Case study note: Resilience of intensive groundwater abstraction from weathered crystalline rock aquifer systems to climate change in sub-Saharan Africa

Groundwater Programme

Internal Report IR/10/105

BRITISH GEOLOGICAL SURVEY

GROUNDWATER PROGRAMME

INTERNAL REPORT XX/00/00

Case study note: Resilience of intensive groundwater abstraction from weathered crystalline rock aquifer systems to climate change in sub-Saharan Africa

L Maurice, R Taylor, A. MacDonald, H Sanga, P. Johnson, G Darling, and D Gooddy

Keywords

Groundwater, climate, Africa, residence times.

Front cover

Sampling in Tanzania.

Bibliographical reference

MAURICE, L., TAYLOR, R., MACDONALD, A., SANGA, H., JOHNSON, P., DARLING W., AND GOODDY, D.. 2010. Case study note: Resilience of intensive groundwater abstraction from weathered crystalline rock aquifer systems to climate change in sub-Saharan Africa. *British Geological Survey Internal Report*, XX/00/00. 37pp.

Keyworth, Nottingham British Geological Survey 2010

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461
www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

In 2010 the Department for International Development (DFID) research programme commissioned a BGS-led team to undertake a one-year study aimed to improve understanding of the resilience of groundwater in Africa to climate change and links to livelihoods. As part of this project, the research team undertook hydrogeological field studies in West and East Africa, examined the linkages between water use and household economy, and developed an aquifer resilience map for Africa using existing hydrological maps and data. This is one of a series of technical notes which describes the studies carried by the research team under this project.

This report describes the methodology and results of the East Africa hydrogeological case study, undertaken by University College London and the British Geological Survey. The aim of this case study is to investigate the resilience of intensive groundwater abstractions from weathered crystalline rock aquifer systems to climate change. The sustainability of such abstractions was investigated by examining historical aquifer responses to climate and intensive (> 1 L/s) abstraction, and investigating groundwater residence times at sites of intensive groundwater abstraction using multiple tracers: chlorofluorocarbons (CFCs), sulphur hexafluoride (SF_6) and tritium ($^3H/^3He$). This case study was carried out in Tanzania and Uganda.

Acknowledgements

The authors would like to thank many people who have contributed to this work, including staff at:

- the Rwenzori Beverage Company Limited,

- Ministry of Water & Environment (Uganda),

- National Water & Sewerage Company in Mubende (Uganda),

- Internal Drainage Basin Office and Wamaruvu Basin Office of the Ministry of Water & Irrigation, Tanzania

Contents

Foreword i

Acknowledgements i

Contents ii

Summary iv

1 Introduction 1

2 Project partners 1

3 Background 1

4 Field studies 4

4.1 Introduction 4

4.2 Methodology 4

4.3 Preliminary Results - Uganda 6

4.4 Preliminary Results – Tanzania 18

5 Pumping test analysis 25

6 Conclusions 26

References 27

FIGURES

Figure 1 Map of East Africa showing the locations of study sites in Tanzania and Uganda. 4

Figure 2 Daily pumping rate at DWD18836, Mubende 11

Figure 3 Water level data for monitoring boreholes near DWD18836, Mubende 12

Figure 4 Water level data for boreholes 1 and 2 from May 2009-February 2010 12

Figure 5 Water level data for boreholes 3 and 4 from May 2009-February 2010 13

Figure 6 Weekly pumping rate in Rwenzori bottling company borehole 1 15

Figure 7 Water level in Rwenzori bottling company borehole 1 15

Figure 8 Comparison of weekly pumping rate and water level in Rwenzori bottling company borehole 1 16

Figure 9 Daily rainfall and groundwater levels recorded in a seasonally humid environment (Apac Town) in northern Uganda. 17

Figure 10 Daily rainfall and groundwater levels recorded in a semi-arid environment (Rwonyo) in southwestern Uganda. 17

Figure 11 Map of the Makutapora Depression and Wellfield, north of Dodoma in central Tanzania showing the locations of monitoring wells and sampled production boreholes. 18

Figure 12 Annual rainfall recorded at the Makutapora Meteorological Station (1922 to 2003). 23

Figure 13 Changes in hydraulic head for monitoring well 234/75 in the Makutapora Wellfield (Figure 11) from 2002 to 2006. 23

Figure 14 Time series of groundwater levels in monitoring well 234/75 within the Makutapora Welfield (Figure 11) from 1990 to 1999. Note the strong positive deflection in the groundwater levels in response to exceptionally high rainfall associated with positive phases in ENSO-IOD in 1997/1998 (months 96-108). 24

TABLES

Table 1 Borehole information, Uganda 7

Table 2 Borehole geology, Uganda 7

Table 3 Field chemistry data, Uganda 8

Table 4 Preliminary CFC and SF6 data for Uganda 9

Table 5 Pumping test data analysis for boreholes at Mubende 13

Table 6 Transmissivity of boreholes at the Rwenzori site 16

Table 7 Borehole information - Tanzania 19

Table 8 Borehole geology - Tanzania 20

Table 9 Field chemistry data - Tanzania 21

Table 10 Preliminary CFC and SF6 data - Tanzania 22

Table 11 Preliminary results of pumping test analysis, Uganda (T derived from Theis recovery method in AQTESOLV). 25

Summary

In October 2010 field studies were carried out in three areas in Uganda and two areas in Tanzania with the aim of assessing the resilience of larger borehole abstractions in weathered and fractured basement aquifers to climate change. Larger abstractions are defined as those using electrical pumps with yields of > 1 l/s.

At each site one or more boreholes were sampled for residence time indicators including chloroflurorcarbons (CFC-12, CFC-11), sulphur hexafluoride (SF_6) and tritium. In addition field chemistry parameters were measured (pH, SEC, dissolved oxygen (DO), Eh (redox potential), and temperature), and samples were taken for laboratory analysis for major ions, dissolved organic carbon and fluorescence.

Where possible, borehole logs were obtained for the sample sites to determine the geology. Monitoring data (groundwater level, abstraction, and rainfall) was also sought at each study area to enable the impacts of climate and abstraction on groundwater levels to be assessed.

Preliminary results/discussion points are listed below:

1. In Central Tanzania at the Makutapora Depression (Wellfield) there are a series of unusually high yielding boreholes (up to 93 m^3/hour). A thick (>30m) sequence of sediments overlying the unconsolidated weathered basement and fissured bedrock at this location is thought to provide substantial groundwater storage to sustain the high yields.
2. At Makutapora, a benchmark dataset comprising a 55-year record of groundwater levels, rainfall and abstraction is being assembled from digital information, chart recordings, and a series of historical plots uncovered through this research. These data provide an early indication of the pivotal importance of extreme events of very high rainfall in sustaining intensive groundwater abstraction at this site. Exceptionally high, seasonal rainfall associated with years featuring strong positive phases in the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (e.g. 1963, 1972, 1982 and 1997/8), gives rise to substantial recharge leading to sharp rises in groundwater levels that typically follow a steady declining trend (1 m/year) during most, other years.
3. Yields from boreholes in other study sites in Tanzania and Uganda are not as high as those in Makutapora but are still higher than are typically encountered in weathered and fractured basement aquifer systems (~ 5 to 20 m^3/hour). Geological information is limited for several of these sites but these higher yields appear to depend upon the presence of permeable alluvial and fluvio-lacustrine sediments with high storage overlying weathered basement rocks.
4. Preliminary CFC results suggest that CFCs may be affected by degradation at some sites, particularly in waters with very low dissolved oxygen (below about 0.5 mg/l). Preliminary SF_6 data suggest that at some sites SF_6 is an unsuitable residence-time indicator because of in situ contamination from the host bedrock. However, combined CFC and SF_6 residence-time data indicate a component of modern recharge water (i.e., recharged in the last 10-30 years) at all sampled locations.
5. The results from our study sites in East Africa suggest that in areas featuring high groundwater storage, anomalously high recharge fluxes associated with extreme rainfall events may sustain intensive groundwater abstraction over many years and thereby provide a degree of resilience to climate variability and change. Indeed, the potential for high groundwater abstraction, resilient to climate variability, for irrigation and town water supplies likely exists elsewhere in hard-rock environments with similarly favourable geological conditions (e.g. thick sedimentary sequence overlying weathered basement rocks) and episodically high seasonal rainfall.

6. The dependence upon episodic, extreme rainfall events greatly complicates groundwater management and determination of "sustainable yield". The benchmark dataset at Makutapora highlights, nevertheless, the importance of long-term monitoring of groundwater levels, abstraction and rainfall to assess effectively the sustainability of intensive abstraction in terms of decades rather than hydrological years as is currently the norm.

1 Introduction

The British Geological Survey (BGS), University College London (UCL) and the Overseas Development Institute (ODI) conducted a one year DFID-funded research programme, aimed at improving understanding of the impacts of climate change on groundwater resources and local livelihoods – see http://www.bgs.ac.uk/GWResilience/. This study involved three components: (1) Construction of an aquifer resilience map for Africa using existing hydrogeological data. (2) A case study in West Africa to assess the vulnerability of rural water supplies to climate change using groundwater residence time indicators. (3) A case study in East Africa lead by University College London to investigate the resilience of larger borehole abstractions.

This report describes the methodology, and preliminary results of the East Africa hydrogeological case study, carried out in Tanzania and Uganda. The aim of this case study was to investigate the resilience of intensive groundwater abstractions from weathered crystalline rock aquifer systems to climate change. In this hydrogeological context intensive groundwater abstractions are defined as those with abstraction from multiple boreholes using submersible pumps with individual borehole yields of > 1 l/s. The study involved sampling boreholes for residence time indicators: chlorofluorocarbons (CFCs), sulphur hexafluoride (SF_6) and tritium ($^3H/^3He$), and collating hydrogeological information for the study sites. These data were then used to assess the timescales over which recharge occurs to provide an indication of aquifer resilience.

2 Project partners

Project partners were involved in all stages of the case study including site selection, field data collection and interpretation of results. Project partners include:

Uganda:

Dr Callist Tindimugaya, Ministry of Water and Environment, Uganda

Dr Michael Owor, Department of Geology, Makerere Unviersity, Uganda

Mr Rashid Kisomose, Ministry of Water and Environment, Uganda

Tanzania:

Mr Lister Kongola, Ministry of Water and Irrigation, Tanzania

Mr Alloice Kaponda, Ministry of Water and Irrigation, Tanzania

Mr Renatus Shinhu, Ministry of Water and Irrigation, Tanzania

Dr Ibrahimu Mjemah, Sokoine Unviersity of Agriculture, Tanzania

3 Background

There is a long history of low-intensity, handpump abstraction of groundwater (< 0.2 L/s) for domestic rural water supplies throughout sub-Saharan Africa (SSA). Low annual recharge fluxes (1-10 mm/year) required to sustain this abstraction (Taylor & Howard, 1995; MacDonald et al., 2009), are expected to occur in most humid regions. Stable, though seasonally variable, groundwater levels observed in rural Uganda (Owor et al., 2009) and Benin (Totin et al., 2009) support this assertion. In semi-arid areas of Africa, recharge occurs more intermittently (Adanu, 1991; Nkotagu, 1996; Edmunds, 2009; Olago et al., 2009; Gavigan et al., 2009; Miguel et al., 2009) so that low-intensity abstraction relies upon inter-annual groundwater storage.

Intensive abstraction of groundwater in SSA using submersible pumps (> 1 L/s) began over the second half of the 20th century primarily in association with urbanisation. Groundwater is a low-cost alternative to surface water for town water supplies on account of its widespread distribution and generally potable quality that avoid the expense and management of conveyance and sophisticated treatment. Despite a growing dependency upon groundwater for town water supplies in SSA (Taylor et al., 2004; Braune & Xu, 2010) – a trend which is expected to increase substantially as the urban population of SSA triples between 2000 and 2050 (UN, 2007) - the sustainability of intensive groundwater abstraction is unclear (Taylor & Howard, 2000). Indeed, few reliable groundwater data exist upon which abstraction policies can be based (MacDonald et al., 2009).

A shift toward more intensive abstraction of groundwater in SSA is also expected for food production as countries seek to reduce their dependence upon highly variable soil moisture by increasing the proportion of arable land under irrigation. Since climate change is projected to exacerbate hydrological variability (Mileham et al., 2009; Nyenje & Batelaan, 2009) and to influence not only seasonality in precipitation (Kingston & Taylor, 2010) but also its predictability (Kniveton et al., 2009), development of groundwater for irrigation by small-scale farmers in SSA is a logical adaptation strategy to enhance food security. The possibility that small (5 to 10%) reductions in rainfall as a result of climate change will substantially impact riverflow, soil moisture, and groundwater recharge in semi-arid regions of SSA (e.g. Cavé et al., 2003; Wit & Stankiewicz, 2006; Döll, 2009), is of concern. Indeed, the viability of large scale groundwater-fed irrigation as a general strategy to adapt to climate variability and change is open to question.

The resilience of intensive groundwater abstraction from weathered crystalline rocks, which underlie 34% of SSA, is most unclear. Saprolite and saprock which comprise an unconsolidated weathered (in situ) overburden and underlying fractured bedrock respectively, form one of the most heterogeneous and least well understood aquifer systems in the world. Aquifers in saprolite and saprock are characterised by low transmissivity and storage though few reliable measures of the latter exist (Taylor et al., 2010). Sustained abstraction from saprock has long been thought to depend upon leakage from the overlying, more porous saprolite (Chilton & Smith-Carington, 1984; Kafundu, 1986; Acworth, 1987; Houston & Lewis, 1988; Chilton & Foster, 1995; Owoade, 1995; Maréchal et al., 2004). Piezometric evidence from pumping tests in India (Sekhar et al., 1994) and Uganda (Taylor & Howard, 2000) supports this assertion but it is unclear whether this is a widespread property of saprolite-saprock aquifer systems.

Notwithstanding concerns over sustainability of intensive groundwater abstraction from saprolite and saprock aquifers, it has occurred at several locations in SSA (e.g. Dodoma, Tanzania; Kampala, Uganda) for many years and, in some cases, decades. The local hydrogeological conditions that sustain intensively pumped boreholes in saprolite or saprock have not been subject to detailed scrutiny. In most cases, it is uncertain whether intensive groundwater abstraction is sustained by active (contemporary) recharge or draws from long-term storage. Recent research from two, well instrumented wellfields in humid areas of Uganda shows both to be actively recharged yet a substantial decline in groundwater levels is observed at one of these sites where intensive abstraction drains a bounded aquifer in saprolite (Tindimugaya, 2008). An improved understanding of the hydrogeological characteristics of saprolite-saprock aquifer systems that sustain intensive groundwater abstraction is urgently required not only to guide future groundwater development but also to evaluate the viability of groundwater development as an adaptive strategy to increased freshwater demand as well as climate variability and change.

The overall aim of this case study is to assess the resilience of intensive groundwater abstraction from saprolite-saprock (weathered basement) aquifer systems to increasing freshwater demand as well as climate variability and change in sub-Saharan Africa. Specifically the study aims to (1) determine the generic hydrogeological characteristics of saprolite-saprock aquifer systems that are intensively abstracted (2) determine the contribution of contemporary recharge to these aquifer systems.

4 Field studies

4.1 INTRODUCTION

Field studies were carried out at 5 sites of intensive groundwater abstraction in Uganda and Tanzania (**Figure 1**). At 4 sites, boreholes and wellfields provided town water supplies. At one location in Kampala, work took place at a commercial location, Rwenzori Beverage Company in the suburb of Seeta.

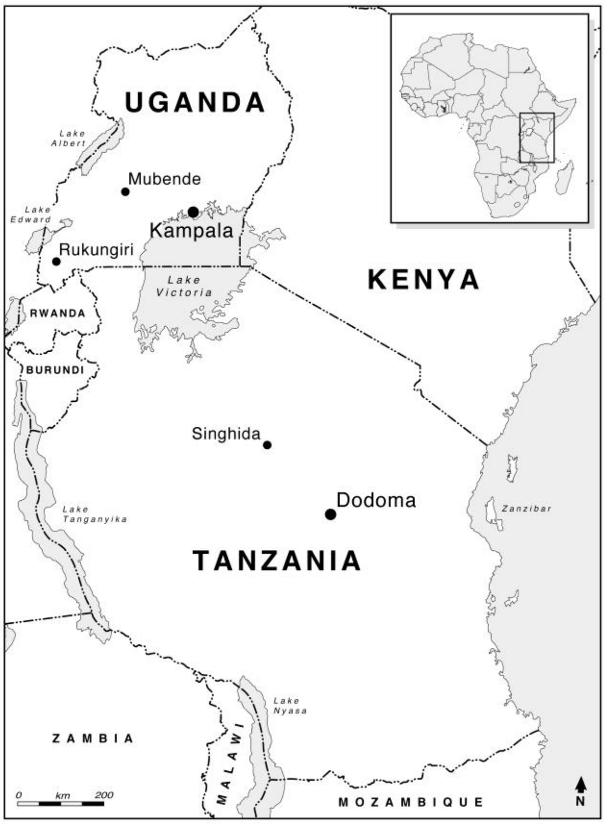

Figure 1 Map of East Africa showing the locations of study sites in Tanzania and Uganda.

4.2 METHODOLOGY

4.2.1 General methodology and rationale

Three complimentary activities were carried out at the study sites to assess the sustainability of the abstractions and their resilience to climate change:

- Boreholes were sampled to investigate groundwater residence times using three environmental tracers: chlorofluorocarbons (CFCs), sulphur hexafluoride (SF_6) and tritium ($^3H/^3He$). The rationale for this is that if groundwater residence times are very short (< 10 years) and depend upon annual recharge then the supplies will be more vulnerable to climate change. If groundwater residence times are longer (10-50 years) then there may be more resilience to climate change in the short term, and if groundwater residence times are very long (>50 years) then abstractions may not be very vulnerable to climate change but they may be less sustainable in the longer term if abstracted water is not replenished by recharge. All residence time data are estimates of bulk residence time as samples contain a mixture of varying proportions of groundwaters with different residence times.

- At each study site, where available, groundwater level, rainfall, and abstraction data were collated to investigate whether abstraction is causing a decline in groundwater levels, and to assess how groundwater levels respond to rainfall. In addition, groundwater level and rainfall data for boreholes in Uganda that are remote from abstraction were reviewed in order to provide a baseline dataset of climate variability and groundwater levels. Data collection also aimed to establish whether there are benchmark datasets that can be used to assess groundwater response to abstraction and climate change.

- Where available, pumping test data were examined to investigate the hydrogeological properties of the study site. Some additional pumping test data from other intensive abstractions was used to investigate whether aquifer properties at the study sites are typical.

4.2.2 Borehole sampling methods

At each borehole tubing was connected to a sampling tap or valve with a good seal 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 long two routes. Probes were placed in a flow through cell connected to one length of tubing to measure dissolved oxygen (Mettler meter), pH (Thermo Orion meter) and Eh (Mettler or Hanna meter). Specific electrical conductance (Mettler meter) and temperature were measured in a bucket fed via a second length of tubing from the Y connector. All meters were calibrated in the morning prior to sampling, and readings were only recorded when they stabilised. Sampling was only carried out once readings had stabilised and a second set of measurements were made at the end of sampling.

The tubing feeding the bucket was used to obtain samples (Plate 1). Samples for cation and anion analysis were filtered and the cation sample was acidified in the field. Samples for DOC/Fluorescence analysis were filtered and collected in glass tubes. Samples for tritium and stable isotope analysis were collected directly from the sampling tube. Bicarbonate Alkalinity was measured in the field using a Hach titration kit. CFC and SF_6 samples were taken under water in the bucket to avoid contamination of samples from the atmosphere. Sample tubing was placed in the inner sample vessels and water was added until the inner and outer sample vessels and the bucket were filled and it was clear that the new water being added to the inner sample vessel could not come into contact with the atmosphere. The inner and outer sample vessels were then sealed under water. At most sites a good seal was present throughout the sampling system and it was considered unlikely that any contamination from the atmosphere occurred.

Plate 1: Field sampling in the Makutapora Wellfield, Tanzania

4.3 PRELIMINARY RESULTS - UGANDA

Information about the boreholes sampled is presented in Table 1 and Table 2, and field chemistry data are presented in Table 3. Note that there were problems with the Eh probe and at most sites a stable reading was not reached over periods of 15-30 minutes. Table 4 summarises the results for the residence time indicators. SF6 results assume an excess air factor of 0.6. Each site studied is discussed individually below.

`

Location	borehole	sample no	East	north	grid	altitude	date drilled	depth (m)	yield (log) m3/hour	pumping/discharge (m3/hour)	T (m2/day)
Rukungiri	RUK 5	U1	826287	9913616	35m	1582		89		70 m3/day	
Mubende	dwd18836	U2	324729	60984	36n	1225	Oct-03	63.75	>35	4 to 20	96
Mubende	dwd18943	u3	342749	60984	36n	1226	Nov-03	61	31		58
Mubende	spring	u4	320424	63300	36n	1321	n/a	n/a	n/a	~ 10.8 (est)	n/a
Mubende	dwd18944	U5	326088	63604	36n	1235	Jan-04	54.57	17		pule?
Mubende	dwd18947	U6	324021	61613	36n	1239	Feb-04	57.65	13.4		no data
Rwenzori Bev. Co.	1	U7	465978	40455	36n	1182	Dec-02	60	20.6	16	70
Rwenzori Bev. Co	2	U8	465972	40665	36n	1183	Nov-07	70	5.6	5	7.7
Rwenzori Bev. Co.	3	U9	466094	40378	36n	1185	NO CFC/SF6 data				

Table 1 Borehole information, Uganda

borehole	geology (sections with open casing)	slotted casing (m)	water strikes	dip when drilled (m bgl)
RUK 5	Alluvium and fractured gneiss	44-51	55 and 69	
dwd18836	weathered granite	25.25-33.5, 36.25-58.25	major 41 m, also 22,32,34,41	4
dwd18943	weathered rock and gneiss	slotted from 30.73-55.48	major 44, also 29,50	16.35
spring		n/a	n/a	n/a
dwd18944	weathered rock, quartzite veins, amphibolite	30.97-39.19, 41.93-50.15, 52.89-54.42	major 36, also 24	15.01
dwd18947	weathered rock and granite	26-42.5, 45.25-53.5	major 30-35, also 18 and 41	14.02
rwenzori 1	weathered granite	32-36m, 41-45m, 52-56 m	25,33	no data
rwenzori 2	weathered and fractured granite/gneiss	34.25-37.00 m, 42.25-48 m, 53.5-59, 64.5-67.25	33-36, 45-48, 60-66	no data

Table 2 Borehole geology, Uganda

borehole	date	time	temp (dC)	SEC (uS/cm)	pH	Eh	DO (%)	DO mg/l	Bicarbonate Alkalinity (mg/l)	notes on CFC and SF6
RUK 5	07/10/2010	12:09-12:51	27.1-27.2	421-461	6.51-6.54	380	22.2	1.6	188	moderate
dwd18836	08/10/2010	11:52	21.6	410	5.99	449	3.5	0.3	109	good
dwd18943	08/10/2010	16:07-16:46	21.1-21.3	237-269	5.9-5.92	452	4.4-5.4	0.35-0.45	78	good
spring	08/10/2010	18:18-18:52	22.4	60-71	5.17	506	13-15	0.95-1.2	15	moderate
dwd18944	09/10/2010	09:59-10:32	21.4	231-232	6.08	434	2.1	0.1	108	good
dwd18947	09/10/2010	11:07-11:41	22.1	303-304	5.88	489	15.4	1.2	82	good
rwenzori 1	11/10/2010	11:20-12:15	23.6-23.9	129-136	5.67	372	19	1.3	51	good
rwenzori2	11/10/2010	12:33-12:53	23-23.4	117-125	5.73	403	35	2.6	34	good
rwenzori 3	11/10/2010	13:39	23.3	236	6.18	-	-	-	-	no CFC/SF6 taken because air in tube

Table 3 Field chemistry data, Uganda

Sample	location	CFC-12 pmol/L	CFC-11 pmol/L	CFC-12 modern fraction	CFC-11 modern fraction	CFC-12 year of recharge	CFC-11 year of recharge	DO	SF6 fmol/L	SF6 Modern Fraction	SF6 year of recharge
U1	Rukungiri	1.140	1.005	0.729	0.399	1985	1974	1.6	0.98	0.6	1990
U2	mubende	0.262	0.534	0.168	0.212	1967	1969	0.3	16.26	9.7	> modern
U2D	mubende	0.299	0.562	0.192	0.223	1968	1970	0.300	16.56734	9.9	> modern
U3	mubende	0.058	0.163	0.037	0.065	1956	1962	0.35-0.45	24.03326	14.4	> modern
U4	spring mubende	1.552	2.756	0.993	1.094	1995	1990	0.95-1.2	0.659452	0.4	1985
U5	mubende	0.424	0.550	0.271	0.218	1971	1969	0.1	28.84356	17.3	> modern
U6	mubende	0.296	0.486	0.189	0.193	1968	1969	1.2	7.027326	4.2	> modern
U7	rwenzori	1.404	1.035	0.898	0.411	1989	1974	1.3	17.02508	10.2	> modern
U8	rwenzori	0.817	1.119	0.523	0.444	1978	1974	2.6	29.04705	17.4	> modern

Table 4 Preliminary CFC and SF6 data for Uganda

4.3.1 Mubende

4.3.1.1 MUBENDE FIELD DATA AND RESIDENCE TIMES

At Mubende, 4 boreholes (DWD18836, DWD18943, DWD18944, DWD18947) and 1 spring were sampled. Logs for 16 boreholes at Mubende suggest that the geology comprises 15-20 m of sediments with variable compositions of sands, clays and occasionally gravels. These are underlain by weathered rock with variable thicknesses (3 to 35 m), which is underlain by a fractured granite bedrock. The 4 boreholes sampled are between 54 and 64 metres deep and open to both weathered and fractured rock, although the major water strikes were generally in weathered material. The boreholes have several open sections between 25 and 58 m, with slight differences in the exact depths of the slotted casing between boreholes. The borehole logs indicate that the boreholes sampled have yields of between 13 and 50 m^3/hour. Logs of the 12 other boreholes indicate that the boreholes sampled were those with the highest yields, and many of the other boreholes at Mubende have lower yields of less than 5 m^3/hour, and some have yields of less than 1 m^3/hour.

There are minor variations in the field chemistry between boreholes (Table 3). SEC ranges from 231 to 410 μS/cm, pH ranges from 5.9 to 6.1, DO ranges from 0.1 to 1.2 mg/l (2.1-15.4%), and bicarbonate varies from 78 to 109 mg/l. The sampled spring, previously the sole source of the Mubende Town Water Supply, had considerably lower SEC (60-71 μS/cm), bicarbonate (15 mg/l), and pH (5.17).

There is good agreement between the CFC12 and CFC11 residence time data for boreholes at Mubende (Table 4). The results for all four boreholes are also fairly similar. CFC12 measurements indicate modern fractions ranging from 0.04 to 0.27 (bulk average recharge dates of 1956-1971) and CFC11 measurements indicate modern fractions of 0.07 to 0.22 (bulk average recharge dates of 1962-1970). At some sites dissolved oxygen concentrations are low (<0.5 mg/l) suggesting that the CFCs may be affected by degradation. If so, the results indicate a minimum estimate of modern fraction and year of recharge. However CFC concentrations are similar to those in samples from other boreholes at Mubende where dissolved oxygen concentrations are higher indicating that the CFCs have probably not been affected by degradation. SF6 data for the boreholes at Mubende cannot be used for dating due to a high level of natural SF6 contamination from the bedrock leading to SF6 concentrations greatly in excess of modern day atmospheric equilibrium concentrations.

Results for the residence time indicators are very different for the spring sample at Mubende. The results for CFC12 and CFC11 are similar and indicate higher modern fractions of 0.99-1.09 (bulk average recharge dates of 2010) than the boreholes. However, SF6 data (assuming an excess air factor of 0.6) indicate a lower modern fraction of 0.4 (bulk average recharge date of 1985) suggesting that the CFCs may be affected by a small amount of contamination.

4.3.1.2 MUBENDE DATA COLLATION

Field records of abstraction and water level data exist for the Mubende Wellfield. Daily pumping data for DWD18836 (the highest yielding borehole) between 08/05/09 and 31/07/10 were digitised (Figure 2). There is, however, no trend of increasing or decreasing pumping rates over this period. There are clearly some errors in the data with apparently negative pumping rates. Daily pumping rates are generally ~ 100-500 m^3/day.

Water level data (from twice daily measurements) for 4 monitoring boreholes were entered for the same period (Figure 3). Data from around February 2010 appear to be fabricated, and the entire dataset must be interpreted with caution. Data between May 2009 and February 2010 are shown in Figure 4 and Figure 5. Boreholes 1 (35 m deep) and 2 (27 m deep) are 10 m from pumping borehole DWD18836, whilst boreholes 3 (52.5 m deep) and 4 (21 m deep) are 50 m from DWD18836. All the boreholes appear to have a slight trend of decreasing water level between May 2009 and February 2010. This effect is most apparent in the deeper boreholes 1 and 3 (see trendline inFigure 5). Overall the water level data are for too short a period and there is too much uncertainty about the accuracy of the data to determine conclusively whether there is a long term decline in water levels due to pumping.

The monitoring data at this site demonstrates the problems that can occur with monitoring data and highlights the need for careful collection and compilation of monitoring data to enable groundwater responses to abstraction and climate to be assessed to determine the long term sustainability of abstractions.

Pumping test data analysis was carried out on data from 5 boreholes at Mubende, two of which were also sampled for residence time indicators. All the pumping test data were for single well constant rate pumping tests and transmissivity was estimated using Theis recovery analysis in AQTESOLV. Transmissivity was similar for all 5 boreholes, ranging from 17 to 96 m^2/day (Table 5).

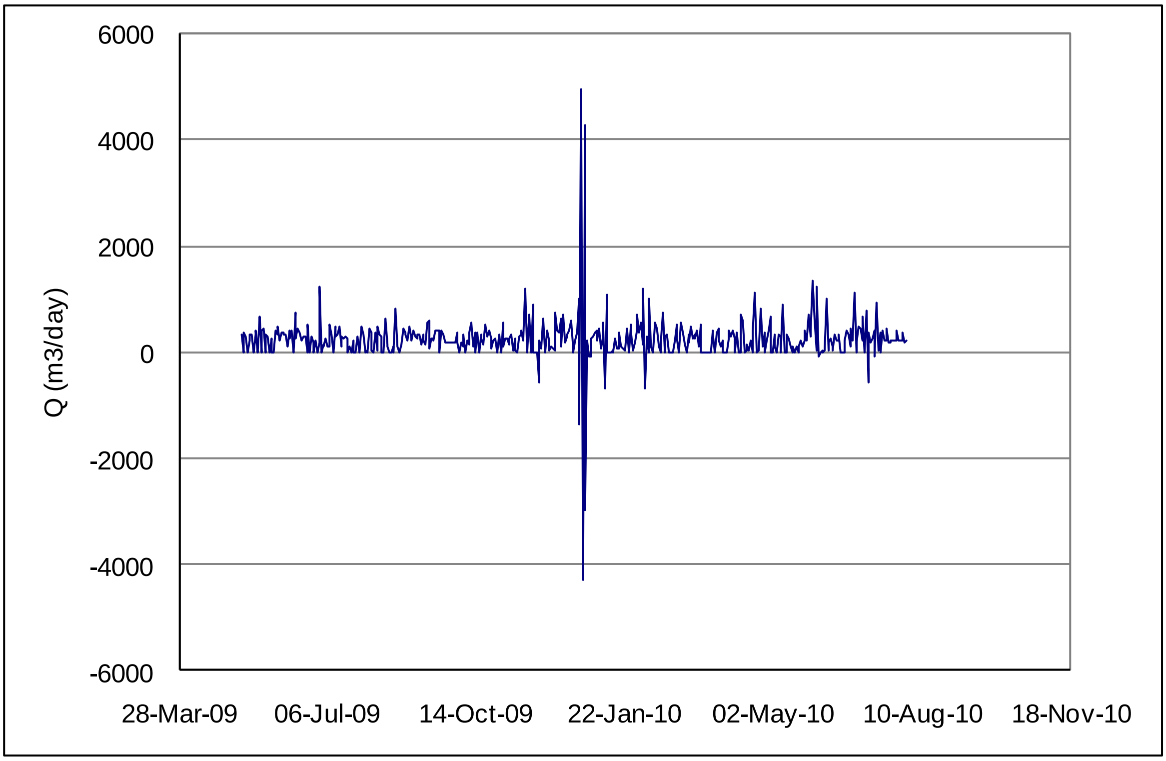

Figure 2 Daily pumping rate at DWD18836, Mubende

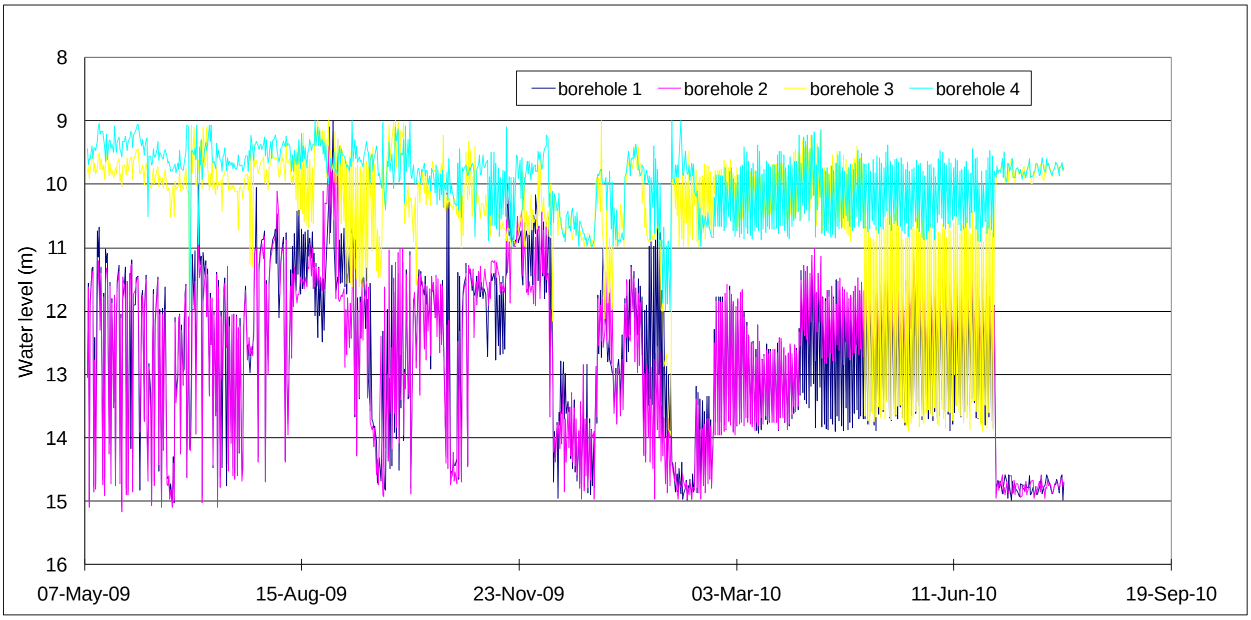

Figure 3 Water level data for monitoring boreholes near DWD18836, Mubende

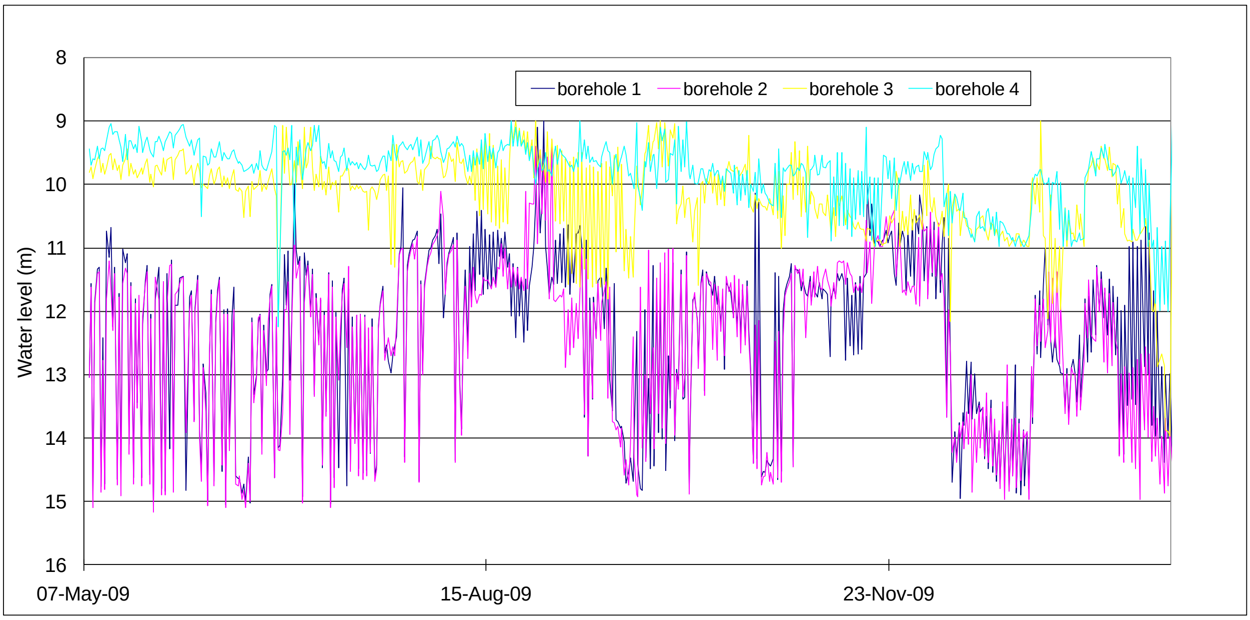

Figure 4 Water level data for boreholes 1 and 2 from May 2009-February 2010

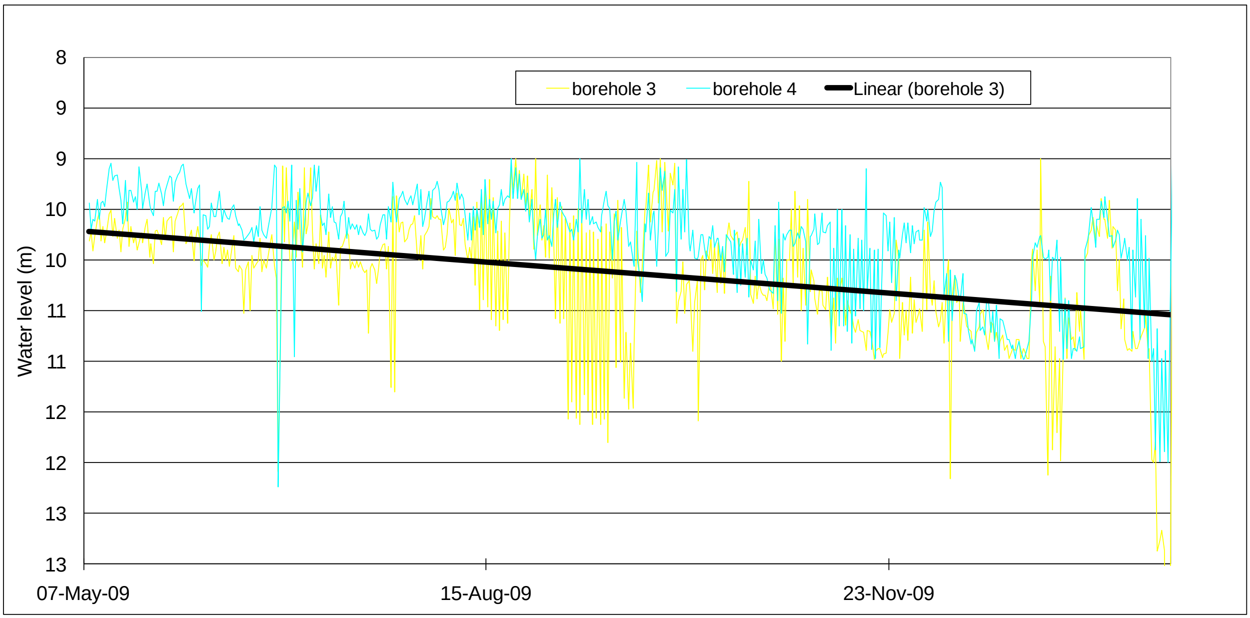

Figure 5 Water level data for boreholes 3 and 4 from May 2009-February 2010

Borehole no.	Log number	T (m2/day)	BGS sample	pumping rate (l/s)	maximum drawdown (m)	depth (m bgl)	water strikes
DWD 18943	T8b	58	U3	6.3-6.4	10.28	63.75	29,44,50
DWD 18836	T4	96	U2	11.8-12.4	7.51	63.75	22,32,34,41
DWD 18946	T8c	25	-	1.92-3.27	8.69	63.84	19,25,29
DWD18835	T52	31	-	3.92-4.17	11.51	90.67	21,34,45,51
DWD 18941	T46	17	-	1.67-1.70	19.72	90.86	26,34,39

Table 5 Pumping test data analysis for boreholes at Mubende

4.3.2 Rukungiri

4.3.2.1 RUKUNGIRI FIELD DATA AND RESIDENCE TIMES

Only one borehole (RUK5) was sampled at Rukungiri because other boreholes either had no suitable sampling point or there was a power failure which prevented sampling. The Rukungiri site is underlain by an alluvial aquifer comprising sands and gravels which extends to a depth of at least 35 m below the surface, and in some boreholes to at least 60 m below the surface, RUK5 abstracts from this alluvial aquifer (Tindamugaya, 2008).

Field chemistry data (Table 3) indicate that water from RUK5 has higher temperature, higher SEC, higher pH, higher bicarbonate alkalinity and slightly higher dissolved oxygen than the Mubende boreholes.

CFC11 and CFC12 data are almost identical to the CFC 11 and CFC12 data for RUK 5 reported by Tindamugaya (2008). The CFC11 and CFC12 data indicate modern fractions of 0.40 and 0.73 respectively (bulk average recharge in 1974, 1985). The CFCs are unlikely to be affected by degradation as dissolved oxygen concentrations are 1.6 mg/l. The SF6 result suggests a higher modern fraction of 0.6 (bulk average recharge in 1990).

4.3.2.2 Rukungiri Data Collation

Groundwater level, rainfall and abstraction data for Rukungiri were collated and assessed by Tindimugaya (2008). Comparison of water level data for RUK5 to rainfall data between 2001 and 2003 before pumping commenced in RUK5 indicated that groundwater levels only increased following periods of exceptionally high rainfall (Tindimugaya, 2008). Data from a nearby monitoring borehole indicate that since the onset of pumping in RUK5 in 2003, groundwater levels are declining at a rate of about 2.6 m/year (Tindimugaya, 2008). Transmissivity estimates for 9 boreholes at Rukungiri ranged from 17-40 m^2/d (Tindimugaya, 2008).

4.3.2.3 Rwenzori Field Data and Residence Times

The Rwenzori bottling company site in the Seeta suburb of Kampala is underlain by up to 50 m of weathered material overlying fractured granite bedrock. Two boreholes were sampled, one with a higher yield (~ 16m^3/hour) and one with a lower yield (~ 5 m^3/hour). Both boreholes abstract from the weathered and fractured bedrock, and have fairly similar wellhead chemistry (Table 3). Borehole 1 has slightly higher SEC, lower pH, higher alkalinity and lower dissolved oxygen than borehole 2. The boreholes are open to similar depths, with 3 slotted sections between 32 and 59 m, borehole 2 is deeper and has an additional open section at 64.5-67.25 m (Table 1). Concentrations of CFC12 are slightly higher than CFC11 (Table 4) with modern fractions of 0.52 and 0.90 (equivalent to bulk average recharge in 1978 and 1989) for CFC 12 and 0.41 and 0.44 (bulk average recharge in 1974) for CFC11. The CFCs are unlikely to be affected by degradation as dissolved oxygen concentrations ranged from 1.3-2.6 mg/l. SF_6 data cannot be used for dating because the concentrations are higher than modern day atmospheric equilibrium concentrations.

4.3.2.4 Rwenzori Data Collation

Pumping data from hand written sheets for borehole 1 from November 2004 to December 2010 were digitised (Figure 6). There is some variability in pumping rates with weekly pumping rates of between 486 and 2738 m^3. Water level data for borehole 1 for the same period were also digitised (Figure 7). There is a sudden apparent decrease in water level on 07/07/07, with water levels before this date all between 4.78 and 5.21 m, and all water levels after this date between 5.72 and 6.0 m. This may be caused by a change in the datum point used for dipping, or some other error in the data acquisition process. There is no sudden increase in pumping rate at the time of the change. There is no apparent systematic decline in water levels due to pumping at any time between 2004 and 2010. However, between 19/03/05 and 02/06/07 there is a slight trend of higher water levels occurring during times of lower pumping rate and lower water levels during higher pumping rates (Figure 8). There is a single reading of 7.2 m on 13/05/10 (Fig 2) which suggests that the water level may have declined, but this is the only reading following that of 5.94 m on 22/02/10. Overall it is not possible to assess whether pumping is having a long term effect on water levels as the monitoring period is too short and the quality of the data are questionable.

Raw pumping test data from drilling reports for 5 boreholes at the Rwenzori site were digitised and analysed using the Theis recovery solution in AQTESOLV. Transmissivity ranged over three orders of magnitude from 0.6 to 70 m^2/day (Table 6). Only one borehole has the higher transmissivity, other boreholes at the same site seem to be less transmissive and lower yielding, despite no substantial differences in the geology recorded in the borehole logs.

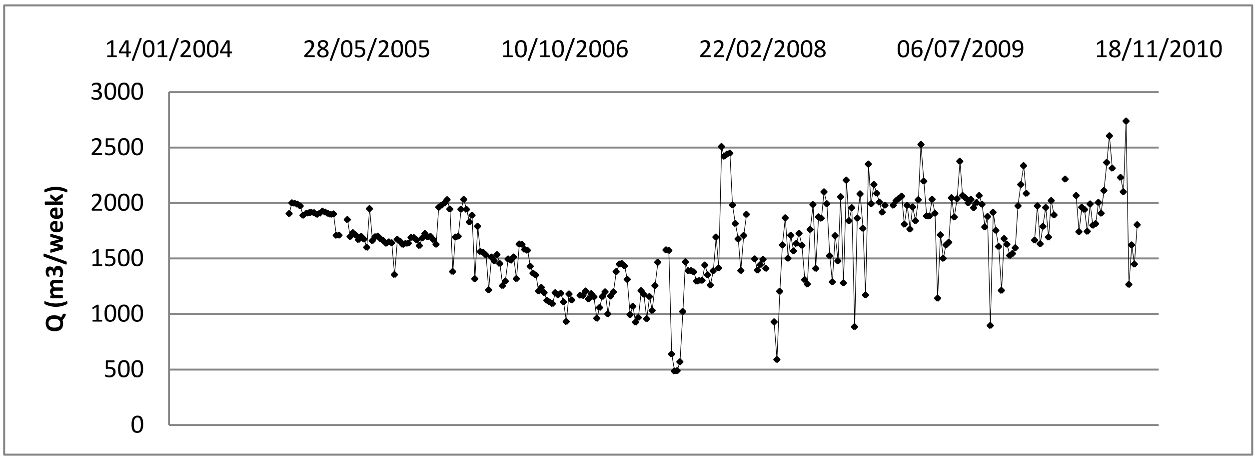

Figure 6 Weekly pumping rate in Rwenzori bottling company borehole 1

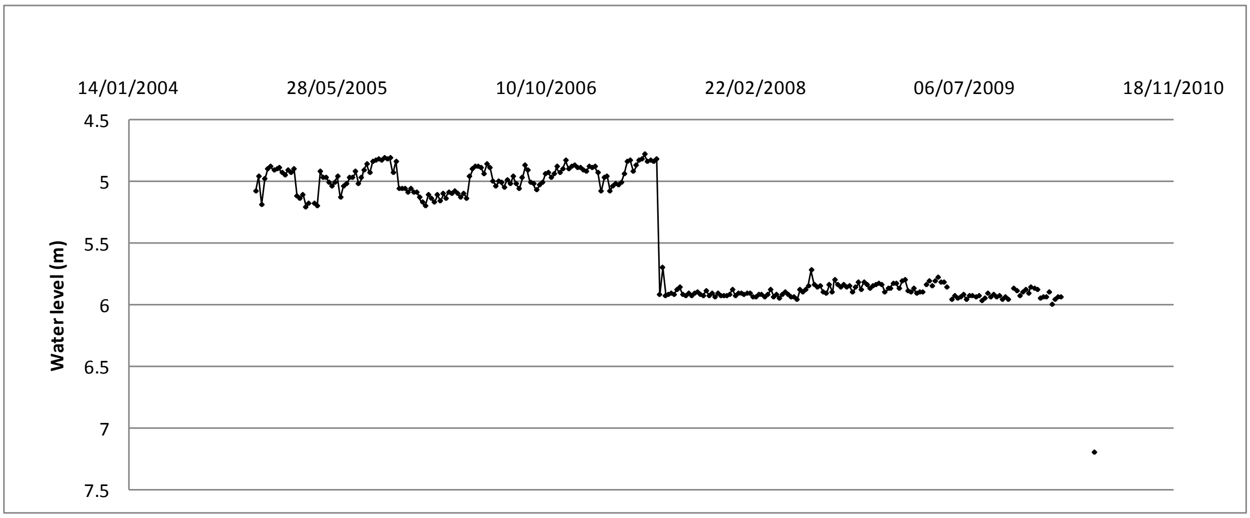

Figure 7 Water level in Rwenzori bottling company borehole 1

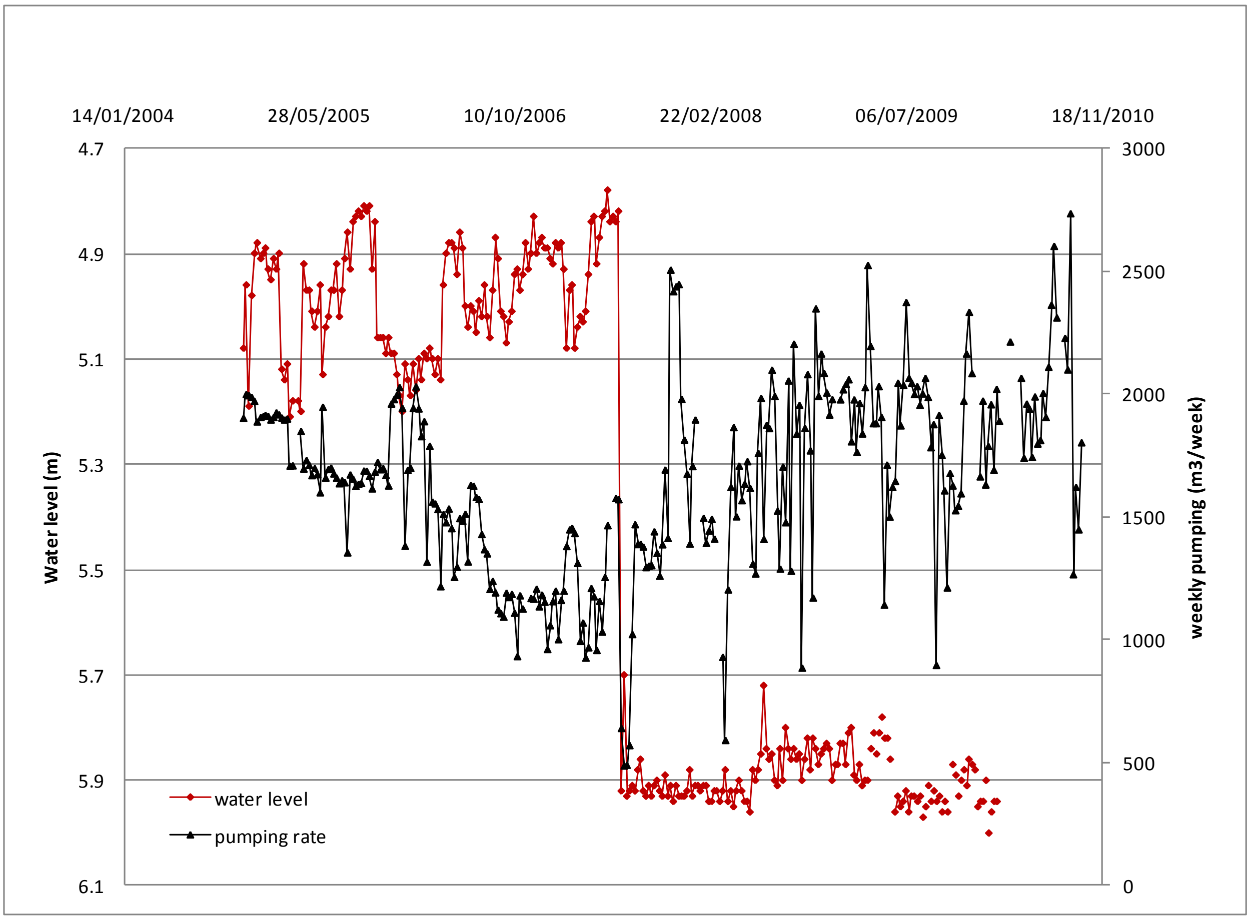

Figure 8 Comparison of weekly pumping rate and water level in Rwenzori bottling company borehole 1

Borehole No.	depth (m bgl)	BGS sample	Date drilled	T (m^2/day)	test type	pumping rate (l/s)	Maximum drawdown (m)
DWD 17465	60	U8	Dec-02	70	constant	16.8-18.4	20.05
DWD 17467	90	none	Dec-02	0.6	step	0.08-0.14	52.43
DWD 17468	87	none	Dec-02	6	constant	0.5-0.69	46.2
DWD 25940	70	U9	Nov-07	8	step	4.5-6.00	49.38
DWD 25941	81	none	Nov-07	0.7	constant	0.77-0.86	67.22

Table 6 Transmissivity of boreholes at the Rwenzori site

4.3.3 Baseline water level and rainfall data

Monitoring of daily rainfall and groundwater levels, remote from groundwater abstraction, was instituted in Uganda in 1998 under the Water Resources Action Plan (WRAP) project, a joint initiative of the Ministry of Water & Environment (Uganda) and DANIDA. The only data available prior to this are 2 groundwater-level monitoring stations established in 1994 in northern Uganda (Apac, Loro) through research conducted by co-author (Taylor). Data for two stations, one in a seasonally humid environment (Apac) and one in semi-arid environment (Rwonyo), are presented inFigure 9 and Figure 10. Evident for the seasonally humid site (Figure 9) is that recharge to the weathered overburden occurs in most years and coincides with bimodal (seasonal) rainfall. No climate-driven trend in groundwater levels in the weathered overburden is detectable. In contrast, a steady decline in groundwater levels is evident over much of the period of observation at Rwonyo (Figure 10). Heavy rainfall during the second rainy season in late 2009 is shown to have arrested this declining trend. These two plots are representative of observational data in 6 seasonally humid locations and 2 other semi-arid locations in Uganda. These datasets provide a very useful tool for assessing links between climate variability and groundwater levels unaffected by abstraction. Owor et al. (2009) used these records to show the dependence of the recharge flux on intense (>10 mm/day) rainfall events.

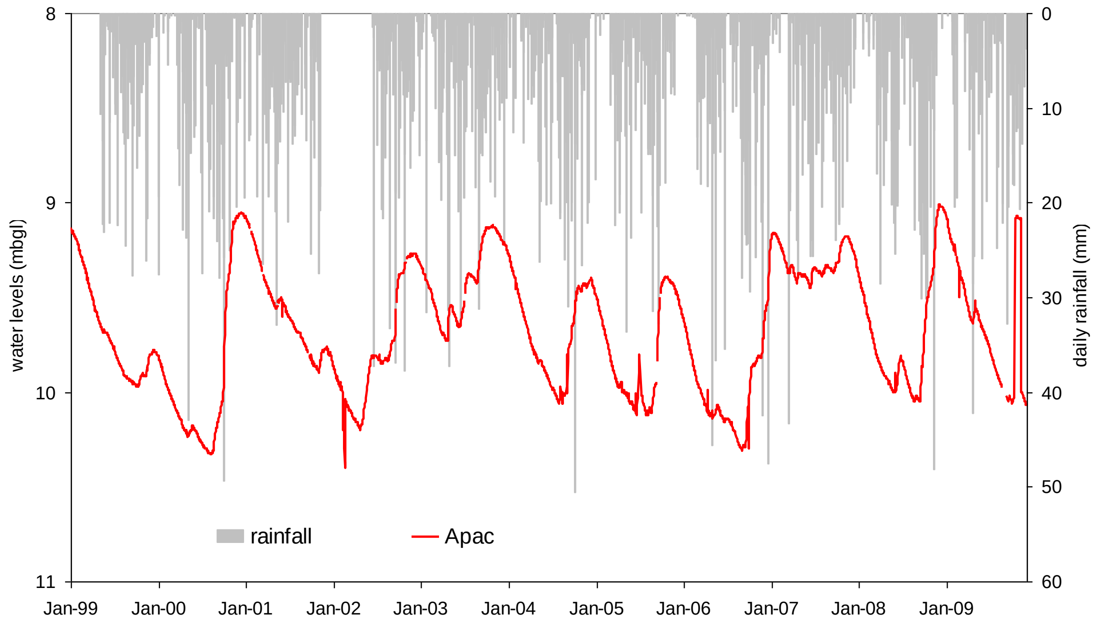

Figure 9 Daily rainfall and groundwater levels recorded in a seasonally humid environment (Apac Town) in northern Uganda.

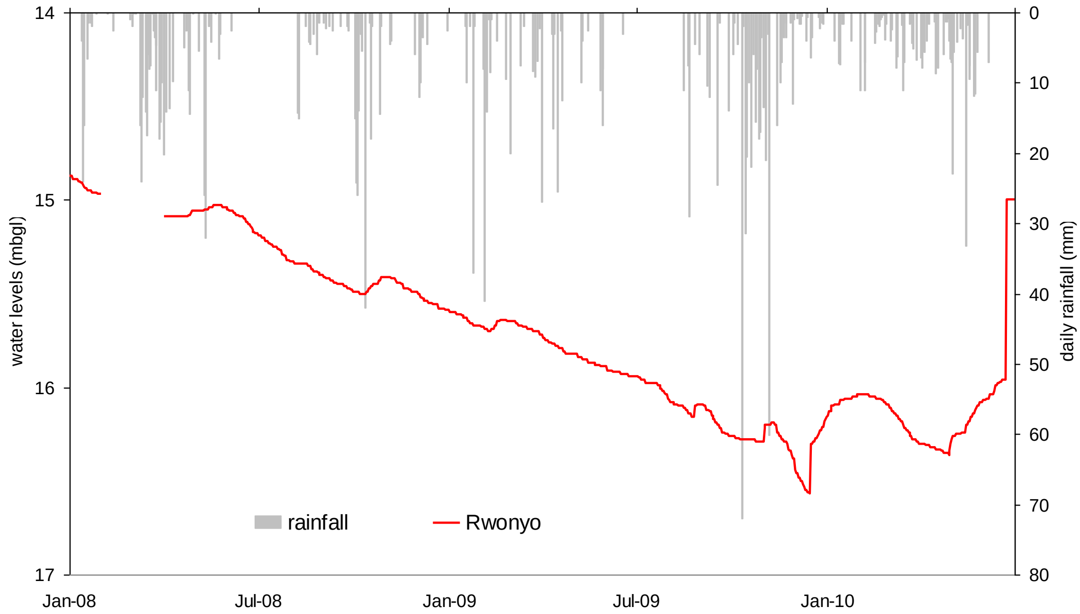

Figure 10 Daily rainfall and groundwater levels recorded in a semi-arid environment (Rwonyo) in southwestern Uganda.

4.4 PRELIMINARY RESULTS – TANZANIA

Information about the boreholes sampled is presented in Table 7 and Table 8, and field chemistry data are presented in Table 9. Table 10 summarises the results for the residence time indicators. SF6 results assume an excess air factor of 0.6.

4.4.1 Makutapora, Dodoma

4.4.1.1 MAKUTAPORA FIELD DATA AND RESIDENCE TIMES

The Makutapora wellfield supplies the town of Dodoma in Tanzania and is underlain by sediments and weathered material varying from 50 to 100 m in thickness over fractured bedrock (Nkotagu, 1996). 7 boreholes with depths of 74-132 m were sampled (Figure 11). These boreholes are mostly open to both weathered and fractured granite although two of them are also open to sand/gravel (Table 8). The boreholes have high yields of between 39 and 94 m^3/hour. The boreholes have quite similar water chemistry (Table 9). Dissolved oxygen is below detection at all boreholes and SEC is quite high (1000-1150 µS/cm). A previous study at Makutapora (Bowell et al., 1996) found high concentrations of coliforms in many boreholes indicating a component of very short residence time groundwater (less than 2 months).

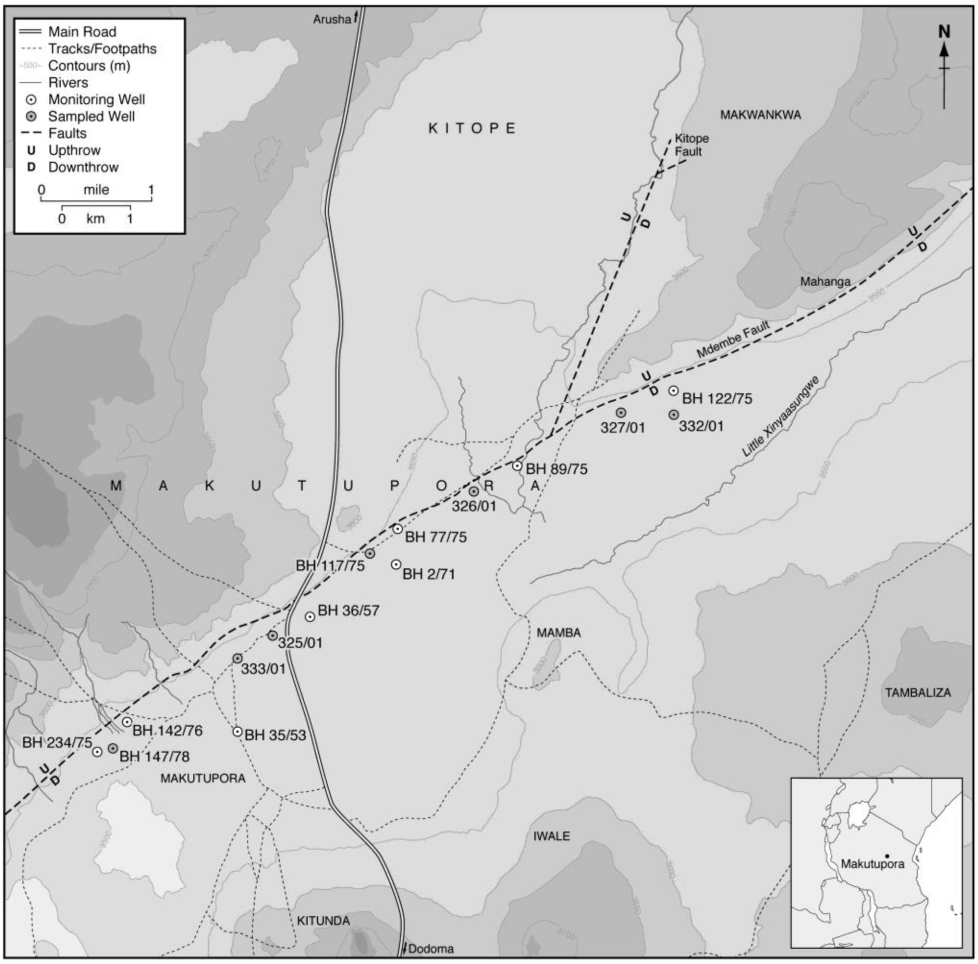

Figure 11 Map of the Makutapora Depression and Wellfield, north of Dodoma in central Tanzania showing the locations of monitoring wells and sampled production boreholes.

Location	borehole number	BGS sample no.	east	north	altitude	date drilled	depth (m)	yield (log) m3/hour	drawdown (m)	Pumping time of test (hrs)
Makutapora C8	332/01	T1	806740	9343426	1047	2001	106.8	93.6	6.18	20
Makutapora C3	327/01	T2	806207	9343240	1057	2001	132.2	93.6	2.39	19
Makutapora	117/75	T3	804135	9341996	1075	1975	121.51	39.204	-0.15	24
Makutapora C2	326/01	T4	803187	9341148	1082	2001	122.5	78.48	24.3	23
Makutapora C1	325/01	T5	802003	9340152	1087	2001	123.4	93.6	2.2	17
Makutapora C9	333/01	T6	801545	9339956	1085	2001	98	93.6	2.3	18
Makutapora	147/78	T7	800441	9339216	1097	1978	74.3	72.36	9.06	23
Utemini, Singhida	23/99, Mkapa	T8	693509	9467918	1510	1999?	39.4	3.9	10.8	?
utemini, singhida	438/09	T9	639532	9467812	1518	2009?	?52	?33.3	?41.2	?
utemini, singhida	24/54, burundani	T10	693234	9468080	1527	1954?	53	6.364	?	?
kittimo, singhida	97/02, Mkoni Chini	T11	697334	9466316	1523	2002?	?86.5	?	8?	?
kittimo, singhida	414/07 Kit-Mwisho	T12	697573	9465754	1528	2007?	?	?	?	?
Njuki, Singhida	141/06	T13	692371	9470750	1509	2006?	115	12.5	?	?
Uhasabu, singhida	61/99	T14	692227	9469380	1520	1999?	91	18.2	18.2	?
Mwankoko, Singhida	414/07	T15	684693	9464290	1471	?	?	?	?	?

Table 7 Borehole information - Tanzania

Location	borehole number	geology (sections with open casing)	slotted casing
Makutapora C8	332/01	weathered and fractured granite	88.55-102.80
Makutapora C3	327/01	weathered and fractured granite	64.69-76.09, 89.47-92.32, 101.67-127.32
Makutapora	117/75	no info	open 60.96-121.51
Makutapora C2	326/01	clayey sand and gravel, fractured and weathered granite	69.59-80.99, 82.69-108.34, 114.69-117.54
Makutapora C1	325/01	weathered and fractured granite	50.64-59.19, 60.94-92.29, 109.82-118.37
Makutapora C9	333/01	weathered and fractured granite	47.14-58.54, 61.67-93.02
Makutapora	147/78	sand and weathered granite	slotted 41.2-58, open 58-74.26
Utemini, Singhida	23/99, Mkapa		
utemini, singhida	438/09		
utemini, singhida	24/54, burundani		
kittimo, singhida	97/02, Mkoni Chini		
kittimo, singhida	414/07 Kit-Mwisho		
Njuki, Singhida	141/06		
Uhasabu, singhida	61/99		
Mwankoko, Singhida	414/07		

Table 8 Borehole geology - Tanzania

Location	borehole number	date	time	temp (dC)	SEC (uS/cm)	pH	Eh	DO mg/l	Bicarbonate Alkalinity (mg/l)	CFC/SF6 notes
Makutapora C8	332/01? (or 333 in field)	22/10/2010	10:00-10:42	30-30.4	1016-1030	7.05-7.06	273	0	386	Good
Makutapora C3	327/01? (or 328 in field)	22/10/2010	11:24-11:57	30.7-30.8	1008-1036	7.1	280	0	396	Good
Makutapora	117/75	22/10/2010	13:05-13:49	29.8	1081-1147	7.13	289	0	328	Moderate
Makutapora C2	326/01	22/10/2010	14:12-14:38	29.7	1084-1128	7.12-7.13	297	0	358	Good
Makutapora C1	325/01	22/10/2010	15:05-15:30	29.2	1070-1071	7.24-7.25	232	0	321	Good
Makutapora C9	333/01	23/10/2010	12:12-12:35	29.1	1033-1048	7.02	271	0	346	Good
Makutapora	147/78	23/10/2010	13:04-13:25	29.3	1055-1059	7.06	262	0	289	Good
Utemini, Singhida	23/99, Mkapa	24/10/2010	11:33-12:10	27.4-27.5	1310-1317	6.31	316	0	180	Moderate
utemini, singhida	438/09	24/10/2010	12:41-13:13	27.7-27.8	1728-1746	6.12	356	2.65-2.72	163	Good
utemini, singhida	24/54, burundani	24/10/2010	13:53-14:43	32.7-39.1	1512-1516	6.31-6.35	290	4.63-4.87	144	Good
kittimo, singhida	97/02, Mkoni Chini	24/10/2010	16:49-17:08	28.5-28.6	905	7.01-7.02	294	4.27	252	Poor
kittimo, singhida	414/07 Kit-Mwisho	24/10/2010	17:43-18:04	28.1	1054	7.11-7.12	266	0	262	Good
Njuki, Singhida	141/06	25/10/2010	09:11-09:36	27.2	975-987	7.13	312	0.31	244	Good
Uhasabu, singhida	61/99	25/10/2010	10:57-11:31	27.2	711-716	6.30-6.32	364	4.67-4.91	103	Moderate
Mwankoko, Singhida	artesian well - see richard for number	25/10/2010	12:53-13:21	28.6-28.7	1785-1883	7.48-7.50	242	0	287	Moderate

Table 9 Field chemistry data - Tanzania

Sample	CFC-12 pmol/L	CFC-11 pmol/L	CFC-12 modern fraction	CFC-11 modern fraction	CFC-12 recharge year	CFC-11 recahrge year	DO mg/l	SF6 fmol/L	SF6 modern fraction	SF6 Recharge Year
T1	0.000	0.260	0.000	0.131	<1948	1966	< 0.05	0.580	0.375	1986
T2	0.028	0.070	0.022	0.035	1953	1959	< 0.05	0.370	0.239	1982
T3	0.000	0.116	0.000	0.058	<1948	1962	< 0.05	0.447	0.289	1983
T4	0.107	0.198	0.085	0.099	1962	1965	< 0.05	0.906	0.586	1991
T5	0.069	0.093	0.055	0.046	1959	1961	< 0.05	1.009	0.653	1992
T6	0.000	0.088	0.000	0.044	<1948	1960	< 0.05	1.257	0.813	1995
T7	0.027	0.048	0.021	0.024	1952	1957	< 0.05	1.237	0.800	1995
T8	0.354	0.626	0.283	0.314	1971	1972	< 0.05	172	112	> modern
T9	0.115	1.527	0.092	0.766	1963	1982	2.65-2.72	50	33	> modern
T10	0.068	1.678	0.054	0.842	1959	1984	4.63-4.87	16	10	> modern
T11	0.797	0.457	0.637	0.229	1982	1970	4.27	191	124	> modern
T12	0.038	0.111	0.030	0.056	1955	1962	< 0.05	344	222	> modern
T13	0.000	0.761	0.000	0.382	<1948	1973	0.31	112	72	> modern
T14	0.751	2.805	0.600	1.407	1981	>modern	4.67-4.91	46	30	> modern
T15	0.022	0.073	0.017	0.037	1951	1959	< 0.05	58	38	> modern

Table 10 Preliminary CFC and SF6 data - Tanzania

SF6 data indicate modern fractions of 0.24-0.81 (bulk average recharge years of 1982-1995). CFC11 and CFC12 indicate lower modern fractions of 0 to 0.13 (bulk average recharge years of <1948-1962), with CFC12 concentrations generally lower than CFC11. The lack of dissolved oxygen suggests that the CFCs may have been degraded.

4.4.1.2 MAKUTAPORA DATA COLLATION

A benchmark dataset comprising a 55-year record of groundwater levels, rainfall and abstraction is in the process of being assembled from digital information, chart recordings, and a series of historical plots uncovered through this research. These data, some which are presented in Figure 12, Figure 13, and Figure 14 provide an early indication of the pivotal importance of extreme events of very high rainfall is sustaining intensive groundwater abstraction. Exceptionally high, seasonal rainfall associated with years featuring strong positive phases in the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (e.g. 1068 mm in 1997/8), gives rise to substantial recharge leading to sharp rises in groundwater levels (Figure 14) that typically follow a steady declining trend (1 m/year) during most, other years (Figure 13).

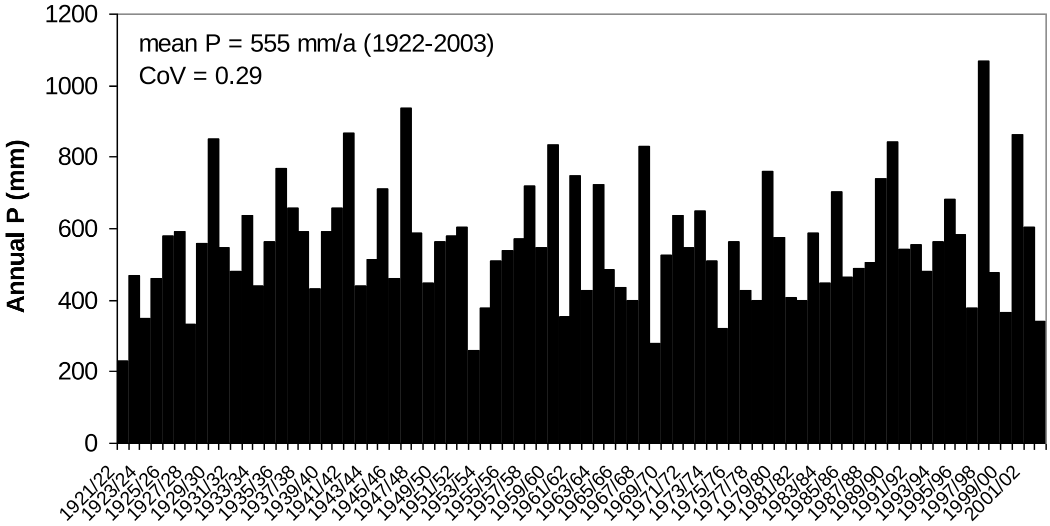

Figure 12 Annual rainfall recorded at the Makutapora Meteorological Station (1922 to 2003).

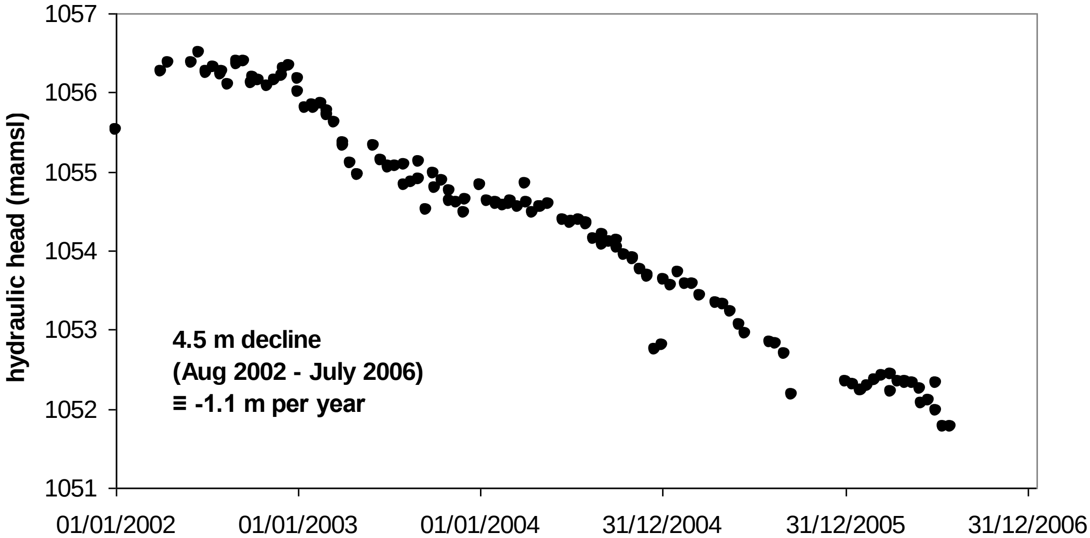

Figure 13 Changes in hydraulic head for monitoring well 234/75 in the Makutapora Wellfield (**Figure 11**) from 2002 to 2006.

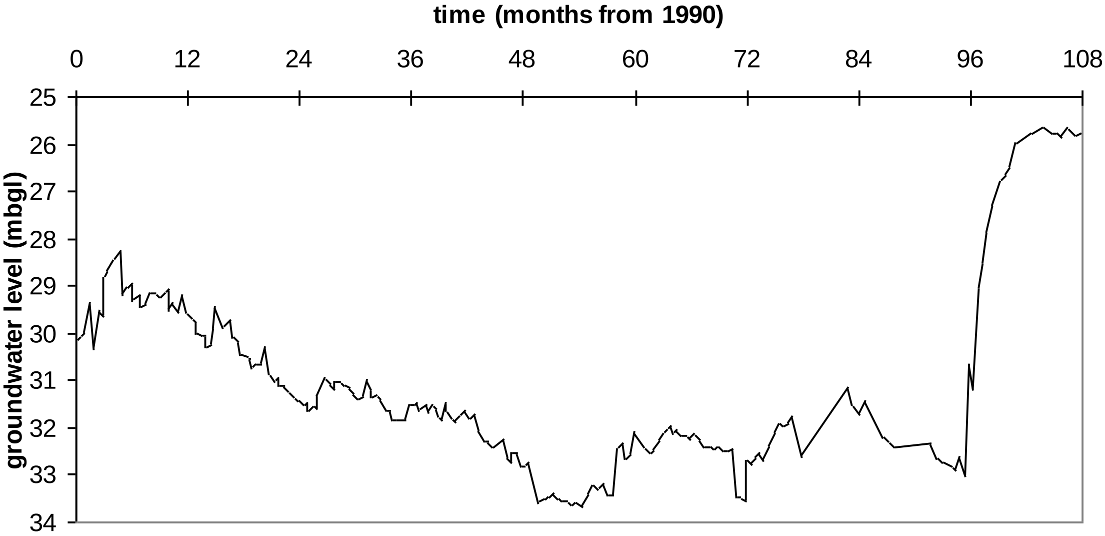

Figure 14 Time series of groundwater levels in monitoring well 234/75 within the Makutapora Welfield (**Figure 11**) from 1990 to 1999. Note the strong positive deflection in the groundwater levels in response to exceptionally high rainfall associated with positive phases in ENSO-IOD in 1997/1998 (months 96-108).

4.4.2 Singhida

4.4.2.1 Singhida Field Data and Residence Times

8 boreholes were sampled at 5 sites in the Singhida area, but there are limited data about the construction and geology of these boreholes (Table 7 and Table 8). Boreholes with construction data have variable depths of 39 to 115 m. There is no information on the geology. The chemistry of the boreholes is quite variable (Table 9). For example dissolved oxygen varies from 0 to 4.9 mg/l and SEC varies from 711 to 1883 µS/cm.

SF6 data for Singhida is unusable for dating purposes as concentrations greatly exceed modern day atmospheric concentrations (Table 10). CFC11 data indicate modern fractions of 0.06 to 0.84 (bulk average recharge from 1959-1973) with CFC11 contamination apparent at one site with concentrations in excess of modern day atmospheric concentrations. CFC12 data indicate modern fractions of 0 to 0.64 (bulk average recharge from before 1948-1981). The CFCs may be affected by degradation where the dissolved oxygen concentrations are very low.

4.4.2.2 Singhida Data Collation

Groundwater-level monitoring has only recently been initiated within the last year at Singhida. Neither borehole lithological logs nor pumping test data are currently available.

5 Pumping test analysis

Single well pumping test data from a number of sites in Uganda were analysed using the Theis recovery analysis method in AQTESOLV. Preliminary results were discussed previously in relation to individual sampling sites but are collated here in Table 11. Overall transmissivity at these sites varies over three orders of magnitude from 0.6 to 96 m^2/day, with the higher yielding boreholes having transmissvities ~10s m^2/day. Preliminary pumping test analysis suggests that the transmissivity of the productive boreholes at Makutapora in Tanzania is much higher at ~ 3800 m^2/day.

Location	Borehole DWD no.	T (m2/day)	BGS sample	pumping rate (l/s)	maximum drawdown (m)	Borehole depth (m bgl)
Mubende	18943	58	U3	6.3-6.4	10.28	63.75
Mubende	18836	96	U2	11.8-12.4	7.51	63.75
Mubende	18946	25	-	1.92-3.27	8.69	63.84
Mubende	18835	31	-	3.92-4.17	11.51	90.67
Mubende	18941	17	-	1.67-1.70	19.72	90.86
Rwnezori water	17465	70	U8	16.8-18.4	20.05	60
Rwnezori water	17467	0.6	-	0.08-0.14	52.43	90
Rwnezori water	17468	6	-	0.5-0.69	46.2	87
Rwnezori water	25940	8	U9	4.5-6.00	49.38	70
Rwnezori water	25941	0.7	-	0.77-0.86	67.22	81
Nyabihiko	21454	5	-	1.94	17.34	72
Katinda	21455	37	-	5.6	7.24	72.7
Kabulangiti, Lukaya	15303	2	-	0.83	37.29	no info
Kabulangiti, Lukaya	15304	12	-	1.7	26.49	no info

Table 11 Preliminary results of pumping test analysis, Uganda (T derived from Theis recovery method in AQTESOLV).

6 Conclusions

Boreholes in Tanzania and Uganda which provide larger yields (> 1 l/s) were investigated to assess their hydrogeological characteristics and resilience to climate change.

Geological information suggests that areas with higher yielding boreholes tend to be characterised by thick sediments/weathered material overlying the fractured bedrock in which there can be significant storage which sustains the yields which are derived from both the weathered material and the fractured bedrock.

Pumping test data indicate transmissivities in the range of 10s m^2/day for the highest yielding boreholes for all sites with the exception of Makutapora where individual boreholes have transmissivities of 1000s $m^{2/}$d.

At many sites (e.g. Rwenzori, Uganda; Mubende; Rukungiri) borehole yields are quite variable with low yielding boreholes proximate to high yielding boreholes.

At Makutapora in Tanzania there is a 50 year benchmark dataset of groundwater level, precipitation and abstraction that can be used to assess the response of the aquifer to precipitation and abstraction. Good datasets of groundwater level and precipitation in areas remote from abstraction are available in Uganda to illustrate the natural response of aquifers to precipitation. However, inconsistencies in datasets from Mubende and Rwenzori illustrate the types of problems that can occur during data collection and compilation and illustrate the need for improvements to enable groundwater level responses to climate and abstraction to be properly evaluated.

Preliminary CFC results suggest that CFCs may be affected by degradation at some sites, particularly in waters with very low dissolved oxygen (below about 0.5 mg/l). At one site in Tanzania concentrations of CFC11 are higher than present day atmospheric concentrations indicating contamination. Preliminary SF_6 data suggest that at some sites SF_6 is an unsuitable residence-time indicator because of in situ contamination from the host bedrock. However, combined CFC and SF_6 residence-time data indicate a component of modern recharge water (i.e., recharged in the last 10-30 years) at all sampled locations.

Overall the preliminary results suggest that higher yielding boreholes supplying towns in Uganda and Tanzania are sustained by enhanced groundwater storage provided by alluvial and fluvio-lacustrine sediments overlying unconsolidated weathered overburden and fractured bedrock aquifer systems. Groundwaters comprise a mixture of water of different ages but include a substantial proportion of modern water recharged within the last 10-40 years. At Makutapora, very intensive abstraction appears to be sustained by episodic recharge during years (seasons) of anomalously high rainfall once or twice a decade; water levels decline steadily during most years.

These results suggest that high storage and abstraction of water recharged over many decades provide a degree of resilience to climate change at the sites under investigation. Indeed, there may be potential for similar groundwater abstractions for irrigation or town supply in other areas with favourable geological conditions (thick sediments/weathered material), enabling increased resilience to climate change due to year round supplies from groundwater. The study highlights the dependency of very intensive groundwater abstraction, observed under semi-arid conditions at Makutapora, on high intensity rainfall events (e.g. ENSO-IOD). Long term monitoring of groundwater level, abstraction and rainfall is critical to assessing the long term sustainability of these higher intensity abstractions to enable the aquifer to be managed sustainably and responsively to climate change.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

Acworth, R.I. (1987) The development of crystalline basement aquifers in a tropical environment. *Quarterly Journal of Engineering Geology*, 20, 265-272.

Adanu, E.A. (1991) Source and recharge of groundwater in the basement terrain in the Zaria-Kaduna area, Nigeria: applying stable isotopes. *Journal of African Earth Sciences*, 13, 229-234.

Braune, E. & Xu, Y. (2010) The role of ground water in sub-Saharan Africa. *Ground Water,* 48, 229-238.

Cavé, L, Beekman, H.E. & Weaver, J. (2003) Impact of climate change on groundwater recharge estimation. In Xu and Beekman, Groundwater recharge estimation in southern Africa. UNESCO IHP Series No 64.

Chilton, P.J. & Smith-Carington, A.K. (1984) Characteristics of the weathered basement aquifer in Malawi in relation to rural water-supplies. In: *Challenges in African Hydrology and Water Resources, Proceedings of the Harare Symposium*, July 1984, IAHS Publication 144, 57-72.

Döll, P. (2009) Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environ. Res. Lett*., 4, doi: 10.1088/1748-9326/4/3/035006

Edmunds, W.M.E. (2009) Palaeoclimate and groundwater evolution in Africa—implications for adaptation and management. *Hydrol. Sci. J.,* 54, 781-792.

Gavigan, J., M. Cuthbert & R. Mackay (2009) Climate change impacts on groundwater recharge in semi-arid Uganda and the role of groundwater in livelihood adaptation and peacebuilding. In: Groundwater and Climate in Africa, edited by Taylor *et al.*, IAHS Publication No. 334, pp. 153-162.

Kafundu, R.C. (1986) A general outline of groundwater supplies in Malawi. In: Geohydrology of drought-prone areas in Africa (Commonwealth Technical Series No. 202), 68-79.

Kingston, D. & Taylor, R.G. (2010) Projected impacts of climate change on groundwater and stormflow in a humid, tropical catchment in the Ugandan Upper Nile Basin. *Hydrol. Earth Syst. Sci.*, 14, 1297-1308.

MacDonald, A. M., Calow, R. C., Macdonald, D. M., Darling, G. W. & Dochartaigh, B. E. O. (2009) What impact will climate change have on rural water supplies in Africa? *Hydrol. Sci. J.,* 54(4), 690-703.

Miguel, G., L. Rebollo & M. Martín-Loeches (2009) Episodic recharge to the Quelo-Luanda aquifer in Angola: anticipating the impacts of climate change. In: Groundwater and Climate in Africa, edited by Taylor *et al.*, IAHS Publication No. 334, pp. 229-233.

Mileham, L., R.G. Taylor, Todd M., Tindimugaya, C. and J. Thompson, 2009. Climate change impacts on the terrestrial hydrology of a humid, equatorial catchment: sensitivity of projections to rainfall intensity. *Hydrol. Sci. J.,* 54(4), 727-738.

Nkotagu, H. (1996) Application of environmental isotopes to groundwater recharge studies in a semi-arid fractured crystalline basement area of Dodoma, Tanzania. *Journal of African Earth Sciences*, 22, 443-457.

Nyenje, P. M. & Batelaan, O. (2009) Estimating effects of climate change on groundwater recharge and base flow in the upper Ssezibwa catchment, Uganda *Hydrol. Sci. J.* 54(4), 713-726.

Olago, D., Opere, A. & Barongo, J. (2009) Holocene palaeohydrology, groundwater and climate change in lake basins of the Central Kenya Rift. *Hydrol. Sci. J.* 54(4), 765-780.

Owor, M., Taylor, R. G., Tindimugaya, C. & Mwesigwa, D. (2009) Rainfall intensity and groundwater recharge: evidence from the Upper Nile Basin. *Environ. Res. Lett. Vol. 4, doi:10.1088/1748-*

9326/4/3/035009

Sekhar, M., Mohan Kumar, M.S. and Sridharan, K. (1994) A leaky aquifer model for hard rock aquifers. *Journal of Applied Hydrogeology*, 3, 32-39.

Taylor, R.G., Barrett, M.H. & Tindimugaya, C. (2004) Urban areas of sub-Saharan Africa; weathered crystalline aquifer systems. In: *Urban Groundwater Pollution* (ed. by D. N. Lerner), 155–179. Balkema, Amsterdam, The Netherlands.

Taylor, R.G. & Howard, K.W.F. (2000) A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: evidence from Uganda. *Hydrogeol. J.,* 8, 279-294.

Taylor, R.G. & Howard, K.W.F. (1995) Averting shallow well contamination in Uganda. In: *Sustainability of water and sanitation systems* (Proceedings of the 21st WEDC Conference, Kampala), 62-65.

Tindimugaya, C. (2008) Groundwater flow and storage in weathered crystalline rock aquifer systems of Uganda: evidence from environmental tracers and aquifer responses to hydraulic stress. Unpub. PhD Thesis, University College London, UK.

Totin, H.S.V., M. Boko & M. Boukari (2009) Groundwater recharge mechanisms and water management in the coastal sedimentary basin of Benin. In: Groundwater and Climate in Africa, edited by Taylor *et al.*, IAHS Publication No. 334, pp. 127-134.

UN (United Nations) (2007) Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. World Population Prospects: the 2006 revision and World Urbanization Prospects: the 2005 revision. http://esa.un.org.unpp.

de Wit, M.J. and Stankiewicz J. (2006) Changes in surface water supply across Africa with predicted climate change. *Science*, 331, 1917-192