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Groundwater and climate change in Africa: review of recharge studies

Groundwater Science Programmes

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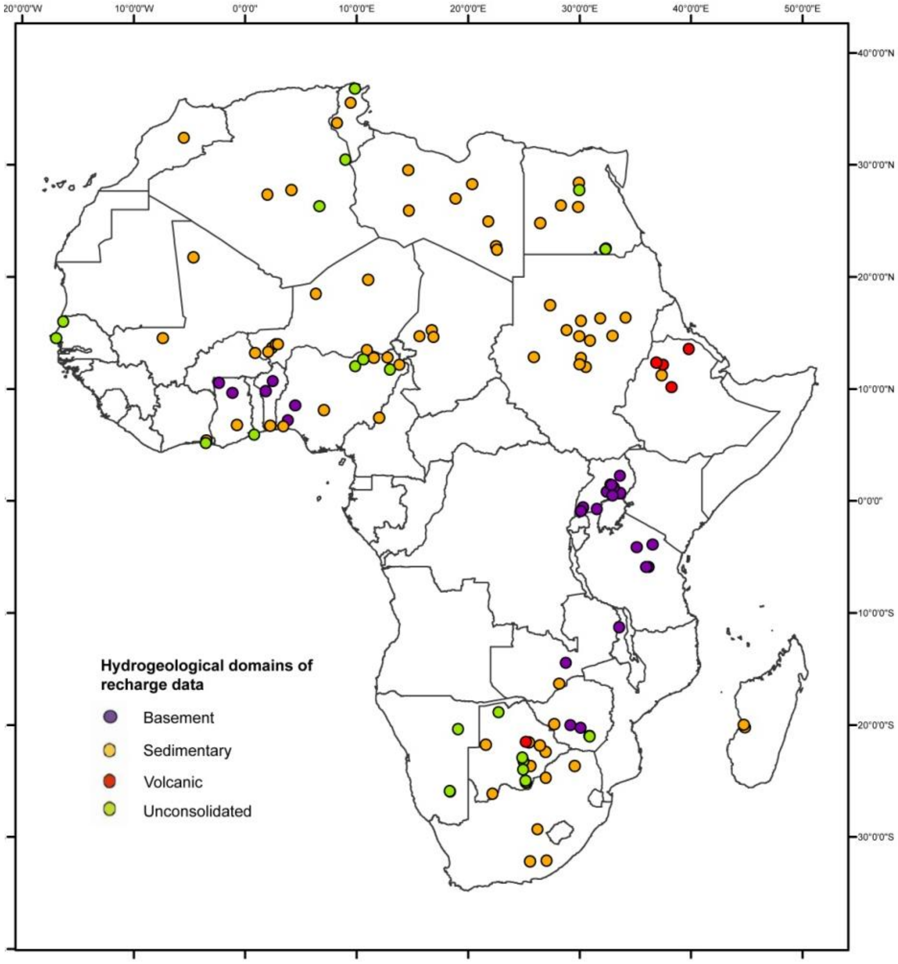

BRITISH GEOLOGICAL SURVEY

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Groundwater and climate change in Africa: review of recharge studies

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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 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 progress reports written for the project partners and steering group to help discussion.

This report describes the methodology and results of a systematic review of recharge studies in Africa, undertaken within the one-year project. The aim of this review of recharge studies was to: strengthen the evidence base between climate change and aquifer resilience, alongside the other project outputs; and, to provide a review of recharge studies to help with calibration of future hydrological models 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:

Mike Edmunds (UoOx), of the Project Steering Group for providing expert peer review of the systematic recharge review.

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

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1 Introduction

The review of recharge studies was conducted as 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 – see http://www.bgs.ac.uk/GWResilience/. The review is one of a series of components within the project. The overall outputs of the project are:

- **Two hydrogeological case studies in West and East Africa** – which assess the storage and availability of groundwater in different aquifers across different climate zones in Africa
- **A water use and livelihood case study** (analysis of Water Economy and Livelihoods (WELs) data, Ethiopia) – examining the linkages between water use and household economy
- **A review** of hydrogeological data for Africa
- **A map** of groundwater resilience to climate change in Africa

The aim of the review of recharge studies is to: strengthen the evidence base of the resilience of groundwater to climate change (alongside the other project outputs); and to provide a review of recharge data to help with validation of future hydrological models in Africa. Individual data from the review should not be over-interpreted, however, due to the strong spatial variability in recharge at a local-scale.

In total, 132 recharge studies from Africa have been identified in the review from 94 published and grey literature reports. This report is a progress report for the project partners and steering group to help discussion. The report describes the criteria used to identify and systematically review the studies. An initial analysis of the data is also provided in this report.

2 The review of recharge studies in Africa

2.1 A COMPREHENISVE REVIEW

Information on recharge is found in published papers and in grey literature. Although there are other reviews of recharge data in Africa, they tend to focus on specific areas and groups of data. In this review we aimed to be comprehensive for Africa, bringing in as many recharge studies as possible and applying systematic inclusion and confidence criteria to the data. We have also included reviews on the applicability and use of different recharge estimation techniques in Africa, as these often included some recharge data, as well as providing the basis to the review of other studies.

2.2 THE SEARCH CRITERIA

Most of the studies identified by the review were found from a systematic web search using several of the main search engines – Web of Science, Science Direct, Google, Google scholar and Google books. The web search criteria utilised are outlined in Appendix 1. Each search generally pulled up between 5000 and 30 000 hits (up to 100 000 hits), from which 1-4 recharge studies might be sourced. Recharge studies were selected from the web search results, using the following search criteria:

- the title of item included the word “recharge” or relates to recharge
- the title of item includes, or refers to, a geographic location, or aquifer, in Africa
- the item is within published scientific literature, or downloadable grey literature (e.g. a United Nations report, or a USGS technical document)

In general, only the first 100 hits were found to be relevant to any one search.

An initial sift of the studies identified was used to exclude any reports which did not:

- contain at least some information (qualitative or quantiative) relating to recharge
- include some description of the geology

In addition to the web, recharge studies were identified within grey literature (e.g. BGS field data reports, country water ministry reports) and through individual researchers and organisations known to the project team. The same inclusion criteria were applied to the results of these more focused searches, as were to the web searches (see above).

In total 132 recharge studies were identified from 94 reports in peer-reviewed and grey literature – see Fig. 1.

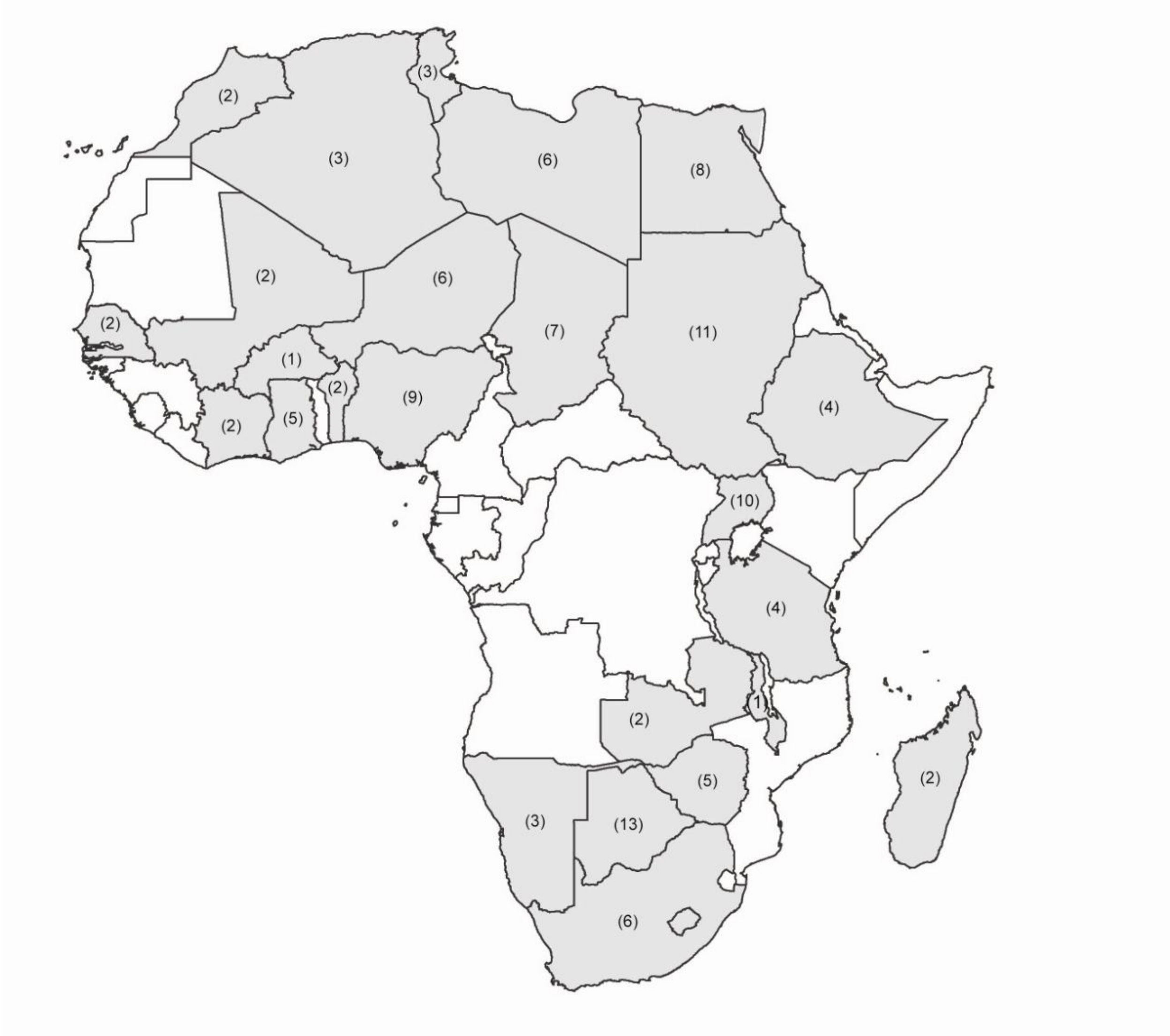

Fig. 1 – Distribution and number of recharge data identified from peer-reviewed and grey literature in Africa.

2.3 THE CONFIDENCE CRITERIA

A confidence rank was assigned to all studies included within the review using set criteria (see Table 1). In general, highest confidence was assigned to the data studies which provide direct recharge estimates. Qualitative recharge estimates (e.g. from groundwater dating studies), and review studies are assigned a lower confidence.

1. *Data studies*

   High confidence (1-2) was assigned to the data studies which include more than 2 recharge estimation techniques appropriate to the geology and climate of the study area (see Applicability of methods section below); include sufficient hydrogeological and climatic data required by the estimation techniques (see Applicability of methods section below); base the recharge estimate from a large sample base; and include description of the regional geology. Generally, observational-based recharge estimates are considered to be more reliable than estimates that rely solely on modelling.

Recharge studies which use appropriate techniques to the geology and climate of the recharge area, but use a small sample base, or include insufficient information to the geology or methodology were assigned a confidence of 3.

Studies were only assigned a low confidence rating (4-5) if one of the techniques used in the study is inappropriate to the climate and geology (if all are inappropriate, the study is excluded), or there is limited information to the methodology, or geology of the study area.

2. *Qualitative studies*

Studies providing qualitative recharge data (e.g. groundwater dating studies) were some of the most common information sources identified by the review. These tend to be high quality studies which give a quantitative indication of groundwater age and residence time. The studies do not, however, provide quantifiable estimates of modern recharge rates, and as a result the studies are assigned a moderate confidence level (3-4) within this data review.

3. *Review studies*

Review studies, by their nature, are based on a wide range of data and field experience and as a result can provide more reliable recharge information than a small sampling survey. The identified studies all include some raw data, but very few describe explicit inclusion or confidence criteria for the data reviewed, or contain sufficient information to the methodology of the recharge estimates. Due to this, review studies were assigned a moderate confidence level (3-4) and original data studies were preferred.

Confidence	Confidence rank	Criteria
High	1	• Recharge estimate is based on observational data from at least 2 techniques appropriate to geology and climate; • Large sample base within recharge area (>20); • Good description of field methods, including raw data; • Description of site including geology and land-use *Plus either of the following:* • Inclusion of long-term, reliable hydroclimatic data; • Recent study (recharge estimate <30 years old)
High-Medium	2	• Recharge estimate is based on observational data from at least 2 techniques appropriate to geology and climate; • Large sample base within recharge area (>20); • Description of geology *Plus 2 of the following:* • Good description of field methods, including raw data; • Comparison of study results, to other recharge estimates within region; • Inclusion of long-term, reliable hydroclimatic data, or qualitative estimate of recharge from groundwater dating study; • Recent study (recharge estimate <30 years old)

Medium	3	• Single field-data based recharge estimation technique is used, which is appropriate to the climate and geology; • Comparison of study results, to other recharge work within region; *And/or:* • Recharge review with a good evidence base, or approximate recharge data from groundwater dating studies. *Plus 2 of the following:* • Small sample base within recharge area (<20) • Description of field methods and geology; • Inclusion of long-term, reliable hydroclimatic data; • Modelled recharge estimate, using sufficient accurate hydrogeological field-data, or qualitative estimate of recharge from groundwater dating study
Medium-Low	4	• Single recharge estimation technique is used, which is appropriate to the climate and geology, but results are not compared to other recharge work within region. *Or:* • Recharge review with poor evidence-base *Plus 2 of the following:* • Small sample base within recharge area (<20) • Limited description of field methods or geology; • No inclusion of long-term, reliable hydroclimatic data; • Modelled recharge estimates, based on little, or no, hydrogeological field-data, but are validated to other recharge studies based on observational data; • study (>30 years)
Low	5	• The recharge estimate is modelled, based on little, or no, accurate hydrogeological field-data • No comparison of study results, to other recharge work within region; *Plus 1 of the following:* • No inclusion of long-term, reliable historical hydroclimatic data; • Poor description of model • Limited description of the geology

Table 1 – Confidence criteria applied to recharge studies.

Applicability of methods

The applicability of recharge estimation techniques can vary with climate and geology in Africa (Checkley 2009; Xu and Beekman 2003). Table 2 sets out the main factors to the applicability of different recharge estimation techniques within Africa. All methods have different strengths and weaknesses as highlighted below for the primary techniques, and it is important to ensure the methods are applied to the appropriate terrain and climate. Confidence in recharge estimates can be increased by using several methods in conjunction.

Chloride mass balance technique – is suitable to most types of natural permeable terrain where there is no geological (e.g. from evaporite sequences) or contamination input of chloride to groundwater. The technique is particularly applicable in areas with low rainfall (e.g. where annual rainfall <600 mm/yr), as chloride accumulation is inversely proportional to the amount of recharge. In wetter areas, some of the chloride mass leaves the catchment as runoff. One of the major benefits of the CMB technique is that it gives a long-term estimate, integrating recharge inputs at a decadal scale, which water balance studies cannot do.

Water balance methods – are most applicable in high rainfall areas (e.g. where annual rainfall >500 mm/yr) where recharge can occur mostly through diffuse soil moisture approaches. In semi-arid areas a greater proportion of recharge is through focussed recharge and bypass flow (Xu and Beekman, 2003). Another limitation to water balance and soil moisture studies is that the techniques often measure output from the soil zone, rather than actual input to the aquifer. The applicability of water balance methods can therefore depend strongly on the availability of data on land-use, which influences the depth of the zero flux plane; depth of zero flux plane is dependent on temperature, soil structure, rooting depth, and seasonality and amount of rainfall (Wellings and Bell, 1982).

Water-table fluctuation method – is most applicable within: high rainfall areas (e.g. where annual rainfall >500 mm/yr) where there are large differences in large amounts of rainfall and evaporation; and, within low storage geologies, where changes in the water-level can be related to inputs of rainfall. However, a very good understanding of the storage coefficient of the hydrogeology is required to be able to interpret the water-table fluctuations. Care needs to be taken that the method is not applied in areas affected by local abstractions.

The applicability of recharge methods within Africa also varies according to the availability of accurate climatic data (Xu and Beekman; Scanlon et al. 2002). Groundwater models, and other water balance approaches, are also reliant on primary field data (e.g. values of hydraulic conductivity and specific yield). The scarcity of quantitative hydrogeological field-data for Africa means that there is often insufficient data to validate the models at an appropriate scale.

Recharge estimation technique	Principles of technique	Applicability of method	
		Advantages	Disadvantages
Primary techniques			
Chloride mass balance (CMB)	Chloride mass is conserved - therefore the chloride concentration in groundwater indicates effective rainfall.	• Suitable in many areas, particularly areas of low rainfall (where annual rainfall <600 mm/yr). • Widely suitable to natural permeable terrain. • Provides a long term recharge estimate, integrating recharge inputs at a decadal scale. • Data requirements not extensive.	• Method is less applicable where geological input of chloride to groundwater –e.g. in sedimentary sequences with significant evaporite rocks • Care needs to be taken when applying technique to high rainfall areas (e.g. >600 mm/yr rainfall).
Water balance methods (WB) – soil moisture balance, saturated volume methods	Recharge estimated from numerical calculation of soil water balance using current climatic data and hydrological data.	• Most appropriate within wet climate zones (e.g. rainfall >500 mm/yr) where difference between rainfall and evaporation is small. • Widely suitable to natural permeable terrain.	• Methods often measure output from the soil zone rather than actual input to the aquifer • Applicability depends strongly on the surrounding land-use. • Less applicable in semi-arid regions (e.g. rainfall <500 mm/yr)
Water table fluctuations (WTF); cumulative rainfall departure method (CRD)	Water-level fluctuations are proportional to the recharge or discharge	• Most appropriate within wet climate zones (e.g. rainfall >500 mm/yr) where difference between rainfall and evaporation is small. • Water level fluctuations easily measured	• Requires detailed information on aquifer storage • Applicability depends strongly on no local abstractions of groundwater. • Less applicable in semi-arid regions (e.g. rainfall <600 mm/yr), and in high storage geologies, or where depth to groundwater is significant
Modern groundwater residence time – Tritium ($^3H/^3He$) and CFC/SF_6	Recharge date can be estimated from the dissolved concentration of tracers within groundwater – age gradient. Tritium provides accurate validation to historical recharge, and CFC/SF_6 validation to current recharge estimates.	• Provide unrivalled accurate independent validation of other recharge estimates/techniques. Special value of ^3H profiles to validate CMB method. • Widely suitable to natural permeable terrain and climates. • IAEA studies and database available.	• SF_6 concentrations often naturally contaminated in basement areas. • CFC concentrations can degrade leading to overestimation of residence time. • Analysis is expensive and conducted in specialist laboratories – mainly in Europe and USA.
Secondary technique			

Distributed groundwater modelling (GM)	Recharge derived from numerical simulation of water balance	• Easy to carry out and cover large areas.	• Models are data intensive – often insufficient hydrogeological data to calibrate models at an appropriate scale. • Recharge estimates from large-scale models (hundreds of km) cannot be downscaled to local data. • Often unreliable
Qualitative techniques			
Palaeo-groundwater residence time indicators– (^{14}C)	Recharge date of palaeo-groundwaters can be estimated from the dissolved concentration of tracers– age gradient. ^{14}C is the main technique, providing semi-quantitative residence time values.	• Widely suitable to natural permeable terrain and climates. • Provide unrivalled accurate independent validation of other recharge estimates/techniques. • IAEA studies and database available.	• Analysis is expensive and conducted in specialist laboratories – mainly in Europe and USA. Often water balance methods used instead of isotope studies in wet climates due to the expense of the technique. • ^{14}C is less applicable within fractured systems, where groundwater residence times are very short.
Palaeo-groundwater residence time indicators– (^{2}H, ^{18}O)	^{2}H and ^{18}O provide qualitative estimates, supporting the ^{14}C method.	• Relatively inexpensive to sample and analyse	• Ambiguous and often only useful in support of other methods.

Table 2 – Applicability of recharge estimation methods in Africa.

3 Recharge data identified

In total, 132 recharge studies from Africa were identified from 94 published and grey literature reports by this review. The studies provide data for many of the major sedimentary basins in Africa, but there are limited recharge data (quantitative or qualitative) for central Africa and from basement rock types across the continent – see Fig. 2. High confidence (1-2) data are scarce (only 10% of studies reviewed), with most (40%) of the identified recharge studies containing either moderate confidence (3) recharge data or qualitative recharge estimates. Appendix 2 shows the full reference list of recharge studies reviewed, with assigned confidence values.

The review aimed to be comprehensive for Africa, and as a result was inclusive of both high and low quality data to ensure the best spatial coverage of data. Low quality data can be useful, particularly within regions where there is very little data. The confidence rank, systematically assigned to the data, ensures appropriate emphasis is placed on the different quality data.

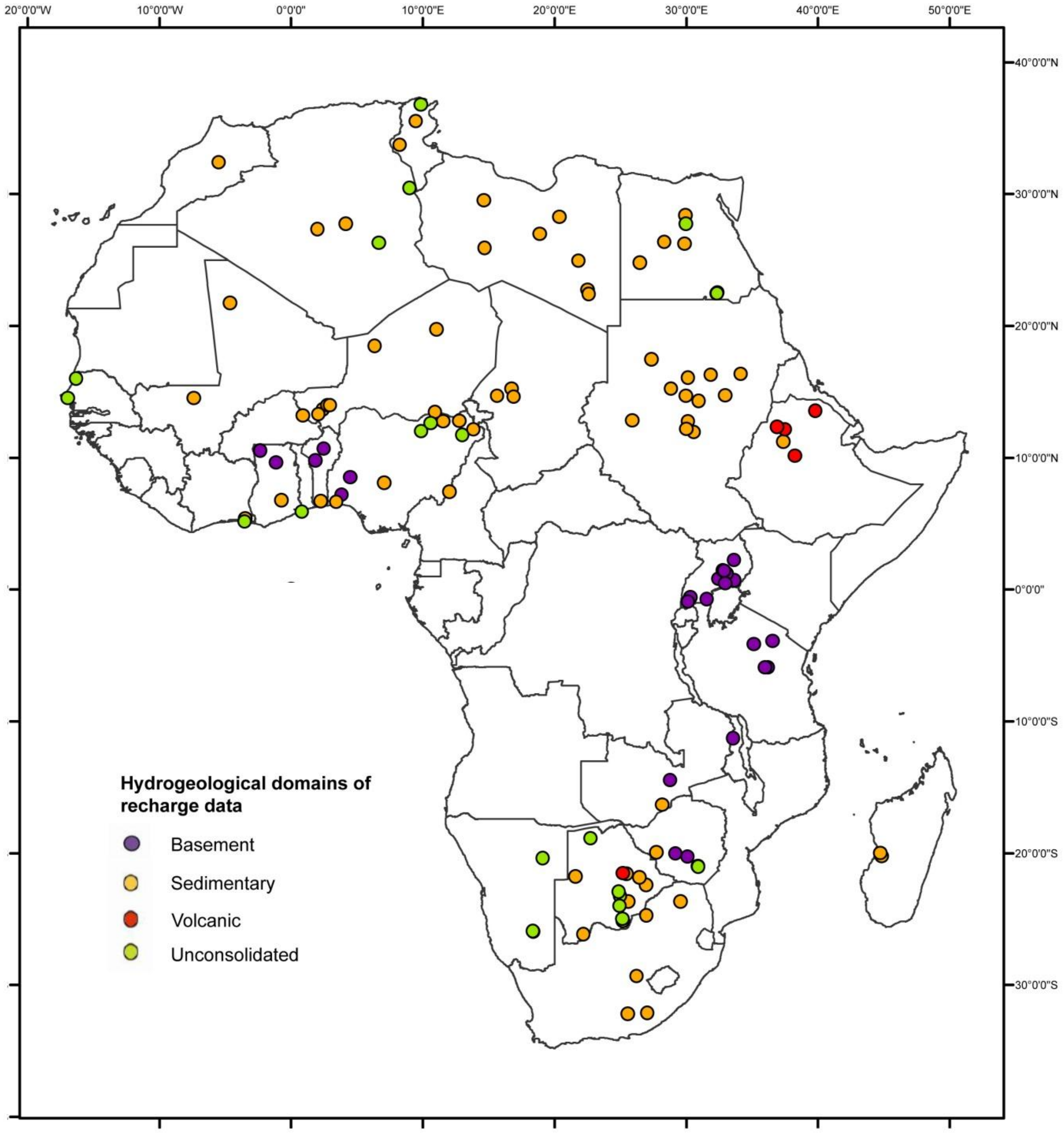

Fig. 2 – Spatial and geological distribution of reviewed recharge data within Africa.

4 Preliminary analysis of recharge data

Below we set out a preliminary analysis of the recharge data identified in the review.

Recharge and climate

Looking at the entire dataset collated, a broad range of modern annual recharge is identified across Africa – Fig.3. Taking into account data from all of the hydrogeological domains in Africa, a broadly linear relationship rainfall and recharge is indicated by the data – see Fig. 3. The correlation is moderately strong – R^2 coefficient calculated to be 0.75.

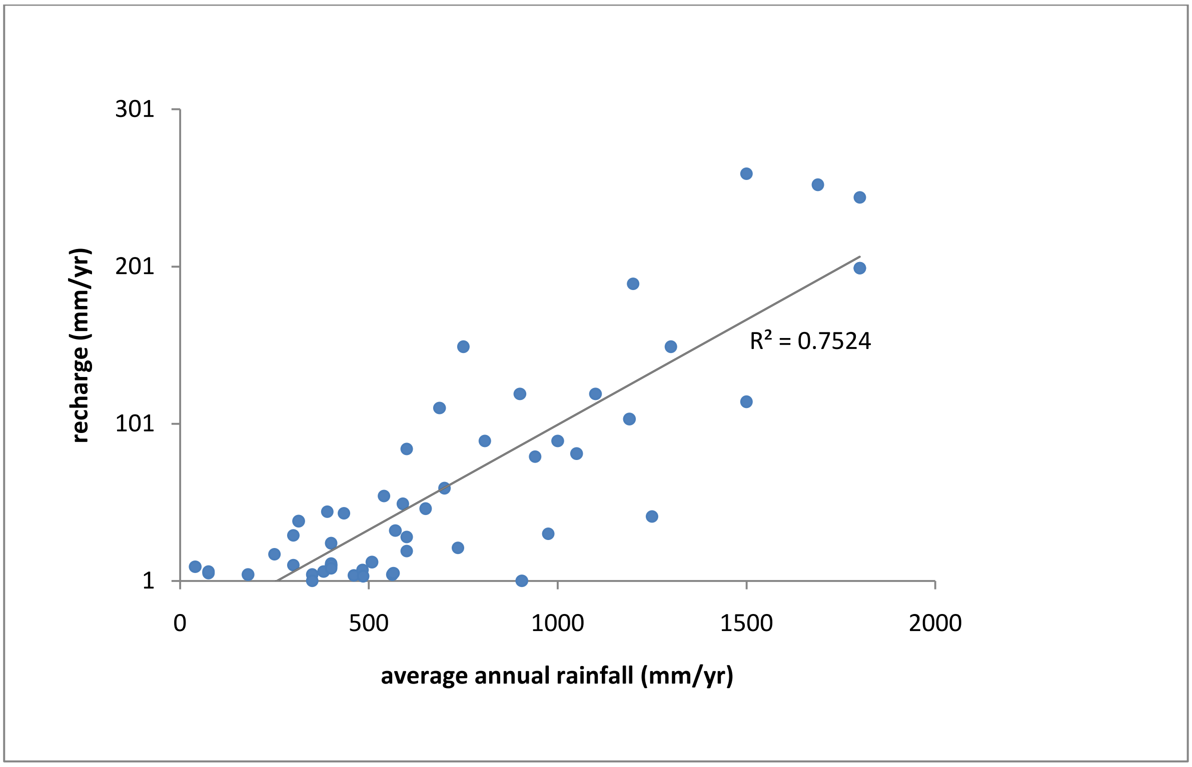

Fig. 3 – Recharge with respect to average annual rainfall for Africa.

Recharge, climate and geology

Fig. 4 shows how recharge varies with both climate and the aquifer geology.

In basement geology, a strong linear relationship between rainfall and recharge is displayed in the data reviewed (R^2 coefficient of 0.73) – see Fig. 5. In contrast, in sedimentary aquifers a non-linear relationship is observed between rainfall and recharge – Fig. 5. In these aquifers low recharge can be observed even in areas of wet seasonal climate (average annual rainfall 500-1000 mm/yr) – Fig. 5.

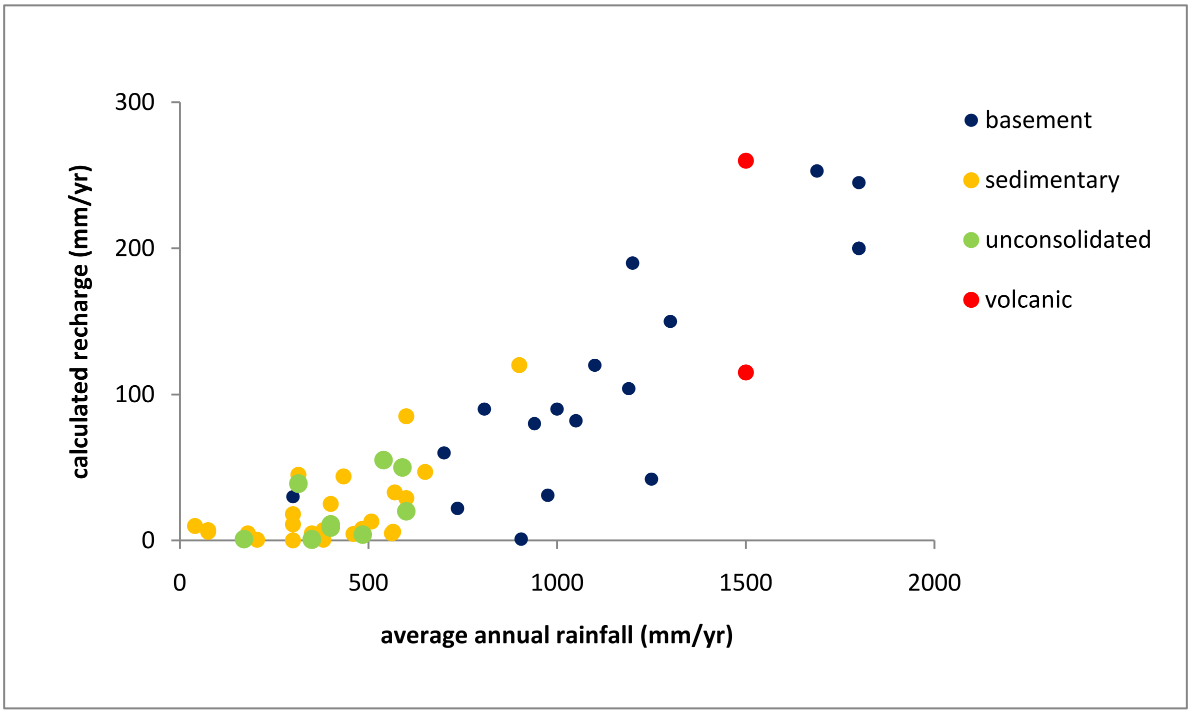

Fig. 4 – Recharge with respect to average annual rainfall and the main hydrogeological domains in Africa.

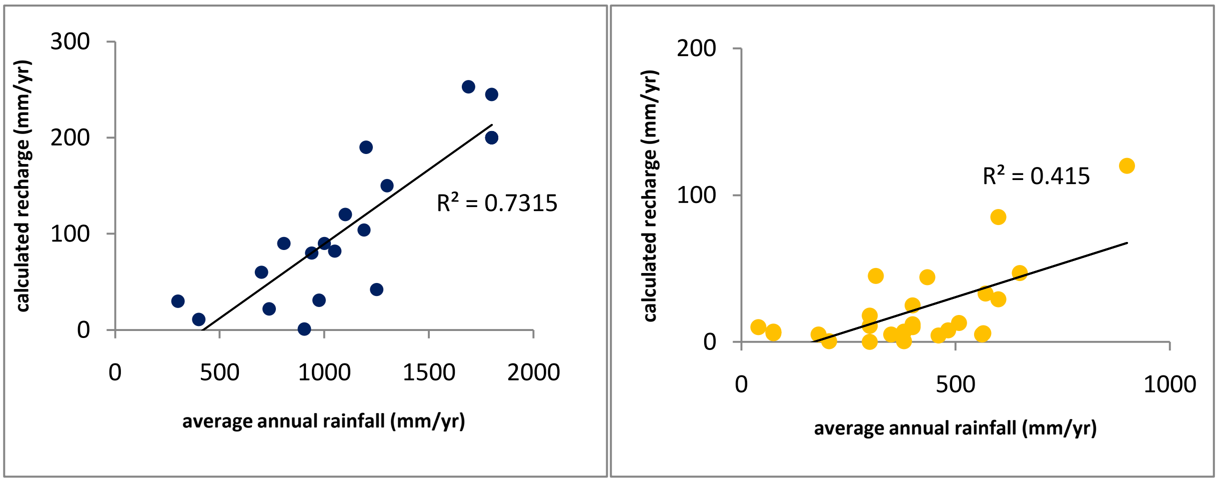

Fig. 5 – (a) relationship between recharge and rainfall within Basement hydrogeological domain; and (b) recharge and rainfall within sedimentary hydrogeological domains.

Ignoring the difference in geology shown in Figure 4, the recharge data from across Africa indicate that: where annual rainfall is <200 mm/yr minimal active recharge occurs (i.e. groundwater resources are finite); where annual rainfall is between *ca.* 200-500 mm/yr region recharge shows a complex non-linear relationship with rainfall; and where rainfall is above 500 mm/yr, a more linear relationship between recharge and climate is observed.

Sampling bias

Results from this analysis should not be over-interpreted. Whilst the data provide a useful insight into the broad range of recharge at a continental scale, there is a clear sampling bias to the data. As shown in Figs. 2 and 4, recharge estimates for each hydrogeological domain are derived predominantly from a single climate zone. For example, recharge data for basement geology are derived largely from seasonally wet climate zones in Africa, whilst recharge data from sedimentary geology is from semi-arid and arid regions – see Fig. 4. As a result, inferences cannot be drawn to the controls on recharge.

The sampling bias is in part reflective of the natural outcrop of the different geologies in Africa, but it also reflects the difficulty in accessing parts of Africa in the last 50 years, and the general lack of systematic hydrogeological work in Africa.

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SCANLON BR, HEALY RW and COOK PG (2002) Choosing appropriate techniques for quantifying groundwater recharge, *Hydrogeology Journal,* 10; 18-39.

WELLINGS, S.R. and BELL, J. P. (1982) Physical controls of water movement in the unsaturated zone, *Quarterly Journal of Engineering Geology and Hydrogeology,* 15; 3; 235-241.

XU, Y, and BEEKMAN, H E. (2003) Review of groundwaterwater recharge estimation in arid and semi-arid southern Africa, in XU and BEEKMAN (eds) Groundwater recharge estimation in Southern Africa, UNESCO, Paris pp. 3-18.

Appendix 1

Table of search criteria used to identify recharge data studies within web searches.

Search engine	**Search criteria**
Google, Google Scholar, and Google Books	Groundwater + Chad basin Aquifer + Chad Basin Recharge + Chad Basin Isotopes + Chad basin Groundwater + Kufra Basin Recharge + Kufra Basin Recharge + Sirte Basin Isotopes + Kufra basin Groundwater model + Kufra Basin Groundwater + Upper Nile Basin Recharge + Upper Nile Basin Isotopes + Upper Nile basin Groundwater + Senegal basin Recharge + Senegal Basin Isotopes + Senegal basin Senegal Basin aquifer Groundwater + Volta basin Recharge + Volta Basin Isotopes + Volta basin Groundwater + Taoudeni basin Recharge + Taoudeni Basin Isotopes + Taoudeni basin Groundwater + Iullemeden basin Recharge + Iullemeden Basin Isotopes + Iullemeden basin Groundwater + Sokoto Basin Recharge + Sokoto Basin Isotopes + Sokoto basin Groundwater + Congo Basin Recharge + Congo Basin Isotopes + Congo basin Groundwater + DRC basin Recharge + DRC Basin Isotopes + DRC basin Groundwater + Zaire Basin Recharge + Zaire Basin Isotopes + Zaire basin Congo aquifer Central Africa + groundwater Central Africa aquifers Groundwater + West African Coastal Basin West Africa coastal aquifers Recharge + West Africa Isotopes + West Africa Groundwater + East Africa coastal basins

	East Africa coastal aquifers Recharge + East Africa Isotopes + East Africa Groundwater + Kalahari basin Recharge + Kalahari Isotopes + Kalahari Kalahari recharge Kalahari water supplies Groundwater + Karoo basin Recharge + Karoo Basin Isotopes + Karoo basin Karoo aquifer + groundwater Karoo aquifer basin
Web of Science and Science Direct	Groundwater + Chad basin Aquifer + Chad Basin Recharge + Chad Basin Isotopes + Chad basin Groundwater + Kufra Basin Recharge + Kufra Basin Recharge + Sirte Basin Isotopes + Kufra basin Groundwater model + Kufra Basin Groundwater + Upper Nile Basin Recharge + Upper Nile Basin Isotopes + Upper Nile basin Groundwater + Senegal basin Recharge + Senegal Basin Isotopes + Senegal basin Senegal Basin aquifer Groundwater + Volta basin Recharge + Volta Basin Isotopes + Volta basin Groundwater + Taoudeni basin Recharge + Taoudeni Basin Isotopes + Taoudeni basin Groundwater + Iullemeden basin Recharge + Iullemeden Basin Isotopes + Iullemeden basin Groundwater + Sokoto Basin Recharge + Sokoto Basin Isotopes + Sokoto basin Groundwater + Congo Basin Recharge + Congo Basin Isotopes + Congo basin Groundwater + DRC basin Recharge + DRC Basin Isotopes + DRC basin Groundwater + Zaire Basin Recharge + Zaire Basin Isotopes + Zaire basin Congo aquifer Central Africa + groundwater Central Africa aquifers Groundwater + West African Coastal Basin

	West Africa coastal aquifers Recharge + West Africa Isotopes + West Africa Groundwater + East Africa coastal basins East Africa coastal aquifers Recharge + East Africa Isotopes + East Africa Groundwater + Kalahari basin Recharge + Kalahari Isotopes + Kalahari Kalahari recharge Kalahari water supplies Groundwater + Karoo basin Recharge + Karoo Basin Isotopes + Karoo basin Karoo aquifer + groundwater Karoo aquifer basin

Appendix 2

References of the recharge studies reviewed listed according to confidence rank. Some references are assigned multiple confidence values – these are review papers or regional studies which contain recharge data relating to more than one aquifer.

Confidence rank	Study reference
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