ions have led to the same conclusions. These results are well confirmed by isotopic techniques. Stable isotope analysis of surface waters, which should display enriched stable isotope signatures due to evaporation, has signatures similar to those of groundwater and springs. Similarly, the obtained piezometric maps from the conducted hydrogeological investigations indicated groundwater flow direction towards the Ouémé Valley, as well as towards the coastal lagoon system in the south. In addition, the information given by isotopic techniques and piezometry, especially the groundwater discharge areas, corresponds to the geographical locations of the springs that are identified in the field, which means that results from the different methods coherently support each other.

This study has demonstrated that surface water is significantly recharged by groundwater even in the rainy season. However, the reverse is not found, which implies that groundwater is protected from pollution that could arise from surface-water sources. The results could then be useful to the integrated utilisation and management of groundwater and surface-water resources in the Ouémé Delta and other similar areas. However, this study deserves to be complemented by other investigations, in particular a study using radioactive isotopes such as radon ^{222}Rn , with a short half-life (3.83 days) and a concentration in groundwater often 2–3 orders of magnitude higher than that in surface water; such a study could also be used to estimate the quantity of groundwater discharge into rivers.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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