Sustainable Water Resources Management (2022) 8:162
https://doi.org/10.1007/s40899-022-00737-7

ORIGINAL ARTICLE

# Major ions, trace elements and stable isotope characteristics of shallow groundwater in the Bonaberi district, Douala, Cameroon

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Received: 2 December 2021 / Accepted: 11 August 2022 / Published online: 5 September 2022


**Abstract**

Shallow groundwater of unknown quality, mineralisation and recharge processes is a major source of water supply to most households in the informal settlements in the Bonaberi (Douala IV) district, Cameroon. Accordingly, this study (December 2018) investigated the quality, hydrogeochemical controls, and recharge mechanism of 18 shallow groundwater (< 10 m deep) and 6 surface water sources in Bonaberi. Apart from $Na^+$, $Cl^-$, $SO_4^{2-}$, Fe, Mn, and Al in some water sources, all other analysed chemical parameters were within the WHO (2011) guidelines for drinking water. The order of major ions abundance (meq/l) in the studied water was $Na^{2+} > Cl^- > Ca^{2+} > HCO_3^- > SO_4^2 > K^+ > NO_3^- > Mg^{2+}$ while the trace element abundance (ppb) was Ti > Fe > Mn > Sr > Ba > Al > Rb > Zn > As > Se > Cr. Two main water types identified in Bonaberi are Na-Cl and mixed Ca-Na-$HCO_3$. Mineral weathering and leaching from pit toilets and waste dumps are major factors influencing groundwater composition. Stable isotopes show overlaps in surface water and groundwater, indicating hydraulic connectivity. The narrow ranges in $\delta^{18}O$ values of the shallow groundwater suggest good water mixing and a homogenous aquifer. The major source of groundwater recharge is rainfall occurring by direct diffused rapid recharge through the permeable alluviums. This recharge favours the leaching of pollutants from residential pit toilets into the shallow aquifer. However, the groundwater mixing and its dilution by heavy rains results in relatively low $NO_3^-$ and $Cl^-$ concentrations in the water though relatively higher in densely populated areas. The shallow aquifer in Bonaberi is vulnerable to pollutants generated within the city. Thus, drilling deep boreholes (after detailed hydrogeochemical studies) is recommended for a good quality groundwater supply. This will prevent water-borne infections given the increasing urbanisation.

**Keywords** Shallow groundwater chemistry · Trace elements · Stable environmental isotopes · Bonaberi-Douala · Cameroon

## Introduction

Groundwater plays a pivotal role in social and economic development (Mora et al. 2017; Li et al. 2021). It is an alternate source of water supply for agriculture (Harun et al. 2021) and domestic (drinking) purposes in areas where pipe-borne water or surface water is not available (Zakaria et al. 2022). Potable water contains major ions and small quantities of trace elements essential to the human body, but they can be harmful to humans if in excess (Vetrimurugan et al. 2017). More than 500 million Africans depend on water sources, especially groundwater found close to their communities, for drinking and other domestic purposes (Bonsor et al. 2011). The resource is important in sustaining urban livelihoods and supporting various commercial and agricultural activities (Lapworth et al. 2017; Mora et al. 2017; Harun et al. 2021; Li et al. 2021; Gao et al. 2021). Consequently, groundwater quality studies have received significant attention, especially in urban cities of developing countries, including Mexico (Mora et al. 2017), China (Li et al. 2021), Malaysia (Harun et al. 2021) and Ghana (Zakaria et al. 2022). In Sub-Saharan Africa, where 250 million

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people live in urban centres, groundwater is vital in improving human health (Lapworth et al. 2017). The groundwater, like in the city of Douala (Cameroon), is mainly accessed through hand-dug wells (< 50 m deep) in low-lying coastal terrains (Adelana and MacDonald 2008; Bonsor et al. 2011). Despite this dependence on groundwater, hydrochemical and hydrological investigations, which are vital components of sustainable groundwater resource evaluation and management, are limited in most communities (Adelana and MacDonald 2008; Adelana et al. 2011) like in the Douala IV (Bonaberi) district. The quality of shallow urban groundwater resources is often very low due to poor waste management and source protection. This quality issue poses a significant health risk to users (Lapworth et al. 2017). Onsite sanitation in most cities in developing countries presents significant groundwater quality issues such as $NO_3^-$, $Cl^-$ and trace element contaminations that should be identified and managed (Foster et al. 2010; Mtoni et al. 2013; Mora et al. 2017; Harun et al. 2021). Water drawn from shallow wells is generally used in most households in developing countries without prior knowledge of any potential contaminants (quality) other than an aesthetic assessment.

Shallow groundwater within the Douala coastal city of Cameroon is easily accessible and consequently forms a major source of water supply to most households, especially in the low-income residential areas (Takem et al. 2010; Wirmvem et al. 2017a). Pipe-borne water is available in the city. However, the high costs and recurrent water supply cuts make this commodity available only to a small percentage of the population (Ketchemen-Tandia et al. 2017). The network of pipe-borne water has not been expanded to meet the rapidly growing population in the informal settlement areas. Thus, most of the population relies on shallow groundwater for domestic water supply. Additionally, most households in the informal settlements within the city use pit latrines mostly dug on permeable sandy soils (Ndjama et al. 2008). Solid waste, which in some cases includes faecal material that contains pathogens, is often disposed of in open dumps in the area (Ketchemen-Tandia et al. 2017). These pit toilets and improper waste disposal increase the direct risk of contaminants in the groundwater (Wirmvem et al. 2017a). Consequently, hydrological investigations in the Douala urban city have revealed some $NO_3^-$ and $Cl^-$ contamination (Takem et al. 2010; Eneke et al. 2011; Fantong et al. 2016; Wirmvem et al. 2017a) and bacteriological deterioration (Akoachere et al. 2013; Takem et al. 2010) of this valuable groundwater which is attributed to man-made pollution. However, there is no report on major ion investigation in the shallow aquifer of the Douala IV (Bonaberi) district.

Groundwater contamination by trace metals is one of the most significant environmental issues in the world (Tanji and Valoppi 1989; Levins and Gosk 2008; Kumar et al. 2012; Vetrimurugan et al. 2017), especially in developing countries where it is a vital source of water supply (Lapworth et al. 2017; Mora et al. 2017; Odukoya and Ifarajinmi 2021). Trace metals are chemical elements found in low concentrations in the environment. Some of these trace elements, including Cu, Fe, Mn, Ni and Zn, are essential in life processes, while others like Cr, As, Cd, Pb and Hg, above certain limits, are detrimental to life (Verma and Dwivedi 2013; Vetrimurugan et al. 2017). Sources of heavy metals in groundwater could be geogenic, anthropogenic or both (Tanji and Valoppi 1989; Towfiqul Islam et al. 2017; Vetrimurugan et al. 2017; Harun et al. 2021). Natural contamination occurs when the weathering of minerals in rocks and soils supply heavy metals into the environment (Tanji and Valoppi 1989; Asaah et al. 2006). Meanwhile, anthropogenic contamination of trace elements occurs through several activities, including urban runoff, industrial-household wastes, mining, exhaust-industrial emissions, fertilizers, pesticides and insecticides (Tanji and Valoppi 1989; Asaah et al. 2006; Odukoya and Ifarajinmi 2021).

According to Lapworth et al. (2017), relatively few studies have characterised trace element contamination in urban groundwater within Sub-Saharan Africa. Studies published to date usually report results for only a handful of these elements (e.g., Fe, Mn, Pb, Zn, Ni, V, Cr and Cd) as in Nganje et al. (2020). This limitation is partly due to the cost and access to suitable analytical facilities in the region for multi-elements (ICP-MS or AES) and the relatively poor detection limits for some single element methods (Lapworth et al. 2017). Asaah et al. (2006) have reported soil pollution by some trace elements from urban effluents, mainly from industries in the Bassa Industrial Zone of Douala (Cameroon). However, trace metal concentrations in groundwater and surface water and their potential health consequences in Douala, particularly in Bonaberi, have not been investigated. The Bonaberi district is second to the Bassa Industrial Zone, which hosts many industries in Douala.

Besides quality concerns, the source and mechanism of groundwater recharge also constitute an essential tool for its management (Taylor and Howard 1996; Diaw et al. 2012; Heiderscheidt et al. 2022). Stable isotopes are integral parts of the water molecule and are valuable in groundwater recharge studies (Taylor and Howard 1996) as tracers of groundwater infiltration (Heiderscheidt et al. 2022). The rapid and diffused groundwater recharge from precipitation in the Douala central city has been reported (Ketchemen-Tandia et al. 2007; Fantong et al. 2016; Wirmvem et al. 2017a). However, no studies have been done on groundwater recharge mechanism in Bonaberi. A spatial distribution of major ions and trace elements in groundwater can give an understanding of possible sources of ions/elements and identify the degree of contaminated areas (Towfiqul Islam et al. 2017; Li et al. 2021).

Accordingly, this study attempts to assess the groundwater quality (major ions and trace elements) in Bonaberi, the factors controlling its chemistry and the spatial distribution of the chemical components. It will also determine the origin and recharge mechanism of the groundwater using stable isotopes. The findings will contribute to groundwater management in the increasingly urbanized city of Douala.

## Materials and methods

### Location, climate and drainage

Bonaberi (the study area) is a district (Douala IV) situated at 04°05′ N and 09°38′ E within the city of Douala, covering a surface area of about 44 $Km^2$. Douala IV is bounded north by the Mungo Division; south and east by River Wouri; and west by the Fako Division, where River Mungo naturally separates the two localities. The district is subdivided into several quarters, including Carrefour Music, Bodjongo, Bepelle, Ngwelle, Bonamatoumbe and Bonassama (Fig. 1) and hosts several industries.

Douala is a coastal city found in the Littoral Region of Cameroon in tropical Africa. It is located northeast of the Gulf of Guinea at 04°03′ N and 09°47′ and covers a surface area of about 286 $km^2$. The local climate is equatorial, influenced by monsoon winds from the Gulf of Guinea with 9 months of wet/rainy season (March–November). It has a short dry season from December to February, characterized by little or no rainfall (Wirmvem et al. 2017b; Ketchemen-Tandia et al. 2017). The area is mainly characterized by a mean inter-annual temperature of 27.4 °C and is influenced by Mount Cameroon (4095 m in elevation) in the west. A recent decrease in average annual precipitation occurred in 1982 (Feumba et al. 2011). Metrological data from 1951 to 2015 (65 years) obtained from the Douala Air-port station indicate an average yearly rainfall of 4000 mm in the Douala city. This makes Douala the wettest African urban centre (Ketchemen-Tandia et al. 2017; Emvoutou et al. 2018). The high rainfall in the region is accompanied by

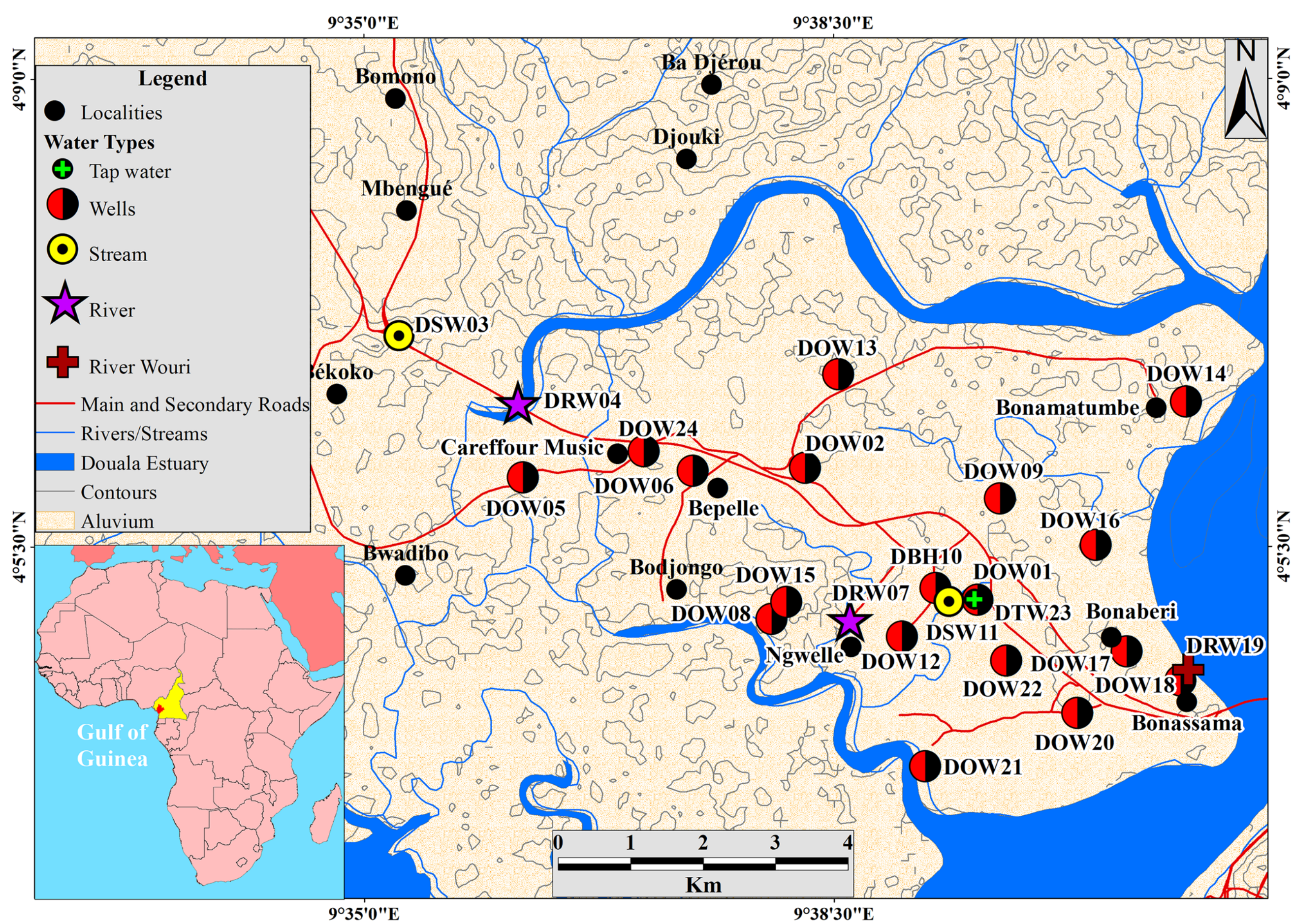


**Fig. 1** Location map of the Bonaberi (Douala IV) district showing the drainage and sampling points. The numbers against water types correspond to the water samples from 1 to 24 in Tables 1, 2 and 3

a dense cloud cover maintaining a persistent high humidity. The maximum monthly relative humidity values vary very little, with an annual average of about 82%. This high relative humidity results from the regularity with which the monsoon winds blow in this part of Cameroon (Ketchemen-Tandia et al. 2017). Moist evergreen mangrove forest covers undeveloped areas of the city (Tening et al. 2013). About 60–75% of the precipitation in the African tropical forest (including Douala) is re-evaporated as continental moisture (Monteny and Casenave 1989). The significance of inland recycled moisture to rainfall in the city has been reported (Ketchemen-Tandia et al. 2013; Wirmvem et al. 2017b). Groundwater recharge in the area is by rainfall, particularly during the monsoon season from April to August and November (Wirmvem et al. 2017a).

The Douala city has a gentle relief, varying from 2 m asl at the shores of River Wouri to 62 m asl in Logbessou, with an average elevation of 21 m asl (Wirmvem et al. 2017a). Rivers Wouri and Dibamba are perennial and constitute the primary drainage system in Douala. The former flows from the northwest to the southwest of the city between Akwa and Bonaberi, while the latter flows through the eastern part of Douala. These rivers are fed by numerous first- and second-order streams (Fig. 1) that are usually loaded with solid and liquid wastes from factories/industries, households and open garbage dumps (Wirmvem et al. 2017a; Ketchemen-Tandia et al. 2017). The rivers eventually dump their content into the Atlantic Ocean (Tening et al. 2013). Human activities include subsistence agriculture in the outskirts and industrial activities in the central city. This city hosts over 80% of industries in the country, including fertilizer, cement, soap, chemicals, brewery, glass and shipyard companies (Ketchemen-Tandia et al. 2017; Akoachere 2019). Collective sanitation, found only in some parts of the city, is non-functional due to a lack of implementation/maintenance of the operating systems. Effluents from the industries are mostly discharged directly into the immediate environment (Ketchemen-Tandia et al. 2017).

## Geological and hydrogeological settings

The study area forms part of the Douala sedimentary basin. This basin has a 5 km-thick sequence of unconsolidated to semi-consolidated sedimentary rocks. Stratigraphically from the bottom to top (i.e., the oldest to the youngest), there are the Mundeck, Logbadjeck (Mungo River Formation), Logbaba, N'kapa, Souellaba, Matanda and Wouri formations (Regnoult 1986). Many authors have described the continuous stratigraphic section of the Douala basin (Regnoult 1986; Tamfu et al. 1995; Mafany 1999; Takem et al. 2010; Fantong et al. 2016; Emvoutou et al. 2018). Figure 2a, b show a chronostratigraphic sequence and cross-section of the basin, respectively. From the sequence, the basin, which sits on the Precambrian basement, ranges in age from the Aptian (Lower Cretaceous) in the Moundeck Formation to Pleistocene (Quaternary) in the Wouri Formation (Fig. 2a). According to Takem et al. (2010), the primary lithologies of the basin include conglomerate, sandstone, limestone, shale, and alluvium (Fig. 2a). Yellow through brown to black sandy ferralitic soil overlies the sandy-clayey subsoil in the area (Asaah et al. 2006). Contrary to the other marginal basins around the south Atlantic, the Douala basin lacks massive Albian carbonates and thick regional salt (Tamfu et al. 1995), as recently confirmed by hydrogeochemical studies in the city (Fantong et al. 2016; Wirmvem et al. 2017a).

Regnoult (1986) has reported four primary aquifer units in the Douala basin (Fig. 2a). These have been classified based on depth into shallow-Pleistocene alluvium and Pliocene sands (< 50 m) and deep-Paleocene sands and Cretaceous basal sandstone (> 50 m) aquifers (Takem et al. 2010). The deep Cretaceous basal sandstone lies between the Precambrian granites, shales and marls of the Logbaba Formation. Above the Logbaba Formation are Paleocene sands that lie on the shales and marls of the Souellaba Formation emplaced during the Eocene (Fig. 2a, b). Djeuda-Tchapnga et al. (2001) have reported groundwater discharge of about 250 $m^3$/hr/well in the roughly 200 m thick Paleocene sand aquifer, exploited by most companies, including Guinness Cameroon.

Overlying the Mio-Pliocene sands is the Pleistocene alluvium, composed of quartz and kaolinite. This sand and alluvium constitute the shallow aquifer of the Wouri Formation within which Bonaberi is located (Regnoult 1986; Eneke et al. 2011). The aquifer's materials consist of fine to coarse-grained sand and gravel mixed with minute quantities of clay (Fig. 2a) and lie on the Miocene shale (an aquiclude) belonging to the Matanda Formation (Mafany 1999; Ketchemen-Tandia et al. 2007). Several lentils of channel-filled sands hosted in the minute clay layers occur in the Wouri Formation and serve as perched aquifers (Mafany 1999). The dominant minerals include quartz with minor ilmenite, magnetite, muscovite, hypersthenes, sillimanite, epidote and sphene (Regnoult 1986). Pockets of clay lenses separate the Mio-Pliocene sands and the Pleistocene alluvium; thus, they are hydraulically connected (single aquifer). This connectivity observed from field measurements and chemical analyses subject the primary aquifer to pollution from the surface (Ketchemen-Tandia et al. 2007).

Within the Pleistocene alluvium aquifer, the water table has been observed to be less than 10 m below ground level (Mafany (1999; Neh et al. 2015; Wirmvem et al. 2017a) and even less than 1 m below the ground (Wirmvem et al. 2017a; Emvoutou et al. 2018). Groundwater level fluctuation ranges between 0.3 and 2.1 m between the dry and rainy seasons in this aquifer (Takem et al. 2010). High borehole discharges of about 80 $m^3$/hr/ well have been reported in the Pleistocene

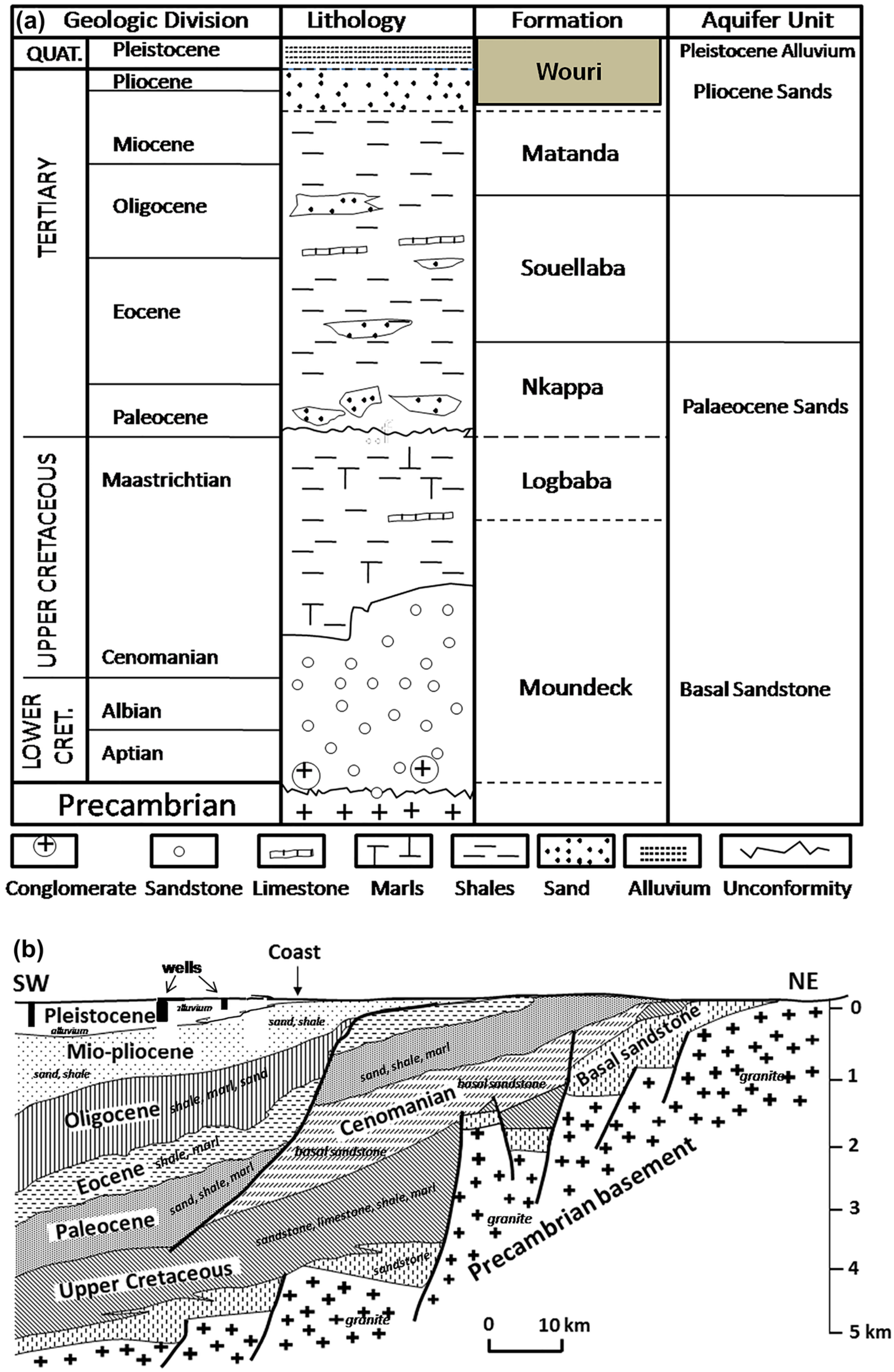


Fig. 2 A chronostratigraphic sequence (modified after Takem et al. 2010) (**a**) and cross-section (modified from Fantong et al. 2016) (**b**) of the Douala Basin. The sequence shows four major aquifer units in the basin including the shallow-Pleistocene alluviums and Pliocene sands of the Wouri Formation (**a**). Bonaberi is part of this Formation. The investigated shallow groundwater taps water from the Pleistocene alluvium (**b**)

alluvium and Mio-Pliocene sands aquifers (Djeuda-Tchapnga et al. 2001). Water discharges from this aquifer as springs have contributed to the base flow of many streams and the Wouri River (Emvoutou et al. 2018). Majority of shallow wells owned by most households are found within the Pleistocene alluviums and Mio-Pliocene sands (Mafany 1999; Ketchemen-Tandia et al. 2007; Fantong et al. 2016; Wirmvem et al. 2017a). The study area (Bonaberi) is part of the Wouri Formation, where the permeable and unconfined aquifer materials expose the groundwater to anthropogenic activities. All the investigated wells tap water from the sands of the Pleistocene alluvium aquifer (Fig. 2a, b).

### Water sampling and analyses

A field campaign was conducted in January 2018, where 24 water samples were collected from 17 shallow open wells, a borehole, 5 rivers and tap water (Fig. 1) in triplicates. Apart from the tap water, the criteria for selecting the other water types included sampling from sparsely and densely populated areas and active wells under daily use by the population. Two of the three collected samples per point were filtered into 50 ml bottles using plastic syringes fitted with 0.45 µm low-adsorption cellulose acetate membrane filters. The non-filtered samples were used for stable isotope analysis, while the duplicate filtered samples were used for major cations and trace elements (acidified); and major anions (non-acidified) analyses. The water sampling, alkalinity determination, major ions and stable isotope analyses (in Tokai University, Japan) were done following the method described in Wirmvem et al. (2017a). Trace elements, including Li, Be, Al, Ti, V, Cr, Mn, Fe, Co, Cu, Zn, As, Se, Rb, Sr, Ag, Cd, Cs, Ba, Hg, TI, and Pb were analysed in the same institution using an ICP-MS. Blanks were simultaneously run with the samples to ensure the accuracy and consistency of analytical results. Ionic balance calculations for major ions in 75 and 92% of the samples were within ± 5 and ± 10%, respectively.

Results of the analyses were treated using various statistical packages, including Excel, SPSS 22.0 and Diagrammes. Element distribution maps were drawn using ArcGis 10.4.1 and Surfer 13. For each software used, data in Microsoft Excel were imported and gridded. These grids were further imported into each given software and contoured to produce the maps in UTM coordinate system.

## Results and discussion

### Major ions in groundwater and surface water

The physicochemical composition of the investigated water (Table 1) showed a wide range in the chemical composition, particularly $Na^+$, $Cl^-$ and $SO_4^{2-}$. This wide variation suggests a large spatial heterogeneity of the water chemistry (Mora et al. 2017). The average temperature of the studied groundwater was 28.31 °C which is close to the mean annual ambient temperature of 27 °C in Douala. This similarity in temperature suggests the influence of current atmospheric conditions in the aquifer. The range in pH values from 4.70 to 6.80 with a mean value of 5.82 in the groundwater suggests an acidic aquifer system. Similar low pH values have been recorded in the Douala basin since 1998 (Takem et al. 2010). Recent studies confirm the acidity of the aquifer (Wirmvem et al. 2017a; Emvoutou et al. 2018), linked to groundwater acidification. Ketchemen-Tandia et al. (2007) attributed this acidification to silicate hydrolysis and decomposition of organic matter into the shallow aquifer. From the results, DRW19 (River Wouri sample), DRW07, and DSW11 (stream) at Ngwelle quarter with salty tastes had remarkably high EC/TDS, $Na^+$ and $Cl^-$ values more than other water sources investigated (Table 1). These high values and the salty tastes suggest their possible interaction with seawater from the Atlantic Ocean. Remarkably, open well OW06 with a brown-yellowish colour had exceptionally high $SO_4^{2-}$ (851 mg/l), suggesting anthropogenic contamination likely from industrial waste given that Bonaberi is an industrial area. The order of major ions abundance in the groundwater and surface water (in meq/l) was $Na^{2+} > Cl^- > Ca^{2+} > HCO_3^- > SO_4^{2-} > K^+ > NO_3^- > Mg^{2+}$.

From the Piper plot, Na + K (alkali metals) exceeded Ca + Mg (alkali earth metals) while $SO_4$ + Cl (strong acids) surpassed $CO_3 + HCO_3$ (weak acids) in most groundwater sources. The main hydrochemical facies were Na-Cl (open wells and rivers) and mixed Ca-Na-$HCO_3$ (mainly open wells). River Wouri (DRW19) and two surface water sources (DRW07 and DSW11) at Ngwelle plotted much close to seawater (Fig. 3). This observation further suggests seawater's influence on their chemistry. Unlike most groundwater, the open well (DOW6) at Bepelle Block 3 with very high $SO_4^{2-}$ (Table 1) was distinctively $CaSO_4$ (Fig. 3). As previously observed (Wirmvem et al. 2017a), the tap water (DTW23) originating from River Mungo was Ca-Mg-$HCO_3$ water, while the tap water type indicates freshwater. The Na-Cl and Ca-$SO_4$ water types are pollution indicators (Jalali 2009; Ketchemen-Tandia et al. 2017). The variation in water types and mineralisation suggest that different processes account for the groundwater chemistry in the Bonaberi area. Water–rock interactions and human activities generally influence the chemical composition of groundwater (Petrides and Cartwright 2006; Jalali 2009).

### Hydrochemical controls on major ions

Ratios between ionic species in water have been used to determine the sources of ions in water and processes that produce the chemical species (e.g., Revelle 1941; Jalali 2009; Diaw et al. 2012; Wirmvem et al. 2017a; Gao et al. 2021). In Bonaberi, 80% of the investigated groundwater samples had $Na^+/Cl^-$ molar ratios > 1 (Table 2, Fig. 4) with an average ratio of 2.05. This high $Na^+/Cl^-$ ratios > 1 suggest a $Na^+$ source other than halite dissolution or seawater intrusion into the groundwater. The high enrichment in $Na^+$ relative to $Cl^-$ suggests silicate dissolution and/or ion exchange as the main processes controlling $Na^+$ in the water (Diaw et al 2012) as reported in groundwater from the central city of Douala, very close to Bonaberi (Wirmvem et al. 2017a). Like in the Piper diagram, the $Na^+/Cl^-$ molar ratios of River Wouri (DRW19) and the two surface waters (DRW07 and

**Table 1** Physico-chemical composition of groundwater and surface water in the Bonaberi shallow aquifer sampled during the dry season (January 2018)

| Location | Name | Water type | AT (℃) | wT (℃) | EC (µS/cm) | TDS (mg/l) | pH | Dtw (m) | $Na^+$ (mg/l) | $K^+$ (mg/l) | $Ca^{2+}$ (mg/l) | $Mg^+$ (mg/l) | $F^-$ (mg/l) | $Cl^-$ (mg/l) | $NO_3^-$ (mg/l) | $SO_4^{2-}$(mg/l) | $HCO_3^-$ (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grand hangar | DTW23 | Tap | 33 | 30.2 | 127 | 63 | 7.4 | 0.0 | 6.8 | 3.6 | 8.0 | 5.3 | 0.1 | 2.5 | 1.9 | 13.6 | 47.9 |
| Ngwelle block 2 | DBH10 | Borehole | 32 | 29.2 | 650 | 324 | 6.2 | 10.0 | 39.6 | 15.8 | 27.3 | 2.5 | 0.1 | 71.3 | 48.1 | 60.9 | 143.0 |
| Grand Hangar | DOW01 | Well | 31 | 27.0 | 470 | 234 | 6.7 | 0.0 | 29.7 | 18.5 | 27.7 | 5.8 | 0.4 | 34.8 | 0.2 | 1.9 | 139.9 |
| Ndobo | DOW02 | Well | 21 | 27.1 | 190 | 95 | 5.7 | 1.2 | 20.2 | 10.0 | 10.8 | 0.6 | 0.1 | 22.1 | 36.2 | 13.9 | 9.9 |
| Mink-welle | DOW05 | Well | 33 | 27.6 | 55 | 27 | 5.4 | 0.5 | 5.0 | 1.5 | 3.7 | 0.4 | 0.1 | 3.7 | 0.2 | 5.9 | 12.4 |
| Bepelle block 3 | DOW06 | Well | 34 | 28.9 | 1650 | **822** | 6.2 | 0.2 | 57.3 | 17.5 | 75.1 | 50.0 | 0.2 | 13.1 | 1.1 | **851** | 58.9 |
| Ngwelle | DOW08 | Well | 35 | 31.4 | 221 | 110 | 6.4 | 0.5 | 19.4 | 5.8 | 22.0 | 2.1 | 0.1 | 24.3 | 3.0 | 37.3 | 40.4 |
| Sodiko | DOW09 | Well | 32 | 26.9 | 133 | 66 | 4.8 | 1.4 | 15.5 | 4.9 | 4.4 | 0.4 | 0.1 | 16.4 | 38.3 | 3.3 | 0.1 |
| Ngwelle block | DOW12 | Well | 31 | 28.2 | 185 | 92 | 5.2 | 3.5 | 25.2 | 5.7 | 4.3 | 0.6 | 0.1 | 39.2 | 35.9 | 5.8 | 6.0 |
| Bonan-dale | DOW13 | Well | 31 | 27.3 | 36 | 18 | 4.7 | 1.1 | 7.3 | 1.1 | 1.1 | 0.1 | 0.3 | 6.6 | 17.7 | 0.2 | 0.1 |
| Bonama-tumbe | DOW14 | Well | 31 | 28.9 | 38 | 19 | 5.4 | 0.5 | 16.0 | 2.9 | 1.9 | 0.4 | 0.2 | 4.6 | 0.9 | 6.0 | 33.5 |
| Bojongo | DOW15 | Well | 32 | 28.6 | 37 | 18 | 5.7 | 0.6 | 9.1 | 2.9 | 3.2 | 0.2 | 0.2 | 4.6 | 0.3 | 3.7 | 25.9 |
| Ancienne route | DOW16 | Well | 34 | 27.6 | 87 | 43 | 5.6 | 0.7 | 14.9 | 3.6 | 8.7 | 0.9 | 0.3 | 4.5 | 14.5 | 9.7 | 35.0 |
| Bonami-kano | DOW17 | Well | 34 | 28.9 | 300 | 149 | 5.8 | 0.6 | 37.2 | 11.2 | 15.9 | 0.5 | 0.1 | 51.1 | 44.4 | 31.9 | 20.3 |
| Bonas-sama | DOW18 | Well | 32 | 28.6 | 265 | 132 | 5.9 | 0.3 | 25.3 | 12.7 | 18.1 | 1.8 | 0.3 | 27.4 | 25.7 | 38.5 | 31.7 |
| Nkumba | DOW20 | Well | 33 | 28.1 | 155 | 77 | 6.1 | 0.7 | 20.5 | 12.4 | 16.5 | 1.0 | 0.2 | 29.3 | 42.1 | 22.4 | 20.1 |
| Alpicam | DOW21 | Well | 33 | 28.8 | 470 | 234 | 6.8 | 0.2 | 26.9 | 14.9 | 56.0 | 5.4 | 0.1 | 30.8 | 0.1 | 1.3 | 209.8 |
| Foret Bar | DOW22 | Well | 33 | 28.7 | 500 | 249 | 6.2 | 0.4 | 55.3 | 22.3 | 25.5 | 1.3 | 0.1 | 92.4 | 44.7 | 29.2 | 37.6 |
| Careffour music | DOW24 | Well | 27 | 27.7 | 352 | 175 | 6.0 | 0.5 | 30.6 | 20.9 | 24.9 | 2.5 | 0.2 | 42.3 | 45.0 | 47.0 | 29.2 |
| Bekoko | DSW03 | Stream | 32 | 26.6 | 109 | 54 | 5.5 | 0.0 | 22.4 | 0.5 | 0.2 | 0.1 | 0.1 | 0.4 | 0.2 | 0.7 | 54.2 |
| Yabaki | DRW04 | River | 33 | 28.0 | 36 | 18 | 6.1 | 0.0 | 3.9 | 1.1 | 1.8 | 1.0 | 0.1 | 5.5 | 0.1 | 4.0 | 9.9 |
| Ngwelle | DRW07 | River | 34 | 29.7 | 5540 | **2761** | 6.3 | 0.0 | **1176** | 63.0 | 44.3 | 121.0 | 0.1 | **2055** | 3.4 | 203.8 | 36.5 |

**Table 1** (continued)

| Location | Name | Water type | AT (°C) | wT (°C) | EC (µS/cm) | TDS (mg/l) | pH | Dtw (m) | $Na^+$ (mg/l) | $K^+$ (mg/l) | $Ca^{2+}$ (mg/l) | $Mg^+$ (mg/l) | $F^-$ (mg/l) | $Cl^-$ (mg/l) | $NO_3^-$ (mg/l) | $SO_4^{2-}$ (mg/l) | $HCO_3^-$ (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ngwelle block 25 | DSW11 | Stream | 31 | 29.1 | 2990 | **1490** | 6.9 | 0.0 | **494** | 48.0 | 49.1 | 51.6 | 0.2 | **959** | 15.9 | 79.5 | 133.2 |
| Bonas-sama | DRW19 | River | 32 | 30.3 | 1750 | **872** | 6.8 | 0.0 | **269.2** | 16.3 | 12.2 | 32.8 | 0.1 | **568** | 4.1 | 78.3 | 59.2 |
| | Minimum | | 21 | 26.6 | 36.0 | 17.9 | 4.7 | 0.0 | 3.9 | 0.5 | 0.2 | 0.1 | 0.1 | 0.4 | 0.2 | 0.2 | 0.1 |
| | Maximum | | 35 | 31.4 | 2990 | 1490 | 6.9 | 3.5 | 494.1 | 48.0 | 75.1 | 51.6 | 0.4 | 959.4 | 45.0 | 851.1 | 209.8 |
| | Mean | | 31.6 | 28.2 | 414.0 | 206.3 | 5.8 | 0.6 | 46.8 | 10.9 | 18.5 | 6.3 | 0.2 | 70.6 | 18.3 | 59.7 | 45.4 |
| | Standard deviation | | 3.1 | 1.1 | 703.4 | 350.5 | 0.6 | 0.8 | 106.3 | 11.2 | 20.5 | 15.3 | 0.1 | 210.3 | 18.6 | 187.4 | 54.1 |

DRW19 is River Wouri; bold values are above the WHO (2011) guideline values for drinking water. The detection limits for cations and anions were 0.03 and 0.01, respectively

*AT* atmospheric temperature, *wT*, temperature, *Dtw* depth to water,

DSW11) plotted much closer to that of seawater (Fig. 4), clearly indicating their connection with water from the Atlantic Ocean, particularly during tidal movements. Amazingly, an open well (DOW08), very close to DRW07 (Fig. 1), had a $Na^+/Cl^-$ ratio of 1.23, suggesting a more negligible effect of seawater intrusion on its composition. Meanwhile, the open well (DOW12) closer to DSW11 had a $Na^+/Cl^-$ ratio of 0.99 (Table 2), indicating some hydraulic connection with DSW11 that is intruded by seawater. Thus, varied controls, including silicate weathering and intrusion by rivers affected by tidal movements, influence the concentration of salts in the Bonaberi shallow aquifer.

The extent of salinisation in the aquifer was determined using the mass ratios of $Cl^-/HCO_3^-$ vs. $Cl^-$ (Fig. 5). According to Revelle (1941), the $Cl^-/HCO_3^-$ ratios < 0.5, 0.5–6.6 and > 6.6 indicate water unaffected, moderately affected and strongly affected by salinisation, respectively. In this study, the $Cl^-/HCO_3^-$ ratios in 5 (21%) of the samples, including River Wouri (DRW19), the 2 surface water samples (DRW07 and DSW11), were strongly affected by saline water, most likely from the Atlantic Ocean (Table 2; Fig. 5). Two open wells (DOW09 and DOW13) also plotted in the strongly affected portion but had relatively low $Cl^-$ values than DRW19, DRW07 and DSW11. Apart from the River Wouri sample and DRW07 with low $NO_3^-$ concentrations of 4.1 mg/l and 3.4 mg/l, respectively, the other 3 water samples (DOW09, DOW13, DSW11) had relatively high $NO_3^-$ values > 15.9 mg/l (Table 1). These high $NO_3^-$ values suggest that besides saline water from the Atlantic Ocean, anthropogenic activities in the area also contributed to their salinisation. Most groundwater (79%) samples with relatively high $NO_3^-$, $SO_4^{2-}$/or $Cl^-$ values plotted in the moderately affected and not affected fields (Fig. 5), indicating a low degree of salinisation. Hence, the chemical enrichment of groundwater in the Bonaberi aquifer is mainly due to mineral dissolution from rocks and anthropogenic controls given the $NO_3^-$ content other than seawater intrusion as recently observed elsewhere in the Wouri Estuary at Youpwe, Douala (Ramatlapeng et al. 2021).

Various chemical processes occur during rock-water interaction, such as weathering and dissolution, ion exchange processes, oxidation and reduction (Elango and Kannan 2007). In this study, the excess of $Na^+$ over $Cl^-$ implies that the meteoric NaCl is not the only source of $Na^+$ and indicates feldspar dissolution (Petrides and Cartwright 2006). Thus, the higher $Na^+/Cl^-$ ratios are probably associated with weathering of Na-feldspars (silicates) in the aquifer. The $Ca^{2+}$ was the most abundant cation after $Na^+$ followed by $HCO_3^-$ and $SO_4^{2-}$. Table 2 shows the dominance of $Ca^{2+}$ over $SO_4^{2-}$ in 79% of the samples indicating a $Ca^{2+}$ source other than gypsum, probably calcite/dolomite or the silicates (Hounslow 1995).

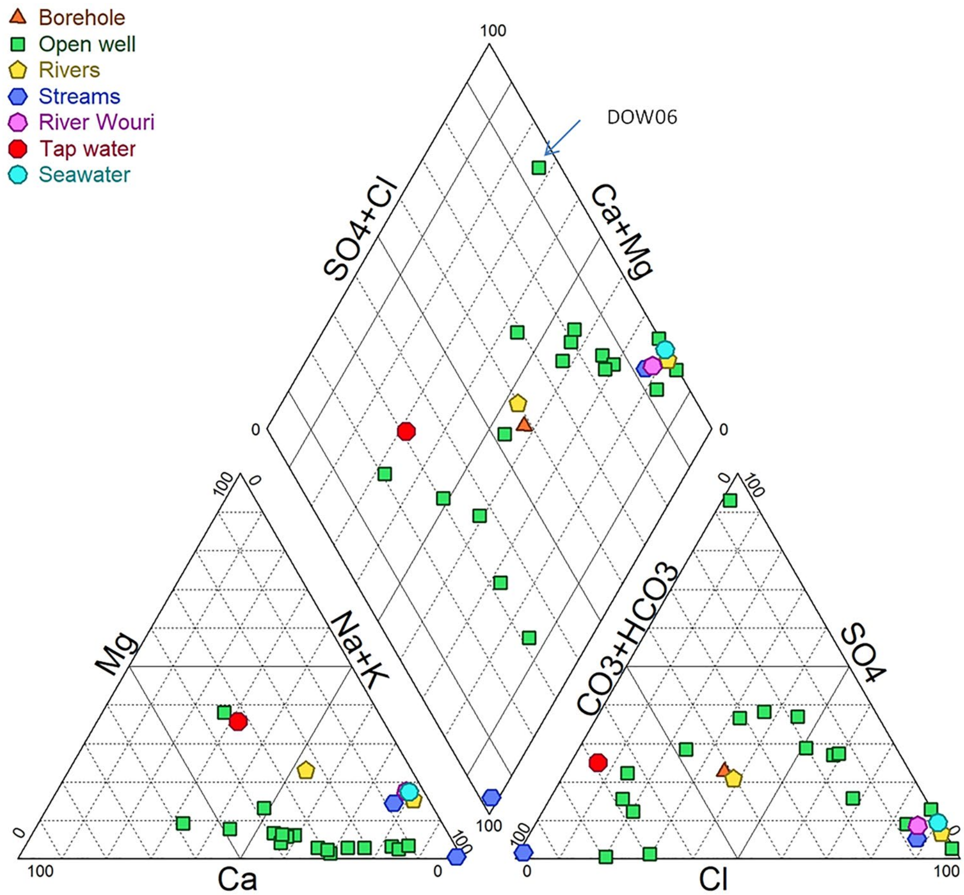


**Fig. 3** Piper plot showing the main water types in Bonaberi. Two main facies are Na-Cl in shallow open wells and rivers, and Ca-Na-$HCO_3$ in the open wells. Open well DOW06 is distinctively a $CaSO_4$ water type

To further determine the main source of ions in the groundwater, the molar ratios of $Mg^{2+}/Ca^{2+}$ versus $Na^+/Ca^{2+}$ were calculated (Table 2). These ratios in limestone, dolomite and silicates are about 0.03 and 0.005, 1 and 0.01 (Han and Liu 2004) and 1 and 1.73 (Mtoni et al. 2013), respectively. In seawater, the $Mg^{2+}/Ca^{2+}$ and $Na^+/Ca^{2+}$ are about 5 and 22.5, respectively (Mtoni et al. 2013). In this study, the $Mg^{2+}/Ca^{2+}$ and $Na^+/Ca^{2+}$ molar ratios varied from 0.05 to 4.51 and 0.42 to 90.05, in that order (Table 2), with most samples plotting closer to the silicate portion and further away from dolomite and limestone ratios (Fig. 6). Thus, silicate dissolution through weathering processes provides a high proportion of dissolved loads and controls major ions composition in the Bonaberi aquifer as recently reported in the central city of Douala (Wirmvem et al. 2017a; Emvoutou et al. 2018; Ramatlapeng et al. 2021). There is no contribution from carbonates, but the influence of seawater on River Wouri (DRW19) as well as the surface waters (DRW07 and DSW11) is apparent (Fig. 6).

## Anthropogenic contamination and spatial distribution of major ions in the aquifer

Spatial analyses have been widely used in hydrochemical studies (Li et al. 2021; Zakaria et al. 2022). A spatial plot of groundwater level shows a complex subsurface circulation with several flow directions in the Bonaberi shallow aquifer (Fig. 7a). The complex flow system suggests groundwater mixing but with some localised flow patterns shown by the concentric flow contours (Fig. 7a). A similar flow pattern has also been observed in groundwater within the Douala city (Mafany 1999; Wirmvem et al. 2017a). It is well known that high $Cl^-$, $NO_3^-$ and $SO_4^{2-}$ as well as $Na^+$ in groundwater are mostly derived from human activities (Han and Liu 2004; Jalali 2009); hence, they are indicators of anthropogenic pollution, especially in Sub-Saharan Aquifers (Lapworth et al. 2017). The anions: $Cl^-$, $NO_3^-$ and $SO_4^{2-}$ showed a varied distribution across the Bonaberi groundwater system (Fig. 7b–d) regardless of the supposed water mixing. Densely populated informal settlement areas

**Table 2** Molar ratios of chemical species and stable isotope composition of groundwater and surface water in Bonaberi ($n=24$)

| Name | Latitude | Longitude | Elevation(m) | $Na^+/Cl^-$ | $Cl^-/HCO_3^-$ | $Ca^{2+}/SO_4^{2-}$ | $Mg^{2+}/Ca^{2+}$ | $Na^+/Ca^{2+}$ | $\delta^{18}O$ (‰) | δD (‰) | d-excess (‰) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DTW23 | 04°05′06.26″ | 09°39′32.83″ | 5 | 4.18 | 0.09 | 1.41 | 1.09 | 0.74 | − 3.37 | − 12.36 | 14.59 |
| DBH10 | 04°05′11.3″ | 09°39′15.3″ | 6 | 0.86 | 0.86 | 1.07 | 0.15 | 1.26 | − 2.61 | − 7.89 | 13.03 |
| DOW01 | 04°05′06.0″ | 09°39′34.7″ | 5 | 1.32 | 0.43 | 0.21 | 0.35 | 0.93 | − 2.86 | − 10.29 | 12.61 |
| DOW02 | 04°06′05.3″ | 09°38′17.11″ | 6 | 1.41 | 3.84 | 2.09 | 0.10 | 1.63 | − 2.71 | − 8.77 | 12.94 |
| DOW05 | 04°06′01.2″ | 09°36′10.9″ | 9 | 2.09 | 0.52 | 106.22 | 0.17 | 1.18 | − 2.48 | − 6.62 | 13.23 |
| DOW06 | 04°06′04.0″ | 09°37′26.9″ | 9 | 6.74 | 0.38 | 34.56 | 1.10 | 0.66 | − 2.70 | − 7.69 | 13.90 |
| DOW08 | 04°04′57.5″ | 09°38′02.0″ | 7 | 1.23 | 1.04 | 1.27 | 0.16 | 0.77 | − 2.47 | − 6.90 | 12.83 |
| DOW09 | 04°05′51.5″ | 09°39′44.3″ | 29 | 1.46 | 461.49 | 1.20 | 0.14 | 3.10 | − 2.57 | − 7.88 | 12.69 |
| DOW12 | 04°04′49.6″ | 09°39′00.3″ | 4 | 0.99 | 11.29 | 1.13 | 0.22 | 5.09 | − 2.65 | − 7.33 | 13.90 |
| DOW13 | 04°06′47.4″ | 09°38′31.9″ | 3 | 1.71 | 190.32 | 1.42 | 0.19 | 5.91 | − 2.68 | − 8.12 | 13.32 |
| DOW14 | 04°06′34.9″ | 09°41′07.4″ | 4 | 5.32 | 0.24 | 1.86 | 0.33 | 7.45 | − 2.86 | − 8.65 | 14.20 |
| DOW15 | 04°05′05.2″ | 09°38′08.6″ | 14 | 3.07 | 0.30 | 1.78 | 0.12 | 2.50 | − 2.80 | − 7.99 | 14.42 |
| DOW16 | 04°05′30.7″ | 09°40′27.1″ | 9 | 5.04 | 0.22 | 1.77 | 0.18 | 1.49 | − 2.93 | − 8.45 | 14.99 |
| DOW17 | 04°04′42.9″ | 09°40′40.8″ | 6 | 1.12 | 4.34 | 3.21 | 0.05 | 2.03 | − 2.62 | − 7.25 | 13.73 |
| DOW18 | 04°04′29.8″ | 09°41′04.8″ | 1 | 1.43 | 1.49 | 2.16 | 0.16 | 1.22 | − 2.63 | − 7.16 | 13.86 |
| DOW20 | 04°04′15.3″ | 09°40′18.7″ | 12 | 1.08 | 2.50 | 1.53 | 0.10 | 1.08 | − 2.97 | − 8.91 | 14.85 |
| DOW21 | 04°03′51.3″ | 09°39′10.7″ | 5 | 1.35 | 0.25 | 0.75 | 0.16 | 0.42 | − 2.65 | − 7.06 | 14.10 |
| DOW22 | 04°04′38.7″ | 09°39′46.9″ | 13 | 0.92 | 4.23 | 2.05 | 0.08 | 1.89 | − 2.58 | − 7.10 | 13.52 |
| DOW24 | 04°06′12.8″ | 09°37′04.9″ | 5 | 1.12 | 2.49 | 10.68 | 0.17 | 1.07 | − 2.58 | − 7.39 | 13.25 |
| DSW03 | 04°07′04.7″ | 09°35′15.6″ | 9 | 91.98 | 0.01 | 1.48 | 0.55 | 90.05 | − 2.61 | − 7.85 | 13.05 |
| DRW04 | 04°06′34.7″ | 09°36′08.8″ | 9 | 1.08 | 0.96 | 0.75 | 0.97 | 1.91 | − 2.24 | − 6.83 | 11.06 |
| DRW07 | 04°04′57.2″ | 09°38′37.1″ | 9 | 0.88 | 96.97 | 0.52 | 4.51 | 23.15 | − 2.10 | − 5.57 | 11.20 |
| DSW11 | 04°05′05.2″ | 09°39′21.5″ | 5 | 0.79 | 12.39 | 0.37 | 1.73 | 8.76 | − 2.36 | − 7.06 | 11.83 |
| DRW19 | 04°04′34.6″ | 09°41′08.3″ | 7 | 0.73 | 16.54 | 1.05 | 4.42 | 19.16 | − 2.74 | − 9.14 | 12.75 |
| | Minimum | | 1 | 0.73 | 0.01 | 0.21 | 0.05 | 0.42 | − 3.37 | − 12.36 | 11.06 |
| | Maximum | | 29 | 91.98 | 461.49 | 106.22 | 4.51 | 90.05 | − 2.1 | − 5.57 | 14.99 |
| | Mean | | 7.96 | 5.75 | 33.88 | 7.52 | 0.72 | 7.64 | − 2.66 | − 7.93 | 13.3 |
| | Standard deviation | | 5.47 | 18.44 | 100.36 | 22.15 | 1.23 | 18.47 | 0.55 | 1.36 | 1.02 |

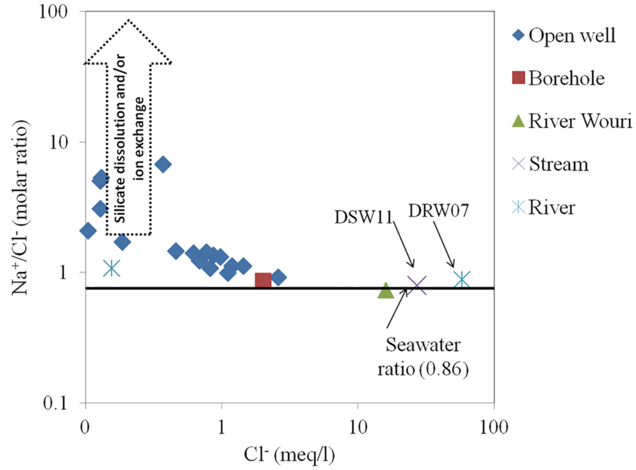


**Fig. 4** Plot of log of $Cl^-$ against $Na^+/Cl^-$ of the investigated water in Bonaberi. While River Wouri and two surface waters DRW07 and DSW11 had $Na^+/Cl^-$ ratios closed to that of seawater, most samples especially wells had ratios higher than in seawater

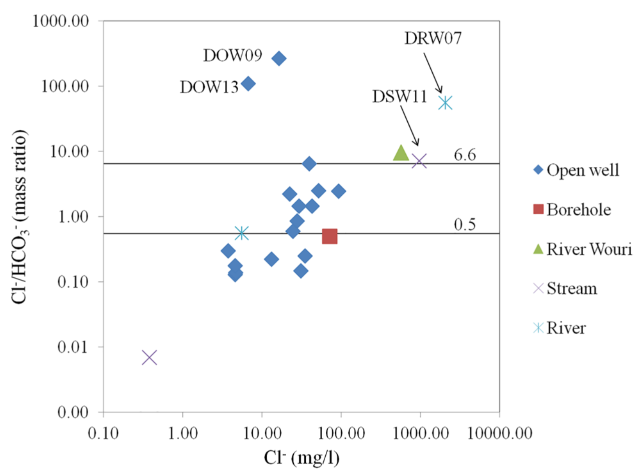


**Fig. 5** Mass ratios of $Cl^-/HCO_3^-$ vs $Cl^-$ of the studied water sources. Most water samples especially the shallow wells had $Cl^-/HCO_3^-$ ratios > 6.6, plotting in the moderately and less affected portions by salinisation

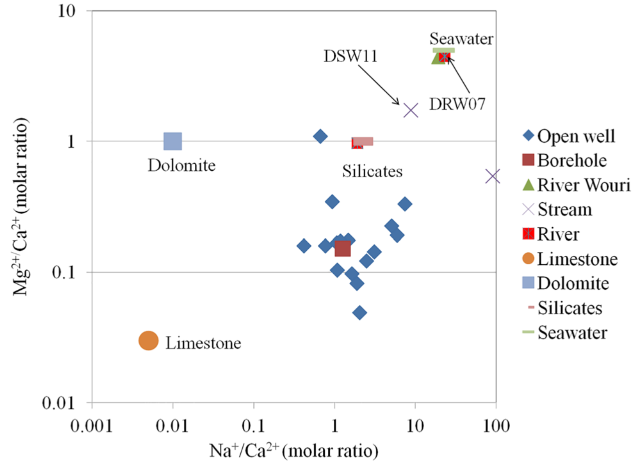


**Fig. 6** Molar ratios of $Mg^{2+}/Ca^{2+}$ versus $Na^+/Ca^{2+}$ of the investigated water. Almost all shallow wells have these molar ratios closed to the silicates than limestone, dolomite and seawater. The ratios in River Wouri, DRW07 and DSW11 are closer to those of seawater

like Bepelle, Ngwelle, Sodiko, Foret Bar, Bonassama and Carrefour Music were generally associated with higher concentrations of these chemical parameters than the less densely populated areas in the outskirts like Bodjongo and Bonamatumbe (Fig. 7b–d). This observation indicates that the high levels of $Cl^-$, $NO_3^-$ and $SO_4^{2-}$ in groundwater are caused by man-made activities, as shown by previous studies in the central Douala city (Takem et al. 2010; Fantong et al. 2016; Wirmvem et al. 2017a). Despite this inference, a plot of $Cl^-$ against $NO_3^-$ showed a positive but weak correlation ($R^2 = 0.43$) in the shallow open wells, possibly due to varied anthropogenic sources and/or different degrees of contamination.

Ratios of $Cl^-$ and $NO_3^-$ have been used to identify various anthropogenic inputs in water (e.g., Fantong et al. 2016). To investigate these contributions, the disposition of the water samples on the $Cl^-$ versus $NO_3^-$ plot was analysed considering the 1:1 line (Fig. 8). The plot of the water samples on the graph gives four subgroups of water contamination (A, B, C and D). Subgroup A are surface waters, including River Wouri, DRW07 and DSW11, with very low $NO_3^-$ (< 4 mg/l) but high $Cl^-$ content (> 500 mg/l) most likely coming from seawater intrusion. Subgroup B represents samples with contamination caused by more $Cl^-$ than $NO_3^-$ (mostly open wells). Given the absence of rock salt in the study area, besides atmospheric deposition, the $Cl^-$ source is likely from laundry activities, chlorination of wells and leaching from pit toilets. Subgroup C is the dominant group and is represented by samples from open wells in densely populated areas with contamination resulting from high and almost equal inputs of $Cl^-$ and $NO_3^-$. The primary source of contamination in C is likely faecal material from pit latrines and municipal waste. Subgroup D represents samples with higher $NO_3^-$ than $Cl^-$. The variation in chemical components of pollutants in the water bodies suggests that point sources may be the dominant origin of groundwater contamination in Bonaberi. These contaminants are probably leaching from the dominant pit latrines in most households closed to the wells. A similar observation has been inferred in groundwater from the central city of Douala (Wirmvem et al. 2017a; Ketchemen-Tandia et al. 2017). Despite the contamination, the concentrations of major ions in most of the investigated groundwater were within the WHO (2011) guidelines for drinking water. Exceptions were DOW06 (open well) at Bepelle Block 3 (with very high $SO_4^{2-}$ of

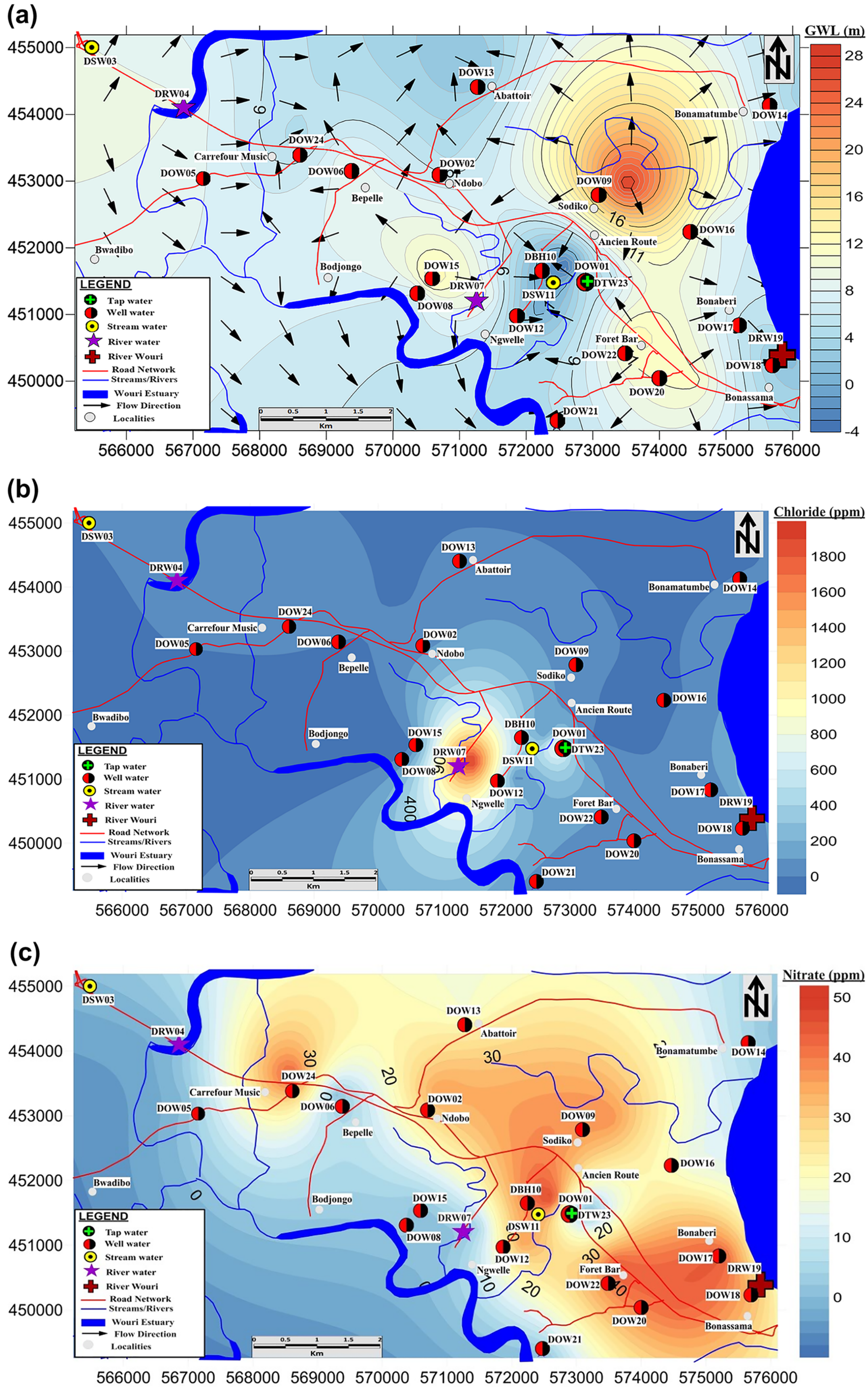


**Fig. 7** Groundwater level (GWL) map (**a**) and spatial distribution of $Cl^-$ (**b**), $NO_3^-$ (**c**) and $SO_4^{2-}$ (**d**) in Bonaberi. Surfer-generated arrows show a complex flow of the shallow groundwater with numerous flow directions (**a**). $Cl^-$, $NO_3^-$ and $SO_4^{2-}$ show different geographical distribution patterns

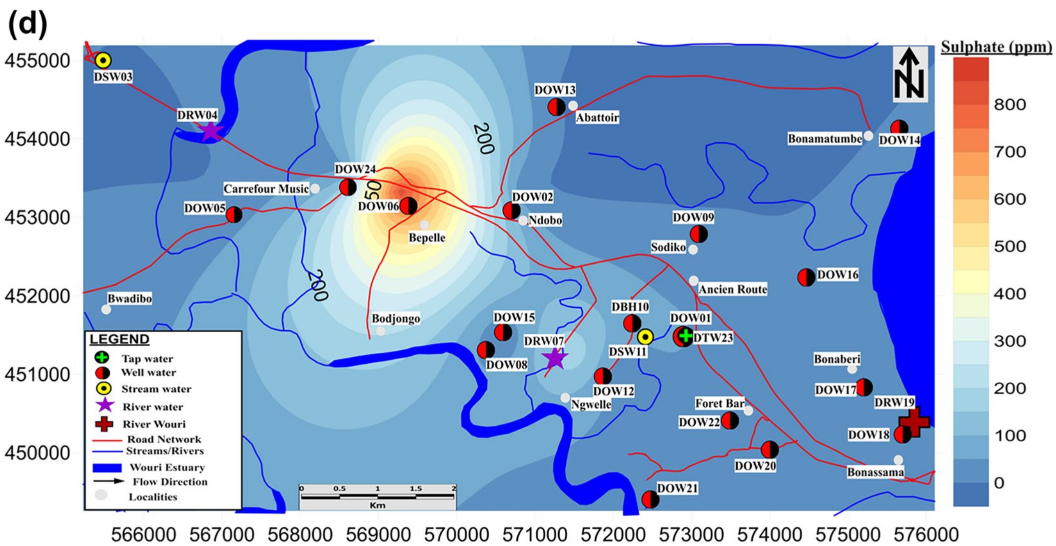


**Fig. 7** (continued)

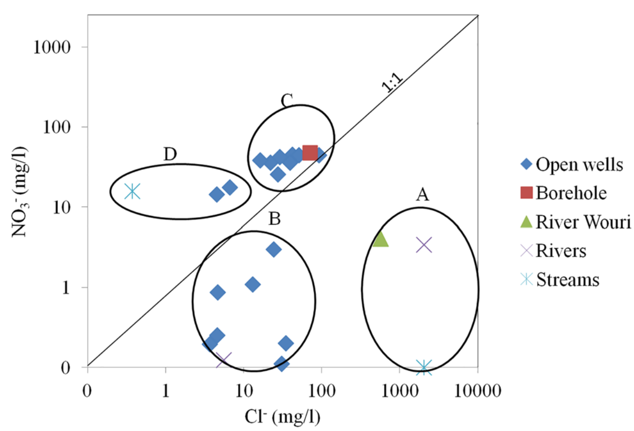


**Fig. 8** Plot of $Cl^-$ versus $NO_3^-$ showing four groups of water contamination (**A**, **B**, **C**, and **D**) in Bonaberi

851 mg/l and a brown-yellowish colour) and the 3 surface water sources (DRW07, DSW11 and DRW19) with very high $Cl^-$ and $Na^+$ values.

## Trace element composition and sources in groundwater and surface water

Mineral dissolution and several geological processes determine the composition of trace elements in groundwater (Mora et al. 2017). Lithium, Co and Cs were not included in data analysis because of many non-detects in the analysed water samples. Trace elements results showed slight variations in the concentrations of Cr, Se, and As (Table 3). This variation is further shown by their small standard deviation values (Table 4) relative to Zn, Rb, Al, Ba, Sr, Mn, Fe and Ti. Zn, Fe and Mn concentrations showed high positive skewness (Table 4); hence, they are considered extreme in the groundwater (Towfiqul Islam et al. 2017). The order of trace element abundance (ppb) was Ti > Fe > Mn > Sr > Ba > Al > Rb > Zn > As > Se > Cr. It is worth mentioning that DOW01, DRW04, DOW06, DSW11 and DOW21, with brown-yellowish colours, as well as DRW07, DRW19 (River Wouri), DOW20 and DOW21, with high EC values, had very high Fe and Mn concentrations above the WHO (2011) and US EPA (2018) guidelines for drinking water. Aluminium values in DOW09, DOW12 and DOW13 were above the US EPA (2018) guidelines for drinking water (Tables 3 and 4). Oral exposure to high Al can cause bone, brain and kidney diseases (US EPA 2018). High Fe, Mn, and Al above the guideline have also been reported for groundwater in Kumba town, South West Region of Cameroon (Nganje et al. 2020). All other water sources, including the tap water, had trace element concentrations within the drinking-water guidelines. Amazingly, DOW06, typically characterised by the brown-yellowish colour with exceptionally high $SO_4^{2-}$ (851.03 mg/l), had the highest concentration of Fe (487.31 mg/l). Meanwhile, groundwater and surface water sources having high Fe, Mn and Al concentrations were associated with high $NO_3^-$, $Cl^-$ or $SO_4^{2-}$ values (Table 1). This relationship indicates that Fe, Mn and Al have anthropogenic origins.

Titanium was the most abundant element in water but has no guideline value for drinking water. Although Li concentrations were very low or absent in most water sources, its values in salty water samples (DRW07, DSW11 and DRW19) with extremely high EC, $Na^+$ and $Cl^-$ concentrations (Table 3). Open well DOW12, which is affected by saline water from DSW11 (stream), also had a Li value of 3.85 ppb, the highest in open wells (Table 3). Li is one of

**Table 3** Trace element results (ppb) of groundwater and surface water in the Bonaberi shallow aquifer ($n = 24$)

| | Li | Al | Ti | Cr | Mn | Fe | Co | Zn | As | Se | Rb | Sr | Cs | Ba |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DTW23 | 0.5 | 130.59 | 10555.04 | 0.81 | 1.86 | 59.31 | bdl | 2.09 | 6.01 | 3.54 | 12.74 | 90.01 | bdl | 28.25 |
| DBH10 | bdl | 43.88 | 40482.18 | 0.12 | 16.87 | 94.16 | bdl | 24.34 | 6.22 | 8.45 | 37.26 | 109.54 | 1.32 | 177.05 |
| DOW01 | bdl | 9.56 | 35949.83 | 0.01 | **1371** | **1680** | 7.73 | 0.66 | 6.38 | 3.82 | 48.62 | 93.6 | 0.2 | 8.29 |
| DOW02 | bdl | 48.9 | 11605.37 | 0.1 | 32.92 | 28.46 | bdl | 2.51 | 6.3 | 5.47 | 20.72 | 54.53 | bdl | 167.8 |
| DOW05 | bdl | 21.12 | 4033.79 | 0.11 | 32.45 | **1534** | bdl | 2.07 | 6.13 | 4.06 | 3.47 | 18.79 | bdl | 11.55 |
| DOW06 | 2.02 | 12.35 | 12203.7 | 1.05 | **3310** | **487307** | 0.4 | 3.61 | 7.26 | 3.95 | 78.57 | 1196.28 | 0.9 | 136.3 |
| DOW08 | 0.07 | 13.36 | **26589** | 0.73 | 35.74 | 136.82 | bdl | 0.36 | 6.23 | 4.37 | 9.69 | 114.15 | bdl | 37.07 |
| DOW09 | 0.54 | **446** | **6841** | 0.21 | 18.42 | 45.32 | 0.26 | 5.94 | 6.24 | 9.03 | 13.53 | 27.63 | bdl | 89.1 |
| DOW12 | 3.85 | **252** | **6318** | 0.3 | 31.52 | 104.16 | 0.65 | 5.86 | 6.14 | 6.82 | 19.6 | 55.27 | bdl | 398.44 |
| DOW13 | 0.15 | **305** | 1984.25 | 0.65 | 22.08 | 88.66 | bdl | 2.74 | 5.98 | 4.47 | 3.34 | 14.3 | bdl | 30.49 |
| DOW14 | 0.13 | 25.18 | 2554.6 | 0.7 | 15.73 | 201.44 | bdl | 9.18 | 5.96 | 4.46 | 7.58 | 18.99 | bdl | 21.43 |
| DOW15 | 0.29 | 30.26 | 4140.05 | 1.19 | 18.65 | 82.22 | bdl | 8.06 | 7.21 | 4.11 | 7.35 | 15.19 | bdl | 18.06 |
| DOW16 | bdl | 30.12 | 10432.55 | 0.41 | 12.69 | 36.34 | bdl | 6.87 | 6.05 | 4.88 | 7.83 | 21.04 | bdl | 16.45 |
| DOW17 | bdl | 30.78 | 21352.3 | 0.68 | **87.21** | 21.94 | 0.04 | 59.51 | 6.11 | 4.74 | 31.96 | 108.95 | 0.48 | 113.14 |
| DOW18 | bdl | 2.97 | 34954.64 | 0.42 | 27.13 | 0.02 | bdl | 0.3 | 6.16 | 4.82 | 41.2 | 259.12 | 0.74 | 173.52 |
| DOW20 | 3.62 | 41.11 | 21245.34 | 0.68 | **73.44** | **431.1** | 0.14 | 7.72 | 6.1 | 4.28 | 36.94 | 113.75 | 0.9 | 190.87 |
| DOW21 | 0.19 | 12.01 | 79957.94 | 1.19 | **426.6** | **3290** | 0.21 | 0.32 | 7.56 | 3.82 | 33.79 | 341.72 | 0.25 | 52.09 |
| DOW22 | bdl | 17.66 | 36014.59 | 0.67 | 32.57 | 47.55 | bdl | 3.49 | 6.29 | 4.02 | 42.49 | 137.56 | 0.47 | 147.37 |
| DOW24 | bdl | 35.76 | 35400.03 | 0.95 | 34.4 | 73.01 | bdl | 2.5 | 6.69 | 4.47 | 30.44 | 137.78 | 0.1 | 42.74 |
| DSW03 | bdl | 86.39 | 1279.09 | 0.84 | 18.35 | **938** | bdl | 0.24 | 6.21 | 3.62 | 1.62 | 4.51 | bdl | 14.66 |
| DRW04 | 0.48 | 98.3 | 2747.65 | 0.86 | **102.3** | **838** | bdl | 5.47 | 6.2 | 3.67 | 4.61 | 20.43 | bdl | 12.78 |
| DRW07 | 42.04 | 90.2 | 93899.24 | 0.82 | **800** | **614** | 0.79 | 2.26 | 7.02 | 4.1 | 44.54 | 1690.79 | bdl | 129.85 |
| DSW11 | 12.43 | 35.36 | 96977.85 | 1.46 | **784** | **1910** | 0.19 | 0.1 | 7.26 | 3.6 | 63.53 | 1009.04 | 0.04 | 200.22 |
| DRW19 | 9.69 | 166.33 | 22983.27 | 0.91 | **451.3** | **352** | bdl | 0.73 | 6.64 | 3.7 | 14.74 | 383.27 | bdl | 39.17 |
| DL | 0.0002 | 0.0002 | 0.0004 | 0.0006 | 0.0002 | 0.0008 | 0.0001 | 0.0001 | 0.002 | 0.2 | 0.0003 | 0.0003 | 0.0003 | 0.0003 |

Cu (bdl = 0.0005 ppb) was detected in only DBH10 (3.24 ppb); Be, V, Ag, Cd, Hg, TI and Pb were below the detection limits of 0.0002, 0.0009, 0.0001, 0.0005, 0.0006, 0.0007, 0.0001 ppb, respectively. Bold values are above the guideline values for drinking water. DOW01, DRW04, DOW06, DSW11, DOW21 had brown-yellowish colours

*DOW* open well, *DBH* borehole, *DSW* stream, *DRW* river, *DRW19* River Wouri, *DTW* tap water, *DL* detection limit, *bdl* below detection limit

**Table 4** Descriptive statistics of selected trace elements in water of the study area and guideline values for drinking water ($n = 24$)

| Element | Min (ppb) | Max (ppb) | Mean (ppb) | Std Dev | Skewness | WHO (2011) guideline value (ppb) | No. of samples above guideline values |
|---|---|---|---|---|---|---|---|
| Cr | 0.01 | 1.46 | 0.66 | 0.39 | − 0.12 | 50 | 0 |
| Se | 3.54 | 9.03 | 4.68 | 1.44 | 2.18 | 40 | 0 |
| As | 5.96 | 7.56 | 6.43 | 0.47 | 1.22 | 10 | 0 |
| Zn | 0.1 | 59.5 | 6.54 | 12.4 | 3.81 | 5000[a] | 0 |
| Rb | 1.62 | 78.6 | 25.67 | 20.6 | 0.87 | NM | – |
| Al | 2.97 | 445.5 | 82.7 | 109.2 | 2.22 | 200[a] | 3 |
| Ba | 8.29 | 398.4 | 94.03 | 93.6 | 1.59 | 700 | 0 |
| Sr | 4.51 | 1690.8 | 251.5 | 429.1 | 2.48 | 4000[a] | 0 |
| Mn | 1.86 | 3310.5 | 323.3 | 722.5 | 3.47 | 50[a] | 9 |
| Fe | 0.02 | 487,307.7 | 20,829.8 | 99,362.7 | 4.90 | 300 | 9 |
| Ti | 1279.1 | 96,977.9 | 25,854.3 | 28,023.1 | 1.59 | NM | – |

*NM* not mentioned

[a]USEPA (2018)

the trace elements in seawater that is considered an indicator of saline intrusion (Sanchez-Martos et al. 1999) as well as $Na^+$, $Cl^-$ and EC (Vetrimurugan et al. 2017). Thus, the variation in Li concentration further confirms the influence of the Atlantic Ocean on some surface waters and a few wells in Bonaberi.

Cr, Se, and As concentrations in the investigated water were very low, with subsequent low mean values (Table 4). Background levels for Cr in surface water and groundwater aquifers are a function of regional geology, mineral weathering processes, the rate of sediment loading and precipitation patterns (Health Canada 2016). Levels in uncontaminated waters are usually very low (< 1 ppb), although leaching of wastewater from landfills or release through anthropogenic activities may cause contamination of drinking water (WHO 2019). Sources of Se in groundwater include rock weathering and rainfall (Dhillon and Dhillon 2016). Rock-water interactions in aquifer systems are the primary cause of the release of As and deterioration of groundwater quality (Shaji et al. 2021). The low background values and even distribution of Cr, As and Se in the groundwater and surface suggest leaching from rock weathering and atmospheric deposition.

Spatial distribution maps of the trace elements with concentrations above the WHO (2011) guidelines (Al, Mn, and Fe) showed high concentrations in densely populated areas (Fig. 9a–c). Aluminium concentrations were higher in the investigated shallow wells at Sodiko, Ngwelle and Abbatoir (Fig. 9a). Manganese and Fe displayed a similar spatial distribution to $SO_4^2$, with higher values occurring in shallow wells at the Bepelle and Ngwelle neighbourhoods (Fig. 9b, c). The spatial distribution in densely populated areas suggests the influence of human activities, accounting for the high concentrations of Al, Mn and Fe.

Pearson's correlation coefficients of the investigated water showed a very strong positive correlation ($r^2=0.88$) between Fe and Mn (Table 5). This relationship indicates their co-precipitation effect and similar geochemical behaviour. Given their wide ranges and high concentrations in water, besides a natural origin, an anthropogenic source is most likely.

Based on the Pearson's correlation, Fe and Mn were positively correlated with Rb ($r^2=0.55$ and 0.72) and Sr ($r^2=0.47$ and 0.65) as well as As ($r^2=0.38$ and 0.54). Arsenic displayed a positive correlation with Ti, Rb, Sr and Cr, with $r^2$ values from 0.53 (Rb) to 0.66 (Cr). Like As, Ti showed positive correlations with As, Rb, Sr and Cr, having $r^2$ values from 0.37 (Cr) to 0.68 (Sr) (Table 5). Also, there were good positive correlations of Sr with Ti, Mn, Fe, As, Rb and Cr ranging from 0.43 (Cr) to 0.68 (Ti). Similarly, Rb positively correlated with Ti, Mn, Fe, As, Sr and Ba, with $r^2$ values ranging from 0.45 (Ba) to 0.68 (Sr). Given the low and homogeneous distribution of As and Cr, their inferred geologic origin, and their observed distinctive correlations with these trace elements indicate a natural origin for Ti, Fe, Mn, Rb, Sr, Ba.

Selenium on the other hand positively correlated with Al ($r^2=0.53$) and Ba ($r^2=0.42$) but negatively correlated with Cr ($r^2=-0.57$). Like Se, Al is mainly released into the water through natural processes, including atmospheric deposition (WHO 2003). However, the relatively high concentrations in a few wells (DOW09, DOW12, and DOW13) suggest some anthropogenic inputs into the shallow groundwater. Zinc did not show any significant correlation with any element suggesting its distinctive origin and behaviour in the aquifer.

Principal component analysis (PCA) is a multivariate statistical tool used to group several dependent variables into a fewer number of unrelated master variables, usually called components (Kandakji et al. 2015). It has been applied in hydrogeochemical studies to distinguish natural and anthropogenic sources of chemical contents in groundwater (Levins and Gosk 2008; Kandakji et al. 2015; Mora et al. 2017; Zhang et al. 2020). The PCA loadings of trace elements were used to further identify their potential sources in the water. By considering the critical Eigen value > 1, four significant factors (PC1, PC2, PC3 and PC4) were extracted (Table 6) and interpreted. These factors accounted for 80.85% of the total variance in the data.

PC1 that accounted for 39.07% of the total variance expressed strong positive loadings between Ti, As, Sr, and Rb and moderate correlation with Cr. As and Cr in soils of the Bassa Industrial Zone of Douala only show moderate pollution (Asaah et al. 2006). The low concentrations and uniform distributions of As and Cr in Bonaberi near-surface groundwater can be attributed to natural sources. This factor, therefore, indicates rock weathering and related processes.

PC2, accounting for 18.05% of the total variance, principally included Fe and Mn with very high positive and moderate loadings of Rb and Sr. Very high Fe and Mn observed in some water sources have been attributed to man-made sources. Thus, this factor represents a blend of natural and anthropogenic sources.

PC3 accounted for 13.2% of the total variance and showed a strong positive relationship between Se and Ba and a moderate loading of Al. A strong negative loading was shown by Cr in PC3, indicating that its source was different from that of Al, Se, and Ba. Thus, besides natural processes, human activities contribute to these elements in the water.

Finally, PC4 had mainly Zn with a high positive loading but a very strong negative loading of Al, implying that the source of Al does not contribute to Zn. Despite its low concentrations in water sources, relatively higher values were found in groundwater samples with high $Cl^-$ and $NO_3^-$ (DBH10 and DOW20). Sources of Zn in groundwater include natural processes, atmospheric deposition, and industrial activities (Pedroli et al. 1990; Bodrud-Doza

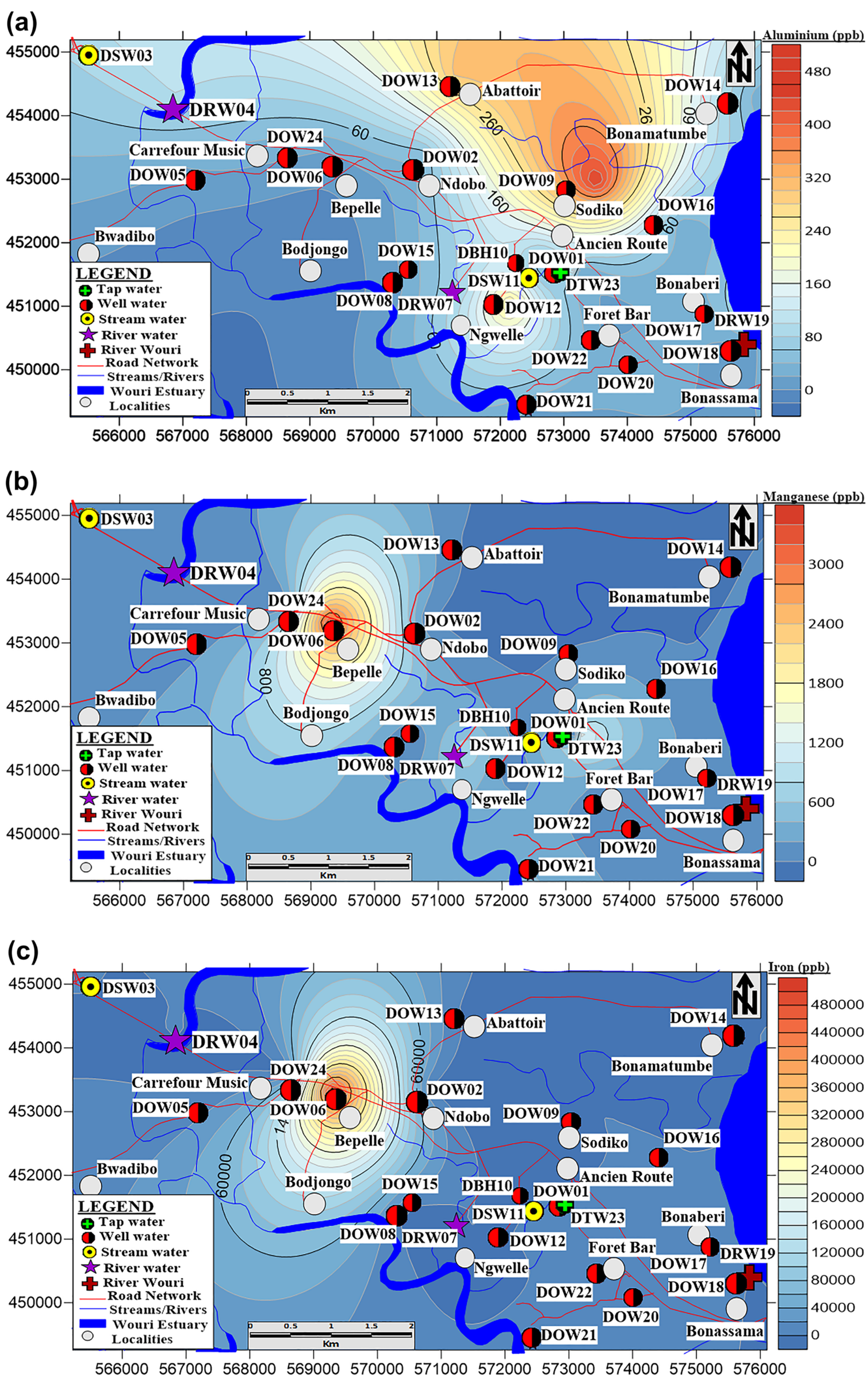


Fig. 9 Spatial distribution of Al, Mn and Fe in the studied water (a–c). Unlike Al, Mn and Fe show a similar distribution pattern in the shallow aquifer

**Table 5** Pearson's correlation coefficient of trace elements in the groundwater and surface water in Bonaberi

| | Al | Ti | Mn | Fe | Zn | As | Se | Rb | Sr | Ba | Cr |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Al | 1.00 | | | | | | | | | | |
| Ti | − 0.29 | 1.00 | | | | | | | | | |
| Mn | − 0.19 | 0.20 | 1.00 | | | | | | | | |
| Fe | − 0.14 | − 0.10 | 0.88 | 1.00 | | | | | | | |
| Zn | − 0.08 | − 0.09 | − 0.14 | − 0.05 | 1.00 | | | | | | |
| As | − 0.25 | 0.63 | 0.54 | 0.38 | − 0.22 | 1.00 | | | | | |
| Se | 0.53 | − 0.16 | − 0.24 | − 0.11 | 0.27 | − 0.28 | 1.00 | | | | |
| Rb | − 0.35 | 0.62 | 0.72 | 0.55 | 0.04 | 0.53 | − 0.07 | 1.00 | | | |
| Sr | − 0.14 | 0.68 | 0.65 | 0.47 | − 0.15 | 0.65 | − 0.23 | 0.68 | 1.00 | | |
| Ba | 0.13 | 0.23 | 0.06 | 0.20 | 0.12 | 0.03 | 0.42 | 0.45 | 0.24 | 1.00 | |
| Cr | − 0.20 | 0.37 | 0.23 | 0.22 | − 0.11 | 0.66 | − 0.57 | 0.21 | 0.43 | − 0.15 | 1.00 |

Correlation coefficients are significant at 0.05 level (2-tailed)

**Table 6** Principal component analysis of groundwater and surface water in Bonaberi

| Element | PC1 | PC2 | PC3 | PC4 |
|---|---|---|---|---|
| Al | − 0.25 | − 0.12 | 0.56 | − 0.63 |
| Ti | 0.95 | − 0.09 | 0.01 | 0.09 |
| Mn | 0.26 | 0.93 | − 0.09 | − 0.03 |
| Fe | 0.01 | 0.98 | − 0.05 | − 0.02 |
| Zn | − 0.15 | − 0.06 | 0.22 | 0.76 |
| As | 0.75 | 0.34 | − 0.25 | − 0.18 |
| Se | − 0.20 | − 0.10 | 0.88 | − 0.01 |
| Rb | 0.65 | 0.60 | 0.17 | 0.30 |
| Sr | 0.75 | 0.48 | 0.00 | − 0.10 |
| Ba | 0.35 | 0.10 | 0.73 | 0.17 |
| Cr | 0.54 | 0.11 | − 0.55 | − 0.18 |
| Eigen values | 4.30 | 1.99 | 1.45 | 1.15 |
| Variance % | 39.07 | 18.05 | 13.20 | 10.53 |
| Cumulative % | 39.07 | 57.12 | 70.32 | 80.85 |

et al. 2019). Thus, natural processes enhanced by human-induced activities such as industrial activities within Bonaberi, fertilizers and agrochemicals through atmospheric deposition are possible sources of Zn in the groundwater, given the proximity of Bonaberi to several plantations in Penja. Soil contamination by Zn has been reported in Bonanjo and Joss (less industrialized) localities in the city of Douala (Asaah et al. 2006).

Despite the report of soil contamination by heavy metals, including Zn, Fe, Mn, As, Cr, Cd, Cu, and Pb in the Bassa Industrial Zone, Joss and Bonanjo in Douala by Asaah et al. (2006), shallow groundwater in Bonaberi hosting several industries, generally have low concentrations of these trace elements. These low concentrations are likely due to their retention in the topsoil through ion exchange, sorption, and solubility processes (Tanji and Valoppi 1989). This may imply that trace elements do not typically accumulate in the shallow groundwater of Bonaberi. The primary source of trace elements in the groundwater of this area (mainly within the guidelines for drinking water) is related to geological factors. Thus, human activities rather than geologic factors likely affect the shallow groundwater.

## Stable isotope composition and groundwater recharge

Apart from the tap water with the most depleted isotopic signature given its source from River Mungo (out of Bonaberi), the groundwater and surface water showed narrow variations and overlaps in $\delta^{18}O$ from − 2.97 to − 2.47 ‰ (mean − 2.69 ‰) and − 2.74 to − 2.10 ‰ (mean − 2.41 ‰), respectively (Table 2). These ranges were very narrow compared to $\delta^{18}O$ of Douala precipitation (Ketchemen-Tandia et al. 2007; Wirmvem et al. 2017b). Moreover, the ranges and overlaps suggest a limited/selective recharge period in a hydrological year and hydraulic connection between surface water sources and groundwater sources, as well as good water mixing within the aquifer. The $\delta^{18}O$ and δD of all water sources were plotted along the Douala Meteoric Water Line (DMWL) by Wirmvem et al. (2017b) to determine the origin recharge of groundwater in the area. The plot (Fig. 10) showed that δ values for groundwater and surface water were aligned on and close to the DMWL; thus, indicating their meteoric origin. This alignment also implies that rainfall is the dominant component of groundwater in the Bonaberi aquifer. Unlike some of the surface water sources (DRW04, DRW07, and DSW11) with relatively low d-excess values (Table 2) that plotted below the DMWL (Fig. 10); thereby, indicating some evaporation effect, groundwater recharge generally takes place under insignificant evaporation conditions most likely through rapid infiltration in the Bonaberi area.

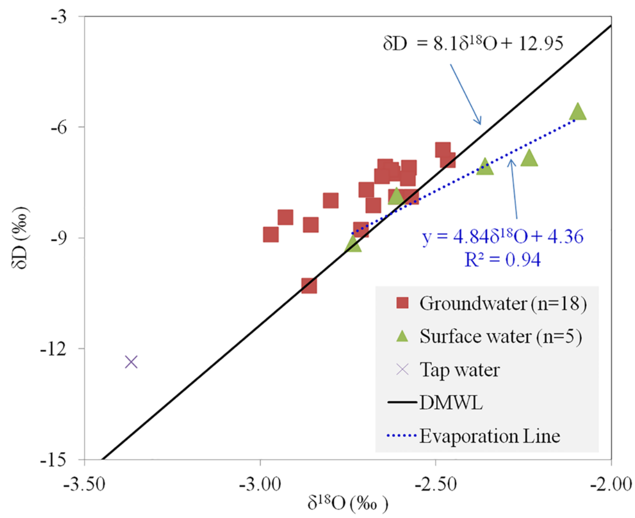


**Fig. 10** Relationship of $\delta^{18}O$ and δD of the studied water sources in Bonaberi. Both groundwater and surface water plotted along the Douala Meteoric Water Line (DMWL) but the latter show an evaporation line with a slope of 5

The low temperature of the groundwater (Table 1) indicates that its *δ* values are conservative (Taylor and Howard 1996) in the Bonaberi shallow aquifer. The high d-excess values of the groundwater (Table 2) that reflect significant recycling of inland moisture to groundwater recharge (Wirmvem et al. 2017b) also suggest negligible evaporation effect before and after recharge. Hence, the *δ* values of the groundwater are a replica of the recharging rains. Given the similarity between the δ values of the groundwater and recent rainfall, paleo-recharge is ruled out. In addition to the narrow cluster of *δ* values in groundwater, these arguments suggest a homogeneous shallow aquifer receiving direct rainfall infiltration through the sandy formation as observed in the central city of Douala (Ketchemen-Tandia et al. 2007; Wirmvem et al. 2017a). The rapid direct recharge favours the leaching of contaminants, including $NO_3^-$ and $Cl^-$ from pit toilets into the shallow aquifer; hence, the relatively high $NO_3^-$ and $Cl^-$ in densely populated areas. The vulnerability of this valuable commodity to pollutants generated within the city is a serious public health concern that needs imperative management to prevent water-borne diseases. Given that rainfall is the primary source of recharge, the heavy rainfall in Douala city results in dilution of contaminants within the shallow groundwater; hence, the relatively low $NO_3^-$ and $Cl^-$ compared to other highly urbanised cities in developing countries of Sub-Saharan Africa (Lapworth et al. 2017).

## Conclusion

Apart from $Cl^-$, $Na^+$, $SO_4^{2-}$, Fe, Mn, and Al in some surface water and groundwater sources in Bonaberi, the concentrations of the other investigated parameters are within the WHO (2011) guidelines for drinking water. From ionic ratios and factor analysis, the chemical composition (major ions and trace elements) of surface water and groundwater in Bonaberi is affected by two main factors: natural weathering with associated processes and anthropogenic activities, mainly leaching from pit toilets and waste dumps. Stable isotope data show the hydraulic connection between the surface water and shallow groundwater, and a mixed shallow aquifer system receiving rapid direct uniform areal recharge from rainfall. This recharge process favours the leaching of pollutants from the numerous pit toilets into the shallow aquifer. However, given the heavy rainfall in Douala and good water mixing, there is a dilution of contaminants in the shallow aquifer. The surface water sources within Bonaberi are not suitable for drinking water as they are vulnerable to anthropogenic pollution, especially from industries and salinisation from the Atlantic Ocean. The salinisation is only partly affecting the shallow groundwater. Thus, apart from rainwater and deeper boreholes (> 60 m), there is no alternative source of good water supply in the low-income residential areas of Bonaberi. Thus, protecting the shallow groundwater easily accessible to most poor inhabitants at a lower cost is imperative. Overall, groundwater quality concerns in Bonaberi should be focussed on anthropogenic rather than natural contamination.

**Acknowledgements** The paper constitutes part of an MSc research thesis of the second author, Aicha Foupouagnigni. The staff of Ohba Laboratory, Tokai University in Japan, is acknowledged for their support during the chemical analyses. The manuscript was improved thanks to the comments from two anonymous reviewers.

**Availability of data and materials** The corresponding author will provide data and material in this study upon request.

## Declarations

**Conflict of interest** The corresponding author states that there is no conflict of interest on behalf of all authors.

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