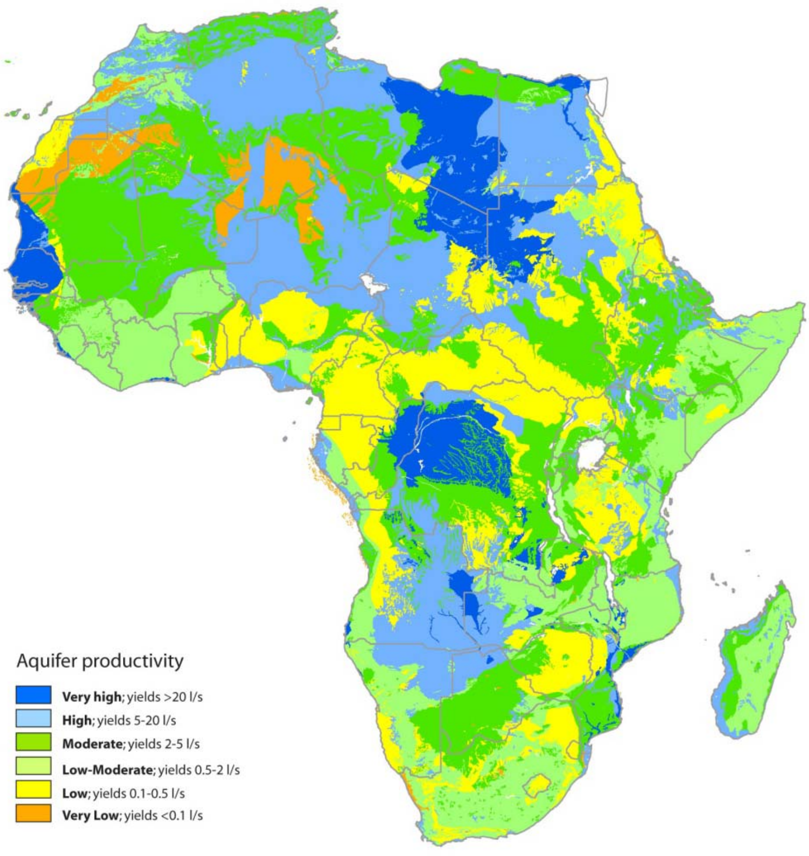
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

DFID Department for International Development

Developing quantitative aquifer maps for Africa

Groundwater Programme

Internal Report IR/10/103



BRITISH GEOLOGICAL SURVEY

GROUNDWATER PROGRAMME

INTERNAL REPORT IR/10/103

Developing quantitative aquifer maps for Africa

A M MacDonald, B É Ó Dochartaigh, H C Bonsor, J Davies, R Key

Keywords

Africa; aquifer map; groundwater resilience; climate change

Bibliographical reference

MACDONALD AM, Ó DOCHARTAIGH BÉ, BONSOR HC, DAVIES J AND KEY R, 2010. Developing quantitative aquifer maps for Africa. *British Geological Survey Internal Report*, IR/10/103. 34pp.

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) commissioned a BGS-led team to undertake a one-year study aimed to improve understanding of the resilience of African groundwater 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 geological and hydrologeological maps and information.

This is one of a series of progress reports written for the project partners and steering group to help discussion. The report describes the approach used to develop the quantitative base maps required to build a final map of groundwater resilience to climate change in Africa.

Acknowledgements

As with all projects we would like to thank are a number of BGS and external colleagues for their help and assistance:

The Project Steering Group, for their general comments and helpful insight with this work – Guy Howard (DFID); Stephen Foster (World Bank GW-MATE); Mike Edmunds (UoOx); Declan Conway (UAE); Richard Harding (CEH); Richard Carter (WaterAid); Vincent Casey (WaterAid) and Tamiru Abiye (University of Witwatersand, Johannesburg).

Specialists in African hydrogeology who provided peer review of the initial aquifer maps: Guillaume Favreau; Seifu Kebebe; Nabil Chabour; Moustapha Diene; Enoch Asare; Sudhir Gupta; John Weaver; Jacob Nyende; and Hosea Sanga.

Contents

FIGURES

TABLES

1 Introduction

Quantitative groundwater maps were developed for Africa to act as the basemaps to construct a map of aquifer resilience to climate change. This forms part of a one year DFID-funded research programme, aimed at improving understanding of the impacts of climate change on groundwater resources and local livelihoods in Africa – see http://www.bgs.ac.uk/GWResilience/. The overall outputs of the project are:

- **Two hydrogeological case studies** – one examining small rural water supplies in West Africa, and the other larger supplies for towns and irrigation in East Africa.
- **A water Security and livelihoods study** (analysis of WELs data, Ethiopia) – examining the linkages between water use and household economy.
- **A review** of hydrogeological data (aquifer properties and recharge) for Africa
- **A map** of groundwater resilience to climate change in Africa

The purpose of the map of groundwater resilience is to provide a preliminary assessment at a continent-scale of how groundwater can support adaptation and build resilience to climate change in Africa. To produce a map of aquifer resilience, information on three different aquifer parameters must be available: aquifer permeability, storage and thickness (MacDonald *et al.* 2001, Calow *et al.* 2010). The scarcity of quantitative aquifer properties data in Africa (aquifer transmissivity and storage) meant surrogate aquifer properties data were mapped instead: typical borehole yields, interpreted storage and flow type, and aquifer saturated thickness.

This progress report was written for the project partners and steering group to help discussion and aid development of the final maps – which will be released online in 2011, at http://www.bgs.ac.uk/GWResilience/aquifermap. This report sets out and discusses:

- the methodology and approach used to develop the input aquifer maps
- data sources
- results of the aquifer maps.

The work to develop the aquifer input maps was contributed to by two projects: the BGS science budget project ‘Groundwater and Climate change in Africa’ (which is aimed at developing a continental-scale understanding of groundwater recharge in Africa); and the DFID funded groundwater resilience project.

2 Methodology used to develop quantitative aquifer maps for Africa

2.1 APPROACH

To produce a map of groundwater resilience to climate change requires an understanding of aquifer properties, particularly transmissivity (T) and storage (S). However, quantitative data on transmissivity and storage are scarce for most of Africa, and most existing hydrogeological maps of Africa give only quantitative indices of aquifer properties based on lithological descriptions of rocks. Therefore, in order to provide the basic information required for the resilience map, quantitative aquifer properties must be developed using robust proxies: namely, typical borehole yields, aquifer storage type (e.g. fracture or intergranular), and saturated aquifer thickness.

Existing hydrogeological and geological maps were used to attribute the new aquifer maps, but additional quantitative aquifer properties data identified from approximately 300 studies in published and grey literature were used to further parameterise and increase confidence in the new maps (Bonsor and MacDonald 2010). The maps were subject to peer review by experts in African hydrogeology, and following revision, were combined to produce the aquifer resilience map for Africa.

2.2 DEVELOPMENT OF AQUIFER PROPERTIES MAPS FOR AFRICA

In order to provide the basic information to create an aquifer resilience map, robust, quantitative maps of aquifer productivity, storage type and saturated thickness had to be developed for Africa at a continental-scale using proxy aquifer properties data. These input maps were developed using a five stage process.

1. Geological base map

The UNESCO 1:5 million scale geological map of Africa was used as the geological base map for the new aquifer maps. This map provides the most detailed and up-to-date digital geological linework for Africa at a continental scale. The geological data is provided digitally by the USGS as an ArcGIS compatible shapefile with associated metadata (Persits et al. 2002).

The geological base map was modified so that geological units were grouped or divided into significant hydrogeological units. Figure 1 shows the final modified geological map. Precambrian rocks were split into three hydrogeologically significant units:

- *Metasedimentary rocks*
- *Mobile belt rocks* – crystalline metamorphic and igneous rocks within linear, mostly Proterozoic, orogenic belts.
- *Cratonic rocks* – Archean and Palaeoproterozoic rocks not affected by Proterozoic and younger orogenic events.

Sedimentary rocks of Africa were grouped by the major groundwater sedimentary basins to which they belong – e.g. the Taoudeni and Chad Basins.

The modifications were explicitly recorded within the attribute table of the map, so that the changes were transparent. The attribute field "GLG-BGS" within the map shapefile records the final classification of geological units within the modified base map – Appendix 1.

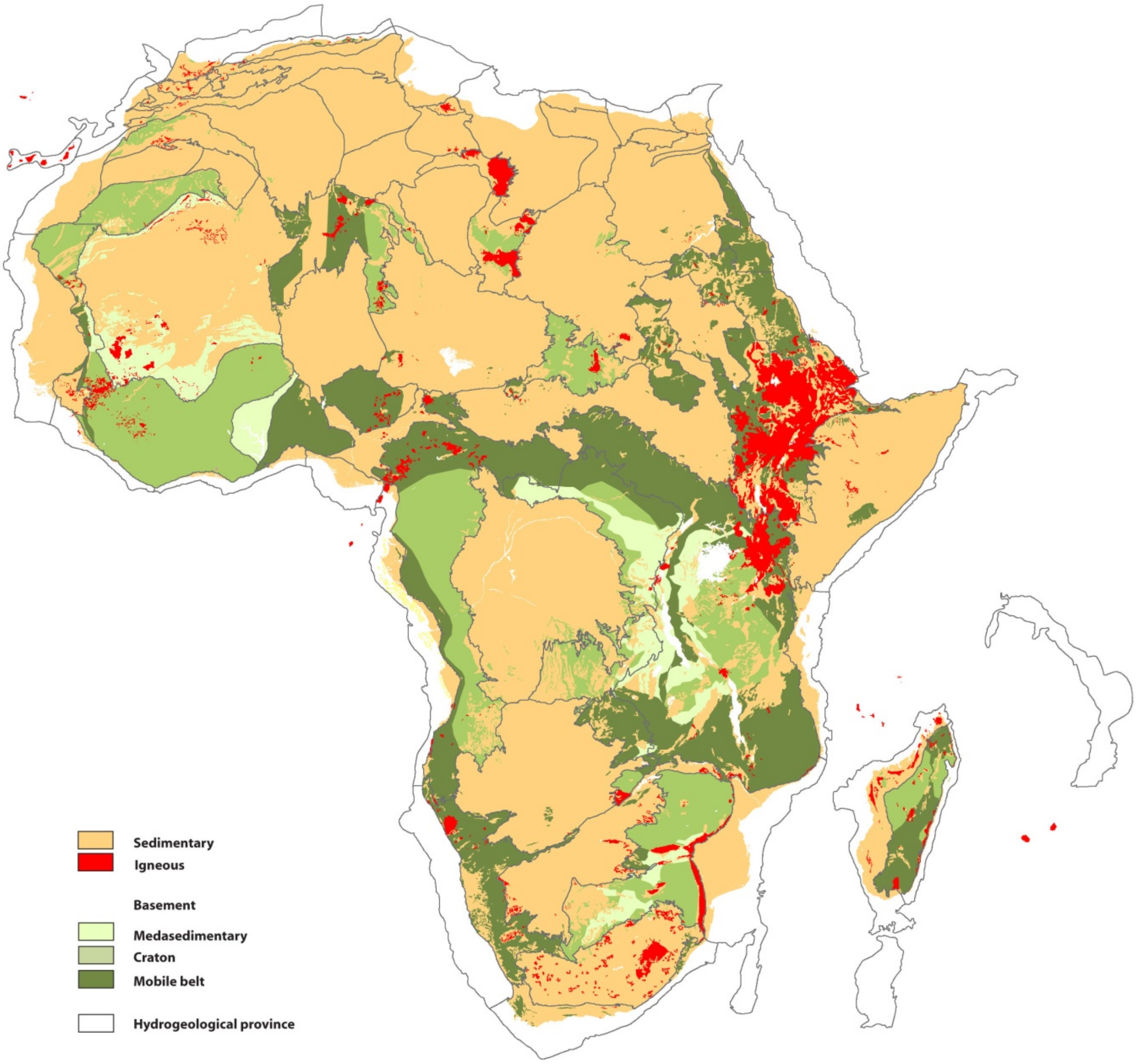


Figure 1 – A simplified version of the 1:5 million scale geological base map, adapted from Persits et al. 2002, showing the main hydrogeological provinces.

2. Attribution of geological map using existing hydrogeological maps

Published hydrogeological maps were used to help further combine or divide geological units, and to attribute the geological map with proxy aquifer properties data. Virtually all of Africa is covered by a hydrogeological map of some form, although they vary greatly in published age and quality, with many providing only qualitative data. Most of the maps are at a national or country scale, typically 1:1 million to 1:2 million. A few are regional maps (e.g. West and Central Africa), at a 1:5 million scale. The maps were sourced from UNESCO, BRGM, SADC and individual country ministries. References of all the maps used to attribute the new hydrogeological map are listed in Appendix 2.

The hydrogeological maps were scanned and georeferenced to enable comparison between the maps and the geological base map within GIS – Figure 2. Geological units on the base map were related to hydrogeological units on the hydrogeological maps by visual comparison, and attributed with proxy aquifer properties data. Three hydrogeological attributes were assigned to each geological unit within the base map: aquifer productivity (or likely yield); aquifer storage type; and saturated thickness. Each attribute was entered into a separate field within the attribute table of the map shapefile – Appendix 1. The source map for each attribution was also recorded within the attribute table to ensure the development of the new hydrogeological map was as transparent as possible – Appendix 1.

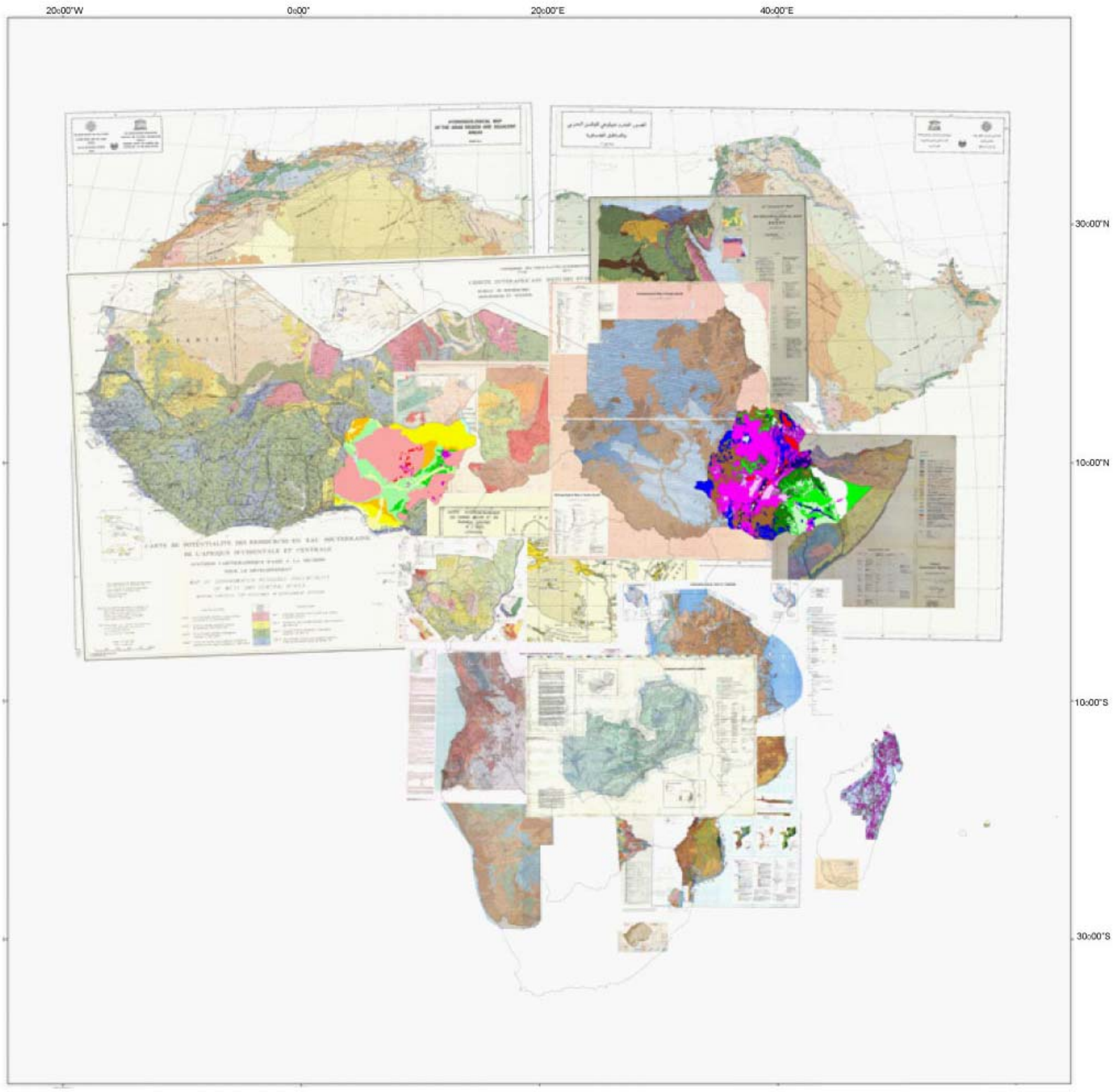


Figure 2 – Some of the scanned and georeferenced published hydrogeological maps for Africa.

Limitations

The hydrogeological maps enabled an initial attribution of the geological base map. However, due to significant differences in linework between the geological and hydrogeological unit, and the variable (and often low) quality of the hydrogeological maps, the attribution was not straightforward. The main limitations of the initial attribution of the new hydrogeological are outlined below:

- *Significant differences in linework between geological and hydrogeological maps* – Differences in linework between the geological base map and hydrogeological maps were due primarily to the difference in detail between the maps, which meant it was very difficult to compare and relate units. Often proxy aquifer properties data from a single unit on the hydrogeological map covered several different geological units in the map, or vice versa. Comparison of the map data was also difficult if the surficial geology was not the main aquifer unit mapped on the hydrogeological maps.
- *Mapping of quaternary deposits* – Quaternary deposits were not included within all areas in the geological base map, or within all the hydrogeological maps, making it difficult to map them consistently within the hydrogeological map.
- *Variable quality of the hydrogeological maps* – The quality of the hydrogeological maps varied significantly. Some maps are very detailed and provide quantitative proxy aquifer properties data; other – particularly the older maps – are much less detailed and provide only qualitative indices of aquifer properties.

3. Use of existing aquifer properties data

To refine the hydrogeological attribution of the base map, and to increase confidence in the new map, the map was attributed with additional hydrogeological data and information from published and unpublished literature. Nearly 300 studies from easily accessible published and unpublished literature were collated and georeferenced – Appendix 3. Proxy aquifer properties data from the georeferenced studies were compared with the initial attributes of the hydrogeological map and also to the data shown by the existing hydrogeological maps. By this process previous hydrogeological attributions were checked, and blank areas were attributed.

Borehole yield data were incorporated into the new map as a proxy of transmissivity – i.e. aquifer productivity. Yield data are much more widely available than T and S data in Africa and have been shown to be a useful proxy for T data in various hydrogeological domains (e.g. MacDonald et al. 2004; Banks et al. 2005; Graham et al. 2009). Inclusion of yield data ensured a better spatial distribution of data, and the approach was found to be particularly useful in areas of low data availability.

Significant effort was made to ensure, all information used to develop the map was captured, to help indicate confidence Figure 3. Further information on the confidence of each of the reports is given in Bonsor and MacDonald (2010).

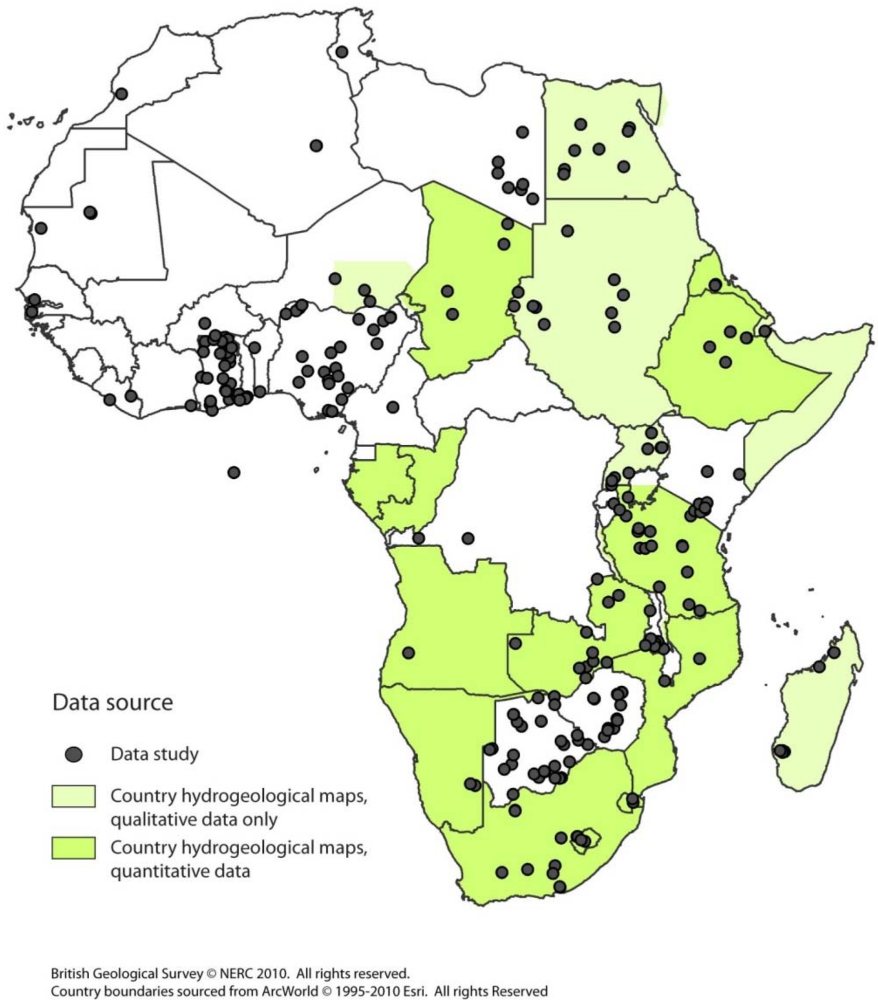


Figure 3 – Map of Africa showing some of the main data sources used to attribute the aquifer maps.

4. Classification of aquifer properties

To produce the aquifer properties maps values of aquifer yield, storage type and saturated thickness were divided into significant ranges.

- **Yield –** based on the distribution of yield values collated, six yield categories were mapped as a proxy for aquifer productivity – Table 1. In general non-weathered Precambrian basement is mapped to be of the lowest productivity. The more productive aquifers in Africa are the Cretaceous-Tertiary sedimentary basins (Figure 4).

- **Storage and flow type** – a semi-quantitative range of aquifer storage types were mapped based on lithology and inferred porosity – Table 2. In general, Cretaceous-Tertiary sedimentary basins are mapped to have 'intergranular' flow and storage type, whilst volcanics and undeformed Precambrian metasedimentary rocks (e.g. in West Africa) are mapped to have 'fracture flow' (Figure 5). Special cases of flow and storage type were mapped for karst rocks and weathered Precambrian weathered basement rocks.

- **Saturated thickness** – four significant ranges of saturated thickness were mapped – Table 3. Greatest saturated thickness is mapped for the major sedimentary basins of Africa (e.g. the Sirte and Kufra Basins in North Africa), whilst shallow weathered basement aquifers have been mapped as the thinnest aquifers (Figure 6).

Aquifer productivity	Yield range (l/s)
Very high	>20
High	5-20
Moderate	2-5
Low-Moderate	0.5-2
Low	0.1-0.5
Very Low	<0.1

Table 1 – Classification of aquifer productivity

Aquifer flow and storage type	**Description**
Main types	
Intergranular	Intergranular storage highly significant – porosity of rocks generally >0.25. Intergranular flow dominant.
Intergranular and fracture	Significant intergranular storage, with mixed intergranular and fracture flow. Average porosity of rocks approx. 0.1 – 0.25.
Fracture	Predominantly fracture flow and storage within rocks, with only a minor component of intergranular storage. Average porosity of rocks <0.1.
Special cases	
Fracture (karst)	Predominantly fracture flow and storage within karst rocks.
Fracture (weathered)	Significant fracture flow, with some intergranular storage in weathered zones of otherwise very low porosity <0.01) rocks. All Precambrian rocks (craton, mobile belt, metasedimentary) are mapped as this case, with the exception of metasedimentary rocks in West Africa which show relatively little tectonic deformation.

Table 2 – Classification of aquifer storage type

Aquifer saturated thickness (m)	Description
<25	Thin
25-100	Moderate
100-250	Thick
>250	Very thick

Table 3 – Classification of aquifer saturated thickness

5. Peer review

The first drafts of the aquifer properties maps were subject to peer review by experts in African hydrogeology – maps were available online on the BGS project webpage via an interactive server.

The reviews received (12) were well distributed across Africa, and provided consistent comments to the maps and additional aquifer properties data, or references. The main points of the review are summarised in Appendix 4. Feedback from the review was incorporated to produce the final aquifer properties maps – shown in Figures 4-6.

2.3 FINAL AQUIFER MAPS DEVELOPED

The final maps of aquifer productivity, aquifer storage and flow types, and saturated thickness are shown below in Figures 4 to 6. The maps provide a continent-scale assessment of semi-quantitative aquifer properties across the major aquifers of Africa. The most productive and high storage aquifers (based on saturated thickness and storage type) mapped in Africa are the large sedimentary basins in North Africa. Lower productivity, and much lower storage aquifers, in which there is a significant component of storage is in fractures, are weathered basement aquifers.

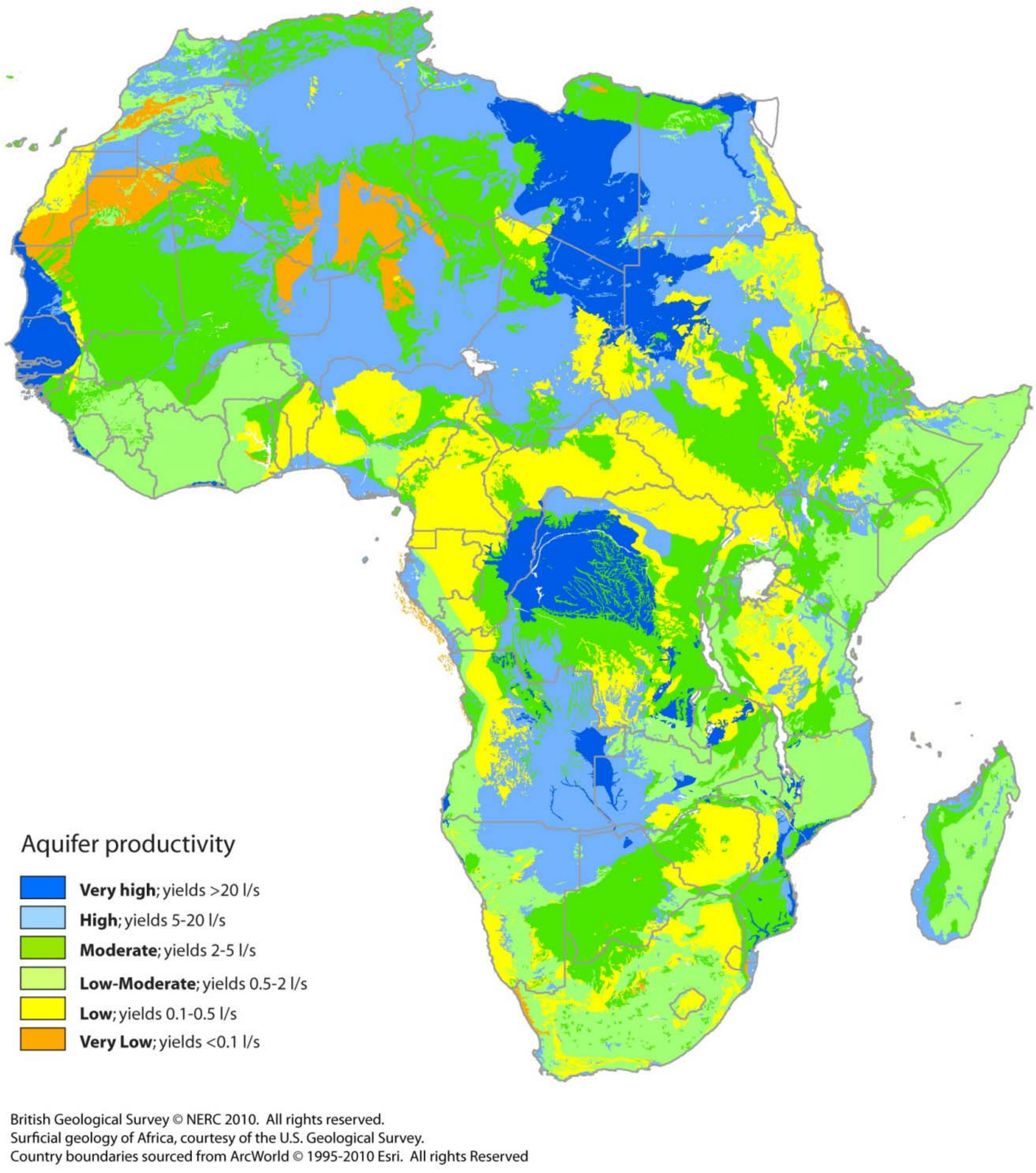


Figure 4 – Final aquifer productivity map.

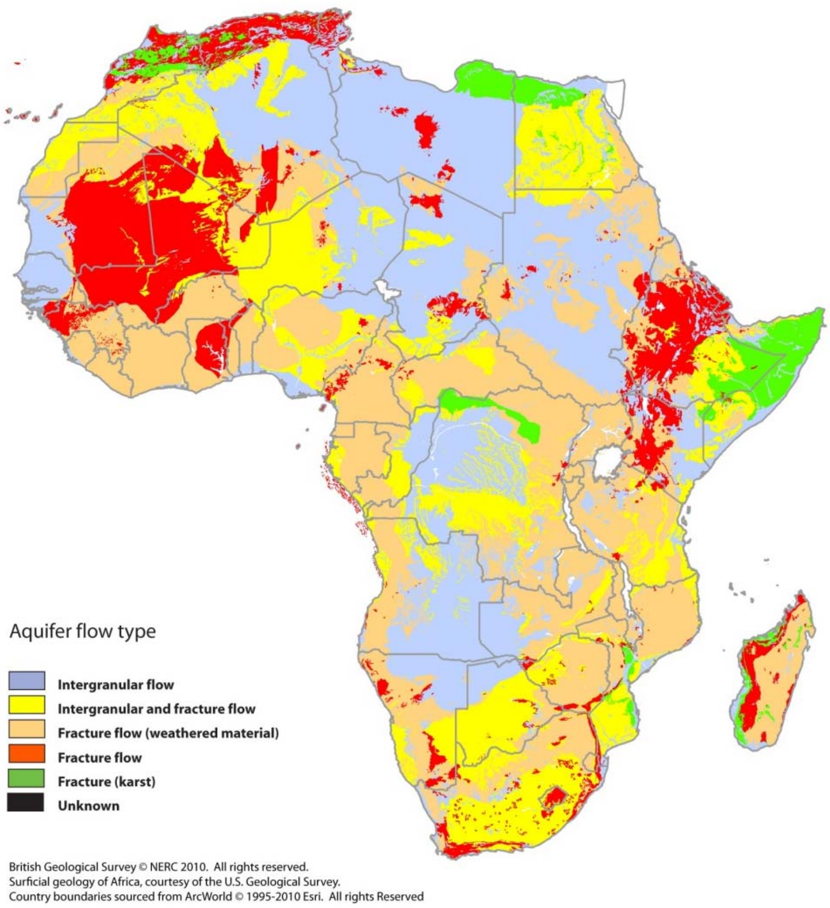


Figure 5 – Final map of aquifer flow and storage type.

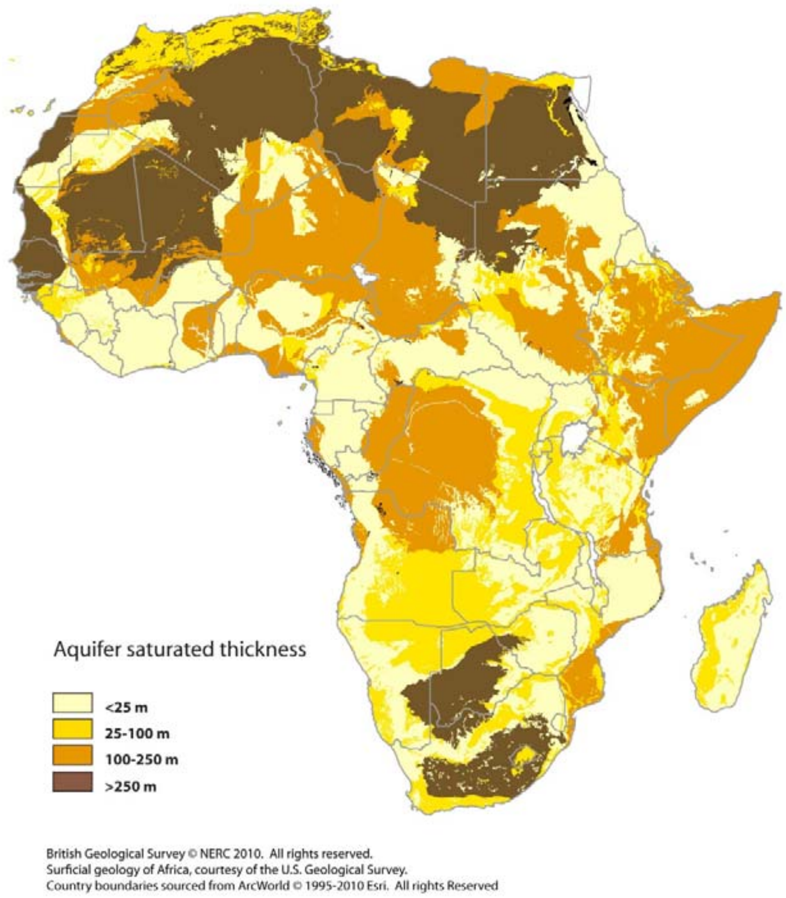


Figure 6 – Final map of aquifer saturated thickness.

2.4 DATA SOURCES AND CONFIDENCE

The inclusion of proxy aquifer properties data from aquifer studies as well as quantitative and semi-quantitative data from existing hydrogeological maps ensured that the aquifer properties maps were developed on the best spatial distribution of data as possible. Virtually all of Africa is covered by a hydrogeological map of some form, although they vary greatly in published age and quality, with many providing only qualitative data. Inclusion of proxy aquifer data – e.g. borehole yields – was found to be particularly useful in data poor areas.

Inevitably, some spatial bias to the input data does exist. Few aquifer properties data or proxy data is available for the Congo Basin or some of the sedimentary basins within North and West Africa (e.g. Touadeni Basin in West Africa, and the Grand Erg and Murzuq basins in North Africa). As a result these aquifer units were not subdivided within the maps to the same extent as aquifer units where more aquifer properties data were available.

As a result of both high and low quality data sources being used to attribute the new hydrogeological maps, significant effort was made to assign a confidence value to the different data sources following a systematic set of criteria – see the aquifer properties review report, IR/10/076. The variability of confidence in the maps could therefore be assessed – Figure 3.

3 Summary

In order the provide the basic information required to create an aquifer resilience map for Africa, new quantitative aquifer properties maps have been developed for Africa, using robust proxies for aquifer properties data: namely, typical borehole yields, aquifer storage type (e.g. fracture or intergranular), and saturated aquifer thickness. The maps are designed to be used at a continent-scale.

- Geology is divided into five classes of productivity, ranging from very high (>20 l/s) to very low (<0.1 l/s). In the absence of transmissivity data for much of Africa typical borehole yields were used as a useful proxy of aquifer productivity.
- The main aquifer units were divided into four classes of saturated thickness based on water-level data available and total thickness of aquifer units.
- Five classes of flow and storage type were attributed to aquifer units based on the type of lithology.

The map will eventually be available online in several forms appropriate the different users, such as GIS-users, modellers, and policy makers.

The methodology used to construct the resilience map will be reported with the final aquifer resilience map. http://www.bgs.ac.uk/GWResilience/dfid_aquiferMap.html.

Inevitably these maps can be improved. They should be viewed as a first attempt to provide quantitative groundwater maps for Africa. It is hoped that second versions can be made after these maps are published and commented on, and as more information becomes available.

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.

BANKS, D., MORLAND, G. and FRENSTAD, B. 2005. Use of non-parametric statistics as a tool for the hydraulic and hydrogeochemical characterization of hard rock aquifers, *Scottish Journal of Geology*, 41; (1) 69-79.

BONSOR, H. C. AND MACDONALD, A. M. 2010. Groundwater and climate change in Africa: a review of aquifer properties data, *British Geological Survey Internal Report,* IR/10/076, 30 pp.

CALOW, R. C., MACDONALD, A. M. NICOL, A. L., AND ROBINS, N. S. 2010. Ground water security and drought in Africa : linking availability, access and demand. *Ground Water,* 48 (2). 246-256.

GRAHAM, M.T., BALL, D.F., Ó DOCHARTAIGH B.É. and MACDONALD, A.M. 2009. Using transmissivity, specific capacity and borehole yield data to assess the productivity of Scottish aquifers, *Quarterly Journal of Engineering Geology and Hydrogeology*, 42; 227-235.

MACDONALD, A.M., BALL, D.F. and Ó DOCHARTAIGH, B. É. 2004. A GIS of aquifer productivity in Scotland: explanatory note, *British Geological Survey Commissioned Report*, CR/04/047N, 21pp.

MACDONALD, A. M., CALOW, R. C., NICOL, A. L., HOPE, B. AND ROBINS, N. S. 2001. Ethiopia: water security and drought (map). *British Geological Survey* Technical Report WC/01/02.

GRAHAM, M.T., BALL, D.F., Ó DOCHARTAIGH B.É. and MACDONALD, A.M. (2009), Using transmissivity, specific capacity and borehole yield data to assess the productivity of Scottish aquifers, *Quarterly Journal of Engineering Geology and Hydrogeology*, 42; 227-235.

PERSITS, F., AHLBRANDT, T., TUTTLE, M., CHARPENTIER, R., BROWNFIELD, M. and TAKAHASHI, K. 2002. Map showing geology, oil and gas fields and geological provinces of Africa, Verson 2.0, USGS Open File Report 97-470A.

Appendix 1

The attribute fields of the new hydrogeological map, developed throughout the construction of the map. Each phase of attribution was recorded within a new field, so that changes to the maps were transparent and traceable. The source of data for each attribution was also recorded within the attribute table of the map, to ensure the development of the map was transparent and repeatable. Attribute fields in bold denote the final hydrogeological attributions.

Field heading	**Description**
Shape, Area, Perimeter, Geo2_7G_, Geo2_7G_ID	GIS shapefile attributes, not used for hydrogeology map
GLG	Chronostratigraphical code for geological polygons (Persits et al. 2002) http://pubs.usgs.gov/of/1997/ofr-97-470/OF97-470A/
HG_AMM	Five-fold hydrogeological attribution by MacDonald and Davies (2000)
GLG_BRGM	*Additional geological descriptions obtained from BRGM geological map (Milesi et al. 2004) http://www.sigafrique.net/*
GLG_OTHER	*Additional geological descriptions obtained from scanned national/regional geological maps*
DetailHG2	Hydrogeological description from maps (more comprehensive and detailed than DetailHG)
AqProd	Attribute field to hold qualitative aquifer productivity extracted from DetailHG2; from expert opinion (derived from 1 day workshop); and from aquifer properties point data.
AqYield	Attribute field to hold quantitative yield values extracted from DetailHG2; from expert opinion (derived from 1 day workshop); and from aquifer properties point data.
AqFlowType	Attribute field to hold description of aquifer flow type i.e. fracture, intergranular or mixed extracted from DetailHG fields and where relevant from GLG
AqStorType	Attribute field to hold description of aquifer storage type i.e. fracture, intergranular or mixed extracted from DetailHG fields and where relevant from GLG
AqExtent	Attribute field to hold qualitative lateral extent of aquifer extracted from DetailHG2
AqStor	Attribute field to hold qualitative &/or quantitative aquifer storage values extracted from DetailHG2 (and later from aquifer properties point data)
AqThick	Attribute field to hold quantitative data on aquifer depth/thickness (including depth to water & rock unit thickness) extracted from interpretation of DetailHG and where relevant from GLG, and from aquifer properties point data
AqSpecCap	Attribute field to hold quantitative specific capacity values extracted from DetailHG2 (and later from aquifer properties point data)
SatThick	*Interim field*
AqProd2	*Interim field*
AqFlow2	*Interim field*
SatThick2	*Interim field*
GLG-BGS	**Geological descriptor field combining updated geological knowledge gained during map production (based on fields GLG & HGAMM)**
Metadata	*Interim field: code referring to hydrogeological map from which DetailHG2 information was sourced (see also Appendix 1)*
Metadata2	*Interim field: source of aquifer properties data used in AqYield*
Metadata3	*Interim field: source of info used by Alan during 2nd phase of attribution*

Metadata4	*Interim field: source of info used by Brighid during 3rd phase of attribution*
Metadata5	*Interim field: making refs consistent; combining/finalising refs from metadata1,2,3+4*
Metadata6	*Interim field: AqFlow & SatThick refs from reviewers*
Metadata7	*Interim field: AqProd refs from reviewers & other additional refs*
Metadata8	**Final combined references**
AqProd3	**Final aquifer productivity categories**
FlowStor	**Final aquifer flow/storage categories**
SatThick3	**Final saturated thickness categories (still some small areas unknown)**

Appendix 2

Reference list of all the maps used to attribute to the new hydrogeological map. The "Ref" field shows the unique code used within the attribute table of the new hydrogeological map, to identify the source of the hydrogeological attribute data.

Ref	Country	Map title	Date	Scale	No. sheets	Author	Organisation
AfB10	Africa	Carte hydrogeologique de l'Afrique at 1/10 M; Hydrogeological map of Africa at 1/10 M scale	2008	1: 10 M	1		BRGM
An1	Angola	Mapa Hidrogeologico de Angola	1990	1:1.5 M	1		Hidroprojecto Consultores de Hidraulica e Salubridade SA, Lisboa & MacDonald & Partners Ltd Cambridge
ARA1	Arab Region & adjacent Areas	Hydrogeological Map of the Arab Region and Adjacent Areas	1988	1:5 M	2 (east & west)	J Khouri & A Droubi	Regional Office for Science & Technology in the Arab States, ACSAD; WRD & UNESCO
Bo1	Botswana	Groundwater resources map of the Republic of Botswana	1987	1:1 M	1	M von Hoyer & W Struckmeier	Geological Survey Department, Lobatse
Bo2	Botswana	The Pre-Kalahari Geological Map of the Republic of Botswana	1997	1: 1 M		T P Machacha, R M Key	Geological Survey Department, Lobatse
BRGM1	Africa	Carte Hydrogeologique de l'Africe a 1/10M	1969	1:10 M	1		BRGM
Ch1	Chad (Tchad)	Carte Hydrogeologique de la Republique du Tchad	1969	1:500 K	1	J L Scheider & J P Wolff	Bureau de Recherches Geologiques et Minieres (BRGM), Orleans
DRC1	Democratic Republic of Congo (and Rwanda)	Carte hydrogeologique du Congo Belge et du Ruanda Urundi	1957	1:5 M	1	M J Snel	Service Geologique du Congo Belge
Dj1	Djibouti	Alimentation des nappes souterraines au territoire de la	1982	1:300 K	1	K L Bornhorst	Cooperation Hydrogeologique Allemande, Service du Genie Rural

		Republique de Djibouti					Djibouti, Office Federale des Geosciences et des Ressources Minerales Hannover
Eg1	Egypt	Hydrogeological Map of Egypt	1988	1:2 M	1		Research Institute for Groundwater, Water Research Center, Ministry of Public Works and Water Resources Arab Republic of Egypt
Et1	Ethiopia	Hydrogeological Map of Ethiopia, hydrogeological attributions from A MacDonald	1988	1:2 M	1	T Chernet	Ethiopian Institute of Geological Surveys, Ministry of Mines and Energy, Addis Abeba
GC1	Gabon et Congo	Carte de planification des resources en eau du Gabon et du Congo	1982	1:1 M	1		Le Comite Interafricaine d'Etudes hydrauliques, Ouagadougou; Haute-Volta par BRGM, Orleans
Le1	Lesotho	Hydrogeological map of Lesotho	>1993	1:300 K	1	G Arduino, P Bono & P Del Sette	Government of Lesotho Ministry of Natural Resources, Department of Water Affairs, Ground Water Division; Government of Italy General Directorate of Development Cooperation
Md1	Madagascar	Carte Hydrogeologique du Sud de Madagascar	1957	1:500 K		J Aurouze	Service Geologique de Madagascar
Ml1	Malawi	Hydrogeological reconnaissance maps	1987	1:250 K	9	various	Department of Surveys, Blantyre
Mr1	Mauritius	Ile Maurice Carte Geologique au 1:50 000 Schema hydrogeologique	1999	1:50 K	1 (north & south)	L Giorgi, S Borchielli ni & L Delucchi	Republique du Maurice; Union Europeene; Ministere des Affaires Etrangers Cooperation et Francophonie
Mo1	Mozambique	Carta Hidrogeologica de Mocambique	1987	1:1 M	2	B P A Ferro & D Bouman	Direccao Nacional de Aguas, Ministerio da Constucao e Aguas, Maputo

Na1	Namibia	Hydrogeological Map of Namibia	2001	1:1 M	1	A E van Wyk, H Strub & W F Struckmeier	Geological Survey Namibia, Department of Water Affairs, Windhoek & Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR), Hannover
Ni1	Niger	Carte de reconnaissance hydrogeologique du Niger Sud Oriental	1963	1:1 M	1	F Pirard	BRGM
So1	Somalia	Somali Democratic Republic Hydrogeological Map	1971?	1:2 M	1		
SADC	Southern Africa	SADC Hydrogeological Map and Atlas	2010	1:2.5 M	1	Technical assistance to the Southern Africa Development Community (SADC)	Sweco Internationl (Sweden); Council for Geoscience (South Africa); Water Geosciences Consulting (South Africa) and Water Resources Consultants (Botswana).
SA1	South Africa	Hydrogeological Map of the Republic of South Africa	2004	1:2 M	2004	I du Toit (ed)	Department of Water Affairs & Forestry, Pretoria
SA2	South Africa	Hydrogeological map series of the Republic of South Africa	1997 - 2002	1:500 K	17	various	Department of Water Affairs & Forestry, Pretoria
Su1	Sudan	Hydrogeological Map of Sudan	1989	1:2 M	1		National Corporation for Development of Rural Water Resources, Sudan & TNO-DGV Institute of Applied Geoscience, The Netherlands
SS1	Sudano-Sahel	Carte de planification pour l'exploitation des eaux souterraines de l'Afrique soudano-sahelienne	1976	1:1.5 M	3 (west, central & east)		BRGM with Bureau Central d'Etudes pour les equipments Outre-Mer (Mali) & Comite Inter-africain d'Etudes Hydrauliques (Niger)
Sw1	Swaziland	Groundwater resources of		1:250 K	1		Canadian International

		Swaziland: Hydrogeologic Map					Development Agency; Kingdom of Swaziland Department of Geological Surveys and Mines
Tz1	Tanzania	Hydrogeological map of Tanzania	?	1:500 K	1		Sir M MacDonald & Partners Ltd, Cambridge with Hidroprojecto Consultores de Hidraulica e Salubridade, SA, Lisboa
Ug1	Uganda map	Hydrogeological map of Uganda	1987	1:1 M	2		Sir Alexander Gibb & Partners Ltd, Institute of Hydrology and the British Geological Survey
WCA1	West/Central Africa	Map of Groundwater Resource Potentiality of West and Central Africa	1986	1:5 M	1		Bureau de Recherches Geologiques et Minieres (BRGM), Paris
Za1	Zambia	Hydrogeological Map of Zambia	?	1:1.5 M	1		? Geological Survey Department, Lusaka; Department of Water Affairs
Zi1	Zimbabwe	Zimbabwe Regional Hydrogeological Map	1986	1: 500 K	4		Ministry of Energy & Water Resources & Development, Harare
Zi2	Zimbabwe	Geological Map of Zimbabwe	1977	1:1 M	1		Zimbabwe Geological Survey

Appendix 3

References of all the aquifer properties studies used to validate and attribute the hydrogeological maps. The references are grouped according to confidence rank, assigned using explicit and systematic criteria, and also split according to whether the studies provide quantitative aquifer properties data, or qualitative aquifer review.

Table 1 – References of aquifer properties studies, which provided proxy aquifer properties data.

Confidence rank	Study reference
1	Cheney CS, Rutter HK, Farr J and Phofuetsile, P (2006) Hydrogeological potential of the deep aquifer of the Kalahari, southwestern Botswana, QJEGH; 39, 303-312 Davies, J (1978) Jwaneng GW Resources Study - Area A - Final Report, Ministry of Mineral Resources, *unpublished* **Jalludin M & Razach M (2004) Assessment of hydraulic properties of sedimentary and volcanic aquifer systems under arid conditions in the Republic of Djibouti (Horn of Africa), Hydrogeology Journal, 12; 159-170.**
2	Acheampong SY and Hess JW (1999) HG framework and hydrochemical framework of the shallow GW system in the southern Voltaian Sed Basin, Ghana, Hydrogeology Journal; 6; 527-537. **Barthel R, Sonneveld BGJS, Gotzinger J, Keyzer MA, Pande S, Printz A, & Gaiser T (2009) Integrated assessment of groundwater resources in the Oueme Basin, Benin, Physics and chemistry of the Earth, 34; 236-250** Buckley, DK (1983) The Mochudi GW exploration Project, Final Report, Government of Republic Botswana, Depart. Of Geological Survey Cheney CS (1981) Report GS10/13 Hydrogeological investigations into Stormberg Basalts on the Lephepe/Dibete area Chilton PJ & Smith-Carington AK (1984) Characteristics of the weathered basement in Malawi in relation to rural water supplies, in 'Challenges in African Hydrology and Water Resources (Proceedings of the Harare Symposium, July 1984), IAHS Publ no 144. DANDIA (1982) Water Master plan for Iringa, Ruvumba and Mbeya reions: Hydrogeology, Vol. 9 Farr JL, Baron J, Peart RJ, Milner E (1979) Investigation into supplementary GW sources for augmentation of the Caborone/Lobatse w/supply, Report GS10/7 **Government of Republic of Botswana (August 1974) Redevelopment of Francistown gw resource, Report on Phase III,** **Graham MT (2008) The Hydrogeology of the Northern Agago County in Padar District, Uganda, BGS Groundwater Programme Open Report, OR/08/040, NERC** Herbert, R (1992) Final report on ODA/BGS R&D Project 97/7: Development of horizontal drilling rig for alluvial aquifers of high permeability IBRD (1980) Tabora Region Water Master Plan, Final Report, Volume 6A, borehole catalogue, The United Repub of Tanzania, Ministry of water, energy and minerals Kortatsi BK & Quansah J (2004) Assessment of groundwater potential in the Sunyani and Techiman Areas of Ghana for Urban Water Supply, West African Journal of Applied Ecology, 5; 75-94.

	Martin N (2005) Development of a water balance model for the Atankwidi catchment, West Africa - a case study of groundwater recharge in a semi-arid climate, Dissertation, Univeristy Gottingen. **Martin N & van de Giesen N (2005) Spatial distribution of GW production and development potential in the Volta River basin of Ghana and Burkino Faso, Water International, 30; 2, 239-249.** **Macdonald AM, Kemp SJ and Davies J (2005) Transmissivity variations in mudstones, Ground Water, 43; 2; 259-269** **Moallim M. A. (1993) Management of groundwater resources in Somali, MSc Thesis King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia pp 212.** Neumann Redlin (1984) Palapye, groundwater exploration project, Vol 2 Neumann-Redlin, C and Hutchins, D (1981) Morupule Power Station, GW resource study, Letshana area, Government of Republic of Botswana, Depart. Of Geological Survey Taylor R and Howard K (2000) A tectono-geomorphic model of the hydrogeology of depply weathered crystalline rock: evidence from Uganda, Hydrogeology Journal; 2000; 8, 279-294. Tearfund (2007) Dufur: water supply in a vulnerable environment; Phase 2 of Tearfunds Durfur Env Study, October 2007. Thangarajan M, Linn F, Uhl V, Bakaya TB and Gabaake GG (1999) Modelling ana inland delta aquifer system to evolve pre-development management schemes: a case study in Upper Thamalakane River Valley, Botswana, southern Africa, Env. Geology, 38; 4; 285. **Thompson, DM and Lovell, CJ (1995) Small-scale irrigation using collector wells pilot project - Zimbabwe; hydrogeological evaluation and pumping test analysis** **Wright EP (1992) Hydrogeology of crystalline basement aquifers in Africa, in Wright EP & Burgess WG (eds) The hydrogeology of crystalline basement aquifers in Africa, Geol. Soc. Spec. Publ. No 66, 1992** **Wright EP, Benfield AC, Edmunds WM and Kitching R (1982) Hydrogeology of the Kufra and Sirte Basins, eastern Libya, QJEG, 15; 83-103.**
3	Abdalla O A E (2009) GW recharge/discharge in semi-arid regions interpreted from isotope and chloride concentrations in the White Nile Rift, Sudan, Hydrogeology J., 2009, 17; 679-692. **Adelana SMA, Olasehinde PI & Vrbka P (2003) Isotope and geochemical characterization of surface and subsurface waters in the semi-arid Sokoto Basin, Nigeria, African Journal of Science & Technology, 4; 2, 80-89.** Agyekum WA & Dapaah-Siakwan S (2008) the occurrence of gw in northeastern Ghana, in Adalena&MacDonald (eds) Applied GW Studies in Africa, IAH selected papers, 13; IAH press Ahmad, MU 1983. A quantitative model to predict a safe yield for well fields in Kufra and Sarir Basins, Libya, Ground Water; 21, 1, 58-66 Aynew, T (2004) the movement and occurance of groundwater in the Ethiopian volcanic terrain, In GW climate conference proceedings, www.gwclim.org Ayamsegna JA & Amoateng-Mensah P (2002) Well monitoring: World visions experience in Ghana, In Conference Proceedings ' Sustainable environmental sanitation and water services, 28th WEDC Conference, Calcutta, India Bannerman & Ayibotele (1984) Some critical issues with monitoring crystalline rock aquifers for GW management in rural areas, In Challenges in African Hydrology and Waert Resources,

Proceedings of the Harare Symposium July 1984, IAHS Publ 144.

Bauer P, Held RJ, Zimmermann S, Linn F and Kinzelback, W (2006) Coupled flow and salinity transport modelling in semi-arid envs: The shashe river valley, Botswana, Journal of Hydrology, 316; 163-183

Bouchaou, Michelot, Vengosh et al. (2008) Application of multiple isotopic and geochemical tracers for investigation of recharge, salinization and residence time of water in the Souss-Massa aquifer, southwest of Morocco, J. of Hydrol., 352; 267-287.

Carter RC (1994) The groundwater hydrology of the Manga grasslands, NE Nigeria: importance to agricultural development strategy for the area: Quarterly J. of Engineering Geology, 27; S73-S83.

Chilton J & Foster SSD (1995) Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa, Hydrogeology J., 3; 1, 36-49.

Chilton J (1991) Report on a visit to Zimbabwe 20th to 30th April 1991, BGS Technical Report, WD/91/27R

Davies (2003) Lesotho Lowlands Water supply feasibility study, BGS commissioned report, CR/03/176C

Dassi L, Zouari K & Faye S (2005) Identifying sources of groundwater recharge in the Merguellil Basin (Tunisia) using isotopic methods: implication of dam reservoir water accounting

Ebraheem AM, Riad S, Wycik P & Seif El Nasr AM (2002) Simulation of impact of present and future groundwater extraction from the non-replenished Nubian SST aquifer in SW Egypt, Env. Geology, 43; 188-196

Edet A, and Okereke C (2004) Hydrogeological and hydrochem character of the regolith aquifer, norther Obudu Plateau, S Nigeria, Hydrogeology Jounral; 13; 391-415.

Fass, T and Reichart, B (2005) Geochemical and Isotopic characterisation of a local catchment within a crystalline basement in western African Benin, in XX, pp 271-278

Faye S, Cisse Faye S & Evans D (2001) Origin and distribution of saline groundwater in the Saloum coastal aquifer, in Proceedings of the first international conference on Saltwater intrusion and coastal aquifers, Morrocco, April 23-25, 2001

Faye S, Maloszewski P, Stichler W, Trimborn P, Faye SC and Gaye CB (2005) GW salinization in the Saoum (Senegal) delta aquifer: minor elements and isotopic indicators, Sci of Tot Env., 343; 243-259.

Fridel MJ & Finn C (2008) Hydrogeology of the Islamic Republic of Mauritania, USGS Open File Report 2008-1138.

Foster SSD, Bath AH, Farr JL & Lewis WJ (1984) The likelihood of active groundwater recharge in the Botswana Kalahari, J. of Hydrol., 55; 113-136.

Goverment of the Republic of Botswana (August 1972) GW investigation report for construction of botswana-zambia highway, Chief Roads Engineer

Hazell JRT & Barker M (1995) Evaluation of alluvial aquifers for small-scale irrigation in part of Southern Sahel, West Africa, QJEG, 28; S75-S90.

Howard KWF & Karundu J (1992) Contraints on the exploitation of basment aquifers in East Africa - water balance implications and the role of the regoolith, J. of Hydrol., 139; 183-196

Hydromin consultants (1990) Consolidated emergency water supply programmes, Final Report, Vol 1, Republic of Botswana, Department of Water Affairs

Iyioriobe SE & Ako BD (1986) The hydrogeology of the Gombe subcatchment, Benue

valley, Nigeria, J. of African Earth Sciences, 5; 5; 509-518.

JICA (1988) The study on GW resources development and managment in the internal drainage basin in the united republic of tanzania, Final Report, Summary, Internal drainage basin water office, Ministry of water, United republic, Tanzania

JICA (1991) GW development study in SW region of the democratic republic of Madasgcar, Vol 1, summary report, July 1991, Japan Internation Cooperation Agency.

JICA (1995) The study on national water resources master plan in the republic of zambia: final report supporting report (V) well inventory study, Yachiyo Engineering Co, Ltd (YEC)

JICA, Sanya Consultants (1985) RWS project in Midlands Province, Zimbabwe: Terminal construction report, Vol 1 Main Report

Jones MJ (1985) THe weathered zone aquifers of the basement complex areas of Africa, in Wright EP (ed) Hydrogeology of crystalline basement aquifers in Africa

Kortatsi BK (1994) Groundwater utilisation in Ghana, Conference Proceedings, Helsinki, June 1994 'Future GW resources at Risk' IAHS Publ no. 222, 1994

LeBlanc M, Favreau G, Tweed S, Leduc C, Razack M and Mofor L (2007) Remote sensing for groundwater modelling in large semi-arid areas: Lake Chad, Africa, Hydrogeology Journal, 15; 97-100.

Lloyd JW and Farag MH (1978) Fossil groundwater gradients in arid regional sedimentary basins, Ground Water, 16; 6, 388-394,

Lovell C (2000) Productive water points in dryland areas: guidelines for planning RWS, ITDG publishing

Lutz A, Thomas JM, Pohll G & McKay A (2007) Groundwater resource sustainability in the Nagobo Basin of Ghana, Journal of African Earth Sciences, 49; 61-70. AND Lutz PHD thesis (also saved as AFT235)

MacDonald AM, Davies J & Calow RC (2008) Africa hydrogeology and RWS, in Adalena&MacDonald (eds) Applied gw studies in Africa, IAH selected papers, vol 13; IAH press

Obuobie E (2008) Estimation of groundwater recharge in the context of future climate change in the White Volta Basin, W Africa, PhD Thesis, University of Bonn, 2008

Offodile ME (2002) Groundwater study and development in Nigeria, Mecon., Jos, Nigeria, 451 pp.

Ofosu S (2006) The Hydrgeology of the Voltaian Fm of the northern region of Ghana, MSc Thesis, Univseriity of Nevada.

Rwebugisa R. A. (2008) Groundwater recharge assessment in the Makutupora Basin, Dodoma, Tanzania, MSc Thesis, ITC institute, Netherlands.

Solomon S and Quiel F (2006) GW study using remote sensing and GIS in the central highlands of Eritrea, Hydrogeology Jounral; 14; 729-741.

Sami K & Hughes DA (1996) A comparison of recharge estimates to a fractured sedimentary aquifer in South Africa from a chloride mass balance and ana integrated surface-subsurface model, J. of Hydrol., 179; 111-136.

Shata, AA (1982) Hydrogeology of the Great Nubian Sandstone Basin, Egypt, QJEG London, 15; 127-133.

Sultan M et al. (2007) Natural discharge: A key to sustainable utilization of fossil groundwater, Journal of Hydrology; 335; 25; 36.

	Sultan, Yan, Sturchio et al. (2007) Natural discahrge: a key to sustainable utilization of fossil groundwater, J of Hydrol., 335; 25, 36. **Taylor and Howard (1996) Groundwater recharge in the Victoria Nile basin of east Africa: support for the soil moisture balance approach using stable isotope tracers and flow modelling, J. of Hydol., 180; 31-35.** Tearfund (2007) Dufur: water supply in a vulnerable environment; Phase 2 of Tearfunds Durfur Env Study, October 2007. **Tijani MN & Nton ME (2009) Hydraulic, textural and geochemical characteristics of the Ajali Formation, Anambra Basin, Nigeria; implication for groundwater quality, Environ. Geol. 56; 935-951** Van Tonder GJ & Kirchner J (1990) Estimation of natural groundwater recharge in the Karoo Aquifers of South Africa, J. of Hydrol., 121, 395-419. **Wright, EP, Murray KH, Herbert R, Kitching R and Carruthers R (1985) BGS/ODA Zimbabwe Government collector well project, Internal Report** Yidana SM, Ophori D & Baneong-Yakubo (2008) Hydrogeological and hydrochemical characterization of the Voltaian Basin: the Afram Plains areas, Env Geology, 53; 6,
4	Akudago JA, Kankam-Yeboah K, Chegbeleh LP & Nishigaki M (2007) Assessment of well design and sustainability in hard-rock Formations in northern Ghana, Hydrogeology J., 15; 789-797. **Akujieze, CN, Coker SJL, Oteze GE (2003) GW in Nigeria - a millennium experience - distribution, practice, problems and solutions, Hydrogeology J. 11; 250-274.** Anthony E (2006) GW exploration and management using geophysics: northern region of Ghana, PhD Thesis, Brandenburg Technical Univeristy of Cottbus, Faculty of Env Sciences and Process Engineering, BTU Davies, J et al. 1977 - Department of Geological Survey, Republic of Botswana (1977) Interim report for Jwaneng, investigation on gw resources, in Area A Dawoud MA, Arabi NE, Khater A and van Wonderen J (2006) Impact of rehabilitation of Assuit barrage, Nile River, on groundwater rise in urban areas, Journal of African Earth Sciences, 395; 407. **Gossel W, Sefelnasr AM, Wycisk P and Ebraheem AM, (2008) A GIS-based flow model for gw resources management in the developemnt areas in eastern Sahara, Africa, in Adelana and MacDonald (eds) Applied GW studies in Africa, IAH selected papers, Vol 13, IAH.** Guendouz, Moulla, Reminin & Michelot (2003) Hydrochemical & isotopic behaviour of a Saharan phreatic aquifer suffering severe natual and anthropic constraints (case of Oued-Souf region, Algeria), Hydrogeology J., 14; 955-968. Kebede S, Travi Y, Asrat, A, alemayehu T, Ayenew T & Tessema Z (2007) Groundwater origin and flow along transects in Ethipoian rift volcanic aquifers, Hydrogeology J., doi 10.1007/s10040-007-0210-0 Kortatsi BK & Jorgensen NO (2001) The origin of high salinity waters in the Accra Plains groundwaters, Conference proceedings - First international conference on saltwater inrusion and coastal aquifers - monitoring, modelling, management, Morocco, April01 MacDonald Shand Consortium (1991) Joint Upper Limpopo Basin Study, Stage 1, Annex G, Department of Water Affairs Republic of South Africa, Report No. A000 00 0291 Magowe M & Carr JR (1999) Relationship between lineaments and groundwater occurrence in western Botswana, Ground Water, 37; 2, p282-286

	Mailu GM (1994) The influence of Precambrian metamorphic rocks on groundwater in the Chyulu area, Kenya, Hydrogeology J., 2; 2, 26-32. **Mazor E (1982) Rain recharge in the Kalahari - a note on some approaches to the problem, J. of Hydrol., 55; 137-144.** Mpamba NH, et al. (2008) GW mining: a reality for Lusaka urban aquifers? In Adalena&MacDonald (eds) Applied GW studies in Africa, IAH selected papers, vol 13; IAH press **Okoye-Krhoda, G (1989) Groundwater assessment in sedimentary basins of eastern Kenya, Africa, in Regional Characterisation of Water Quality - Proceedings of the Baltimore Symposium, May 1989, IAHS Publ. 182, 1989** Sami K (1996) Evaluation of variations in BH yield from a fractured Karoo aquifer, South Africa, Ground Water, 34; 1; 114-121. SWECO (1978) Botswana Rural Water Supply: evaluation of existing RWS and preparation guidelines for nitrate reduction, Final Report, VBB-59497 Vouillamoz JM, Descloitres M & Toe G (XXXX) La caraterisation des aquiferes de socle du Burkina Faso par sondages RMP Vrbka, Bussert and Abdalla (2008) GW in North and Central Sudan, in Adelena&MacDonald (eds) Applied GW studies in Africa, IAH selected papers, 13;
5	**Gear, D (1977) The manner of groundwater occurrence in Rhodesia, Hydrological Branch, Ministry of Water development, Salisbury** Jorgensen NO & Banoeng-Yakubo BK (2001) Env isotopes (18O, 2H, 87Sr/86Sr)as a tool in groundwater investigations in the Keta Basin, Ghana, Hydrogeology J., 9; 190-201. Osenbruck, Stadler, Sultenfuss et al. (2009) Impact of recharge variations on water quality as indicated by excess air in groundwater of the Kalahari, Botswana, Geochimica et Cosmochimica Actoa, 73; 911-922. Uma KO & Kehinde MO (1992) Quantitative assessment of groundwater potential of small basins in parts of SE Nigeria, Hydrol. Sci. J., 37; 4;

Table 2 - References of aquifer reviews, which provided qualitative information.

Confidence rank	Study reference
1	Cobbing JE and Davies J (2008) The benefits of a scientific approach to sustainable dev of GW in SSA, in Adalena&MacDonald (eds) Applied GW studies in Africa, IAH selected papers, Vol 13; IAH press Dapaah-Siakwan & Gyau-Boake (2000) Hydrogeologic framework and borehole yields in Ghana, Hydrogeology J., 8; 405-416. **Davies J (2009) Hydrogeological mapping of north-central Madagascar using limited data, Groundwater conference Cape Town, South Africa, 16-18 Nov 2009**

	Descroix L, Mahe G, Lebel, T, et al. (2009) Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: a synthesis, J. of Hydrology, 375; 90-102 Guiraud R (1988) L'hydrogeoloie de l'Afrique, J. of African Earth Sciences, 7; 3, 519-543. **Gyau-Boakye P, et al. 2008. GW a sa vital resource for rural development: an example from Ghana, in Adalena&MacDonald (eds) Applied studies in gw studies in Africa, IAH selected papers, 13; IAH press** **Houston J (1992) RWS: comparative case histories from Nigeria and Zimbabwe, in Wright EP (ed) Hydrogeology of crystalline basement aquifers in Africa** Kehinde MO & Loehnert EP (1989) Review of African Groundwater resources, Journal of African Earth Sciences, 9; 1,, 179-185 **Lamouroux C and Hani A (2006) Identification of groundwater flow paths in complex aquifer systems, Hydrol. Processes, 20; 14, 2971-2987.** **Rueedi, J., Brennwald MS, Purtschert R, Beyerle U, Hofer M and Klipfer R (2005) Estimating the amount and spatial distribution of recharge in the Iullemmeden Basin (Niger) based on 3H, 3He and CFC-11 measurements, Hydrological Processes, 19; 17, 3285-3298** **Shahin M (2007) Water Resources and Hydrometrology of the Arab region, Water Science and Technoloyg Library, Vol. 59, Springer, Netherlands.** UNDP (1989) Swaziland country report: groundwater UNDP (1989) Tanzania Country report: groundwater **UNDP (1989) Zambia country report: groundwater** **Wright EP (1992) Hydrogeology of crystalline basement aquifers in Africa, in Wright EP & Burgess WG (eds) The hydrogeology of crystalline basement aquifers in Africa, Geol. Soc. Spec. Publ. No 66, 1992**
2	Alker M (2008) The Lake Chad Basin Aquifer system, in Scheumann&Harrfahrdt-Pahle (eds) Conceptualising Cooperation for Africa's transboundary Aquifer systems, d.i.e, German Dev Institute, 2008, Bonn **Faillace C (2007) Hydrogeological of hard rocks in some eastern and western Africa countries, in Krasney and Sharp (eds) Groundwater in fractured rocks, IAH green book, Vol 9. IAH press.** **Farah, Mustafa & Kumai (2000) Sources of groundwater recharge at the confluence of the Niles, Sudan, Environmental Geology, 39; 6, 667-675.** Grossmann M The Kilimanjaro Aquifer, in Scheumann&Harrfahrdt-Pahle (eds) Conceptualising Cooperation for Africa's transboundary Aquifer systems, d.i.e, German Dev Institute, 2008, Bonn **International Atomic Energy Agency (1991) Hydrogeological investigation of sites for the geological disposal of radioactive waste, Technical Reports Series, No. 391, 68 pp.** **Kouame KJ, Jourda JP, Biemi J and LeBlanc Y (2008) Groundwater modelling and implication for groundwater protection: Case study of the Abidjan aquifer, Cote d'Ivoire, in (Eds) Adalena & MacDonald, Applied Groundwater Studies in Africa, IAH 13, p457-473.** **Mwango F. K., Muhangu B. C., Juma C. O. And Githae I. T. (2002) Groundwater resources in Kenya, in Proceedings of the International Workshop, Tapoli, Libya, 2-4 June 2002** **Oga, Marlin, Dever, Filly, and Njitchoua (2008) Hydrochemical and isotopic**

	characteristics of coastal GW near Abidjan, in Adelena&MacDonald (eds) Applied GW studies in Africa, IAH selected papers, 13; **Onugba A, and Yaya OO (2008) Sustainable gw development in Nigeria, in Adalena&MacDonald (eds) Applied gw studies in Africa, IAH selected papers, Vol 13; IAH press** UNDP (1989) Madagascar country report: groundwater UNDP (1989) Malawi country report: groundwater **UNDP (1989) Mozambique country report: groundwater** UNDP (1989) South Africa country report: groundwater UNDP (1989) Zaire DRCongo country report: groundwater
3	**Africa Borehole Initiative (2005) Groundwater in Kenya.** Amin I. E. & Khayat Z. A. (2002) Groundwater mining in the Tripoli Area, Lebanon, at 2002 Denver Annual Meeting 27-30 October, Session 108: Hydrogeology in Developing Countries: Opportunities and Challenges (Poster). **Bakker B. H. (XXXX) Groundwater Management in Kenya; the need for improved legislation, delegation of authority and independent decision-making, in Experiences from Developing Countries, ILRI Workshop, pp 111-126.** Bisson R. A. And Lehr J. H. (2004) Case Study North West Somali, in Modern groundwater exploration: discovering new water resources in consolidated rocks using innovative concepts, exploration, drilling, aquifer testing and managment, Wiley p33-117. **Foster S. F. and Tuinhof A. (2005) Kenya: The role of groundwater in the water-supply of Greater Nairobi, in Sustainable Groundwater Management: lessons from practice, GW-MATE World Bank case profile collection, No. 13,**

Appendix 4

Summary of the main points of the peer review received for the initial aquifer properties maps. Other reviews, providing minor comments are not included within this summary table. All reviews were used to produce a set of revised aquifer maps.

Region/aquifer	**Review**	**Reviewer(s)**
Sagden sedimentary basin, SE Ethiopia and Somali	Two reviewers, and additional data sources indicate the productivity of this sedimentary aquifer is low. Depth to groundwater is >300 m. The key point made by reviewers is that relative to the Volcanic Plateau and Rift Basin deposits, the Sagden sedimentary basin should be lower yielding.	Tamiru Abye Seifu Kebede
Sengalese-Maastrichtian Basin, West Africa	Outcrop of Cret-Tertiary sediments in Senegal should be increased to "very high" according to map key, so as the same as surrounding Cret-Tertiary sedimentary deposits within the basin.	Moustapha Diene
Murzuq Basin, S Algeria-SW Libya	Basement which underlies the Murzuq basin Basin outcrops in southern Algeria. This Basement is mostly Neoproterozoic to Archean plutonic and metamorphic rocks. However, a band Cambro-Ordovician rocks – see OneGeology for outcrop pattern – outcrops through the basement. A reviewer has stated these rocks are of "moderate" productivity, with yields >5 l/s typical (rarely up to 20 l/s). Saturated thickness of these deposits should also be increased from that mapped (<25 m).	Nabil Chabour
Atlas mountains, northern Algeria – sedimentary basins: graben fill	Aquifer units in graben basins of Atlas mountains currently mapped as "low" productivity. Local knowledge and additional references from reviews indicate sedimentary rocks in Atlas Mountains are of "moderate" productivity. This also applies to the sedimentary rocks within the northern and central Tunisia. Saturated thickness of the Cret-Tertiary sedimentary aquifers is indicated to be higher than mapped. Quaternary deposits above the Cret-Tertiary sedimentary rocks in the graben basins are correctly mapped as "high productivity" aquifers. Local well fields in these deposits are important sources of water to Algiers.	Nabil Chabour
Tanzania	Cretaceous-Tertiary sedimentary rocks surrounding Lake Rukwa, southwestern Tanzania, are not "very high" yielding rocks as mapped. Productivity should be reduced to "moderate" productivity, based on qualitative descriptor in SADC map.	Hosea Sanga