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An investigation of decreasing groundwater levels in hand-dug wells in Ouédo, southern Benin

The fate of shallow groundwater resources in a fast-growing suburban area

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An investigation of decreasing groundwater levels in hand-dug wells in Ouédo, southern Benin

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Abstract

Hand-dug wells are the primary sources of potable water for many in West Africa, yet the security of shallow groundwater supplies is compromised by climate variability, land-use and land-cover change, population growth and groundwater abstraction. In Ouédo, a fast-growing suburban town in southern Benin, residents are encountering declining shallow groundwater levels and attributing this drawdown to the development of a new wellfield in Ouédo which supplies Cotonou, the largest city and economic capital of Benin.

It is known that the hand-dug wells in Ouédo tap into the unconfined Quaternary aquifer, while the boreholes of the wellfield access water from the underlying Mio-Pliocene sandstone aquifer known as the Continental Terminal. If the hand-dug wells are hydraulically connected to the deeper wellfield, then abstraction of significant volumes daily from the Ouédo production wellfield can deplete the shallow reserves with time and decrease water availability for communities. However, urban encroachment and population growth are also straining groundwater resources in the area. With the increase of impervious cover there will be less recharge to the shallow aquifer. This groundwater recharge can also decrease due to climate variability with decreased precipitation inputs and/or increased evapotranspiration. Moreover, with population growth in Ouédo there will be increased demand. In this regard, the water levels in hand-dug wells will decrease due to the multiplication of hand-dug wells throughout the area. Increased anthropogenic activities with population growth will also heighten the risk of bacterial contamination in the unprotected hand-dug wells. Should the aquifers be hydraulically connected, therefore, there is enhanced risk of these surface contaminants being transported to the Continental Terminal through downward fluxes.

By evaluating the driving forces of declining groundwater levels in the hand-dug wells (climate variability, land use/land cover change, population growth and abstraction), the impact of each can be compared within a well-researched context and assist in management practices in the study area. Results of this study confirm that recharge in the shallow Quaternary aquifer is strongly connected to local precipitation, but analysis of recent climate variability provided no clear evidence to support the hypothesis of decreased precipitation and/or increased evapotranspiration causing decreased recharge. On the other hand, increased urban encroachment in and around the study area has led to increased impervious cover and therefore decreased infiltration capacity of the soils. With urban encroachment, the study area experienced rapid population growth in recent years. The subsequent multiplication of hand-dug wells allowed for increased groundwater abstraction from the shallow Quaternary aquifer by local residents. Isotopic and hydrogeochemical characterization of the aquifers were largely inconclusive with respect to mixing between the two groundwater bodies as a result of wellfield abstraction but directed recommendations for further monitoring in the Ouédo study area.

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Abbreviations

CSB	Coastal Sedimentary Basin
CT	Continental Terminal
DG-Eau	General Directorate of Water of Benin (*Direction Générale de l'Eau du Bénin*)
GMWL	Global Meteoric Water Line
EC	Electrical Conductivity
IGRAC	International Groundwater Resource Assessment Centre
INE	National Water Institute, Benin (*Institut National de l'Eau*)
INSAE	National Institute of Statistics and Economic Analysis (*Institut National de la Statistique et de l'Analyse Économique*)
IRD	Institute for Research and Development, Benin (*Institut de Recherche pour le Développement*)
LHA	Laboratory of Applied Hydrology (*Laboratoire d'Hydrologie Appliquée*)
LMWL	Local Meteoric Water Line
SNIEAU	National Water Information System of Benin (*Système National d'Information sur l'Eau du Bénin*)
SONEB	National Water Company of Benin (*Société Nationale des Eaux du Bénin*)
TDS	Total Dissolved Solids

CHAPTER 1

Introduction

1.1. Background

Increased population growth in West African countries in the last few decades has put a strain on limited freshwater reserves and compromised the basic need for clean potable water and improved sanitation for persons living in the region (United Nations 2014). In particular, the heavily abstracted shallow coastal aquifers are vulnerable to rapid storage depletion, increased anthropogenic pollution from rapidly urbanizing coastal cities and seawater intrusion (Boukari et al. 1996; Silliman et al. 2010; Murray-Rust and Fakhruddin 2014). For the region of southern Benin, more than half of the country's population inhabits only 11% of the country area (INSAE 2015). With population growth and urban encroachment as drivers, increased groundwater abstraction became necessary for satisfying domestic and industrial demand. However, the resulting pressures on groundwater reserves are the risk of over-exploitation and water quality deterioration with anthropogenic pollution (Boukari et al. 1996; Silliman et al. 2007; Edet 2010; Totin et al. 2010).

While the larger Coastal Sedimentary Basin hydrogeological system underlies only 10% of Benin territory, it contains approximately 35% of Benin's total groundwater reserves and is used to supply the almost 7 million inhabitants living in southern Benin (Boukari 2007). Abstraction activities within the basin have expanded to rural areas to satisfy rising demand in peri-urban and urban areas. In the rural town of Ouédo, a new wellfield was developed in 2014 to supplement the supply from the deteriorating reserves of the older Godomey wellfield. Prior to this, the Godomey wellfield in the southeast had provided most of the groundwater supply to Cotonou, Benin's largest city, until groundwater quality deteriorated due to saline intrusion and anthropogenic contamination (Boukari et al. 1996; Silliman et al. 2010; McInnis et al. 2013) and compelled experts to propose the Ouédo reserves as more favourable for groundwater supply to southern Benin.

Since the development of the Ouédo wellfield, however, concerns arose over long-term abstraction of the reserves (Kotchoni et al. 2016). In particular, there were growing tensions in Ouédo over the impact of the new boreholes on the surrounding hand-dug wells in the shallow aquifer, on which Ouédo residents are solely dependent. Residents claimed that since construction of the wellfield many hand-dug wells have run dry or experienced greatly decreased groundwater levels. even though the wellfield exploits a much deeper aquifer that is assumed to be generally confined in the study area. Added to the conflict is the frustration expressed by residents over the diversion of groundwater from Ouédo to Cotonou and other urban areas while demand in Ouédo itself remains largely unmet.

A team of Beninese researchers launched a hydrogeological assessment of the Coastal Sedimentary Basin in southern Benin using new geophysical and cost-effective approaches to improving the knowledge of the groundwater resources. Through the *NOEVA* project, Kotchoni et al. (2016a) identified significant knowledge gaps in southern Benin hydrogeological research and factors limiting groundwater development in the region. No baseline piezometric studies were performed on the shallow Quaternary aquifer tapped by these hand-dug wells and therefore claims of decreased groundwater levels remained unsubstantiated. Further, hydrogeological studies in Ouédo are limited since most of the investigations in the basin were carried out at the older Godomey wellfield and unconsolidated beach sand aquifers along the coastal plain.

However, the region has received attention from the Embassy of the Kingdom of the Netherlands in Benin, which has launched the OmiDelta programme, supporting activities for achieving the Sustainable Development Goal #6: To ensure availability and sustainable management of water and sanitation for all by 2030. The present study adds to these ongoing activities in terms of data collection, creation of scientific knowledge and information sharing.

1.2. Problem Statement

Decreasing groundwater levels in hand-dug wells is a threat for Ouédo residents, since these wells constitute the main supply of potable water in the town. It is also a source of conflict between the local users of hand-dug wells and the company running the new production wellfield, since the residents in Ouédo believe that groundwater is diverted from their hand-dug wells to the wellfield. In order to ensure water security for Ouédo residents and resolve the water conflict, it is necessary to assess the factors that may be contributing to decreased water availability in the shallow Quaternary aquifer. In addition, water quality of the shallow groundwater abstracted in the area must be assessed for establishing the suitability of the water for drinking purposes and potential contamination in the Continental Terminal aquifer should downward fluxes be established.

1.3. Hypotheses

Three hypotheses are proposed to explain the decreasing groundwater levels in the hand-dug wells:

Hypothesis A. Decrease in groundwater recharge

A recent decrease in recharge to the shallow Quaternary aquifer is responsible for decreased groundwater levels in the hand-dug wells. Decreased rainfall and/or increased evapotranspiration in the area may result in less groundwater available in the shallow Quaternary aquifers. Land-use conversion in the fast-growing town can also result in increased impervious area and diversion of rainfall inputs as surface runoff to the streams, which could also contribute to the decrease of groundwater levels.

Hypothesis B. Increase in abstraction by Ouédo residents

Recent increased abstraction through hand-dug wells by residents in the fast-growing area is responsible for decreased groundwater storage in shallow reservoirs. There is increased water demand in the study area and therefore there are increased abstraction activities from the shallow reservoirs.

Hypothesis C. Abstraction in the new wellfield

The aquitard separating the shallow aquifer, tapped by the Ouédo residents by means of hand-dug wells, from the deeper aquifer, exploited by the wellfield supplying Cotonou, may not be as confining as expected. This aquitard may be thinner or even absent in some parts of the study area, or may be more permeable than expected, allowing hydraulic connection between the shallow aquifer and the deeper aquifer. Therefore, abstraction in the new wellfield can create downward fluxes that reduce groundwater storage in the shallow Quaternary aquifer. If this hypothesis proves true, it may result in increased conflict between the company running the wellfield and the residents of Ouédo. It also means that the deeper aquifer tapped by the wellfield is more vulnerable to contamination, and measures should be taken to protect it from contamination.

1.4. Objectives

The main objective of this study is to evaluate the three hypotheses and determine which could be responsible for decreasing shallow groundwater levels or eliminated from consideration. The absence of groundwater monitoring in the shallow aquifer poses a challenge to execute hypothesis the testing. Alternatively, testing was done following three lines of investigation:

i. Identify *recent climate variability*
   - ➔ Hypothesis A. Decrease in groundwater recharge: If any decrease in precipitation and/or increase in evapotranspiration can be identified, it would support the hypothesis of a decrease in groundwater recharge.

ii. Identify *recent changes in land use/land cover and population growth*
   - ➔ Hypothesis A. Decrease in groundwater recharge: If any increase in impermeable land cover can be identified, it would support the hypothesis of a decrease in groundwater recharge.
   - ➔ Hypothesis B. Increase in abstraction by Ouédo residents: If increased urbanization of Ouédo can be identified, including population growth and increased economic activities, it would support the hypothesis of an increase in groundwater abstraction by Ouédo residents.

iii. Determine *stable isotopic and hydrogeochemical signatures of groundwater*
   - ➔ Hypothesis C. Abstraction in the new wellfield: If the shallow and the deeper aquifers have different isotopic and hydrogeochemical signatures, some mixing could be identified and support the hypothesis of downward fluxes decreasing groundwater storage in the shallow aquifer.

Each line of investigation consisted first in a literature review, then in the collection and interpretation of additional data, followed by a discussion. Building on the discussion of these three investigation lines, a conclusion was made on which of the three hypotheses are likely and which are not.

CHAPTER 2

Study Area

2.1. Location

The study area of size 26 km^2 is located between 6.4 – 6.50° N and 2.24 – 2.28° E. It is defined by the administrative limits of the peri-urban town of Ouédo in the southern region of the Republic of Benin, West Africa (Figure 1).

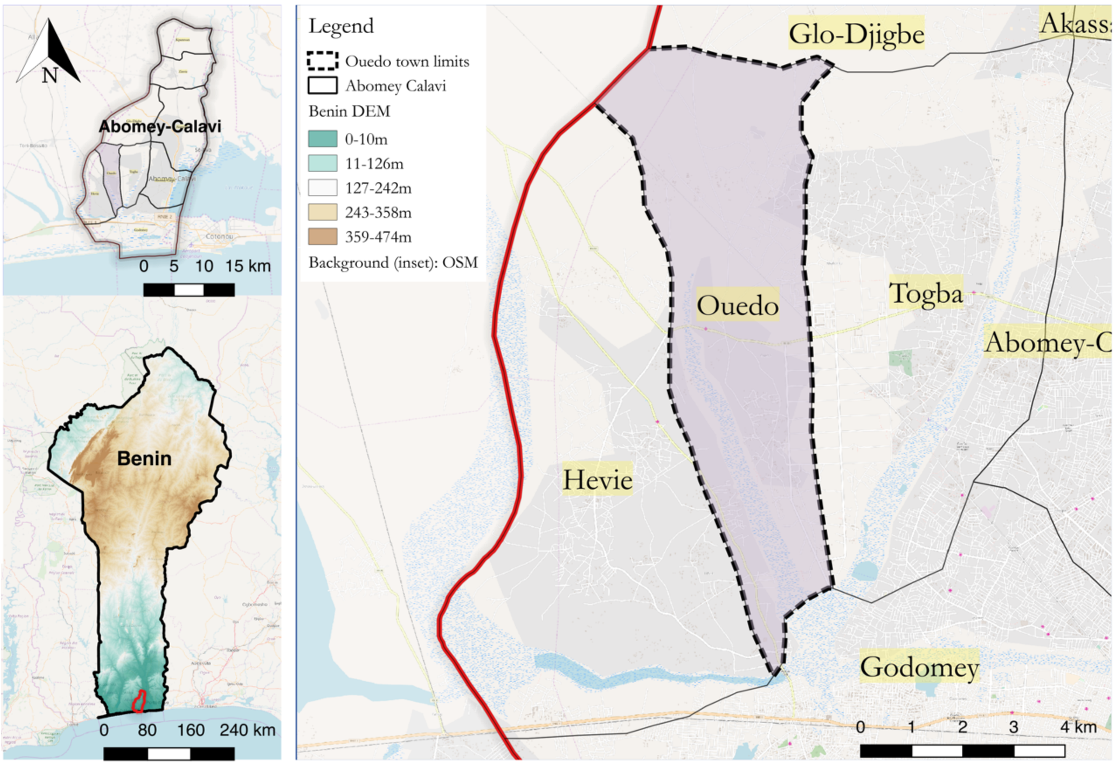

Figure 1 Map showing Ouédo study area in the commune of Abomey-Calavi in southern Benin

Administratively, Ouédo is one of nine towns belonging to the Abomey-Calavi commune (inset Figure 1). The Abomey-Calavi commune falls under the Atlantique department of southern Benin.

Ouédo is located in a flat-lying area of average elevation 30 m above sea level. It lies on the edge of the Allada Plateau which rises north toward the large central granitic complex encompassing the majority of Benin's landscape. To the east, west and south of Ouédo there is a "V" boundary comprised of streams and rivers of the Ouémé River watershed. These rivers all flow south and drain into coastal wetlands before the Gulf of Guinea (Atlantic Ocean) just

10 km away from the study area. Lake Nokoué, the country's largest lagoon, is located approximately 15 km southeast of the study area. Directly below the lake and within 20 km of Ouédo town limits is the city of Cotonou – the largest city and economic capital of Benin.

2.2. Climate

The climate of southern Benin is defined as subequatorial. Typical of the West African region, it is established predominantly by the interactions between the Inter-Tropical Convergence Zone (ITCZ) and the West African Monsoon (WAM). The movements of these two systems determine the timing and duration of wet and dry seasons in the region. In southern Benin, the alteration results in two rainy seasons per year: a large rainy season from March to July and a smaller rainy season from mid-September to early December.

Southern Benin experiences a high mean annual rainfall of 1148 mm and Penman-Monteith estimated annual evapotranspiration of 1549 mm (Achidi et al. 2012). The bimodal rainfall distribution presented in Figure 2 shows monthly averages for nearby Cotonou produced from recent climate datasets (METEO Benin 2018). June is the wettest month of the large rainy season and contributes approximately 25% to total annual rainfall. On average, the driest months of December and January each experience less than 20 mm of rain per month.

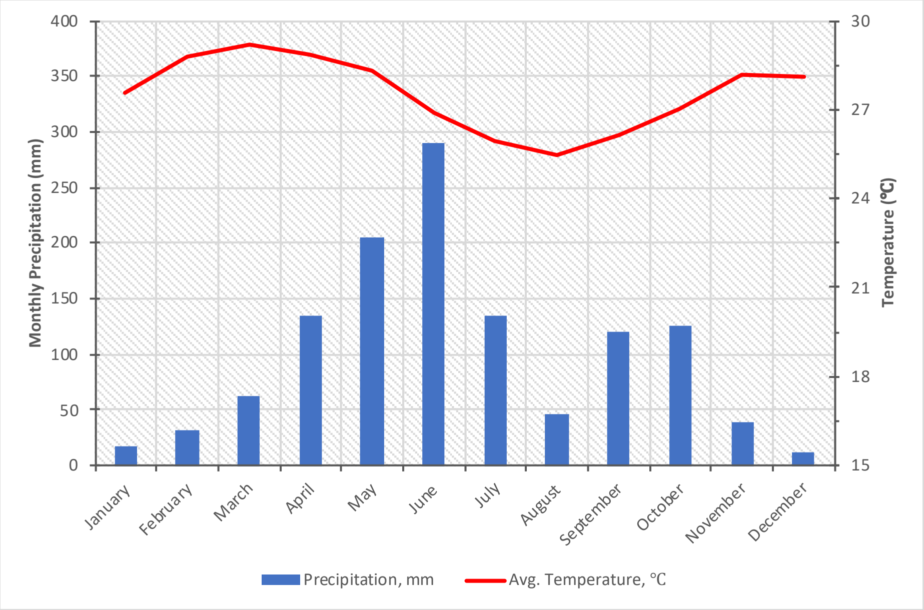

Figure 2 Monthly Precipitation and Average Temperature in Cotonou, Benin (1991-2017). Datasets sources: METEO Benin 2018; NOAA 2018

Figure 2 also shows the intra-annual temperature variation for the southern region derived from satellite data (NOAA 2018). Monthly temperatures average between 25-30 °C during the year and reach a maximum between February and April.

2.3. Hydrogeology

2.3.1. Soils

Ferralsols (Oxisols in US taxonomy) comprise the dominant soil type in the Ouédo study area (Volkoff 1976). Here the ferralsols are represented by the sandy-clay sediments of the Continental Terminal while soils closer to the river are alluvial sands and transported colluvium material. Typical of the humid tropics, ferralsols are deeply weathered, red or yellow soils with diffuse horizon boundaries, low activity clays and oxides (Driessen et al. 2001). They are low pH, nutrient-poor soils that require nutrient cycling for agricultural activities. However, the study area in the Allada plateau is part of the larger Terre de Barre plateau of southern Benin – a fertile plateau of high bio-productivity soils that is supported by the moisture from surrounding marshland (USGS 2016).

2.3.2. Geology

The Ouédo study area lies within the Coastal Sedimentary Basin (CSB) formation that encompasses an area of approximately 12,000 km^2 across southern Benin (Boukari et al. 2016). The geological context of the CSB and location of Ouédo study area at the base of the Allada Plateau is presented in Figure 3.

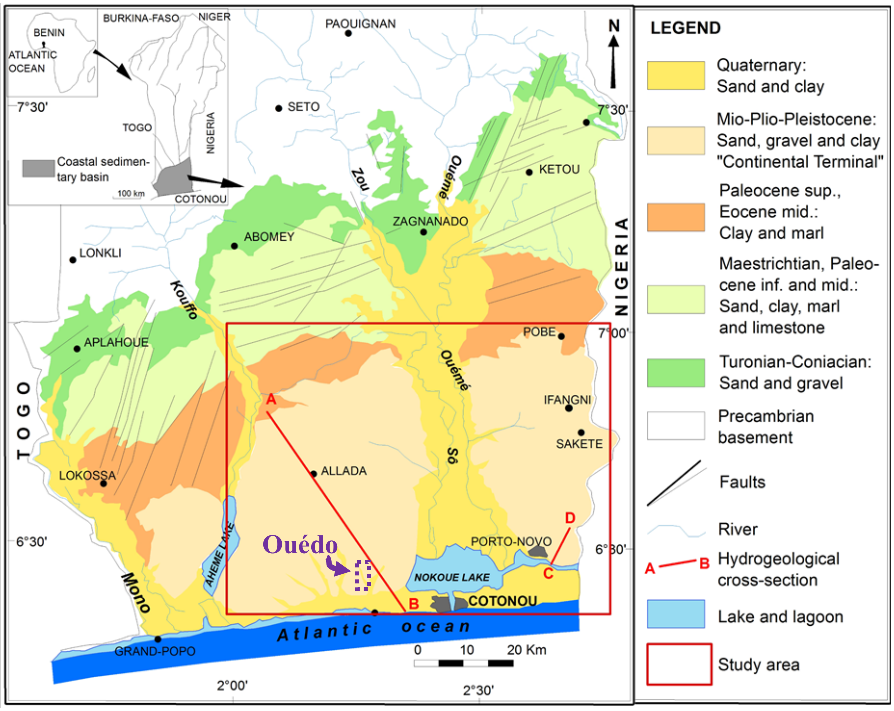

Figure 3 Modified geological map of the CSB as presented in the study of Alassane et al. (2015) with original map produced by IRB (1987). Ouédo study area shown in purple dotted rectangle.

The CSB formation is of Lower Cretaceous to Quaternary age and contains marine deposits (sandstone, limestone, clay, marl and conglomerate) of the greater transboundary Keta Basin that extends from Ghana to Nigeria (IRB 1987; Boukari 2007). The CSB has a monoclinal structure dipping to the southwest, where its thickness reaches up to 2000 m (Boukari 2007).

In Ouédo, the surface geology of the CSB is represented by first a Quaternary cover of alluvial deposits and/or unconsolidated sediments and the Mio-Pliocene sandstone or "Continental Terminal". The modified geological map from Kotchoni (2012) is presented in Figure 4.

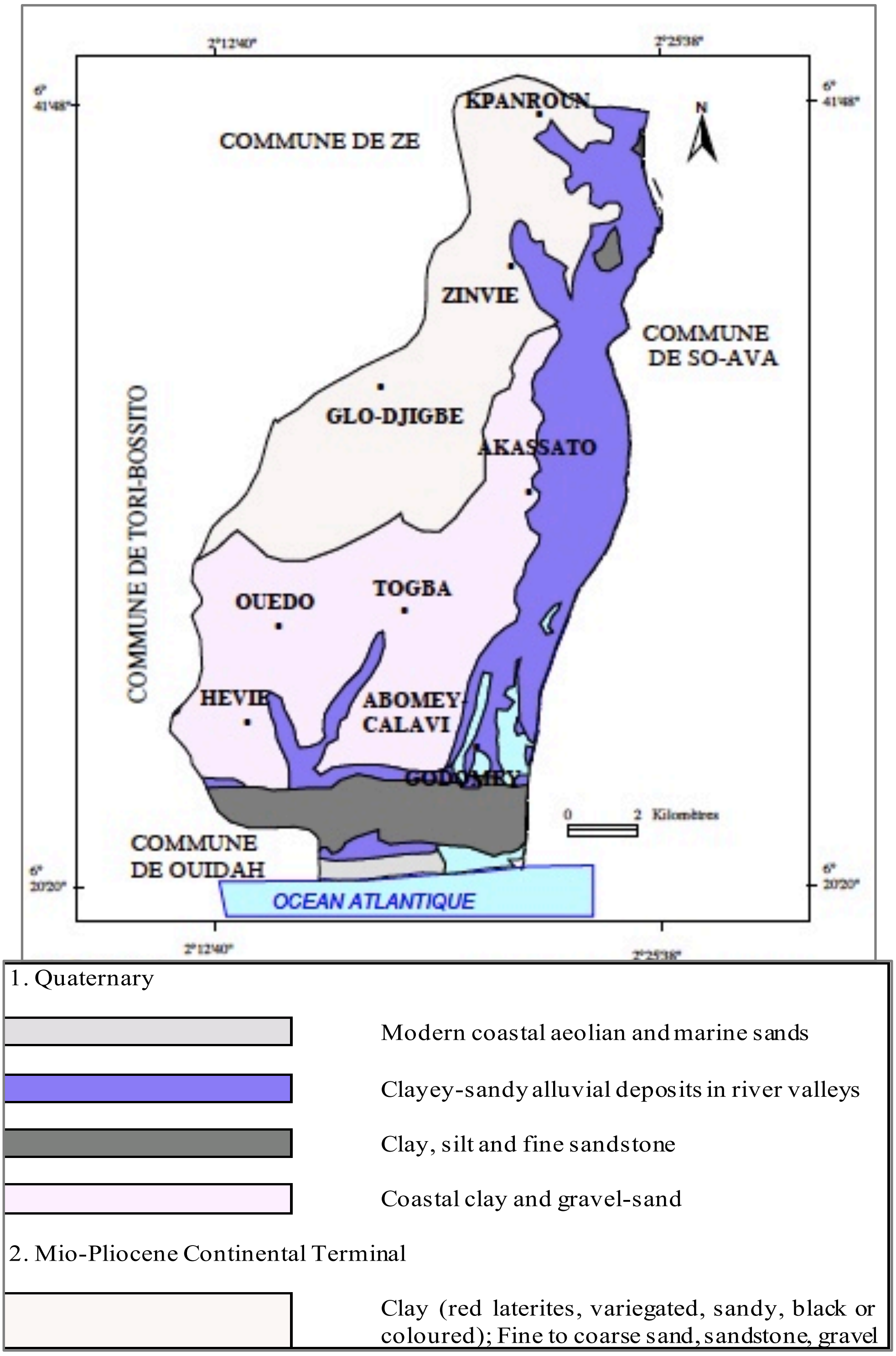

Figure 4 Modified geological map of the Abomey-Calavi, Benin (Kotchoni 2012)

The Quaternary deposits comprise sand and clay, and occur as alluvial deposits near the rivers running through the basin or colluvium transported from the plateaus (IRB 1987; Boukari et al. 2016). The CT consists of sands, gravels and clays packaged in irregular discontinuous layers with lenticular forms (IRB 1987; Alassane et al. 2015).

2.3.3. Characterization of Aquifers

The Ouédo study area in the CSB belongs to the Keta/Dahomey/Cotier Basin transboundary aquifer system of southern Benin. The Keta Basin transboundary aquifer (AF48) has an area of 36,904 km^2 shared by Ghana, Togo, Benin and Nigeria (IGRAC and UNESCO-IHP 2015).

While the CSB underlies only 10% of Benin territory, it contains approximately 35% of Benin's total groundwater reserves and is used to supply the almost 7 million inhabitants living in southern Benin. The vast central granitic basement complex encompassing the majority of Benin allows for limited groundwater storage in intermittent fractured bedrock aquifers (Boukari et al. 2016). Therefore, the high-yielding CSB is one of the most important and productive aquifers in the country.

The basin is comprised of four aquifers (Boukari 2007) but only the two upper aquifers are exploitable in the study area as the two lower aquifers are too deep. The exploited aquifers are described as follows, in order of increasing age and depth:

1. Quaternary aquifer (coastal and alluvial sands)
2. Mio-Pliocene Continental Terminal aquifer (sands)

These aquifers provide the majority of drinking water supplied to southern Benin. Their hydrogeological characteristics sourced from Boukari et al. (2016) are summarised in Table 1 below:

Table 1 Hydrogeological parameters of CSB (Boukari et al. 2016).

Aquifer and borehole properties	**Ranges of values**
Aquifer thickness	20 – 150 m
Depth to water table (from the surface)	5 – 50 m
Borehole depths	10 – 100 m
Yield	2 – 50 L/s
Transmissivity	80 – 900 m^2/day
Storage coefficient	10^{-6} – 10^{-5}

In the study area, the two aquifers of interest are the shallow Quaternary aquifer and the underlying Continental Terminal (CT) aquifer. The known parameters of these two aquifers are presented in Table 2 with data sourced from the available literature in the study area (Kotchoni 2012; Alassane et al. 2015; Kotchoni et al. 2018):

Table 2 Characteristics of Quaternary and Continental Terminal aquifers in study area. Data sources: Kotchoni 2012; Alassane et al. 2015; Kotchoni et al. 2018

	Shallow Quaternary aquifer	**CT aquifer**
Type	Unconfined	Confined to unconfined
Aquifer thickness	< 20 m	60 – 140 m
Transmissivity	(unknown)	$4 \times 10^{-3} - 14 \times 10^{-3}$ m^2/s
Storage coefficient	(unknown)	$2 \times 10^{-4} - 9 \times 10^{-4}$
Specific yield	(unknown)	21.3%

The shallow and unconfined Quaternary aquifer contains unconsolidated sediments of the Terre de Barre and allows for the storage of shallow groundwater less than 20 m below the surface in Ouédo. The CT aquifer can occur throughout the CSB as unconfined, semi-confined and confined due to discontinuities in the sand and clay layers and the irregular occurrence of lenticular clays. These aquifers are recharged by precipitation and the CT also receives direct recharge where it surfaces to the north of the plateau (Boukari 2007).

While hand-dug wells (*puits*) in Ouédo access groundwater stored in the sands of the Quaternary aquifer, the new boreholes (*forages*) drilled in 2012 and operational since 2014 tap into different layers of the underlying CT aquifer. The production boreholes operate at flow rates between 79.2-182.7 m^3/hour. The borehole logs commissioned for the new wellfield allowed for preliminary characterisation of the lithology and local hydrogeology. They describe the presence of a confining clay unit above the CT aquifer but the continuity of the clay unit between boreholes remains ambiguous and therefore, it is unknown whether the CT is confined or semi-confined within the study area itself.

Lithostratigraphic correlations of the borehole logs were executed by Kotchoni (2012) for the evaluation of the zone of capture of the wellfield before full operation of the production wells began in 2014. These interpretations aid in understanding the hydrogeological context of the boreholes and hand-dug wells of the study area. The section in Figure 5 follows a transect (A-B) across boreholes in the north of the study area while Figure 6 presents a transect (C-D) across the boreholes in the south. In both sections, the thickness of the confining clay unit separating the unconsolidated sediments of the shallow Quaternary aquifer (identified as Terre de Barre) from the sandstone of the CT aquifer ranges from only a few meters to up to 50 m in some places. These interpretations will benefit from further investigation of the lithology in the area since gaps of up to 2 km between some boreholes introduces the possibility for error in interpolation.

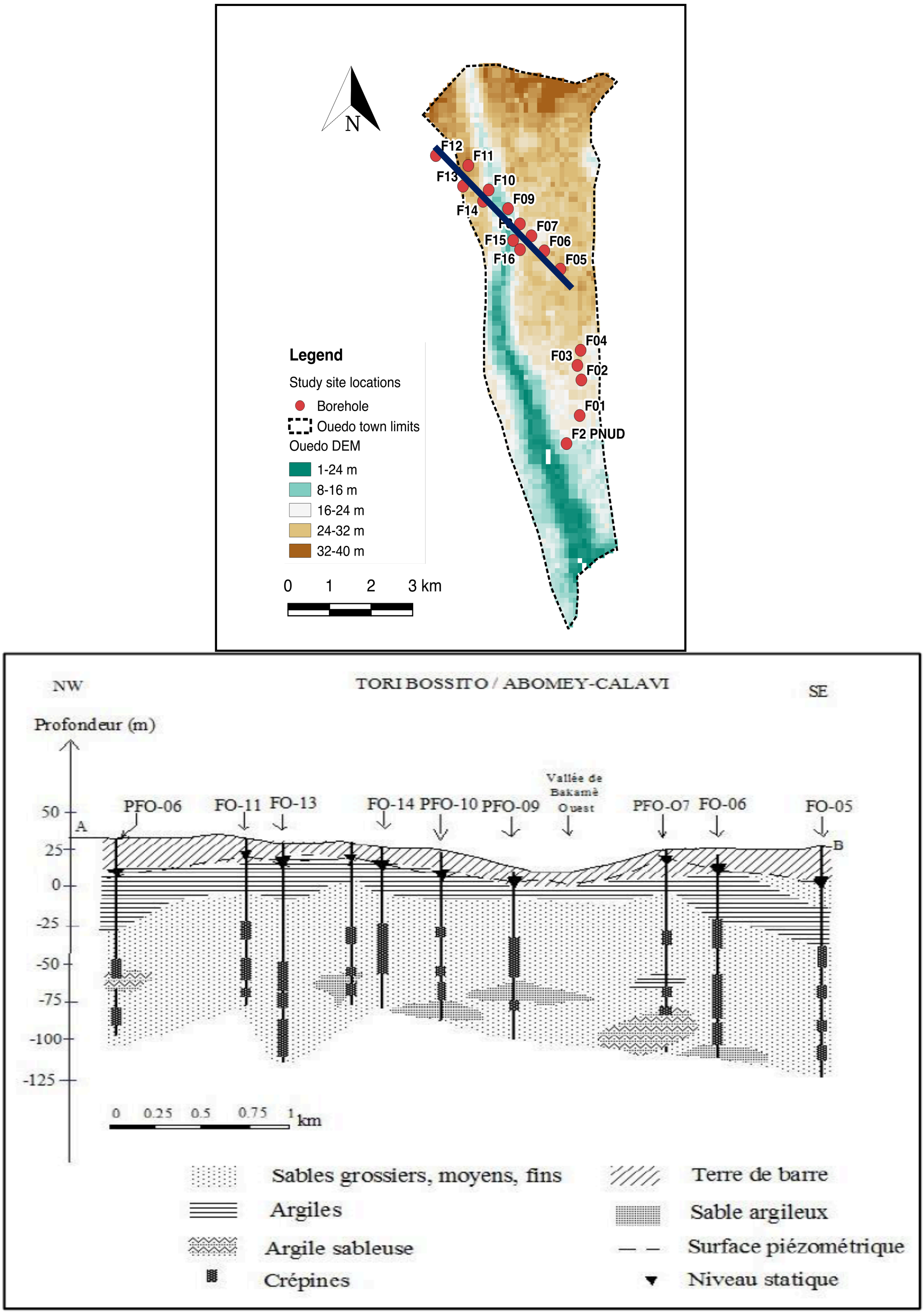

Figure 5 Lithostratigraphic correlation of borehole logs in northern Ouédo (Kotchoni 2012) following cross-section A-B of inset map.

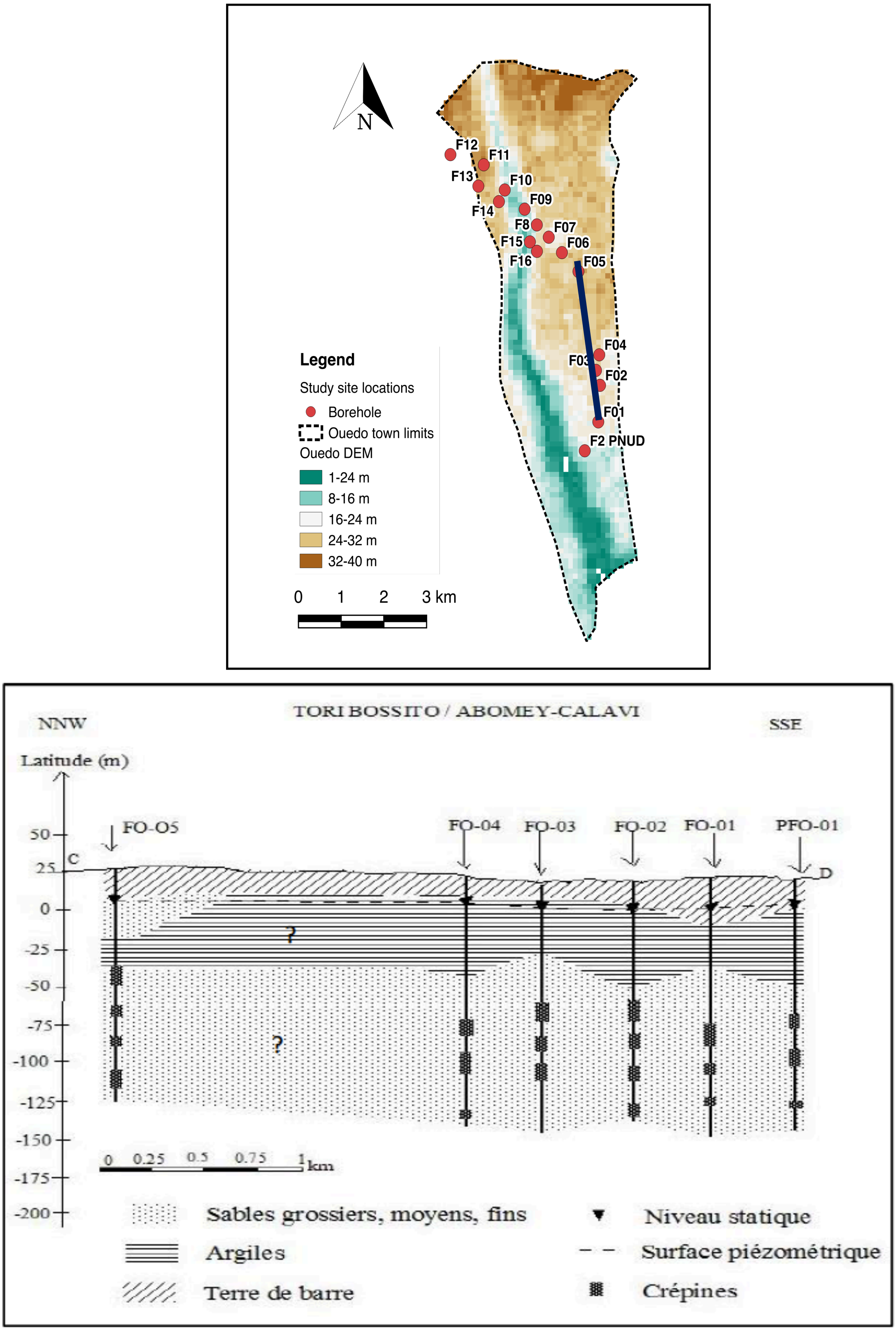

Figure 6 Lithostratigraphic correlation of borehole logs in southern Ouédo (Kotchoni 2012) following cross-section C-D of inset map

2.3.4. Water Use and Governance

The two main institutions responsible for groundwater management in Benin are the National Water Company of Benin (SONEB), in charge of water supply to urban areas, and the General Directorate of Water (DG-Eau), in charge of water supply to rural areas. In Ouédo, SONEB manages the new wellfield for groundwater supply to the Greater Cotonou Area (SONEB 2014).

DG-Eau supplies water to rural communities. However, out of the almost 6000 households in Ouédo, the 2013 census revealed that only 1.5% had access to potable water (INSAE 2016). This was the lowest access rate of all towns in the Abomey-Calavi commune. Ouédo residents rely primarily on groundwater for domestic and agricultural purposes. Over 60% of local households are described as agricultural households (INSAE 2015) and most practice subsistence farming, utilizing traditional or improved traditional irrigation methods (FAO 2016).

Improved water points in the study area include standpipes (*bornes-fontaines*), modern wells and boreholes equipped with handpumps (DG-Eau 2015). However, residents of Ouédo rely greatly on hand-dug wells for water supply and/or buy drinking water from local water-sellers.

The majority of hand-dug wells were constructed while others were provided by NGOs, private donors and foreign agencies. Some of these wells are protected and equipped with hand-pumps while most are open and allow the retrieval of water through the bucket and pulley setup. The maintenance of each well and management of the shared use is administered by a local committee set up by residents (personal communication). Local water sellers have domestic boreholes (*forages domestiques*) drilled by lorry and can access groundwater at depths of up to 100 m into the CT aquifer.

With regard to the new Ouédo wellfield, all of the abstracted groundwater is currently transmitted to the urban water network supplying Cotonou and other nearby urban areas. In the environmental impact report for the development of the Ouédo wellfield (SONEB 2011), SONEB noted the risk of drying up of village wells and the necessity for a monitoring network and implementation of corrective measures should such an event occur. However to date, no monitoring program has been implemented for the shallow Quaternary aquifer. Recently, SONEB halted production on one of the Ouédo production boreholes (F07 in Figure 7) with plans to build a local connection for residents (personal communication). To date, no work on the local supply network has begun.

Water quality concerns also exist in the area, particularly the possible introduction of bacteria through hand-dug wells into both the shallow and semi-confined aquifers. Improper sanitation and hygiene practices near hand-dug wells present great health risks with bacterial contamination. Further risks include contamination from infiltrated runoff near mounds of untreated waste in the area or from the leachates of two landfills (14 ha combined area) established by the Cotonou municipality in the southern Ouédo village of Allansankomé. There is a third now-closed landfill further southwest (downstream) in the adjacent town of Hevié (SONEB 2011). Here on-site incineration of medical waste and other material had occurred, but no treatment of wastes or remediation works were conducted after closure of the site.

Although “hundreds” of hand-dug wells have been constructed in Ouédo in recent years, no official data is available on the number of wells, average daily consumption, depth to water table, water quality and function of the wells (Kotchoni et al. 2016a). Neither is there any information on observed trends with the hand-dug wells and any correlation to water abstraction at the nearby pumping field. In addition to supply, DG-Eau together with the National Water Institute (INE) are the organizations responsible for groundwater monitoring in Benin. Although the national “Code of Water” dictates that persons wishing to abstract water must apply for permits through the Ministry of Mines, Energy and Water (DG-Eau 2018), lack of enforcement of regulations, limited freshwater reserves and large unmet water demand contribute to increased unregulated construction of hand-dug wells for households and agricultural use in Ouédo and other rural and peri-urban areas.

CHAPTER 3

Literature Review

3.1. Recent climate variability

3.1.1. Climate studies

Climate variability studies in the region are restricted to datasets prior to 2010. In a recent analysis of climate variability in West Africa for the period 1960-2010, Barry et al. (2018) determined significant trends of increasing precipitation and increasing daily rainfall intensity index, particularly from 1990-2010. However, they highlighted the drought immediately preceding this period of increased rainfall. The authors considered whether the wet conditions were in response to the decade of dry conditions, a response to increased greenhouse gases since 1910, or rather a long-term response to increased warming in the region. In the 2010 study of the CSB of southern Benin, Totin (2010) investigated the climate and land-use changes in the basin and the sensitivity of groundwater quality to these variations. For the studied period of 1951-2005, Totin (2010) described annual rainfall decrease of 17% in southern Benin.

Achidi et al. (2012) determined long-term averages for rainfall in southern Benin for datasets ranging from 1980-2009. The authors determined mean annual rainfall to be 1,148 mm. Daily precipitation in tropical regions like southern Benin often occurs as large sporadic convective storms rather than well-distributed rainfall events (Barry et al. 2018). These intensive rainfall events are further known to contribute significantly to groundwater recharge in the southern Benin region (Jasechko et al. 2015).

In terms of temperature, Barry et al. (2018) determined an upward trend of at least 0.09 °C/decade for southern Benin. This was provided within a West African context that saw regional annual maximum and annual minimum temperatures in West Africa increase by 0.16 °C/decade and 0.28 °C/decade, respectively. These trends were averaged over climate data between 1960-2010 from 16 West African countries and 166 meteorological stations, 18 of which were located in Benin. For southern Benin, Totin (2010) had determined an absolute temperature increase of 1.8°C in southern Benin over the studied period of 1951-2005, therefore a value of approximately 0.36 °C/decade. This value is higher than the West Africa regional trend identified by Barry et al. (2018).

There is a need to examine more recent climate datasets in order to determine how recent climate variability may be affecting recharge to the aquifers. This is necessary for isolating the impact of climate on shallow Quaternary aquifers since abstraction began in the wellfield in 2014.

3.1.2. Recharge studies

Research into groundwater flow and transport (Kpegli et al. 2017), aquifer storage estimation using geophysics (Nicaise et al. 2012; Vouillamoz et al. 2014, 2015) and recharge estimation using hydrochemistry and piezometry (Kotchoni et al. 2015; Kpegli et al. 2015) are channelled towards the development of improved conceptual groundwater models for Benin. However, recharge in the CSB, and in particular the shallow Quaternary aquifer, is not well quantified.

In the first major assessment of recharge in the CSB, Totin (2010) determined seasonal variation of groundwater levels in the CT aquifer averaged over the period 1991-2007. The author demonstrated a unimodal piezometric pattern in response to the bimodal rainfall distribution. Piezometric levels gradually increased from May to September as the aquifer was continuously recharged. Using a soil-moisture balance, Totin (2010) determined recharge to the CT to be 50-104 mm/year.

Kotchoni et al. (2018) provided recent estimates of recharge for important aquifers in Benin, including the CT aquifer at the location of the study area (Allasankomey). The shallow Quaternary aquifer was also investigated but nearby Cocodji (approximately 4 km south of Ouédo), where the nature of the sediments and the hydrodynamics differ due to the location on the coastal plain. Using the water table fluctuation method for a network of piezometers in southern Benin, the authors determined a linear relationship between rainfall and recharge beyond a rainfall threshold of 140-250 mm/year. This was determined for piezometric datasets ranging 19-25 years and using the recent estimates of specific yield determined using Magnetic Resonance Sounding (MRS). Annual recharge to the shallow Quaternary aquifer at Cocococodji accounts for 40% of annual rainfall while annual recharge to the CT aquifer is 13% annual rainfall. The authors considered the thickness and high clay content of the unsaturated zone as limiting factors in the recharge of the CT aquifer. The authors compared their estimates to previous studies and highlight the limitations of the latter with respect to limited dataset, assumptions on specific yield or soil-moisture balance models with high uncertainties. Kotchoni et al. (2018) found a strong correlation between rainfall and recharge for the aquifers studied. The correlation was strong on an annual scale for both aquifers of interest but weaker on the monthly scale for the CT aquifer. Further, the time series of piezometric fluctuations at the two stations showed a long-term trend of increasing groundwater level in the shallow Quaternary aquifer at Cocococodji and equilibrium for groundwater levels for the CT at Allasankomey.

These studies provide an estimate of general recharge in the region and show that a decrease in precipitation could indeed translate into a decrease in groundwater storage in the shallow Quaternary aquifer in the study area. However, they also highlight the need for groundwater monitoring in the shallow Quaternary aquifer in Ouédo.

3.2. Recent changes in land use/land cover and population growth

3.2.1. Land use and land cover (LULC)

Benin has amongst the fastest average annual rate of cropland expansion in West Africa, where agriculture is replacing and/or fragmenting the indigenous forests, wetlands and savannas (CILSS 2016). This trend comes about as West Africans face conflicting needs for food and economic security against ecosystem conservation and biodiversity protection. The most significant LULC changes in West Africa in the last four decades were observed along the Gulf of Guinea coastal zone where rapid urban expansion was taking place (CILSS 2016).

Throughout Benin, urban and agricultural land cover have been replacing natural vegetation. In southern Benin, these man-made landscapes have replaced or fragmented the historic dense natural forests known for their bio-productivity. Urban expansion from Cotonou has moved from the coastal zone to further inland and exerting pressure on peri-urban areas (Nlend et al. 2018). Agricultural landscapes, particularly cropland with oil palm trees, now dominate the landscape of the Terre de Barre plateau. In Ouédo, the majority of households are described as agricultural households (INSAE 2015). Here, subsistence farming is norm and farmers utilize rudimentary manual tools and traditional or improved traditional irrigation practices (FAO 2016). However, slash-and-burn practices are widespread throughout the commune (INSAE 2004) and significantly degrade the landscape. In Abomey-Calavi the most cultivated agricultural produce are cassava and maize while palm oil and pineapple are considered cash crops (INSAE 2016). Information on agriculture and the distribution of crops in Ouédo was unavailable.

To determine how the Ouédo landscape has changed in recent years and the potential impact on recharge to the shallow Quaternary aquifer, it is necessary to obtain land use and land cover (LULC) data for the study area. Studies exist on land conversion in more urbanised areas in southern Benin (M'barek et al. 2005; Totin et al. 2010, 2013a; Nlend et al. 2018). However, data on land-use and land-cover changes in the Ouédo study area are not available in the literature. Therefore, it is necessary to source satellite-derived LULC datasets and extract site-specific information relevant to solving the hypothesis. Settlement growth can also serve as a proxy for assessing population growth and support observed demographic trends (CILSS 2016). Therefore, the LULC results will be used to supplement population growth results in the study area.

3.2.2. Population growth

A recent study of water consumption in Benin concluded that in peri-urban areas, estimated consumption was 20 liters/capita/day (M'barek et al. 2005). Since in Ouédo the main source of water is groundwater and regionally the groundwater is used primarily for domestic purposes (Houngnandan 2015; Nlend et al. 2018), this consumption value can be used to estimate per capita daily consumption of groundwater in the study area. Accordingly, population growth statistics will aid in the estimation of groundwater abstraction from the shallow groundwater reserves.

In Benin, population growth is considered the strongest driver of land-cover change (CILSS 2016). The south of Benin, in particular, faces increased population growth. With a population density of 220-442 persons/km^2, the south has more than half of Benin's population occupying 11% of total country area (INSAE 2015). There is increased migration from Cotonou to nearby communes due to overpopulation and the associated pressures (e.g. environmental degradation, high costs of living) (INSAE 2015). One of these target communes is Abomey-Calavi to which the Ouédo town belongs.

3.3. Stable isotopic and hydrogeochemical signatures of groundwater

3.3.1. Isotope tracer hydrology

Isotope tracer hydrology is a prominent tool for characterizing water in atmospheric, surface and subsurface environments. The guiding principle is the use of environmental or natural tracers in the water to inform on the history and status of a water body. Amongst the many applications in hydrological research, environmental tracers are commonly used to characterize the evolution of a water body from source to sink. They provide unique information on recharge sources, groundwater flow pathways, residence times, age, quality, geochemical reactions, and surface water-groundwater interactions (Clark and Fritz 1997). To aid in understanding stable isotopes, the fundamental theory is described in Appendix A.

Through a process known as isotope fractionation, the proportions of heavy and light isotopes in a water sample can provide information on phase transitions and physicochemical reactions that occurred. Evaporative effects are the most common example of fractionation in groundwater. In arid and semi-arid areas where evaporation rates are high, evaporation processes can occur for infiltrated water in the unsaturated zone before it arrives as recharge in the unconfined aquifer. However, for soils with fast infiltration rates due to preferential flow paths and macropores, minimal evaporation will take place in the unsaturated zone and so groundwater will have a similar isotopic composition to the mean precipitation. With open wells e.g. the traditional hand-dug wells in Ouédo, the stagnant water at the top of the well water column is expected to be enriched in heavy isotopes because of evaporation processes. To get a more representative sample it is therefore necessary to remove as much stagnant water as possible and sample from fresh inflow into the well. This was a challenge in the hand-dug wells without compromising the structural integrity of the well and the water supply for the private owners. Further discussion of the modified sampling method is described in the Methodology section 4.2.

A review of isotope studies in Benin by Totin et al. (2013) determined that there is only partial coverage of available studies in the country and a lack of connection between results and sustainable resource management. In central Benin, investigations of the hydrogeochemical and isotopic properties of the crystalline basement were used to identify recharge sources and develop conceptual hydrogeological models (Fass and Reichert 2004; Kpegli et al. 2015;

Kotchoni et al. 2016b). For southern Benin, the earliest application of isotope geochemistry investigated recharge processes of the then little-understood CSB (Dray et al. 1989). Odeloui et al. (2013) investigated the extension of the basin in the littoral plain (along the coast) and used isotopes to confirm the influence of seawater intrusion. Kpegli et al. (2018) investigated stable isotopes and piezometry for determining groundwater flow in the deeper Turonian-Coniacian aquifer underlying the CT. While this study was conducted in an area north of the Allada Plateau (approximately 30 km north of Ouédo), the findings confirmed the recharge area for the CT aquifer as located north of Ouédo and also confirmed groundwater flow as flowing southeast across the Allada Plateau (towards Ouédo).

No published literature exists on the stable isotopic investigations that have taken place in the study area. However, the results of precipitation, surface and groundwater samples taken for monitoring studies and ongoing research in the basin are available in the International Atomic Energy Agency (IAEA) database (IAEA/WMO 2018). The IAEA has stations around the world that monitor isotopic compositions of surface and groundwaters (IAEA/WMO 2018). In Benin two IAEA stations were established: the first at Bohicon (approximately 70km north of the study area) and the second in the Abomey-Calavi area. The stations have records of isotopic signatures of 180 water samples in southern Benin starting from 2005 and can be used in validating the composition of samples obtained. The sample locations and results of stable isotope analysis from the IAEA database in southern Benin (IAEA 2007) are presented in Appendix A. Analyses of the raw data from this study and later monitoring provide spatial and temporal context for variations in the CSB. The establishment of regional trends (e.g. monthly precipitation signatures) and validation of observed isotopic compositions will aid in the interpretation of the timing and locality of recharge to the shallow alluvial and CT aquifers and illustrate any fractionation and evaporative effects that may have occurred in the water bodies. Further, the analyses and interpretation of results will be used to contribute to the IAEA dataset and facilitate ongoing and future research of the coastal aquifers.

For surface water recharge sources that underwent evaporative processes, the sampled groundwaters $\delta\,^{2}H$: $\delta\,^{18}O$ ratios will follow an evaporative line (linear regression) (Clark and Fritz 1997). For aquifers recharged by direct precipitation, the isotopic composition of the groundwater will not differ significantly from the composition of mean precipitation (Clark and Fritz 1997).

Groundwater mixing between the two aquifers in the study area will be estimated using isotope tracer hydrology methods. The mixing can be quantified using the amount of ^{2}H or ^{18}O isotopes in the two aquifers (A and B) through simple linear algebra:

Equation 1

$$\delta_{sample} = X * \delta_A + (1 - X)\delta_B$$

where δ represents the ratio of heavy to light isotopes compared to the standard in the investigated aquifer and X the fraction of groundwater A present in a mixture of A and B (Clark and Fritz 1997). This two-component mixing equation (binary mixing model) can be used for any conservative tracer or chemical constituent of the water (e.g. chloride concentrations) and is effective when the chemical characteristics of the two waters combining in the well are distinct (Eberts et al. 2013).

Stable isotopes can also be used for establishing the timing of recharge to the groundwater reservoirs. The stable isotopic composition in precipitation is strongly correlated to temperature and rainfall amount and therefore can be traced based on seasonal fluctuations (Clark and Fritz 1997). Through analysis of the available isotope data in the IAEA database as a component of this study, seasonal variations can be investigated and used to determine the timing of recharge of shallow groundwaters in southern Benin. From the report of the 2005-2007 study, monthly sampling and monitoring in southern Benin revealed seasonal variations in the ^{18}O composition of precipitation water after (IAEA 2007).

3.3.1. Hydrogeochemistry

For the investigation of the CT aquifer in a study area that includes the town of Ouédo (Figure 3), Alassane et al. (2015) used multivariate statistical analysis to identify mineralization sources in the aquifer and concluded that mixing with surface lagoons introduced salinity into groundwater systems while cation exchange, soil CO2 diffusion and anthropogenic activities influenced water chemistry and groundwater evolution in the subsurface. This is consistent with other studies in southern Benin on the key controls on water quality and water chemistry (Silliman et al. 2007; Edet 2010; Totin et al. 2010; Odeloui et al. 2013). The study by Alassane et al. (2015) further concluded that mineralization in the CSB was determined by the predominance sodium and calcium for cations and chloride and bicarbonate for anions. The sodium and chloride ions are sourced from coastal lagoons, sea spray and coastal rainwater in southern Benin. The study also determined the occurrence of cation exchange processes due to the presence of clay units in the aquifer. It is therefore expected that groundwater samples in the study area will have varying concentrations of the major ions described and there may be evidence of cation exchange processes occurring in the deeper aquifer.

The evaluation of water quality parameters in the shallow Quaternary aquifer and deeper CT aquifer will further aid in the determination of the mixing of shallow groundwater in the deeper aquifer as a result of wellfield abstraction. Since agricultural activity is high in the southern Benin, the evaluation of nitrates is particularly useful in assessing the transport of surface contaminants to the deeper aquifer. Nitrates occur naturally in surface water and groundwater bodies but high concentrations are linked to the application of fertilizers to crops in agriculturally-intensive regions and domestic effluents from the improper disposal of waste and poor sanitation (Appelo and Postma 2004). Nitrate pollution is especially common in those agricultural areas with nutrient-poor and/or bare soils, such as the ferralsols of the Ouédo study area. Nitrogen compounds can also originate at point sources such as waste disposal sites and septic tanks (Appelo and Postma 2004) and is of particular concern in areas with low access to improved sanitation. Analysis of total nitrogen concentrations of groundwater samples will be evaluated against the EU and WHO regulation of 50 mg/L for potable water. Totin et al. (2010) determined that groundwater degradation in southern Benin was more a result of bacterial contamination from surface anthropogenic inputs more than natural mineralization in the subsurface. However, the analysis of water quality with respect to bacterial analysis is outside the scope of this study.

CHAPTER 4

Methodology

4.1. Introduction

The literature review revealed knowledge gaps for better understand groundwater dynamics in the shallow reservoirs of the study area. These knowledge gaps include: (i) recent climate data, (ii) indications on recent land-use/land-cover change and population growth and (iii) isotopic and hydrogeochemical signatures.

To obtain this information, a three-week field survey in Ouédo was carried out from April 19 – May 10, 2018. Additional data was processed from remote-sensing derived online datasets.

4.1. Recent climate variability

The closest meteorological station to the Ouédo study area with complete datasets for the climate parameters of interest is the Cotonou airport station (WMO code: 653440). Since the station is less than 15 km away from Ouédo, the Cotonou climate data is assumed to be representative of the study area.

The precipitation data from 1991 – 2017 were sourced from the Benin meteorological office (METEO Benin 2018). Precipitation data for the month of May 2017 in the Benin meteorological office dataset were incomplete and therefore replaced by NOAA estimated satellite data (NOAA 2018).

The accessible temperature datasets of the Benin meteorological office were incomplete and so the NOAA data was used as an estimation of actual station records. The temperature data from 1991 – 2017 were sourced completely from NOAA satellite data (NOAA 2018).

Actual evapotranspiration and interception (ETIa) data were sourced from WaPOR remotely-sensed 100-m resolution datasets and cover a more restricted period of 2009 – 2017 (FAO 2018). ETIa data for both the Cotonou station and the Ouédo study area were selected in the WaPOR raster dataset in order to compare how trends at each location relate to southern Benin precipitation and temperature data.

4.2. Recent changes in land use/land cover and population growth

The land use and land cover (LULC) raster datasets were for West Africa were sourced from Tappan et al. (2016). These were three-period rasters (1975, 2000 and 2013) using an LULC class system of twenty-six (26) classes to identify variations on Landsat satellite imagery. Each pixel represented in 4 km^2. Further details on the classification can be accessed at Tappan et al. (2016).

Population data was sourced from the National Institute of Statistics and Economic Analysis (INSAE) for Ouédo and the surrounding commune of Abomey-Calavi. Baseline information on population growth were obtained in the last two national censuses in 2002 (RGPH3) and 2013 (RGPH4) (INSAE 2004, 2016). Further data on recent growth and abstraction were calculated using population estimates in country profile reports (CIA 2018; IndexMundi 2018), peri-urban consumption rate analysis (M'barek et al. 2005) and regional groundwater usage trends (Houngnandan 2015). These estimates and growth rates were applied to calculations on estimated water use trends in the Ouédo study area.

Household surveys on consumption habits, water treatment and groundwater level changes in hand-dug wells were carried out during the field program. The survey questions were prepared prior to field work and were based on knowledge gaps on shallow groundwater abstraction in the study area. The survey template and translation are located at Appendix B and Appendix C. Interviews were conducted in French and the local Fon language by an MSc student field assistant of the University of Abomey-Calavi.

Aerial surveying of the study area was carried out during the field campaign with the assistance of a local NGO, Benin Environment and Education Society (BEES). A drone was used to capture high-resolution aerial photography of the study area to get an overview of the distribution of all the hand-dug wells, including those that could not be surveyed or were not easily accessible. The Phantom 4 drone was deployed at midday on May 9th, 2018. However, thunderstorms and windy conditions on the day of survey necessitated early termination of the drone survey. The aerial survey therefore captured less than 0.4 km^2 section of the study area in the vicinity of borehole F05. Still, the orthomosaic provides an estimate on the density and distribution of hand-dug wells in the study area.

4.3. Stable isotopic and hydrogeochemical signatures of groundwater

Hand-dug wells, boreholes, surface water and precipitation sites were investigated for piezometric and hydro-chemical characteristics during the field campaign. The locations of investigated hand-dug wells (including dry wells), boreholes and surface water bodies are presented in Figure 7. The precipitation sampling points for the study area were at OC08 and the base station in Cotonou (not shown on the map). The following tasks were executed:

- Collection of water samples (pump, bailer and/or direct tapping from production well)
- Direct testing of EC, T, pH and alkalinity (field kits)
- Measurements of piezometric levels and borehole/hand-dug well dimensions (top of casing, diameter, elevation)
- Hourly monitoring of piezometric levels in hand-dug wells (divers)

4.3.1. General sampling procedure

Groundwater levels, electrical conductivities, temperature, pH, alkalinity and nitrate ranges were measured at selected boreholes, piezometers, hand-dug wells and surface water sites in the study area. Calibration procedure was observed for the conductivity and pH meter where the latter was re-calibrated during the three-week data collection period using pH 7 and pH 10 buffer solutions. All equipment was rinsed with diluted water between sample/measuring points.

Samples obtained in the field were pre-filtered before filling bottles and vials. These samples would be processed upon return to IHE lab for characterization of water chemistry i.e. stable isotopic composition, major cations and anions, total organic carbon (TOC) and total nitrogen (TN). For the cations samples the bottles were pre-treated with 5 drops of nitric acid while for the TOC/TN samples the bottles were pre-treated with 3 drops of sulphuric acid. Sample volumes for O-18 and H-2 stable isotopes were 2.5 mL each while volumes for other water chemistry were 25 mL each. Alkalinity was tested in the field at most sampling sites using a titration kit with bromcresol green-methyl red indicator solution and 0.020 M sulphuric acid standard solution.

All other field sampling protocol was observed and described fully (Thermo Fisher Scientific 2008; IAEA 2010). The full materials and equipment list are provided at **Error! Reference source not found.**.

4.3.2. Wellfield boreholes

For the boreholes of the Ouédo wellfield, samples were obtained directly from the tap of the production well. The proposed plan was to pump groundwater from the piezometers at five of the production borehole sites and sample the groundwater after stagnant water had been evacuated. At the first two boreholes piezometers (PF08 and PF09), water was pumped out of the piezometer and samples taken once the conductivity stabilized. However, upon discussion with supervising researchers it was determined that after two hours of pumping the average EC of the samples was still not representative of the CT aquifer. In fact, instead of decreasing to the representative range of < 80 µS/cm, conductivity levels began increasing to over 200 µS/cm and stabilizing within the range of 210 +/- 10 µS/cm. The plan was revised and, with the permission of SONEB, sampling was carried out directly from the tap of the production borehole. Here representative conductivity values were obtained. Where possible, water levels and conductivities were measured with the LHA sounder at the piezometer adjacent to the production borehole while samples were obtained from the production borehole tap.

4.3.3. Hand-dug wells

Due to the multitude of hand-dug wells in the area, selection was based on the most utilized wells in the villages of Ouédo and ease of access (which included securing permission from the well owners and/or village chiefs).

For the hand-dug wells, a plastic bailer was used to retrieve samples were from the deepest depth without disturbing the settled sediments at the base of the well. These hand-dug wells could not be evacuated as standard well sampling procedure because of concerns over well construction, clogging of pumps by the thick layer of sediments at the base of the well, pumping duration and high fuel costs. Since only the most regularly used hand-dug wells were sampled, this minimized the risk of sampling stagnant or long-standing water and the associated evaporative effects.

4.3.4. Surface water and precipitation

Surface water sites were also investigated, and samples taken from the streams using the bailer. The surface water locations were selected for their proximity and potential hydrological connectivity to the study area. These sites were Hevié, Djonou, Ayato and Lake Toho. On a separate activity, samples for isotope analysis were taken from Lake Nokoué for comparison with the Ouédo samples. The samples from Lake Nokoué were also analysed for pH and conductivity. Further precipitation samples were collected in Cotonou during two rain events. Divers and a barometer were installed at three hand-dug wells in the north, centre and south of the study area to monitor groundwater fluctuations.

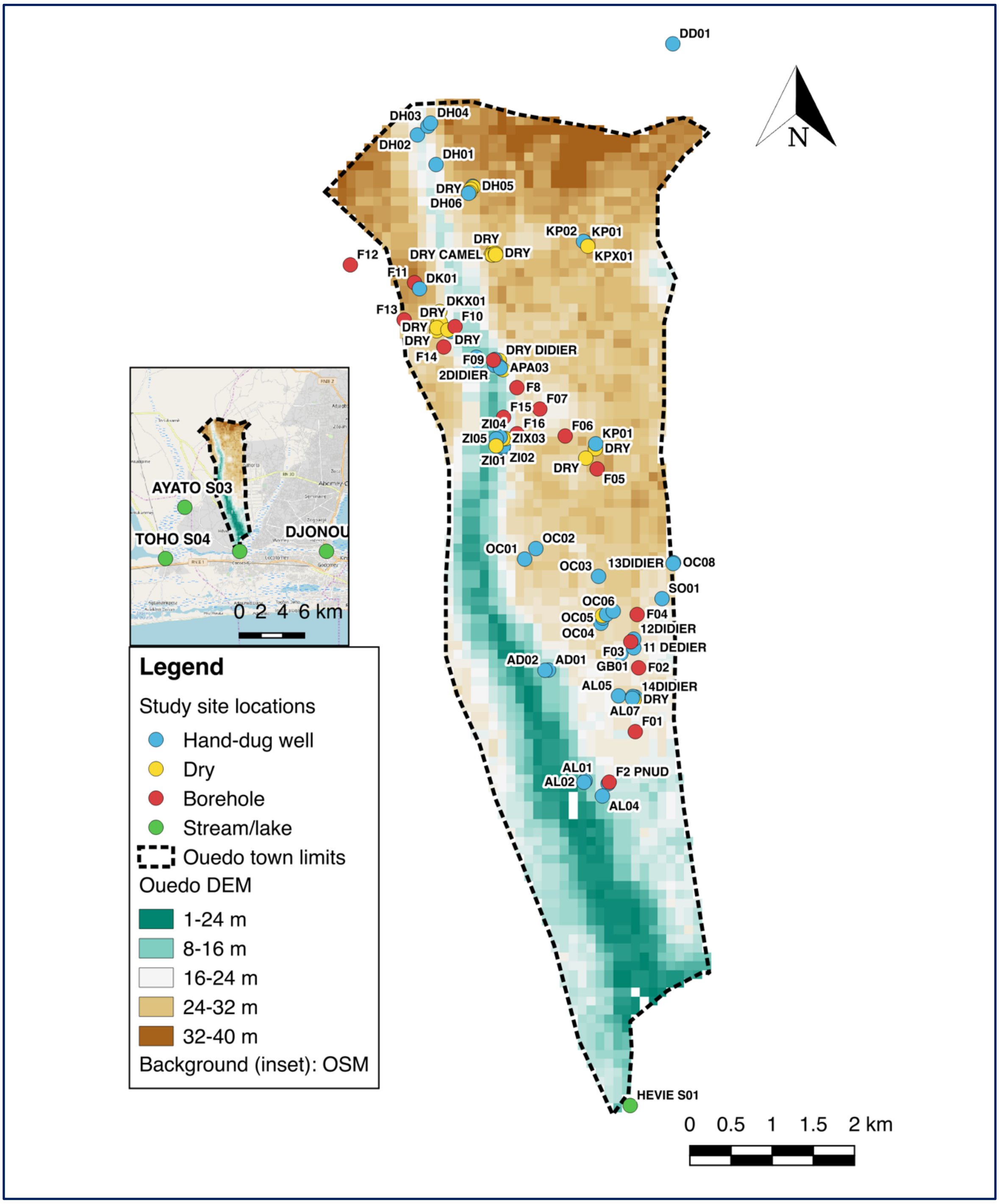

Figure 7 Locations of investigated hand-dug wells, boreholes and surface water points

The data collection campaign is summarized in Table 3:

Table 3 Field work data collection summary

	Item	Quantity
Location	Hand-dug wells	44 (water) + 27 (dry)
	Boreholes	16
	Streams/lakes	5
	Precipitation events	3
Samples	Stable isotope	37
	Major ions, TOC, TN	30
	EC, pH, alkalinity, nitrates	75-80
Other	Household surveys	30
	Divers	5 (boreholes) + 3 (hand-dug wells)

4.3.5. Lab Analysis

The samples were analysed at the IHE Delft laboratory for major cations and anions, total organic carbon, total nitrogen and stable isotopic composition.

The cations were analysed using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analytical technique. Samples with high calcium concentrations were reanalysed using Flame Atomic Absorption Spectroscopy (FAAS) specifically targeted for a limited range of elements occurring at high concentrations.

Anions were analysed using the Ion Chromatography System (ICS) where anions were separated based on their affinity to the ion exchanger. During anion analysis, several out of the 31 samples registered ion concentrations below detection limits of the ICS-1100 instrument: 9 samples for NO_3-N (<0.3 mg/L), 12 samples for SO_4 (<2 mg/L), and 2 samples for Cl (<2 mg/L). Further, ions whose concentrations exceeded the calibration limits of the ICS instrument were diluted and reanalysed.

For ion concentration quality check, an estimate using the EC at 25 °C was considered (Appelo and Postma 2004):

Equation 2

$$\frac{EC}{100}\left(\frac{uS}{cm}\right) \approx \sum anions\left(\frac{meq}{L}\right) = \sum cations\left(\frac{meq}{L}\right)$$

For those samples where alkalinity was not tested in the field (or the test failed due to low pH of samples), the ‘Electroneutrality Principle’ was considered to determine the HCO_3^- concentration using the Electrical Balance (EB, %) (Appelo and Postma 2004):

Equation 3

$$EB\ (\%) = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} * 100$$

Since by the Electroneutrality Principle aqueous solutions must be electrically neutral, the electrical balance should be within +/- 5% (Appelo and Postma 2004). An error of 0% was assumed for those samples with missing bicarbonate concentrations and the HCO_3^- values calculated. These samples are noted in the chemistry results at Appendix H.

TOC/TN were analysed using catalytic thermal decomposition/ chemiluminescence methods on a combined Total Organic Carbon analyser (TOC-L) and Total Nitrogen Measuring unit (TNM-L). The detection limits for non-purgeable organic carbon (NPOC) and TN were 0.5 mg/L and 20 mg/L, respectively.

The stable isotopes were measured on DLT-100 Liquid-Water Isotope Analyser. Samples were analysed several times until successive errors were less than 2%.

CHAPTER 5

Results and Discussion

5.1. Recent climate variability

5.1.1. Annual climate datasets

Figure 8 presents the inter-annual variability in precipitation and temperature in Cotonou between 1991-2017 along with actual evapotranspiration and interception in Cotonou and Ouédo between 2009 – 2017.

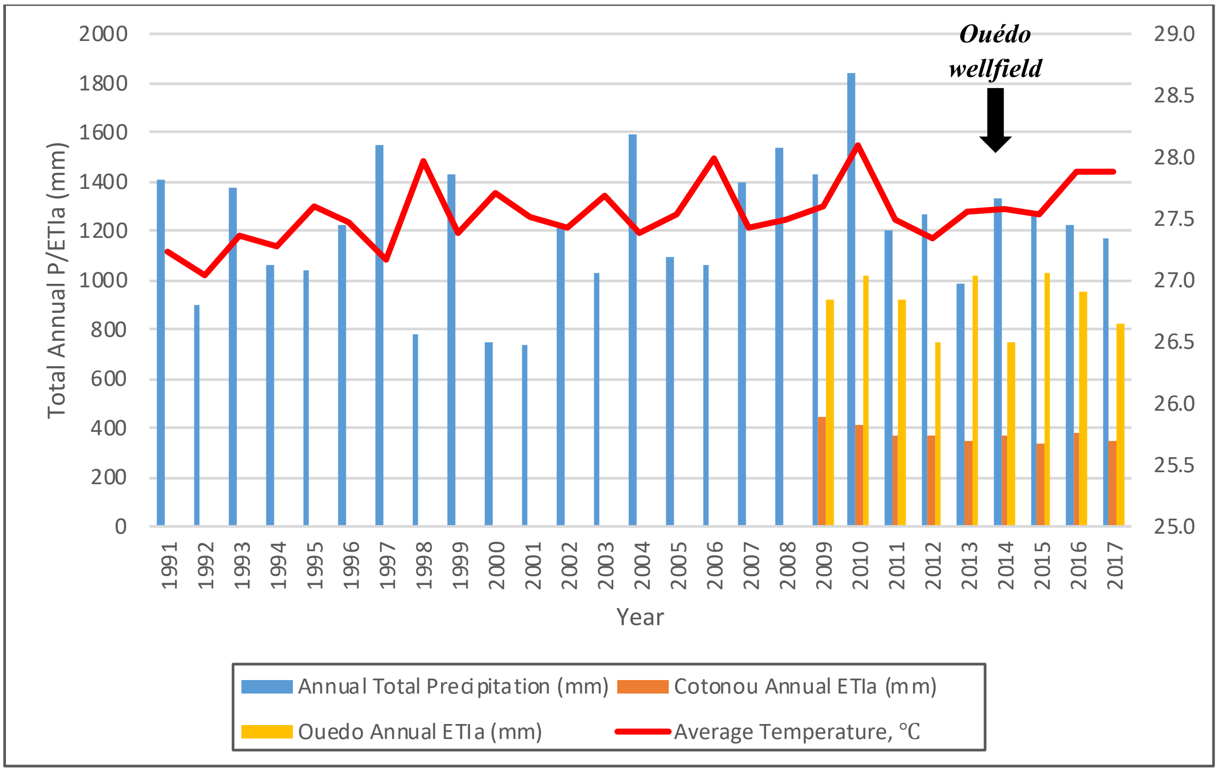

Figure 8 Total Annual Precipitation (P) and Temperature (T) in Cotonou for 1991-2017 and Actual Evapotranspiration + Interception (ETIa) in Cotonou and Ouédo for 2009-2017. Dataset sources: FAO 2018; METEO Benin 2018; NOAA 2018

The following sub-sections analyse the individual trends in these climate parameters and conclude on their combined impact on groundwater recharge and storage in the shallow Quaternary aquifers.

5.1.2. Precipitation trend

Annual total precipitation was at a minimum at the start of the 21st century (Figure 9). The rainfall of 1998, 2000 and 2001 were each below an annual total 800 mm. This dry period was interrupted by the wet year of 1999 where total rainfall registered at 1425 mm.

With respect to the wet periods, the annual total precipitation was at a maximum value of 1843 mm in 2010 and corresponded to the year of the great Benin flooding disaster (World Bank 2011). The maximum observed temperature of the period also occurred that year. The lowest annual total precipitation of the period was observed earlier in the decade. Less than 750 mm total of rainfall occurred in both 2000 and 2001.

Figure 9 presents precipitation data in Cotonou compared to the long-term average of 1148 mm for southern Benin (Achidi et al. 2012) and a calculated 3-year moving average of the dataset.

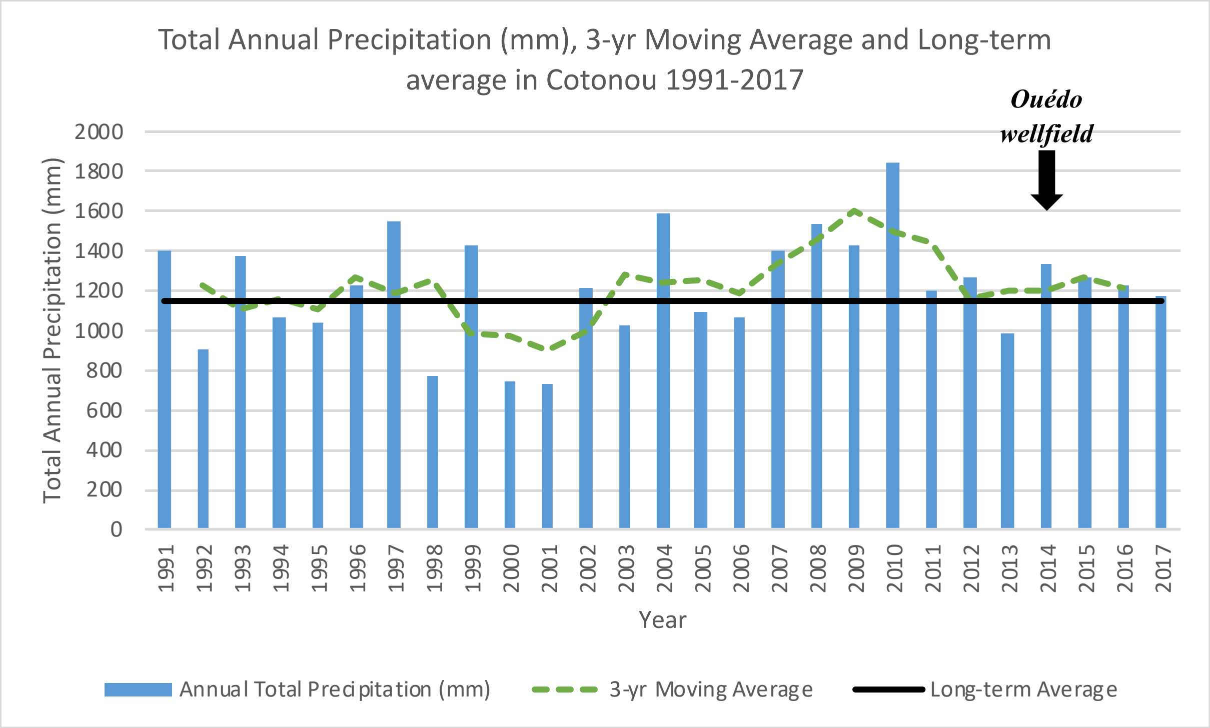

Figure 9 Total Annual Precipitation (mm), 3-yr Moving Average and Long-term average in Cotonou 1991-2017. Dataset sources: Achidi et al. 2012; METEO Benin 2018

The 3-yr moving average smooths out rainfall fluctuations in order to better observe trends over the period. The graph shows a general equilibrium in rainfall fluctuations around the long-term average. The drought years (2000-2001) correspond to the longest-sustained low rainfall trend of the period while the wet period (2006-2012) which includes the great floods corresponds to the longest high rainfall trend of the period.

Since 2009 to present, however, there has been a downward trend in total annual rainfall. This drying out trend was steeper in the period 2009-2012 after which there is a general flattening with a brief increase to slightly wetter conditions between 2014 and 2015 followed by drying toward the last years of record.

In order to consider the rainfall data in a statistical context, Figure 10 presents the frequency distribution for annual total rainfall for the period 1991-2017.

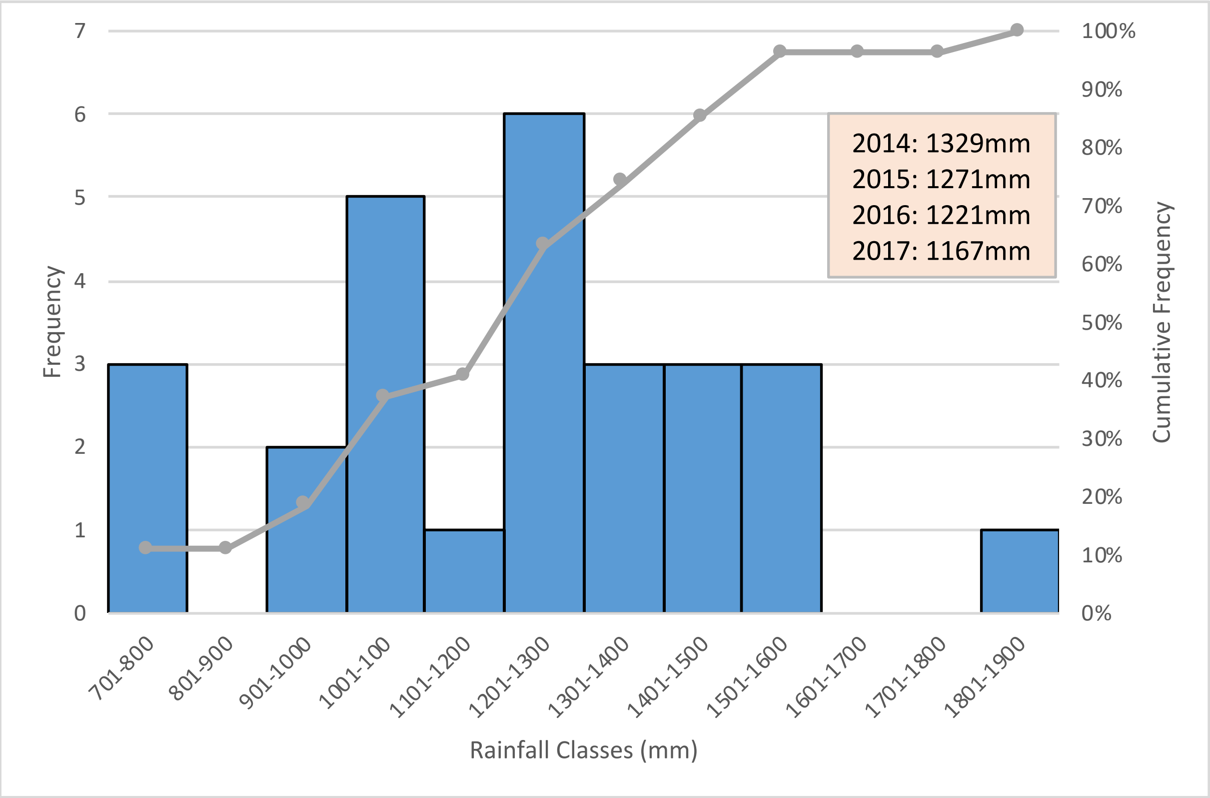

Figure 10 Frequency distribution of Annual Total Rainfall (mm) in Cotonou for 1991-2017. Dataset source: METEO Benin 2018

The 2014 annual total (1329 mm) exceeded 74% of the rainfall within the 16-year period. While the year 2015 and 2016 were both relatively wet years (exceeding 63% of annual total rainfall), 2017 produced amongst the lowest rainfall with an annual total of 1167 mm exceeding only 40% of annual total rainfall between 1991-2017.

5.1.3. Temperature trend

The temperature variability from 1991-2017 shows average annual temperature fluctuations between 27.0 – 28.1 °C (Figure 11). During this period the minimum average annual temperatures were observed in the early 1990s and maximum values at the end of the 2000s.

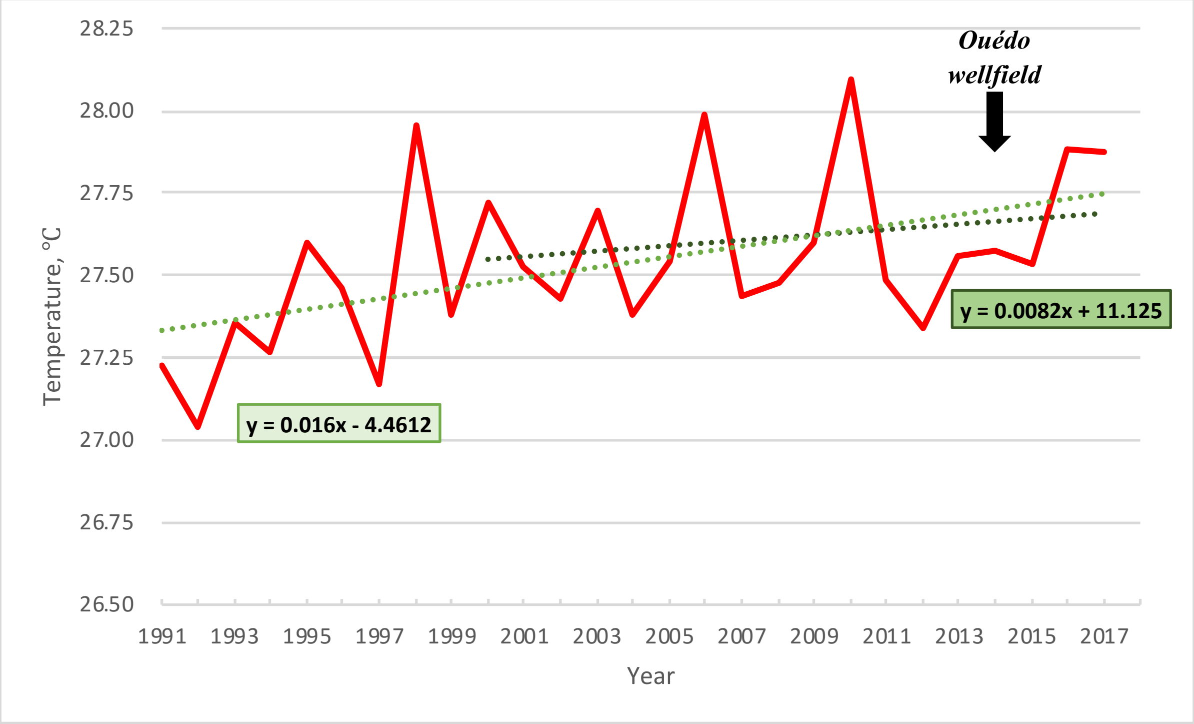

Figure 11 Average Annual Temperature (°C) showing linear long-term and short-term trends in Cotonou 1991-2017. Dataset source: NOAA 2018

Over the 16-year period, the temperature shows an increasing trend of +0.016 °C/year. This is consistent in direction although smaller in magnitude than the trend of +0.09 °C/year reported by Barry et al. (2018) for southern Benin for the period 1960-2010. Since 2000 the short-term trend of +0.008 °C/year indicates that the rate of increase of temperature is further slowing down in recent years.

These temperature trend analyses for the study area indicate that while temperature is increasing in the region, it is increasing at a slower rate than in recent decades. While higher temperatures can contribute to higher evapotranspiration and bring about a decrease in groundwater storage in the shallow Quaternary aquifers, the small increase would not contribute greatly towards evapotranspiration trends in the study area.

5.1.4. Evapotranspiration and interception trend

The remotely-sensed actual evapotranspiration and interception data for Cotonou and Ouédo locations over the period 2009-2017 are presented in this section for context on climate outputs from the system. While the Ouédo data is more relevant for discussions on climate in the study area, the Cotonou data is considered for comparison with rainfall data at the same station.

Figure 12 provides annual ETIa for both locations alongside the respective 3-year moving averages for analysis of trends in and surrounding the study area.

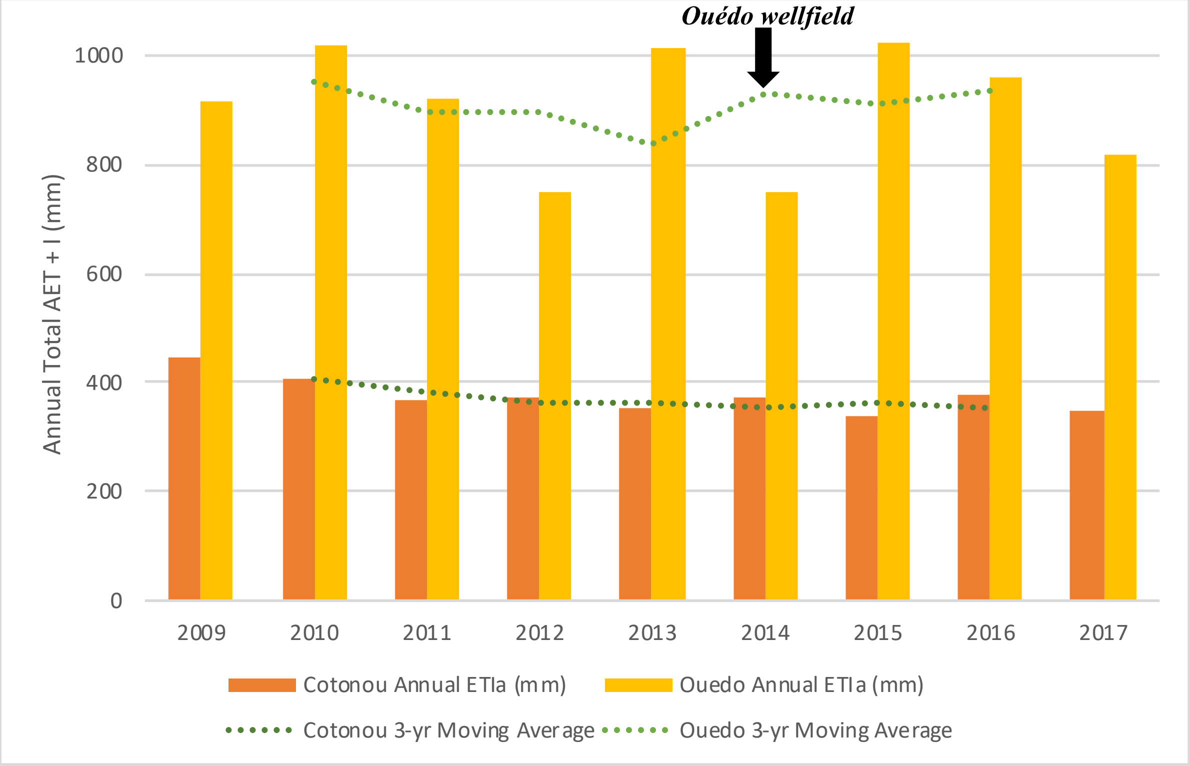

Figure 12 Annual Actual Evapotranspiration and Interception (mm) in Cotonou and Ouédo for 2009-2017. Dataset source: FAO 2018

Annual ETIa at Cotonou registered a maximum value of 444 mm in 2009 and a minimum value of 340 mm in 2015. The 3-year moving average for ETIa at the location shows a slightly downward trend from 2009-2017. The most recent year experienced approximately 22% less ETIa than the 444 mm of the first year of the study period.

The Ouédo annual data ranges between a minimum of 748 mm and a maximum of 1026 mm during the period of study. Overall, annual ETIa in the study area fluctuates around an equilibrium during the period of study. The construction of the wellfield in 2014 was followed in the immediate year by an increase of 37% in total annual ETIa. Since this jump in annual values, Ouédo has experienced declining ETIa with the 2017 record of 819 mm being 20% less than the 2015 annual value of 1027 mm.

For Ouédo, annual ETIa values were generally more than double those observed at Cotonou. To explain the differences in magnitude at the two locations, the spatial variability in weather (e.g. radiation, air temperature, humidity, wind speed) and crop characteristics (e.g. crop type and development stage, soil type, tree canopy) were considered. The most likely variable is infiltration since lower rainfall infiltration in the highly urbanized Cotonou landscape can limit the amount of water available in the shallow subsoils for evapotranspiration and therefore partially explain reduced values over the city.

Annual actual evapotranspiration and interception for the study area shows a general trend of equilibrium with a slight tendency towards decreased ETIa in the region. Inter-annual fluctuations in Ouédo leaves ambiguity regarding future ETIa trends but regional decrease in ETIa can indicate the potential for decreased outputs from the shallow subsoils and therefore increased recharge and storage in the shallow Quaternary aquifers.

5.1.5. Discussion

Despite the observation that since the construction of the wellfield in 2014 there has been a tendency towards slightly drier conditions in Ouédo, the climate data for the 16-year period does not show a consistent trend in decreasing rainfall for the study area. The longer datasets studied by other authors (and described in section 3.2) provided a consensus of long-term decreasing rainfall for southern Benin. However, the short-term analysis of more recent climate data provides neither a confirmation nor vigorous denial of this drying trend.

The combined effect of the recent trends in annual total precipitation, average temperature, total evaporation and interception shows no evidence of recent climate variability that could affect groundwater storage and recharge in the shallow Quaternary aquifer.

A detailed investigation of the shallow Quaternary aquifer in the study area will require more data in order to consider factors such as field capacity, runoff coefficient and daily rainfall intensity for determining the quantity of rainfall that is infiltrated after evapotranspiration and interception. Daily rainfall intensity data were accessed from the extreme climate indicators CLIMDEX database from 18 stations in Benin (Barry et al. 2018) however, the publicly available records for this and other proxy rainfall data (maximum 1-day and maximum 5-day rainfall) ended in 1980. A more extensive search for relevant and accessible daily rainfall intensity datasets included the Cotonou daily climate archives of the Benin meteorological office. However, these datasets were largely incomplete and therefore unsuitable for analysis.

Future studies of a longer climate dataset post-wellfield construction will more clearly identify climate trends before and after abstraction commenced and therefore justify a reanalysis of the research hypothesis.

5.2. Recent changes in land use/land cover and population growth

5.2.1. Land use and land cover

The trends in traditional agricultural practices and slash-and-burn activities described in section 3.2 were supported by field observations in the study area. Cassava and maize were cultivated almost exclusively on observed agricultural land while oil palms were distributed throughout the landscape.

The land-use and land-cover (LULC) datasets from Tappan et al. (2016) were considered for analysis of recent changes in recharge to the shallow Quaternary aquifer. Since the resolution for these raster images were 4 km^2 per pixel, LULC maps for the commune (Figure 13) are presented for considering land conversion in the immediate region surrounding the study area.

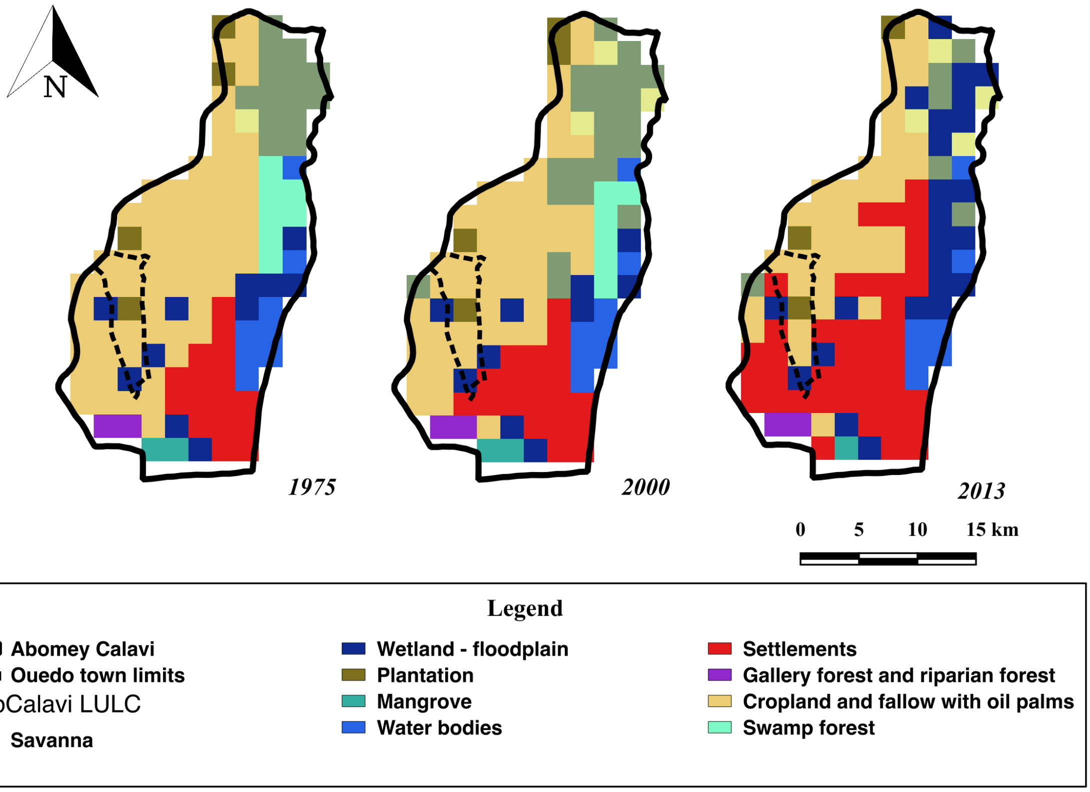

Figure 13 Land-use and land-cover evolution in Ouédo and Abomey-Calavi from 1975-2013. Datasets source: Tappan et al. 2016

The LULC maps in Figure 13 show the increased settlement encroachment into Ouédo by 2013 although the dominant land cover remained cropland and fallow with oil palms.

For the commune of Abomey-Calavi, analysis of the coverage area of the settlement class (Figure 14) reveals that settlement areas covered only 12% of the total area of Abomey-Calavi in 1975 and 16% in 2000. However, by 2013 the settlement areas had doubled and represented 32% of total area in the commune.

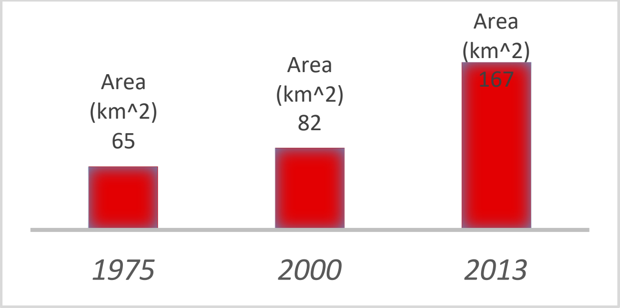

Figure 14 Settlement area in Abomey-Calavi for 1975, 2000 and 2013

The increased settlement encroachment trend in Ouédo and the greater Abomey-Calavi commune implies increasing impervious area in and around the study area. When, land cover with cropland and fallow with oil palms is converted for settlement, the increased impervious area will lead to decreased infiltration capacity of soils and increased runoff to streams. A consequence of this is decreased recharge to the shallow Quaternary aquifer.

Furthermore, increased settlement is associated with the construction of new hand-dug wells. Communication with workers at houses under construction confirmed that new wells are dug on the sites to supply water for cement mixing and other construction activities. Once the houses become habitable, these wells then become the main source of potable water for the households.

5.2.2. Population growth and groundwater abstraction

From 1992-2002, the population of Abomey-Calavi doubled and the commune is now among the ten most highly populated communes in Benin (INSAE 2015).

In the 11 years between the last two national demographic surveys, the population of Ouédo grew by 173% (Table 4) (INSAE 2004, 2016). The population density almost tripled during this time as settlements encroached on the natural landscape. Household sizes became smaller, going from 6.0 persons/household in 2002 to 4.7 persons/household in 2013. The proportion of the population engaged in agricultural activity also decreased, with less than a quarter of the households from 2002 registering as agricultural in 2013. This decrease may reflect changing economics in the study area as new residents engage in activities outside the agricultural sector.

Table 4 Summary demographics for Ouédo and Abomey-Calavi from the most recent national censuses (INSAE 2004, 2016)

	Ouédo		Abomey-Calavi	
	2002	2013	2002	2013
Population	10,067	27,522	307,745	656,358
Population density (hab/km^2)	360	983	571	1,218
No. of households	2,011	5,849	64,701	145,510
% of households as agricultural	62	15	15	25

The population data and calculated average annual water use in Ouédo are presented in Figure 15. The data shows that estimated groundwater use in the study area for 2018 will have increased by 41% in the last five years.

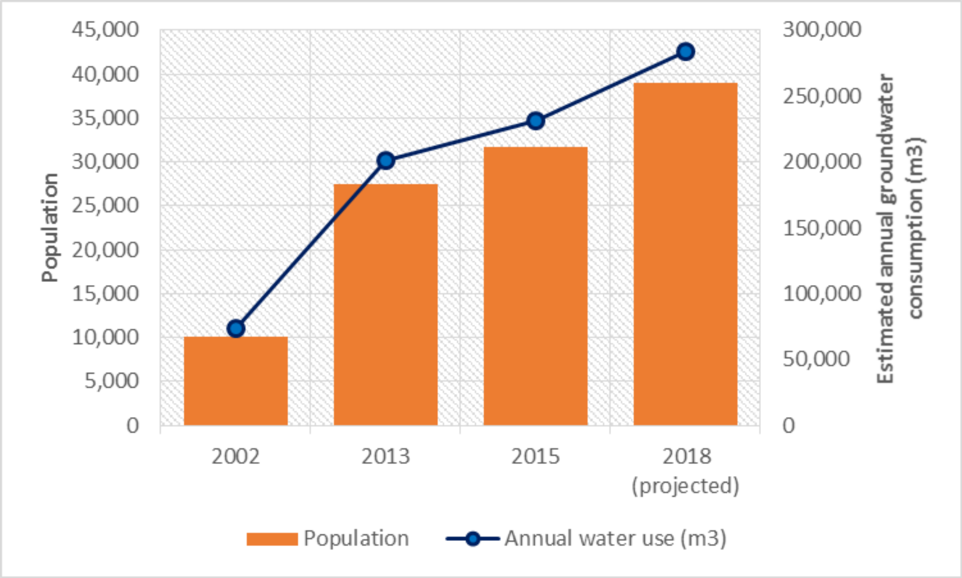

Figure 15 Population growth and estimated daily water consumption in Ouédo. Datasets sources: INSAE 2004, 2016; M'barek et al. 2005; CIA 2018; IndexMundi 2018

Results from 30 household surveys (Appendix E) provide an indication of trends in the study area with regard to groundwater abstraction in the shallow Quaternary aquifer.

The survey revealed that 27% of the hand-dug wells surveyed in the study area were constructed after 2014 i.e. when the Ouédo wellfield was already in operation (Figure 16). These results were from a sample group where 26 responses were obtained from the 30 surveys (n=26).

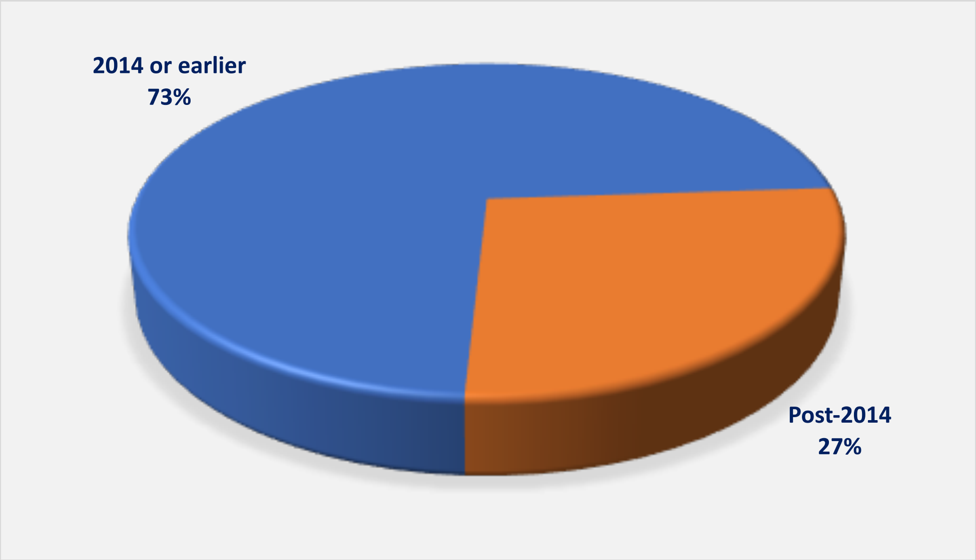

Figure 16 Year of construction of hand-dug wells (n=26)

With an increase of 37% in the number of hand-dug wells constructed since 2014, there is an expected increase in abstraction of 37% from the shallow Quaternary aquifer only within the last four years (assuming equal abstraction rates in all boreholes). This figure is in good agreement with the population growth statistics for Ouédo of 41% increase in five years.

Besides, the field survey provided additional insight on groundwater abstraction in Ouédo. In terms of groundwater use, the majority of residents mention cooking, washing and drinking as primary uses (Figure 17). Other uses included water for irrigating crops and drinking water for animals. While 72% of those surveyed reported using the water from the hand-dug wells for drinking water, 29% reported that they purchased drinking water from local vendors.

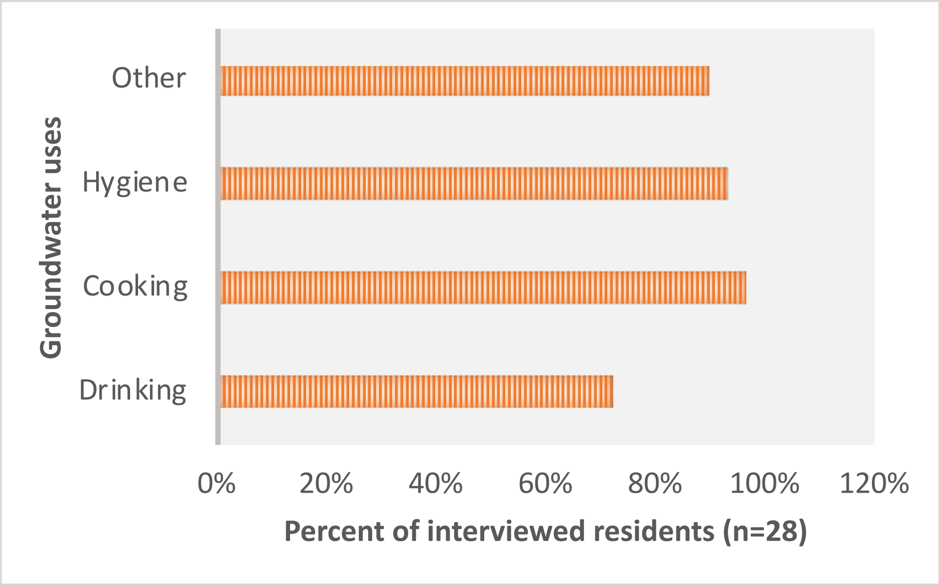

Figure 17 Household survey results for groundwater use

Residents supplied information on the estimated abstraction from hand-dug wells in the study area (Figure 18). The majority of households (25%) abstracted in the range 400-599 litres/day (0.4-0.6 m^3/day). Per household, 15% of residents abstract as low as 200 litres/day but an equivalent percent of responders claims to abstract over 1400 litres/day.

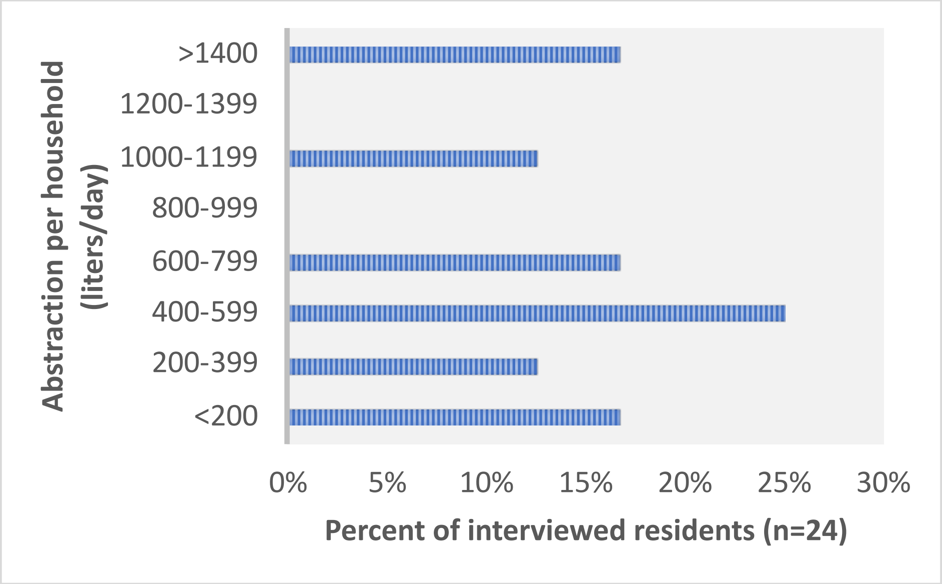

Figure 18 Household survey results for daily groundwater abstraction per household

Since the average Ouédo household is 4.7 persons (INSAE 2016), this implies that the minimum groundwater use is 42.5 litres/capita/day and the maximum is 298 litres/capita/day. The minimum estimate is higher than both the peri-urban estimate of 20 litres/capita/day and the urban estimate of 29 litres/capita/day proposed by M'barek at al. (2005) but more aligned to the urban estimate of 41.32 litres/capita/day proposed by the African Development Bank Group (2016).

The maximum consumption of 298 litres/capita/day far exceeds all estimates of average consumption. One household that reported the use of 1000 litres/day was the water vendor at Dassekomey (DK01) in the north of Ouédo. This hand-dug well was equipped with a pump that pumped water up to a storage tank before selling to locals in the area. When the volume of water in the 1000 l tank was low, they would switch on the pump and abstract water until the volume was replenished.

With respect to the perception of residents on declining groundwater levels in the study area, the residents were first asked if they observed any seasonal changes throughout the year (number of responses, n= 26). The responses showed that the majority of residents (62%) observed seasonal changes where the static water level decreased significantly during the dry periods and increased in the rainy seasons. Some residents further commented that they were forced to deepen their wells in the dry season in order to access the lowered groundwater level. This supports the theory that groundwater level in the shallow Quaternary aquifer is strongly related to the recharge. The residents at a shared property with high abstraction (AL05 on Figure 7) reported that the groundwater turned a reddish colour in the dry season. This can be attributed to heavier sedimentation at the bottom of the well from the red soil of the Terre de Barre as residents of the complex abstract the maximum possible groundwater from the well.

Another resident claimed that seasonal changes were only observed after the wellfield began abstracting water. The impact of abstraction activities by SONEB in the wellfield was a cause for concern for the majority of residents interviewed. On the topic of observed changes since the wellfield was constructed, 50% of responders claimed that they have noticed declining water levels while 19% responded no observed change (Figure 19). Among the other responses, residents either constructed their wells after 2014 and so could not comment on trends before and after wellfield construction or experienced declining groundwater levels prior to the wellfield construction.

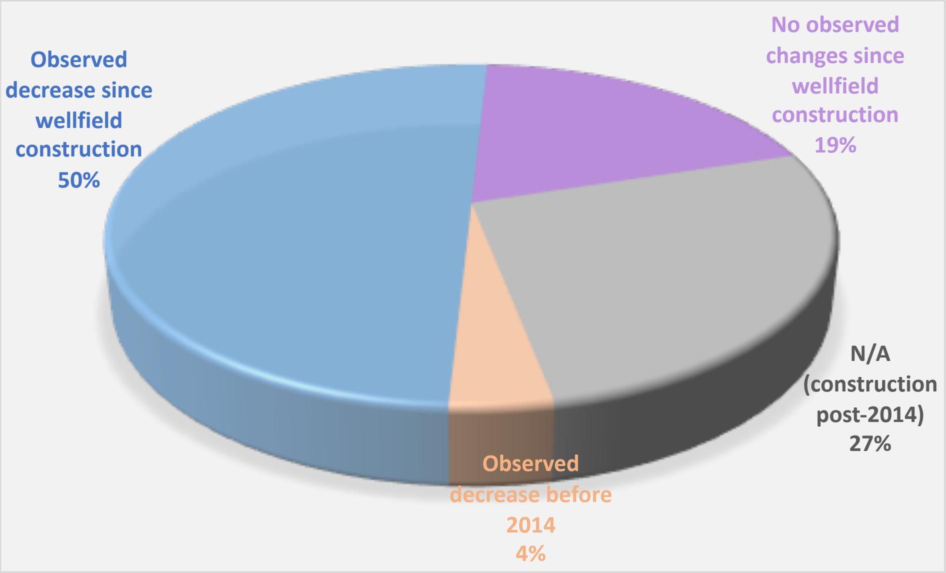

Figure 19 Household survey results on observed changes in hand-dug well groundwater levels since wellfield construction in 2014

The aerial survey of a section of the study area provided insight into the distribution of hand-dug wells. The Phantom 4 drone mapped an area of 38.8 ha (0.388 km^2) in the vicinity of borehole F05 in the centre of the Ouédo study area. Although the aerial survey of the full study area was incomplete, the orthomosaic obtained from the survey provides an overview of the density and distribution of hand-dug wells in the study area (Figure 20).

The aerial imagery shows that in central Ouédo, individual households have at least one hand-dug well. The imagery also shows hand-dug wells located in or adjacent to agricultural plots. The density of hand-dug wells in this section of the study area is considered:

Area of aerial survey = 0.388 km^2
No. of hand-dug wells observed = 49
Density of hand-dug wells = 126 wells/km^2

By extrapolating this well density to the overall Ouédo study area, one estimate of total number of hand-dug wells in the 26 km^2 study area is approximately 3,280 wells. However, the distribution of wells in central Ouédo is in contrast to the distribution observed in villages in the north and south of the study area. There, 3-5 communal wells were observed to provide water for all the households in the village i.e. a density of 6-10 wells/km^2 (household surveys and personal observation). Furthermore, on school compounds the sole hand-dug well often supplied water to all the students as well as residents in adjacent households.

Construction activities are observed in the aerial orthomosaic, particularly in the south-west quadrant where over 30 large incomplete structures stand. This gives an idea of the increased settlements in the area as soon this green space in the study area will be replaced by mostly impervious cover.

Another observation from the analysis of the aerial imagery is that the majority of hand-dug wells are uncovered and unsecured. This reiterates the concerns about water quality in the hand-dug wells and their vulnerability to surface contamination.

Figure 20 Drone aerial imagery for overview of hand-dug wells distribution in 0.388 km^2 section of study area (Ouédo centre)

5.2.3. Discussion

The high population growth and urban encroachment in Ouédo indicates a great increase in groundwater demand from the shallow groundwater reservoirs. Since the residents are not (yet) connected to the SONEB distribution network, hand-dug wells will continue to be the main source of water supply and there will be increased pressure on the shallow reservoirs to sustain growing demand.

The household survey responses provided greater insight into consumption habits in the study area and the perception of risk with respect to water security. Of the 30 households surveyed, 27% of the hand-dug wells were constructed after 2014 and therefore contributed to an estimated increase of 37% in abstraction from the shallow aquifer only within the last four years, which is in good agreement with the estimated increase in abstraction of 41% with population growth within the last five years. While the majority of residents claim consider SONEB abstraction activities to be the main driver of declining groundwater levels in hand-dug wells, the abstraction trend of residents themselves shows that heavy abstraction is occurring in the shallow aquifer with withdrawals from these hand-dug wells. Of particular concern are the water vendors and shared properties where groundwater is heavily abstracted from a sole water point to supply demand for a large number of residents. Monitoring of groundwater levels around these high abstraction points is recommended as they may have a greater impact on surrounding piezometric head than previously considered. Hourly monitoring of groundwater levels was carried out for one week during the study period but revealed no insights on general groundwater abstraction. The monitoring data and discussion are found at Appendix F.

Moreover, there is a need to revisit existing legislature on groundwater abstraction as regulation on water points is generally not enforced in Benin. With increased enforcement of the Water Law Limit and monitoring of groundwater levels in the shallow reserves, there can be improved and sustainable management of resources.

5.3. Stable isotopic and hydrogeochemical signatures of groundwater

5.3.1. Stable isotope composition characterization

Isotopic composition and fractionation processes

The summary statistics of the isotopic composition ranges are provided in Table 5 below.

Table 5 Isotopic composition of groundwater and surface water samples collected April-May, 2018 in Ouédo, Benin

Source	δ2H, in ‰				δ18O (‰)			
	Average	Std.dev	Min	Max	Average	Std.dev	Min	Max
Wells	-14.81	1.35	-16.40	-12.10	-3.51	0.30	-4.11	-2.90
Boreholes	-16.00	1.17	-18.10	-13.70	-3.50	0.29	-3.84	-2.98
Precipitation	-15.40	2.86	-18.70	-13.70	-3.17	0.23	-3.31	-2.91
Surface	2.00	8.36	-3.00	14.50	-0.18	1.79	-1.35	2.49

For the surface water samples collected just south of the study area, the average isotopic composition was $\delta^{2}H = +2.00$ ‰, $\delta^{18}O = -0.18$ ‰ while the signature of the brackish Lake Nokoué (located 15 km southeast of the study area) was $\delta^{2}H = 7.60$ ‰, $\delta^{18}O = 1.59$ ‰.

For the groundwater and precipitation samples collected within the Ouédo study area, the average isotopic compositions were: hand-dug wells ($\delta^{2}H = -14.81$ ‰, $\delta^{18}O = -3.51$ ‰), boreholes ($\delta^{2}H = -16.00$ ‰, $\delta^{18}O = -3.50$ ‰) and rainfall ($\delta^{2}H = -15.40$ ‰, $\delta^{18}O = -3.17$ ‰).

Figure 21 considers the signatures of the four groups of samples: shallow Quaternary aquifer of hand-dug wells, deeper CT aquifer, surface water sources and precipitation. The Global Meteoric Water Line (GMWL) is included for comparing the samples to the global average relationship between hydrogen (^{2}H) and oxygen (^{18}O) isotopes in natural waters (Clark and Fritz 1997). The Local Meteoric Water Line (LMWL) was created using datasets from the IAEA GNIP database for Cotonou, Benin (IAEA/WMO 2018) and allows for comparison with the regional averages for southern Benin.

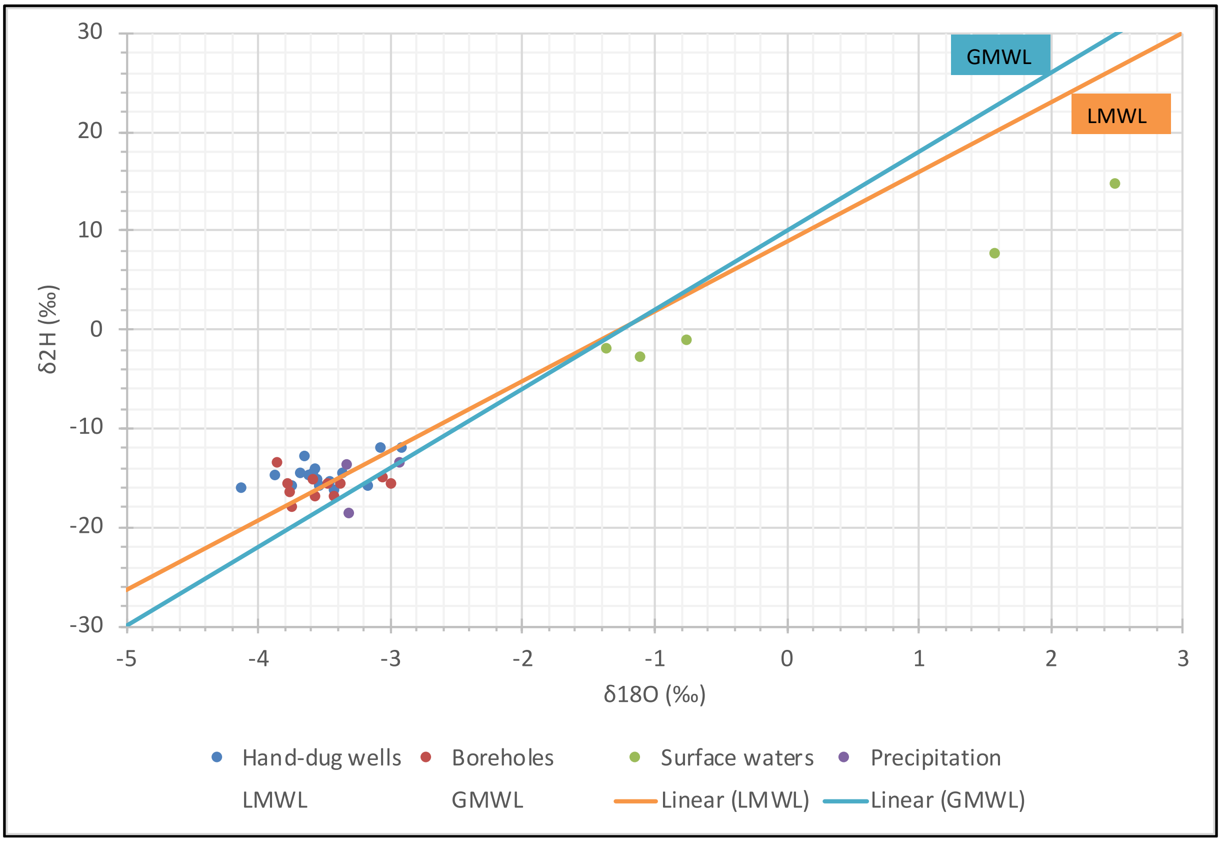

Figure 21 δ^2H - $\delta^{18}O$ relationship in groundwaters, surface waters and precipitation sampled. LMWL dataset source: IAEA/WMO 2018

The stable isotopic composition of groundwater and precipitation samples contrasted with the composition of surface water samples south of the study area. The surface water samples plot toward the more positive end of the spectrum and are therefore more enriched in lighter oxygen and hydrogen isotopes. On the other hand, the hand-dug wells, boreholes and precipitation samples plot toward more negative values indicating greater depletion of light isotopes. The isotopic compositions for the groundwater, surface water and precipitation are comparable with the ranges established in the study of waters of southern Benin in Appendix A.

A closer inspection of the groundwater and precipitation isotopic signatures in Figure 22 considers offsets amongst the groups and possible fractionation effects.

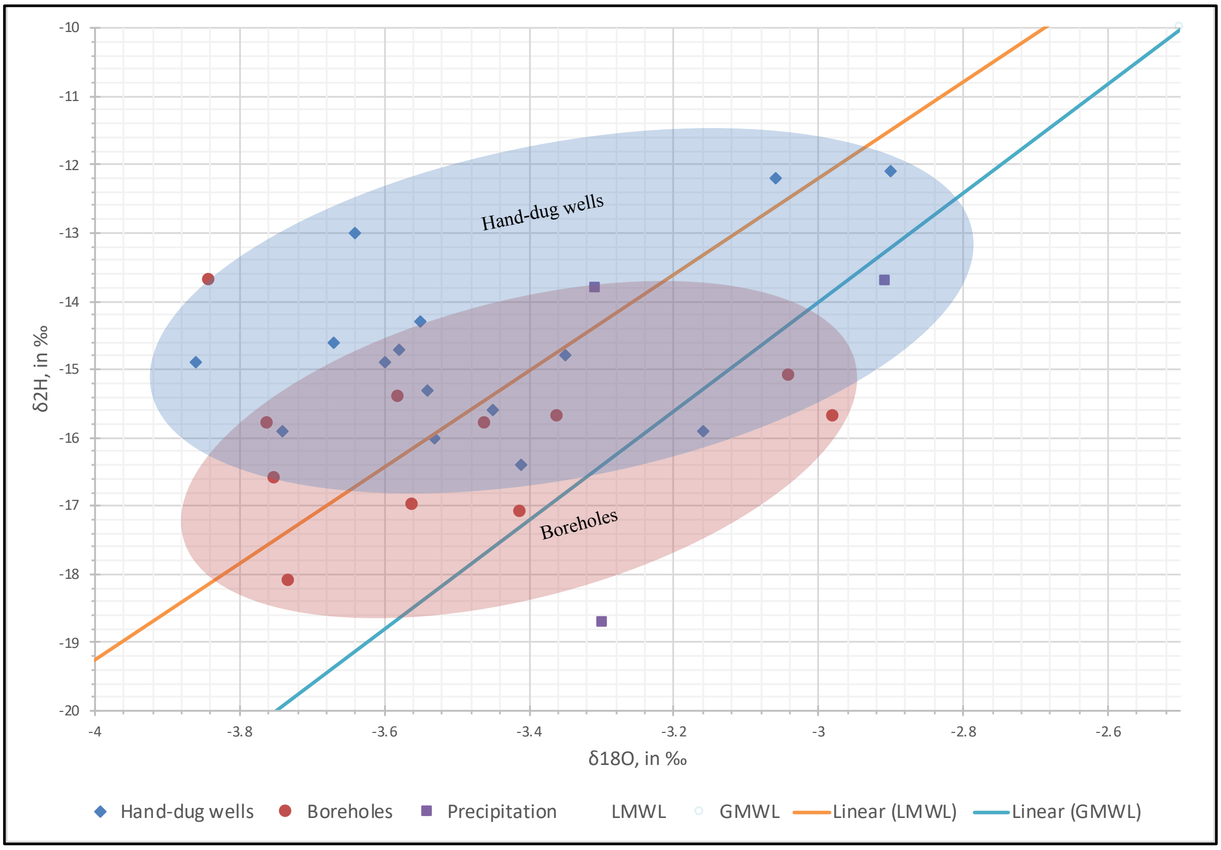

Figure 22 δ^2H - $\delta^{18}O$ relationship in groundwaters and precipitation sampled in study area.

Groundwater from boreholes and hand-dug wells show a slight offset with respect to the composition of deuterium (^2H) i.e. groundwater from the shallow Quaternary aquifer (average δ^2H = -14.81 ‰) is more enriched in lighter hydrogen isotopes than the groundwater from the CT aquifer (average δ^2H = -16.00 ‰). However, the ^{18}O ranges overlap where the shallow aquifer gives an $\delta^{18}O$ range of -3.51 +/- 0.31 ‰ and the deeper aquifer an $\delta^{18}O$ range of -3.50 +/- 0.29 ‰.

No evaporation effects are observed for groundwater in the study area since all the groundwater samples generally plot above the LMWL.

Surface water samples, on the other hand, all plot below the LMWL. Figure 23 presents a closer view of the surface water samples isotopic composition, where the samples are fitted to a linear regression line.

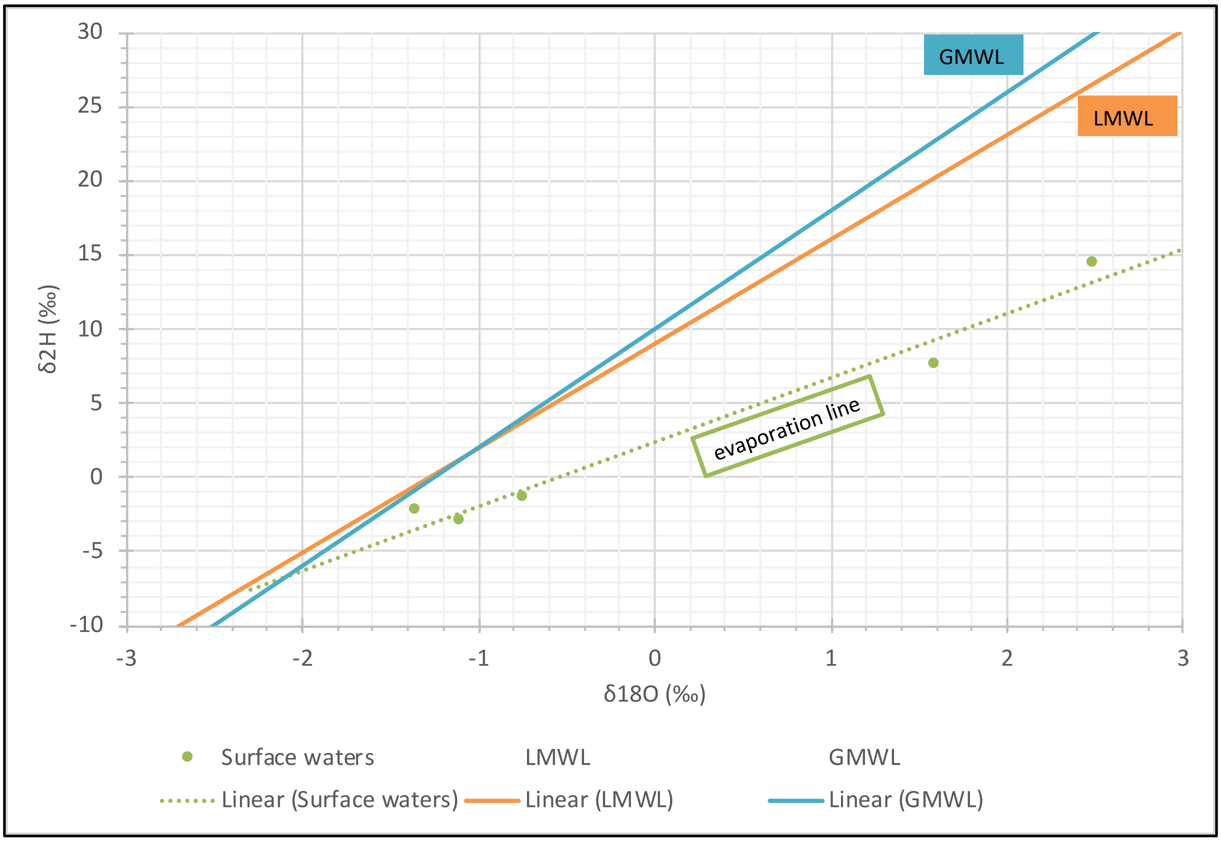

Figure 23 δ2H - δ18O relationship in surface water samples compared to southern Benin LMWL and the GMWL. LMWL dataset source: IAEA/WMO 2018

Since the slope of this line is less than the LWML and originates back to a groundwater source, the results confirm that fractionation through evaporative processes has occurred in the investigated surface water bodies.

Recharge sources

The isotopic signatures of the shallow and CT aquifers closely matched the signature of the precipitation collected in the study area during the field campaign. In order to consider how the groundwater samples compare to all sampled precipitation in southern Benin, data sourced from the IAEA GNIP Cotonou database (IAEA/WMO 2018) was considered in Figure 24.

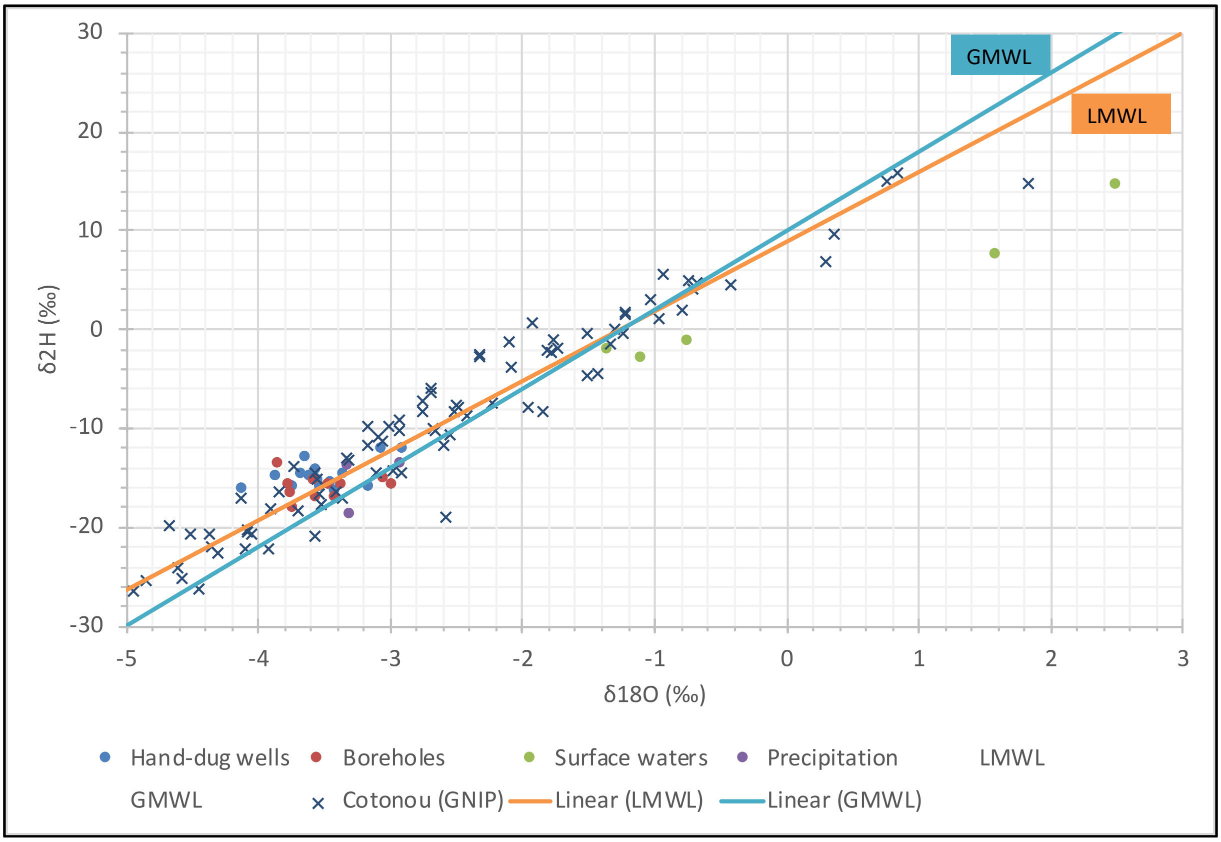

Figure 24 δ^2H - $\delta^{18}O$ relationship in precipitation waters sampled in southern Benin (crosses) compared to samples from study area in Ouédo, Benin. LMWL dataset source: IAEA/WMO 2018

The graph in Figure 24 shows that the isotopic signatures of the Ouédo groundwater and precipitation samples are comparable with regional signatures and fall on the more depleted end of the spectrum for all precipitation in southern Benin.

To determine the timing of recharge for the groundwater samples, the comparison of the signatures of both groups of groundwater samples (collected from late-April to early-May) compared to seasonal fluctuations in southern Benin is considered. Seasonal fluctuations of precipitation isotopic composition are determined by processing the GNIP Cotonou database for average monthly isotopic composition in δ^2H (Figure 25) and $\delta^{18}O$ (Figure 26).

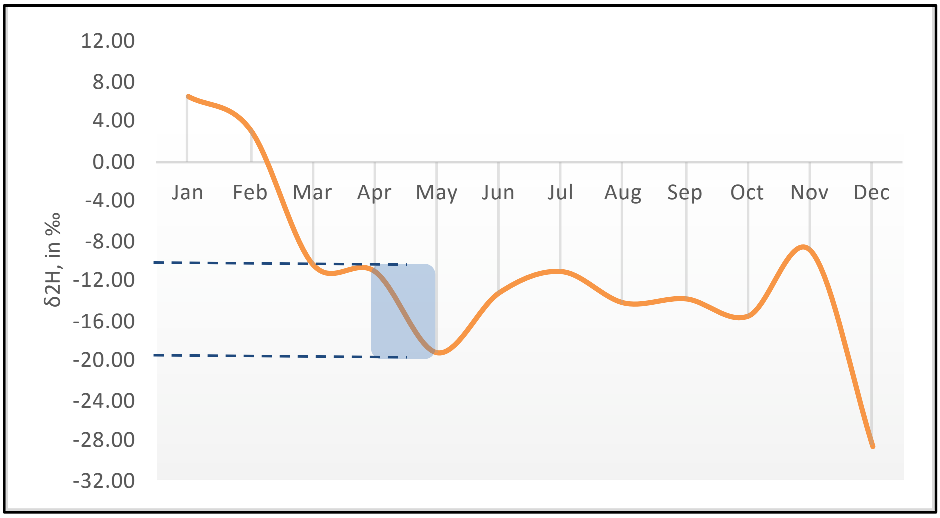

Figure 25 Seasonal variations in δ2H composition in precipitation samples in southern Benin. Dataset source: IAEA/WMO 2018

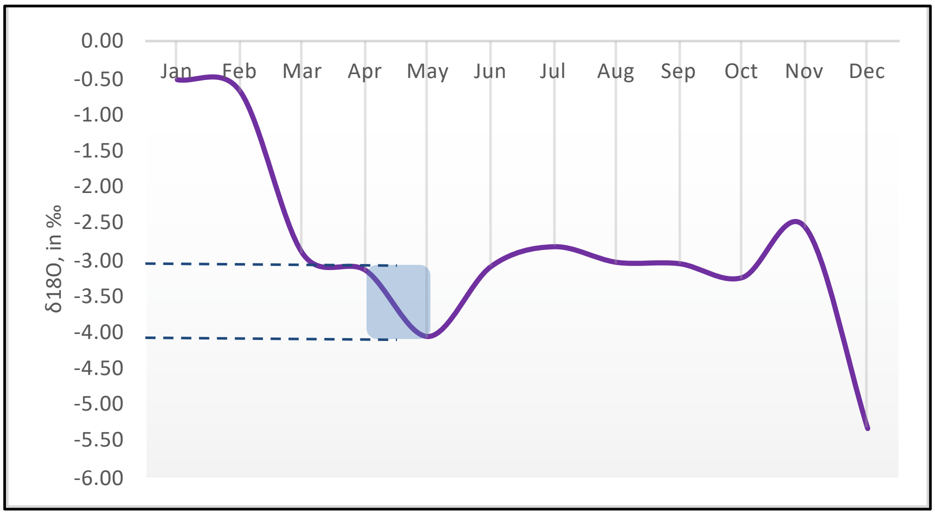

Figure 26 Seasonal variations in δ18O composition in precipitation samples in southern Benin. Dataset source: IAEA/WMO 2018

By considering the average isotopic composition of the shallow Quaternary aquifer (δ^2H = -14.81 ‰, $\delta^{18}O$ = -3.51 ‰) and the CT aquifer (δ^2H = -16.00 ‰, $\delta^{18}O$ = -3.50 ‰) in the study area, it is apparent that the collected groundwater samples fall within the range coinciding with recharge between April to May or between November to December. However, since shallow groundwater systems usually have short residence times, it stands to reason that rainfall to the aquifers occurs within the more recent April to May period. Therefore, the seasonal precipitation signatures may indicate that groundwaters in the study area are recharged by recent precipitation. Further analysis of the mean residence time of groundwater in both aquifers using other methods – e.g. tritium isotope, ^3H, dating for modern groundwaters (Clark and Fritz 1997) – is required to confirm the exact timing of recharge to the two reservoirs.

Mixing between groundwater reservoirs

The isotopic signature between the two groups of groundwater samples is too indistinct to establish end-members and perform a mixing equation for estimating the amount of shallow groundwater entering the deeper CT aquifer in the study area (as described in section 3.3).

As an alternative consideration, trends in isotopic signature were considered with respect to physical and chemical characteristics of the sample sites. By considering the properties that make the two reservoirs distinct (depth below surface elevation, pH, EC, major ions concentrations), it could be determined if isotopic enrichment or depletion correlates with other reservoir properties. However, the graphs showed no correlation between $\delta^{18}O$ isotopic compositions of groundwater samples in the study area and physio-chemical characteristics of the respective reservoirs (Appendix G).

Discussion

The stable isotopic composition of the groundwater from the two aquifers were characterized in order to evaluate mixing of the two sources due to wellfield abstraction in the CT (Hypothesis A). However, the isotopic signatures of the two reservoirs are too alike to distinguish end-members. Therefore, quantifying the amount of mixing occurring in the CT and, therefore, the amount of shallow groundwater entering the CT aquifer is not possible using mixing model equations. The attempt to correlate isotopic signatures with physical and chemical characteristics of the reservoirs was also unsuccessful.

The lack of evaporation effects in the shallow Quaternary groundwater is indicative of fast infiltration rates in the unsaturated zone that prevent infiltrating precipitation from experiencing evaporation prior to reaching the aquifer. Therefore, the isotopic signature of the shallow groundwater will be similar to that of local precipitation.

The analysis of stable isotopic composition of the water samples in Ouédo did confirm that groundwater in both aquifers is recharged predominantly by recent precipitation. Further analysis using other techniques can define the timing of recharge and use groundwater ages to aid in the investigation of the amount of shallow groundwater that is diverted to the deeper aquifer. Seasonal monitoring of isotopic compositions of groundwater samples may also contribute to establishing distinct signatures between the two reservoirs, particularly in the dry seasons when evaporation should be strongest in the shallow aquifer.

5.3.2. Hydrogeochemistry characterization

In considering Hypothesis C, if abstraction through the boreholes in the CT is creating a downward flux from the shallow Quaternary aquifer, then similarities are expected between the hydrogeochemistry of the boreholes and the hand-dug wells. The samples from the surface water sources are expected to show a different water chemistry since they are downgradient of the studied water points and are subject to influences from the surrounding area.

The summary statistics of the physico-chemical parameters of sampled waters in hand-dug wells, boreholes and surface water streams/lakes are presented in Table 6:

Table 6 Summary statistics of physico-chemical parameters of water samples in the study area

	Hand-dug wells	Boreholes	Surface water
Depth to SWL (m)	15.14 +/- 6.40	32.11 +/- 7.09	n/a
pH	5.63 +/- 0.41	6.07 +/- 0.33	6.58 +/- 0.86
Temperature (℃)	31.11 +/- 1.05	30.11 +/- 0.68	31.85 +/- 2.26
EC_25 (µS/cm)	184.57 +/- 132.75	67.38 +/- 23.82	102.95 +/- 22.19
TDS (ppm)	119 +/- 86.29	43.80 +/- 15.48	66.91 +/- 14.43

The results show that on average, shallow groundwater in hand-dug wells has a lower pH, higher electrical conductivity (EC) and total dissolved solids (TDS) than groundwater in the deeper CT aquifer. Therefore, the shallow groundwater is slightly more acidic and has a higher degree of mineralisation than groundwater in the deeper aquifer.

The major cations and anions in the water samples are next considered. Table 7 summarizes the concentrations of sodium (Na^+), calcium (Ca^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}) and bicarbonate (HCO_3^-) ions in the water samples:

Table 7 Mean concentrations and standard deviations of major cations and anions in water samples of study area

		Hand-dug wells	Boreholes	Surface water
Cations	Na^+ *(mg/L)*	21.90 +/- 15.56	6.00 +/- 0.94	14.29 +/- 3.63
	K^+ *(mg/L)*	2.19 +/- 4.45	0.71 +/- 0.45	1.60 +/- 0.52
	Mg^{2+} *(mg/L)*	2.12 +/- 1.90	1.10 +/- 0.57	2.15 +/- 0.33
	Ca^{2+} *(mg/L)*	9.02 +/- 5.09	6.20 +/- 3.07	6.15 +/- 2.26
Anions	Cl^- *(mg/L)*	31.87 +/- 20.78	10.68 +/- 9.22	25.95 +/- 5.52
	SO_4^{2-} *(mg/L)*	18.80 +/- 34.72	4.10 +/- 6.40	< 2
	HCO_3^- *(mg/L)*	20.15 +/- 22.03	15.10 +/- 14.18	23.79 +/- 7.47

The Schöeller-Berkaloff diagram (Figure 27) presents the concentrations in milliequivalents/litre (meq/L) for comparing the relative contribution of each anion and cation to the water chemistry in the sampled groundwater and surface water sources.

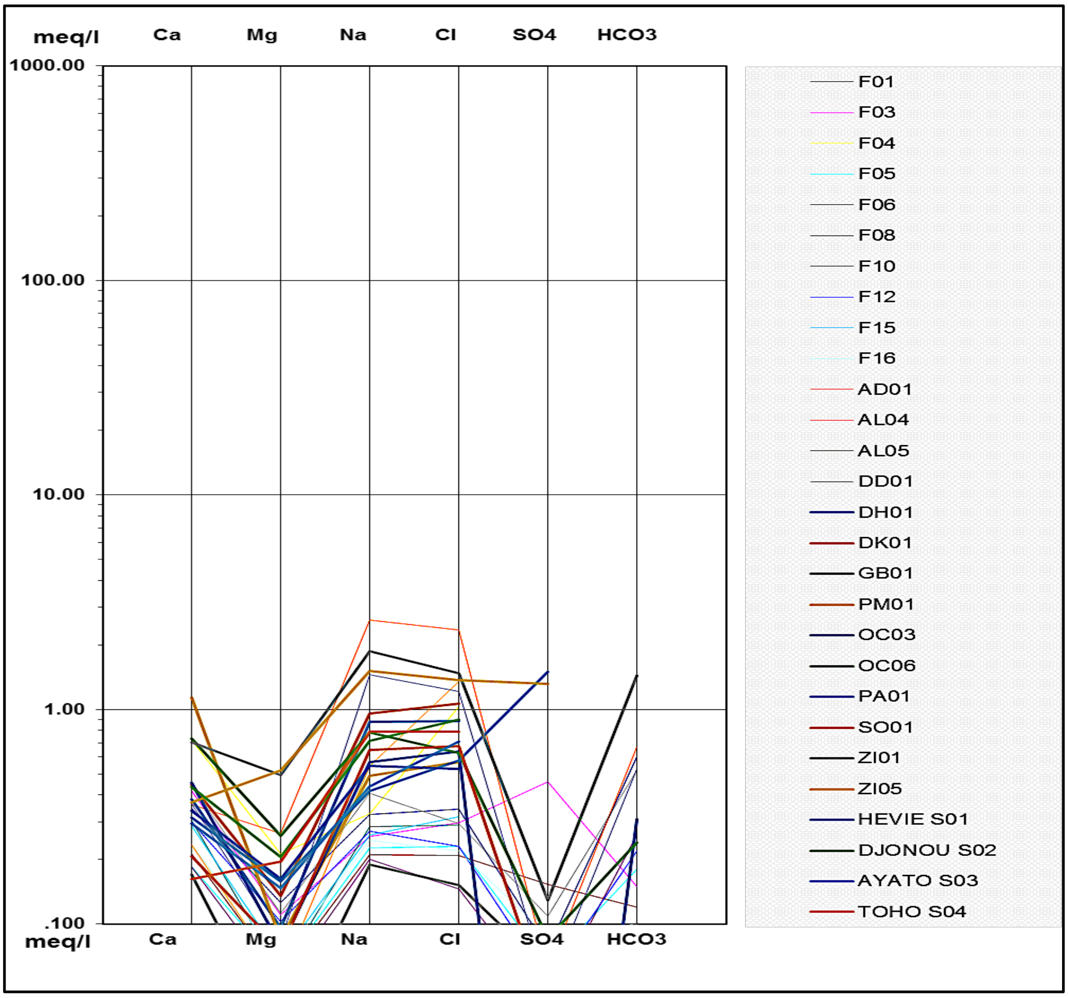

Figure 27 Schöeller-Berkaloff diagram presents the relative concentrations of anions and cations in all water samples of Ouédo study area

The diagram shows the dominant cations of Ca^{2+} and Na^{+} in the range of approximately 0.2-1.3 meq/L and the dominant anions of Cl^{-} and HCO_3^{-} in the approximate range of 0.2-3.0 meq/L.

The relative impact of the negative ions on measured EC in the groundwater is considered in Figure 28.

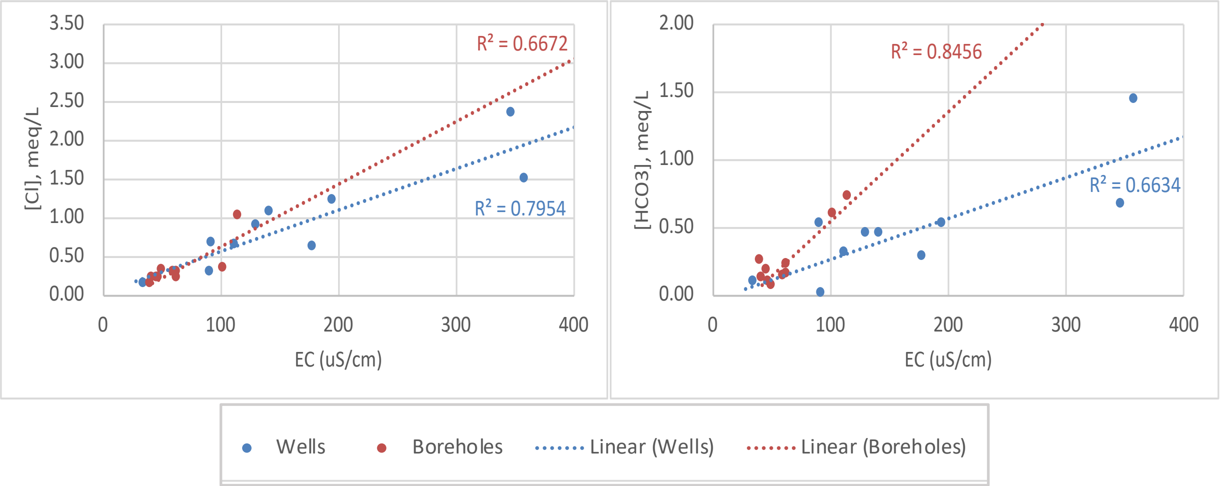

Figure 28 Correlation of major anions to EC in groundwater samples of Ouédo study area

The results show high correlation (R^2 = 0.80) between Cl^- and EC in samples from hand-dug wells, and high correlation (R^2 = 0.85) between HCO_3^- and EC in samples of boreholes. This shows that conductivity is strongly dependent on the presence of these ions in the study area.

Water type classification

The Piper diagram (Figure 29) is used to categorize the dominance of cations and anions in the water samples and to determine the hydrochemical water type.

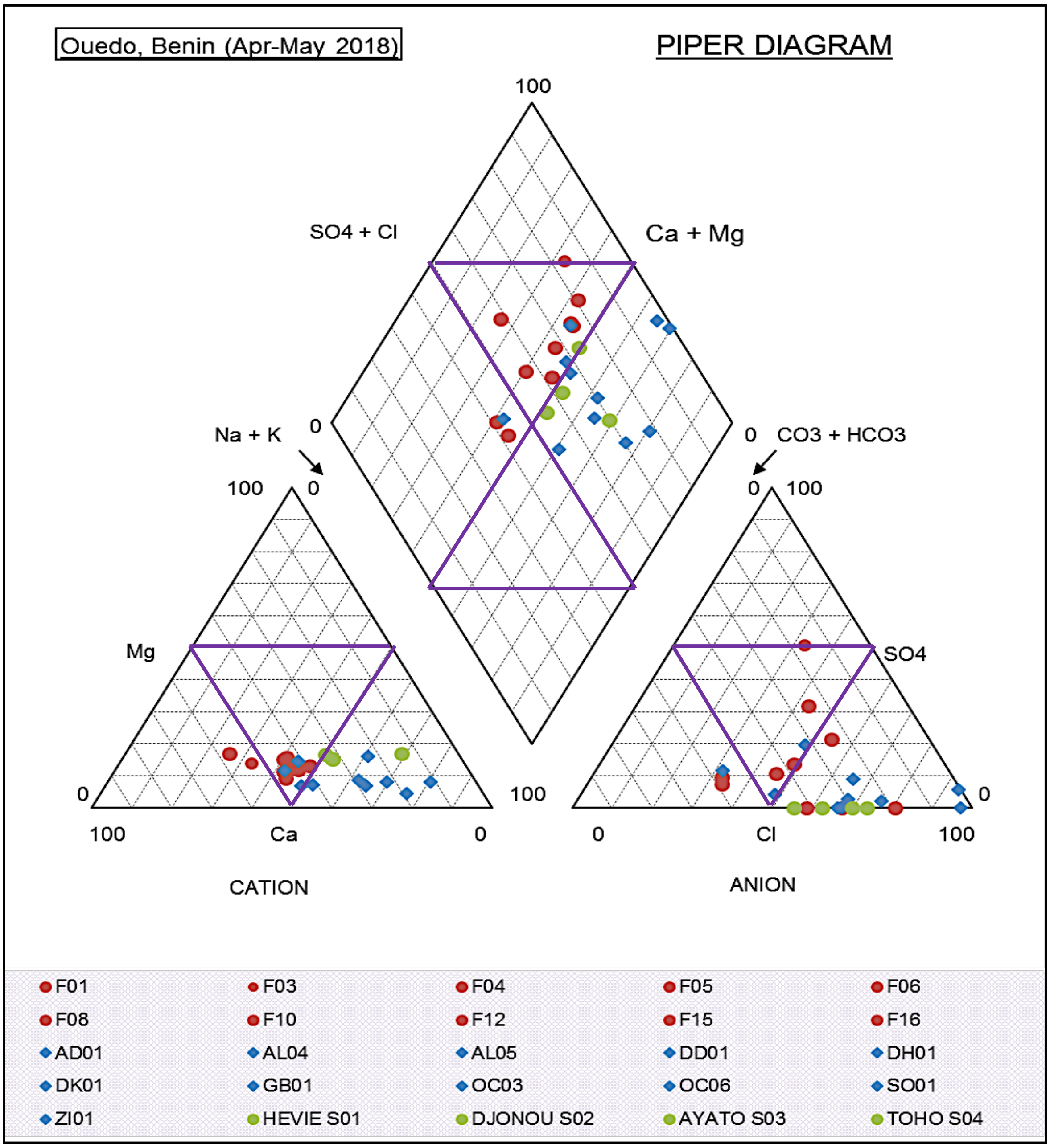

Figure 29 Piper diagram classification of water types for samples from boreholes (red), hand-dug wells (blue) and surface water (green) in study area

From the plot it is observed that groundwater from the hand-dug wells and surface water sources (streams and lakes) are predominantly Na-Cl type waters. The Na-Cl water type for shallow groundwater and surface water sources confirms the freshwater input to the reserves, indicating direct recharge through precipitation as shown in the stable isotopic composition of section 5.3.1.

The groundwater sampled from the boreholes generally show a mixed water type with no dominance of cations and anions. Samples from F04 and F10 showed dominance of Cl^- ions (57% and 64% of total anions, respectively). With respect to cations in these samples, the F04 sample showed dominance of Ca^{2+} ions (55%) but the F10 sample had no dominant cation (Na^+ = 43% and Ca^{2+} = 46% of total anions). The sample from F05 also showed dominance of Cl^- anion but the ion balance error was too high to allow consideration of this sample in interpretation of results. One borehole sample (F03) registered dominance of the $SO4^{2-}$ anion and had the highest concentration (49 meq/L or 22 mg/L) of all waters sampled in the study area.

Na:Cl correlation and Sea-water mixing line

There are no evaporites in the detritus lithology of the aquifers (Alassane et al. 2015) and so the NaCl water type can be attributed to coastal rain water recharge containing dissolved sea spray salts from the nearby Atlantic Ocean. To investigate this theory, the relationship between Na^+ and Cl^- concentrations in the water samples is considered within the context of sea-water mixing in Figure 30.

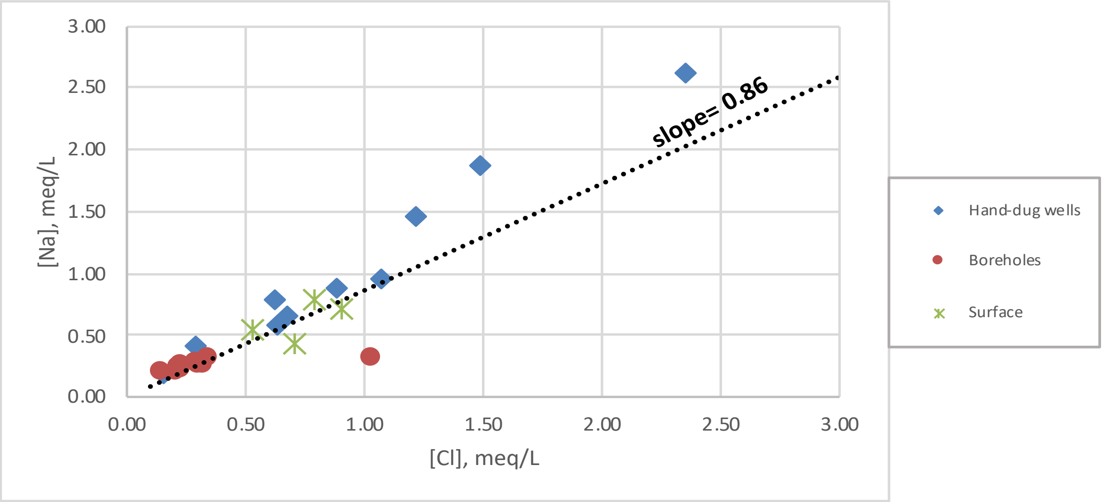

Figure 30 Correlation of Na^+ and Cl^- concentrations in sampled waters of the study area and the sea-water mixing line (Na:Cl=0.86)

There is high correlation along the sea-water mixing line for the majority of samples, indicating that sea-water mixing by way of coastal rainwater contributed to recharge in all the reservoirs.

For hand-dug well samples plotting above the mixing line, however, the Na^+ excess can indicate silicate mineral weathering processes taking place in unconsolidated sediments of sands and clays in the shallow Quaternary aquifer. Since this does not occur with the borehole samples, silicate weathering processes appear to only occur in the shallow aquifer.

Two hand-dug well samples (GB01 at the centre of the study area and DD01 in the north on Figure 7) plot very low on the mixing line, amongst the cluster for the boreholes. These are both communal hand-dug wells where the depths to groundwater level were 23 m and 19.5 m, respectively, but the depths to the base of the wells were unknown. The conductivity values of the samples were also relatively low: 39.60 µS/cm and 100.40 µS/cm, respectively.

Borehole sample F04 (in the centre of the study area) has higher Cl^- concentrations more comparable with the range of Cl^- in hand-dug well samples than the other boreholes. The sample also shows a strong deficit of Na^+ ions and plots well below the sea-water mixing line, indicating the removal of Na^+ ions from solution. Since the F04 sample has Ca^{2+} cation dominance, this indicates the removal of Na^+ ions from solution and release of Ca^{2+}ions through cation exchange. Although borehole F10 also registered a pre-dominance of Cl^- ions, the concentration was too low (0.29 meq/L or 10.3 mg/L) to be comparable with the Cl concentrations observed in hand-dug wells.

Ca:HCO_3 correlation

Figure 31 shows the relationship between Ca^{2+} and HCO_3^- ions in the groundwater and surface water samples of the study area.

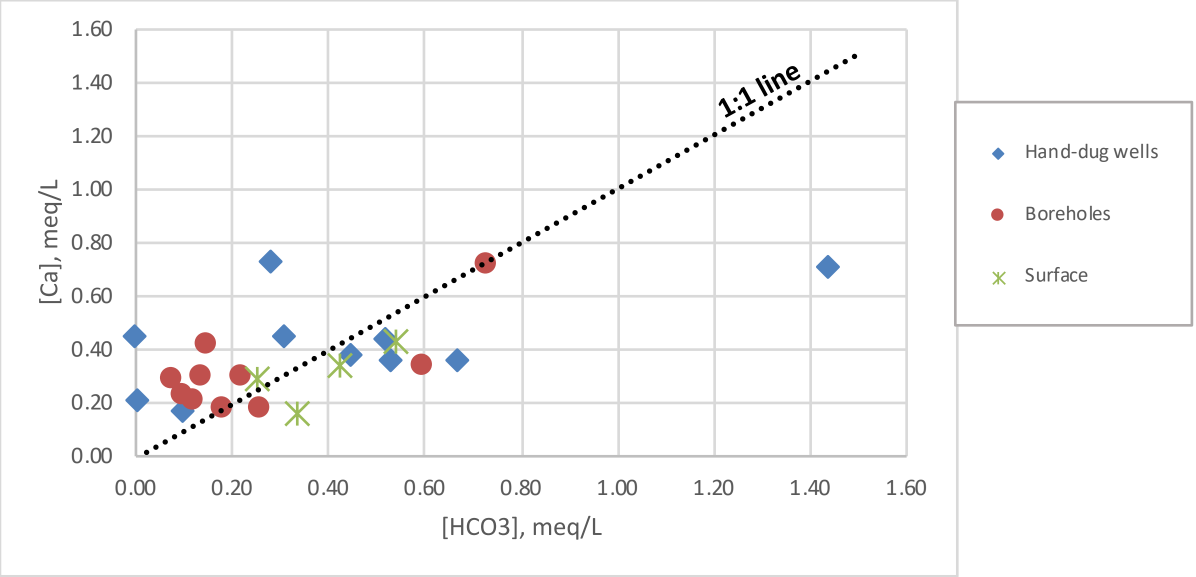

Figure 31 Correlation of Ca^{2+} and HCO_3^- concentrations in water samples and the calcite dissolution 1:1 line

The hand-dug well samples do not show significant correlation between Ca^{2+} and HCO_3^- ions ($R^2 = 0.37$) while boreholes and surface water samples showed slightly higher though still insignificant correlation ($R^2 = 0.52$ and 0.65, respectively).

Groundwater samples from boreholes generally plot above the calcite dissolution mixing line. Borehole sample F04 (which previously showed a deficit of Na+ ions) has high concentrations of Ca^{2+} and HCO_3^- ions that align with the calcite dissolution line, although still at concentrations too low to be found in a calcite-dissolving environment. Borehole sample F01 also showed high HCO_3^- concentration in field alkalinity tests but had a deficit of Ca^{2+} ions. Since this sample did not have an excess of Na+ ions, reverse cation exchange was not responsible for Ca-removal from solution.

Hydrochemistry of groundwater in piezometers PF08 and PF09

At the first two production boreholes visited for sampling, the proposed methodology for sampling groundwater required that the piezometers be emptied of twice the volume prior to the collection of groundwater samples. The depths to the screened interval of the piezometers were 100-120 m and the cross-sectional area of 7.9 m^2. Therefore, the volume of the piezometers did not exceed 1 m^3. With a pump capacity of 1 m^3/hour, it was expected that after two hours of pumping the conductivity values would stabilize in the range of 80-100 µS/cm as typical of the CT aquifer in the basin (Alassane et al. 2015).

Figure 32 shows the changes in conductivity and pH with pumping at the two piezometers.

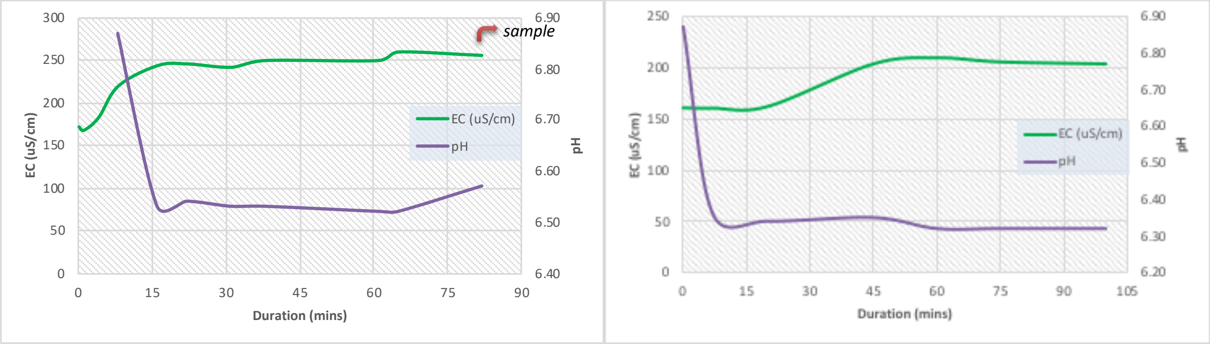

Figure 32 Conductivity and pH variations in water samples during pumping at PF08 (left) and PF09 (right) piezometers on April 24th, 2018

However, after an initial reading in the range of 160-170 µS/cm, the conductivities in both piezometers began to climb during pumping and stabilized for almost an hour at approximately 250 µS/cm and 205 µS/cm in PF08 and PF09, respectively.

A sample was taken at the end of pumping from PF08 for later analysis in the lab which revealed Ca-type water of relatively high TDS for the study area (141 ppm), organic carbon (1.37 mg/L) and Fe (3.90 mg/L). Due to the observation of high TDS after analysis of cations, the sample was diluted prior to analysis of anions in order to avoid damage to the analytical sensors. However, the anion analysis for this sample provided inconclusive results: all tested were anions below detection limit and the alkalinity was not measured in the field at these two early sites. Anion dominance was therefore not possible to determine.

The isotopic composition was (δ^2H = -21.70 ‰; $\delta^{18}O$ = -4.23 ‰). This shows that the water in this piezometer was more depleted in light isotopes than any of the groundwater samples in both the shallow and deeper aquifer in the study area.

Discussion

The shallow Quaternary groundwater has a higher degree of mineralisation than groundwater in the deeper CT aquifer. Typically, deeper groundwater experiences higher mineralization due to longer residence time and travel along longer groundwater flow paths. However, the groundwater in the CT aquifer demonstrates lower mineralization than shallow groundwater in the study area. The low degree of mineralization in the CT aquifer is consistent with other studies in the CSB (Alassane et al. 2015; Kpegli et al. 2018) and may be attributed to groundwater flow paths through geological layers with low contents of reactive minerals.

The water types are consistent with other groundwater water types found in the CSB (Alassane et al. 2015; Kpegli et al. 2018). Groundwater from the hand-dug wells (and surface water sources) is dominated by Na-Cl type waters that receive direct recharge through precipitation of coastal rainwater, as first indicated in the stable isotopic composition analysis of section 5.3.1. The groundwater sampled from boreholes show a mixed water type with no dominance of cations and anions. Borehole 10 had dominance of Cl^- ions, albeit at concentrations much lower than typical of the shallow aquifer. Borehole sample, F04, has high Cl concentrations that are more comparable with the hand-dug well samples and indications of cation exchange processes that removed Na+ ions from solution. This can support a hypothesis of mixing within the deeper aquifer around the siting of this borehole in Ouédo centre.

The correlation of Na and Cl ions showed that the majority of groundwater and surface water reservoirs in the study area receive varying contributions of recharge from coastal rain water. Some silicate weathering occurs in the unconsolidated sediments of the shallow Quaternary aquifer while Na-removal processes are possible occurring at one location in the CT aquifer. The two hand-dug wells (GB01 and DD01) with Na and Cl concentrations in the range of the borehole samples can already be tapping water from the CT aquifer and introduce a constraint that not all hand-dug wells in the area may be abstracting from solely the shallow Quaternary aquifer. However, abstraction with buckets from these communal hand-dug wells will have negligible effect on the shallow aquifer compared to continuous pumping at the boreholes.

The higher alkalinity and Ca-deficit for borehole F01 requires further investigation in order to determine if reverse cation exchange processes are indeed occurring or if Ca-removal is occurring through precipitation of solid minerals in over-saturated solutions or other processes. However, the concentrations of bicarbonate in the study area were so low and the potential for error in titrating with the strong acid too high for safely making conclusions on alkalinity-based theories. This uncertainty is also evident in the lack of correlation between pH and obtained alkalinity values (Appendix H). Further field alkalinity tests should be carried out using a weaker acid that would allow for a greater range in titration values and reduce errors in estimation. Then this method could be revisited, and the bicarbonate concentrations considered with respect to the saturation index of calcite in groundwater.

The relatively high EC observed during sampling of groundwater pumped from the two piezometers indicates possible infiltration of higher TDS groundwater from the shallow aquifers into the deeper CT aquifer. However, the Ca-type classification of the water sample and highly depleted isotopic composition introduce further theories on the groundwater origin.

One such theory is that the construction of the piezometer itself may be compromised and have fractures that allow for local diversion of shallow groundwater into piezometer during occasional pumping. Increased sampling from the piezometers and evaluation of the integrity of construction are required for making a final determination on the water abstracted from the monitoring wells and interactions with the shallow aquifer.

While overall the hydrogeochemical characterization of groundwater from the hand-dug wells and boreholes does provide no clear evidence supporting Hypothesis C that shallow groundwater is diverted to the deeper aquifers, there are preliminary indications that shallow groundwater may have been diverted by abstraction at borehole F04 and experienced mixing and cation exchange processes. Further monitoring is recommended at this and other boreholes in the study area to confirm hydrogeochemical signatures and monitor water chemistry for changes indicative of inter-aquifer mixing.

5.3.3. Water quality

To determine the status of groundwater contamination in the investigated aquifers, the water quality parameters of nitrates, iron, organic carbon and TDS are analysed. The water treatment methods that are utilised in the study area are also investigated to determine the risk to residents in using groundwater from hand-dug wells for drinking water purposes.

Nitrates

In Figure 33 the total nitrogen concentrations are considered alongside organic carbon concentrations for groundwater and surface water in the study area. The results show that hand-dug wells generally have higher concentrations of total nitrogen than boreholes and slightly higher concentrations of organic compounds. Although organic compounds are not toxic and not regulated for drinking water, the concentrations are relatively low in the groundwater of the study area (< 3 mg/L) and higher in the surface water bodies.

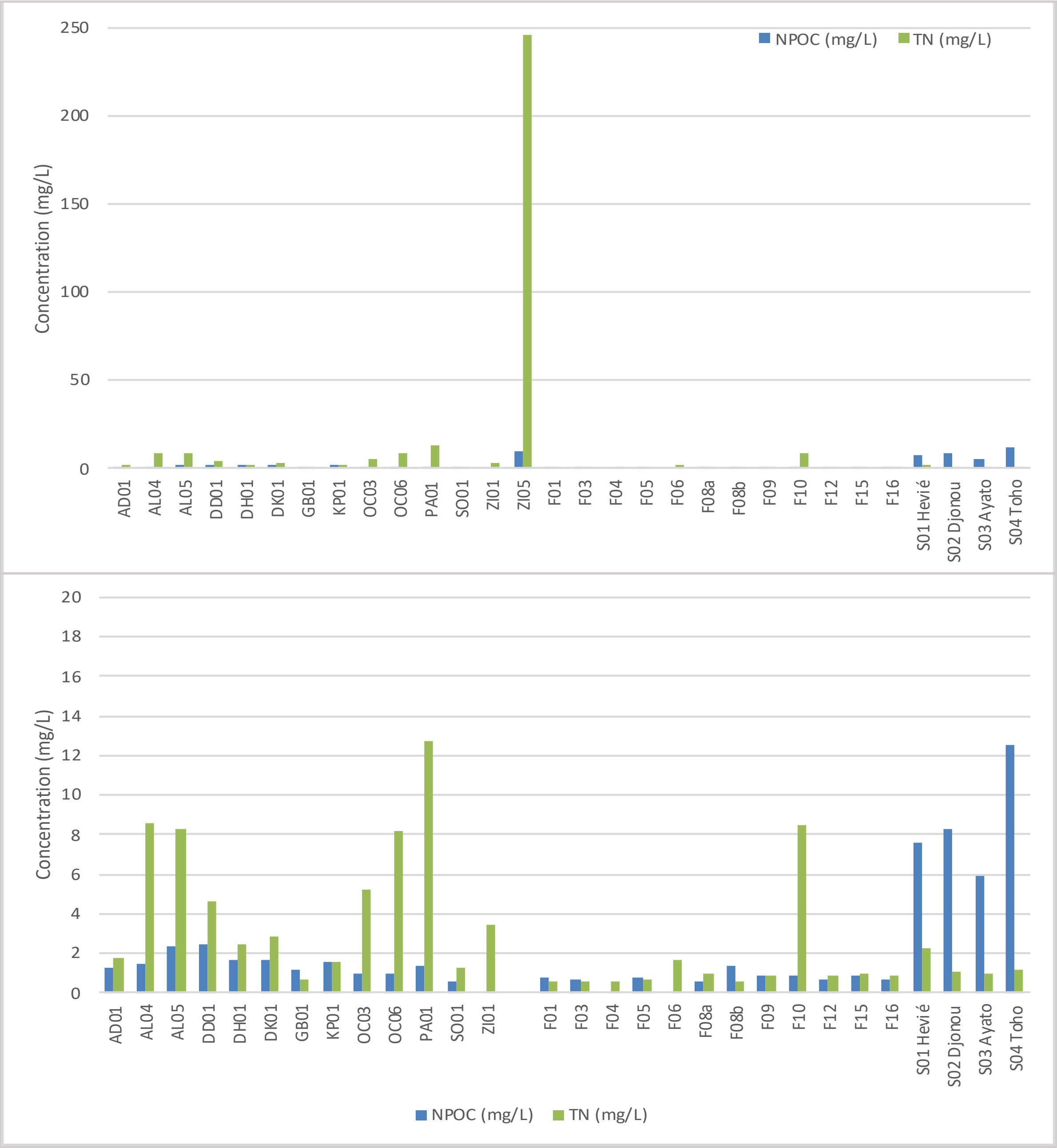

Figure 33 Concentrations of organic carbon (NPOC) and total nitrogen in groundwater and surface water samples of the Ouédo study area. Bottom graph with ZI05 removed.

The majority of sampled waters are within the European Union regulatory total nitrogen limit of 10 mg/L and within an acceptable range for total organic carbon. One sampled well, ZI05 in the Zekanme-Dessato village in central Ouédo produced total nitrogen levels well in excess of the limit. Field observations in this village noted several pits and abandoned dry wells filled with garbage and solid waste. These were located amongst the operational hand-dug wells in the village. General water quality in the village was poor, with samples registering amongst the highest EC (395-560 µS/cm) and the highest amount of sediment in the water. Algae were observed growing inside all wells on the site. The nitrate strips used at three wells in the village all registered values exceeding 100 mg/L. This includes the well at ZI01 although lab anion analysis revealed nitrate concentration <4 mg/L. Residents were allowed to test groundwater samples for nitrate themselves in order to engage them on a brief lecture on protection of the water supplies to avoid nitrate contamination.

One borehole stands out as having a higher than average total nitrogen concentration. Borehole F10, which is also located in northern Ouédo, registered a total nitrogen concentration of 8.5 mg/L. While this is still within the water quality permissible range and the range of natural nitrogen levels (<10 mg/L), the higher concentration than background at F10 is comparable with the shallow Quaternary aquifer where the median TN concentration is 4.04 mg/L.

Further drinking water standards are considered in Table 8, using water quality parameters that could be determined from analysis of the groundwater and surface water samples collected in the study area.

Table 8 Water samples of the Ouédo study area with respect to drinking water guideline. Limits sourced from Appelo and Postma 2004

Parameter	Drinking water limits/ guidelines	Samples
Fe	<0.2 mg/L	Hand-dug wells: AD01(0.6 mg/L) Boreholes: F04 (0.53 mg/L), F12 (0.42 mg/L), F16 (0.18 mg/L) Surface: Hevie S01 (0.26 mg/L), Djonou S02 (3.30 mg/L), Ayato S03 (0.98 mg/L)
TDS	<500 ppm	(none)

Drinking water limits are mostly adhered to for hand-dug wells in the study area. Three boreholes had iron concentrations exceeding the drinking water limit. This was supported by field observations of iron precipitation along the strings of divers in a few piezometers located on the site of production boreholes.

Further water quality testing is recommended for testing bacteria and phosphate levels in aquifers. These aquifers are at risk of bacterial contamination considering the proximity to latrines and open pits with wastes. Further, phosphate levels can indicate the amount of agro-chemicals entering the groundwater system and serve as a precaution for farmers in the study area.

Groundwater abstracted through the boreholes is pumped through a chlorine disinfection system prior to connection to the distribution network. However, water treatment in the hand-dug wells is subject to the will of residents in Ouédo. To determine water treatment for groundwater in the hand-dug wells, the household survey results are considered in Figure 34.

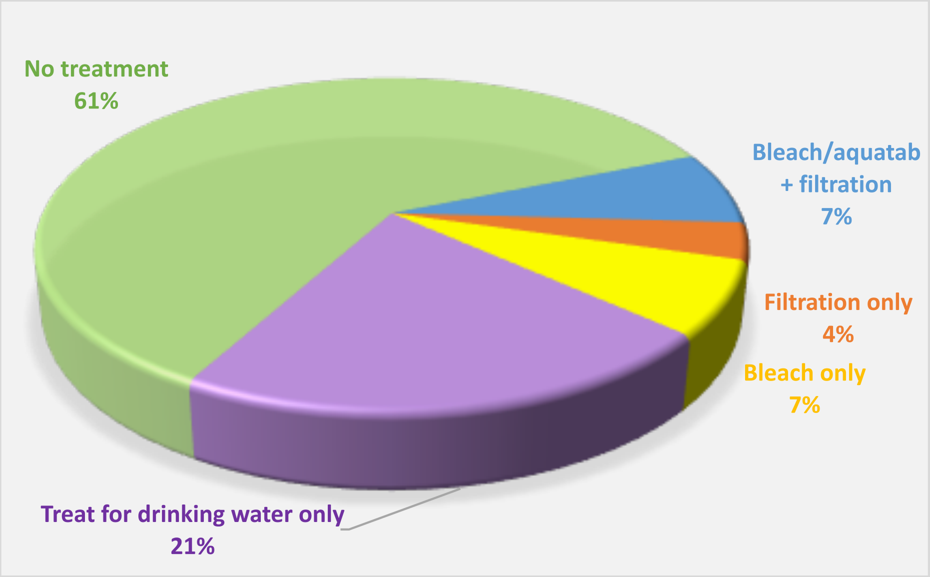

Figure 34 Water treatment practices for hand-dug wells in Ouédo (n=28)

The survey responses show that the majority of residents (61%) do not treat water from the hand-dug wells while 21% treat for drinking water purposes only. However, in considering the proximity of hand-dug wells to latrines and open pit dumps, 68% of sites observed had contaminant sources within 15-30 m and 18% within an even closer range of less than 15 m.

Discussion

The analysis of tested water quality parameters in water samples of the study area showed generally good water quality and little contamination for groundwater abstracted from both boreholes and hand-dug wells. It should be cautioned that the presence of pathogens was not evaluated in water quality testing and this could significantly impact the suitability of the groundwater for drinking purposes. Thorough and frequent water quality monitoring is recommended for study area since the majority of residents are vulnerable to a variety of illnesses and water-borne diseases from drinking untreated water from the mostly uncovered wells.

There are currently no water quality concerns for the CT aquifer based on the parameters tested. The thickness of overburden buffering the deeper aquifer may hinder the transport of contaminants to the CT aquifer as sorption, degradation and other processes take place in the aquifer matrix.

However, one borehole stands out as having a higher than average total nitrogen concentration. Borehole F10, which is also located in northern Ouédo, registered a total nitrogen concentration of 8.5 mg/L and presents the possibility of expedited pathways for surface nitrate contaminants to enter the deeper aquifer at this site, supporting Hypothesis C. F10 also showed dominance of Cl- ions (albeit at low concentrations) which suggests further monitoring at this production borehole site to determine with certainty if in fact downward fluxes from abstraction at F10 are diverting shallow groundwater to the deeper aquifer.

The water quality test further revealed that the water from hand-dug wells and surface water sources are not suitable for irrigation and the high sodium concentrations in the waters will contribute to long-term degradation of soils in the Ouédo study area.

5.3.4. Discussion

Groundwater from the shallow Quaternary aquifer and the CT aquifer were characterised based on stable isotopic composition and hydrogeochemistry for the investigation line of Hypothesis C. This hypothesis put forward that abstraction in the new wellfield is creating downward fluxes that reduce groundwater storage in the shallow Quaternary aquifer and relies on the characterization of the groundwater samples to identify mixing in the deeper CT aquifer.

The characterisation of the aquifers did not provide strong conclusions to validate Hypothesis C. Stable isotopic compositions of the reservoirs were too indistinct to distinguish end members for the application of mixing model equations but did present precipitation as the main source of recharge to the aquifers. Groundwater from the hand-dug wells was dominated by Na-Cl type waters and confirmed that the shallow Quaternary aquifer receive direct recharge through precipitation of coastal rainwater. However, in comparing the water-type signature of shallow groundwater to those determined for borehole samples, the F04 borehole showed preliminary indications of mixing between shallow and deeper groundwater (high Cl concentrations and evidence of Na-removal processes) and supports the hypothesis of diversion of shallow groundwater to the borehole during abstraction. The presence of increasingly high-TDS groundwater in the two pumped piezometers investigated suggests the diversion of shallow groundwater into the piezometer, but perhaps due to compromised piezometer construction rather than the occasional pumping that occurs at the monitoring well. Water quality analysis suggests surface nitrate contaminants may be diverted to borehole F10. Since this borehole also showed a dominance of Cl anions, although in low concentrations, it presents another possible borehole site supporting the hypothesis of downward diversion of shallow groundwater to the CT aquifer.

Recommendations for further studies include frequent and seasonal monitoring of water chemistry in groundwater from more hand-dug wells and boreholes in the study area. For the investigation of alkalinity in the study area, it is recommended to use a weak titration acid to obtain alkalinity results that could provide more information on the geochemical processes taking place in the aquifer and contribute to the validation of Hypothesis C.

5.4. Assessment of the hypotheses

Climate variability did not show a strong signature in recent years and seems unlikely as the main cause of decreasing groundwater levels in the area. While precipitation showed moderate decline in recent years, long-term trends of precipitation and evapotranspiration showed a climate system in relative equilibrium. Temperature continues to rise in the region, however, and so there may be more effects triggered by a warming climate. Results indicate that the decrease in groundwater recharge in the study area due to climate variability appears unlikely and does not support Hypothesis A.

Land-use and land-cover changes with recent population growth presented a stronger recent trend affecting groundwater storage in the shallow Quaternary aquifer. With settlement encroachment in and around Ouédo, the increased impervious cover will alter recharge pathways to the shallow Quaternary aquifer and divert more input precipitation to overland runoff where it will eventually end up in the streams and wetlands down-gradient of the study area. The settlement encroachment is also expressed by the increased population growth in Ouédo and the current high population density. The shallow aquifers are being heavily abstracted to meet fast-growing demand in the area – in one sample group, an increase in abstraction by 37%, which is in good agreement with the estimated increase in abstraction of 41% with population growth within the last five years. The results indicate that there is a potential decrease in groundwater recharge with urban encroachment in the surrounding commune, supporting hypothesis A. Results further indicate an increase in shallow groundwater abstraction from a fast-growing population, supporting Hypothesis B.

Although hydrogeochemistry was expected to be a useful tool in characterizing the groundwater of the two aquifers and quantifying the amount of mixing occurring in the deeper aquifer, there were challenges in application of proposed techniques. The absence of distinct stable isotopic end-members in the groundwater samples prevented the application of binary mixing model equations. Further, the overall low mineralisation of groundwater samples produced small ranges in ion concentrations that could be masked by analytical errors and hindered interpretation of water chemistry, particularly using alkalinity measurements. Nevertheless, the analysis of results reveals some mixing of shallow groundwater in the deeper CT aquifer at borehole F04, located at the centre of the study area (Figure 7). There were also indications of mixing, albeit to a lesser extent, at other sites. Further investigation of potential mixing at identified sites can prioritize mitigation efforts for groundwater drawdown due to wellfield abstraction in the area and ensure the security of shallow groundwater reserves for the residents of Ouédo. Despite the isolated cases, results from the characterization of groundwater are largely inconclusive and give no clear evidence supporting Hypothesis C.

Conclusion and Recommendations

The study investigated the potential reasons for declining groundwater levels in the hand-dug wells tapping the shallow Quaternary aquifer in Ouédo, namely a decrease in groundwater recharge to the aquifer, an increase in abstraction by Ouédo residents and creation of downward fluxes with abstraction in the new wellfield.

The results of this study confirm that the recharge of the shallow aquifer is highly connected to local precipitation. However, no evidence of a decrease in precipitation could be identified over recent years. The same holds for temperature and evapotranspiration, which are climate parameters that also influence recharge. On the contrary, a clear increase in impervious land cover was identified and attributed to rapid urban encroachment in Ouédo and the surrounding area. This could alter recharge pathways to the shallow Quaternary aquifer and divert more input precipitation to overland runoff where it will eventually end up in the streams and wetlands down-gradient of the study area.

The urban encroachment is also expressed by the increased population growth in Ouédo and the higher population density. From 2002 to 2013, the population tripled. Today, the shallow aquifers are being heavily abstracted to meet fast-growing demand in the area. The field survey of 30 hand-dug wells showed that 27% of them were constructed after 2014, representing an increase of 37% in abstraction over the last four years. The results supported the hypothesis that the decrease in water levels in the hand-dug wells is due to increased abstraction by residents in the study area.

The isotopic and hydrogeochemical analyses were inconclusive. Groundwater in the shallow Quaternary aquifer tapped by the hand-dug wells, and the deeper Continental Terminal aquifer exploited by the boreholes have similar isotopic signatures comparable to that of local precipitation. While it could imply that the two aquifers are connected it could also be an expression of the similarity in lithologies and recharge processes of the aquifers. However, additional isotopic and geochemical techniques are recommended for defining the groundwater flow pattern in the system, including the use of dating tracers such as tritium isotopes.

Technical recommendations include the execution of pumping tests at boreholes with the installation of divers in hand-dug wells to monitor groundwater levels. Tritium isotope dating can aid in determination of groundwater residence time and the characterization of groundwater end-members.

Future work in the study area should include long-term frequent monitoring of the shallow aquifer, where shallow piezometers could be installed at the already established F2PNUD monitoring station. There should also be zoning for wellhead protection of boreholes to decrease the risk of introduction of surface contaminants into the deeper CT aquifer.

With respect to the conflict resolution, enforcement of regulations on shallow groundwater abstraction will aid in the monitoring and management of resources. Further, since the water demand of the growing population still needs to be addressed, immediate connection of residents to the SONEB distribution network through borehole F07 is recommended.

Further studies in the area by OmiDelta and the NOEVA researchers will aid in understanding of groundwater dynamics in Ouédo and inform managers on appropriate adaptation and mitigation measures for ensuring water security for all residents. By understanding the threats to shallow groundwater in the study area, other peri-urban areas within the transboundary Coastal Sedimentary Basin can be monitored for declining groundwater levels and water security strategies implemented particularly for other towns experiencing rapid urbanization and increased groundwater abstraction.

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Appendices

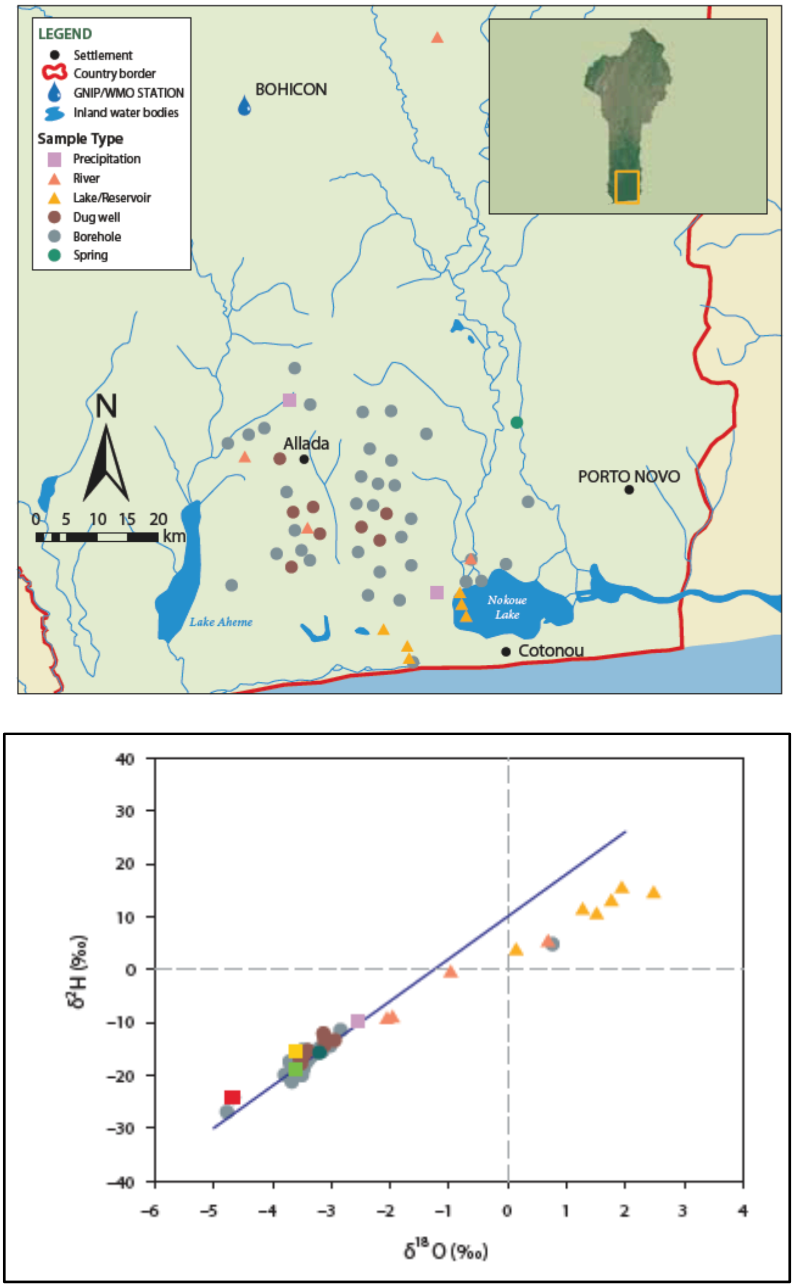
Appendix A **Stable Isotope Tracers**

Fundamental theory

Isotopes are atoms of the same element with the same number of protons but different number of neutrons i.e. different total mass of the atoms. For the oxygen element, all atoms have 8 protons, but the number of neutrons vary from 5 to 12 neutrons. This produces a range of isotopes, of which ^{16}O ^{17}O and ^{18}O isotopes are stable and ^{16}O being the most frequently occurring. Similarly, hydrogen has isotopes ^{1}H, ^{2}H and ^{3}H, where ^{1}H and ^{2}H ("deuterium") are stable isotopes and ^{3}H ("tritium") is unstable or radioactive. For the water molecule, the hydrogen and oxygen atoms combine using any of the combination of isotopes. The most common combination is ^{1}H-^{16}O -^{1}H but the present or absence of the heavier ^{2}H and ^{18}O isotopes in the molecule can provide information on the evolution of that body of water through the hydrological cycle (Clark and Fritz 1997).

Through a process known as isotope fractionation, the proportions of heavy and light isotopes in a water sample can provide information on phase transitions and physicochemical reactions that occurred. That is to say, the historical record of the droplet becomes available. Fractionation or partitioning occurs for every thermodynamic reaction, with the redistribution of heavy and light isotopes on either side of the equation depending on the reaction rates for varied molecular species (Clark and Fritz 1997). Factors affecting fractionation include temperature, humidity, altitude, amount of rainfall and proximity to the coastline. These have been thoroughly investigated in scientific literature (Clark and Fritz 1997).

Stable isotopes can also be used for establishing the timing of recharge to the groundwater reservoirs. The stable isotopic composition in precipitation is strongly correlated to temperature and rainfall amount and therefore can be traced based on seasonal fluctuations (Clark and Fritz 1997).



Map of GNIP stations and water sample points in southern Benin (top) and associated stable isotopic compositions (bottom) (IAEA 2007)

Appendix B **Household survey for hand-dug well owners in study area (French version)**

ETUDE DES PUITS DOMESTIQUES DANS L'ARRONDISSEMENT D'OUÉDO : QUESTIONNAIRE

Date de la visite: ____________

Identifiant du puits: ID: __________ ID local: ______________

Emplacement: Lat: _________ Long: __________ Adresse: __________________________

Resolution du GPS:

Caractéristiques du puits: Propriétaire: _________________ Année de construction: _____________

Type: ________________________ Méthode de prélevement:____________

Profondeur ____ Diamètre _____ Altitude ______ SWL ______

USAGE DES EAUX SOUTERRAINES

1. Quelle est la part d'eau souterraine dans la consommation en eau totale (%) ?

____

2. Quelles sont les principales utilisations de l'eau souterraine au-sein du ménage ? Cochez toutes les cases.

Eau potable / Cuisine
Hygiene
Agriculture (non commerciale)
Agriculture (commerciale)
Autre

3. Quelle quantité d'eau souterraine est retirée quotidiennement du puits ?

Volume quotidien estimé: ____

4. OUÉDO a-t-il des changements saisonniers observés dans le niveau de l'eau souterraine ? Décrire.

____

5. OUÉDO a-t-il des changements saisonniers dans la qualité de l'eau souterraine ? Décrire.

____

6. OUÉDO a-t-il des changements observés dans le niveau moyen des eaux souterraines depuis la construction ?

____

7. OUÉDO a-t-il des changements observés dans la qualité moyenne des eaux souterraines depuis la construction ?

____

QUALITÉ / ASSAINISSEMENT

1. L'eau souterraine est-elle traitée avant utilisation ? Décrire.

Aucun traitement
Ébullition
Ajout de javellisant / chlore
Filtration à travers un chiffon
Filtration à l'aide d'un filtre à eau (céramique, sable, composite, etc.)
Désinfection solaire
Decantation
Autre: ____

2. Existent-t-il des sources potentielles de pollution à l'intérieur de la propriété (déchets, latrines)? Estimer la distance.

____

3. Quelles sont les autres sources potentielles de pollution a proximité du puits ? Estimer la distance.

____

COMMENTAIRES

Appendix A Household survey for hand-dug well owners in study area (French version)

Appendix C **Household survey for hand-dug well owners in study area (English version)**

STUDY OF HOUSEHOLD HAND-DUG WELLS IN THE TOWN OF OUÉDO : SURVEY

Date of visit: ____________
Hand-dug well ID: ID: __________ ID local: ______________
Location: Lat: _________ Long: __________ Address: __________________________
GPS location:

Well characteristics: Owner: _________________ Year of construction: _____________
Type: ________________________ Withdrawal method:____________
Depth ____ Diameter _____ Elevation ______ SWL ______

GROUNDWATER USAGE

1. What is the proportion of groundwater in total water consumption (%)?

____

2. What are the main uses of groundwater in your household? Check all that apply.

Potable water / Cooking
Washing
Agriculture (non-commercial)
Agriculture (commercial)
Other

3. How much groundwater is withdrawn daily from the hand-dug wells?

Estimated daily volume: ____

4. Have there been any observed seasonal changes in the groundwater level? Describe.

____

5. Have there been any observed seasonal changes in the groundwater quality? Describe.

____

6. Have there been any observed changes in the average groundwater level since well construction? Describe.

____

7. Have there been any observed changes in the average groundwater quality since well construction? Describe.

____

QUALITY / SANITATION

1. Is the groundwater treated before use? Describe.

No treatment
Boiling
Addition of bleach/chlorine
Cloth filtration
Filtration with aid of water filter (ceramic, sand, composite, etc.)
Solar disinfection
Settling
Other: ____

2. Are there potential pollution sources on the compound (wastes, latrines)? Estimate the distance.

____

3. Are there other potential pollution sources near the hand-dug wells? Estimate the distance.

____

COMMENTS

Appendix B Household survey for hand-dug well owners in study area (English version)

Appendix D **Materials / Equipment list**

The materials and equipment described below for thirty sampling points in study area.

GENERAL
- 1- Submersible pump + supplemental accessories (hose, clock meter, valve, outlet)
- 1- Generator/power connection
- 1- Bailer
- 1- Water level sounder
- 3- Divers (pressure transducers) + 1- Barometer + attachment cords
- 1- 30m measuring tape
- 1- Garmin GPS unit
- 1- set of sample labels
- 30- plastic bags

STABLE ISOTOPES - *O18, H2*
- 100- 2.5ml sample bottles

WATER QUALITY
- 100- 25ml sample bottles
- 20- syringes + replacement filters
- 1- bottle distilled water
- 1- EC meter
- 1- pH meter kit + 2- buffer solutions
- 1- Titration field kit (alkalinity)
- 1- nitrate strips set

Appendix E **Household survey responses summary**

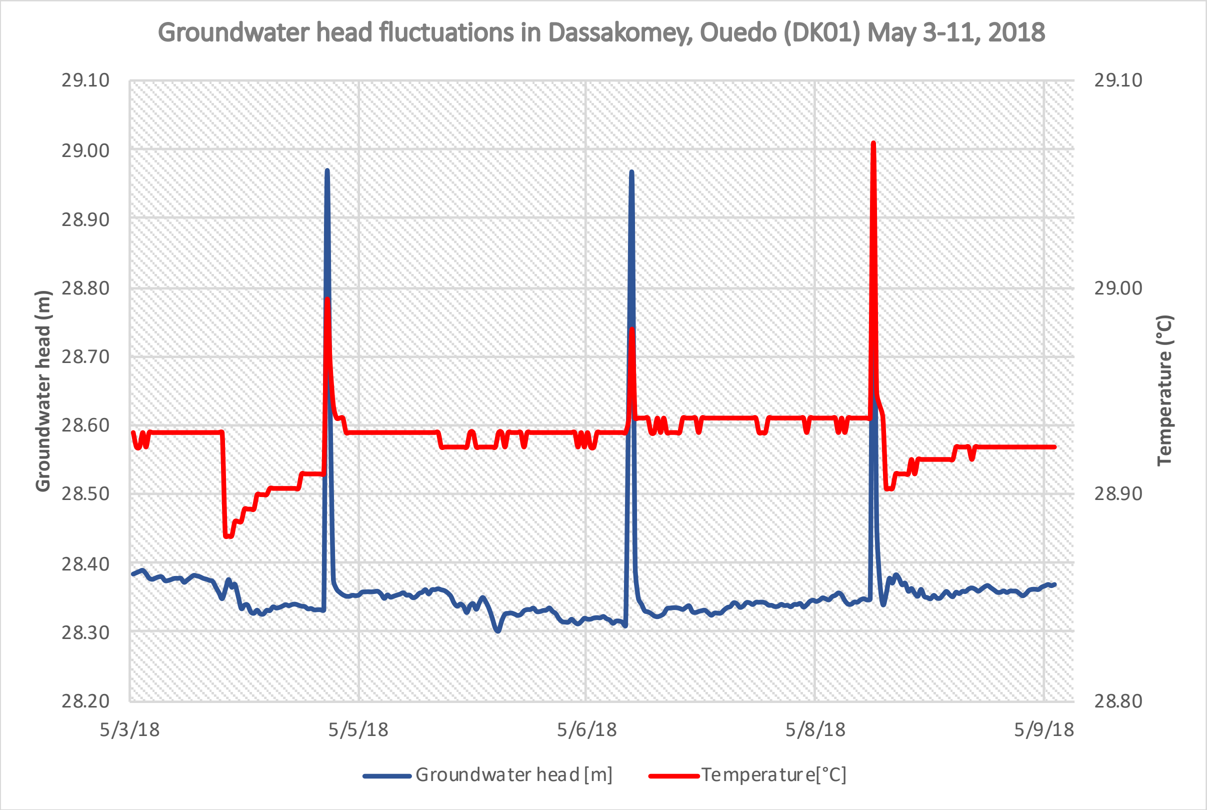
		Main uses of groundwater in household				Estimated daily abstraction from hand-dug wells
ID	Site	potable water	cuisine	Hygiene	autre	
1	DK01	1	1	1	1	1000 L
2	DH01	1	1	1	1	
3	PA01	1	1			
4	ZI01	purchase from those who have private drilling	1	1		plus de (20*25)L
5	KP01	1	1	1	1	per house (5*25L à 10*25L) but community(1600 L/day in rainy season, et 1600 L/day in dry season)
6	DD01	1	1	1	1	min 25*25L - max 5*25L
7	AD01	1	1	1	1	Max of (20*25)L
8	OC01	purchase from those who have private drilling	1	1	1	min 4*15L - max 8*25L
9	OC02	purchase from those who have private drilling	1	1	1	min 16*25L- max 24*25L
10	OC03	1	1	1	1	
11	SO01	1	1	1	1	min 16*25L- max 20*25L
12	PM01					
13	OC04	1	1	1	1	Max of 30*25L
14	OC05	purchase from those who have private drilling	1	1	1	Max of 30*25L
15	OC06	1	1	1	1	Max of 60*25L
16	OC07	1	1	1	1	min= 25*25L- max 70*25L
17	AL04	1	1	1	1	Max of 60*25L
18	AL05	1	1	1	1	approximately 100*25L
19	GB01	1	1	1	1	40 * 25L
20	OC08	1	1	1	1	
21	DH02	1	1	1	1	30*25L
22	DH03	1	1	1	1	min 6*25L- max 20*25L
23	DH04	1	1	1	1	20*25L
24	DH05	1	1	1	1	100*25L
25	DRY	1	1	1	1	min 8*25L(for 3 days)- max 16*25L(for 3 days)
26	DH06	1	1	1	1	20*25L
27	DRY (Came	purchase from those who have private drilling				
28	DRY DK02	purchase from those who have private drilling	1	1	1	9*25L
29	DRY DK03	purchase from those who have private drilling	1	1	1	min 6*25L - max 9*25L
30	5DIDIER	purchase from those who have private drilling	1	1	1	min 10*25L - max 20*25L

ID	Site	Observed seasonal changes in groundwater level	Observed changes in groundwater level after wellfield construction	Water treatment methods used
1	DK01	not really	no	filtration using a water filter
2	DH01	there was drying up when the school was under construction	yes for well located 60 m	no treatment
3	PA01	yes (commentary)	yes since constrcution soneb	adding aquatab and filtering through a cloth
4	ZI01	dry in harmattan, deepening every year by the owners	Yes	no treatment
5	KP01	dewatering wells after drilling soneb	Yes	no treatment
6	DD01	yes, the decreasing static level in the dry season	no	no treatment
7	AD01	yes, decrease of the static level, deepening of the well by the owners	Yes	no treatment
8	OC01	yes, drying up for three months	Yes	no treatment
9	OC02	yes, refer to how.	Yes	no treatment in general but addition of bleach / chlorine for drinking water only
10	OC03	Yes	Yes	no treatment
11	SO01	no	no	adding bleach / chlorine
12	PM01			
13	OC04	yes drying up, which leads to deepening and nozzles	no	adding bleach / chlorine about 4 months before this day.
14	OC05	Yes	Made after SONEB	no treatment
15	OC06	Yes	Made after SONEB	no treatment
16	OC07	decrease in the dry season of the static level	Yes	no treatment
17	AL04	no	realized before SONEB	no treatment
18	AL05	yes, the water turns red	Yes	adding bleach / chlorine for drinking water
19	GB01	Yes	not really	adding bleach / chlorine for drinking water
20	OC08		achieve after soneb	no treatment
21	DH02	yes, dries up in the dry season	achieve after soneb	addition of bleach / chlorine for drinking water + filtration through rag
22	DH03	no	yes, slight dimunition of the static level	no treatment
23	DH04	yes, decrease of the static level	achieve after soneb	no treatment
24	DH05	no		addition of bleach / chlorine (aquatab)
25	DRY	no	achieve after soneb	no treatment in general but addition of bleach / chlorine for drinking water only
26	DH06	not really	achieve after soneb	no treatment
27	DRY (Came	yes drying up		no treatment for paid water
28	DRY DK02			adding bleach / chlorine for drinking water
29	DRY DK03		probably dry after SONEB	sometimes adding bleach / chlorine (aquatabs) for drinking water
30	5DIDIER	yes, the static level decreases in dry season and increases in rainy season	dry up after the coming of the soneb	no treatment

ID	Site	Location of potential pollution sources	Further comments
1	DK01	latrine at 12 m	drilling done inside a well, sale of water
2	DH01	latrine 45 m from the school well	public well in the school
3	PA01	latrine at 19 m (close to marsh)	deepening of the well by the owner about 10 months before-before drilling soneb, increase of water level in rainy season - after soneb, water dimunition in rainy season - before drilling soneb, water was coming to the edge the upper level of the well, little to none sediment, near F09
4	ZI01	latrine at about 30 m	green moss on the inner flank of the well-not too dirty, little sediment-near unmounted borehole (X = 417689, Y = 715114) -in concession interior
5	KP01	latrine at about 22 m	well dried for 2 years
6	DD01	latrine at 200 m	no dewatering of wells after the drilling of the soneb
7	AD01	latrine at 22m	the decrease of the static level has been accentuated after the work of the SONEB, close to the swamp, is disturbed from time to time. Well located 50m from 7.
8	OC01	latrine at about 20m- about 100m old well drained before the arrival of the SONEB but filled with garbage	In the area, wells made after the arrival of the SONEB only provide water for 4 months and dry up - Existence of many dry wells
9	OC02	latrine about 22m	Decrease of the water in the well since the arrival of the SONEB- but practically dry that three to four boreholes were made by neighbors-dry wells to 15 m filled with skeptic-pit trash to 12m
10	OC03	latrine at about 12m	Not welcomed
11	SO01	latrine at about 12m	treatment with bleach / aquatabs in the well- Neighbors come to draw water for drinking and cooking- Solicitation of neighbors increases in the dry season
12	PM01	latrines at about 12m (?) and about 20m (not in use)	Currently in use for construction of the house-mason met on-site-well treated with aquatabs, bleach and "sindakin" (local name)
13	OC04	latrines at about 40m and about 20m (not in use)	Existence of an old closed well in the vicinity before the construction of this well.
14	OC05	latrine at about 20m	Not use for drink. This well is close to survey 15- Existence of a closed well (X = 418979 Y = 713063) with sand and gabages- At Mr Jonas.
15	OC06	latrine at around 20m	close to tomb at around 2m - close to FO4
16	OC07	latrine at around 23m	falls at 30m from the well- regular treatment of the well-watering about 17 m
17	AL04	latrine at around 40m	at the former village chief-well who hosted the Diver south
18	AL05	latrine at around 25m	well used by the landlord and his tenants
19	GB01	latrine at around 15m	
20	OC08	Septic tank at about 20m	Domestic borehole
21	DH02	latrine at around 60m - garbage pit nearby at around 30 to 40m	also use rainwater except drink- in the morning, after 5 * 25L draws the finished water and it is necessary to wait around 14h to be able to draw more water
22	DH03	latrine at around 60m	family home - likely proximity of grave
23	DH04	latrine at around 30m	close to tomb at about 6m-well that dries up after drawing 20 * 25L
24	DH05	latrine at 25m	many come to draw
25	DRY	latrine at 25m	dry well but they draw in survey 26 and 10m away from 24
26	DH06	latrine at around 12m	
27	DRY (Came	latrine at around 30m	
28	DRY DK02		close to several dry wells
29	DRY DK03		in general dry well probably because of the pumping of the soneb
30	5DIDIER	latrine at around 15m	deepening of the well 1 month before

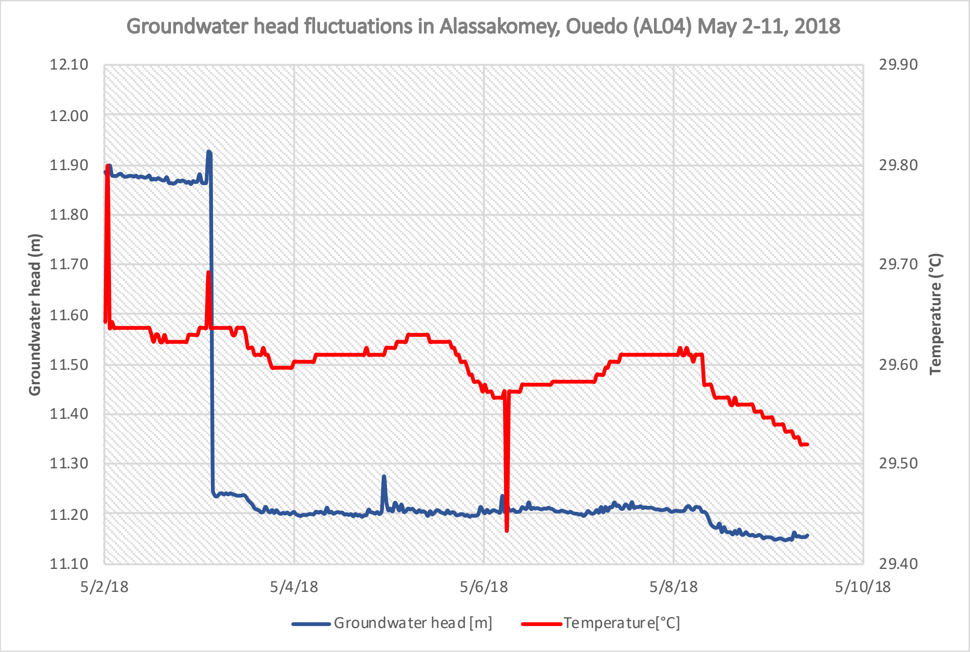
Appendix F **Piezometric level monitoring in shallow aquifer**

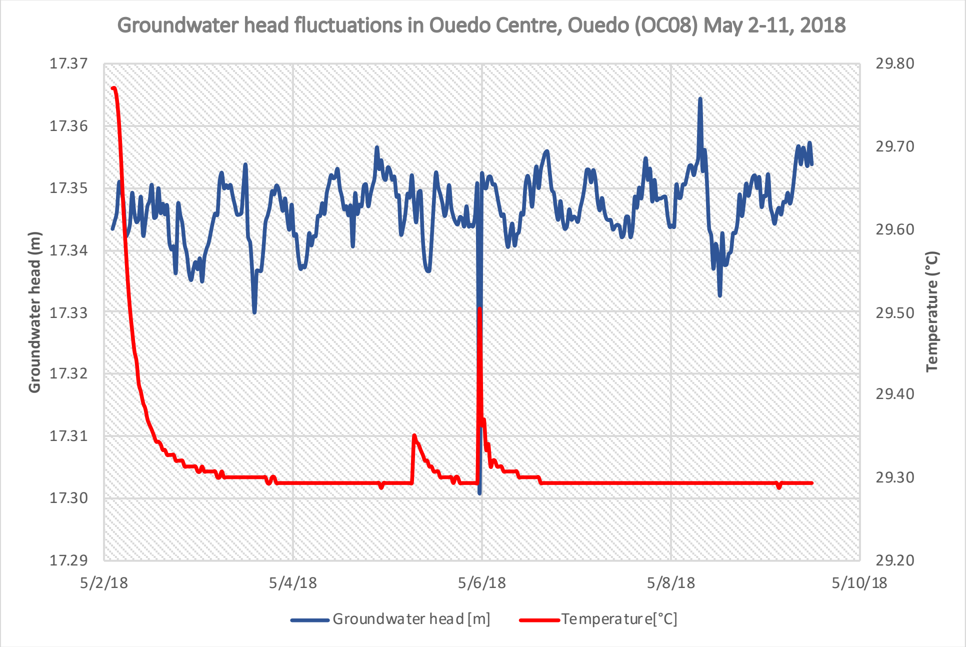
A diver was installed at the DK01 site to monitor groundwater levels over the period of a week.



The upsurges in groundwater level on three occasions indicate the disturbance generated during pumped abstraction events in the hand-dug well. From the time series, it is observed that the groundwater level reached a maximum decline of 10 cm which corresponded to a volume of 0.075 m^3 (75 liters) water in the well. Since the well owners reported that they actually abstract 1000 liters/day, either the groundwater was quickly being replenished in the hand-dug well (indicating high aquifer transmissivity) or their usage estimate was inaccurate. Further monitoring of the hand-dug wells of water vendors in Ouédo can provide a more representative estimation of groundwater abstraction in the study area. Another response with high abstraction was at the site of a shared property (AL05) where 2500 liters/day was the total estimated to be abstracted by the landlord and tenants (total number of residents not disclosed). This shows that the "household size" will have to be closely examined when estimating per capita consumption of groundwater from the hand-dug wells.

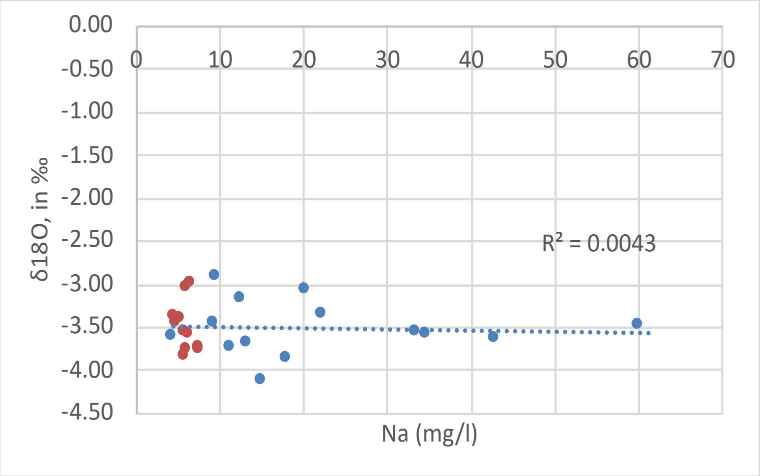
Groundwater monitoring data for one hand-dug well (AL04) in the south of the study area and one domestic borehole (OC08) in the centre.

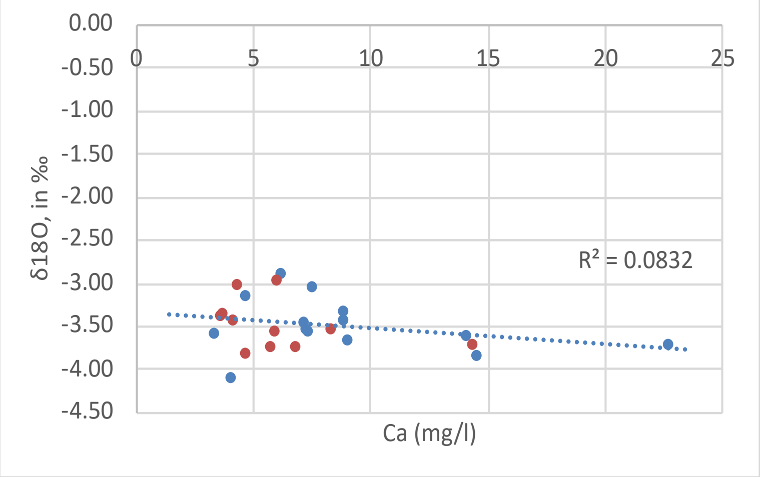


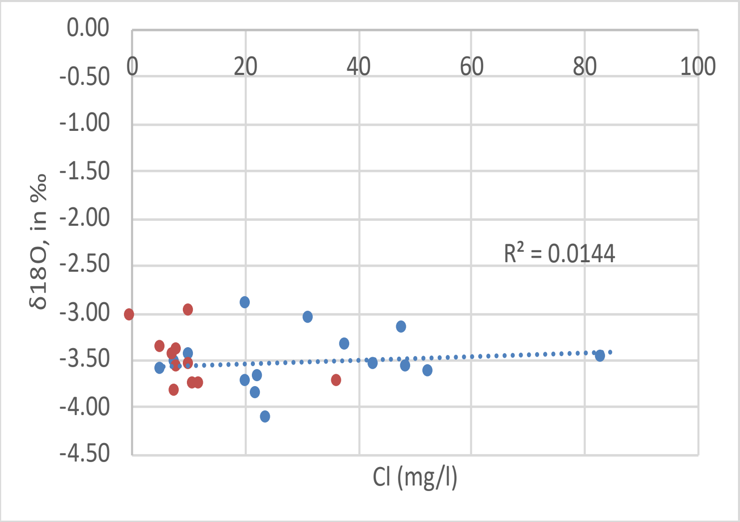


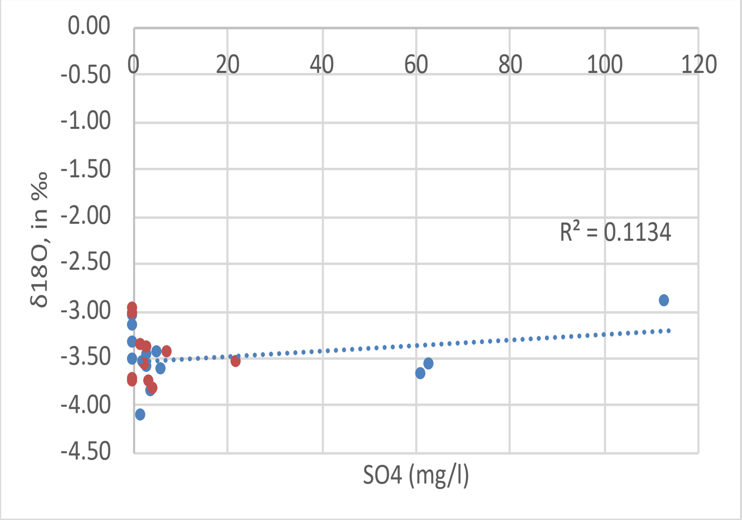
Appendix G **Stable isotope correlations**

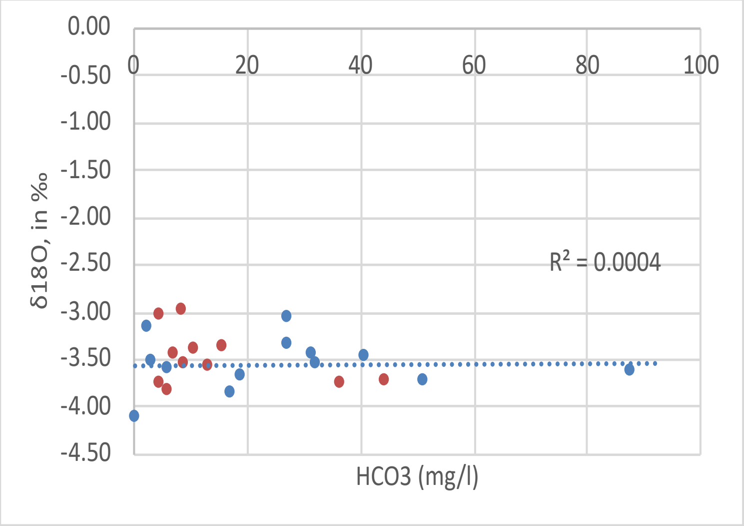
The following figures consider changes in the ^{18}O isotopic composition of groundwater samples with major cation concentrations, major anion concentrations and well physio-chemical characteristics.

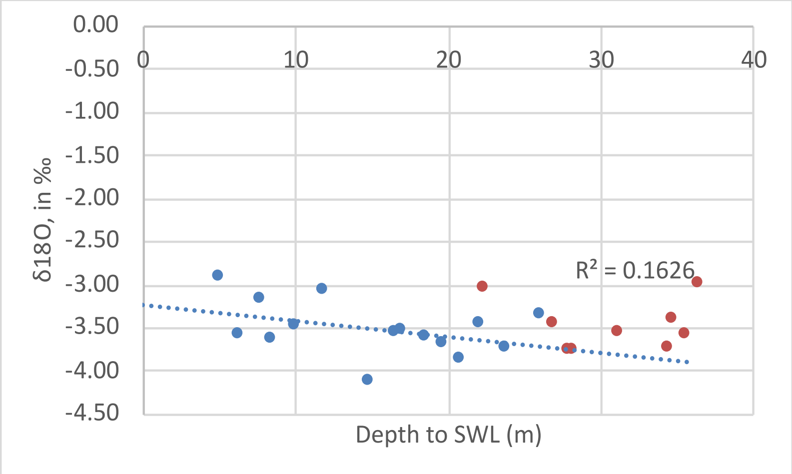


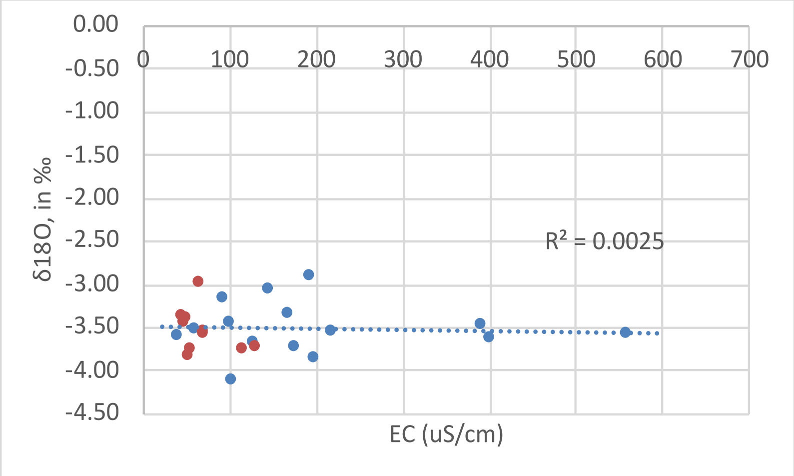


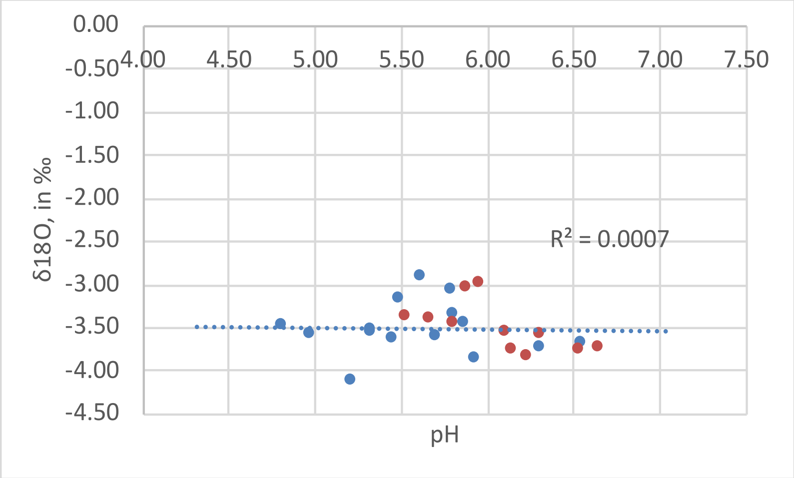

0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
δ18O, in ‰
0
20
40
60
80
100
R² = 0.0144
Cl (mg/l)


0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
δ18O, in ‰
0
20
40
60
80
100
120
R² = 0.1134
SO4 (mg/l)


0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
δ18O, in ‰
0
20
40
60
80
100
R² = 0.0004
HCO3 (mg/l)


0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
0
10
20
30
40
δ18O, in ‰
R² = 0.1626
Depth to SWL (m)


0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
0
100
200
300
400
500
600
700
δ18O, in ‰
R² = 0.0025
EC (uS/cm)


0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
4.00
4.50
5.00
5.50
6.00
6.50
7.00
7.50
δ18O, in ‰
R² = 0.0007
pH

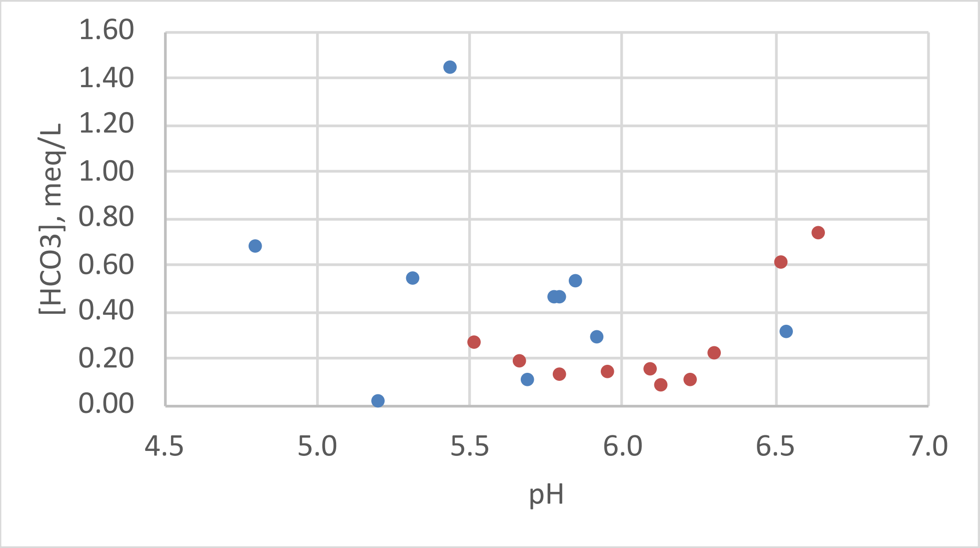
Appendix H **Water type characterization**

	Date	20101221	20101222	20101224	20101224	20110224	20101226	20101229	20110104	20110105
	SAMPLE	**F01**	**F03**	**F04**	**F05**	**F06**	**F08**	**F10**	**F12**	**F15**
Coord	**X**	**419378.92**	**419324.41**	**419401.41**	**418914.95**	**418527.61**	**417940.63**	**417189.45**	**415917.93**	**417778.98**
Coord	**Y**	**711654.64**	**712746.87**	**713077.42**	**714846.2**	**715246.18**	**715833.97**	**716575.23**	**717325.35**	**715473.03**
	EC (uS/cm)	102.94	63.76	116.43	46.75	41.45	43.09	60.52	64.14	50.64
	TEMP (°C)	31.2	30.6	31.3	30.3	30.0	30.0	29.2	29.8	29.6
	pH	6.53	6.10	6.65	5.67	5.52	5.80	5.96	6.31	6.14
	TAC (mg/L CaCO3)									
	DUR (mg/L CaCO3)									
	TSD (mg/L)									
					ADD HCO3	ADD HCO3	ADD HCO3			
	Add									
Anion		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
	HCO3-	**36.61**	**9.15**	**44.54**	**10.98**	**15.86**	**7.32**	**8.54**	**13.42**	**4.58**
	SO4=	**3.69**	**22.1**		**3.12**	**2.04**	**7.38**		**2.61**	
	Cl-	**12.2**	**10.5**	**36.6**	**8.17**	**5.19**	**7.39**	**10.3**	**8.16**	**11.2**
	NO3-		**1.98**	**3.8**		**0.31**	**0.54**	**1.57**	**0.45**	**0.66**
	sum aniones	52.5	43.73	84.94	22.27	23.4	22.63	20.41	24.64	16.44
Cation		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
	Na+	**7.47**	**5.89**	**7.52**	**5.2**	**4.61**	**4.86**	**6.56**	**6.23**	**6.01**
	K+	**0.786**	**0.513**	**1.494**	**0.363**	**0.423**	**0.428**	**0.571**	**1.677**	**0.486**
	Ca++	**6.9**	**8.34**	**14.4**	**3.69**	**3.71**	**4.23**	**6.1**	**5.96**	**5.75**
	Mg++	**1.519**	**1.34**	**2.57**	**0.748**	**0.627**	**0.707**	**0.719**	**1.246**	**0.846**
	sum cationes	16.675	16.083	25.984	10.001	9.37	10.225	13.95	15.113	13.092
		mg/L	mg/L							
	NH4+	**0**	**0**							
	Add									
	Cl-+NO3-	12.2	12.48	40.4	8.17	5.5	7.93	11.87	8.61	11.86
	Na+ + K+	8.256	6.403	9.014	5.563	5.033	5.288	7.131	7.907	6.496
anions (meq/L)		meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L
	HCO3-	0.60	0.15	0.73	0.18	0.26	0.12	0.14	0.22	0.08
	SO4=	0.08	0.46	0.00	0.07	0.04	0.15	0.00	0.05	0.00
	Cl-	0.34	0.30	1.03	0.23	0.15	0.21	0.29	0.23	0.32
	NO3-	0.00	0.03	0.06	0.00	0.01	0.01	0.03	0.01	0.01
	Cl-+NO3-	0.34	0.33	1.09	0.23	0.15	0.22	0.32	0.24	0.33
	sum aniones	1.02	0.94	1.82	0.48	0.45	0.49	0.46	0.51	0.40
cations(meq/L)		meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L
	Na+ + K+	0.34	0.27	0.37	0.24	0.21	0.22	0.30	0.31	0.27
	Na+	0.32	0.26	0.33	0.23	0.20	0.21	0.29	0.27	0.26
	K+	0.02	0.01	0.04	0.01	0.01	0.01	0.01	0.04	0.01
	Ca++	0.35	0.42	0.72	0.18	0.19	0.21	0.31	0.30	0.29
	Mg++	0.13	0.11	0.21	0.06	0.05	0.06	0.06	0.10	0.07
	NH4+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	sum cationes	0.82	0.80	1.30	0.48	0.45	0.49	0.66	0.71	0.63
anions(%)		%	%	%	%	%	%	%	%	%
	HCO3-	58.80	15.99	40.07	37.88	57.31	24.46	30.74	43.01	18.71
	SO4=	7.53	49.08	0.00	13.68	9.37	31.34	0.00	10.63	0.00
	Cl-	33.67	31.53	56.57	48.44	32.22	42.43	63.70	44.94	78.63
	NO3-	0.00	3.40	3.36	0.00	1.10	1.78	5.56	1.42	2.65
	Cl-+NO3-	33.67	34.93	59.93	48.44	33.33	44.20	69.26	46.36	81.29
	sum aniones	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
cations(%)		%	%	%	%	%	%	%	%	%
	Na+ + K+	42.30	33.78	28.14	48.86	47.09	45.16	45.14	43.90	43.37
	Na+	39.83	32.13	25.20	46.94	44.68	42.93	42.94	37.90	41.40
	K+	2.47	1.65	2.94	1.93	2.41	2.22	2.20	6.00	1.97
	Ca++	42.31	52.32	55.49	38.30	41.35	42.97	45.92	41.69	45.55
	Mg++	15.40	13.90	16.37	12.83	11.55	11.87	8.95	14.41	11.08
	NH4+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	sum cationes	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Ionic Relationship										
	rNa/rK	16.16	19.52	8.56	24.35	18.53	19.30	19.53	6.32	21.02
	rMg/rCa	0.36	0.27	0.29	0.34	0.28	0.28	0.19	0.35	0.24
	rSO4/rCl	0.22	1.56	0.00	0.28	0.29	0.74	0.00	0.24	0.00
	rCl/rHCO3	0.57	1.97	1.41	1.28	0.56	1.73	2.07	1.04	4.20
	icb	0.00	0.09	0.65	-0.02	-0.44	-0.07	-0.03	-0.37	0.13
	Kr	0.50	0.21	0.73	0.18	0.23	0.14	0.18	0.24	0.12
INDEX	SAR	0.7	0.5	0.5	0.6	0.6	0.6	0.7	0.6	0.6
	Error (%)	-11.18	-8.14	-16.82	0.68	-0.57	0.16	18.65	16.57	22.27
	Laboratory	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft

	Date	20110114	20110116	20110117	20110117	20110117	20110124	20110125	20110125	20110125	20110201	20110201	20110201	20110211	20110213
	SAMPLE	**AD01**	**AL04**	**AL05**	**DD01**	**DH01**	**DK01**	**GB01**	**PM01**	**OC03**	**OC06**	**PA01**	**SO01**	**ZI01**	**ZI05**
Coord	**X**	**418325.55**	**418979.57**	**419175.17**	**419835.4**	**416959.49**	**416757.88**	**419203.11**	**418768.55**	**418932.53**	**419030.18**	**417447.76**	**419703.91**	**417736.31**	**417690.91**
Coord	**Y**	**712402.83**	**710873.15**	**712089.4**	**720010.69**	**718544.2**	**717035.66**	**712601.44**	**717601.18**	**713540.87**	**713080.72**	**716202.94**	**713270.46**	**715102.18**	**715211.69**
	EC (uS/cm)	82.65	348.21	195.69	91.61	131.13	142.04	36.26	153.68	112.61	178.67	171.70	93.71	359.07	491.23
	TEMP (ºC)	31.20	31.00	30.70	29.80	30.90	34.70	29.60	32.00	31.70	30.80	31.00	30.60	30.70	32.00
	pH	5.49	4.81	5.32	5.86	5.79	5.80	5.70	6.31	6.55	5.93	5.61	5.21	5.45	4.97
	TAC (mg/L CaCO3)														
	DUR (mg/L CaCO3)														
	TSD (mg/L)														
		REMOVED			ADD HCO3	ADD HCO3	ADD HCO3		REMOVED			REMOVED		ADD HCO3	REMOVED
	Add														
Anion		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
	HCO3-	**2.4404**	**40.88**	**32.34**	**31.73**	**27.45**	**27.45**	**6.101**		**18.9131**	**14.6424**		**0.30505**	**87.85**	
	SO4=		**2.97**	**2.42**	**5.22**			**2.94**		**0.01**	**4.14**	**72**	**1.95**	**6.21**	**63**
	Cl-	**48.1**	**83.3**	**43.1**	**10.4**	**31.4**	**37.8**	**5.38**	**20.2**	**22.6**	**22.2**	**20.5**	**23.9**	**52.6**	**48.9**
	NO3-	**3.1**	**9.93**	**7**	**3.67**	**1.44**	**2.65**		**1.34**	**1.99**	**12.1**	**7.2**	**1.1**	**25.8**	**18.4**
	sum aniones	53.6404	137.08	84.86	51.02	60.29	67.9	14.421	21.54	43.5131	53.0824	99.7	27.25505	172.46	130.3
Cation		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
	Na+	**12.57**	**60**	**33.4**	**9.38**	**20.1**	**22.1**	**4.34**	**11.32**	**13.14**	**18.05**	**9.58**	**14.97**	**42.9**	**34.7**
	K+	**0.21**	**0.391**	**0.537**	**0.76**	**0.323**	**0.583**	**0.224**	**1.511**	**0.646**	**0.822**	**0.156**	**0.247**	**15.72**	**8.46**
	Ca++	**4.7**	**7.2**	**7.28**	**8.86**	**7.61**	**8.92**	**3.4**	**22.7**	**9.1**	**14.6**	**6.27**	**4.14**	**14.1**	**7.4**
	Mg++	**0.689**	**3.21**	**1.014**	**1.364**	**1.168**	**1.641**	**0.322**	**1.03**	**0.952**	**3.12**	**1.918**	**0.926**	**5.98**	**6.29**
	sum cationes	18.169	70.801	42.231	20.364	29.201	33.244	8.286	36.561	23.838	36.592	17.924	20.283	78.7	56.85
	NH4+														
	Add														
	Cl-+NO3-	51.2	93.23	50.1	14.07	32.84	40.45	5.38	21.54	24.59	34.3	27.7	25	78.4	67.3
	Na+ + K+	12.78	60.391	33.937	10.14	20.423	22.683	4.564	12.831	13.786	18.872	9.736	15.217	58.62	43.16
anions (meq/L)		meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L
	HCO3-	0.04	0.67	0.53	0.52	0.45	0.45	0.10	0.00	0.31	0.24	0.00	0.01	1.44	0.00
	SO4=	0.00	0.06	0.05	0.11	0.00	0.00	0.06	0.00	0.00	0.09	1.50	0.04	0.13	1.31
	Cl-	1.35	2.35	1.21	0.29	0.88	1.06	0.15	0.57	0.64	0.63	0.58	0.67	1.48	1.38
	NO3-	0.05	0.16	0.11	0.06	0.02	0.04	0.00	0.02	0.03	0.20	0.12	0.02	0.42	0.30
	Cl-+NO3-	1.40	2.51	1.33	0.35	0.91	1.11	0.15	0.59	0.67	0.82	0.69	0.69	1.90	1.67
	sum aniones	1.44	3.24	1.91	0.98	1.36	1.56	0.31	0.59	0.98	1.15	2.19	0.74	3.47	2.99
cations(meq/L)		meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L
	Na+ + K+	0.55	2.62	1.47	0.43	0.88	0.98	0.19	0.53	0.59	0.81	0.42	0.66	2.27	1.73
	Na+	0.55	2.61	1.45	0.41	0.87	0.96	0.19	0.49	0.57	0.78	0.42	0.65	1.87	1.51
	K+	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.04	0.02	0.02	0.00	0.01	0.40	0.22
	Ca++	0.24	0.36	0.36	0.44	0.38	0.45	0.17	1.14	0.46	0.73	0.31	0.21	0.71	0.37
	Mg++	0.06	0.27	0.08	0.11	0.10	0.14	0.03	0.09	0.08	0.26	0.16	0.08	0.49	0.52
	NH4+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	sum cationes	0.84	3.24	1.91	0.98	1.36	1.56	0.39	1.75	1.12	1.79	0.89	0.94	3.47	2.61
anions(%)		%	%	%	%	%	%	%	%	%	%	%	%	%	%
	HCO3-	2.77	20.69	27.79	53.02	33.14	28.89	31.97	0.00	31.67	20.93	0.00	0.68	41.53	0.00
	SO4=	0.00	1.91	2.64	11.08	0.00	0.00	19.58	0.00	0.02	7.52	68.38	5.52	3.73	43.94
	Cl-	93.77	72.45	63.65	29.86	65.15	68.36	48.45	96.34	65.03	54.53	26.33	91.40	42.73	46.12
	NO3-	3.46	4.95	5.92	6.03	1.71	2.74	0.00	3.66	3.28	17.02	5.29	2.41	12.00	9.94
	Cl-+NO3-	97.23	77.40	69.56	35.89	66.86	71.11	48.45	100.00	68.31	71.55	31.62	93.81	54.73	56.06
	sum aniones	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
cations(%)		%	%	%	%	%	%	%	%	%	%	%	%	%	%
	Na+ + K+	65.40	80.72	76.60	43.47	64.90	62.65	49.72	30.32	52.41	44.93	47.11	69.86	65.41	65.97
	Na+	64.77	80.42	75.88	41.49	64.30	61.70	48.26	28.11	50.94	43.75	46.67	69.19	53.81	57.70
	K+	0.64	0.31	0.72	1.98	0.61	0.96	1.47	2.21	1.47	1.17	0.45	0.67	11.60	8.27
	Ca++	27.85	11.10	19.02	45.07	27.99	28.64	43.47	64.82	40.57	40.70	35.13	22.00	20.34	14.15
	Mg++	6.75	8.18	4.38	11.47	7.10	8.71	6.81	4.86	7.02	14.38	17.76	8.14	14.26	19.88
	NH4+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	sum cationes	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Ionic Relationship															
	rNa/rK	101.76	260.87	105.74	20.98	105.79	64.44	32.94	12.74	34.58	37.33	104.40	103.03	4.64	6.97
	rMg/rCa	0.24	0.74	0.23	0.25	0.25	0.30	0.16	0.07	0.17	0.35	0.51	0.37	0.70	1.40
	rSO4/rCl	0.00	0.03	0.04	0.37	0.00	0.00	0.40	0.00	0.00	0.14	2.60	0.06	0.09	0.95
	rCl/rHCO3	33.87	3.50	2.29	0.56	1.97	2.37	1.52	🟥	2.05	2.61	🟥	134.63	1.03	🟥
	icb	0.59	-0.12	-0.21	-0.46	0.00	0.08	-0.28	0.07	0.08	-0.29	0.27	0.02	-0.53	-0.25
	Kr	0.07	0.54	0.47	0.49	0.43	0.45	0.12	0.00	0.35	0.35	0.00	0.02	1.14	0.00
INDEX	SAR	1.4	4.7	3.1	0.8	1.8	1.8	0.6	0.6	1.1	1.1	0.9	1.7	2.4	2.3
	Error (%)	-26.26	0.08	0.16	0.10	0.05	0.00	11.11	49.55	6.79	22.00	-42.16	12.17	-0.01	-6.64
	Laboratory	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft	IHE Delft

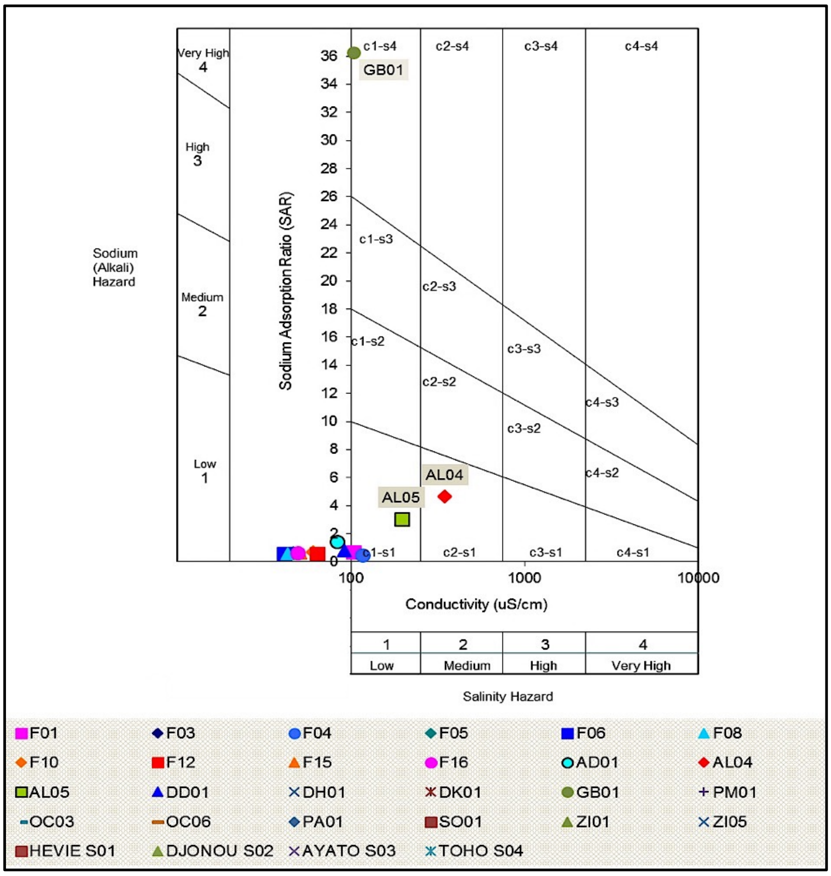
	Date	20110216	20110218	20110218	20110222
	SAMPLE	**HEVIE S01**	**DJONOU S02**	**AYATO S03**	**TOHO S04**
Coord	**X**	**419317.05**	**427325.68**	**414247.38**	**412464.9**
Coord	**Y**	**707112.77**	**707116.67**	**711180.95**	**706450.07**
	EC (uS/cm)	92.65	128.43	77.93	112.78
	TEMP (°C)	30.10	29.70	33.90	33.70
	pH	5.80	6.11	6.64	7.76
	TAC (mg/L CaCO3)				
	DUR (mg/L CaCO3)				
	TSD (mg/L)				
	Add				
Anion		mg/L	mg/L	mg/L	mg/L
	HCO3-	**26.0309333**	**32.9454**	**15.4558667**	**20.7434**
	SO4=	**0**	**0**	**0**	**0**
	Cl-	**18.8**	**31.9**	**25.1**	**28**
	NO3-	**0**	**0**	**0**	**0**
	sum aniones	44.83093333	64.8454	40.55586667	48.7434
Cation		mg/L	mg/L	mg/L	mg/L
	Na+	**12.53**	**16.4**	**10.12**	**18.1**
	K+	**1.285**	**2.17**	**1.06**	**1.89**
	Ca++	**6.77**	**8.7**	**5.86**	**3.25**
	Mg++	**1.969**	**2.48**	**1.776**	**2.37**
	sum cationes	22.554	29.75	18.816	25.61
	NH4+				
	Add				
	Cl-+NO3-	18.8	31.9	25.1	28
	Na+ + K+	13.815	18.57	11.18	19.99
anions (meq/L)		meq/L	meq/L	meq/L	meq/L
	HCO3-	0.43	0.54	0.25	0.34
	SO4=	0.00	0.00	0.00	0.00
	Cl-	0.53	0.90	0.71	0.79
	NO3-	0.00	0.00	0.00	0.00
	Cl-+NO3-	0.53	0.90	0.71	0.79
	sum aniones	0.96	1.44	0.96	1.13
cations(meq/L)		meq/L	meq/L	meq/L	meq/L
	Na+ + K+	0.58	0.77	0.47	0.84
	Na+	0.54	0.71	0.44	0.79
	K+	0.03	0.06	0.03	0.05
	Ca++	0.34	0.44	0.29	0.16
	Mg++	0.16	0.20	0.15	0.20
	NH4+	0.00	0.00	0.00	0.00
	sum cationes	1.08	1.41	0.91	1.19
anions(%)		%	%	%	%
	HCO3-	44.62	37.54	26.38	30.13
	SO4=	0.00	0.00	0.00	0.00
	Cl-	55.38	62.46	73.62	69.87
	NO3-	0.00	0.00	0.00	0.00
	Cl-+NO3-	55.38	62.46	73.62	69.87
	sum aniones	100.00	100.00	100.00	100.00
cations(%)		%	%	%	%
	Na+ + K+	53.54	54.56	51.51	69.98
	Na+	50.50	50.62	48.52	65.93
	K+	3.05	3.94	2.99	4.05
	Ca++	31.38	30.88	32.31	13.61
	Mg++	15.08	14.55	16.18	16.41
	NH4+	0.00	0.00	0.00	0.00
	sum cationes	100.00	100.00	100.00	100.00
Ionic Relationship					
	rNa/rK	16.58	12.85	16.23	16.28
	rMg/rCa	0.48	0.47	0.50	1.21
	rSO4/rCl	0.00	0.00	0.00	0.00
	rCl/rHCO3	1.24	1.66	2.79	2.32
	icb	-0.09	0.14	0.34	-0.06
	Kr	0.40	0.50	0.27	0.27
INDEX	SAR	1.1	1.3	0.9	1.9
	Error (%)	6.02	-1.06	-2.87	2.79
	Laboratory	IHE Delft	IHE Delft	IHE Delft	IHE Delft

The relationship between alkalinity and pH in groundwater samples



Appendix I **Water quality and sodium hazard**

With respect to the water quality of groundwater for other purposes, salinity diagrams use the concentrations of ions in the water sample to assess risk in using abstracted groundwater for irrigation in the study area. When sodium concentrations are high in irrigation waters, the Na^+ ions adsorb onto clay matrices, displacing Ca^{2+} and Mg^{2+} in the soil. This leads to long-term degradation of the soils. The figure below presents the salinity diagram for classifying hazard:



Salinity diagram for sampled waters in the study area

The salinity diagram classifies all the groundwater samples from boreholes as having low sodium (alkali) hazard and low salinity hazard. This classification is due to the low EC of borehole samples and low concentration of sodium ions and, therefore, low sodium adsorption ratios (SAR) of less than 10.

For the hand-dug wells, the majority of samples sodium adsorption ratios that far exceed 'Very High' sodium hazard classification limit. The SAR ratios of these samples range from 36 at GB01 to a maximum of 360 at ZI01. Surface water samples also fall within the very high sodium hazard limit (SAR in the range 78 to 130). These ratios are high because of the predominance of Na-Cl water type and, therefore high Na^+ concentrations, in shallow groundwater and surface water of the study area.