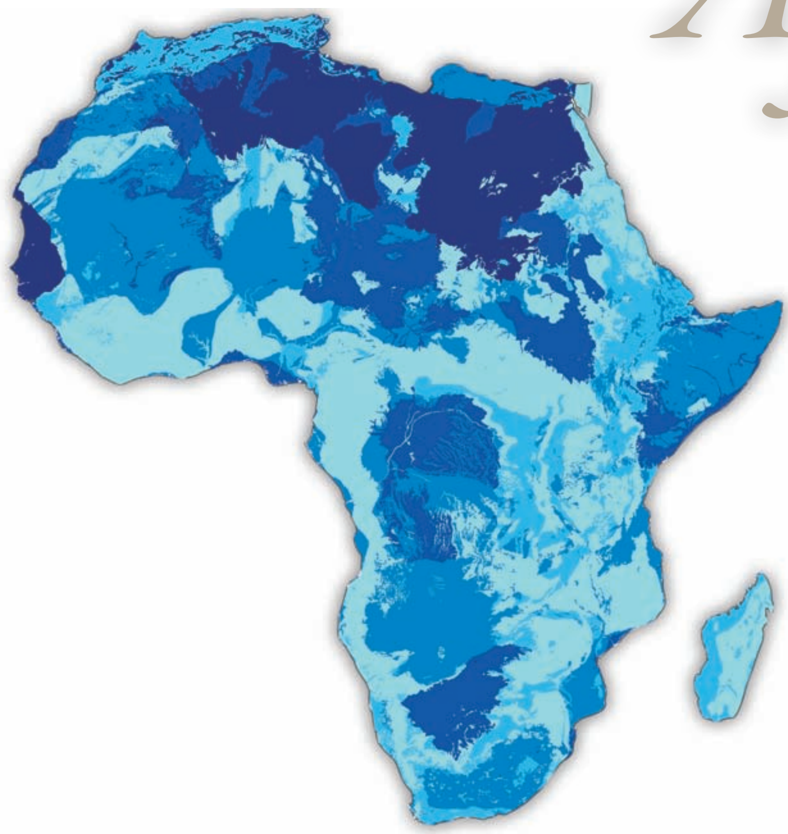
Groundwater Science Programme | **Open Report OR/11/031**

Groundwater resilience to climate change in *Africa*



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Front cover

Estimated groundwater storage per square kilometre across Africa.
For key see figure 3, p8.

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Contents

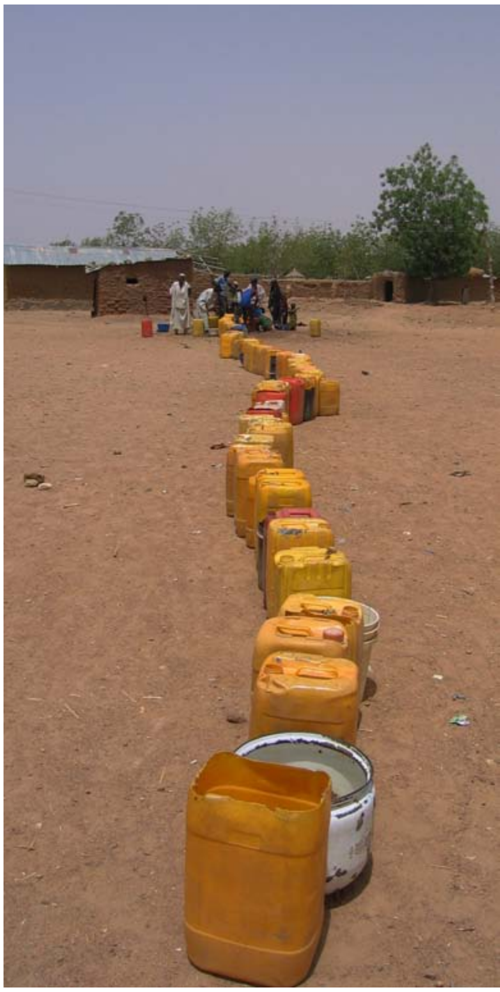
1 Introduction

Groundwater provides most of the domestic water supply in rural Africa and supports poverty reduction through irrigation. Climate change along with rapid population growth are likely to impact all water resources, but the response of groundwater will be slower than that of surface water. This could provide a potential buffer to support adaptation strategies. A key advantage of groundwater is its reliability: aquifer storage ensures that groundwater supplies can be maintained during periods of little or no rainfall and help to even out meteorological variability. As a natural store of water, aquifer storage is many orders of magnitude greater than that which can be achieved through constructing surface water reservoirs.

The IPCC Fourth Assessment report review of climate model projections shows a consistent pattern of progressive warming of the climate in all regions of Africa, but a much less consistent pattern for rainfall (Solomon et al. 2007). The increased temperature will lead to higher rates of evapotranspiration and likely increase in the intensity and variability of rainfall (Conway 2011). Although the exact impact on runoff and groundwater recharge is unclear, most scientists agree that both will become less reliable.

Making more use of groundwater will therefore be critical in helping communities and countries adapt and build resilience to changes in climate. This is likely to include the increasing use of groundwater for both small-scale household/village irrigation and larger-scale commercial irrigation; and increased use of motorized borehole pumps for reliable urban water supply (small towns to larger conurbations).

The benefits of groundwater are well recognised (MacDonald et al. 2005), but there is limited knowledge of African groundwater resources and how they might respond to changes in climate. There has been little systematic assessment of groundwater storage and availability which was reflected in the paucity of information on groundwater presented in the IPCC Fourth Assessment Report and Technical Paper on Water, where there was major uncertainty as to how changes in climate may affect groundwater (Solomon et al. 2007; Bates et al. 2008).



2 Research aims and methodology

2.1 Research objectives

The overall aim of this research project is to improve understanding of groundwater resources across Africa and examine their relative resilience to climate change. This aim can be broken down into three main objectives:

1. to strengthen the evidence base linking groundwater resources, climate variability and livelihood vulnerability.

2. to support local and international research agendas by collating and interpreting disperse groundwater data and transforming to policy-relevant information and knowledge.

3. to develop evidence-based guidance for assessing the resilience of groundwater to climate variability.

The main outputs from the project are robust quantitative groundwater maps for Africa which highlight which areas are more likely to be resilient to climate change and also where sufficient groundwater resources may be available to help adaptation. The maps are underpinned by dedicated case studies and systematic data/literature reviews which will be published separately.

These quantitative groundwater maps are the first produced for Africa and have wider uses than for this specific climate related project. For example they can be used as a first pass in helping to appraise the feasibility and costs of groundwater options in the continent.

[1] The project was funded by the UK Department for International Development and ran from February 2010 to March 2011. The project team was led by the BGS and included researchers from UCL and ODI. Project partners for individual case studies comprised the Nigerian Geological Survey Agency, the University of Ibadan, RiPPLE Ethiopia, the Ministry of Water and Irrigation (Tanzania), the Ministry of Water and Environment (Uganda), Makerere University, Sokoine University and WaterAid Mali. The project was overseen by a steering committee comprising seven international experts, who met regularly to review progress and provide feedback.

2.2 Research methods

To help achieve the project aim, research was undertaken using three main methods: systematic reviews of published and grey literature, field case studies, and a detailed geological and hydrogeological analysis using GIS. These component parts of the project will be published separately in peer review journals and BGS Open Reports.

Reviews – Two systematic reviews were carried out from published and unpublished literature. The first review identified approximately 100 studies of groundwater recharge for Africa; a second review examined 250 published and grey literature on African aquifer properties. The review process enabled unreliable studies to be excluded, but allowed for some low quality studies which passed minimum criteria to be used in areas with few data.

Case studies – Three detailed case studies were undertaken during 2010 (Figure 1). In ***West Africa*** approximately 60 boreholes were sampled across a transect from semi-arid to humid climate. Detailed chemical analysis was undertaken to assess the residence time of shallow groundwater used to sustain rural water supply boreholes (<0.5 l/s). In ***Uganda and Tanzania*** high yielding groundwater supplies from basement rocks (see Box 3) were examined to help understand the hydrogeological conditions required to sustain higher yielding supplies (>1 l/s). Available monitoring records were collated and analysed along with pumping test data and new chemical analysis targeted to assess residence times. The ***Ethiopian*** case study involved the analysis and interpretation of detailed household surveys about seasonal water access, use and livelihoods in 24 communities across three livelihood zones.

Groundwater maps – The groundwater maps were developed to provide quantitative groundwater information for Africa. Several groundwater maps already exist for Africa, but provide only qualitative information. Significant effort was put into collating, assessing and systematising available regional and site specific information on groundwater using GIS. The methodology is explained in more detail in Chapter 3.

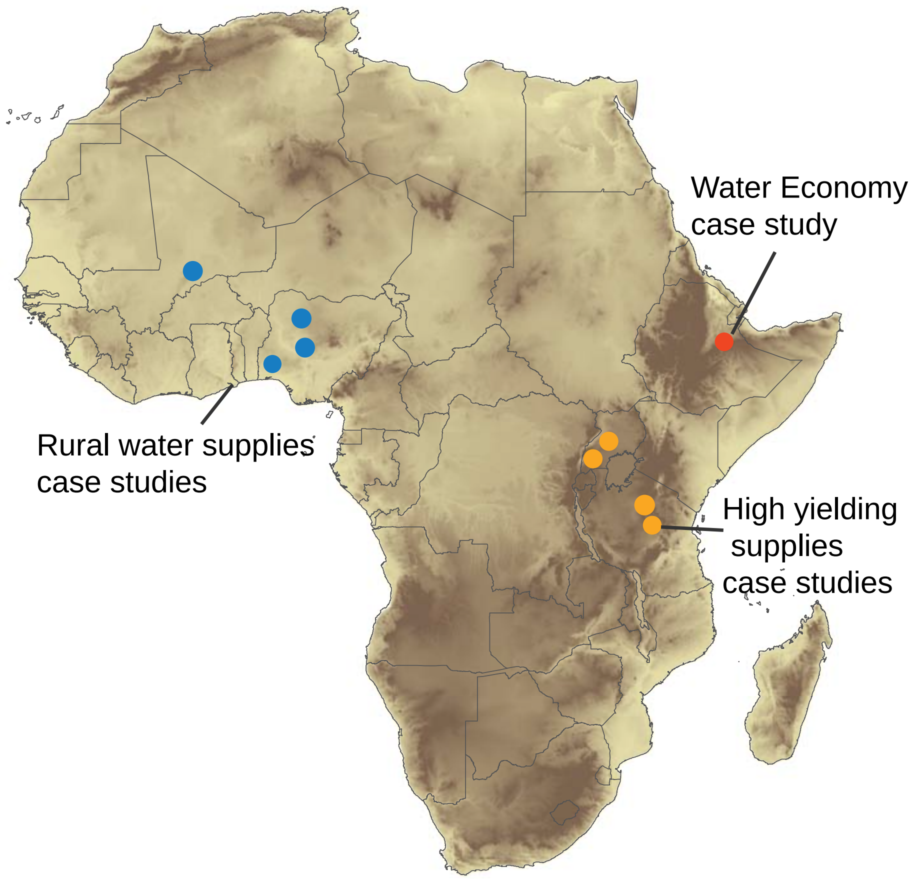


Figure 1
Location of the three project case studies.

Box 1 Groundwater resilience: some definitions

In ecological science, the term resilience encompasses two aspects of a system: the ability to resist long term damage, and the time taken to recover from a perturbation (Gunderson 2000). Adapting this approach to groundwater resources we have two scenarios:

The resilience of groundwater resources to long term (decadal) shifts in climate: dominated by the available groundwater storage – larger groundwater bodies will be much less affected by long term shifts in climate than smaller bodies. For example, the thick sandstone aquifers in northern Africa contain large volumes of groundwater despite having received little recharge during the last 5000 years (Edmunds et al. 2008). Comparatively thin weathered basement aquifers contain much smaller volumes of groundwater – groundwater resources would soon be exhausted if recharge was to cease completely.

The resilience of groundwater resources to short term (inter annual) climate shocks: also dominated by the available groundwater **storage**, but is also influenced by the **long term average (decadal) recharge** to the groundwater system which will help the system recover more quickly (Calow et al. 2010). Therefore, in an area with generally high long term average recharge, groundwater within a thin weathered basement aquifer would recover much more quickly from several years drought than if the aquifer was in an area where long term average recharge was low (Calow et al. 1997).

For many people the more important issue is the **resilience of the water supplies** dependant on groundwater rather than the actual groundwater resource itself. A sustainable approach to developing groundwater resources usually involves balancing the long term abstraction with the long term recharge after taking into account the needs of the environment. However, research from the behaviour of water sources during droughts has shown two important issues beyond this simple water balance approach:

1. Improved sources are much more reliable than unimproved sources (Bonsor et al. 2010).

2. Boreholes in higher yielding (more permeable) aquifers are generally much more reliable than in lower yielding aquifers (MacDonald et al. 2009).

Therefore, for estimating the resilience of water sources to changes in climate, the aquifer permeability (or its surrogate productivity) should be considered alongside storage and long term recharge. For the purposes of this project we assume that groundwater is accessed through improved water sources (for example a borehole 50 m deep).

Long queues at a borehole which provides the only resilient supply in the area.

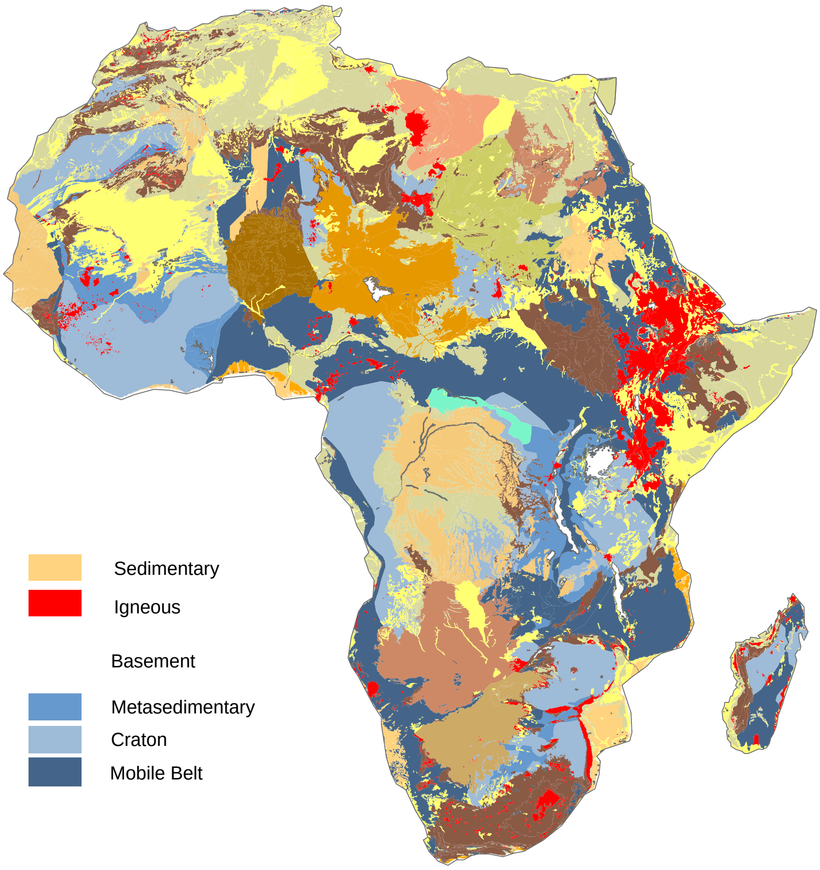
3 Groundwater resilience maps for Africa

Resilience is an important attribute of an ecosystem, but the concept has rarely been applied to groundwater. Box 1 explains how the term can be applied to groundwater in the context of climate change. It is important to distinguish the resilience of the resource itself from the individual water sources (e.g. boreholes) that use groundwater, and also whether the resilience is to short term shocks, such as drought, or long term shifts in climate. In this chapter we discuss the development of the groundwater maps for exploring resilience, and their potential use and limitations. We also discuss the results of the systematic review of groundwater recharge.

3.1 Developing groundwater base maps

Groundwater occurrence depends primarily on geology, geomorphology/weathering, and rainfall (both current and historic). The interplay of these three factors gives rise to complex hydrogeological environments with countless variations in the quantity, quality, ease of access and renewability of groundwater resources (see Box 2).
To understand and characterise the resilience of African groundwater to climate change requires an understanding of the spatial distribution of groundwater storage, aquifer permeability and the annual rate of recharge (see Box 1). In groundwater science this means characterising: aquifer transmissivity (the permeability of the rocks integrated over thickness); the effective porosity of the rocks; the saturated thickness of the aquifers; and annual groundwater recharge.

Figure 2
A simplified version of the geological base map used to develop the aquifer maps.



 Surficial geology of Africa, Courtesy of the U.S Geological Survey.

Quantitative data on transmissivity and effective porosity are scarce for much of Africa, and instead we use a series of proxies for these parameters which have been found to be an effective surrogate in data poor areas elsewhere (e.g. Graham et al. 2009). For transmissivity we use the typical borehole yields of well sited boreholes (termed *aquifer productivity*); effective porosity is estimated by determining the flow and storage characteristics of different lithologies (termed *aquifer flow/storage*). The saturated thickness is estimated from reports where available. Most of the major sedimentary basins in Africa have some data on aquifer thickness; for other aquifers the information is from general borehole depths and reports were used to give general thicknesses. Groundwater recharge data were taken from the global WaterGap model developed by Döll and Fiedler (2008).

The development of three new base maps (aquifer productivity, aquifer flow/storage type, and saturated aquifer thickness) is summarised in Box 3. Every effort was made to use all available information: reliable geological base maps; all available national, regional and sub-national hydrogeological maps; 250 papers and documents reporting groundwater studies in Africa; and good information on borehole yields for basement rocks. The final draft was sent for peer review to experts in African groundwater who generally agreed with the classifications, with some small modifications in local areas.

Figure 2 shows a simplified version of the final geological base map which formed the basis of the aquifer maps.

Aquifer productivity is defined as the typical yield (taken as the interquartile range) of effectively sited boreholes in an aquifer; yields outside this range would also be expected 50% of the time.

Aquifer flow/storage type is divided into five categories varying from fractured to intergranular, which denote the predominant flow and storage mechanisms in the aquifer.

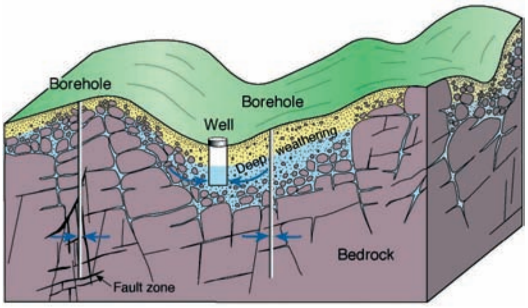
Saturated aquifer thickness is divided into four categories (<25 m, 25–100 m, 100–250 m, >250 m).

Box 2 Groundwater occurrence in different geological environments

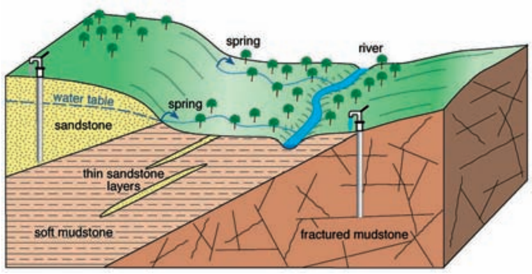
(MacDonald et al 2005; MacDonald and Calow 2009)

There are many different hydrogeological environments in Africa, but five of the most important are described below

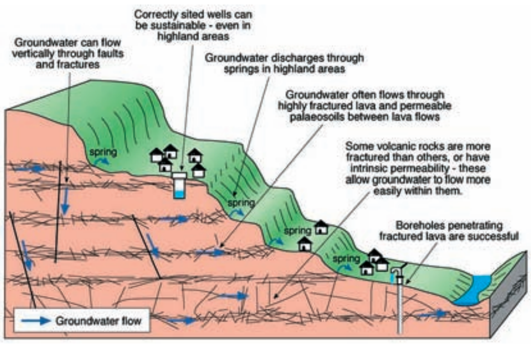
Precambrian crystalline basement rocks occupy 34 % of the land surface of Africa and comprise crystalline rocks with very little primary permeability or porosity. Groundwater can be found within the weathered overburden or fractures in the bedrock. Yields of properly sited boreholes are commonly 0.1–1 l/s, but can occasionally be as high as 10 l/s.



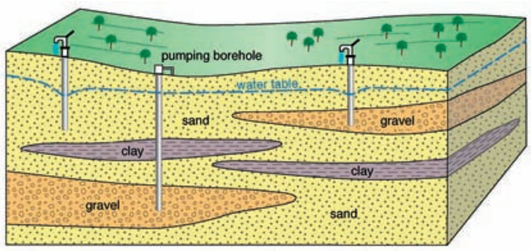
Consolidated sedimentary rocks occupy 37 % of land area of Africa — but mainly across un–inhabited areas. Sandstone basins can store considerable volumes of groundwater and support high yielding boreholes of 10–50 l/s. However within low permeability mudstones and shales boreholes are often unsuccessful or only support yields of less than 0.5 l/s. Limestones rocks are soluble, and groundwater can flow through solution enhanced fractures; yields of boreholes can be very high (>20 l/s), but storage may be more variable.



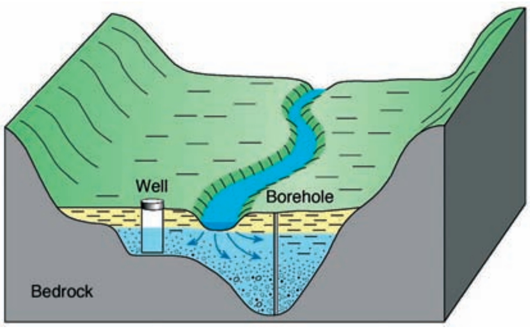
Volcanic rocks occupy only 4 % of the land area of Africa and are found in east and southern Africa where they underlie some of the poorest and drought stricken areas of Africa. Groundwater tends to be found in the fractures at the top and base of lava flows and within ash layers. Yields of 1–5 l/s can be achieved through well sited boreholes, but storage can be highly variable.



Unconsolidated sediments form some of the most productive aquifers in Africa. They cover approximately 25 % of the land surface. They have a high porosity and can store large volumes of groundwater; yields of 5–50 l/s are possible from individual boreholes.



Unconsolidated sediments in river valleys are highly significant aquifers in Africa. They probably cover <1 % of the land area, but can be present within most river valleys. They can vary in thickness from several metres to 100 m thick, and have a high porosity. Individual yields of boreholes are commonly 1–10 l/s.



Box 3 The methodology used for developing the suite of groundwater base maps

UNESCO 1:5M geological map of Africa with digital linework from USGS used as a base

Subdivision of Precambrian and classification of sedimentary rocks into major basins using more detailed geological information

Geological base map

Published hydrogeological maps scanned and georeferenced and used to attribute the geological base map

Groundwater maps Draft 1

Information from the review of aquifer studies used to refine map attributions

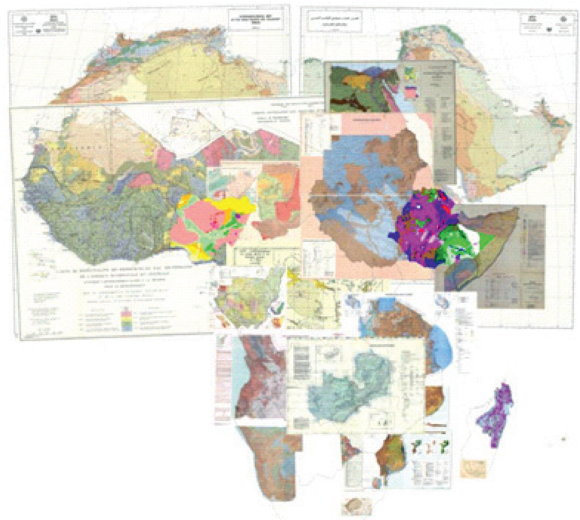
Database of basement borehole yields used to check productivity map

Groundwater maps Draft 2

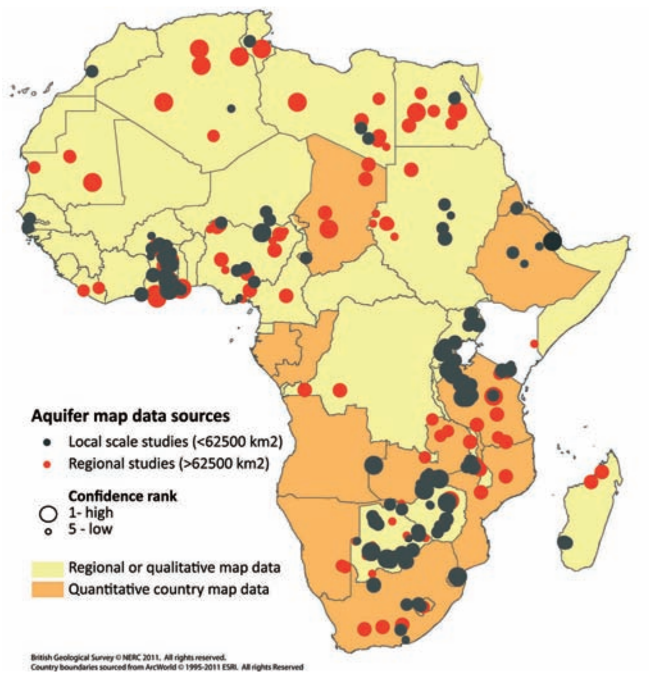
Maps sent for peer review and available on website

Draft presented at international conferences and feedback invited

Final groundwater maps;
Aquifer productivity
Aquifer flow/storage type
Saturated aquifer thickness



Some of the georeferenced hydrogeological maps used in developing the Africa wide maps



The location of the site specific aquifer review studies used to generate the second draft

3.2 Derived groundwater resilience maps

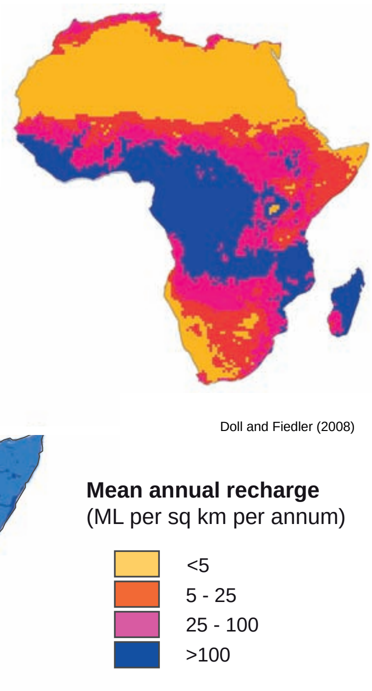
The quantitative groundwater maps described above can be used, and further interpreted, to help us understand the resilience of groundwater to climate change and the potential of groundwater to support adaptation strategies.

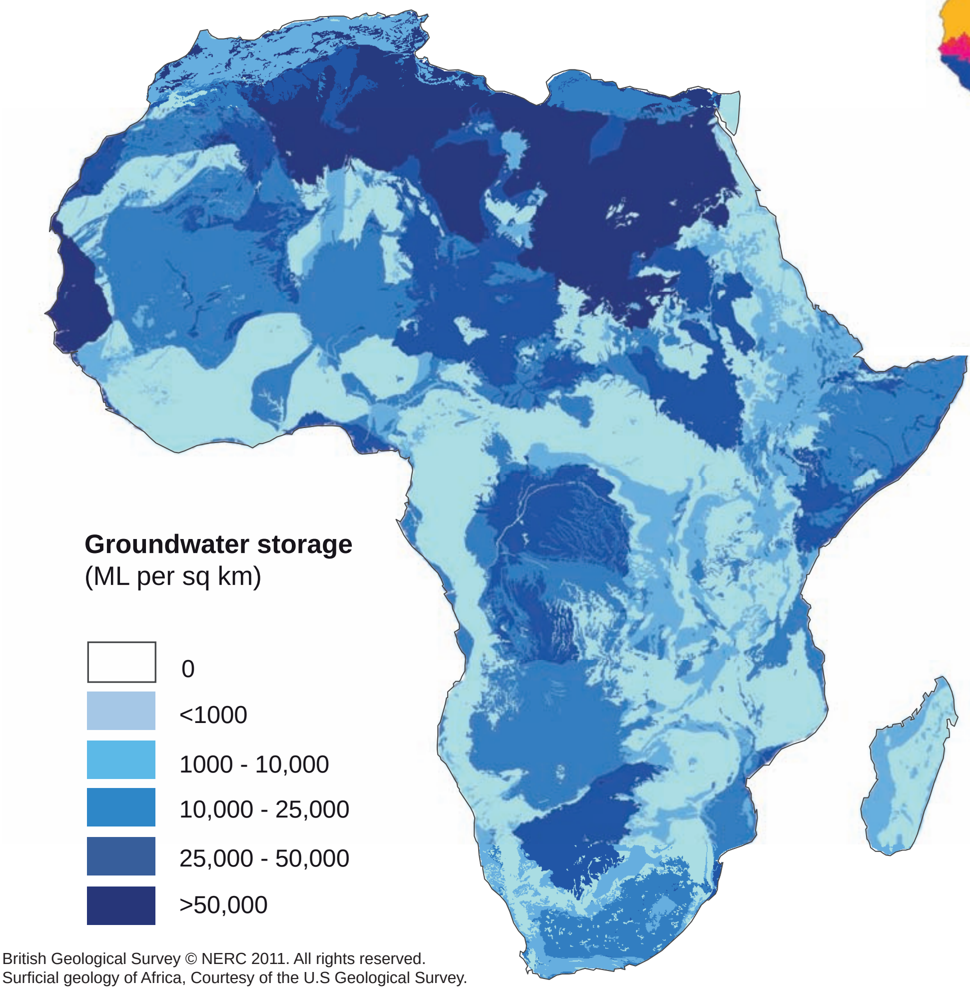
3.2.1 Groundwater storage and recharge

The resilience of groundwater resources to long term shifts in climate is governed by the available groundwater storage (see Box 1). Larger groundwater bodies contain groundwater storage several orders of magnitude greater than average annual recharge and therefore will respond very slowly to long term changes in recharge or short term shocks. Smaller groundwater bodies with little storage are not resilient to long term (decadal) changes in climate, but can recover quickly from drought if recharged regularly (MacDonald et al. 2009).

Groundwater storage was estimated by assigning an effective porosity to each aquifer flow/storage type based on studies carried out in typical environments (see Appendix). This effective porosity was multiplied by the map of average saturated thickness (see Box 3) to give an estimate of groundwater volume (Figure 3). The results are quoted in mega-litres (Ml) per square kilometre (equivalent to mm of storage). Potential annual recharge taken from the WaterGap Global hydrological model is also shown in Figure 3 (Döll and Fiedler 2008) and is broadly related to annual rainfall.

Figure 3
Estimated groundwater storage for Africa. Note that the groundwater chemistry is not taken into consideration.





Surficial geology of Africa, Courtesy of the U.S Geological Survey.

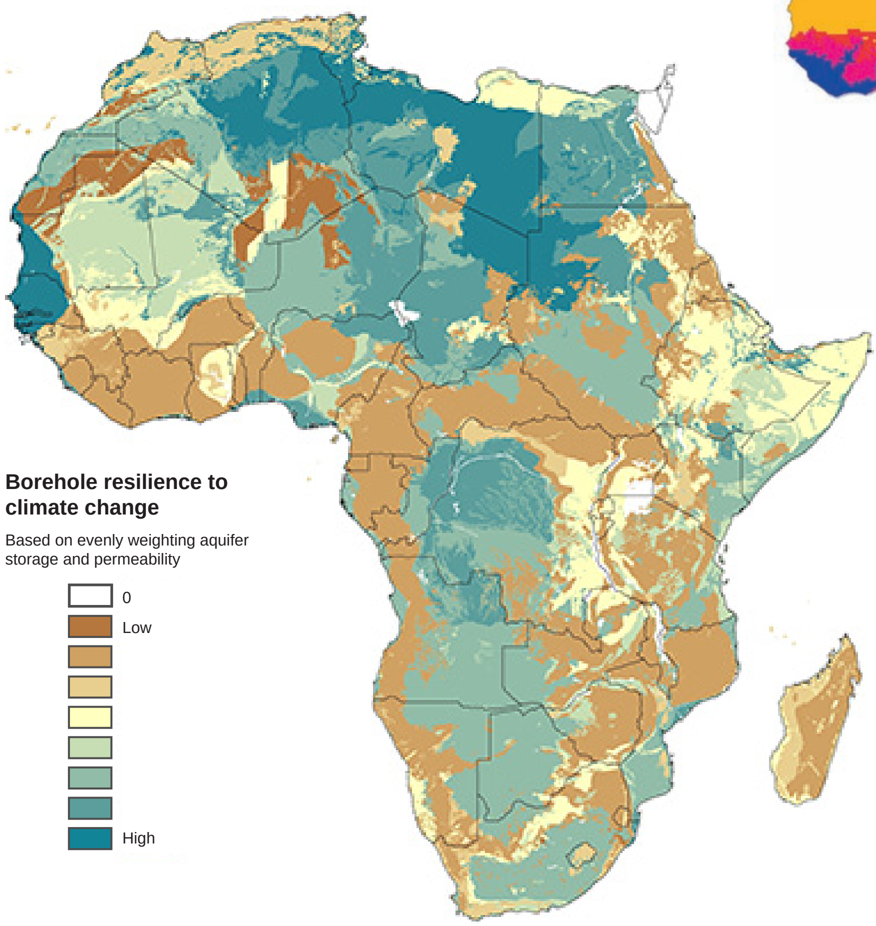
The areas of largest groundwater storage are in the large sedimentary basins (Figure 3). The large aquifers in North Africa contain much of Africa's groundwater, and are presently not actively recharged; much of the recharge to these aquifers occurred more than 5000 years ago when the climate of the area was much wetter. The aquifers with the least storage are generally the thin weathered Precambrian basement rocks. However, even these contain significant stores of groundwater, many times the annual recharge.

3.2.2 Resilience of boreholes to climate change

The resilience of boreholes to climate change is governed by the groundwater storage and the permeability of the aquifers. For the purposes of interpreting borehole resilience, the aquifer productivity and groundwater storage were equally weighted following the approach of Calow et al. (2010).

The most resilient areas are again the large sedimentary basins, with areas underlain by basement rocks having low resilience. However, many of the basement aquifers are located in areas with high average annual recharge relative to the rest of Africa (Fig. 4, insert), which increases the resilience of groundwater dependent supplies.

Figure 4
An interpreted map of the resilience of boreholes to climate change based on aquifer storage and permeability. High average annual recharge will increase the resilience to short term (ie interannual) climate variability.

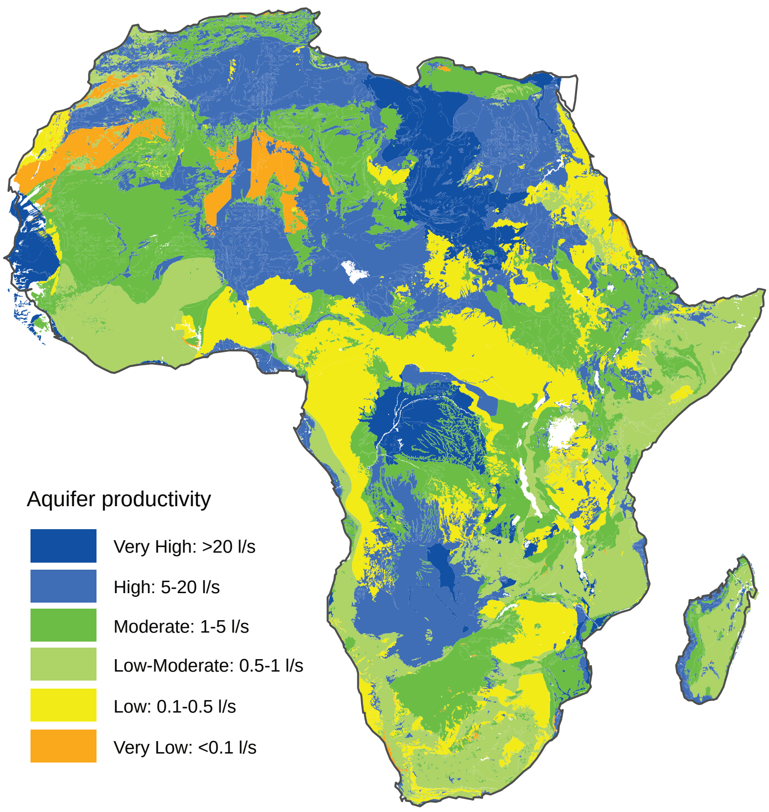


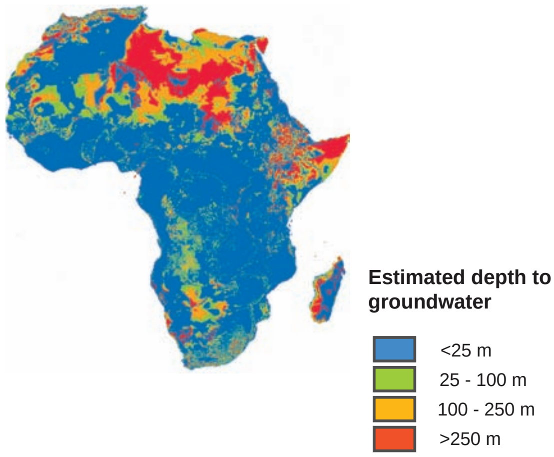
3.3 Maps for adaptation

One of the major drivers for producing African wide quantitative groundwater maps was to help assess where groundwater could be used to help adapt to climate change and population growth. These adaptation strategies may include more water for intensive irrigation, installing more improved rural drinking water and multiple use supplies, small scale irrigation and increased groundwater based urban supply. For this purpose the aquifer productivity map is the most useful as it indicates what borehole yields could reasonably be expected in an area. Another factor is the depth at which the water table lies, as this often determines the ease of access to groundwater. For example, if groundwater is > 40 m deep it is difficult to use a handpump. Deeper boreholes are much more expensive to drill, and the ongoing costs of pumping are much higher. Unfortunately there are very few measurements of depth to groundwater across Africa. A different approach was used here, which has been applied in other regions with few measured data. A surface representing the base-level of main perennial rivers was interpolated and subtracted from the ground surface. This assumes that the perennial rivers are the surface expression of the water-table and works well close to rivers; however it is fairly unreliable where unconstrained by nearby rivers. Figure 5 shows the aquifer productivity map for Africa with an inset of the estimated depth to groundwater assumed from river base-levels and a map of population density.

The adaptation maps indicate the following:

- For much of Africa, carefully sited and well-constructed boreholes will be able to sustain rural handpumps. In some semi-arid and arid areas water-levels may be below the depth at which groundwater can be easily exploited, but these areas are generally less densely populated than wetter areas.
- The potential for boreholes yielding greater than 5 l/s is not widespread across Africa, although the potential will exist locally if accompanied by proper borehole siting and investigation. Yields of >5 l/s are required for larger town supplies or intensive irrigation.
- Boreholes with smaller yields of 0.5 to 5 l/s, which could be suitable for small scale irrigation, or multiple use systems, are easier to develop, but require effective investigation and siting in many environments. Even in areas where typical yields are <0.5 l/s, boreholes with yields in the range of 0.5–5 l/s may be found in some environments with careful investigation.
- The majority of large groundwater stores in the sedimentary basins which can accommodate high yielding boreholes are often far from population centres and are accompanied by deep water-levels.





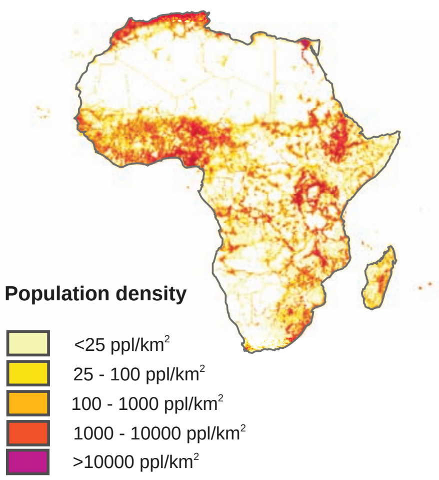


Figure 5
The aquifer productivity map across Africa and an estimated depth to groundwater and population density.

3.4 Proposed use and limitations of the maps

The maps have been developed using the best available data at a continental scale for Africa. Box 3 illustrates the extent of available data and confidence in the resulting maps. There is a lack of good quality hydrogeological maps in North, West and Central Africa. In West Africa, this is compensated for by the availability of many individual smaller studies, most notably in Nigeria and Ghana. In northern Africa, the size of individual studies tend to be much larger and involve characterising major regional aquifers, and so again can compensate for the lack of good quality national maps. In Central Africa, however, both maps and study information are scarce.

The maps are designed to show information at the continental, or perhaps regional scale (e.g. to be used at a nominal scale of approximately 1:20M). Their primary aim is to highlight the variations in groundwater resources, their resilience to climate change, and their potential use for adaptation strategies. They should not be used for national planning. The approach could be repeated for individual countries, but would require more detailed geological and hydrogeological information. For many countries this would require the collection of primary data.

3.5 Groundwater recharge

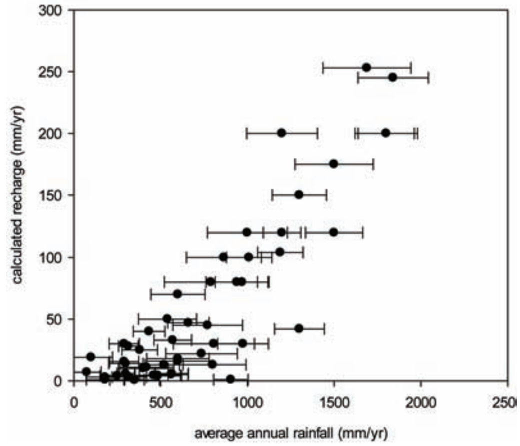
Critical to the response of groundwater to climate change is an understanding of how groundwater is replenished. Outputs from climate models include estimates of precipitation totals and intensity, but translating that into groundwater recharge is difficult (Bates et al. 2008). There is little consensus on what mechanisms dominate groundwater recharge in the variety of climatic and geological conditions within Africa.

A systematic review of available groundwater recharge studies was carried out as part of this research project. Rigorous inclusion and confidence criteria were used to evaluate the papers and approximately 100 studies were included in the systematic review. For most of the studies an estimate of mean annual groundwater recharge can be obtained, but no information on how the recharge has occurred. The data can be interpreted to show relationships between current climate conditions and recharge, but do not give much insight into recharge mechanisms which could be used in predictive modelling. No systematic bias was found between the different methods of estimating recharge, although some are more appropriate in semi arid areas than humid areas.

Figure 6 shows the estimates of recharge from the review plotted against the mean annual rainfall 1951–1990, and the standard deviation in the period as error bars. Further analysis of the data show:

- estimates of recharge are generally related to annual rainfall with a linear relationship above 1000 mm annual rainfall.
- below 1000 mm annual rainfall there is a non linear relationship between rainfall and recharge; analysis showed that the annual rainfall and length of dry season together were the best predictor of recharge below 1000 mm, indicating that intensity of rainfall is important.

Figure 6
Calculated recharge in Africa with respect to average annual rainfall and interannual rainfall variability.



4 Case studies

4.1 General introduction to case studies

Three case studies were designed to increase the evidence for how groundwater and groundwater-based water supplies currently respond to climate and are linked to livelihoods. The main premise is that by understanding how these factors are currently interlinked, their response to future possible scenarios can be forecast with greater confidence. The results from the case studies are therefore independent of future climate predictions, which continue to have considerable variability and uncertainty across Africa (Bates et al. 2008).

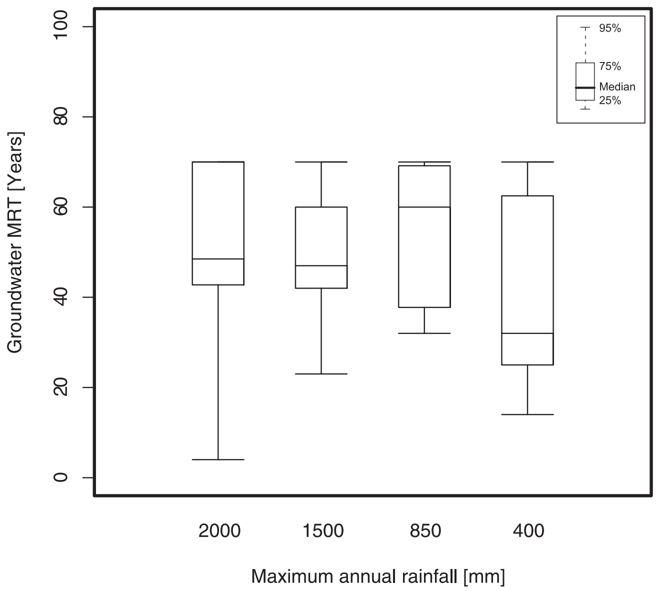
This research project was commissioned to be short and intensive (1 year), and therefore the case studies were designed to use techniques that could yield useful results from one round of sampling or surveys. For the two hydrogeological case studies this meant using several novel techniques for estimating groundwater residence times, and carefully designing the research to gather all appropriate data from one sampling campaign. For the study linking access to water and poverty reduction, highly detailed household surveys were analysed to explore water access and use in different wealth groups across different livelihood zones.

4.2 Rural water supplies case study

This case study explored the resilience of shallow groundwater supplies (borehole depth <50 m) to climate variability. Boreholes of this depth are often the only sources that are operational during the dry season, and are widespread throughout Africa.

A transect was sampled in West Africa comprising four study areas with different climates, from humid near Lagos in coastal Nigeria to semi-arid climate in Mali. Each study area contained a weathered basement aquifer and a sandstone aquifer, and samples were taken from both. Only shallow boreholes with handpumps were sampled at each location to minimise sampling bias. Samples were taken for the groundwater residence time tracers SF6 and CFC, stable isotopes, and comprehensive inorganic water chemistry analysis. A short discussion was also held with village elders and representatives of the community at each sampling site to gather information about water use. Fifty-six boreholes were sampled in total: seven in each aquifer type in each of the four climate zones.

Figure 7
Box plot showing mean residence times (MRT) of shallow groundwater in unstressed aquifers in humid to semi-arid climates.



The results of the case study demonstrated a high degree of resilience to climate change for hand pump supplies across the range of climate zones and aquifers sampled (mean annual rainfall 400–2000 mm):

- Groundwaters in shallow aquifers (<50 m) are a product of waters of different ages with a mean residence time of approximately 20–70 years. They are therefore well buffered against short term variations in climate.

- Modern recharge is still occurring in semi arid areas to the extent that mean residence times are similar to humid areas in unstressed aquifers — therefore across much of populated Africa (where rainfall is generally >600 mm) even if the climate becomes drier many rural water supplies are likely to remain functional (Figure 7).

- The residence time of shallow groundwater in weathered basement rocks is similar to the residence time in sandstones, indicating that weathered basement can store considerable groundwater which moves slowly because of the low permeability.

4.3 High yielding groundwater supplies case study

This study explored the sustainability and characteristics of higher yielding (>1 l/s) boreholes in weathered basement rocks. Basement rocks underlie approximately 34 % of Africa's land surface, supporting more than 230 million rural inhabitants. Increased irrigation, or more reliable town supplies, are expected to depend upon boreholes in weathered basement rocks being able to sustain yields that are at least ten times more than typically abstracted by handpumps. The aquifer productivity maps (Figure 5) already show that the typical range of basement rocks is generally between 0.1 and 1 l/s; therefore higher yields are already atypical.

Field studies were carried out in Uganda and Tanzania, targeting boreholes and wellfields that were already supplying >l/s. The aim was to assess the reliability of these larger supplies, and work out the conditions necessary to have these larger supplies by gathering historical data on borehole performance, interpreting aquifer test data and taking various samples for groundwater residence times.

The research indicates the following:

- High-yielding boreholes in weathered basement rocks exist and are commonly located in areas where alluvial sediments overlying basement rocks locally enhance aquifer transmissivity and storage. Intensive abstraction (>1 l/s) may still be possible in weathered basement rocks not overlain by alluvium. For example, a survey of 2200 successfully sited boreholes from 9 countries indicated yields of >1 l/s in 35 % of boreholes, and yields of >10 l/s in 2 % of boreholes (Figure 8).

- The sustainability of high-yielding boreholes (and wellfields) in basement rocks depends on access to higher than normal volumes of groundwater storage. This additional storage can be present where there is a thick porous overburden comprising weathered rock and often alluvium. Enhanced groundwater storage in this aquifer environment is of particular importance in semi-arid regions (e.g. Dodoma, Tanzania) where significant recharge occurs episodically in association with extreme climate events a few times or less each decade (Figure 9).

- A 55 year long record of groundwater levels, rainfall and abstraction has been compiled for Makutapora in Tanzania and provides a unique opportunity to examine the sustainability of long term abstraction.

Figure 8
Rank percentile analysis of basement yields from 2200 successful boreholes across Africa.

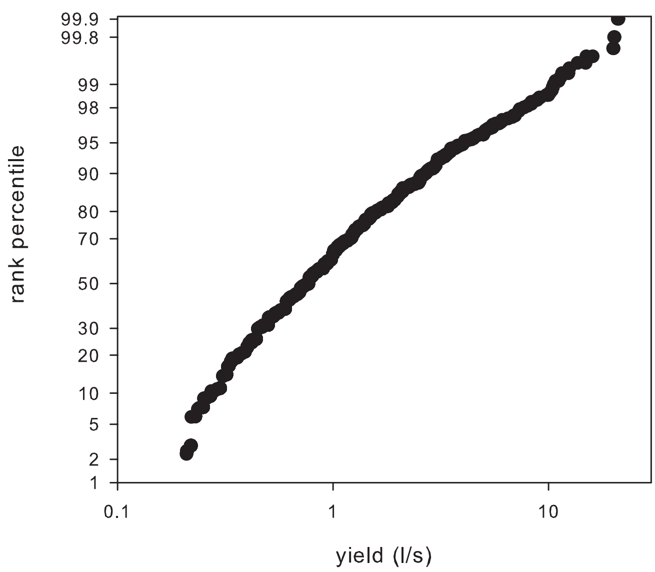
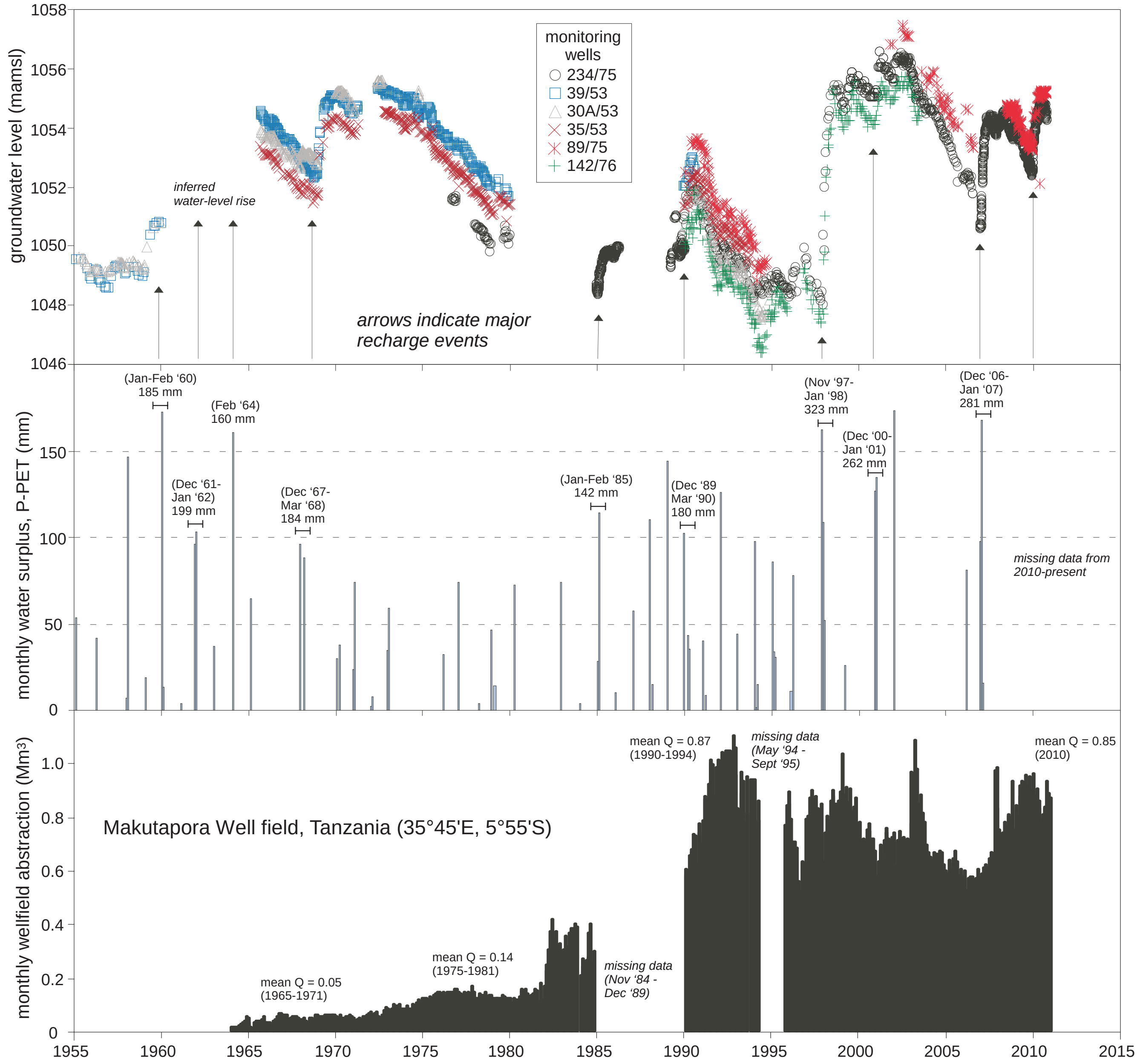


Figure 9
Groundwater levels in the Makutapora well field, where large volumes of groundwater are pumped from basement rocks overlain by thick sands and gravel. The aquifer is recharged by episodic recharge from runoff from nearby hills.



4.4 Access to improved water supplies and wealth

This case study analysed detailed survey data to examine links between water use, water access and wealth in Ethiopia, with a particular focus on how different wealth groups with access to different water sources deal with climate variability.

The imperative to address impacts of climate change has led to renewed interest in climate risk management and drought preparedness, and in particular in whether water is a missing link in current understandings of vulnerability. Despite major shifts in the conceptualisation of, and approaches to, drought preparedness and early warning in sub-Saharan Africa, food needs still dominate vulnerability assessment. This case study examines the role of water access in livelihood security: understanding how seasonality and variability in water availability affects livelihoods to help strengthen disaster risk assessment and response.

The dataset used in the analysis was collected from January to March 2009, and formed the baseline component of a pilot Water Economy for Livelihoods (WELS) assessment conducted by RiPPLE and the Food Economy Group in eastern Ethiopia (Further details in Coulter 2010). WELS identifies 'typical' communities within specified livelihood zones, and within these communities selects 'typical' households from three to four wealth groups (categorised as 'better-off', 'middle', 'poor', and (in some zones) 'very poor'). Through focus group discussions, members of each wealth group agree on values of water use, collection times and water quality which are 'typical' or 'average' (in a non-statistical sense) for their wealth group. Proponents of the WELS approach argue that while the figures generated for water use are therefore not precise, they usually have a high level of accuracy in terms of representing the majority of water users in a zone. This approach mirrors that used in Household Economy Analysis, a methodology in widespread use internationally to identify those at risk of food insecurity.

There is a clear link between wealth and the use of water, with implications for livelihoods.

More wealthy groups use more water, for all purposes, across all livelihood zones. Differences are especially pronounced in the dry season (See Figure 10). There is evidence that for some income generating activities, poorer households suffer disproportionately when water is scarce. In the agro-pastoral zone studied, poor households are less likely to be able to meet minimum water needs for their livestock, particularly in the dry season and report that they receive lower prices at market as a result of poor livestock condition.

The important role of wealth in determining water use is likely to relate to a combination of factors including labour availability (household size declines consistently with wealth) and possibly the availability of water storage and transport assets (better-off households have more, and larger, jerry cans, and more donkeys for water transport). Poor households report labour shortages at times of year when the longest collection times for water (in the long dry season) coincide with peak times for critical livelihood activities such as agricultural labour, leading to a reduction in water use.

Figure 10
Wealth and water use for drinking and cooking, in the midland 'Sorghum, Maize, Chat' (SMC) livelihood zone . Water use is related to wealth in both wet and dry season. Blue dashed line indicates the Sphere standard of 5 lpcd for drinking and cooking.

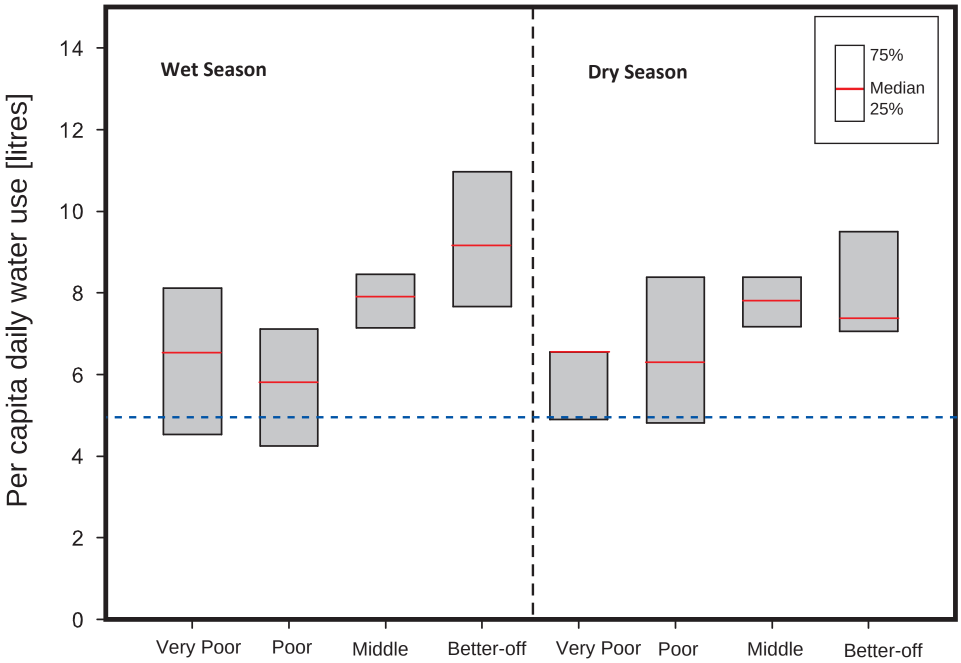
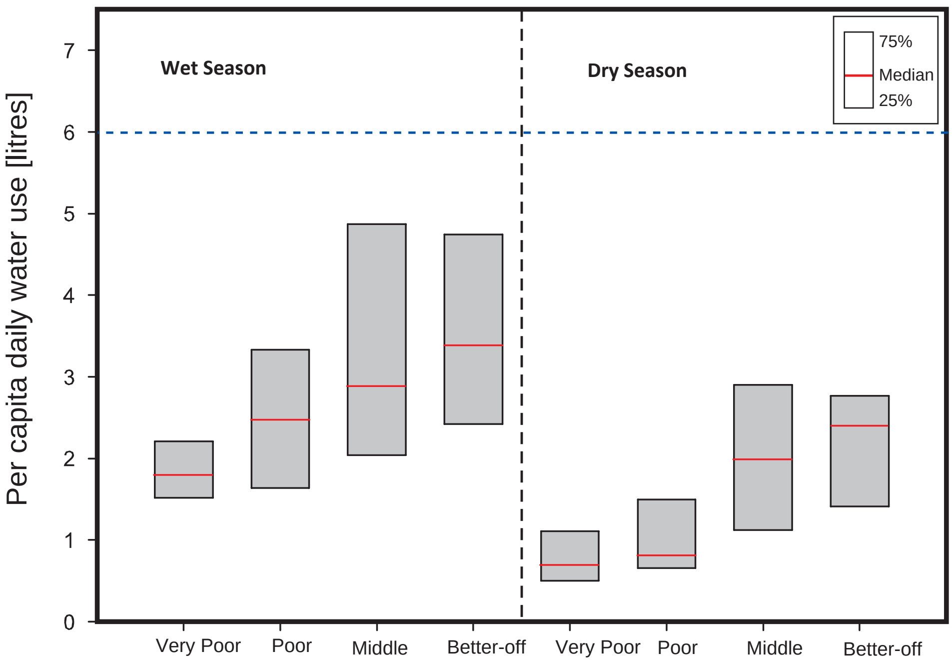


Figure 11
Water use for personal hygiene in highland 'Wheat, Barley and Potato' (WBP) zone. Volumes reduce in the dry season and become negligible for poor and very poor. Blue dashed line indicates the Sphere standard of 6 lpcd required to maintain health in emergency situations.



Levels of water use in the case study areas in Ethiopia are low, with no wealth groups abstracting sufficient water for hygiene uses at any time of year.

Overall levels of water use are low in the case study areas. Water use for personal hygiene in all zones falls well below even the minimum Sphere standard of 6 litres per capita per day (lpcd), which aims to represent the absolute minimum volume needed to maintain health in emergency situations (Sphere 2011) (Figure 11). Volumes for drinking and cooking are generally above the Sphere standard of 5 lpcd (though not in every case), but still well below more developmentally-oriented standards such as the 20 lpcd suggested by WHO for drinking and cooking, which even the better-off groups in the Ethiopian case study never attain.

The overall low level of water use for hygiene may be due to lack of demand rather than lack of available water, but the drop-off in water use for hygiene by poor groups in the dry season suggests that access constraints do come into play and that water use for hygiene is sacrificed when collection times are high and labour short. Ethiopia may not be representative of other parts of Africa.

Collection times increase considerably in the dry season for all sources apart from boreholes and perennial rivers

Collection times for water generally increase from typical figures of 1-2 hours in the wet season to 2–3 hours in the long dry season of a normal year. This coincides with reductions in water use for hygiene and livestock by poorer groups, suggesting that labour becomes a major constraint at this time. Some women reported that they were forced to compromise either on water collection or taking food to their husbands in the fields during the dry season, leading to increased domestic conflict. In a drought, the situation is expected to get much worse as collection times rise further.

Of all source types, boreholes offer the most consistently high quality water and collection times do not significantly increase in the dry season. In contrast, collection times from protected springs (the main improved water source found in midland and highland areas of Ethiopia) still increase notably in the long dry season due to falling water tables.

5 Summary and conclusions

This research project has examined the resilience of groundwater to climate change in Africa; an area of science that has been under-researched, but has much relevance for the formulation of climate adaptation policies. There are several outcomes from the research:

A series of quantitative groundwater maps for Africa — the first of their kind. These indicate the wide variation in groundwater resources across the continent. For much of Africa, carefully sited and constructed boreholes will be able to sustain rural handpumps. The potential for shallow boreholes yielding greater than 5 l/s is not widespread across Africa, although smaller yields of 0.5 to 5 l/s will be easier to find. Large groundwater stores in the major sedimentary basins, which can accommodate high yielding boreholes, are often far from population centres and associated with deep water-levels.

New data from focused groundwater case studies. Three case studies were undertaken to gather new data on groundwater and climate change in Africa:

Detailed sampling in West Africa from hand-pumped boreholes abstracting shallow (<50 m deep) groundwater indicates significant resilience to climate variability across the range of climate zones sampled (mean annual rainfall 400–2000 mm). The mean residence of groundwater in shallow aquifers was approximately 20–70 years and therefore well buffered against short term variations in climate. The residence time of shallow groundwater in weathered basement rocks was found to be similar to the residence time in sandstones, indicating that weathered basement can contain considerable volumes of groundwater which moves slowly because of the low permeability.

A study of higher yielding supplies from crystalline basement rocks in Uganda and Tanzania indicates that sustainable larger supplies are often associated with a thick regolith (often including alluvium) over weathered basement rocks, and that yields of >1 l/s may be available in approximately 35 % of effectively sited boreholes in these areas. Enhanced groundwater storage in this aquifer environment is of particular importance in semi-arid regions (e.g. Dodoma, Tanzania) where significant recharge occurs episodically in association with extreme climate events a few times or less per decade.

Detailed analysis of data on water use in Ethiopia found that both wealth and the seasonality of water access are important drivers of domestic and productive water use, probably due to higher collection times in the dry season and the labour shortages faced by poor households. Policy responses in the water sector need to centre on: extending reliable services to reduce collection times, even where coverage statistics may look positive; safeguarding health and livelihood needs, especially at critical times of year; and enhancing the storage and transport facilities of poorer households.

It is clear from this research that groundwater possesses a high resilience to climate change in Africa and should be central to adaptation strategies. Increasing access to improved groundwater sources based on handpumps is likely to be highly successful. However, building strategies that depend on the availability of widespread higher reliable yields from groundwater is likely to be problematic.

This research project has been targeted at groundwater resilience to climate change in Africa. There are still substantial knowledge gaps related to this areas of research:

1. Lack of knowledge of recharge mechanisms — particularly whether recharge occurs annually or only episodically. This will become increasingly important if groundwater use increases significantly.

2. There is very little information on groundwater quality in Africa. Although groundwater may be available, it may not be usable due to poor quality, or may even be harmful to human health.

3. The groundwater maps are designed to be used at a continental scale. A more detailed approach could be repeated for individual countries, but would require more detailed geological and hydrogeological information. For most of the countries in Africa this would require the collection of primary data.

4. The reliability of water points is more than just about the availability of water. There is a pressing need for interdisciplinary research on why water points fail.

5. This research had to be carried out in the near absence of long term datasets. A more robust understanding of how groundwater resources respond to climate variability requires long-term datasets derived from dedicated monitoring programmes and also the archiving of existing, undervalued data.

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Appendix—Porosity values assigned to each flow/storage hydrogeological unit.

The porosity values assigned below represent the 'effective porosity' defined as the total porosity minus the water bound to clays or (more rarely) held in isolated unconnected pore spaces. The volume of water that can actually be released from an aquifer through pumping is often less than the effective porosity but is much more difficult to measure. The few measurements made in Africa (Wright et al. 1982; Taylor et al. 2010) have indicated it to be about half the effective porosity.

Weathered crystalline basement was assigned an average porosity of 5 % - the typical porosity of moderately decomposed crystalline basement (Taylor and Eggleton, 2001; Petford, 2003; Howard et al., 2009). Total porosity can vary up to 25% where the rocks are highly decomposed, but much of this water is bound to clay minerals and therefore will not add to the effective porosity; very slightly weathered granite will typically have a porosity of 1%.

Volcanic fractured rocks were also assigned an average porosity of 5 %, taking into account the variation in porosity within individual lava and tuff layers (Petford, 2003). Porosity can vary considerably in volcanic rocks, with welded ashes having porosity of >25 %. Basalt within lava flows can have low porosity (<1%) depending on the presence and connectivity of gas bubbles; at the top and base of individual flows porosity is often much higher >15 %.

Fractured sedimentary rocks were assigned a mean porosity of 8 % based on studies in the Karoo basin (Van der Voort, 2001); the Voltaian Sediments (Pelig Ba 2010), and the Benue Trough (Lott et al 1998). For the Karoo porosity measurements were typically in the range 5–15 %; (median 8 %) the Voltaian sediments in Ghana had porosity 3–18 % (median 9 %); and within the Benue Trough in Nigeria porosity varied from <1 % to 16 % with median 8 %.

Mixed intergranular and fractured rocks were assigned an average porosity of 15 % based on a studies in Nigeria (Samaila and Singh 2010), Botswana (Jones 2010) and surrogates in the UK (Allen et al. 1997). In Nigeria studies of the Bima Sandstone, a well cemented sandstone had median porosity of 18 %; reported porosity of the cemented Karoo beneath the Kalahari beds suggested porosity of 12–18 %. Oil studies of global cemented siliclastic reservoirs suggest porosities in the range of 14 to 32 % (Morse 1994). Likewise the poorly cemented fracture/integranular permotriassic sandstone the UK has media porosity of 26 % with an interquartile range 20–30 %. A conservative estimate of 15 % is used to account for interbedded low porosity layers which may be present but were not represented in the sampling.

Intergranular aquifers were given a mean porosity of 25 %, a conservative value based on the studies in the Continental Terminale (Adelana and MacDonald 2008), the Chad Basin (Nwankwo et al. 2009) and the Nubian Sandstone (Beavan et al. 1991). Varies studies in the Continental Terminale in Africa have estimated porosity from 5–40 %; more commonly at the higher end. Within the poorly consolidated sediments of the Chad basin, porosity is commonly 35 %; measurements in the Nubian sandstone indicate porosity of 30 %. Low porosity layers are not extensive within many of the unconsolidated aquifers, making an estimate of 25 % across the saturated thickness reasonable.

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Glossary

Abstraction. The removal of water from a groundwater body, usually by pumping. Measured in m^3/day, or l/s.

Aquifer. A rock formation that is sufficiently porous and permeable to be useful for water supply.

Baseflow. Natural discharge of groundwater from an aquifer, via springs and seepages to rivers.

Borehole. A cylindrical hole (usually greater than 20 m deep and less than 0.5 m diameter) constructed to allow groundwater to be abstracted from the aquifer.

Demand. An informed expression on desire for a particular service, assessed by the investments people are prepared to make, over a lifetime of the service, to receive and sustain it.

Effective porosity. This is the total porosity minus the water bound to clays or (more rarely) held in isolated unconnected pore spaces. The volume of water that can actually be released from an aquifer through pumping is often less than the effective porosity but is much more difficult to measure.

Effective rainfall. The proportion of rainfall that is available for run-off and groundwater recharge after satisfying actual evaporation and any soil moisture deficit.

Evapotranspiration. The amount of water that would be lost from the ground surface by evaporation and transpiration from plants if sufficient water were available in the soil to meet the demand is termed the Potential Evapotranspiration (PE). The proportion of PE that is actually evapotranspired under the prevailing moisture conditions is termed Actual Evapotranspiration (AE).

Fracture. The term fracture is used in geology to refer to a parting in a rock, such as a crack, joint or fault.

Fracture flow. The preferential flow of groundwater through dilated cracks, joints, or bedding planes within an aquifer.

Groundwater. The name given to water stored in an aquifer in pore spaces or fractures in rocks and sediments.

Hydraulic conductivity. A measure of how easily groundwater flows through a rock or soil. Usually reported, in m/day it is the velocity that groundwater would flow through the rock under a pressure gradient of 1 m per metre.

Intergranular flow. The flow of groundwater through pore spaces in rocks rather than cracks or joints.

Permeability. Generally, the term is used loosely to mean the ease with which a rock or soil can transmit groundwater. However, the term also has a precise definition: the ease with which a rock can transmit any fluid under unequal pressure. It is the property of the medium only and is independent of the fluid.

Porosity. A measure of the void spaces in a rock or sediment. It is measured as the ratio of volume of the pore spaces to the total volume of rock, usually expressed as a percentage. The term primary porosity is often used for porosity from pore spaces; secondary porosity refers to void spaces caused by cracks or joints. *Effective porosity* includes only the interconnected pore spaces available for groundwater transmission.

Pumping test. A field testing procedure to quantify aquifer properties at a site involving pumping water out of (or less commonly injecting water into) an aquifer and measuring the effect on water levels in that aquifer and sometimes in adjacent strata.

Recharge. Water that is added to groundwater resources from sources, for example from direct infiltration of rainfall or leakage from streams and rivers.

Spring. A place where groundwater naturally overflows at ground surface.

Storage coefficient (S). The storage coefficient is a truer measure than porosity of the amount of groundwater easily abstracted from an aquifer. It is defined as the amount of groundwater released from storage per square metre of aquifer when the water table falls by 1 m.

Transmissivity (T). Describes the ability of an aquifer to transmit volumes of groundwater throughout its entire thickness and is calculated by multiplying the hydraulic conductivity by the aquifer thickness. It is usually measured in m^2/day.

Unconsolidated. A deposit consisting of loose grains that are not held together by cement. River terrace deposits are a typical example of an unconsolidated aquifer.

Water services. The system that provides users with an improved water supply. It includes the physical infrastructure of water supply (e.g. a borehole with a handpump), as well as management, contribution and support systems that help sustain it.

Water table. The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere. It can be measured by the static water level in a well or borehole in an unconfined aquifer.

Well. A large diameter hole (usually greater than 1 m) dug to access groundwater. Usually, but not always, less than 20 m deep.

Yield. The volume of water produced by a spring, borehole or well. Usually measured in m^3/day or l/s.

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