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An initial estimate of depth to groundwater across Africa

Groundwater Science Programme

Open Report OR/11/067

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

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An initial estimate of depth to groundwater across Africa

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Foreword

This work was commissioned by WaterAid UK to help their considerations of the applicability of different hand pump technologies across Africa. For this work, the BGS: developed an estimated depth to groundwater map for Africa; investigated the sensitivity of pumped groundwater-levels to the transmissivity of different aquifers in Africa; and developed an initial estimate of the proportion of Africa's population living on different depths to groundwater.

This report describes the methodology used to develop the initial estimates and maps, presents the final results, and provides some discussion to both the implications and limitations of the work.

Contents

FIGURES

TABLES

Summary

This work aimed to provide an initial estimate of depth to groundwater across Africa, to help with considerations of the applicability of different hand pump technologies in Africa. The main findings and outputs from the work are summarised below:

- ***Developing an estimate of depth to groundwater across Africa*** – In the absence of much observed groundwater-level data in Africa, several modelling approaches were used to estimate depth to groundwater in GIS (refer to section 2.4) using continent-scale datasets of geology, geomorphology and rainfall. Based on comparison to the available observed data, the most successful method was an empirical rule based approach, where depth to groundwater was assigned according to rainfall and aquifer type.

- ***Depth to groundwater*** – Across much of central, western and eastern Africa, where the climate is wet or seasonally wet and basement geology predominates, natural groundwater-levels are generally shallow – approximately 0-25 mbgl. Shallowest groundwater-levels (<7 mgbl) are estimated to be adjacent to perennial rivers. Deepest groundwater levels (>250 mbgl) are mapped in the major sedimentary basins in north Africa where average annual rainfall is low and aquifers are generally hundreds of metres thick.

- ***Expected drawdown*** – At a pumping rate of 5 m^3/d, which is equivalent to that of a hand pump, drawdown is small (<5 m) in aquifers with transmissivity >1 m^2/d. However, where transmissivity is <1 m^2/d, drawdown rapidly becomes limiting. This is as a result of the inverse power relationship between transmissivity and drawdown. Transmissivity of <1m^2/d is most likely in basement aquifers, therefore significant effort should be made to site boreholes in the most productive parts of these aquifers. Higher abstractions from submersible pumps (e.g. 100 m^3/d) will lead to much greater drawdowns, which may become limiting in aquifers with a transmissivity of less than 10 m^2/d.

- ***Population affected*** – The majority (85%) of Africa's population lives in regions where depth to groundwater is 0-50 mbgl, and hand pumps may be used to abstract water. A significant minority however (8%; 80 million) of Africa's population live in regions where depth to groundwater is between 50 and 100 mbgl and common hand pump technologies such as India Mark II are generally inoperable. These areas are mainly within northern and southern Africa, and to a lesser extent the Sahel.

- ***Lack of observed groundwater-level data*** – The need for observed groundwater-level data in Africa cannot be over-estimated; observed data would not only enable a much higher level of validation of the outputs from this work, but enhance many other aspects of hydrogeological work in Africa.

1 Introduction

1.1 BACKGROUND

Groundwater is a major source of drinking water across rural Africa as there are few safe and affordable alternatives (MacDonald and Calow 2009; JMP 2010). Ensuring sustainable and reliable access to clean groundwater relies as much on employing the correct technology to access the resource, as on the overall availability (Calow et al. 2010). Most improved groundwater supplies in Africa comprise boreholes (of varying depth) fitted with a hand pump.

The pump technology choice depends critically on the depth to groundwater, and volume of groundwater required. In regions of shallow groundwater – where depth to the water-table is less than 50 m – standard hand pumps are usually capable of lifting approximately 5 m^3/d of water. Where the depth to groundwater is more than 50 m below the ground surface (mbgl) different pump mechanisms are required. New hand pump technologies are being developed for areas of deeper groundwater – e.g. ‘ultra deep’ hand pump technologies capable of lifting water from depths of 50-75 mbgl.

Considerations of where, and over what area, different pump technologies are applicable require some knowledge of the depth to groundwater across Africa. However, groundwater-level data across Africa is scarce. Accessing the data which do exist is also difficult in the absence of centralised databases or reporting mechanisms. The need for observed groundwater-level data in Africa cannot be under-estimated, not only to inform technology choices, but also to assess the impact of current and future groundwater abstractions. The limited knowledge of African groundwater resources 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 and what resources are currently available to help adaptation (Solomon et al. 2007; Bates et al. 2008).

1.2 AIMS AND OBJECTIVES

The overall aim of this work is to provide an initial estimate of depth to groundwater across Africa, which can be used in considerations of the applicability of different hand pump technologies in Africa.

Under this overall aim, the work had **three main objectives**:

- To develop an estimated depth to groundwater map of Africa, indicating natural groundwater depth.
- To develop a pumped depth to groundwater map, and provide an analysis of the sensitivity of pumped groundwater-levels to different aquifer transmissivities in Africa.
- To produce an initial estimate of the proportion of Africa’s population living in areas with depths to groundwater.

This report describes the methodology used to develop the initial estimates and maps; presents the final results; and provides some discussion to both the implications and limitations of the work.

2 Development of depth to groundwater map

2.1 METHODOLOGY

Depth to groundwater is related to geology, geomorphology/weathering and rainfall. In the absence of much observed groundwater-level data in Africa, several modelling approaches were used to estimate depth to groundwater in a GIS (refer to section 2.4) using continent-scale data for geology, geomorphology and rainfall. Based on comparison to the observed data available, the most successful method was an empirical rule based approach using rainfall and geology data.

Rules approach

The rules based approach assigned depth to groundwater values according to geology and average annual rainfall – Table 1. Empirical rules were developed on the basis of experience of groundwater development in Africa and discussions with partners. The rules were applied by spatial interrogation of the digital geology and rainfall datasets within ArcGIS. In the broadest sense, the rules assign deeper depths to groundwater in areas of lower average annual rainfall; however two additional rules were employed to develop the final estimate of depth to groundwater across Africa, on the basis of special conditions in basement geology and areas adjacent to rivers (Fig. 1).

Experience of groundwater development indicates groundwater-levels within basement rocks to be shallower than in other rock types in areas of lower rainfall (<1000 mm/year). These shallower groundwater-levels occur because of the relatively limited depth (generally <50 m below ground surface (mbgl)) of the impermeable base of the weathered zone within basement terrain (Chilton and Foster 1995; MacDonald et al. 2008). As a result, basement rocks form relatively thin, shallow, aquifers across Africa (Fig. 2) and groundwater-levels remain shallow even in areas of relatively low rainfall. In contrast, sedimentary aquifers have much greater thicknesses (often >100 m) within Africa (MacDonald et al. 2011; Fig. 2) and groundwater-levels within the aquifers decrease with rainfall.

RULE 1	**IF:** average annual rainfall (mm/year)	**THEN:** depth to groundwater (mbgl)
	>1000	0-25
	500-1000	25-50
	250-500	50-100
	50-250	100-250
	<50	>250
RULE 2	**IF:** average annual rainfall (mm/year) in basement rocks	**THEN:** depth to groundwater (mbgl) in basement rocks
	>1000	0-25
	500-1000	0-25
	250-500	25-50
	50-250	25-50
	<50	25-50
RULE 3	**IF:** area is ≤5 km from perennial river	**THEN:** depth to groundwater is 0-7 mbgl

Table 1 – Empirical rules to estimate depth to groundwater in Africa.

A second set of empirical rules were, therefore, developed for depth to groundwater in basement rocks – Table 1. The maximum depth to groundwater estimated anywhere in basement is 50 m as there is no evidence to indicate deeper groundwater-levels in basement terrains in Africa.

A third rule was applied to produce an estimate of depth to groundwater in regions adjacent to rivers. Very shallow groundwater-levels are known to be common within alluvium (often unmapped) close to (within 5 km) perennial rivers. To include this, a depth to groundwater value of 0-7 m was applied for a 5 km distance adjacent to perennial rivers in Africa (Fig. 1).

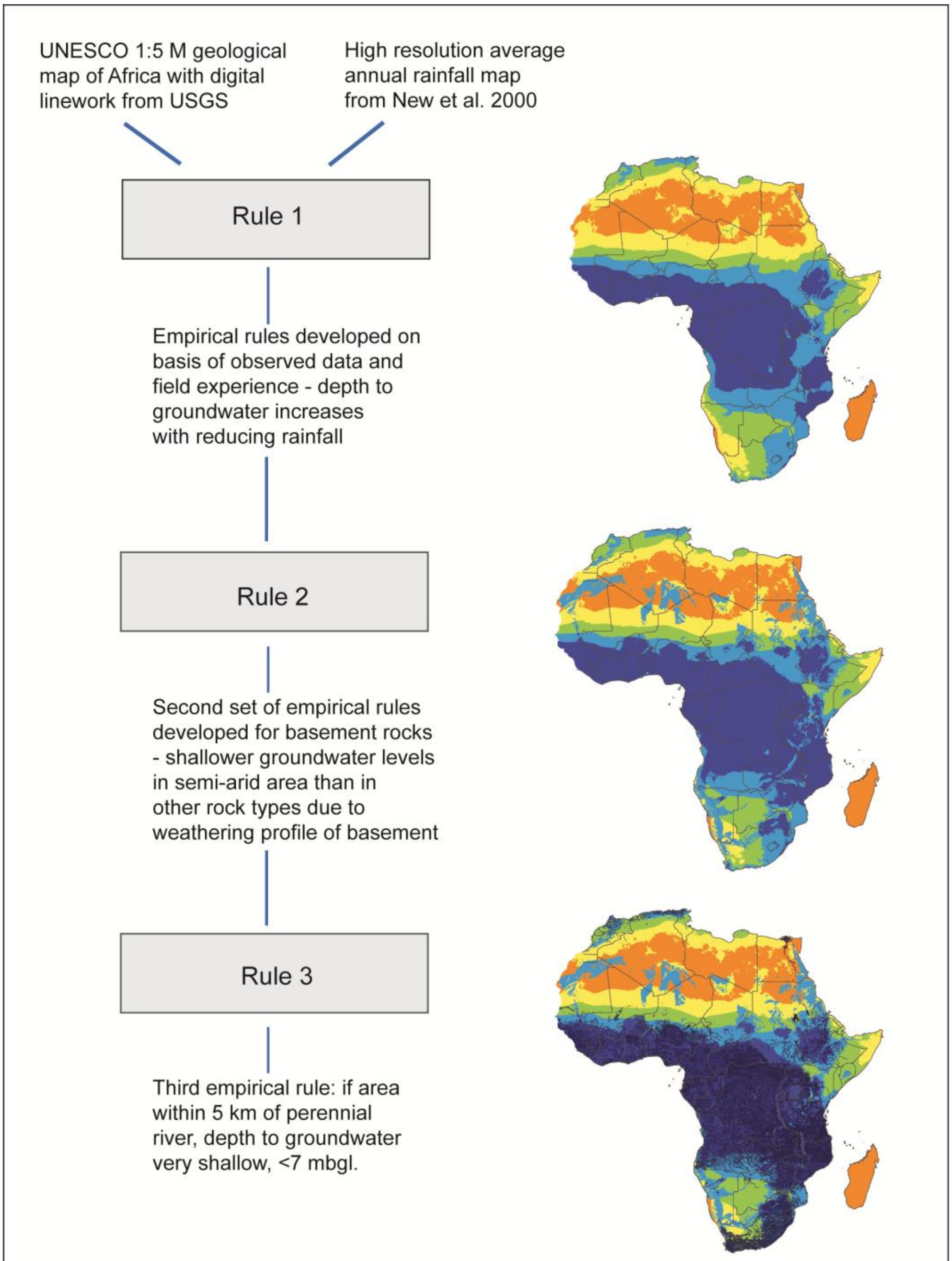


Fig. 1 – The methodology used to develop the estimated depth to groundwater map.

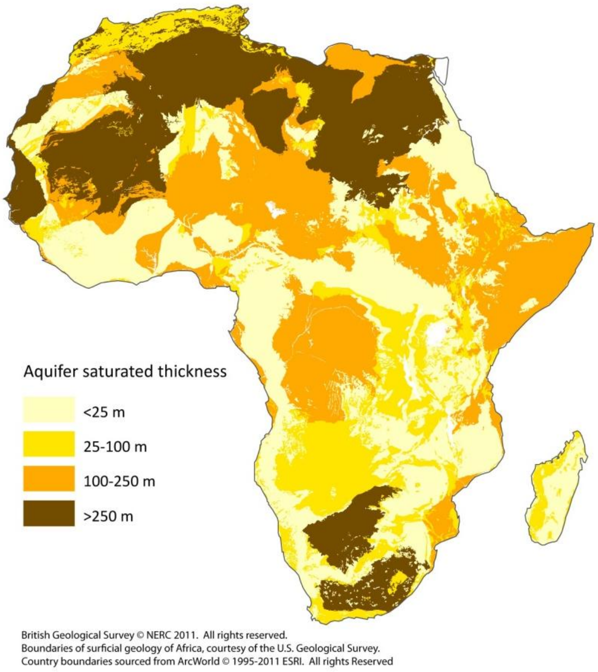


Fig. 2 – A map of saturated aquifer thickness across Africa (MacDonald et al. 2011).

Datasets used within the rules approach:

The UNESCO 1:5 million scale digital geological map of Africa was used as the geological base map for the modelling work. This map provides the most up-to-date digital geological line work for Africa at a continental scale, and is freely available from the USGS as an ArcGIS compatible shapefile with associated metadata (Persits et al. 2002). High resolution (0.05^{o}) digital rainfall data (New et al. 2000) was used as the continent-scale rainfall dataset in the work.

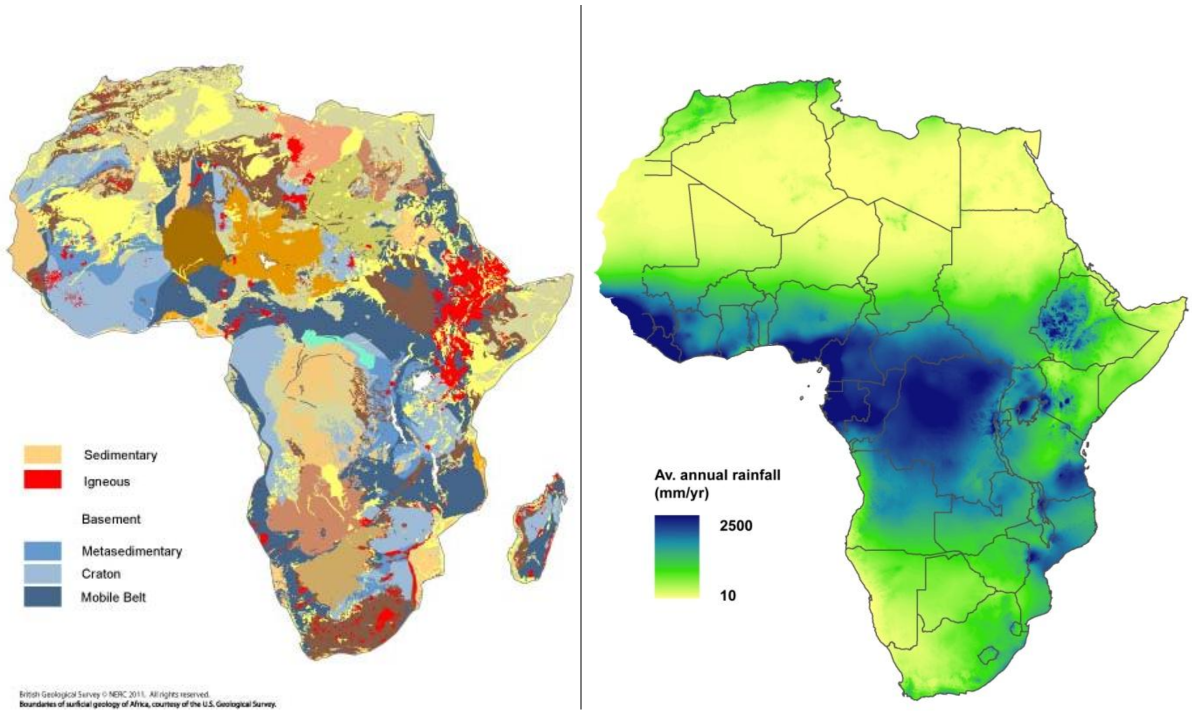


Fig. 3 – Geology and rainfall input data.

2.2 FINAL MAP

The estimated map of depth of groundwater produced by the rules approach is shown in Fig. 4. The final maps are produced on a 0.05^{o} grid and should generally be used at a national scale. Deepest groundwater levels (>250 mbgl) are mapped in the major sedimentary basins in north Africa where average annual rainfall is low and aquifer thickness significantly greater than 100 m. Shallowest groundwater-levels (<7 mgbl) are estimated to be adjacent to perennial rivers. Within much of the seasonally wet and wet areas of Africa, groundwater-levels are estimated to be 7-25 mbgl.

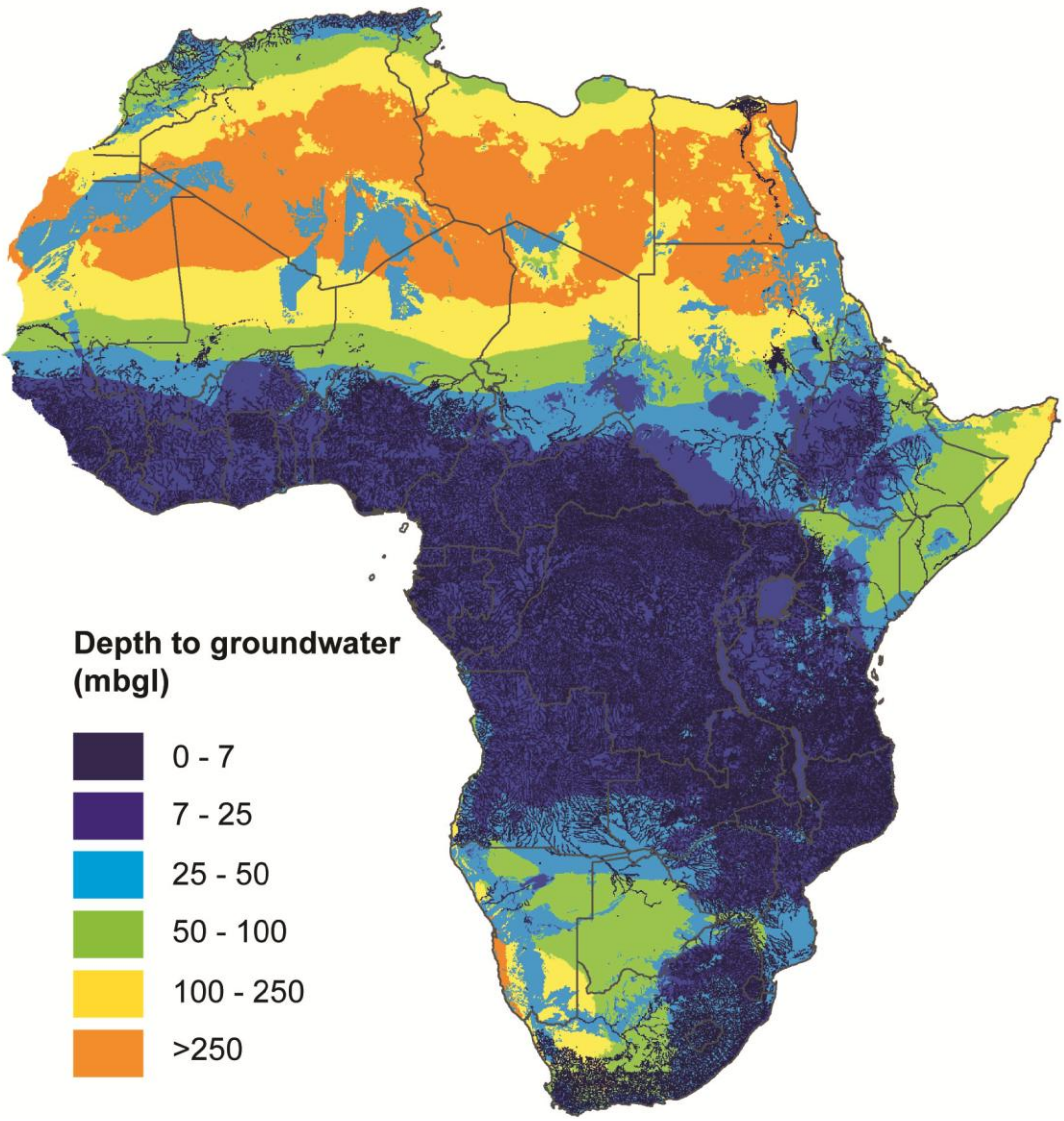


Fig. 4 – An initial estimate of depth to groundwater in Africa.

2.3 VALIDATION

The rules approach was validated against available observed data. The distribution and source of the datasets used by this work are shown in Fig. 5. There are, however, large tracts of Africa for which there is very little, or no, groundwater-level data available. The need for observed groundwater-level data in Africa cannot be under-estimated. The data would not only enable a much higher level of validation of the outputs from this work, but enhance almost any hydrogeological assessment in Africa.

Observed data sources

The observed data used to refine and validate the rules approach were sourced from:

- BGS project data
- WaterAid project data – specific project data from Mozambique and Zambia
- Data in peer-reviewed journals and grey literature
- UNICEF country report assessments on potential for manual drilling in Africa (see sub-section below)

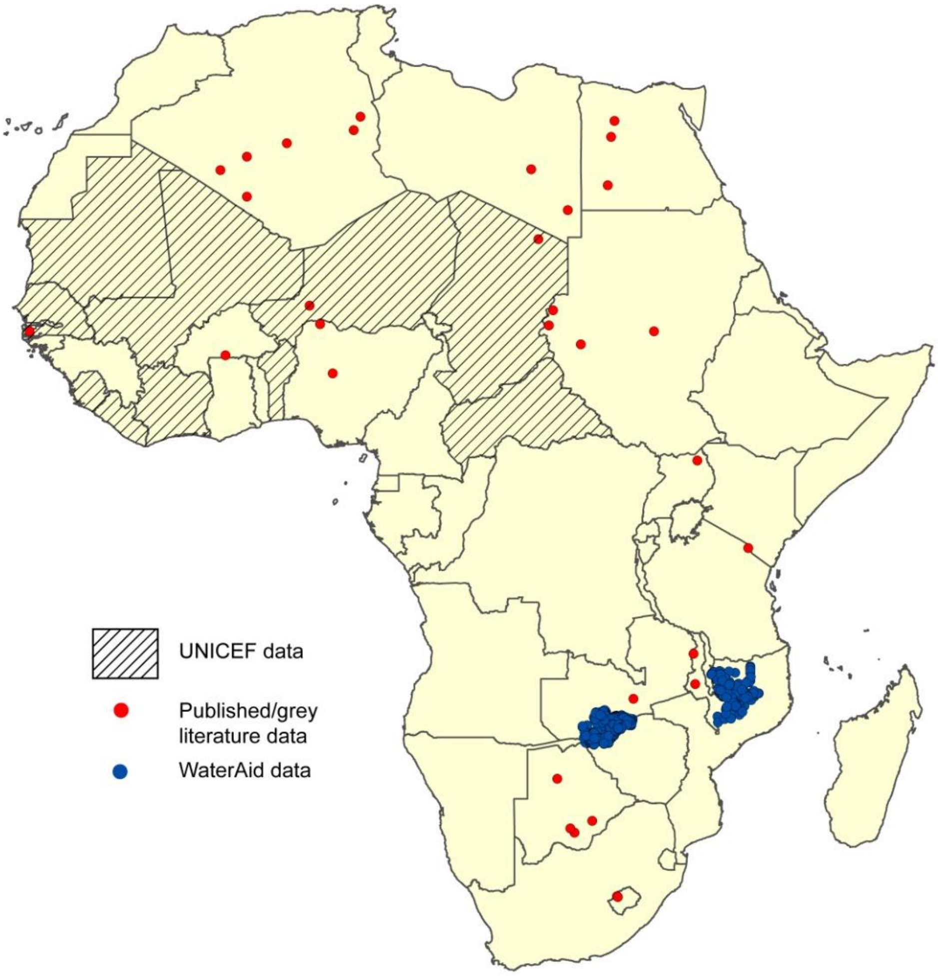


Fig. 5 – Distribution and source of observed groundwater-level data used in the study.

Comparison of estimated and observed depth to groundwater values

Observed and estimated values were found to correspond consistently well across climate zones and geology in Africa (Figures. 6 and 7). There is a significant correlation (R^2 value of 0.48) between observed and estimated groundwater-levels on a continent-scale. The poorest correspondence between the observed and estimated depth to groundwater values was found in regions of high relief and topography – e.g. in parts of east and southeast central Africa.

The estimated depth to groundwater values were also compared to estimated values generated under another approach – where groundwater-levels were estimated from interpolation of river base elevation values and digital elevation data (see section 2.4). This interpolation approach was found to work very well in areas of low relief, but very poorly in areas of high relief, and the approach was inappropriate to use on a continent-scale. Comparison of groundwater-level values produced by the interpolation approach in areas of low relief was, however, a useful second validation to the rules approach, and there was close correspondence between the estimated values from both methods.

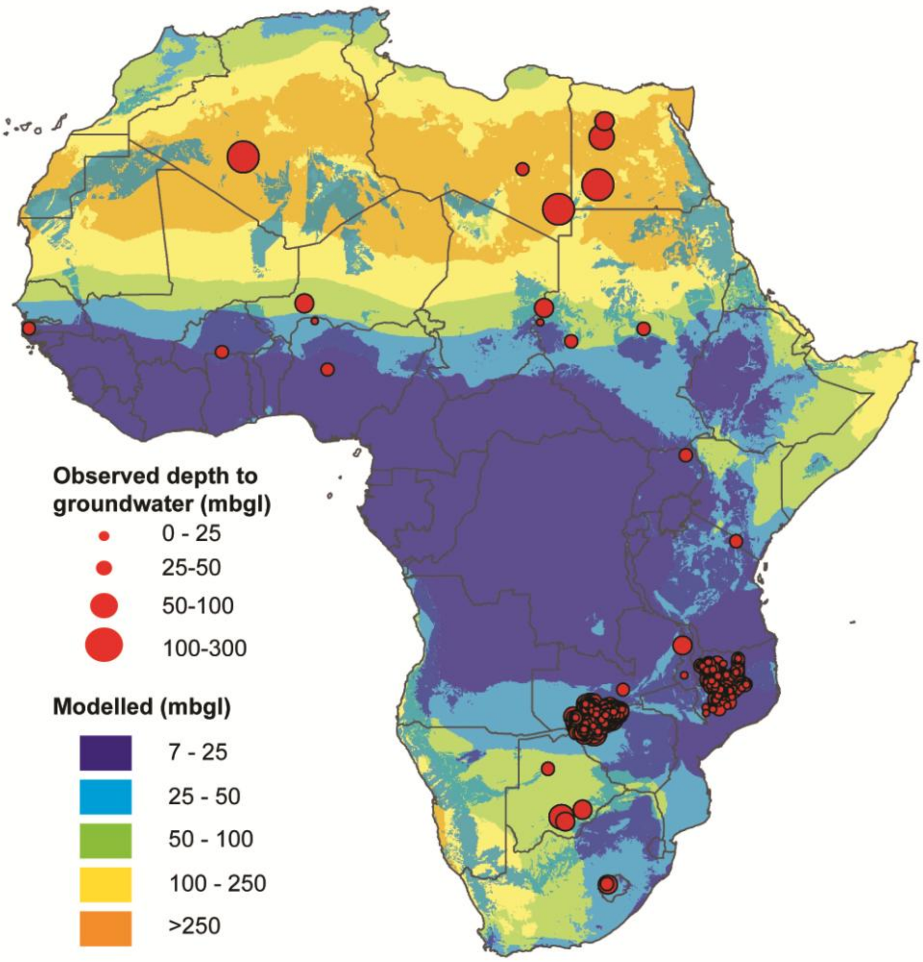


Fig. 6 – Comparison of observed and estimated depth to groundwater.

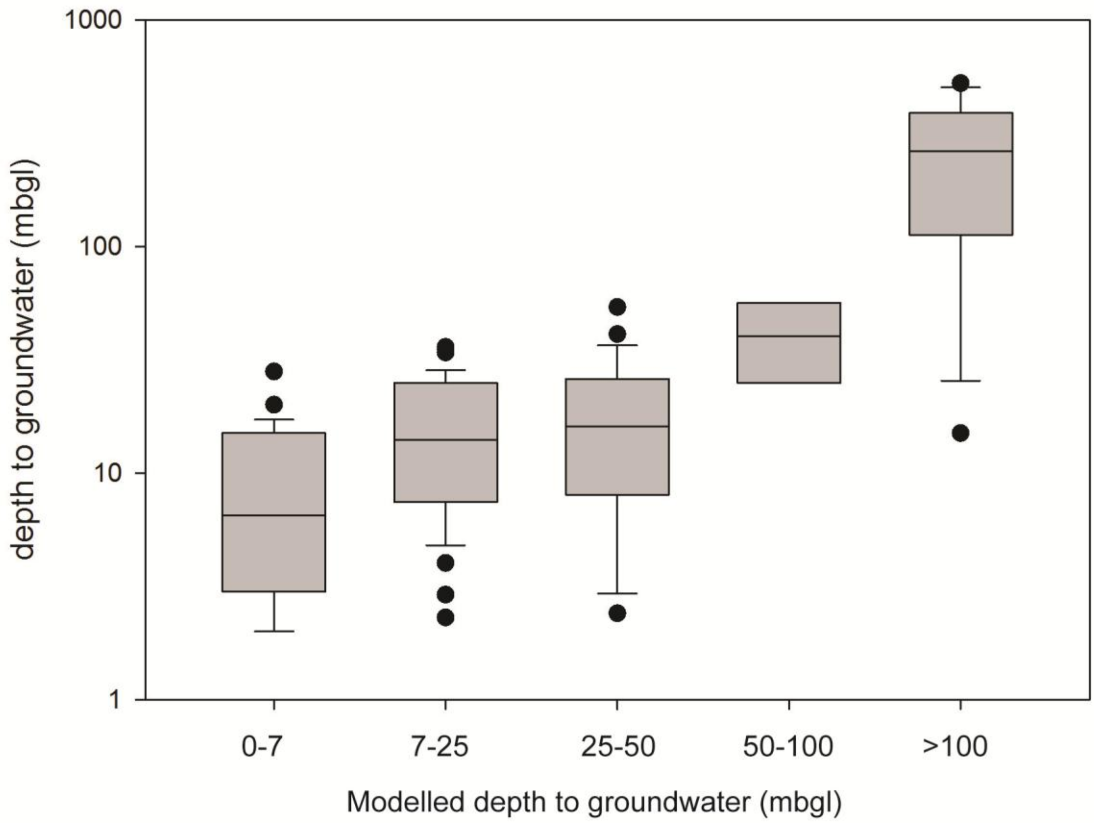


Fig. 7 – Box plot showing observed versus estimated depths to groundwater; the dots show outliers and whiskers show 1.5 the interquartile range.

UNICEF country report assessments on potential for manual drilling in Africa

A series of data reports for northern and western Africa have been published by UNICEF, as part of recent project between UNICEF, Practica and Enterprise Works/VITA to assess the potential for manual drilling in Africa. Using available hydrogeological data (e.g. groundwater-level and yield data), satellite images and population density information, the project has developed a series of maps and technical reports illustrating the potential for manual drilling at a national-scale for each of the countries below:

- Benin
- Cameroon
- Chad
- Cote d'Irove
- Liberia
- Mali
- Mauritania
- Niger
- Sierra Leone
- Senegal

The maps illustrate significant hydrological variations and trends in each of the 10 countries, and were a useful input to the calibration of the depth to groundwater maps developed by this work. The country data reports show individual borehole data, and provide a valuable collation of observed hydrogeological data. To date, outputs from the project are available for 10 countries (UNICEF 2011): http://www.unicef.org/wash/index_54332.html.

2.4 OTHER APPROACHES

Two other modelling approaches were trialled within the GIS to develop an estimate of depth to groundwater across Africa, in addition to the rules approach. In both, depth to groundwater values were estimated from interpolating the elevation of river base levels (perennial rivers only) and with surrounding land elevation data in Arc GIS, using the inverse distance weighting (IDW) interpolation method. The approach is based on the assumption that the river base level will generally approximate to the maximum depth to groundwater. Groundwater-levels are therefore shallowest adjacent to rivers in river valleys, and increase with relief and elevation away from rivers. A similar approach has been used in the UK to develop flooding and vulnerability maps (Ó Dochartaigh et al. 2005). The relationship is likely to be most robust in high transmissivity aquifers, where groundwater rarely develops steep gradients. In lower transmissivity aquifers, where groundwater is less able to move around as quickly, and aquifers can be much more compartmentalised, the relationship is less obvious. The relationship is most useful close to rivers. To investigate the interpolation approach further to help develop a robust tool, however, is beyond the scope of this study.

The **first approach** applied the interpolation across the whole of Africa, irrespective of geology, geomorphology or topography. The estimated depth to groundwater map produced compared well with observed data in flat areas, but very poorly in areas of high relief and in some of the thick sedimentary aquifers in northern Africa, and it was therefore not thought appropriate to apply the approach on a continent-scale.

The **second approach** interpolated river base elevations and elevation data only within regions of low relief/geomorphology. This approach again compared with variable success to observed data. In regions of extensive low relief (e.g. broad valley systems, plains) the approach compared very closely to observed data, however, in regions of incised river valleys large errors were still apparent with comparison to observed data. It was concluded that it was inappropriate to apply either of the interpolation approaches on a continent scale. The modelled depth to groundwater maps were, however, used to assist the calibration of the rules approach in areas of low relief, where the interpolation method was highly successful.

3 Estimating pumped groundwater-levels

3.1 METHODOLOGY

The extent to which natural, or rest, groundwater-levels are lowered as a result of current abstraction is also important to considerations of hand pump technologies in Africa. Across much of rural Africa groundwater abstraction is relatively low: a shallow (30-60 m deep) community borehole fitted with a hand pump generally abstracts only around 5 m^3/d. In contrast, irrigation boreholes or town supplies fitted with motorised pumps can abstract much higher yields.

To produce an estimate of the likely drawdown of groundwater within different aquifers from hand pump abstractions, the work:

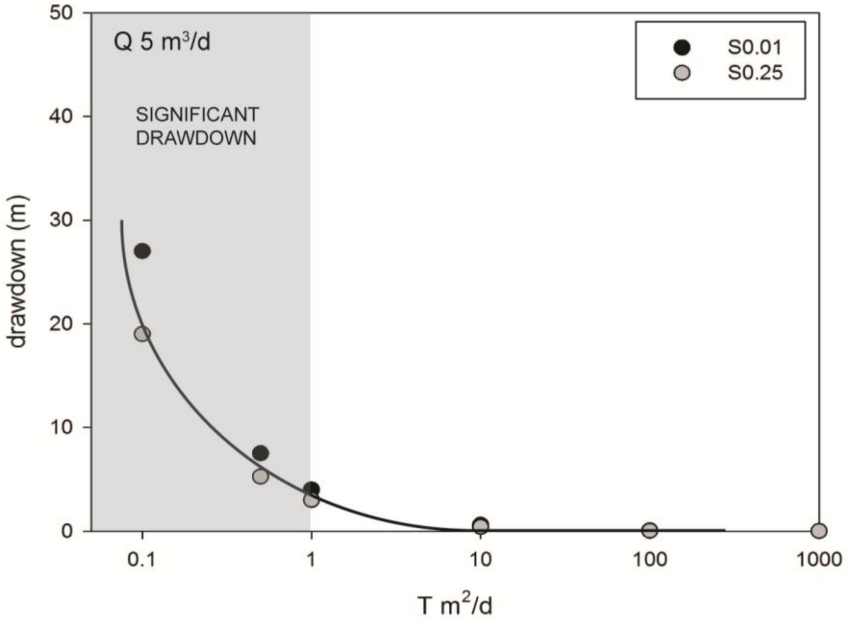
- Analysed the sensitivity of drawdown to aquifer transmissivity under different pumping rates using the BGSPT PTSIM model (Barker and MacDonald 2000) – refer to section 3.2.
- Produced a pumped groundwater-level map, by applying the simulated drawdowns from the BGSPT model to the rest groundwater-level map according to likely aquifer transmissivities – refer to section 3.3.

3.2 SENSITIVITY OF DRAWDOWN TO AQUIFER TRANSMISSIVITY

The range of drawdowns likely for different aquifer transmissivities in Africa was modelled using the BGSPT PTSIM model (Barker and MacDonald 2000). Based on the inversion of the Laplace transform, the BGSPT PTSIM model simulates drawdown around an abstraction borehole at specified times for any given set of parameters.

Drawdown was modelled for a range of aquifer transmissivities under two pumping rates: (1) 5 m^3/d, which would be expected from a hand pump supply; and, (2) 100 m^3/d which would be expected from a small motorised pump on irrigation or town supplies. The simulations were run for 180 days to ensure that long-term drawdowns were modelled.

Fig. 8 shows the results of the analysis. Under a pumping rate of 5 m^3/d, which is equivalent to that of a hand pump, drawdown is small (<5 m) in aquifers of transmissivity >1 m^2/d. However, for transmissivities <1 m^2/d, drawdown becomes increasingly significant due to the inverse power relationship between transmissivity and drawdown (Fig. 8). Under a higher pumping rate (Q 100 m^3/d), the value at which drawdown becomes limiting is approximately 10 m^2/d (Fig. 8).



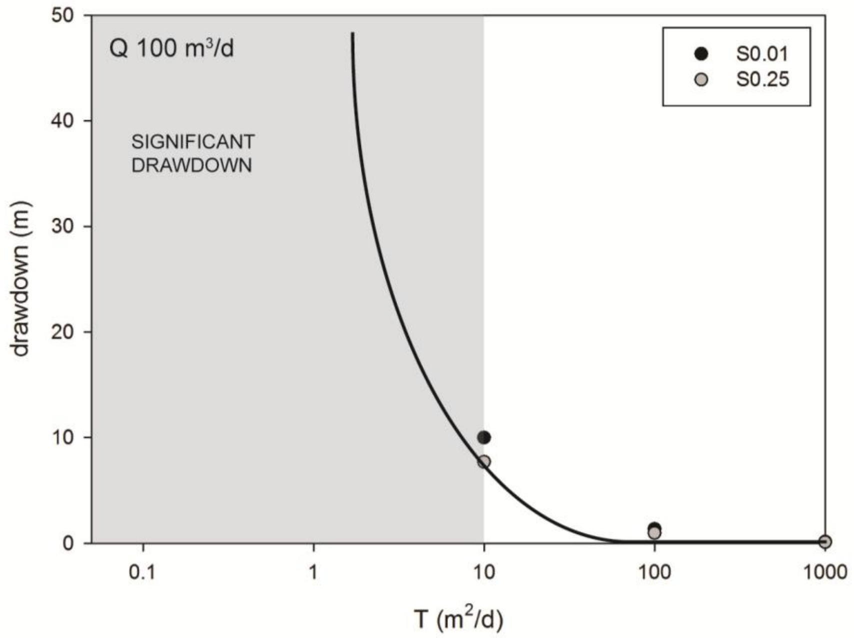


Fig. 8 – Sensitivity of drawdown to aquifer transmissivity.

3.3 PUMPED DEPTH TO GROUNDWATER MAP

An estimate of pumped groundwater-levels across Africa from hand pump abstractions was produced by applying values of drawdown calculated by the BGSPT PTSIM modelling to the natural (i.e. rest) depth to groundwater map of Africa, according to different transmissivities of the major aquifers in Africa.

Reliable, quantitative transmissivity data are scarce in Africa (MacDonald et al. 2011), and as result transmissivity values were estimated for each of the main aquifer types from typical yields of well sited boreholes. Typical yields have been shown to be an effective proxy for transmissivity in data poor areas elsewhere (e.g. Graham et al. 2009). Fig. 9 shows a map of aquifer productivity in Africa based on well sited borehole yields, and Table 2 shows the likely transmissivity ranges for each category of aquifer productivity. It is important to note, that by basing aquifer transmissivity values on yields of well sited, successful boreholes, the subsequent drawdown values applied to the aquifers will be minima values; much greater drawdown is likely in poorly sited boreholes, particularly within low transmissivity aquifers (T <1 m^2/d) – Fig. 8.

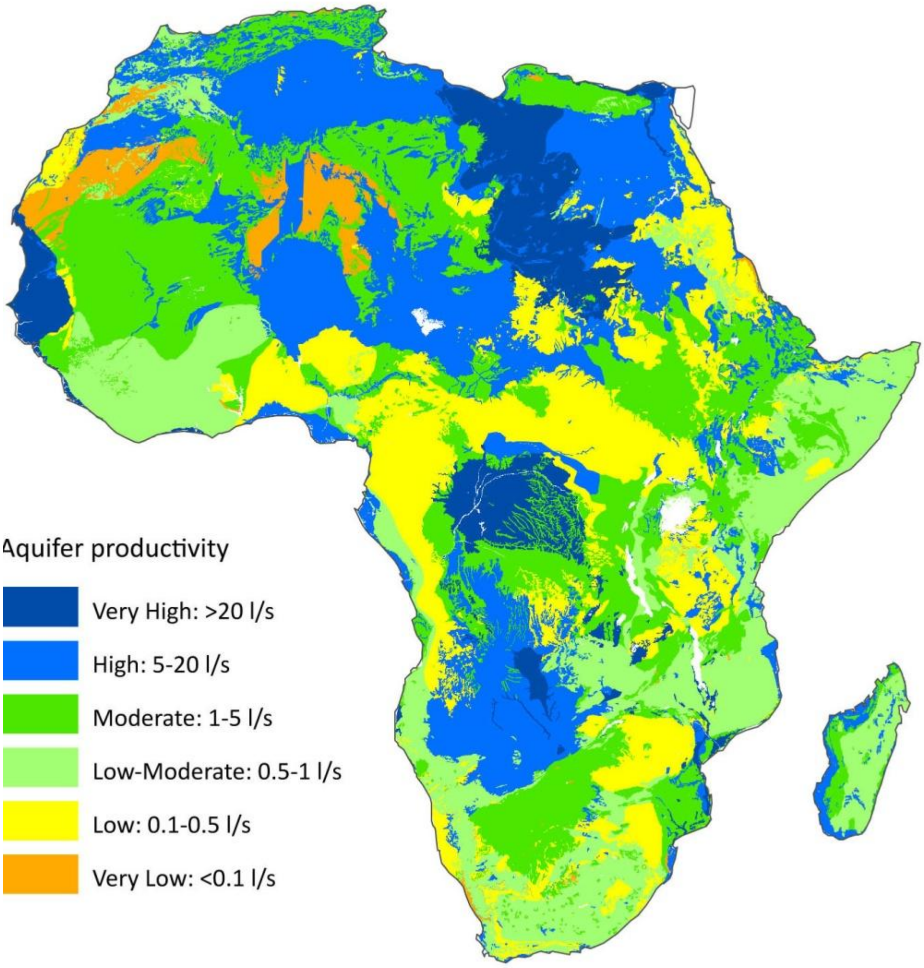


Fig. 9 – Map of aquifer productivity for Africa, based on typical yields of well sited boreholes (MacDonald et al. 2011).

Aquifer productivity	Typical yields of well sited boreholes (l/s)	Transmissivity (m^2/d)
Very High	>20	500-1000
High	5-20	50-500
Moderate	1-5	10-50
Low-Moderate	0.5-1	5-10
Low	0.1-0.5	1-5
Very Low	<0.1	0.1-0.5

Table 2 – Transmissivity ranges based on typical yields of well sited boreholes.

The map of pumped groundwater-levels was produced in ArcGIS by adding the gridded drawdown values to the natural depth to groundwater map previously generated. The final map is shown in Fig. 10. Significant changes in depth to groundwater are only indicated to occur under hand pump abstraction of 5 m^3/d in very low productivity aquifers, which are estimated to have a transmissivity of <1 m^2/d – see Figs. 9, 10 and Table 2.

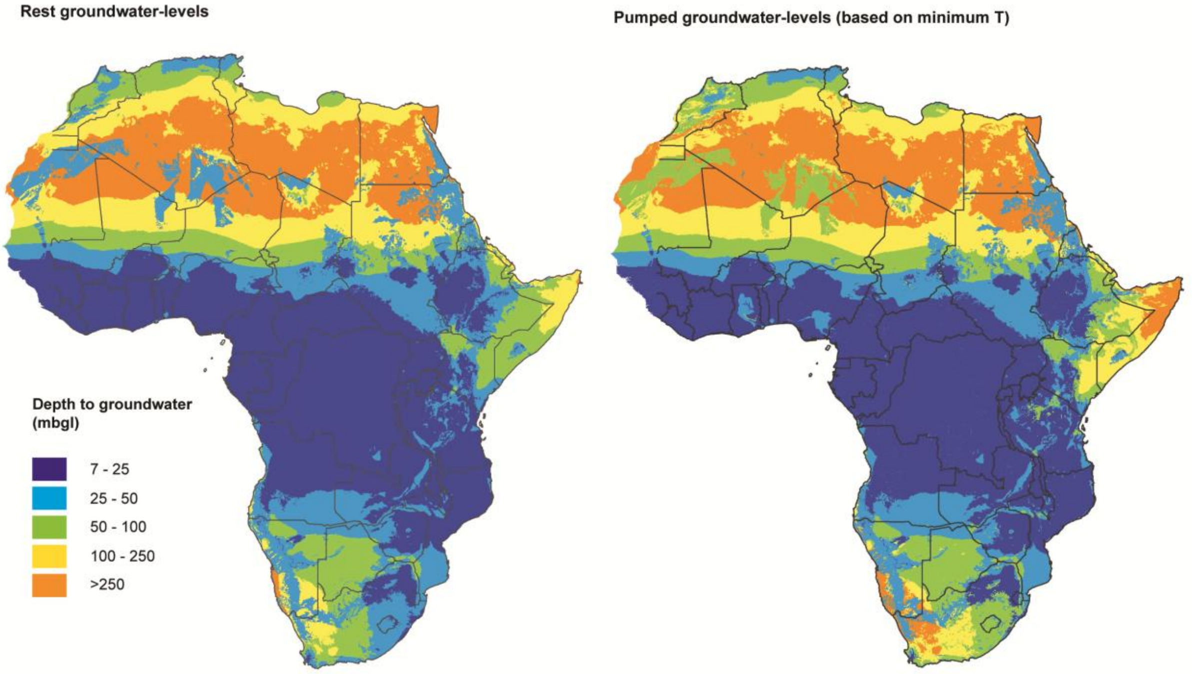


Fig. 10 – Estimated pumped depth to groundwater across Africa from hand pump abstraction (left hand map showing natural estimated depth to groundwater for comparison).

4 Population affected by groundwater-levels

The final part of this work provides an initial estimate of the proportion of Africa's population living in areas with different depths to groundwater. This analysis has been performed for each of the major regions in Africa (Fig. 11); uncertainty in the available gridded population data prohibiting country-scale analysis.

The proportion of the population living on the different depths to groundwater in each region of Africa, was determined by spatially interrogating gridded population data (based on UN census data) and the depth to groundwater map in ArcGIS.

More recent population data, based on UN projections from 2002 census data, and 2004-2006 fertility and mortality and migration data are available in tabular form from the UN (see http://esa.un.org/unpd/wpp/unpp/panel_population.htm). This more recent data were used to estimate the number of the people in each region, from relative proportions as determined using the gridded UN population data.

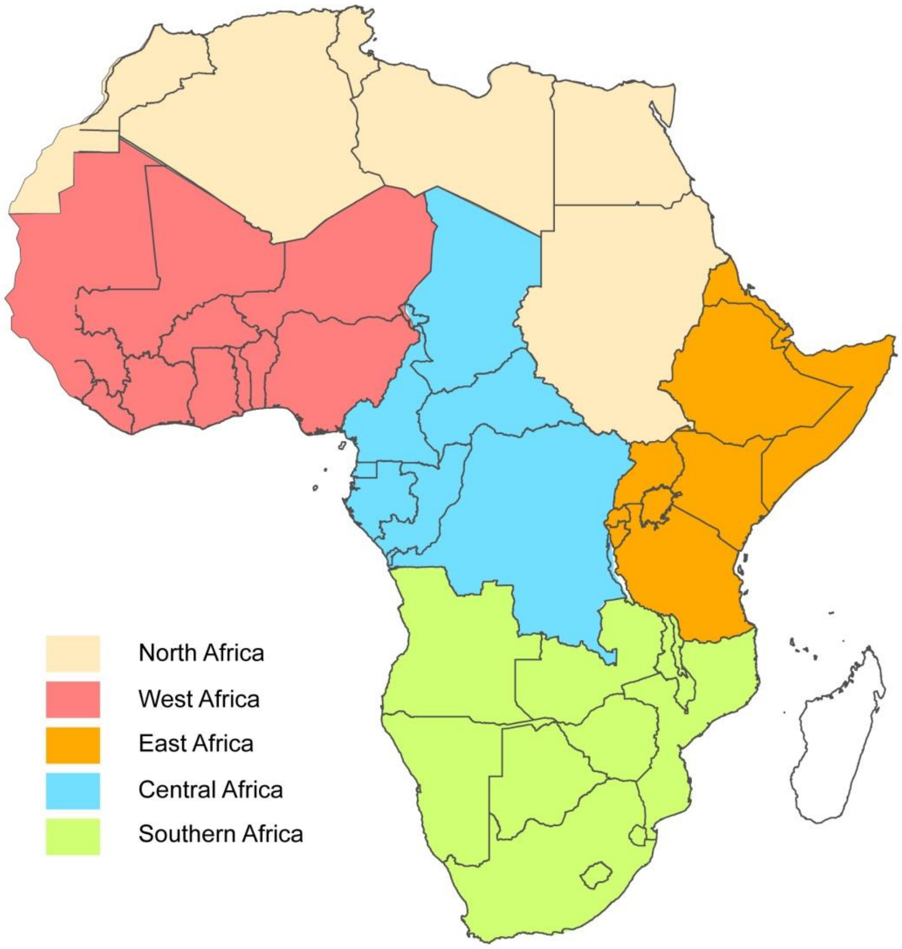


Fig. 11 – The major regions of Africa, as defined by WaterAid.

Continental-scale analysis

The results of the analysis are shown in Fig. 12. Most people (around 85%) within Africa live in areas of shallow depth to groundwater 0-50 mbgl; with nearly 60% of these living in areas where depth to groundwater is 0-25 mbgl (Fig. 12), and 8% living in regions where depth to groundwater is 0-7 mbgl.

Regional analysis

The distribution of Africa's population over different depths to groundwater at a continent-scale, is generally repeated across the individual regions, with the exception of north and southern Africa (Fig. 13). In north Africa, an equal proportion (approx. 80 million people) of the population live in areas where depths to groundwater are estimated to be 0-25 mbgl, and 25-50 mbgl, reflecting the location of population centres over shallow groundwater in the Nile Delta and over deeper groundwater in the thick sedimentary aquifers in the semi-arid and arid climatic areas of the region (Fig. 13). In southern African, the majority (51%; 71 million) of the population lives over areas where depth to groundwater is 25-50 mbgl; only 30% (42 million) shown to live in areas where depth to groundwater is 0-25 mbgl (Fig. 13). This again reflects the location of population centres over sedimentary aquifers in lower rainfall areas.

The number people of people living over areas of deeper groundwater in Africa are not insignificant. Approximately, 80 million people are estimated to live in areas where depth to groundwater is 50-100 mbgl – mostly in northern (54%) and southern (23%) Africa – and around 28 million people are estimated to live in areas where depth to groundwater is 100-250 mbgl – again mostly in northern (64%) and southern (30%) Africa.

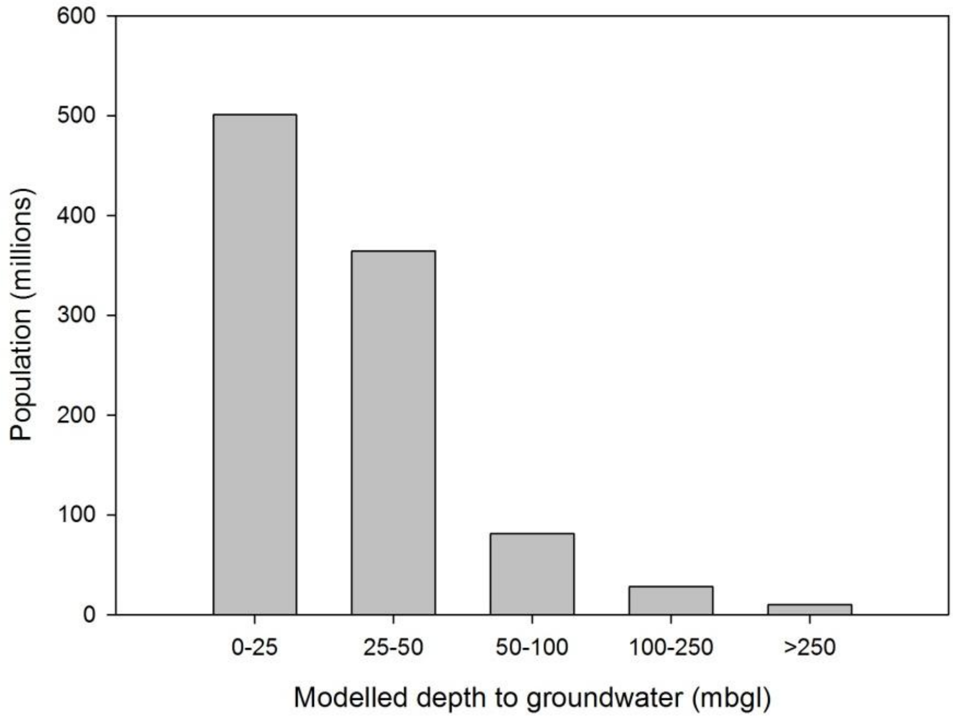


Fig. 12 – Distribution of Africa's population over different depths to groundwater.

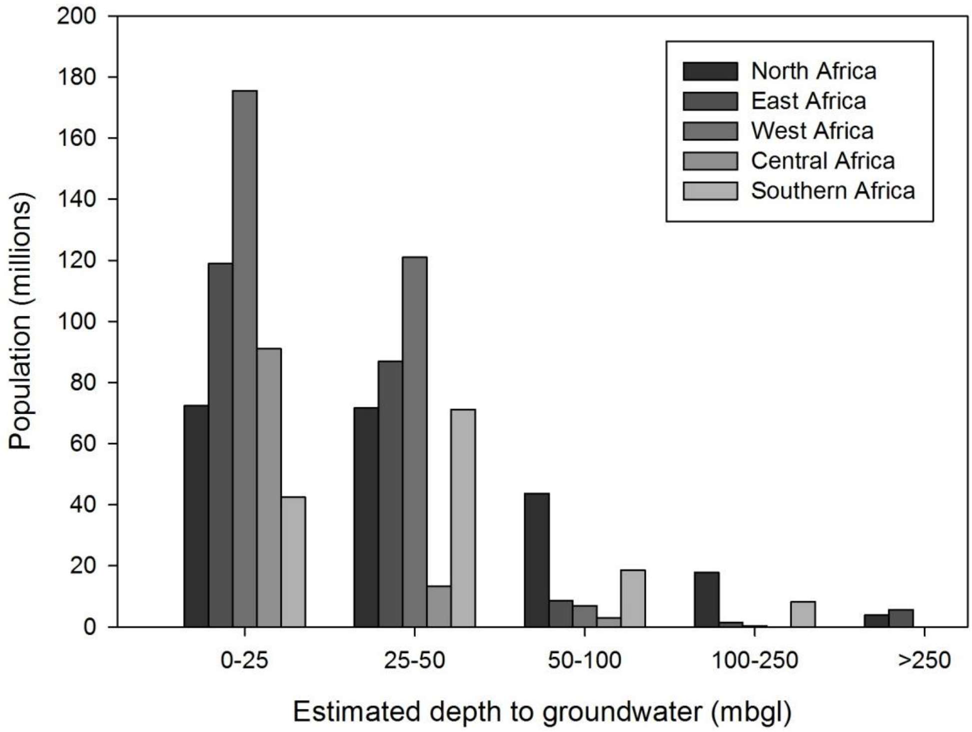


Fig. 13 – Regional population distribution over different depths to groundwater.

5 Implications and limitations of analysis

5.1 IMPLICATIONS OF KEY FINDINGS

Key findings, and the implications of these findings, can be summarised as below:

Depth to groundwater and affected population

- Across much of central, western and eastern Africa natural groundwater-levels are estimated to be shallow – approximately 0-25 mbgl. Shallowest groundwater-levels (<7 mgbl) are estimated to be adjacent to perennial rivers. Deepest groundwater levels (>250 mbgl) are mapped in the major sedimentary basins in north Africa where average annual rainfall is low and aquifers are generally hundreds of metres thick.
- The majority (85%) of Africa's population lives in regions where depth to groundwater is shallow (0-50 mbgl) and where hand pumps may be used to abstract water; 8% (66 million) of these people are likely to live in areas where depth to groundwater is 0-7 mbgl.
- A significant minority (8%) of Africa's population live in regions where the depth to groundwater is between 50 and 100 mbgl and common hand pump technologies (e.g. India Mark II) are inoperable. These areas are mainly within northern and southern Africa and to a lesser extent the Sahel.

Effect of abstractions on groundwater-levels

- The extent to which natural, or rest, groundwater-levels are lowered as a result of hand pump abstractions (generally 5 m^3/d) is minimal (<1 m) in aquifers which have a transmissivity >1 m^2/d. However, in aquifers which have a transmissivity <1 m^2/d, significant drawdown (>10 m) may be induced by hand pumps. This is the result of the inverse power relationship between transmissivity and drawdown.
- Based on typical yields from well sited boreholes, aquifer transmissivities of <1m^2/d are most likely in basement aquifers. It is, therefore, in these hydrogeological environments where greatest care should be used and resources expended to site boreholes in the most productive part of the aquifer.
- Higher abstractions from submersible pumps (e.g. 100 m^3/d) will lead to much greater drawdowns, which may become limiting in aquifers with a transmissivity of less than 10 m^2/d.

5.2 LIMITATIONS OF ANALYSIS

The main limitations of the analyses in this work are outlined below:

- For much of Africa there is very little, or no, observed groundwater-level data available. Depth to groundwater therefore has to be estimated. This work uses an empirical rules based approach, based upon observed groundwater-level data available from specific projects and regions. The final maps are produced on a 0.05^{o} grid and should generally be used at a national scale.
- In the absence of real data, aquifer transmissivity values had to be based on the yields of well sited, successful boreholes. Whilst, this has been shown to be a robust approach in other data poor areas (e.g. Graham et al. 2009), it means that the drawdown values estimated are

minima and much greater drawdown are likely in poorly sited boreholes, particularly within low transmissivity aquifers (T <1 m^2/d) – Fig. 8.

5.3 RECOMMENDATIONS

The need for observed groundwater-level data in Africa cannot be over-estimated; observed data would not only enable a much higher level of validation of the outputs from this work, but enhance many other aspects of hydrogeological work in Africa. Data could be collated from: existing projects and reports; a dedicated field campaign; and a dedicated monitoring network(s).

Observed data from WaterAid programmes:

- Gathering estimated depth to groundwater data from ongoing WaterAid projects would provide an initial, and highly valuable observed dataset of depth to groundwater over large parts Africa.
- Long-term monitoring within WaterAid projects and the establishment of dedicated monitoring boreholes would provide high quality information on seasonal and annual groundwater-level variations in a variety of hydrogeological environments in Africa.
- Collation and reporting of pumping test data from WaterAid projects would provide much better information on likely effect of abstractions in different aquifers.

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