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 the driving forces of 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 can be decreasing due to the multiplication of hand-dug wells throughout the area. Increased anthropogenic activities with population growth can 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 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 multiplication of hand-dug wells in recent years 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.

Keywords: urbanization; climate variability; hydrochemistry; hand-dug wells

1. Introduction

Increased population growth in West African countries in the last few decades is straining limited freshwater reserves and compromising 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 and increased anthropogenic pollution from rapidly urbanizing coastal cities in addition to 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).

In southern Benin, the transboundary Coastal Sedimentary Basin underlies only 10% of Benin territory but contains approximately 35% of the country's total groundwater reserves and is used to supply the almost 7 million inhabitants of the region (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 by the national water company SONEB 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.

1.1. Research hypotheses

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

<u>Hypothesis A. Decrease in groundwater recharge</u>

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.

<u>Hypothesis B. Increase in abstraction by Ouédo residents</u>

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 increased abstraction activities from the shallow reservoirs.

<u>Hypothesis C. Abstraction in the new wellfield</u>

The aquitard separating the shallow aquifer from the deeper aquifer 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 two aquifers. 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.

1.2. Objectives

The main objective of this study is to evaluate the three hypotheses and determine which could be responsible for decreasing shallow groundwater levels and which could be eliminated from consideration. The absence of groundwater monitoring in the shallow aquifer poses a challenge to execute the hypothesis 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 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 supporting the hypothesis of downward fluxes decreasing groundwater storage in the shallow aquifer.

2. Study Area

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).

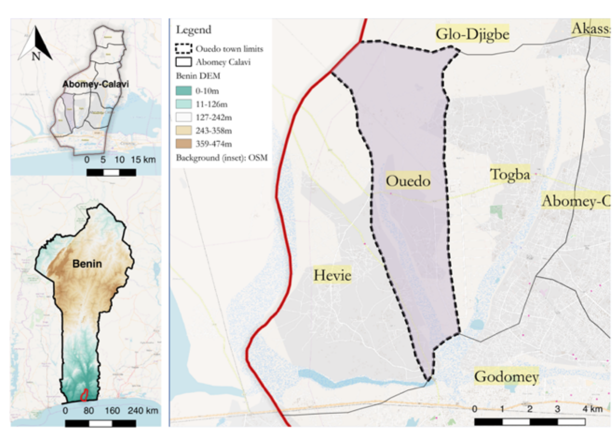

Figure 1 Ouédo study area in Abomey-Calavi, southern Benin

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 Ouédo. 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.

3. Methodology

3.1. Recent climate variability

Annual precipitation, temperature and actual evapotranspiration and interception regional data were collected, where the nearby Cotonou airport meteorological station was assumed to be representative of the study area. The Cotonou precipitation data from 1991 – 2017 were sourced from the Benin meteorological office (METEO Benin 2018) and incomplete data was replaced using NOAA estimated satellite data (NOAA 2018). The temperature data from 1991 – 2017 were sourced completely from NOAA satellite data (NOAA 2018). Actual evapotranspiration and interception (ETIa) data for Cotonou and Ouédo were sourced from WaPOR remotely-sensed 100-m resolution datasets and cover a more restricted period of 2009 – 2017 (FAO 2018).

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

The land-use and land-cover (LULC) raster datasets 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 4 km^2. Further details on the classification and photo-interpretation 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.

3.3. Stable isotopic and hydrogeochemical signatures

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 2.

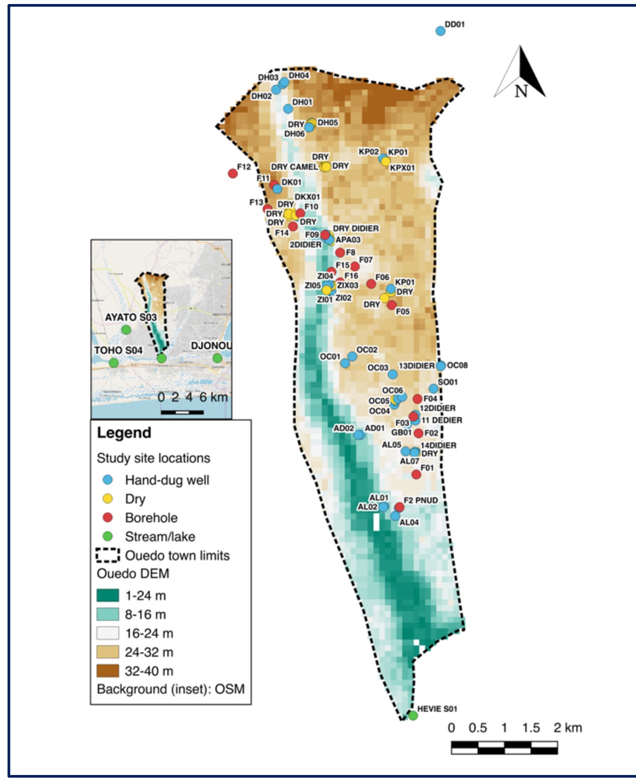

Figure 2 Locations of investigated hand-dug wells, boreholes and surface water points

The precipitation sampling points for the study area were at OC08 and the base station in Cotonou. 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 were for later lab analysis 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 samples were analysed at IHE laboratory instruments: cations analysis using Inductively Coupled Plasma Mass Spectrometry (ICP-MS); anions analysis using Ion Chromatography System (ICS); TOC/TN using catalytic thermal decomposition/

chemiluminescence methods on a combined TOC-L and TNM-L Analyzer; and stable isotopes on DLT-100 Liquid-Water Isotope Analyzer.

4. Results

4.1. Recent climate variability

Figure 3 presents the inter-annual variability in precipitation and temperature in Cotonou from 1991-2017 and actual evapotranspiration and interception in Cotonou and Ouédo between 2009 – 2017.

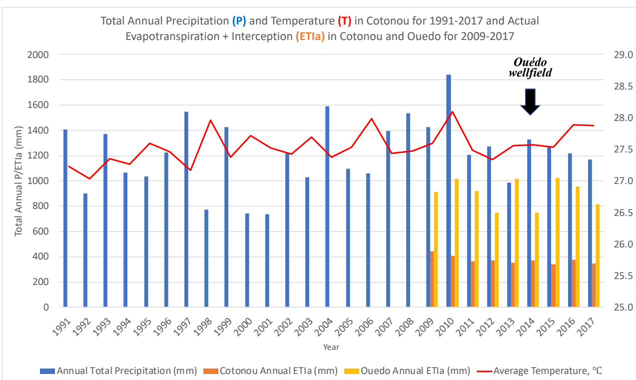

Figure 3 Recent annual precipitation, temperature, and actual evapotranspiration and interception in study area. Dataset sources: FAO 2018; METEO Benin 2018; NOAA 2018

The precipitation data showed a general equilibrium in rainfall fluctuations around a long-term average. The drought years (2000-2001) corresponded to the longest-sustained low rainfall trend of the period while the wet period (2006-2012) corresponded 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 end of the record.

Over the 16-year period, the temperature showed an increasing trend of +0.016 °C/year. This was 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 is +0.008 °C/year. 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.

Overall, annual ETIa in the study area fluctuated around an equilibrium during the 2009-2017 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.

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

Land use and land cover

The LULC maps in Figure 4 show the evolution of the landscape in the study area and surrounding commune for three years: 1975, 2000 and 2013. Although the dominant land cover in Ouédo remained cropland and fallow with oil palms, settlement encroachment had already extended into town by 2013. For the commune of Abomey-Calavi, settlement areas covered only 12% of the total area in 1975 and 16% in 2000. However, by 2013 the settlement areas had doubled and represented 32% of total area in the commune.

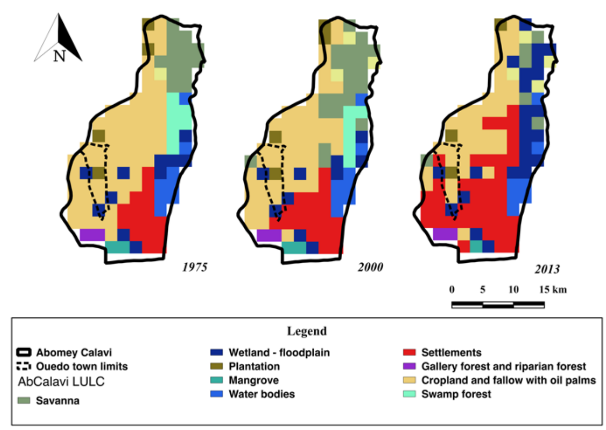

Figure 4 Land-use and land-cover evolution in Ouédo and Abomey-Calavi from 1975-2013. Datasets source: (Tappan et al. 2016)

The increased settlement encroachment trend in Ouédo and the greater Abomey-Calavi commune implies increased 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 residents revealed that new wells are dug on site 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.

Population growth

In the 11 years between the last two national demographic surveys, the population of Ouédo grew by 173% (Table 1) (INSAE 2004, 2016).

Table 1 Population demographics for Ouédo from the most recent national censuses (INSAE 2004, 2016)

	2002	2013
Population	10,067	27,522
Population density (hab/km^2)	360	983
No. of households	2,011	5,849
% of households as agricultural	62	15

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 other economic activities.

The population data and average peri-urban consumption in Benin of 29 liters/capita/day (M'barek et al. 2005) were considered for calculating the average annual water use in Ouédo (Figure 5).

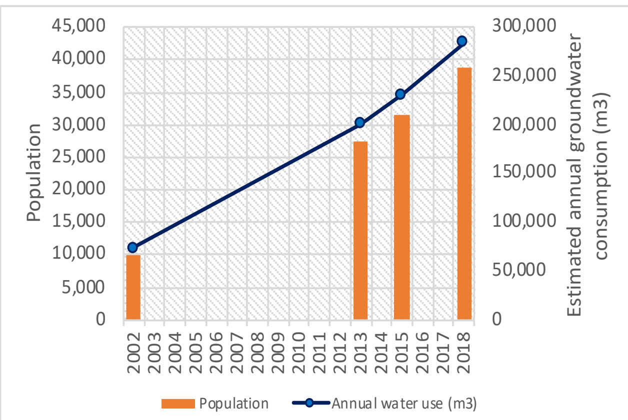

Figure 5 Population growth and estimated daily water consumption in Ouédo. Datasets sources: (INSAE 2004, 2016; M'barek et al. 2005; CIA 2018; IndexMundi 2018)

The results showed an estimated 23% increase in groundwater consumption since 2015 and an increase of 41% over the last five years.

Besides, the field survey provided further insight on groundwater abstraction in Ouédo. The survey revealed that 27% of the hand-dug wells surveyed in the study area were constructed after 2014 i.e. after the Ouédo wellfield was already in operation. With an increase of 27% 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). These results were from a sample group of 26 responses (n=26).

In terms of groundwater use, the majority of residents identified cooking, washing and drinking as primary uses. 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.

Residents also supplied information on the estimated abstraction from hand-dug wells in the study area (Figure 6). 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. 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).

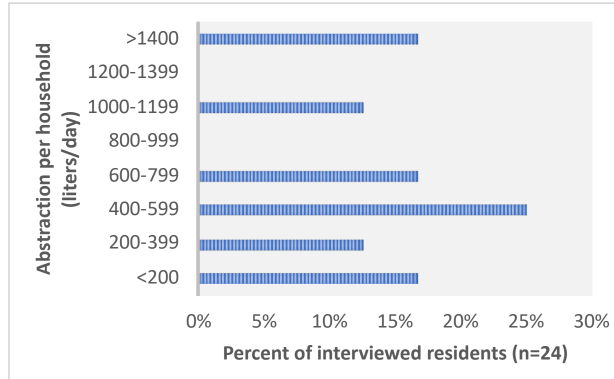

Figure 6 Household survey results for daily groundwater abstraction per household

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. The responses (n= 26) 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 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. 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.

4.3. Stable isotopic and hydrogeochemical signatures of groundwater

Stable isotopic composition

For the groundwater and precipitation samples collected within the Ouédo study area, the average isotopic compositions were as follows:

- Hand-dug wells: δ^2H = -14.81 ‰, $\delta^{18}O$ = -3.51 ‰
- Boreholes: δ^2H = -16.00 ‰, $\delta^{18}O$ = -3.50 ‰
- Precipitation: δ^2H = -15.40 ‰, $\delta^{18}O$ = -3.17 ‰

Figure 7**Error! Reference source not found.** considers the signatures of the shallow Quaternary aquifer, deeper CT aquifer and precipitation. The Global Meteoric Water Line (GMWL) was included for comparing the samples to the global average relationship between ^2H and ^{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 allowed for comparison with the regional averages for southern Benin.

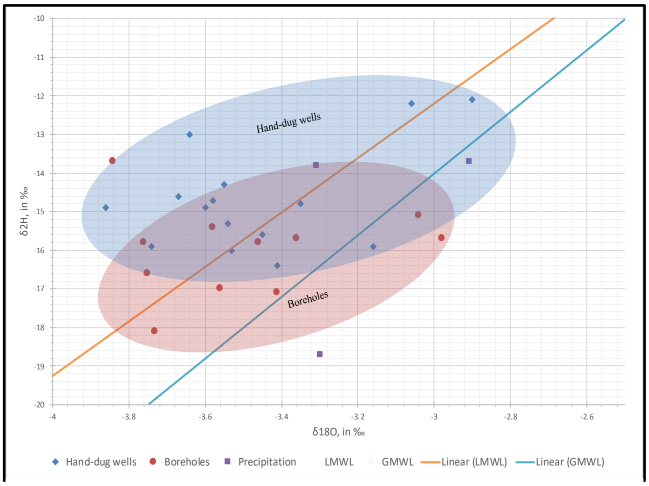

Figure 7 δ^2H - $\delta^{18}O$ relationship in groundwaters and precipitation sampled in study area

Groundwater from boreholes and hand-dug wells showed 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 were observed for groundwater in the study area since all the groundwater samples generally plotted above the LMWL. The isotopic signatures of the Ouédo groundwater and precipitation samples were comparable with regional signatures and fell 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 signatures of both groups of groundwater samples (collected from late-April to early-May) were compared to seasonal fluctuations in southern Benin (Figure 8). Seasonal fluctuations of precipitation isotopic composition were determined by processing the GNIP Cotonou database for average monthly $\delta^{18}O$ composition.

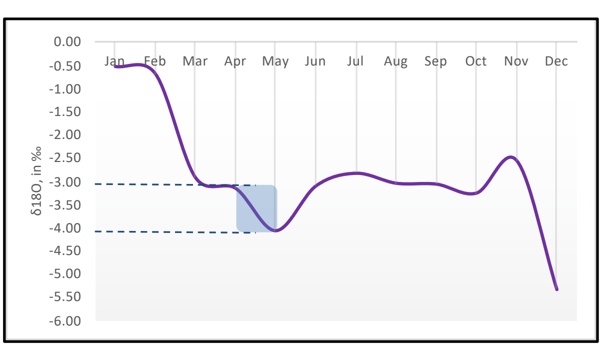

Figure 8 Seasonal variations in $\delta^{18}O$ composition in precipitation samples in southern Benin. Dataset source: IAEA/WMO 2018

By considering the average isotopic composition of the shallow Quaternary aquifer ($\delta^{18}O$ = -3.51 ‰) and the CT aquifer ($\delta^{18}O$ = -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 at least the shallow aquifer occurs within the more recent April to May period. 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.

Hydrogeochemical characterization

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 2*:

Table 2 Summary statistics of physico-chemical parameters of water samples in the study area

	Hand-dug wells	Boreholes	Surface water
Depth to static water line (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 (°C)	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 relative impact of the negative ions on measured EC in the groundwater is considered in Figure 9.

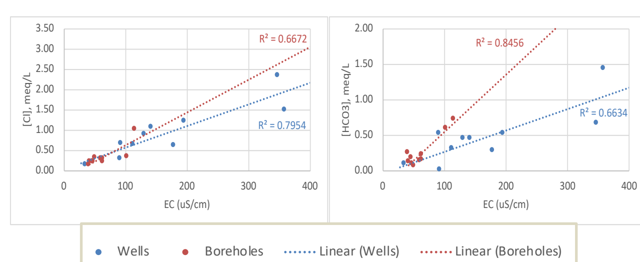

Figure 9 Correlation of major anions to EC in groundwater samples of Ouédo study area

The graphs indicated 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.

The Piper diagram (Figure 10) is used to categorize the dominance of cations and anions in the water samples and to determine the hydrochemical water type.

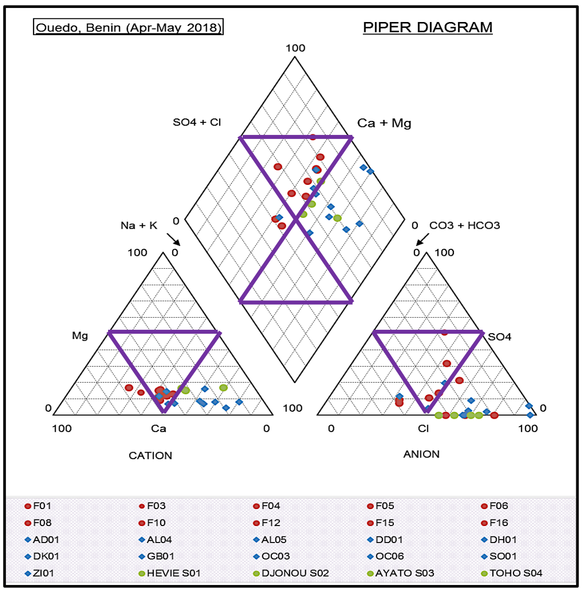

Figure 10 Piper diagram classification of water types for samples from boreholes (red), hand-dug wells (blue) and surface water (green) in study area

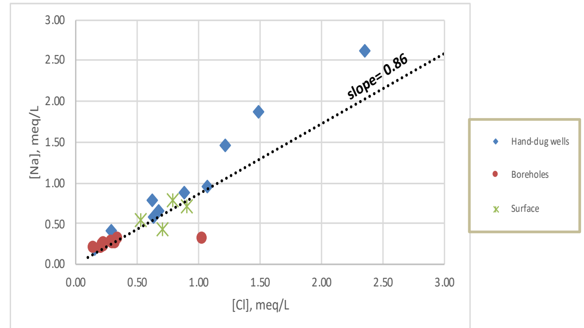

Figure 11 Correlation of Na^+ and Cl^- concentrations in sampled waters and the sea-water mixing line (Na:Cl=0.86)

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 determined from the stable isotopic composition of hand-dug well groundwater samples.

The groundwater sampled from the boreholes generally showed 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). 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 was considered within the context of sea-water mixing in Figure 11.

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 the unconsolidated sand and clay sediments 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. 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.

5. Discussion

5.1. Recent climate variability

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 total 16-year period does not show a consistent trend in decreasing rainfall for the study area. The longer datasets studied by other authors (Totin 2010; Barry et al. 2018) provided a consensus of long-term decreasing rainfall for southern Benin. However, the short-term analysis of more recent climate data provides 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. 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

The high population growth and urban encroachment in Ouédo contributed to an 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. While the majority of residents consider SONEB abstraction activities in the CT aquifer to be the main driver of declining groundwater levels in hand-dug wells, the abstraction trend of residents shows that heavy abstraction is occurring in the shallow aquifer with withdrawals from these hand-dug wells.

Moreover, there is a need to revisit existing legislature on groundwater abstraction since regulation of 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

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 s 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 suggest that the shallow Quaternary aquifer is recharged predominantly by recent precipitation. Further analysis using established dating 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.

The shallow Quaternary groundwater had 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 demonstrated lower mineralization than shallow groundwater in the study area. The low degree of mineralization in the CT aquifer was 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) was dominated by Na-Cl type waters. This confirmed direct recharge through precipitation of coastal rainwater, as first indicated in the stable isotopic composition analysis. The groundwater sampled from boreholes show a mixed water type with no dominance of cations and anions. The correlation of Na^+ and Cl^- ions showed that the majority of groundwater and surface water reservoirs in the study area received varying contributions of recharge from coastal rain water. Some silicate weathering occurred in the unconsolidated sediments of the shallow Quaternary aquifer. Borehole F10 had a predominance of Cl^- ions, albeit at concentrations much lower than typical of the shallow aquifer. Borehole F04 had high Cl^- concentrations that were more comparable with the hand-dug well samples and had indications of cation exchange processes that removed Na^+ ions from solution. This can support a hypothesis of mixing within the deeper aquifer.

While overall the hydrogeochemical characterization of groundwater from the hand-dug wells and boreholes did not provide clear evidence supporting Hypothesis C (diversion of shallow groundwater to the deeper CT aquifer), there were preliminary indications of mixing. Further monitoring is recommended at the boreholes in the study area to confirm hydrogeochemical signatures and monitor water chemistry for changes indicative of inter-aquifer mixing.

5.4. Assessment of hypotheses

Climate variability did not show a strong signature in recent years and seemed unlikely as the main cause of decreasing shallow groundwater levels in the study 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 could have altered recharge pathways to the shallow Quaternary aquifer and diverted more input precipitation to overland runoff where it would 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 – an increase in abstraction by 37% in one sample group. The results indicated that there is a potential decrease in groundwater recharge due to increased settlement area in the study area and surrounding commune, partially supporting hypothesis A.

Results further indicated 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 the 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. Nevertheless, the analysis of results revealed some mixing of shallow groundwater in the deeper CT aquifer at borehole F04. 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 were largely inconclusive and gave no clear evidence supporting Hypothesis C.

6. Conclusion

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 confirmed 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 was 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 hydrogeochemical techniques are recommended for defining the groundwater flow pattern in the system, including the use of dating tracers such as tritium isotopes.

Further studies in the area 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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