Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate

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Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate

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Abstract

Although shallow groundwater (<50 mbgl) sustains the vast majority of improved drinking water supplies in rural Africa, there is little information on how resilient this resource may be to future changes in climate. This study presents results of a groundwater survey using stable isotopes, CFCs, SF_6, and ^3H across different climatic zones (annual rainfall 400-2000 mm/y) in West Africa. The purpose was to quantify the residence times of shallow groundwaters in sedimentary and basement aquifers, and investigate the relationship between groundwater resources and climate. Stable-isotope results indicate that most shallow groundwaters sampled are recharged rapidly following rainfall, showing little evidence of evaporation prior to recharge. Chloride mass balance results indicate that within the arid areas (<400 mm annual rainfall) there is recharge of up to 20 mm/y. Age tracers showed that most groundwaters have mean residence times (MRTs) of 32–65 years, with comparable

MRTs in the different climate zones. Similar MRTs measured in both the sedimentary and basement aquifers suggest similar hydraulic diffusivity and significant groundwater storage within the shallow basement. This suggests there is considerable resilience to short term inter-annual variation in rainfall and recharge, and rural groundwater resources are likely to sustain diffuse, low volume abstraction.

1. Introduction

In Africa's rural communities approximately 500 million people rely on water resources found in close proximity to their communities for their drinking water (Bonsor et al. 2011). The use of hand-pumped boreholes (<50 m deep) accessing shallow groundwater is the main way people get access to improved safe drinking water (Foster et al. 2000; JMP 2008; MacDonald and Calow 2009). With growing evidence that improved access to water has major health and economic benefits (Grey and Sadoff 2007; Carter and Bevan 2008; Hunter et al. 2010) there is increasing emphasis on developing groundwater and extending access to the estimated 300 million who are reliant on unimproved and unreliable water sources (JMP 2008; MacDonald and Calow 2009; Bonsor et al. 2011). Recent quantitative groundwater mapping has indicated the existence of significant groundwater storage across much of Africa and hydrogeological conditions that enable boreholes to be successfully drilled and equipped with hand pumps (MacDonald et al 2012) However, there is currently little information on the future availability of shallow groundwater under conditions of increased inter-annual climate variability and rapidly growing populations (Vörösmarty et al. 2000; MacDonald et al. 2009; Bonsor et al. 2011). Although highly uncertain, simulated changes in diffuse groundwater recharge suggest that average recharge in the central Sahel region may increase by the 2050s while in the western coastal areas of West Africa and southern Africa, and coastal areas of North Africa it may decrease significantly (Döll and Flörke 2005). Africa has high rainfall variability, with highest variability occurring in the wettest months (McMahon et al. 2007, Taylor et al., 2009). Compared to river discharge, there are few quantitative studies investigating the relationship between climate and shallow groundwater resources in Africa, and the relationship remains poorly defined (Taylor et al. 2009; MacDonald et al. 2009).

Ideally, a thorough quantitative understanding of aquifer properties and recharge mechanisms under a variety of climate, land use and geological environments is required to confidently assess current groundwater availability, and forecast future availability under different scenarios. However, such data do not exist for most of Africa (Adelana and MacDonald 2008; Taylor et al. 2009; Baisch 2010) so a different approach is required to investigate the natural resilience of shallow groundwater to changes in climate.

Shallow aquifers containing young waters, a decade or two old, are most susceptible to inter-annual climate variability. Aquifers containing older water with ages in excess of a hundred years are unlikely to be receiving significant modern recharge and although not directly susceptible to climate variability, will be susceptible to groundwater depletion ('mining'). Aquifers with groundwater ages between these two types are likely to be most resilient to high inter-annual rainfall variability.

Measuring groundwater residence times is an effective way of obtaining information about recharge and storage within a hydrogeological system (Cook and Böhlke 2000).Over recent decades environmental tracers have proved to be important tools with a large variety of uses including the quantification of groundwater residence times and mode of recharge (Cook and Herczeg 1999). While these environmental tracer methods have been widely used, and have become important tools for groundwater investigations in parts of Europe, North America and Australia (e.g.Oster et al. 1996; Busenburg and Plummer 1999; Cook et al. 2005; Gooddy et al. 2006) to date there are very few examples of their use within an African context (e.g. Rueedi et al. 2005; Stadler et al. 2010).

The purpose of this work is to help develop the understanding of the hydrogeological processes and assess the resilience of these important resources to short term inter-annual variabililty in the contrasting climates we find in West Africa today. This study represents a first step towards quantifying the mean residence times (MRT) of groundwater pumped from unstressed shallow rural groundwater water supplies in West Africa, by comparing residence times across regions with contrasting rainfall, while controlling for other important factors such as geology, unsaturated zone thickness, rates of abstraction, borehole construction and surface water interaction. In each study area samples were taken from rural water supply boreholes from unstressed aquifers (i.e. diffuse low volume abstraction relative to recharge) in both hard-rock and sedimentary terrains. As part of this study the following environmental tracers were used: stable isotopes, chlorofluorocarbons (CFC-11, CFC-12), sulphur hexafluoride (SF_6) and tritium (^3H).

2. Study areas

The four study areas (Fig.1) were chosen on the basis of annual average rainfall, with distinct climates for each study area, as well as the need to have suitable high-and low-yielding (i.e. sedimentary and basement) aquifers within close proximity. The names given to the four study areas refer to large settlements in each area. Table 1 details the climate zone, rainfall, population and land use characteristics of the four study areas. These data were collected using well established survey methods (Coulter and Calow 2011) within each of the communities where the sampling was carried out.

2.1. Climate

The climate within this area of West Africa is controlled by the migration of the Inter-Tropical Convergence Zone (ITCZ) and the Inter-Tropical Front (ITF) which separates the maritime monsoonal air of the Gulf of Guinea from that of the Sahara in northern Africa (Frappart et al. 2009, Lélé and Lamb 2010). The Sahelian rainfall is thought to be almost exclusively dependent on the location and structure of the ITF and is characterized by a unimodal regime that is controlled by the West African Monsoon (WAM, Nicholson 1981). Since the 1960s the Sahel has experienced a multi-decadal drought, with especially dry years in the early 1970s and 1980s (Taylor et al. 2002). Over this period there has been a shortening of the rainy season, and an overall increase in the intensity of rainfall events. However, future scenarios regarding changes in precipitation in West Africa for 2050 and beyond are highly uncertain (Parry et al. 2007).

2.2. Geology and hydrogeology

2.2.1. Basement rocks

The basement aquifers targeted in the three Nigerian study areas lie within the Benin-Nigeria Shield (e.g. Grant 1968; Ajibade and Wright 1989). The basement is a patchwork of Neoproterozoic and older Precambrian rocks comprised of migmatitic gneisses with infolds of low- to medium-grade schist belts dominated by clastic metasediments, variably deformed Neoproterozoic granitic intrusions (Pan-African Older Granites), and smaller and less common meta-basic and meta-ultrabasic intrusions.

Aquifers in these basement rocks have typical yields off 0.1–1 L/s, with some evidence that the metasediments have slightly higher yields (Hazell et al. 1992; Houston 1992). Groundwater is found mainly within the weathered zone at depths shallower than 40 m below surface (Wright 1992). The basement is most permeable at the base of the weathered zone where the rock is fractured but still coherent; the more weathered material above this has lower permeability, but greater storage (Chilton and Foster 1995). In this study boreholes were sampled within the schist belts and migmatitic gneisses; sites in or close to the Older Granite intrusions were avoided due to potential sources of SF_6 from naturally occurring mineralization (Harnisch et al. 2000).

In the Bandigara study area, Mali, the basement rocks formed part of the lower Cambrian Bandigara Formation and comprise schist and well cemented fractured sandstones and quartzites. Storage at depth is considered low and largely limited to fractures due to reduced inter-granular storage as a result of siliceous cementation and consolidation (van der Sommen and Greinnaert 1988). The upper most part of the aquifer is likely to be more weathered and less well cemented/consolidated with perhaps relatively higher storage and permeability than the weathered basement aquifers of Nigeria. Average yields are in the range 1 – 5 L/s (UNTCD 1988; MacDonald et al. 2012).

2.2.2. Sedimentary rocks

The sedimentary rocks in each case are from Mesozoic and younger sediments. They are typically several tens to hundreds of metres thick. The sedimentary rocks of the Abeokuta study area (Fig.1) were sampled from the Abeokuta Formation. Boreholes within the basin can support higher yields (>20 L/s) and storage is also high (MacDonald et al. 2012). The Upper Cretaceous sedimentary cover

(Nupe Group) within the Bida basin forms the sedimentary aquifer for the Minna study area. Highly variable yields of 1–5 L/s have been reported within this formation (Okafor 1991). The sedimentary aquifer in the Gusau area is the Upper Cretaceous cover of the Gundumi Formation is located in the Sokoto basin and comprising grits, clays and pebble beds (Adelana et al. 2008). This aquifer can support high yielding boreholes (10–30 L/s) and has a high porosity.

In Mali, the sedimentary aquifer is the Continental Terminal Formation (CT) of Eocene age. The shallow CT aquifer comprises mostly unconfined unconsolidated sediments, sealed at depth by clay. Boreholes typically can support a yield of 5–10 $L\cdot s^{-1}$, and storage can be high due to the high porosity (MacDonald et al. 2012). The area sampled in this case study is a closed drainage basin and uncoupled from the seasonal flooding of the nearby Niger basin, but may still be locally coupled to springs emerging from the Bandigara plateau, as well as ephemeral rivers and ponds. Parts of the CT basin have experienced a significant rise in the groundwater table in recent years, equivalent to an increase in groundwater reserves of 10% between 1960s-1990s,which has been linked to decadal scale changes in land use and recharge conditions due to irrigation (Leduc et al. 2001; Favreau et al. 2002).

3. Methodology

3.1. Environmental Tracers

Environmental tracers are the properties acquired by groundwater that enable conclusions to be drawn about the water's origin, residence time and hydrogeochemical evolution. In addition to stable isotopes, which are common in most hydrogeological investigations, two specialised tracer techniques have been used in this study: tritium and trace gases.

3.1.1. Stable Isotopes

Stable O and H isotopes are tracers of physical processes that water molecules undergo between evaporation from the ocean and arrival in the aquifer via recharge of rainfall Clark and Fritz 1997).

They are typically used in semi-arid hydrogeological studies to indicate the degree to which waters may have been modified prior to recharge (e.g. Favreau et al. 2002) or the existence of pre-Holocene waters (Ó Dochartaigh et al. 2010). They have been successfully used within the arid and semi-arid environments of West Africa to assess the modes of both modern and palaeo groundwater recharge (Acheampong and Hess 2000; Edmunds et al. 2004; Goni 2006; Diop and Tijani 2008).

3.1.2. Tritium

The use of tritium in hydrogeological investigations relies on the large input of tritium (^3H, half-life 12.3 yr) to the atmosphere during the thermonuclear testing of the mid-1960s. Almost four half-lives have elapsed since then, resulting in present-day rainfall values near the pre-testing baseline. Nevertheless, ^3H still has a role to play in groundwater studies by supplimenting evidence from other age indicators (Knowles et al. 2010).The rainfall ^3H record for West Africa is not particularly well-constrained, but data from the global network of isotopes in precipitation (GNIP 2011) has been combined with measurements by Leduc et al. (1996) and Onuga and Aboh (2009) to arrive at the curve shown in Fig. S1 in the electronic supplementary material (ESM).

3.1.3. Trace gas age indicators

The use of CFCs and SF_6 as groundwater age tracers relies on the rise in their atmospheric concentrations over the last 50 years together with certain assumptions about atmospheric mixing and recharge solubility (Plummer and Busenberg 1999). These gases are known to be well-mixed in the atmosphere so the curves are considered to be applicable to the study area. The use of several trace gases is recommended as under certain conditions individual tracers may have limitations (Darling et al. 2012). In particular, the CFCs may be affected by pollution, and/or degradation under anaerobic conditions (Plummer and Busenberg 1999), and there are also issues with the use of SF_6 due to terrigenic production (Koh et al. 2007).

Interpreting trace gas indicators relies on consideration of mean recharge temperature, altitude and incorporation of excess air. An average annual air temperature of 28°C was used for this study to represent recharge temperatures. Fig. S2 in the ESM shows the translation of the atmospheric curves into groundwater concentrations at this temperature. Altitude does not exceed 500 m in any of the areas so correction for altitude is considered unnecessary given other sources of error and uncertainty. The phenomenon of ‘excess air’ incorporated during recharge has only a small effect on the CFCs but requires correction for SF_6 measurement. While no ‘excess air’ measurements were made during the study, raw SF_6 measurements have been corrected using a value of 3 ccSTP/L for intergranular sediments and 5 ccSTP/L for fractured formations, based on the data of Wilson and McNeill (1997).

3.1.4. Using residence time tracers to understand groundwater mixing processes

As the four atmospheric environmental tracers used in this study (CFC-11, CFC-12, SF_6 and ^3H) have differing temporal patterns to their input functions, plots of one tracer against another can be useful in distinguishing the hypothetical groundwater flow processes that may affect the samples, in addition to identifying anthropogenic contamination. Lumped parameter models (LPM) typically used to describe some of the variation seen in groundwater mixtures include piston flow (PFM), exponential mixing (EMM) and binary mixing (BMM) (Zuber 1986; Cook and Böhlke 2000). Comparison of multiple environmental tracer data can indicate if simple models like these are applicable, and mean groundwater residence times or mixing ratios calculated accordingly.

3.2. Sample site selection

All sites sampled were functioning boreholes in use by the community immediately prior to sampling. Most of the boreholes were hand-pumped, though in the case of the Abeokuta study area there were very few functioning hand pumps so boreholes fitted with low-yielding submersible pumps were sampled instead. Two sites with larger volume abstractions for irrigation were also sampled in the Gusau area. Only sites with head-works and sanitary seals in good repair were sampled. Apparently suitable sites were avoided if there was a large ponded area, or a natural surface water body, close to the borehole which could potentially lead to additional localised recharge. A total of 57 sites were sampled across zones of contrasting annual average rainfall, with approximately equal numbers of samples taken from each study area and geology (see Table 2). For each of the four study sites an area of approximately 1000 km^2 was covered. This was required in order to sample a sufficient number of hand pumps in good repair, collect samples from across each region and geology, and also because of the dispersed nature of settlements.

3.3. Sampling and analysis

Field measurements of dissolved oxygen (DO_2), pH, specific electrical conductance (SEC) and temperature were made at the wellhead using a flow-through cell. Sampling was carried out only after stable instrument readings were obtained for the field parameters. Samples for chloride determination were filtered (<0.45 μm) in the field, stored in nalgene™ bottles and refrigerated prior to analysis by liquid chromatography.

Samples for stable isotope analysis were collected unfiltered. Analysis was carried out using standard preparation techniques followed by isotope ratio measurement on a VG-Micromass Optima mass spectrometer. Data considered in this paper are expressed in ‰ with respect to Vienna Standard Mean Ocean Water (VSMOW). Tritium samples were collected in 1-L HDPE bottles. Analysis was carried out by decay counting following pre-concentration by electrolytic enrichment.

CFC and SF_6 samples were collected unfiltered and without atmospheric contact in sealed containers by the displacement method of Oster (1994). This method ensures that the sample is protected from possible atmospheric contamination by a protective jacket of the same water. CFCs and SF_6 were measured by gas chromatography with an electron capture detector after pre-concentration by cryogenic methods, based on the methods of Busenberg and Plummer (1999).

Measurement precision was within ±0.1‰ for $\delta^{18}O$ and ±1‰ for $\delta^{2}H$, as indicated for ^{3}H, and ±5% for the CFCs and 10% for SF_6, with detection limits of 0.01 pmol/L (CFC-12), 0.05 pmol/L (CFC-11) and 0.1 fmol/L (SF_6). Chloride analysis and measurement of stable isotopes, CFCs and SF_6 took place at

BGS laboratories in the UK. Tritium was analysed by the International Atomic Energy Agency (IAEA) in Vienna.

4. Results

Summary statistics for groundwater residence time tracers (CFC-11,CFC-12, SF_6 and ^3H), groundwater stable isotopes ($\delta^{18}O$ and δ^2H), groundwater mean residence times (MRT), chloride, as well as field observations of DO_2 are presented in Table 2. A complete set of results is available in Table S1, in the accompanying ESM.

4.1. Stable isotopes

Summary stable isotope results ($\delta^{18}O$ and δ^2H) are provided in Table 2. When plotted on a δ-diagram (Fig. 2) they show a good conformance with the GMWL ($\delta^2H=8\delta^{18}O + 10$), indicating that infiltration occurred either areally during rainfall events or shortly afterwards via focused recharge from minor surface ponding. A robust regression line calculated using the stable isotope data is given as $\delta^2H=8.03\delta^{18}O + 10.04$, with an r^2 of 0.89. It is noteworthy that overall there is no systematic bias towards enriched or depleted values relative to the GMWL. Any recharge from longer-residence ponds or lakes would be likely to exhibit signs of evaporative fractionation, particularly in the semi-arid areas. The only sites showing evidence for this were M1 and M6 from the CT aquifer in Mali. M1 was in close proximity to a large seasonal pond, but the source of recharge to M6 remains unclear. Analysis of variance showed that there are significant differences in stable isotope signatures between different study areas (p<0.001). The trend in decreasing $\delta^{18}O$ (-2 to -5.5 ‰) and δ^2H (-10 to -37 ‰) with decreasing annual rainfall (Fig. 2) is consistent with the largely convective origin of the rainfall as it tracks north from the Gulf of Guinea inland during the wet season. No significant (p>0.05) difference was found for isotope values in the different geology within each study area.

4.2. Tritium

Tritium values range from approximately zero to 7.3 TU (Table 2), suggesting a range of ages, but these are difficult to interpret quantitatively partly owing to the lack of detailed knowledge about inputs of ^3H in rainfall over time. Statistical analysis (Fig. 3a) shows certain differences between the four areas and the two lithologies (basement and sedimentary). A general lowering in activities towards the coast may be due to the dilution effect on rainfall of low-tritium water vapour from the ocean (Gat 1980), while in the basement areas there could be terrigenic production of ^{3}H from the presence of U, Th, Li and B (Andrews and Kay 1982).

4.3. CFCs and SF_6

Results for groundwater residence time tracers are shown in Table 2, divided by study area and aquifer type. It is clear that some of the measured CFC and SF_6 concentrations considerably exceed the maximum equilibrium values for a recharge temperature of 28°C (CFC-12 = 1.4 pmol/L, CFC-11 = 2.4 pmol/L, SF_6 = 1.5 fmol/L), suggesting that concentrations in some waters have been affected by augmentation from anthropogenic or terrigenic sources. It is also apparent from the DO_2 data (Table 2) that there is potential for CFC degradation due to the anaerobic groundwater conditions across the study areas in Nigeria.

Mean residence times for groundwaters were calculated using an exponential mixing model, results were found to fall in the EMM-BMM envelope, and the piston flow model was the least suitable model. A statistical summary of the estimated MRT results is presented in Figure 3b. In most cases SF_6 data were used as the input data, however for the few sites where this exceeded modern recharge values and waters were aerobic (>1 mg/L DO_2) and there was no clear evidence of CFC-12 degradation, CFC-12 values were used instead. The results from a Kruskal-Wallis test (Hollander and Wolfe 1973) comparing MRT results between each climate zone show the mean ranks for the four zones are not significantly different (p >0.1).

5. Discussion

5.1. Recharge processes

Although potential evaporation in arid and semi-arid regions exceeds rainfall, often by a factor of three or four times, other studies in West Africa have shown that this does not mean that diffuse areal recharge is insignificant (Scanlon et al. 2006). For example, in northeast Nigeria recharge of up to 30 mm/yr has been reported based on the use of a range of techniques including chloride mass balance (CMB), water balance calculations, and observations of water level fluctuations (Carter 1994; Carter and Alkali 1996; Edmunds et al. 1999).

While no unsaturated zone CMB studies were undertaken during the present study, a simple estimation of potential recharge R_D was calculated for the Bandigara study area using the formula $R_D = PC_p/C_s$ where P is the average regional annual rainfall (mm), C_p is the spatially averaged rainfall Cl (mg/L) and C_s is the groundwater concentration Cl (mg/L). Rainfall Cl concentrations used were 0.26 mg/L Cl, (Galy-Lacaux et al. 2009). This CMB approach gives an average recharge value of 20 mm·yr $^{-1}$ and a large range of 4 – 43 mm/yr, equivalent to between 1.2 – 12% annual rainfall across this study area. Overall these values compare well with other field based studies in semi-arid areas (Scanlon et al. 2006) as well as modeled estimates (Döll et al. 2003). While this model is useful in semi-arid regions many assumptions behind it break down in wetter regions (Scanlon et al. 2002; Healy 2010) leading to unreliable results and therefore no attempt was made to use this model to estimate recharge in the other study areas.

The generally unfractionated stable isotope values found in this study suggest a rapid recharge mechanism following rainfall, and the predominance of diffuse recharge across most parts of the areas studied. However, this may also include recharge from transient surface ponding that perhaps lasts only a few days. The two observed departures from the GMWL are likely to be due to the effect of focused recharge from longer lasting seasonal ponds and rivers (which were observed in Mali and northern Nigeria) following episodic rainfall events. These findings corroborate other studies which have shown that the shallow groundwaters in West Africa are coupled to recent climate and recharge processes (Edmunds et al. 1999; Acheampong and Hess 2000; Rueedi et al. 2005; Onugba and Aboh 2009) and are also consistent with other studies in semi-arid parts of sub-Saharan Africa (e.g. Favreau 2000; Bromley et al. 2002; Favreau et al. 2002).

The existence of diffuse areal recharge does not in itself imply a particular route to the water table. CMB studies in semi-arid areas indicate delays of up to 10^1–10^2 yr in transit through the unsaturated zone, yet the existence of anthropogenic tracers like the CFCs in the underlying aquifers shows that more direct recharge also occurs, promoted by fracturing, root development or other factors (Edmunds et al. 1999; Stadler et al. 2010). In this study the unsaturated zone was relatively thin (8–20 m) so the lag due to tracer diffusion and transport through the unsaturated zone would be small (<1-4 years) relative to the overall MRT (Cook and Solomon, 2003). In addition, groundwater transport through the unsaturated zone, particularly episodic recharge, would be rapid resulting in only a small travel time in the unsaturated zone (Stadtler et al. 2010).

5.2. Groundwater residence time and mixing

Using multiple residence time tracers has two main benefits: instances of contamination or degradation in one tracer can be offset by others unaffected, and a better understanding of flow processes is potentially achievable (e.g. Darling et al., 2012). Reference has already been made to instances of contamination, such as the production of terrigenic SF_6 in basement rocks and localised CFC contamination (see section 4.4). Results for such samples (identifiable by their over-modern concentrations) have been filtered out of the dataset to be used for dating purposes. The remaining results can be interpreted by co-plotting the tracers (Fig. 4) onto a framework of basic lumped parameter models (LPMs).

A plot of CFC-11 versus CFC-12 shows samples cluster on or around the piston flow (PFM) and binary mixing (BMM) lines (Fig. 4a). The spread of samples beyond the LPM lines suggest that processes apart from residence time are affecting CFC concentrations. One likely process is the degradation of CFCs under low-oxygen conditions (Oster et al. 1996). Samples with <0.5 $mg \cdot L^{-1}$ DO_2 are indicated and tend towards low concentrations of both CFCs. Though it is known that CFC-11 is more rapidly affected by reduction than CFC-12, Fig. 4a does not show a bias towards this, suggesting that reduction has been going on for long enough to affect both CFCs. Unaffected samples show a slight bias towards CFC-12, perhaps indicating a minor source of contamination. Owing to the proximity of the PFM and BMM lines it is not possible to assign samples to a particular flow regime. Most samples unaffected by reduction have a piston-flow mean residence time (MRT)

>30 yr or have <50% modern water in them depending on the chosen hydrogeological model. There appears to be no gross difference between the basement and sedimentary results.

Fig. 4b shows a plot of CFC-12 versus SF_6. The simplest interpretation of this plot is that samples to the left of the LPM envelope have been affected by one of two processes: CFC-12 reduction for low-DO_2 samples, and terrigenic production of SF_6 where DO_2 exceeds 0.5 $mg \cdot L^{-1}$. On the assumption that one or the other process is operating, most samples have an MRT >15 yr or have <40% modern water. The possibility of some samples suffering from both processes cannot be excluded but the number of significantly-affected samples is small and would in most cases not affect the above estimates. As with Fig. 4a it is difficult to discern any difference between basement and sedimentary groundwaters.

Tritium is not affected by reduction or (except in very specific cases) by contamination. Therefore plots involving ^3H have an advantage in that regard. The limitations of the ^3H input for West Africa have been discussed in section 3.1.2. The plot of CFC-12 versus ^3H (Fig. 4c) shows the expected bias of low-DO_2 samples towards low CFC-12 concentrations. Some of these reduced samples project onto the PFM line only, a conclusion that could not be drawn from the plots in 4a and b. Samples below the BMM line support the indications of Fig. 4a that some samples have minor CFC contamination. Most samples appear to have MRTs >25 yr or <70% modern water.

A plot of SF_6 versus ^3H (Fig. 4d) shows the lowest scatter of data points of all the residence time plots, suggesting by reference to Figs 4a–c not only that low-DO_2 conditions have affected the CFCs, but that CFCs in more oxygenated waters may also have been affected by reduction: mixing within the borehole between anaerobic and higher-DO_2 waters could have this effect. Most samples in Fig. 4d fall within the BMM-EMM envelope, and it therefore seems reasonable to use the EMM to calculate MRTs. Highest SF_6 concentrations below the BMM belong to two basement aquifer samples and suggest the existence of terrigenic production. In simple terms the plot indicates most samples have <60% modern water, a few samples have piston flow ages of 20–25 yr, and that some samples are intermediate in origin between EMM and BMM flow models.

5.3. Implications for the hydrogeology of shallow aquifers

Fig. 5 summarises the estimated MRT results as cumulative probability plots for the basement and sedimentary aquifers. The similarity in the distribution of MRTs for the sedimentary and crystalline basement implies that the rate of through-flow of shallow groundwater is comparable in the two aquifer types (Table 2). This would suggest similar hydraulic diffusivity (T/S), where T is transmissivity and S is storage, and shallow circulation within the top 20–50 m of the aquifers. The consistently large range of MRTs in the basement aquifers also indicates that there is sufficient storage within these aquifers to allow a range of differently aged groundwaters to be stored and mixed. These results would be consistent with the slightly higher effective porosity of approximately 1 –10% in the weathered basement aquifer suggested by engineering geology studies (Taylor and Eggleton 2001) than the <1% generally assumed by hydrogeologists (Wright 1992). The higher effective porosity of 25–35% (Adelana et al. 2008; Nwankwo et al. 2009) within the sandstone aquifers is offset by the higher transmissivity. Fig. 6 shows a simplified conceptual diagram of groundwater recharge processes for (a) basement and (b) sedimentary aquifers in arid zones summarising why similar MRTs are found in shallow groundwaters in both types of aquifers.

The similarity of MRTs across the different climate zones is perhaps a more surprising result. In the increasingly arid northern climates it might be expected that residence times would increase, since modeled groundwater recharge reduces (Döll and Fiedler 2008). These preliminary findings suggest that there is no simple link between MRT in shallow groundwaters and current long term average rainfall. Due to the limited current understanding of recharge and hydrogeological processes in the basement, reasons for the observed similar range in MRT for groundwater from 20–50 m boreholes across zones of highly contrasting annual rainfall remain speculative.

Possible explanations for the similar MRT in basement aquifers in both arid and humid zones are presented as a conceptual diagram in Fig. 7. Effective recharge in humid areas (Fig. 7a) is physically limited by lateral flow (when saturated soil flux is exceeded) along shallow permeable layers and surface runoff irrespective of changes in potential recharge. Low permeability layers in the saprolite, as a result of weathering processes, are common and an obvious barrier to groundwater recharge and facilitate rapid lateral flow irrespective of current climatic conditions (Chilton and Smith-Carington 1984; Jones 1985; Chilton and Foster 1999). Generally shallower regional water tables in humid areas (Fig. 7a) lead to a greater saturated thickness of weathered basement and therefore greater groundwater storage than in more arid areas (Fig. 7b) with deeper groundwater levels. Consequently, greater recharge in more humid areas would be offset by the higher storage to give MRTs similar to arid areas; a similar ratio between effective recharge and storage across the zones of contrasting rainfall and would help to explain the similar MRT. In this study the shallowest groundwater levels were found in the most humid areas (Table 1), although overall there was considerable overlap across the study areas.

5.4. Resilience of improved rural water resources to climate variability

Shallow groundwater resources currently play an important role in providing sustainable drinking water sources across Africa, and will continue to do so in the future. While there are major uncertainties in climate model predictions there is some consensus that there will be an intensification of past climate variability in the future (Parry et al. 2007). In light of this, unimproved ephemeral sources will continue to be the least resilient to changes in climate variability, while groundwater resources are better able to buffer any inter-annual variability in rainfall and recharge (MacDonald and Calow 2009; Bonsor et al. 2011). In all of the study areas, even in the most arid, the results of this study show that there is strong evidence of modern recharge. The shallow groundwater abstracted from rural hand pumps in both basement and sedimentary aquifers is a composite water with intermediate MRTs, giving an inherent resilience to short term changes in recharge. Overall, no significant difference in MRT was found within these shallow aquifers across a range of climates, from semi-arid zones to humid tropical zones. These factors together provide compelling evidence to support the assertion that any future changes in rainfall and recharge due to changes in climate are unlikely to lead to continent wide failure of improved groundwater supplies (MacDonald et al. 2009; Bonsor et al. 2011; MacDonald et al. 2012).

There is a growing body of evidence that more intense periods of rainfall and/or landuse changes could lead to increased episodic recharge, and therefore further increase the security of rural water supplies (Taylor and Howard 1996; Favreau et al. 2009). However, future pressures on groundwater resources for irrigation or due to increased population density may lead to much higher abstraction and need to be carefully managed, particularly in hard-rock areas where storage can be highly spatially variable (Foster 2012; MacDonald et al. 2012).

While it is not the main focus of this paper, there are clearly also important water quality implications for shallow groundwater sources from any future changes in rainfall distribution, and/or land use (Bijay-Singh et al. 1995; Kundzewicz et al. 2007). These include the potential for increased microbiological contamination from unsuitable sewerage systems, due the intensification of rainfall and episodic recharge (Howard et al. 2003; Taylor et al. 2009), groundwater pollution from pesticides and nitrate due to shifts towards more intensive crop production (e.g. Favreau et al. 2009) and pollution due to urbanisation/industrialisation (Adelana et al. 2008).

6. Summary and conclusions

This study has attempted to apply environmental tracer techniques to better characterise the shallow (<50 m deep) groundwater resources in West Africa. Comparisons were made between basement aquifers and sedimentary aquifers within four study areas of different annual mean rainfall, from a semi-arid zone in central Mali with rainfall of between 350-400 mm/yr to the humid tropical zone of southwest Nigeria with between 1800-2000 mm/yr. The main conclusions from this study are summarised below:

1. Stable isotopes indicate the predominance of rapid infiltration following rainfall even within the most arid zone with annual rainfall of between 350-400 mm/yr. There is strong evidence of modern recharge from a range of other geochemical tracers (SF_6, CFCs, ^3H).
2. In the most arid study area, recharge estimates using the chloride mass balance approach gave values of 20 mm/yr, equivalent to 6% of annual average precipitation.
3. Shallow groundwaters in the top 50 m of the subsurface have MRTs of 4–70 years (range) and 32–65 years (first and third quartile); median MRT values for each study area were found to be >30 years irrespective of average annual rainfall.

4. Similar MRTs were found in shallow groundwater in sedimentary and basement aquifers, indicating considerable storage within shallow basement and comparable hydraulic diffusivity within the two aquifers.

The results presented here support the view that shallow groundwater resources in both basement and sedimentary aquifers across this region have an inherent natural resilience to climate variability and are able to buffer the effects of reduced rainfall and recharge during short-term periods of drought. However, there is a clear coupling between modern rainfall and active recharge across the region so if, as has been predicted, future monsoon rainfall becomes more intense for parts of West Africa, then episodic recharge may increase in the future within more arid regions.

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FIGURE CAPTIONS:

Fig. 1 Location and geology map of the four study areas across the West African transect. Areas colored black show young volcanics

Fig. 2 Cross-plot of $\delta^{18}O$ vs $\delta^{2}H$. The Global Meteoric Water Line (GMWL) is shown as the dashed line on the plot. For comparison, the dashed area shows where shallow groundwater values plot from NE Nigeria (Edmunds et al. 1999), the solid area show where values plot for groundwaters from central Nigeria (Adanu 1991)

Fig. 3 Box-plots showing variations in (a) ^{3}H for shallow groundwaters within the sedimentary and basement aquifers across the rainfall transect (b) MRT for the four study areas, calculated from mainly SF_6 data, and some CFC-12 data where suitable, using the exponential mixing model. The horizontal dashed line in Fig. 3b is the median MRT value for all the results in this study

Fig. 4 Residence time tracer results in shallow groundwater (a) co-plot of CFC-12 and CFC-11, (b) co-plot of CFC-12 and SF_6, (c) co-plot of CFC-12 and ^{3}H and (d) co-plot of SF_6 and ^{3}H. Lumped parameter model curves are shown on each plot based on guidance by the (2012) for the CFCs and SF_6 and Leduc et al. (1996), Onuga and Aboh (2009) and GNIP (2011) for tritium. The values beside the piston flow model (PFM, solid line) and exponential mixing model (EMM, short-dashed line) curves in each plot shows modelled residence times in years. Symbols: Open symbols show sites with dissolved oxygen (DO) is <0.5 mg/L, filled symbols are sites with DO > 0.5 mg/L. Triangles are sites on the Basement geology, circles are sites on the Sedimentary geology.

Fig. 5 Cumulative probability plot of mean residence times (MRT) for shallow groundwaters within sedimentary (open circles) and basement (filled circles) aquifers across all four study areas. An exponential mixing model was used to calculate MRT.

Fig. 6 Conceptual diagram of groundwater recharge processes in arid zones for (a) basement and (b) sedimentary aquifers, explaining similar MRT results. Typical permeability ranges from Wright (1992) and Allen et al. (1997)

Fig. 7 Conceptual diagram of groundwater recharge and flow processes in basement aquifers for (a) humid zones and (b) arid zones. Arrows are only indicative of fluxes, PE = potential evaporation, ET = evapotranspiration

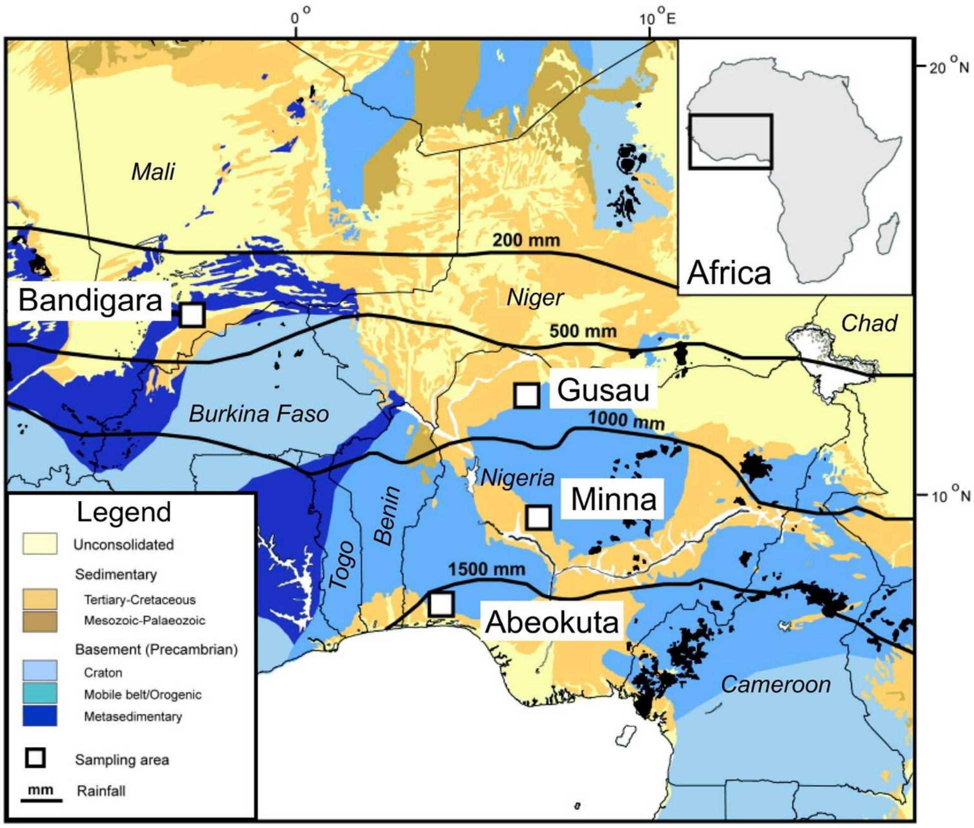

Fig. 1 Location and geology map of the four study areas across the West African transect. Areas colored black show young volcanics
123x103mm (300 x 300 DPI)

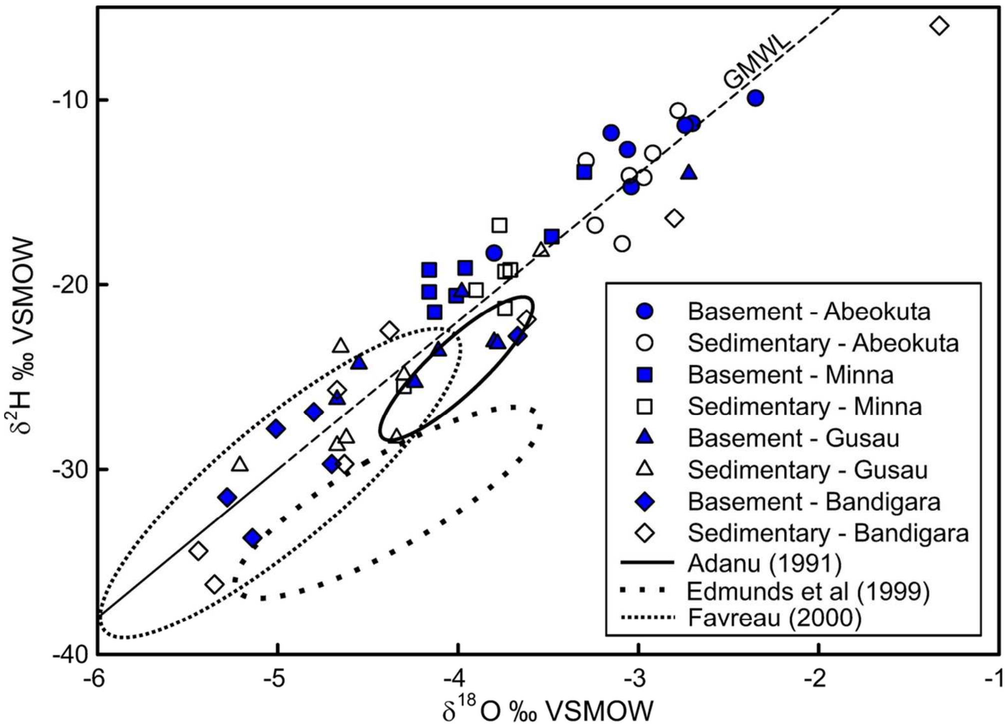

Fig. 2 Cross-plot of δ18O vs δ2H. The Global Meteoric Water Line (GMWL) is shown as the dashed line on the plot. For comparison, the dashed area shows where shallow groundwater values plot from NE Nigeria (Edmunds et al. 1999), the solid area show where values plot for groundwaters from central Nigeria (Adanu 1991)

109x78mm (300 x 300 DPI)

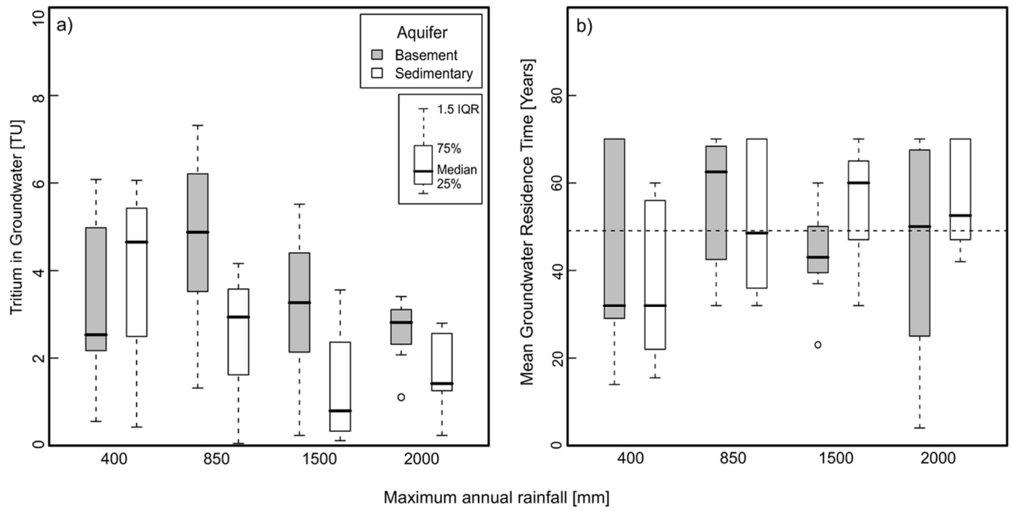

Fig. 3 Box-plots showing variations in (a) 3H for shallow groundwaters within the sedimentary and basement aquifers across the rainfall transect (b) MRT for the four study areas, calculated from mainly SF6 data, and some CFC-12 data where suitable, using the exponential mixing model. The horizontal dashed line in Fig. 3b is the median MRT value for all the results in this study
114x57mm (300 x 300 DPI)

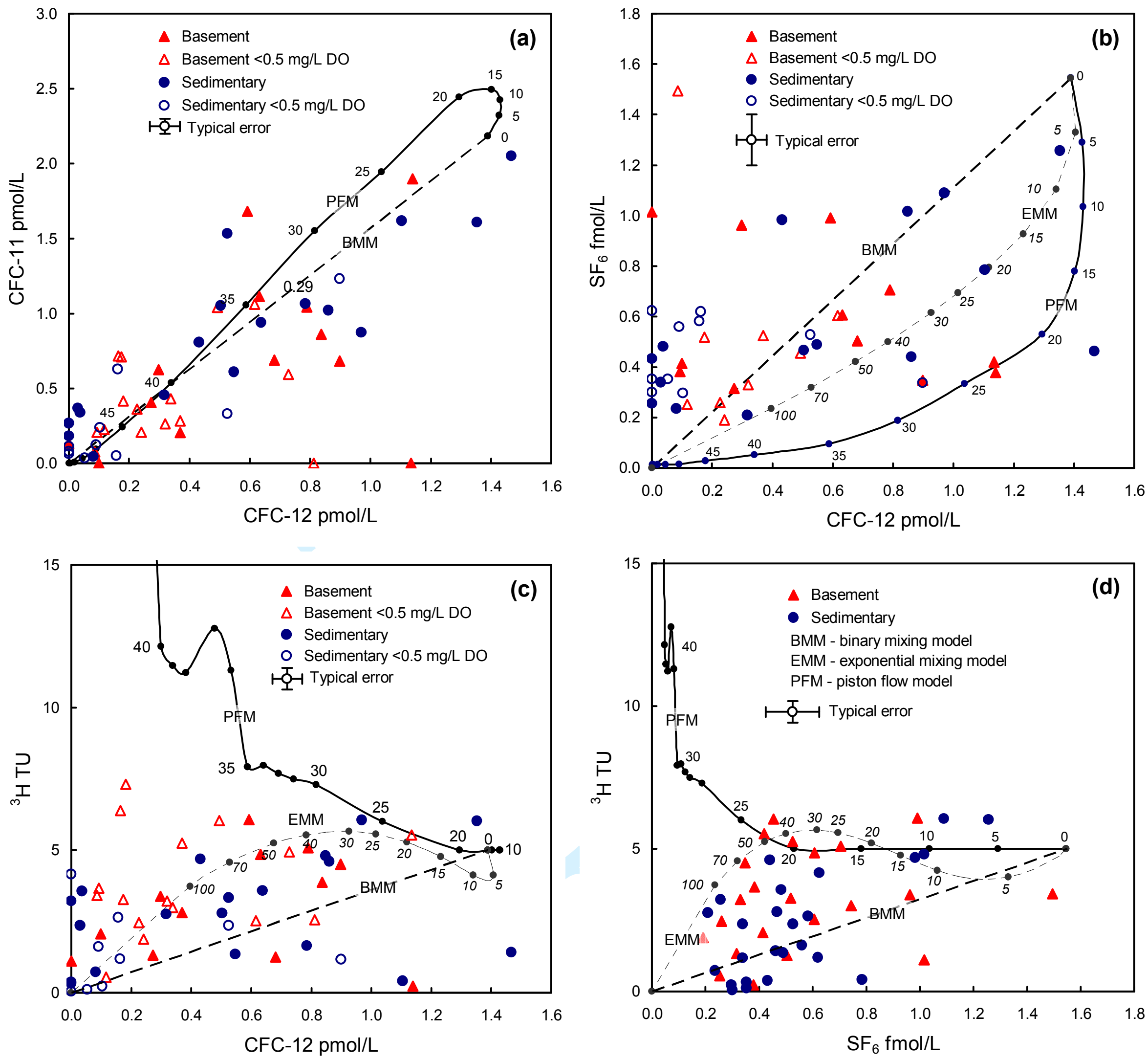

Fig. 4 Residence time tracer results in shallow groundwater (a) co-plot of CFC-12 and CFC-11, (b) co-plot of CFC-12 and SF6, (c) co-plot of CFC-12 and 3H and (d) co-plot of SF6 and 3H. Lumped parameter model curves are shown on each plot based on http://water.usgs.gov/lab/software/air_curve/ for the CFCs and SF6 and Leduc et al. (1996), Onuga and Aboh (2009) and GNIP (2011) for tritium. The values beside the piston flow model (PFM, solid line) and exponential mixing model (EMM, short dashed line) curves in each plot shows modelled residence times in years. Symbols: Open symbols show sites with dissolved oxygen (DO) is <0.5 mg/L, filled symbols are sites with DO > 0.5 mg/L. Triangles are sites on the Basement geology, circles sites on the Sedimentary geology

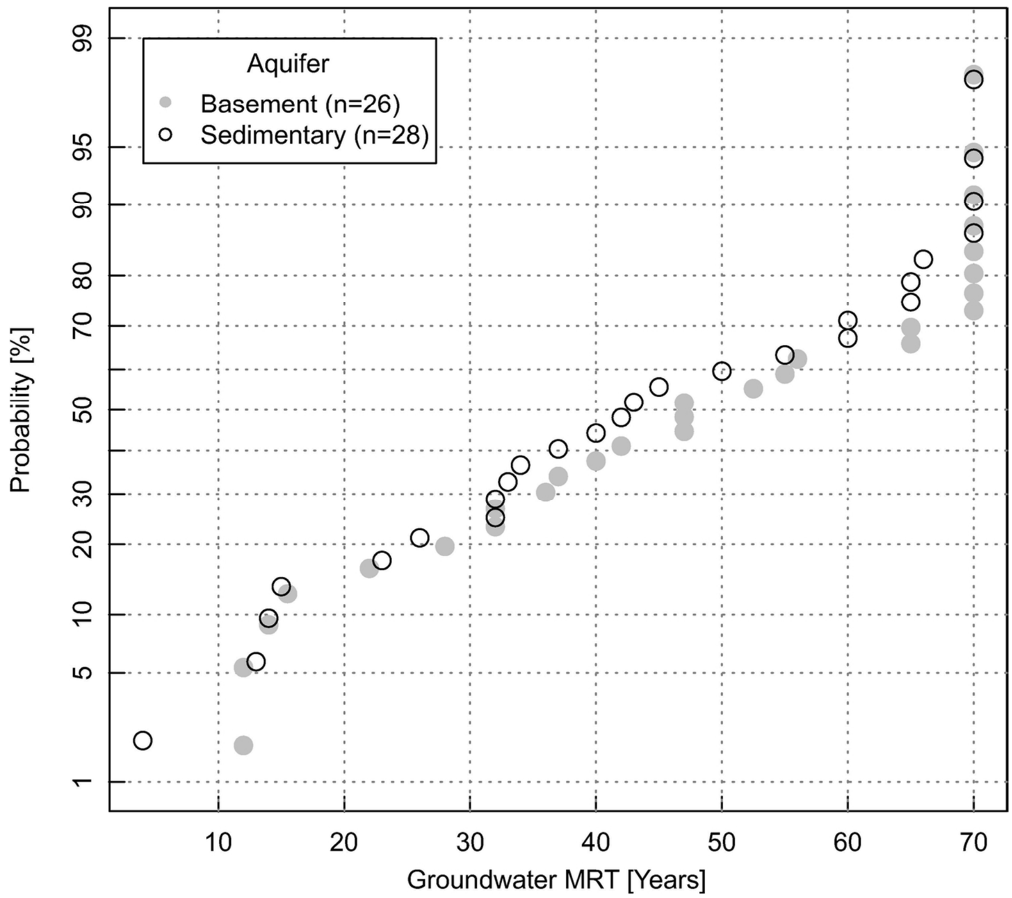

Fig. 5 Cumulative probability plot of mean residence times (MRT) for shallow groundwaters within sedimentary (open circles) and basement (filled circles) aquifers across all four study areas. An exponential mixing model was used to calculate MRT.
112x99mm (300 x 300 DPI)

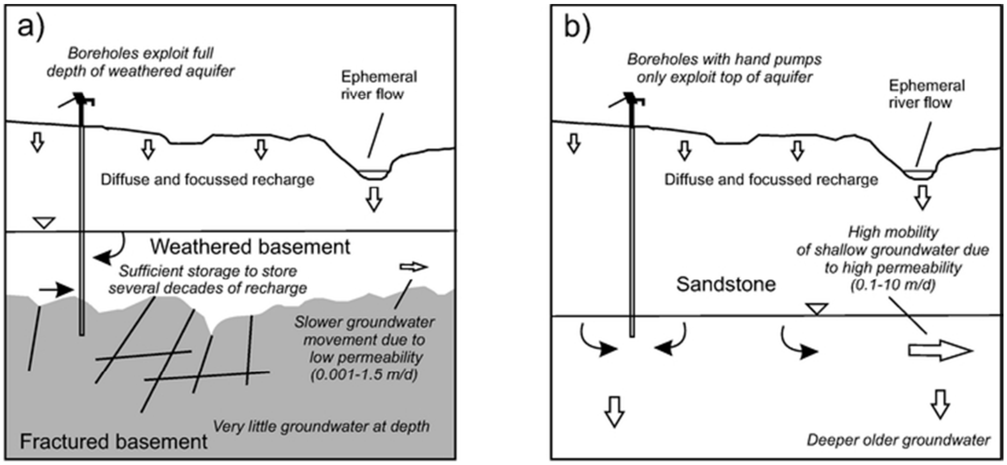

Fig. 6 Conceptual diagram of groundwater recharge processes in arid zones for (a) basement and (b) sedimentary aquifers, explaining similar MRT results. Typical permeability ranges from Wright (1992) and Allen et al. (1997)
61x28mm (300 x 300 DPI)

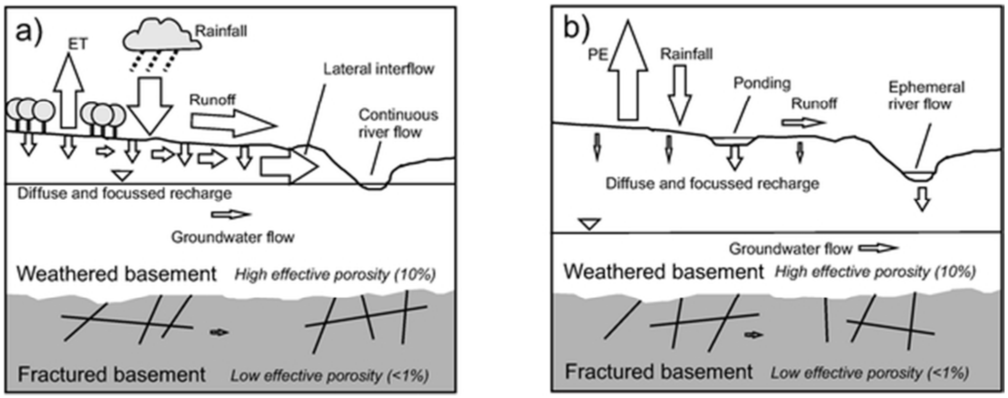

Fig. 7 Conceptual diagram of groundwater recharge and flow processes in basement aquifers for (a) humid zones and (b) arid zones. Arrows are only indicative of fluxes, PE = potential evaporation, ET = evapotranspiration
52x20mm (300 x 300 DPI)

Table 1 Study area summary information: Climate, population, livelihood, land use, number of hand pumps sampled, rest water level and borehole depths across the rainfall transect. Climate zone classification from Peel et al. (2007), population data from Lapworth et al. (2011)

Climate zone± (average rainfall)	**Country and region**, / **Case study**	**Length of dry season**	**Average (range) village population**	**Av. Population increase in last 5 years**	**Sites+**	**RWL range** (mbgl)+	**Borehole depth range** (mbgl)+
Am (1800-2000mm/y)	Nigeria, Abeokuta*	3-4 months (Oct-Jan)	2300 (200-5000)	34%	7 (7)	<10 (3.5-20)	30-40 (20-70)
Aw (1200-1500mm/y)	Nigeria, Minna*	7-8 months (Sep-May)	1100 (100-2000)	40%	7 (6)	<10 (7.5-10)	20-30 (30-40)
BSh (700-850 mm/y)	Nigeria, Gusau**	7-8 months (Sep-May)	2300 (500-5000)	36%	8 (6)	<10-20 (9-15)	20-42 (25-30)
BWh (350-400mm/y)	Mali, Bandigara**	9 months (Oct-Jun)	2000 (420-7000)	14%	7 (5)	8-10 (8-20)	15-62 (25-76)

±Equatorial monsoon (Am); Equatorial savannah (Aw); Arid Steppe (BSh) and Arid desert (BWh). Predominant activity:* Arable farming, ** Mixed arable farming and livestock, + values for sedimentary sites in parenthesis, RWL = rest water level

Table 2 Summary groundwater tracer results in the shallow basement and sedimentary aquifers within the four case study areas: stable isotopes ($\delta^{18}O$, $\delta^{2}H$) residence time tracers (CFC-12, CFC-11, SF_6 and ^3H) estimated mean residence time (MRT), field DO_2 and Cl

	$\delta^{18}O$	$\delta^{2}H$	CFC-12	CFC-11	SF_6	^3H	MRT**	DO_2	Cl
	‰VSMOW		pmol/L	pmol/L	fmol/L	TU	Years	mg/L	mg/L
Basement									
Abeokuta, Nigeria									
Mean	-3.0	-12.9	0.34	0.43	1.92	2.59	34	2.46	45.0
Median	-3.0	-11.8	0.33	0.25	1.41	2.81	37	1.07	37.3
SD	0.5	2.8	0.26	0.55	1.82	0.79	25	3.21	34.2
Min	-3.8	-18.3	0.09	0.08	0.31	1.11	4	0.03	3.4

Max	-2.4	-9.9	0.81	1.64	5.55	3.41	65	7.61	103.9
Minna, Nigeria									
Mean	-3.9	-18.9	0.92	1.00	1.24	3.16	43	2.36	3.5
Median	-4.0	-19.2	0.84	0.86	0.49	3.27	43	1.92	0.2
SD	0.4	2.6	0.48	0.45	1.53	1.89	14	1.70	8.0
Min	-4.2	-21.5	0.17	0.59	0.36	0.23	23	0.49	0.1
Max	-3.3	-13.9	1.73	1.90	4.53	5.52	60	5.15	21.6
Gusau, Nigeria									
Mean	-4.0	-22.5	0.35	0.55	3.32	4.73	46	0.66	7.8
Median	-4.0	-23.4	0.28	0.52	0.46	4.87	45	0.29	4.6
SD	0.6	3.8	0.26	0.27	6.58	1.93	19	0.65	10.1
Min	-4.7	-26.2	0.09	0.21	0.30	1.32	15	0.03	0.8
Max	-2.7	-14.0	0.90	1.04	19.21	7.31	66	1.64	31.8
Bandigara, Mali									
Mean	-5.0	-30.2	0.46	0.81	0.49	3.35	41	0.57	4.2
Median	-5.0	-29.7	0.59	1.04	0.57	2.53	32	0.33	2.8
SD	0.7	5.1	0.26	0.56	0.28	2.01	24	0.59	3.1
Min	-6.1	-38.7	0.12	0.21	0.18	0.55	14	0.05	2.1
Max	-3.7	-22.8	0.79	1.68	0.93	6.08	70	1.54	10.6
Sedimentary									
Abeokuta, Nigeria									
Mean	-3.0	-14.2	0.62	0.85	0.37	1.73	55	2.46	11.6
Median	-3.1	-14.1	0.53	0.61	0.43	1.42	50	1.09	8.0
SD	0.2	2.4	0.44	0.65	0.11	0.95	12	2.43	8.5
Min	-3.3	-17.8	0.10	0.22	0.19	0.23	42	0.41	3.9
Max	-2.8	-10.6	1.47	2.05	0.49	2.79	70	6.10	24.3
Minna, Nigeria									
Mean	-3.9	-20.4	0.07	0.33	0.40	1.32	56	2.11	1.8
Median	-3.8	-19.8	0.04	0.34	0.36	0.79	60	2.50	1.2
SD	0.2	2.9	0.06	0.20	0.10	1.37	14	1.85	1.9

Min	-4.3	-25.5	0.03	0.11	0.31	0.11	32	0.05	0.2
Max	-3.7	-16.8	0.16	0.63	0.57	3.56	70	4.70	4.8
Gusau, Nigeria									
Mean	-4.5	-25.9	0.24	0.28	0.64	2.55	33	1.99	6.3
Median	-4.6	-28.3	0.12	0.12	0.52	2.93	34	1.05	1.1
SD	0.5	4.1	0.27	0.32	0.68	1.50	4	2.31	9.8
Min	-5.2	-29.8	0.08	0.05	0.21	0.05	28	0.05	0.3
Max	-3.5	-18.2	0.64	0.94	2.16	4.16	37	5.71	25.4
Bandigara, Mali									
Mean	-4.0	-24.1	0.86	0.97	3.72	3.95	30	2.79	12.7
Median	-4.5	-24.1	0.85	0.95	0.97	4.65	19	2.72	11.2
SD	1.4	9.9	0.30	0.47	6.79	2.02	23	2.09	6.3
Min	-5.4	-36.2	0.43	0.16	0.41	0.42	12	0.55	2.2
Max	-1.3	-6.0	1.35	1.62	20.25	6.06	70	6.87	21.1

*MRT calculated using an exponential mixing model, SD = Standard deviation

Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate

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Fig. S1 Rainfall ^{3}H curve derived for West Africa. Data from the GNIP (2011; see *References* in the main article) combined with measurements by Leduc et al. (1996) and Onuga and Aboh (2009)

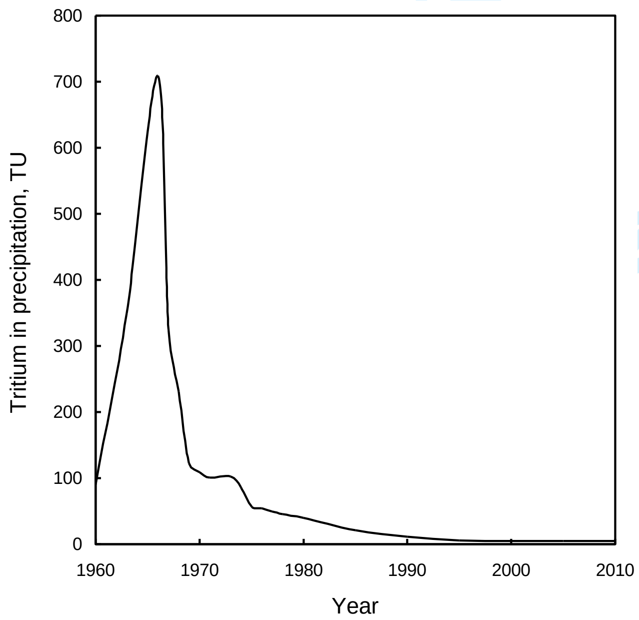

Fig. S2 Variation over time in (a) Northern hemisphere atmospheric mixing ratio curves for CFC-11, CFC-12 and SF_6 based on CMDL/NOAA data. (a) groundwater concentrations assuming equilibrium with Northern Hemisphere mixing ratios and recharge temperatures of 28 °C. Note differences in scales between CFCs and SF_6

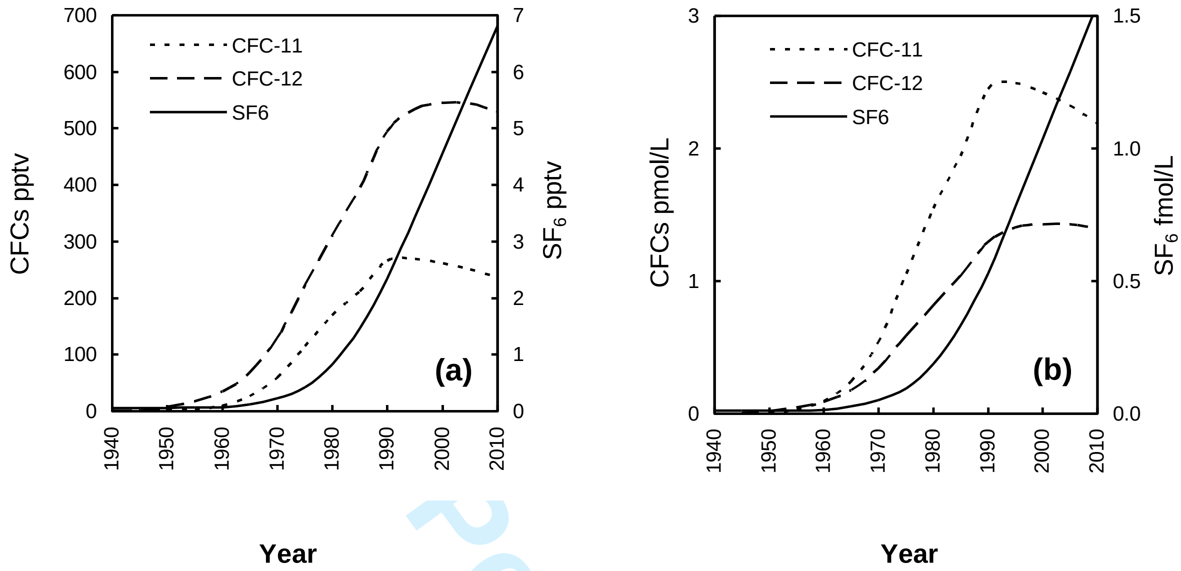

Table S1. Groundwater chemistry results in the shallow basement and sedimentary aquifers within the four West African study areas: field chemistry (temperature, pH, SEC, DO_2), stable isotopes ($\delta^{18}O$, δ^2H) and residence time tracers (CFC-12, CFC-11, SF_6 and ^3H) and estimated mean residence time (MRT)

Site ID	Geol.*	T	pH	SEC	DO_2	Cl	$\delta^{18}O$	δ^2H	CFC-12	CFC-11	SF_6	^3H	MRT**
		°C		$\mu S \cdot cm^{-1}$	$mg \cdot L^{-1}$	$mg \cdot L^{-1}$	‰VSMOW		$pmol \cdot L^{-1}$	$pmol \cdot L^{-1}$	$fmol \cdot L^{-1}$	TU	Years
Abeokuta, Nigeria													
B13	B	29.5	6.66	502	7.61	20.7	-3.15	-11.8	<0.01	0.13	0.96	1.11	13
B14	B	29.5	7.01	705	<0.05	3.4	-2.35	-9.9	0.81	0.25	5.55	2.56	37
B15	B	28.9	6.01	610	3.51	60.8	-2.7	-11.3	0.10	1.64	0.39	2.07	50
B16	B	27.3	5.45	535	<0.05	103.9	-3.06	-12.7	0.32	0.26	0.31	3.21	65
B17	B	29.6	6.16	437	0.03	37.3	-3.04	-14.7	0.09	0.08	1.41	3.41	4
B18	B	27.7	5.53	234	0.06	22.8	-3.8	-18.3	0.34	0.43	2.62	2.99	N/A
B19	B	27	5.75	670	1.07	66.2	-2.74	-11.4	0.37	0.20	2.22	2.81	>70
A17[a]	S	29.2	4.55	32.1	1.09	3.9	-2.97	-14.2	0.55	0.61	0.45	1.35	52.5
A18[a]	S	28.8	5.21	251	5.32	22.3	-2.78	-10.6	0.50	1.05	0.43	2.79	47
A19[a]	S	30.1	6.24	431	0.41	24.3	-3.24	-16.8	0.10	0.22	0.27	0.23	>70
A20[a]	S	28.2	4.49	46.8	0.64	5.2	-3.05	-14.1	0.90	1.23	0.31	1.17	70
A21	S	26.8	5.96	206	0.45	12.8	-2.92	-12.9	0.53	0.33	0.49	2.36	42
A22[a]	S	27.6	4.23	51.6	3.18	8.0	-3.09	-17.8	0.32	0.46	0.19	2.76	70
A23[a]	S	27.8	4.64	45.8	6.1	4.8	-3.29	-13.3	1.47	2.05	0.43	1.42	47
Minna, Nigeria													
A1	B	31.4	5.96	199.7	2.72	1.6	-3.48	-17.4	0.84	0.86	4.53	3.87	34
A2	B	30.3	5.87	170.8	0.49	0.1	-3.3	-13.9	0.73	0.59	1.77	4.93	N/A
A3	B	28.6	6.42	394	1.72	0.6	-4.16	-19.2	1.73	1.20	0.70	3.01	23
A4	B	28.9	6.26	238	0.65	0.1	-4.13	-21.5	1.13	1.08	0.40	5.52	55
A5	B	31.4	6.96	363	5.15	0.2	-4.16	-20.4	1.14	1.90	0.36	0.23	60
B1	B	28.3	6.32	359	1.92	21.6	-4.01	-20.6	0.17	0.71	0.49	3.27	42
B2	B	30.1	6.28	233	3.89	0.1	-3.96	-19.1	0.68	0.69	0.48	1.26	43
A6	S	30.7	5.19	55.2	4.7	1.7	-3.77	-16.8	0.03	0.37	0.31	2.36	70
A7	S	31.3	6.04	196	2.7	3.5	-3.9	-20.3	<0.01	0.18	0.40	0.38	55
A8	S	31.2	5.55	126.7	2.5	4.8	-3.74	-19.3	0.04	0.34	0.44	3.56	47
B3	S	30.7	5.99	236	<0.05	0.2	-4.3	-25.5	<0.01	0.11	0.33	0.33	65
B4	S	31.3	5.72	104.7	0.6	0.7	-3.71	-19.2	0.16	0.63	0.57	1.2	32
B5	S	30.9	5.67	104	0.05	0.2	-3.74	-21.3	0.05	<0.05	0.33	0.11	65
Gusau, Nigeria													
A9	B	29.9	6.56	629	0.22	31.8	-3.8	-23.1	0.16	0.72	0.49	6.38	40
A10	B	30.6	6.53	148.2	0.03	0.8	-3.78	-23.2	0.37	0.28	0.43	5.24	45
A11	B	30.9	6.59	220	0.33	6.9	-4.55	-24.3	0.49	1.04	0.33	6.04	65
A12	B	32	6.6	353	1.46	3.7	-4.11	-23.6	0.90	0.68	19.21	4.5	33
B6	B	29.3	6.08	282	1.64	9.4	-4.24	-25.3	0.30	0.63	0.91	3.39	15
B7	B	31.1	6.78	542	0.18	4.4	-4.67	-26.2	0.18	0.41	4.53	7.31	N/A
B8	B	30.7	5.88	115.1	1.15	0.9	-3.98	-20.4	0.27	0.40	0.30	1.32	66
B9	B	30.6	6.19	148.8	0.24	4.8	-2.72	-14	0.09	0.21	0.36	3.66	60
A13	S	32.3	7	631	5.71	13.9	-4.67	-28.7	0.64	0.94	2.16	3.58	28
A14	S	29.6	6.41	255	0.38	2.2	-3.54	-18.2	<0.01	0.06	0.58	4.16	32
A15	S	30.9	5.58	440	1.71	25.4	-4.34	-28.3	<0.01	0.27	0.24	3.22	>70
A16	S	30.2	6.27	152	0.05	1.1	-4.3	-24.9	<0.01	0.08	0.28	0.05	>70
B10	S	31.2	4.7	38	3.83	0.3	-5.21	-29.8	0.08	0.44	0.21	N/A	>70
B11	S	30.8	5.14	51.5	0.24	0.4	-4.65	-23.4	0.09	0.12	0.52	1.62	37
B12	S	31.3	5.84	102	<0.05	0.6	-4.62	-28.3	0.16	0.05	0.54	2.64	36
Bandigara, Mali													

M9	B	31.1	5.77	129.7	0.05	2.2	-5.14	-33.7	0.23	0.36	0.24	2.46	>70
M10	B	31.2	5.87	183.4	0.33	10.6	-4.7	-29.7	0.62	1.06	0.57	2.53	32
M11	B	32.2	4.84	41.7	1.54	3.5	-5.01	-27.8	0.79	1.04	0.66	5.09	26
M12	B	32.7	4.84	48.3	0.63	2.8	-4.8	-26.9	0.63	1.11	0.57	4.85	32
M13	B	33	5.64	102.2	0.19	2.6	-5.28	-31.5	0.24	0.21	0.18	1.88	70
M14	B	31.5	6.38	317	0.05	5.5	-6.05	-38.7	0.12	0.23	0.24	0.55	70
M15	B	31.9	5.39	53.3	1.21	2.1	-3.67	-22.8	0.59	1.68	0.93	6.08	14
M1	S	32	7.48	427	6.87	10.3	-1.33	-6	0.85	0.67	0.94	4.8	14
M2	S	31.6	7.12	785	2.71	2.2	-5.35	-36.2	1.10	1.62	0.72	0.42	22
M3	S	32.2	6.9	1051	1.36	17.9	-4.63	-29.7	0.53	1.53	4.37	3.33	70
M4	S	33.5	7.06	856	2.72	10.7	-3.62	-21.9	0.43	0.81	0.91	4.68	15.5
M5	S	32.4	6.93	1289	3.87	21.1	-5.44	-34.4	0.78	1.07	20.25	1.65	40
M6	S	33.8	6.19	167	3.68	8.3	-2.8	-16.4	0.97	0.87	1.01	6.06	12
M7	S	33.7	6.35	188	0.59	11.6	-4.67	-25.7	1.35	0.16	1.16	6.03	12
M8	S	33.9	6.46	452	0.55	19.2	-4.38	-22.5	0.86	1.02	0.41	4.61	56

* B = Basement, S= Sedimentary, **MRT = Mean residence time, [a] Small submersible motorised pump used to abstract water from borehole. MRTs calculated using SF_6 data and CFC-12 data where suitable, N/A=data not available