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REPORT

Characteristics of high-intensity groundwater abstractions from weathered crystalline bedrock aquifers in East Africa

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Abstract

Weathered crystalline bedrock aquifers sustain water supplies across the tropics, including East Africa. Although well yields are commonly <1 L s^{-1}, more intensive abstraction occurs and provides vital urban and agricultural water supplies. The hydrogeological conditions that sustain such high abstraction from crystalline bedrock aquifers remain, however, poorly characterised. Five sites of intensive groundwater abstraction (multiple boreholes yielding several L s^{-1} or more) were investigated in Uganda and Tanzania. Analysis of aquifer properties data indicates that the sites have transmissivities of 10–1,000 m^2 day^{-1}, which is higher than generally observed in deeply weathered crystalline bedrock aquifers. At four of the five sites, weathered bedrock (saprolite) is overlain by younger superficial sediments, which provide additional storage and raise the water table within the underlying aquifer. Residence-time indicators suggest that: (1) abstracted water derives, in part, from modern recharge (within the last 10–60 years); and (2) intensive abstraction is sustained by recharge occurring over several decades. This range of encountered residence times indicates a degree of resilience to contemporary climate variability (e.g. short-term droughts), although the long-term sustainability of intensive abstractions remains uncertain. Evidence from one site in Tanzania (Makutapora) highlights the value of multi-decadal groundwater-level records in establishing the long-term viability of intensive groundwater abstraction, and demonstrates the influence of intra-decadal climate variability in determining the magnitude and frequency of recharge.

Keywords Basement aquifers · Water supply · Groundwater age · Sustainability · Sub-Saharan Africa

This article is part of the topical collection "Determining groundwater sustainability from long-term piezometry in Sub-Saharan Africa"

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Introduction

Weathered crystalline bedrock aquifer systems underlie approximately 40% of Sub-Saharan Africa (MacDonald et al. 2012) and provide a vital source of water to over a quarter of a billion people (MacDonald et al. 2008; Taylor and Tindimugaya 2012). For decades, these aquifer systems have sustained low-intensity groundwater abstraction (up to 1 L s^{-1}) from wells, typically via handpumps (Chilton and Foster 1995; MacDonald et al. 2005). More intensive groundwater abstraction (>1 L s^{-1} per well), using electrical submersible pumps, increased over the second half of the twentieth century, primarily in order to supply rapidly growing towns and cities with a low-cost source of safe domestic water (Taylor et al. 2004; Tindimugaya 2008). Dependence on intensive groundwater abstraction to supply domestic water is expected to increase substantially in towns and cities such as Addis Ababa in Ethiopia, Dakar in Senegal, Lusaka in Zambia, Nairobi in Kenya, and Dodoma in Tanzania (Taylor et al. 2009; Braune and Xu 2010), as the urban population of Sub-Saharan Africa is projected to triple between 2000 and 2050 (UN 2007). A shift towards more intensive groundwater abstraction is also predicted for food production as countries seek to reduce their reliance upon highly variable soil moisture by increasing the proportion of arable land under irrigation (Pfister et al. 2011; Pavelic et al. 2012). The distributed, renewable freshwater storage within deeply weathered crystalline bedrock aquifer systems in Sub-Saharan Africa is of fundamental importance to low-cost strategies to adapt not only to increased freshwater demand, but also to climate change and the enhanced climate variability due to anthropogenic warming (e.g. Allan et al. 2010; Taylor et al. 2017). Such strategies represent an important departure from traditional strategies focused on the storage of surface water in reservoirs (e.g. Grey and Sadoff 2007), for which the hydrological and social viabilities are in doubt.

The sustainability of high-intensity groundwater abstraction from deeply weathered crystalline bedrock aquifer systems in Sub-Saharan Africa remains unclear (Taylor and Howard 2000). Indeed, few reliable hydrogeological data exist upon which policies guiding high-intensity abstraction can be based (MacDonald and Calow 2009). An improved understanding of the hydrogeological characteristics of deeply weathered crystalline bedrock or "basement" aquifer systems that sustain high-intensity groundwater abstraction is required to guide future groundwater development, and to evaluate the viability of intensive groundwater exploitation as an adaptive strategy to increased freshwater demand, climate variability and climate change. The purpose of this study is to define the hydrogeological characteristics of five high-intensity groundwater abstractions from deeply weathered crystalline bedrock aquifer systems in East Africa.

Weathered crystalline bedrock aquifer systems

Deeply weathered crystalline bedrock aquifer systems occur throughout tropical and sub-tropical regions and typically comprise in-situ weathered overburden, referred to as saprolite, and underlying fractured bedrock, known as saprock. In places, the shallow saprolite aquifer is overlain by superficial sediments including alluvial and lacustrine deposits, which also store and transmit groundwater. Saprolite-saprock aquifer systems have highly variable but generally low transmissivities ($< 10\ m^2 day^{-1}$: Owoade 1995; Taylor and Howard 2000) and low storage (1–2%: Taylor et al. 2010; Vouillamoz et al. 2015; Kotchoni et al. 2018), though few reliable measures of the latter exist. Sustained low-intensity abstraction from saprock aquifers occurs in many areas of the world and has long been thought to depend on leakage from the overlying, more porous saprolite (Chilton and Smith-Carington 1984; Kafundu 1986; Acworth 1987; Houston and Lewis 1988; Chilton and Foster 1995; George 1992; Owoade 1995; Maréchal et al. 2004; Dewandel et al. 2006; Courtois et al. 2010; Elster et al. 2014). Evidence from 1–3-day pumping tests in India (Sekhar et al. 1994) and Uganda (Taylor and Howard 2000; Taylor et al. 2010) supports this assertion.

Intensive groundwater abstraction from weathered crystalline bedrock aquifer systems has been conducted at a number of locations in Sub-Saharan Africa for many years and, in some cases, decades. With few exceptions (e.g. Tindimugaya 2008), the local hydrogeological conditions that sustain intensively pumped boreholes in saprolite or saprock have not been well characterised. It is also unclear whether intensive groundwater abstraction is sustained by active recharge from recent months or years, or is drawing from long-term storage, recharged over decades, centuries, or even millennia.

Study areas in East Africa

This study focuses on five locations in East Africa where intensive groundwater abstraction occurs and some monitoring data are available (Fig. 1; Table 1). Abstraction at Seeta, on the outskirts of Kampala (Uganda), supplies one of the largest bottled water companies in East Africa; whereas abstraction at the other four locations is conducted for town public water supplies. Study locations are situated in semi-arid areas of Tanzania (Singida and Makutapora near Dodoma) and seasonally humid areas of Uganda (Mubende, Rukungiri and Seeta in peri-urban Kampala). One of the sites at Mubende was a spring, and one of the boreholes at Singida was artesian, but all other sites sampled were pumped boreholes with water tables below the surface.

Makutapora and Singida occur at latitudes of 5° and 4° south, respectively, and experience a single wet season from December to April; the remainder of the year is largely dry. Mean annual temperature and rainfall at Makutapora are ~23 °C and 550 mm, respectively. At Singida it is slightly wetter with mean annual rainfall of between 600 and 800 mm. Low precipitation combined with high mean annual potential evapotranspiration rates exceeding 2,000 mm constrain recharge in Tanzania. In contrast, in Uganda, where the study areas lie within 1° of the equator, mean annual temperatures are slightly lower ~21 °C but mean annual rainfall of ~1,200 mm (Tindimugaya 2008), is substantially greater. In Uganda, a bimodal rainfall distribution results in wet seasons from March to May and September to December. Mean annual potential evapotranspiration ranges from 1,500 to 1,700 mm.

Methods

Hydrogeological characterisation

Hydrogeological data were collated for each site from the Ministry of Water and Environment (Uganda) and the

Fig. 1 The location of the five study sites in Uganda and Tanzania

Table 1 Summary data for high-intensity abstraction study sites

Country	Location	Water use	Drainage basin area (km^2)	No. boreholes abstracting	Individual borehole yield range (L s^{-1})	Total yield at site at one tim (L s^{-1})	Transmissivity (m^2 day^{-1})	No. boreholes sampled for water chemistry and residence-time indicators
Uganda	Seeta	Bottled water	~0.5	1	0.8–5.7	Unknown	~ 0.7–70	2
	Mubende	Town supply	~35	5	1.1–8.6	Unknown	~ 15–100	4
	Rukungiri	Town supply	~8	3	0.8–1.4	1.7	~15–40	1
Tanzania	Makutapora	Town supply	~ 650	7	11–26	~ 340	~3,800	7
	Singida	Town supply	0.07–368	8	1.1–9.25	Unknown	No data	8

Ministry of Water and Irrigation (Tanzania). These include borehole logs of geology and construction, borehole yield data, and datasets of abstraction quantities, groundwater levels, and precipitation where these were available. Data from 72-h constant-rate pumping tests were obtained for five boreholes at Seeta and five boreholes at Mubende. These data were analysed using the Theis (1940) recovery method in AQTESOLV (Duffield 2000) to obtain transmissivity values. Data were also obtained from a 12-h constant-rate pumping test at Makutapora. This did not include recovery data, and therefore the Moench (1997) unconfined solution was applied to the drawdown data. Transmissivity data from 72-h constant rate pumping tests at Rukungiri in Uganda were documented by Tindimugaya (2008) who obtained consistent transmissivity values using Theis, Cooper-Jacob, and Neuman analytical solutions in AQTESOLV. No pumping-test data were available for Singida. Estimates of storage coefficients from pumping-test data were not possible because observation-well water-level data were not obtained during pumping tests.

Topographically defined catchment areas were estimated using digital elevation models of surface basins using NASA Shuttle Radar Topography Mission (SRTM) data (90-m resolution) and a basin delineation routine in ArcGIS-SWAT. These provide an approximation of the potential recharge area, although groundwater catchment areas may not coincide with topographically defined surface-water catchments, and may extend beyond these boundaries.

Field sampling for residence time indicators

Field sampling for CFC-11, CFC-12 and SF_6 residence-time indicators was undertaken in October 2010 during the dry season in Tanzania and 'long rains' wet season in Uganda. Other chemical parameters were measured to provide context for the residence time data. All boreholes sampled were pumped and had sealed head-works. At each borehole, tubing was connected to a sampling tap or valve, sealed to ensure that sampled groundwater was not contaminated by present-day atmospheric concentrations of anthropogenic gases (CFCs, SF_6). A "Y" connector was used to split the flow into two outlets. Probes were placed in a flow-through cell connected to one outlet to measure dissolved oxygen (DO), pH and Eh. Specific electrical conductance (SEC) and temperature were measured in a bucket fed via a second outlet from the Y connector. After stabilisation of these parameters, sampling was carried out. Samples for cation and anion analysis were filtered (0.45 μm) and the cation sample split was acidified in the field. Bicarbonate alkalinity was measured in the field using a micro-titrator. CFC and SF_6 samples were collected in sealed containers by the displacement method of Oster (1994). Major and trace element analysis was carried out by ICP-MS on filtered (<0.45 μm) and acidified (1% v/v HNO_3) samples. Chloride and nitrate were analysed using liquid chromatography on filtered samples. CFCs and SF_6 were measured at the British Geological Survey by gas chromatography with an electron capture detector using the methods of Busenberg and Plummer (1992). Measurement precision was ±5% for the CFCs and 10% for SF_6, with detection limits of 0.01 pmol L^{-1} (CFC-12), 0.05 pmol L^{-1} (CFC-11) and 0.1 fmol L^{-1} (SF_6).

Assuming piston flow through the aquifer, measured concentrations of CFCs and SF_6 can be used to estimate the year of recharge (Darling et al. 2012); however, in practice, most groundwater is a mixture of ages, and preferential groundwater flow via fractures and other discontinuities in the saprolite is likely at each study site. Results are presented in terms of the 'modern fraction' using methods outlined in Darling et al. (2012). CFC11-CFC12 and SF6-CFC12 cross plots are used to compare the data to theoretical piston flow curves, derived from atmospheric trace-gas data records, to assess whether waters may be mainly derived from a single flow path, or are in some way mixed. Where the data plot on or close to the theoretical piston flow curves, an estimate of groundwater age is made. At other sites, where the data plot close to the binary mixing line, it is clear that the waters are mixed and the modern fraction (presumed to be very recent in age) is estimated. Intermediate data share some characteristics of both these models and although ages can be assigned, these are only mean residence times which are likely to include a range of flowpaths and therefore recharge ages.

Results

Hydrogeological characterisation

Topography and geology

The five study sites occur in drainage basins of contrasting sizes; those in Tanzania are generally larger than those in Uganda (Table 1). Singida is situated within the Internal Drainage Basin (IDB) of central Tanzania where relief is very low and surface drainage is often difficult to discern clearly. The range of drainage basin areas in Table 1 reflects computations derived for sampled boreholes using NASA SRTM topographic data.

Available geological and borehole construction information for the boreholes where CFC and SF_6 sampling was conducted, are summarised in Tables 2 and 3. There are no borehole records for the Singida site in Tanzania; geological maps indicate that the bedrock is granite and overlain by saprolite and alluvium (Smedley et al. 2002). Geological maps and cross sections of the Makutapora area suggest that the fractured crystalline bedrock is overlain by about 30 m of saprolite, which is, in turn, overlain by calcareous sediments and "mbuga clay" with a variable thickness of up to 80 m

Table 2 Data for boreholes sampled in Tanzania during this study

Borehole No.	Easting	Northing	Elevation (m)	Depth (m)	Yield (L s^{-1})	Geology of open/slotted section	Thickness of surficial sediments	Saturated thickness of surficial sediments and saprolite (m)	Slotted casing depth (m)
Makutapora									
332/01	806,740	9,343,426	1,047	106.8	26	Weathered and fractured granite	82 m of clay and calcareous clay	70.4	88.55–102.80
327/01	806,207	934,240	1,057	132.2	26	Weathered and fractured granite	63 m of clay, and clay with sand or gravel	61.4	64.69–76.09, 89.47–92.32, 101.67–127.32
117/75	804,135	9,341,996	1,075	121.51	10.89	No data	No data	41.8	Open 60.96–121.51
326/01	803,187	9,341,148	1,082	122.5	21.8	Clayey sand and gravel, fractured and weathered granite	50 m of sandy clay and clay	55.6	69.59–80.99, 82.69–108.34, 114.69–117.54
325/01	802,003	9,340,152	1,087	123.4	26	Weathered and fractured granite	52 m of sandy clay	44	50.64–59.19, 60.94–92.29, 109.82–118.37
333/01	801,545	9,339,956	1,085	98	26	Weathered and fractured granite	24 m of sandy clay and calcareous clay	37.2	47.14–58.54, 61.67–93.02
147/78	800,441	9,339,216	1,097	74.3	20.1	Sand and weathered granite	62 m of clay, sand, calcareous clay, sand and gravel	>84.6	Slotted 41.2–58, open 58–74.26
Singida									
23/99	693,509	9,467,918	1,510	39.4	1.1	–	–	–	–
438/09	693,532	9,467,812	1,518	52	9.25	–	–	–	–
24/54	693,234	9,468,080	1,527	53	1.8	–	–	–	–
97/02	697,334	9,466,316	1,523	86.5	–	–	–	–	–
414/07	697,573	9,465,754	1,528	–	–	–	–	–	–
141/06	692,371	9,470,750	1,509	115	3.5	–	–	–	–
61/99	692,227	9,469,380	1,520	91	5.1	–	–	–	–
Artesian	684,693	9,464,290	1,471	–	–	–	–	–	–

Table 3 Data for boreholes sampled in Uganda during this study

Borehole No.	Easting	Northing	Elevation (m)	Depth (m)	Yield (L s^{-1})	Geology of slotted section	Thickness of superficial sediments	Saturated thickness of superficial sediments and saprolite (m)	Slotted casing depth (m)
Rukungiri									
RUK 5	826,287	9,913,616	1,582	89	0.8	Weathered and fractured gneiss, possibly with some alluvium	Mean of ~ 30 m across the site; uncertain boundary between saprolite and superficial sediments	70.9	44–51
Mubende									
DWD 18836	324,729	60,984	1,225	63.75	13.8	Weathered granite	~ 8.4 m of clay, 10.5 m gravel	50.5	25.25–33.5, 36.25–58.25
DWD 18943	326,249	63,527	1,226	61	8.6	Weathered rock and gneiss	~ 8 m sandy clay, ~22 m clay	29.6	30.73–55.48
DWD 18944	326,088	63,604	1,235	54.57	4.7	Weathered rock, quartzite veins, amphibolite	~ 28 m of sandy clay	22	30.97–39.19, 41.93–50.15, 52.89–54.42
DWD 18947	324,021	61,613	1,239	57.65	3.7	Weathered rock and granite	~ 9 m of clay, ~ 7 m sandy clay, ~3 m sand and gravel	24	26–42.5, 45.25–53.5
Spring	320,424	63,300	1,321	–	–	–	–	–	n/a
Seeta									
DWD 17465	465,978	40,455	1,182	60	5.7	Weathered and fractured granite	0	55.1	31.7–37.3, 40.2–45.8, 51.5–57.1
DWD 25940	465,972	40,665	1,183	70	1.6	Weathered and fractured granite/gneiss	0	48	34.25–37.00, 42.25–48, 53.5–59, 64.5–67.25

(Fawley 1955; Nkotagu 1996a). Borehole logs (Table 2) indicate that sediments overlie saprolite and saprock. Well casing details suggest that abstraction generally draws from saprolite and saprock.

Borehole logs from Mubende in Uganda (Table 3) indicate the presence of alluvium and paludal clays overlying saprolite, which is derived mainly from granite but also gneiss and quartzite. Borehole construction details suggest that abstraction is from the saprolite and saprock. The Rukungiri area is underlain by weathered phyllites, schists, gneisses, and quartzites that are overlain by a thick regolith comprising coarse-grained saprolite that includes sorted (e.g. alluvial) sediments (Tindimugaya 2008). Borehole logs suggest abstraction is from the coarse-grained regolith and saprock. Borehole logs for the bottled water site at Seeta near Kampala indicate that the site is underlain by weathered and fractured granite and gneiss. The geology here comprises a more classical profile of weathered saprolite overlying saprock without superficial sediments.

Borehole yields and aquifer transmissivity

At all sites, considerable variability (up to an order of magnitude) is observed in the yields from different boreholes (Table 1) that are, in some cases, less than 500 m apart. Indeed, at most study sites, some boreholes are not used for abstraction because well yields are insufficient due to substantial heterogeneity in hydraulic conductivity and storage as well as inadequacies in borehole construction. Variability in yield may arise from complex, often tectonically controlled cycles of deep weathering and erosion that produce aquifers in saprock (i.e. fissured bedrock) and saprolite/regoliths (largely in situ weathered).

With the exception of Rukungiri, there are one or more boreholes at all of the sites with yields exceeding 3 L s^{-1} (Tables 2 and 3), equivalent to ~94,600 m^3 $year^{-1}$ if pumping continuously at this rate. This value exceeds the geometric mean of 0.94 L s^{-1} reported by Bonsor and MacDonald (2010) from an analysis of 2,606 boreholes in weathered crystalline bedrock aquifer systems across Africa (Fig. 2). Well yields of >20 L s^{-1} (equivalent to 6.3×10^5 m^3 $year^{-1}$) at Makutapora in Tanzania are thus exceptionally high.

The range of transmissivities measured at each site is presented in Table 1. There is generally a good relationship between transmissivity and borehole yield (e.g. Graham et al. 2009). Where transmissivity data are available, they confirm the patterns observed in the borehole yield data. Transmissivity values of weathered crystalline bedrock aquifers in Africa are generally reported to be less than 1 m^2 day^{-1} and rarely more than 10 m^2 day^{-1} (Howard et al. 1992; Owoade 1995; Taylor and Howard 2000; Holland 2012). The transmissivities of 10–100 m^2 day^{-1} at the study sites is, therefore, higher than generally found in weathered crystalline bedrock aquifers, and transmissivities of 1,000 m^2 day^{-1} at the Makutapora Wellfield are exceptional.

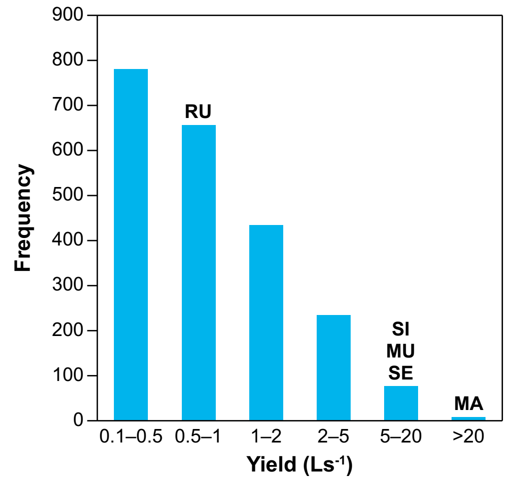


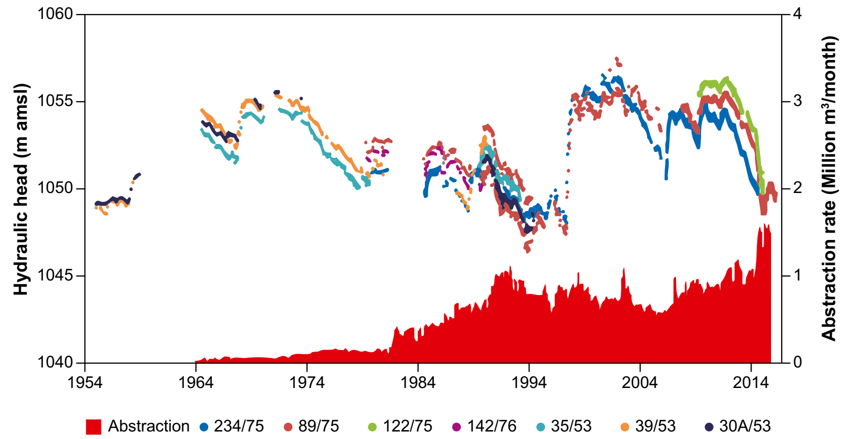
Fig. 2 Yields from 2,206 boreholes in basement aquifers. The category for the highest yields at the study sites are also shown. RU Rukungiri, SI Singida, Mu Mubende, SE Seeta, MA Makutapora

Trends in groundwater storage and abstraction

Long-term water level, abstraction and climate data are only available for one site, Makutapora (Tanzania), and have been published previously (Taylor et al. 2013a). Recharge is biased to seasons of intensive rainfall, predominantly >80th percentile, that are associated with the El Niño Southern Oscillation (ENSO). Borehole hydrographs show long periods of decline interspersed with sudden substantial rises in groundwater levels that occur, on average, two to three times each decade (Fig. 3). Increases in abstraction have amplified recessionary trends in groundwater levels between recharge events, with steeper rates of water level decline following the step changes in groundwater abstraction in 1990, and more recently in 2015. Groundwater-level or abstraction records are not available for Singida in Tanzania.

Short-term groundwater-level records of variable quality are available for some sites in Uganda. At Rukungiri, groundwater level monitoring data are available from 2 years prior to the onset of abstraction which was in March 2003 (Mileham et al. 2008; Tindimugaya 2008; Fig. 4). A pumping test in 2002 resulted in ~14 m of drawdown from a depth of 10 mbgl. Following the onset of intensive abstraction at production well RUK 5, an initial, sharp decline in groundwater level is observed and reflects transience in the aquifer's response to the onset of pumping. Subsequently, a new dynamic equilibrium is reached with seasonal recharge appearing to sustain intensive abstraction of ~110 m^3 day^{-1} (equivalent to 1.3 L s^{-1}) from 2003 to 2009, which continues to the present (2017). Groundwater-level and abstraction records for Mubende and Seeta in Uganda are shown in Fig. 5. At Mubende, high-frequency oscillations in groundwater levels in monitoring

Fig. 3 Groundwater levels and abstraction rates recorded at the Makutapora Wellfield, Tanzania (adapted and updated from Taylor et al. 2013a)



wells adjacent to a production well (DWD18336) reflect twice daily observations during 'pump-on' and 'pump-off' conditions and the impact of a cone of depression forming at radial distances of 10 and 50 m from the production well (Fig. 5a). These short-term records indicate dynamic but slowly declining responses in hydraulic head to intensive (mean: 240 m^3 day^{-1}, equivalent to 2.8 L s^{-1}) though highly variable (SD: 234 m^3 day^{-1}) daily abstraction. At Seeta, no groundwater-level response to intensive pumping (mean: 235 m^3 day^{-1}, equivalent to 2.7 L s^{-1}) is evident from an adjacent monitoring well.

Field sampling and analysis of residence-time indicators

Water chemistry

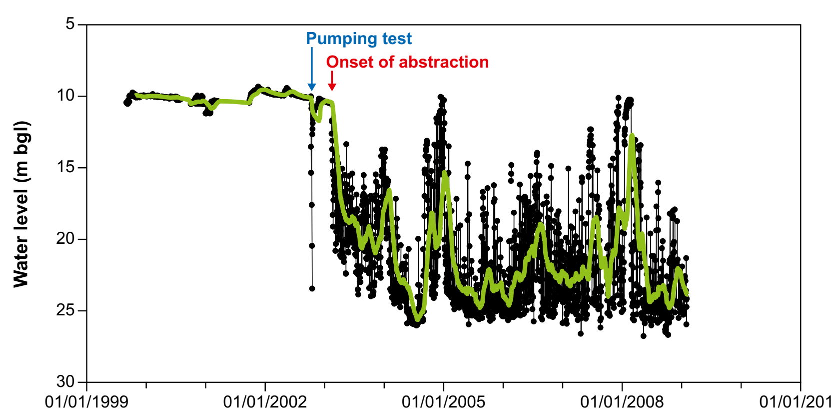
Field and laboratory water chemistry data are presented in Table 4. Sites in Uganda generally had lower temperatures, specific electrical conductance, pH, and bicarbonate alkalinity as well as lower concentrations of calcium, chloride, sulphate and nitrate than sites in Tanzania. The spring sampled in Mubende had a different water chemistry, with substantially lower levels of all these parameters, but higher dissolved oxygen, than the boreholes in Uganda. The majority of the waters sampled are of the sodium-calcium-carbonate type, with the exception of Makutapora where the waters are of sodium-carbonate type.

Dissolved oxygen was low or absent at a number of sites, in particular in the boreholes at Makutapora in Tanzania. At Makutapora nitrate was present, despite the absence of dissolved oxygen, suggesting the absence of de-nitrifying bacteria. Nitrate concentrations vary from 1 to 30 mg L^{-1} at most sites, but are extremely high in seven boreholes at Singida (63–322 mg L^{-1}). These values are considerably in excess of WHO drinking-water guideline values (50 mg L^{-1}) and are assumed to derive from faecal loading (Nkotagu 1996b); the potential contribution of other sources of N such as land-clearing (Faillat and Rambaud 1991) has yet to be explored.

CFC and SF_6 residence time indicators

Results of CFC-12, CFC-11 and SF_6 analysis are presented in Table 5. SF_6 concentrations have been corrected for the presence of excess air (due to seasonal water table fluctuations) on the assumption that this was present at ~3 ccSTP L^{-1} (Aeschbach-Hertig et al. 2002), reflecting the largely intergranular nature of the aquifer (saprolite or sediments) in which the water table moves in both Uganda and Tanzania. Many samples contained amounts of SF_6 well in

Fig. 4 Groundwater levels from 1999 to 2009 in production well RUK 5 at Rukungiri, Uganda (50-point moving average shown in green); observations after 2009 are excluded for clarity due to errors and inconsistencies



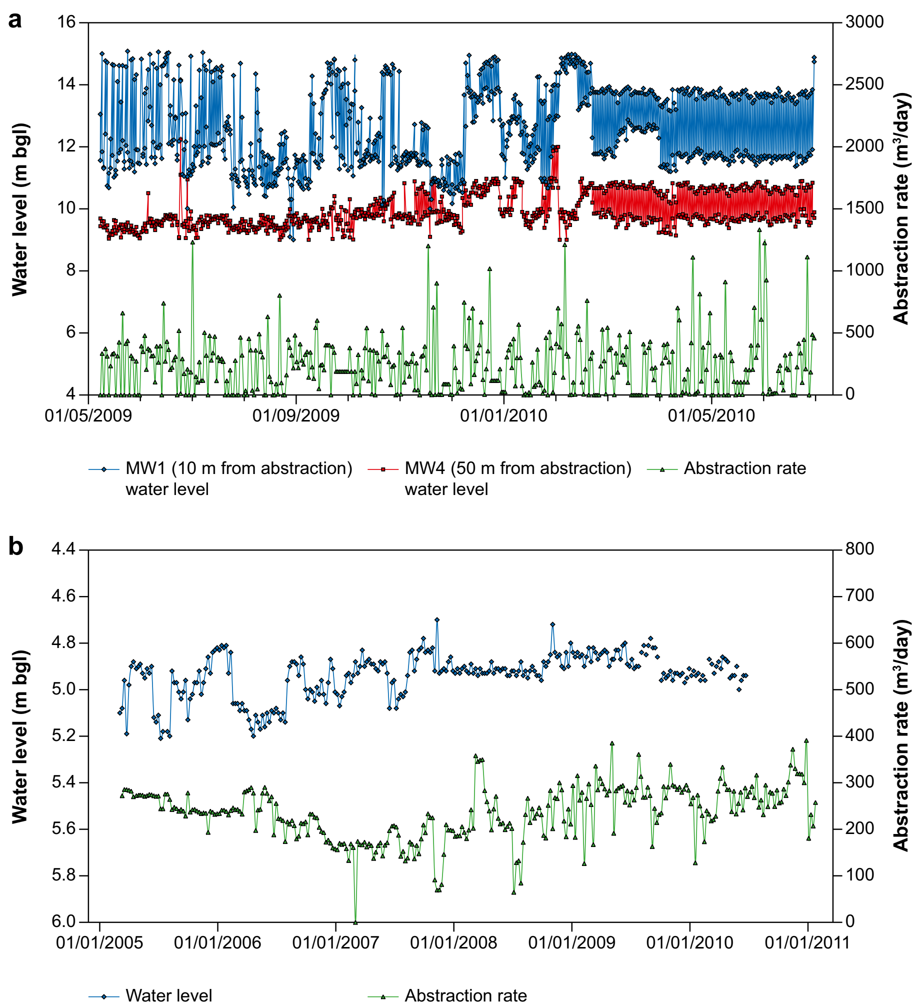


Fig. 5 Water level and abstraction data for **a** Mubende and **b** Seeta in Uganda

excess of present-day atmospheric equilibrium concentrations, indicating that they are highly contaminated (values italicised in Table 5), and these have not been corrected for excess air since they are not considered further. The source of contamination is likely to be terrigenic (Harnish and Eisenhauer 1998), and is of a similar order to that observed in the basement aquifers of Nigeria (Lapworth et al. 2013). By contrast, only one site had obvious CFC contamination: borehole 61/99 in Singida (elevated CFC-11 only). CFC contamination may stem from the inadequate containment of municipal waste (Höhener et al. 2003); however, a more serious consideration in the use of CFCs applied here is the possibility of microbial degradation under low-DO conditions (Oster et al. 1996), which would make waters appear to be older than they actually are. There are several instances where DO was below detection (<0.1 mg L^{-1}), most notably for the Makutapora samples. Given these potentially limiting factors, the results are most easily interpretable by cross-plotting residence-time indicators (Fig. 6).

Figure 6a shows a CFC co-plot. From the Ugandan sites, the Mubende samples lie on or near the piston-flow curve and range from relatively young (spring) to relatively old (DWD 18943). From their concordance with the curve, it is assumed that these waters have not been affected by CFC reduction. Although most of the Mubende samples cannot be tested against SF_6 owing to contamination, the spring sample plots adjacent to the piston-flow curve on the SF_6–CFC-12 plot (Fig. 6b) at approximately the same age as in Fig. 6a. According to Fig. 6a, the RUK 5 sample has either excess CFC-12 or reduced CFC-11; Fig. 6b suggests that the latter is more likely and that this water is a mixture containing ~70% modern water. One of the Seeta sites (DWD 25940) plots close to the mixing line in Fig. 6a, whereas the other may, like RUK 5, have undergone CFC-11 reduction; however, this cannot be verified in Fig. 6b since both sites have elevated SF_6.

The Makutapora samples all plot at close to zero in Fig. 6a. This would imply piston flow ages of 50–60 years or, if the water is mixed, a high proportion of pre-CFC water of unknown age. However, the fact that dissolved oxygen values are all below detection (Table 5) suggests that the CFCs are very likely to have undergone reduction and therefore can

Table 4 Water chemistry data

Borehole No.	Field SEC (μS cm^{-1})	Field pH	Field Eh (mV)	Field dissolved oxygen (mg L^{-1})	Field HCO_3^- (mg L^{-1})	Ca (mg L^{-1})	Mg (mg L^{-1})	Na (mg L^{-1})	K (mg L^{-1})	Cl^- (mg L^{-1})	SO_4^{2-} (mg L^{-1})	NO_3^- (mg L^{-1})	Mn (μg L^{-1})	Fe (μg L^{-1})
Rukungiri														
RUK 5	421–461	6.5	380	1.6	188	40	12	18	7.1	4.6	44	0.7	100	4
Mubende														
DWD 18836	410	6.0	449	0.3	109	22	12	21	2.8	24	38	3.1	1.3	3
DWD 18943	237–269	5.9	452	0.35–0.45	78	14	6.7	19	3.2	18	6.1	13	1.0	3
DWD 18944	231–232	6.1	434	0.1	108	14	7.2	19	2.0	8.4	5.2	0.7	2.8	3
DWD 18947	303–304	5.9	489	1.2	82	16	7.6	23	2.3	26	27	1.4	2.4	3
Spring	60–71	5.2	506	0.95–1.2	15	2.4	1.6	2.7	1.3	1.7	3.6	3.1	82	272
Seeta														
DWD 17465	129–136	5.7	372	1.3	51	8.1	2.9	8.1	3.6	1.6	4.3	4.6	4.3	16
DWD 25940	117–125	5.7	403	2.6	34	7.3	2.2	7.8	3.4	0.9	4.1	0.2	1.8	2
Makutapora														
332/01	1,016–1,030	7.1	273	0	386	60	25	109	6.3	67	67	1.9	2.7	3
327/01	1,008–1,036	7.1	278	0	396	57	24	107	6.0	74	72	2.9	0.6	7
117/75	1,081–1,147	7.1	289	0	328	59	27	102	6.0	108	75	27	0.3	4
326/01	1,084–1,128	7.1	297	0	358	63	29	110	6.5	109	82	33	0.3	5
325/01	1,070–1,071	7.2	232	0	321	51	24	102	5.9	91	83	22	0.5	8
333/01	1,033–1,048	7.0	271	0	346	54	26	97	6.1	91	84	20	1.0	3
147/78	1,055–1,059	7.1	262	0	289	57	27	94	6.3	94	86	27	0.4	3
Singida														
23/99	1,310–1,317	6.3	316	0	180	89	25	103	15	155	62	170	157	14
438/09	1,728–1,746	6.1	356	2.7	163	107	35	124	26	184	58	322	203	10
24/54	1,512–1,516	6.3	290	4.6–4.9	144	102	33	92	17	142	45	295	57	46
97/02	905	7.0	294	4.27	252	52	12	98	3.6	69	46	63	11	4
414/07	1,054	7.1	266	0	262	52	15	116	3.0	86	63	76	19	6
141/06	975–987	7.1	312	0.31	244	34	11	124	4.2	68	39	95	41	14
61/99	711–716	6.3	364	4.7–4.9	103	37	14	56	5.4	35	18	162	1.8	3
Artesian	1,785–1,883	7.5	242	0	287	56	14	226	8.6	329	74	1	33	5

Table 5 CFC and SF_6 results, including excess-air corrected values (SF_6c)

Borehole No.	CFC-12 (pmol L^{-1})	CFC-11 (pmol L^{-1})	SF_6 (fmol L^{-1})	SF_6c (fmol L^{-1})	Diss. O_2 (mg L^{-1})	NO_3^-N (mg L^{-1})
Rukungiri						
RUK 5	1.14	1.00	1.63	1.12	1.6	0.2
Mubende						
DWD 18836	0.26	0.53	*27.1*	–	0.3	0.8
DWD 18943	0.06	0.16	*40.1*	–	0.35–0.45	3.5
DWD 18944	0.42	0.55	*48.1*	–	1.2	0.4
DWD 18947	0.30	0.49	*11.7*	–	0.1	0.2
Spring	1.55	2.76	1.10	0.76	0.95–1.2	0.8
Seeta						
DWD 17465	1.40	1.04	*28.4*	–	1.3	1.2
DWD 25940	0.82	1.12	*48.4*	–	2.6	0.0
Singida						
23/99	0.35	0.63	*287*	–	<0.1	46
438/09	0.12	1.53	*84.1*	–	2.7	87
24/54	0.07	1.68	*26.1*	–	4.6–4.9	79
97/02	0.80	0.46	*319*	–	4.3	17
414/07	0.04	0.11	*573*	–	<0.1	20
141/06	0.00	0.76	*187*	–	0.31	26
61/99	0.75	*2.81*	*76.3*	–	4.7–4.9	44
Artesian	0.02	0.07	*97.1*	–	<0.1	0.3
Makutapora						
332/01	0.00	0.26	1.51	1.02	<0.1	0.5
327/01	0.03	0.07	0.62	0.42	<0.1	0.8
117/75	0.00	0.12	0.74	0.50	<0.1	7.3
326/01	0.11	0.20	1.51	1.02	<0.1	8.9
325/01	0.07	0.09	1.68	1.14	<0.1	5.9
333/01	0.00	0.09	2.10	1.42	<0.1	5.4
147/78	0.03	0.05	2.06	1.39	<0.1	7.3

Also included are dissolved O_2 and NO_3-N as indicators of redox status. Values in *italic* exceed present-day maxima for the temperature and pressure of equilibration

provide no precise age information (Darling et al. 2012). All SF_6 concentrations are less than the present-day equilibrium value (Fig. 6b) and suggest either mixed waters (from ~25 to ~90% modern) or piston-flow waters (from ~5 to ~25 years old), or some exponential flow scenario between these two types. However, the geological similarity of the Makutapora area to other areas in this study with clear SF_6 contamination means these figures should be regarded as upper limits for modern percentage, or lower limits for piston flow ages. For the Singida samples, the elevated CFC-11 value of sample 61/99, referred to earlier, suggests that CFC-11 contamination may have affected other samples from this area (Fig. 6a). Contamination might be expected at Singida, where very high nitrate (Table 4) is further evidence of high pollutant loading and rapid flow affecting these abstractions. With three exceptions (23/99, 414/7 and Artesian), values of DO and NO_3-N are above detection (Table 5) so CFC degradation is unlikely. The apparently unreduced CFC-12 values suggest residence times of >30 years, or mixtures with <50% modern water. The Singida samples have high levels of terrigenic SF_6 contamination which can provide no age information (Table 5).

Discussion

Groundwater residence times

The oldest groundwaters in this study appear to be from Mubende in Uganda, where interpreted mean residence times are around 40–50 years (except at the spring which has a residence time of ~10–15 years). At the other sites in Uganda, groundwater is mixed with ~45% modern fraction at Seeta and a ~70% modern fraction at Rukungiri. A sample from Rukungiri collected in 2000 indicated a modern fraction of 53% (Tindimugaya 2008), which is similar to the result of the current study. At Makutapora the residence time indicators suggest that

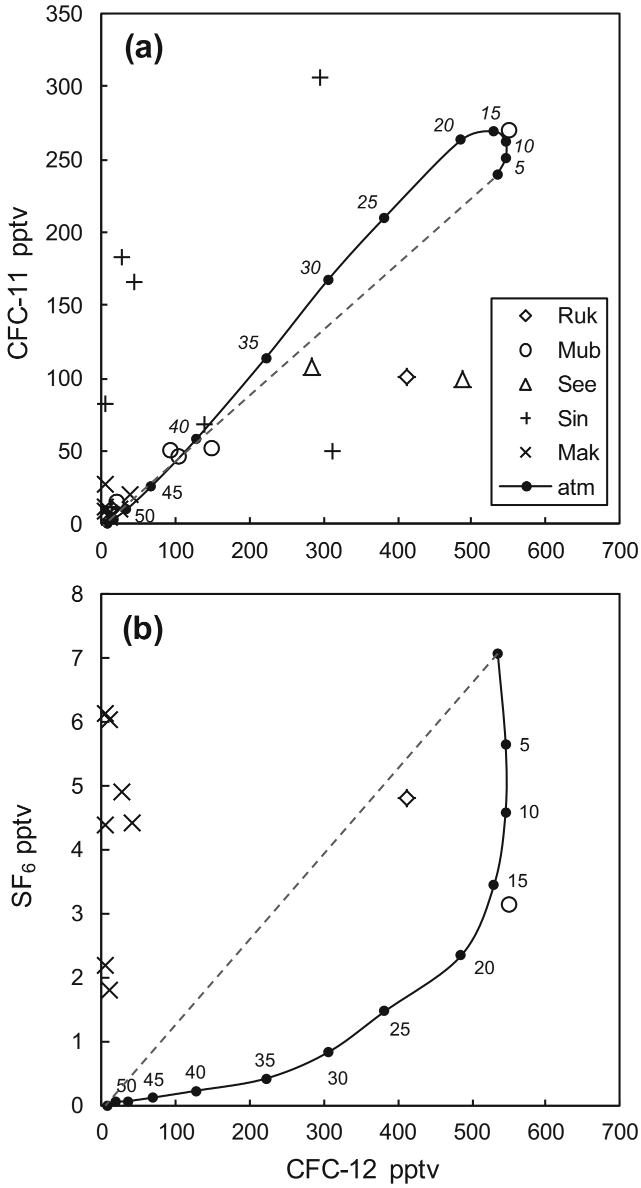


Fig. 6 Plots of residence-time indicators **a** CFC-11 vs CFC-12, **b** SF_6 vs CFC-12 for selected samples from Uganda and Tanzania. Measured dissolved values have been converted to the sea-level atmospheric equilibrium equivalent to allow comparison with the atmospheric trace gas mixing ratio record (USGS 2015). Also shown are the respective piston-flow curves ('atm') in 5-year age steps, and the binary mixing line (dashed) between modern and old water. Ruk Rukungiri, Mub Mubende, See Seeta, Sin Singida, Mak Makutapora

groundwater is from approximately 25–90% modern with a component of water likely to have a residence time >60 years. Sampled groundwaters from Singhida were mixtures with <50% modern water, or residence times of >30 years.

The results at Makutapora are consistent with previous studies in which (1) tritium data indicated residence times of several decades at Makutapora (Senguji 1999); (2) isotopes suggested local recharge at Makutapora with a strong component of bypass flow following high-intensity rainfall events (Nkotagu 1996a); and (3) high concentrations of nitrate were demonstrated (Nkotagu 1996b; but see also data in this study, Table 4). The results are also consistent with the findings of Taylor et al. (2013a) which demonstrated that recharge at Makutapora occurred episodically following intensive precipitation, on average two or three times each decade over the last 60 years (Fig. 3).

Overall the residence time data suggest that most abstracted waters derive, in part, from modern recharge (within the last 10–60 years), and that these high-intensity abstractions are supplied by aquifers recharged over multiple years rather than the most recent wet season. The results are similar to those obtained by Lapworth et al. (2013) from low yielding handpumps in basement and sedimentary aquifers in West Africa.

Factors enabling high-intensity abstraction

All five study sites have higher average borehole yields than typically found in crystalline bedrock aquifers (Bonsor and MacDonald 2010; MacDonald et al. 2012). Higher yields have also been observed in other weathered crystalline bedrock aquifers—for example, mean yields from 314 water wells of 50–150 m depth in areas of low-grade metamorphic and igneous rocks, and high-grade metamorphic rocks in Ethiopia, varied from 1.5 to 5.7 L s^{-1}; see Deyassa et al. 2014) who propose that aquifer properties depend on the thickness of weathering profiles, the degree of fracturing, and whether overlying sediments are present. Other studies have also looked at the factors controlling aquifer properties in weathered crystalline bedrock aquifers—for example, a study of 8,000 borehole records in crystalline bedrock aquifers of the Limpopo Province in South Africa investigated factors influencing productivity (Holland and Witthüser 2011). The authors concluded that bedrock type, topographic and lithological setting, and proximity to surface water all affected aquifer properties; the presence of transmissive heterogeneities such as dykes and lineaments was considered the most important factor.

At the study sites in Uganda and Tanzania, groundwater residence times of several decades suggest that high yields are occurring where there is a combination of favourable conditions for groundwater storage (e.g. coarse and thick saprolite or overlying alluvium) and high aquifer transmissivities. Topographical and geological data suggest that the storage may be due to large drainage basin areas and/or a large saturated thickness. The drainage basin areas vary (Table 1), and the sites with larger drainage basins tend to have higher yields. Topographically defined catchment areas in Uganda are smaller than those in Tanzania, which may be because the threshold volumetric recharge flux required to sustain abstraction, can be met over a smaller area in humid climates than in semi-arid climates. In principle, the storage and transmissivity per unit area may be high due to geological factors such as enhanced fracturing or faulting of the bedrock (e.g. Perrin et al. 2011; Roques et al. 2014); weathering enhanced fracture permeability (Lachassagne et al. 2011); coarser saprolite (e.g. Chilton and Foster 1995; Taylor and Howard 2000); or the presence of sediments overlying the weathered crystalline aquifer system (e.g. Deyassa et al. 2014).

Generally, there are insufficient geological data at the study sites to determine if there is a particularly high degree of fracturing or faulting; however, all sites abstract, in part or in whole, from bedrock, suggesting well-developed fracture networks are required to convey groundwater to the pumping boreholes. At Makutapora, large-scale discontinuities and dense fracture networks associated with faults such as the Mlemu Fault coincide with high well yields (Rwebugisa 2008). Geological data indicate the presence of alluvial sediments overlying the weathered bedrock at four out of the five sites (Tables 2 and 3). The presence of these superficial deposits may increase overall aquifer thickness and, thus, storage available to the aquifer, as well as providing recharge pathways to the underlying saprolite (e.g. Taylor and Howard 2000; Maréchal et al. 2004; Dewandel et al. 2006; Deyassa et al. 2014). Determining the hydrogeological role of superficial sediments is complicated by uncertainties in interpreting borehole logs and the high heterogeneity and local variability in sediment thickness. Bradley (2012) analysed pumping test data from boreholes in weathered/fractured bedrock with overlying fluvio-lacustrine sediments and found that the sediments have generally higher transmissivity than the bedrock. Alluvial aquifers in Malawi have yields of >10 L s^{-1}, which is higher than most yields from crystalline bedrock (Mapoma and Xie 2014).

Overall, in the semi-arid climate of Tanzania, large basins infilled with alluvium overlying saprolite and saprock provide substantial storage which is hydrologically connected to the underlying saprolite and saprock, and contributes to the high yields. The anomalously high transmissivity at Makutapora may arise from both faulting and the thickness of the unconsolidated sediments comprising saprolite and alluvium. At two sites in Uganda (Mubende and Rukungiri) topographically defined catchment areas are smaller and there are higher annual recharge rates under a humid equatorial climate. Unconsolidated sediments also provide additional storage at these sites where there is a substantial saturated thickness of saprolite and coarse-grained, sorted (e.g. alluvial) sediments (Table 3). At Seeta in Uganda, the topographical catchment is small and it may be that high yields result from a dense network of fractures in the crystalline bedrock aquifer, and/or a substantial thickness of weathered saprolite.

Sustainability of high-intensity abstraction

Residence times of several decades at the study sites suggest that whilst abstractions are not mining pre-modern groundwater free of anthropogenic gases (CFCs and SF_6), it is likely that they may incorporate a component of older groundwater. Whilst precise definitions of the sustainability of groundwater abstraction are complicated by transience in hydraulic responses to pumping (e.g. Devlin and Sophocleous 2005), the long-term viability of high-intensity groundwater abstractions depends, in part, on whether there is sufficient recharge replenishing abstracted water. Substantial recharge may not occur on an annual basis. Long-term groundwater level data from the Makutapora Wellfield in Tanzania indicate high inter-annual variability in recharge that is primarily restricted to exceptional seasonal rainfalls associated with El Niño events (Taylor et al. 2013a). Consequently, the long-term viability of high-intensity groundwater abstractions in these relatively low storage aquifers depends on the long-term availability of sufficient recharge to replenish the abstracted water.

The study considers two conceptual scenarios. In scenario 1, mean annual abstraction (over multi-decadal timescales) exceeds mean annual recharge (over multi-decadal timescales) so that groundwater storage declines and abstraction becomes unsustainable. In scenario 2, pumping abstracts either primarily modern water recharged over recent decades or primarily pre-modern water that is replaced by modern recharge over decadal timescales. For scenario 2, abstraction may exceed recharge in some years, whereas in other years recharge may exceed abstraction; however, over decadal timescales, abstraction does not exceed recharge. Under this scenario, abstraction rates are sustainable, assuming current recharge conditions persist. This situation is, however, only possible in aquifers with sufficient storage capacity to store episodic recharge.

Evaluating the sustainability of high-intensity abstractions is critical because unsustainable groundwater use can reduce access to freshwater for domestic, agricultural and industrial purposes, increasing poverty and impairing agricultural and industrial productivity—for example, in India, abstraction from weathered crystalline aquifers is leading to substantial declines in groundwater levels (Perrin et al. 2011; Ferrant et al. 2014). Assessments of the long-term sustainability of intensive groundwater abstraction require accurate long-term (i.e. multi-decadal) groundwater-level monitoring, combined with abstraction and precipitation data, to ascertain whether abstraction is causing a sustained decline in the groundwater storage. At the study sites in Tanzania and Uganda, such data are only available for the Makutapora Wellfield in Tanzania. The study by Taylor et al. (2013a) shows that although abstraction has caused sharp declines in groundwater levels, episodic recharge associated with high rainfall during the El Niño years has led to sharp recovery in groundwater levels, so that contemporary groundwater levels are similar to predevelopment groundwater levels in 1954. Under current climate conditions, abstraction rates appear sustainable over decadal timescales, with recharge sufficient to replenish decadalscale abstraction (scenario 2). A key uncertainty is whether the recent, further intensification of abstraction at the Makutapora Wellfield can be sustained by induced recharge or will lead to groundwater depletion.

Climate conditions are different in humid tropical Uganda relative to semi-arid Tanzania, and higher rainfall may enable more sustainable groundwater abstraction with higher yields per unit area of aquifer—for example, at Rukungiri, a high transmissivity allows intensive abstraction yet available storage is constrained geologically within a small topographically defined catchment area (Tindimugaya 2008). Here the sustainability of intensive abstraction depends on regular, annual replenishment. Limitations in currently available monitoring data make it difficult, however, to assess the sustainability of the high-intensity abstractions in Uganda.

The long-term viability of high-intensity abstractions also depends on their resilience to climate change and drought. Large groundwater bodies with high storage and a component of long-residence groundwater are least affected by short-term droughts (Taylor et al. 2013b; Foster and MacDonald 2014). However, in lower storage aquifers, recharge is required in most years to support high abstraction—and these aquifers are therefore more vulnerable to short-term drought. In this current study, mean groundwater residence times of several decades suggests that groundwater storage is sufficient to store several years recharge and therefore the aquifers may have some in-built resilience to short-term shocks. Understanding aquifer resilience to long-term climate changes requires knowledge of inter-annual variability in recharge over multi-decadal timescales afforded by long-term high-resolution recharge, abstraction and groundwater level data.

Conclusions

The hydrogeological characteristics of weathered crystalline bedrock aquifers sustaining high-intensity groundwater abstractions from three sites in humid-tropical Uganda, and two sites in semi-arid Tanzania, were investigated. Transmissivities of 10^1 m^2 day^{-1} in Uganda and 10^3 m^2 day^{-1} in Tanzania are particularly high for these types of aquifers. The evidence suggests that the presence of overburden storage and high transmissivities enables and sustains high-intensity abstractions, especially in semi-arid Tanzania where annual recharge is highly variable and episodic. Faulting and fracturing is likely to be a key factor enabling high-intensity abstraction. At four of the five sites, the weathered crystalline bedrock aquifer system of saprock and saprolite is overlain by unconsolidated sediments (e.g. alluvium), which may provide an important recharge pathway and a source of additional groundwater storage, and increase the saturated thickness of the underlying crystalline bedrock aquifer. Evidence from residence-time indicators sampled from production boreholes shows a mixture of groundwater ages and includes a substantial proportion of modern water recharged within the last 10–60 years. Abstraction of groundwater recharged over many decades provides a degree of resilience to climate change and short-term droughts at the sites under investigation.

Long-term (multi-decadal), high-intensity (>1 L s^{-1}) groundwater abstraction at five sites within deeply weathered crystalline bedrock in East Africa demonstrates the feasibility of such abstraction from these aquifer systems. Intensive groundwater abstraction in these environments may prove a viable alternative to the conventional water-supply approaches of storing surface water in reservoirs to address rising demand for domestic and agricultural water supplies in Sub-Saharan Africa. The sustainability of intensive groundwater abstraction is constrained, in part, by high inter-annual variability in recharge. Sustained monitoring of groundwater levels, pumping rates, and rainfall, as shown here at one site in Tanzania, are invaluable in assessing the viability of intensive abstraction from this complex and highly variable aquifer system.

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