Hydrological Science Journal 64: 690-703

What impact will climate change have on rural groundwater supplies in Africa?

Alan M MACDONALD[1], Roger C CALOW[2], David MJ MACDONALD[2], W George DARLING[2], & Brighid É Ó DOCHARTAIGH[1]

[1]British Geological Survey, West Mains Road, Edinburgh, EH9 3LA, UK amm@bgs.ac.uk, tel: +44 131 650 0389
[2]British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB

Abstract One of the key uncertainties surrounding the impacts of climate change in Africa is the effect on the sustainability of rural water supplies. Many of these water supplies abstract from shallow groundwater (<50 m) and are the sole source of safe drinking water for rural populations. Analysis of existing rainfall and recharge studies suggests that climate change is unlikely to lead to widespread catastrophic failure of improved rural groundwater supplies. These require only 10 mm of recharge annually per year to support a handpump, which should still be achievable for much of the continent, although up to 90 million people may be affected in marginal groundwater recharge areas (200-500 mm annual rainfall).

Lessons learnt from groundwater source behaviour during recent droughts, substantiated by groundwater modelling, indicates that increased demand on dispersed water points, as shallow unimproved sources progressively fail, poses a much greater risk of individual source failure than regional resource depletion. Low yielding sources in poor aquifers are most at risk. Predicted increased rainfall intensity will also increase the risk of contamination of very shallow groundwater. Looking to the future, an increase in major groundwater-based irrigation systems, as food prices rise and surface water becomes more unreliable, may threaten long-term sustainability as competition for groundwater increases. To help prepare for increased climate variability it is essential to understand the balance between water availability, access to water, and use/demand. In practice this means increasing access to secure domestic water, understanding and mapping renewable and non-renewable groundwater resources, promoting small-scale irrigation and widening the scope of early warning systems and mapping to include access to water.

Key Words groundwater; climate; Africa; water supply; drought; agriculture

INTRODUCTION

One of the key uncertainties surrounding the impacts of a changing climate in Africa is the effect that it will have on the sustainability of rural water supplies. Of Africa's population of 900 million, roughly 60% live in rural areas and rely on small community or household supplies (JMP, 2008). Less than half of the rural population currently have access to secure water (e.g., improved boreholes, wells or treated surface water) – the majority still rely on ponds, seepages or unprotected shallow wells.

The safety and reliability of water supplies are fundamental to the livelihood security of rural communities. Continuing access to safe water generates major health benefits (Moore *et al*., 1993); supports food production and consumption (directly or indirectly) and reduces poverty (Carter & Bevan, 2008; Calow *et al*., 2009). In a global study of the costs and benefits of improved water supply and sanitation, WHO (2004) concluded that the wider socio-economic benefits of safe water and adequate sanitation ranged from US$3 to US$34 per US$ invested, with the highest returns in Africa, hence the international community's commitment to reduce by half those without safe water by 2015 (United Nations, 2000), as set out in the Millennium Development Goals (MDGs). In Africa, however, progress towards meeting these goals has been slow and patchy. At current rates of coverage improvement the target is not expected to be met until 2050, at the earliest (United Nations, 2006).

For a rural water supply to be safe and reliable, and to give the benefits of improved health, livelihood security and poverty reduction, it must meet several basic requirements. For example: water should be of sufficient quantity to meet all domestic needs; consumption should not pose a health risk; it should be reliable across seasons and between years; it should be accessible to all community members within a reasonable distance (usually within 1 km); and the supply should be affordable and capable of being maintained by the user community. At present, meeting these needs from rainwater or runoff is a challenge in Africa, not least because of the long dry season experienced by much of the continent (Figure 1). As a consequence, *groundwater* development is generally the preferred option for meeting dispersed rural demand, with technologies that include boreholes, wells or springs, or more rarely collector wells or infiltration galleries (Figure 2).

Groundwater has many advantages as a source of supply: natural groundwater storage provides a buffer against short-term climatic variability; quality is often good; and infrastructure is affordable to poor communities. However, resource development has to occur within environmental limits, if degradation is to be avoided. Excessive pumping, the risk of pollution from highly persistent contaminants and the long-term threat posed by climate change all highlight the need for groundwater protection and careful management.

What will be the impact of climate change and drought on rural water supplies? In this paper we review the nature of groundwater resources in relation to *improved* rural water supplies and consider the impact of climate change on groundwater availability, access and use.

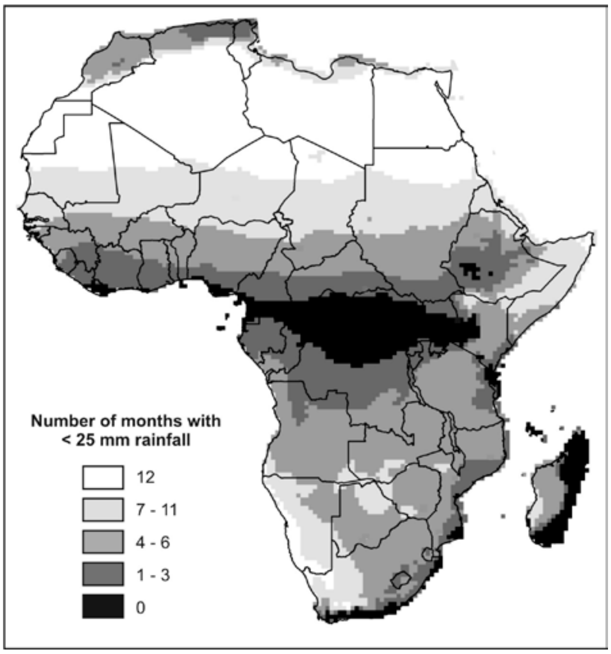

Figure 1 The average length of the dry season in Africa (1961-96) calculated using data from New *et al.* (1999).

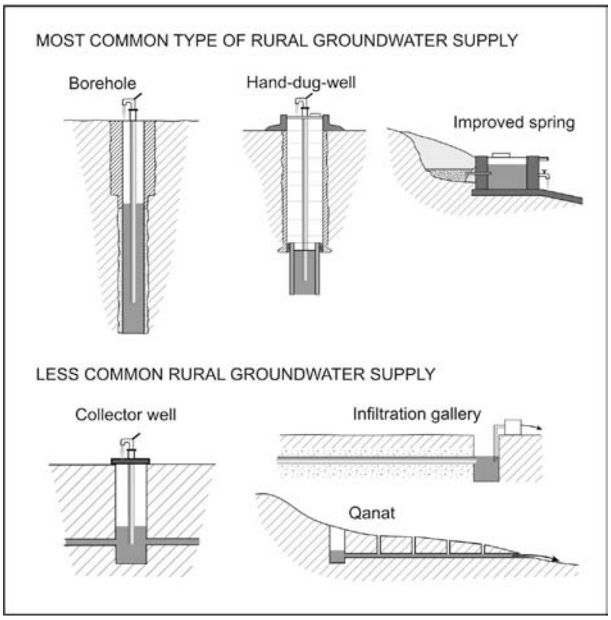

Figure 2. Different types of rural groundwater supplies (from MacDonald *et al.* 2005a).

GROUNDWATER RESOURCES IN AFRICA

Groundwater occurrence depends primarily on geology, geomorphology/weathering and climate (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.

Mean annual rainfall is highly variable across Africa. It ranges from negligible over parts of the Sahara to almost 10,000 mm in the Gulf of Guinea (Figure 3). There are also substantial seasonal, inter-annual and multi-decadal variations in rainfall (Hulme et al., 2000). There is no simple direct relationship between average annual rainfall and recharge, because of the many variables involved – principally temperature, intensity and seasonality of rainfall, topography, vegetation cover and soil or rock type (e.g., Butterworth et al., 1999). While recharge proportions in excess of 10% are possible in some areas with mean annual rainfall below 500 mm, the proportion is generally less than this, typically falling to negligible for areas with rainfall below 200 mm/a (Lerner *et al.*, 1990; Scanlon *et al.*, 2006; Eilers *et al.*, 2007; Edmunds *et al.*, 2008; WHYMAP, 2008).

Figure 4 shows a simplified groundwater resources map for Africa. The map is based on a synthesis of studies (Foster, 1984; Guiraud, 1988; UNTCD, 1988; UNTCD, 1989; MacDonald *et al.*, 2005a; MacDonald et al. 2008a) and uses the 1:5,000,000 scale geological map of Africa as a base (UNESCO, 1991; Persits *et al.*, 1997). The four different environments are: Precambrian basement rocks (covering approximately 34% of the land surface); consolidated sedimentary rocks (37%); unconsolidated sediments (25%); and volcanic rocks (4%).

Precambrian basement rocks comprise crystalline igneous and metamorphic rocks over 550 million years old. Unweathered and non-fractured basement rocks contain negligible quantities of groundwater. However, significant aquifers can develop within the weathered overburden and fractured bedrock (Chilton & Foster, 1995; Taylor & Howard, 2000).

Consolidated sedimentary rocks, particularly large sandstone basins, can store considerable volumes of groundwater but in arid regions much of the groundwater is non-renewable, having been recharged when the area received considerably more rainfall (Edmunds *et al.*, 2008). Also, sedimentary rocks are highly variable and can comprise low permeability mudstone and shale as well as more permeable sandstones and limestones. However, despite their low permeability, sufficient groundwater for rural water supply can often be found in mudstones with careful investigations (MacDonald *et al.*, 2005b).

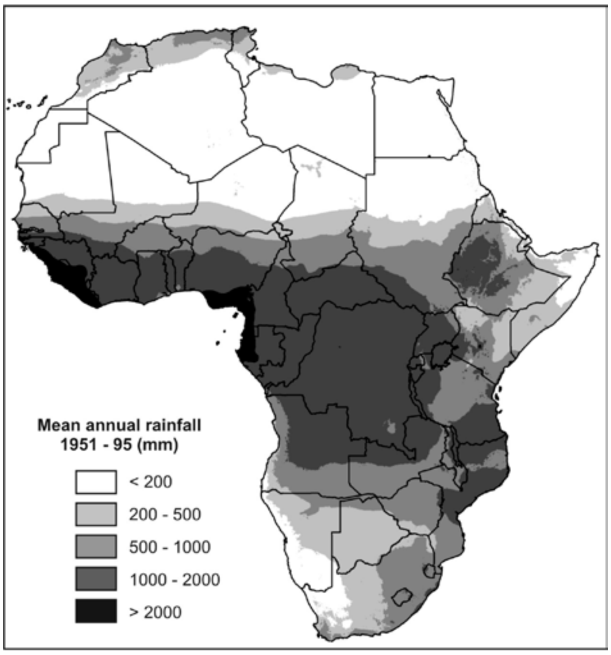

Figure 3 Average annual rainfall for Africa for the period 1951 – 1995 (New & Hulme 1997)

Unconsolidated sediments form some of the most productive aquifers in Africa (Guiraud, 1988). The estimate of their extent (approximately 25% of the land surface of Africa) is probably an underestimate of their true importance, since only the thickest and most extensive deposits are shown on the map. Unconsolidated sediments are also present in many river valleys, where they can form important local aquifers.

Volcanic rocks are found in east and southern Africa where they can form important aquifer systems. Despite their limited extent, they are highly significant aquifers since they underlie many of the poorest and most drought vulnerable areas. The groundwater potential of volcanic rocks varies considerably, reflecting the complexity of the geology (Demlie, *et al.*, 2007).

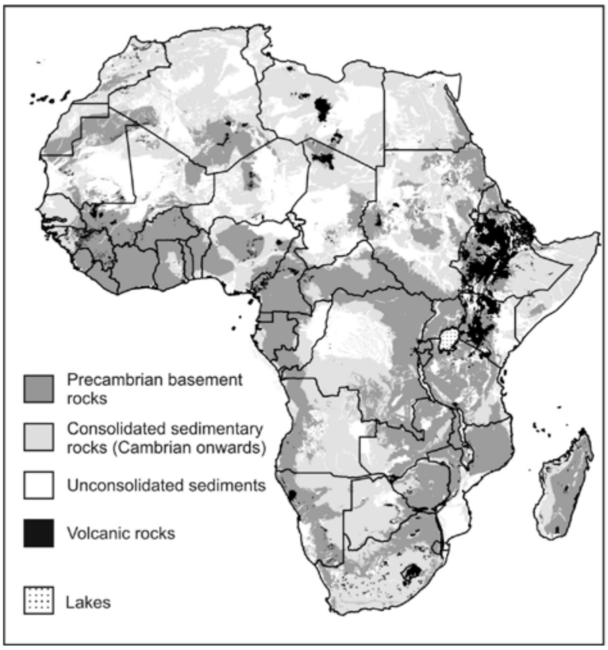

Figure 4. The hydrogeological environments of Africa (adapted from MacDonald *et al.*, 2008a)

THE IMPACT OF CLIMATE CHANGE ON RURAL WATER SUPPLIES

Climate change scenarios

There is considerable uncertainty surrounding the future of Africa's climate, as reported in the IPCC Fourth Assessment Report (Christensen *et al.*, 2007). The results of many of the different climate prediction models differ widely, and the models have difficulty in reproducing the observed climate patterns for the past 50 years. Despite these uncertainties, however, certain future scenarios are being predicted with greater confidence (Christensen *et al.*, 2007): Africa is very likely to warm during the 21st century; annual rainfall is likely to reduce in the northern Sahara and southern Africa; and annual rainfall is likely to increase in the Ethiopian Highlands. However, there is still uncertainty as to how rainfall in the Sahel and West African coast will evolve. Other important aspects of the future climate in Africa, rarely discussed in detail, are changes in the unpredictability of rainfall and the increasing frequency of droughts and floods (Bates *et al.*, 2008).

Various researchers have discussed how these changes will impact on the African population (e.g. Boko *et al.*, 2007). In northern and southern Africa, a reduction in rainfall from existing low levels (Figure 3) will further increase scarcity. However, even in areas where *average* rainfall does not decrease, greater unpredictability may have serious consequences. Changes in the annual distribution of rainfall, and in particular the onset of the rainy season, may have devastating impacts on rain-fed agriculture in more marginal areas, such as in areas where the dry season is more than six months long, Figure 1 (Agoumi, 2003; Thornton *et al.*, 2006).

Rainfall across Africa has been highly variable since records began in the early 1900s. The Sahel, for example, has shown large multi-decadal variability since 1900 and recent drying (Hulme et al., 2000). Droughts are also endemic in Africa and the extent of drought-affected areas is increasing (Sheffield & Wood, 2008). Adapting to climate variability is therefore not new – and learning how water resources and people respond to existing variability is an important method for predicting possible future changes (Calow *et al.*, 2009).

Estimating the impact of changing groundwater recharge patterns

As discussed above, groundwater recharge is a complex process, and most estimates of recharge are poorly constrained. Annual rainfall is clearly important, but other factors, such as the intensity of individual rainfall events, temperature, soil conditions, vegetation and land use are also significant. In addition, the permeability and porosity of underlying aquifers can limit the capacity for recharge to be stored. Nonetheless, for the purpose of making a general assessment for the whole of Africa, it is reasonable to assume that negligible recharge occurs in areas with annual rainfall of less than 200 mm (Eilers *et al.*, 2007), and that recharge in the up to approximately 50 mm can occur in areas with annual rainfall in the range of 200 – 500 mm (De Vries & Simmers, 2002; Edmunds *et al.*, 2008), and greater in areas where rainfall exceeds 500 mm (e.g. Rueedi et al., 2005).

Domestic rural water supply is not a large user of water and the supplies are also limited by the yield of the hand pumps. Most hand pumps have a yield of 5 – 10 m^3/d, which, if uniformly spread across Africa, would require recharge of less than 3 mm per year to supply secure water for all (Wright, 1992; Carter & Alkali, 1996). Even with a closer water supply spacing of 500 m (significantly greater than current averages), the recharge required to sustain the supplies is less than 10 mm per year (MacDonald *et al.*, 2008b).

In this context, and considering water for domestic supply only, people living within areas where rainfall is currently less than 200 mm are, in effect, mining groundwater that is not being actively recharged (Figure 5). In these sparsely populated areas, inhabitants have adapted to the lack of active groundwater recharge, and groundwater supplies are generally located in large sandstone aquifers, where there is sufficient groundwater storage to meet annual domestic needs. The groundwater is already managed as a finite non-renewable resource, and supplies are unlikely to be further affected by climate change.

Community water supplies in areas where annual rainfall is between 200 and 500 mm per annum can generally sustain annual abstraction from ongoing irregular recharge. Boreholes are therefore drilled not only in aquifers with high storage, but also in poorer aquifers, where storage is limited and recharge is required annually (or at least every 2 or 3 years) to maintain reasonable yields. Therefore, any reduction in annual rainfall, changes in intensity or seasonal variations~~,~~ may cause problems for water supply, particularly in aquifers with low storage capacity (Calow *et al.*, 1997; Calow *et al.*, 2009).

In areas where annual rainfall is currently greater than 500 mm per year, it is highly likely that significant recharge (>> 10 mm, and more commonly > 50 mm) occurs in most years (e.g., Rueedi et al. 2005). Even if rainfall were to fall substantially (e.g., by 20%) in these areas, it is likely that there would be enough recharge to replenish aquifers sufficiently to supply the modest requirements (3–10 mm) of hand pumps in rural areas.

Therefore, rural water supplies in areas where rainfall is between 500 and 200 mm are likely to be most at risk from changes in rainfall caused by climate change. These supplies generally rely on regular recharge, rather then large groundwater storage, but this regular recharge often only barely meets demand and may not occur if rainfall were to reduce or change in intensity. Figure 5 illustrates the relative population density in Africa in relation to the mean annual rainfall for 1951-96. Using this population density distribution (UNEP 2000) and the JMP (2008) estimate of the total rural population, we calculate that approximately 90 million people currently live in rural areas with rainfall between 200 and 500 mm, whose domestic water supply may therefore be vulnerable to decreases in recharge due to climate change.

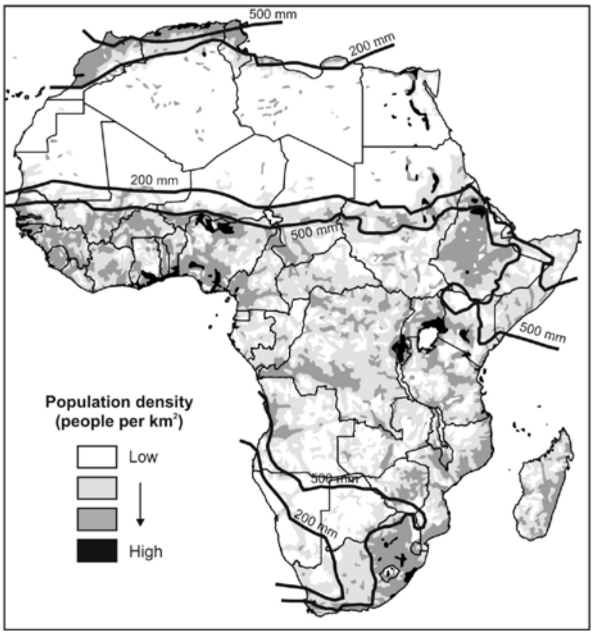

Figure 5 The relative population density of Africa relative to average annual rainfall 1951-96.

Increased demand for reliable domestic supply

As rainfall and surface water become less reliable, as is predicted for much of Africa, there is likely to be an increased demand for groundwater. This increased demand is already observed in current climate variability, for example during droughts in southern Africa in the early 1990s (Calow *et al.*, 1997) and more recently in the droughts in the Horn of Africa (MacDonald & Calow, 2007; Calow *et al.*, 2009). In addition to these stresses, the ever-growing population across Africa puts considerable extra demands on individual sources. During a prolonged dry season or drought, surface water and shallow unimproved groundwater sources (shallow wells and small springs) often fail, leaving only water points abstracting from larger groundwater bodies operational. Therefore, often only the larger springs, deep hand-dug-wells or boreholes are reliable across seasons and in drought years.

However, these ‘reliable’ sources are also prone to failure during drought. The primary reason for this is the increased demand put on the source as others fail. This increased demand can cause two common failures:

Mechanical breakdown due to increased stress on individual sources as other sources run dry. Prolonged pumping throughout the day can put considerable strain on the pump mechanism, leading to breakdowns. This is exacerbated if borehole water levels are falling, and pumping lifts are therefore increasing. The problem may be further exacerbated if maintenance activities on existing sources are reduced or stopped, because relief drilling programmes are given priority during drought.

Localised depletion of the groundwater resource as groundwater levels fall in the immediate vicinity of a well or borehole, or group of sources. This is most likely to occur where high demands on a groundwater source are combined with low aquifer permeability. For example, in a basement aquifer, which often has a low transmissivity of around 1 m^2/d (Wright, 1992), pumping rates of higher than approximately 0.1 l/s (enough to provide domestic supply for about 250 people) can lead to excessive drawdowns and reduce borehole efficiency.

Modelling of borehole behaviour in two aquifers using BGSPT (Barker & Macdonald, 2000) indicates the impact on groundwater levels from increased demand in the dry season (Figure 6). The first is a poor aquifer with transmissivity 1 m^2/d, which would under normal usage sustain a handpump used by 250 people (MacDonald *et al.*, 2008b). The second represents a higher yielding aquifer with transmissivity of 10 m^2/d. More information on the model setup is given in MacDonald et al. (2008b)

The results (Figure 6) demonstrate that in poor aquifers an increase in demand towards the end of the dry season can lead to greatly increased drawdowns, and therefore an increased risk of source failure. This is a problem of *accessing* the available groundwater resources, not a failure in the absolute groundwater availability. Different strategies can be used to help overcome this problem – for example, siting boreholes in more productive parts of the aquifer (Calow et al. 2009), adopting two phase pumping (Holt and Rushton, 1984) and appropriate choice of technology (e.g., MacDonald et al., 2005a). This is discussed further below.

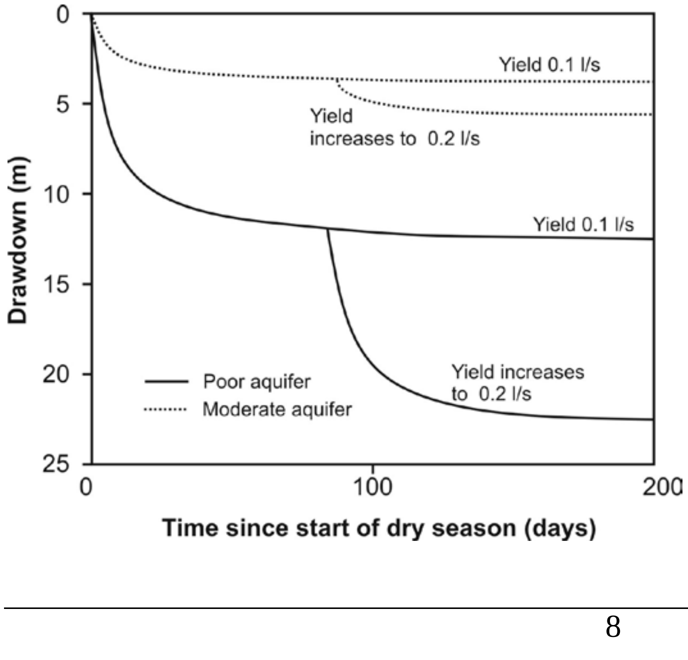

Figure 6 Maximum daily drawdown in a borehole for a poor aquifer (T = 1 m^2/d) and moderate aquifer (T = 10 m^2/d) modelled using BGSPT (Barker & Macdonald, 2000). Two scenarios are modelled: yield at 0.1 l/s for 12 hours per day, and yield doubling to 0.2 l/s for 12 hours per day after 90 days. The model is relatively insensitive to storage (MacDonald *et al.* 2008b.

Increased demand for groundwater for agriculture

Many of the impacts of climate change described in the IPPC Fourth Assessment Report (Boko *et al.*, 2007) relate to agriculture. The report presents a bleak picture for developing countries (and Africa in particular) with projections that between 75 and 250 million people in Africa will be exposed to increased water stress by 2050, and that rain-fed cereal yields will be reduced in some areas by up to 50% within the same time frame. Rising food prices have already raised serious concerns about impacts on poor people (who spend most of their income on food), and whether food production from rain-fed and irrigated systems can be increased to meet growing demand within the constraints imposed by already limited land and water.

In this context, developing groundwater for smallholder irrigation holds promise for strengthening livelihoods and improving food security (IWMI, 2007). Away from the Nile, however, there is little irrigation in Africa. Currently, groundwater is estimated to be used to irrigate less than 2 million hectares (Giordana, 2006), contributing to the livelihoods of only 1.5 to 3% of the rural population. A comparison with the widespread use of groundwater for irrigation in Asia indicates room for growth (Foster *et al.*, 2008), although the groundwater boom experienced in parts of south-east Asia was only made possible through access to cheap energy, credit and market integration, catalysing private investment in productive aquifers, such as the deep sedimentary aquifer in Gujarat and the extensive moderately productive basaltic aquifers of the Deccan (Kulkarni et al. 2000). Comparisons between Africa and Asia should therefore be treated with caution.

A key question is whether groundwater-based irrigation can be promoted as a sustainable Africa-wide strategy for reducing poverty and increasing food production. The answer to this question is probably ‘no’. Increasing abstraction from groundwater by ten-fold to help sustain irrigated agriculture could lead to more widespread over-exploitation problems and threaten the sustainability of domestic water sources. That said, groundwater resources in lower yielding, more complex hydrogeological environments are to some extent self regulating: it is difficult to over-abstract from low yielding aquifers, since drawdowns in individual boreholes become excessive at high yields (Figure 6). The groundwater resources most at risk from over-exploitation, therefore, are arguably those in higher yielding aquifers such as sandstones, unconsolidated sediments, and the more productive areas of basement or volcanic rocks, where regional drawdowns are more likely.

The impact of climate change on groundwater quality

Even without climate change, there are significant pressures on the quality of shallow groundwater across Africa. Poor sanitation and increased urbanisation have caused shallow groundwater to become polluted in many cities and peri-urban areas (Adelana et al., 2008). Even in rural areas, higher population densities and the widespread use of latrines, or absence of sanitation, can lead to shallow groundwater to become grossly contaminated. Intense rainfall events, and the elevated water table during the wet season can enable pathogens (and other suspended contaminants) to enter the shallow groundwater directly and travel tens or hundreds of metres whilst still potent (e.g. Pritchard et al., 2008, Taylor *et al*., 2009).

Increasing intensity of rainfall events across Africa may then lead to increased contamination of shallow groundwater. Rural water supplies, which depend on very shallow groundwater, or are poorly constructed so that shallow groundwater is not excluded, may be particularly vulnerable.

PREPARING FOR CLIMATE CHANGE

A key conclusion from the above is that increasing the resilience of rural water supplies to climate variability will generally require actions already identified for improving water security for communities. This means understanding the balance between water availability, access and use/demand (MacDonald & Calow, 2007; Calow *et al.*, 2009). For those reliant on groundwater in areas where rainfall is currently in the range 200-500 mm/a, absolute water availability for domestic needs may become the main constraint. However, for the majority, the main issues are likely to be access to existing groundwater through reliable water points, or increased demand for groundwater due to irrigation.

Here, we discuss actions that will help to increase the resilience of rural communities to climate variability: (1) improving access to reliable rural water supply as part of efforts to achieve the MDGs; (2) developing and improving access to groundwater for small-scale irrigation; and (3) strengthening links between water and food security programmes, particularly in relation to drought planning and emergency responses.

Improving access to reliable water supplies

Getting water to poor people remains a major investment challenge. An obvious need, therefore, is to ensure that the financial commitments made by the international community are actually met, since improving access to safe and secure water remains key to reducing long-term vulnerability. Investment alone is clearly not enough, however. Funds also need to be targeted at poorer areas, and to poorer communities, in such a way that sustainable and affordable infrastructure is embedded in local communities. How can this be achieved? Looking specifically at future ‘drought-proofing’ of rural water supplies, Calow *et al.* (2009) offer the following recommendations:

- Ensure that the service options offered to communities under demand-responsive policies are based on a sound understanding of hydrological and hydrogeological conditions and trends. MacDonald *et al.* (2005a) describes in more detail how this can be done, and how government, private sector and civil society stakeholders have a role to play in making this happen.

- Ensure that wells or boreholes are located in the most productive parts of the aquifer. Modest investment in resource assessment and siting techniques can pay dividends in terms of higher drilling success rates and higher yielding (more reliable) sources (van Dongen & Woodhouse, 1994; Reedman *et al.*, 2002; MacDonald *et al.*, 2005a; Carter, 2006). Simple tests can also be carried out to assess the performance of a well or borehole, once it has been constructed, providing valuable information on how the source will behave during drought (e.g. MacDonald *et al.*, 2008b). If a single source cannot meet peak dry season or drought demand, further village sources may need to be developed.

- Construct sufficient sources in a village to meet existing and future demand in both drought and non-drought years. In the longer term, this is more cost-effective than attempting to develop extra capacity during a crisis. Such an approach is standard practice in designing urban schemes, and the same rigour should be applied to rural water supply. However, creating excess capacity may be considered contentious, particularly if is done at the expense of other communities.

- Sink deep relief boreholes in the most favourable hydrogeological locations – perhaps away from villages - which can be uncapped and used in emergency situations. Such boreholes could be used by households from different villages should local sources dry up, could be used to provide water for tankering operations, or could be used as emergency watering points in pastoral areas, with complementary livestock interventions (e.g., de-stocking).

- Explore methods of increasing groundwater recharge and reducing evaptranspiration, for example, the use of managed aquifer recharge (Gale, 2005) to enhance recharge or the use of sand dams.

Developing groundwater for irrigation

Smallholder agricultural systems are an important intervention point for measures aimed at reducing poverty and increasing agricultural production. Moreover, strengthening agricultural livelihoods in Africa through water management approaches, including groundwater-based smallholder irrigation, has been identified as a key priority in the recent Comprehensive Assessment report (IWMI, 2007). The report recommends small-scale, divisible and affordable water technologies for Africa (treadle pumps, low cost drip, low cost pumps and small storage tanks), and notes the major benefits these could bring, if resource development and management/protection needs are considered in tandem.

Key questions here relate to how investment in local groundwater irrigation is delivered (and by whom), how to ensure it occurs within safe (sustainable) limits in light of the discussion above, and how (and by whom) such interventions are managed. These are significant questions, and we do not go into detail here. However, it is worth emphasising again that data on local hydrological and hydrogeological conditions are often limited or non-existent (Robins *et al.*, 2006; Calow *et al.*, 2009). This makes identifying suitable areas and appropriate technologies difficult.

Additionally, promotion of low volume, multi-purpose systems, rather than dedicated domestic and irrigation infrastructure, has advantages. Several authors (e.g., Nicol, 2001; Moriarty & Butterworth, 2003; Calow *et al.*, 2009) note that 'domestic' water is often used as a production input in garden irrigation and livestock watering, as well as activities like brewing and brick-making, even though water points are generally not designed with multiple uses in mind. One reason why greater flexibility has not been designed in to most existing systems is that rural water supply and agriculture remain institutionally and functionally separate.

Water and food security – making the link

The impact of drought and climate variability on food security in Africa has received much attention over the last 30 years. One outcome is the establishment of numerous (and sometimes competing) early warning systems. These have moved beyond the simple food balance models that dominated in the 1980s and 1990s to include much more localised information on household 'entitlements' and income. Major gaps and deficiencies remain however, particularly in relation to the narrow focus on food rather than food and water security.

There are various ways in which water security can be included in these analyses. One example is vulnerability mapping that combines data on rainfall with hydrogeology to identify areas of varying groundwater development potential and drought reliability (Figure 7 gives an example for Ethiopia). However, national and regional maps tell us nothing about local relationships between water availability, access and use. This information, beyond coverage data, is vital to an understanding of water insecurity, as insecurity may vary greatly over short distances.

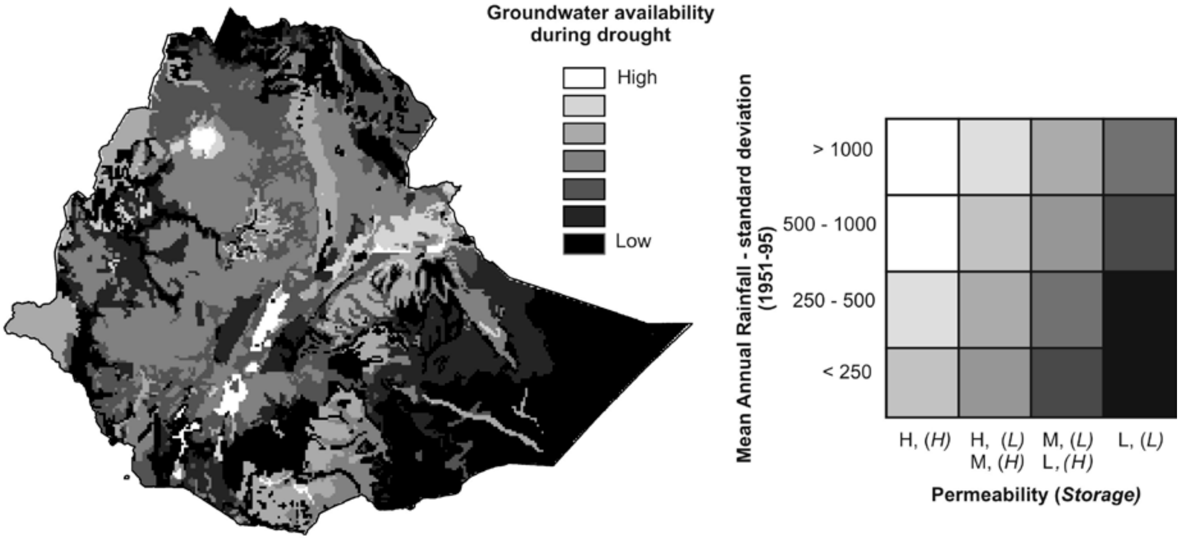

Figure 7 A map of groundwater availability during drought for Ethiopia calculated using hydrogeological and climate data (MacDonald *et al.*, 2001).

To identify the most vulnerable areas and communities, water security data can be combined with data on rural poverty and food security. The rural poor, for example, may include marginal and undiversified resource-poor farmers, female-headed households, landless labourers, pastoralists and displaced people, with the particular manifestation of insecurity varying between groups. From a food security perspective, information about access to production and exchange capabilities is required, and the impact this has on access to food. Combining indicators from all three data sets can then provide a much clearer understanding of livelihood insecurity and the interventions needed to support it. Interventions may include pump repair and maintenance in the early stages of drought, or assistance with water transport and tankering in later stages, combined with actions such as cash transfer and food for work.

CONCLUSIONS

Rural water supplies in Africa are overwhelmingly dependent on groundwater. Groundwater has many advantages over surface water sources, including reliability, ease and low cost of development, and generally good quality. Achieving the MDGs in Africa therefore depends crucially on accelerating groundwater development within sustainable limits. Growing concern over climate change and rainfall variability, however, raises questions about how much development potential there is, whether existing supplies may be threatened in future, and how to mainstream climate scenarios into rural water policy and practice. Below are several issues that should be considered for improved groundwater sources.

1. It is important to emphasise that climate change is unlikely to lead to the widespread catastrophic failure of improved groundwater rural water sources. Domestic supply requires only 3 – 10 mm of recharge annually per year, which should still be achievable for much of the continent. However, although widespread failure is very unlikely, a sizable minority could still be directly affected if rainfall, and thus groundwater recharge, significantly diminishes. Those currently living in low rainfall areas (200 – 500 mm) are most at risk of recharge reducing to the point of groundwater resources becoming non-renewable. Up to 90 million may be directly affected.

2. In most areas, the main determinants of water insecurity will continue to be *access* rather than *availability* related, with source failure occurring when there is overwhelming demand on too few sources. Increasing rural water supply coverage to meet the MDGs, and ensuring that targeting and technology decisions are informed by an understanding of environmental conditions, remain essential.

3. Matching the technology to the groundwater conditions, and siting sources in the most productive parts of the aquifer will improve the security of groundwater supplies. Other options, such as increasing the number of sources in a community, managed aquifer recharge, or relief boreholes may all have benefits.

4. Developing groundwater further for small-scale irrigation could help increase agricultural productivity and increase farm incomes. However, *ad hoc* development could threaten domestic supplies and, in some areas, lead to groundwater depletion as abstraction increases significantly beyond domestic use. Promotion of low volume, multi-purpose systems holds promise, but questions remain about how such systems are financed and managed, and the role government, private sector and civil society stakeholders should play.

5. Increased rainfall intensity predicted by most climate models is likely to lead to greater contamination of shallow groundwater as water-tables rise and flood latrines, or surface flooding washes pathogens into boreholes, or through the soil. The construction of sources should be improved to ensure that shallow layers are sealed out.

6. With respect to drought planning and responses, much more could be done to protect livelihoods before lives are threatened. The prevailing ‘food-first’ culture that dominates vulnerability assessment and emergency response in most African countries ignores the impact of water insecurity on livelihoods, and the role water interventions can play in reducing immediate and longer-term vulnerability. There is therefore a pressing need to broaden assessment and response systems to include non-food needs, develop monitoring systems with defined water indicators and incorporate such systems into existing early warning and response structures.

Finally, it is important to emphasise that the discussions in this paper refer only to *improved* water sources. Those who still rely on shallow unprotect shallow wells and ponds are likely to become increasingly insecure with climate change. Therefore, every effort should be made to extend reliable access to secure water for all throughout Africa

ACKNOWLEDGEMENTS

This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

REFERENCES

Agoumi, A. (2003) *Vulnerability of North African countries to climatic changes: adaptation and implementation strategies for climatic change.* International Institute for Sustainable Development, Winnepeg, Canada.

Barker, J. A. & Macdonald, D. M. J. (2000) A manual for BGSPT: programs to simulate and analyse pumping tests in large-diameter wells. *British Geological Survey Technical Report WC/00/17*. http://www.bgs.ac.uk/bgspt/. accessed April 2009.

Bates, B.C., Z.W. Kundzewicz, S. Wu & J.P. Palutikof, (Eds.) (2008) Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. & Yanda, P. (2007*)* Africa. In: *Climate Change 2007: Impacts*, *Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson) 433-467, Cambridge University Press, Cambridge UK.

Butterworth J.A, Macdonald, D.M.J, Bromley, J. Simmonds, L.P., Lovell, C.J. & Mugabe, F. (1999) Hydrological processes and water resources management in a dryland environment III: groundwater recharge and recession in a shallow weathered aquifer. *Hydrology and Earth System Sciences*, **3**, 345-342.

Calow, R. C., MacDonald, A. M., Nicol, A. L. & Robins, N. S. (2009) Groundwater security and drought in Africa: linking availability access and demand. *Ground Water*. DOI: 10.1111/j.1745-6584.2009.00558.

Calow, R. C., Robins, N. S., MacDonald, A. M., Macdonald, D. M. J., Gibbs, B. R., Orpen, W. R. G., Mtembezeka, P., Andrews, A. J. & Appiah, S. O. (1997). Groundwater management in drought prone areas of Africa. *International Journal of Water Resources Development*, **13**, 241-261.

Carter, R. C. & Alkali, A. G. (1996). *Shallow groundwater in the northeast arid zone of Nigeria.* Quarterly Journal of Engineering Geology, **29**, 341- 356.

Carter R. C. & Bevan, J. E. (2008) Groundwater development for poverty alleviation in sub-Saharan Africa. In: *Applied groundwater research in Africa* (ed. by S. M. A. Adelana & A. M. MacDonald) 25-42. IAH Selected Papers in Hydrogeology **13**, Taylor & Francis, Amsterdam.

Carter, R. C. (2006) *Drilling for Water in Ethiopia: 10 Steps to Cost-Effective Boreholes.* WSP Field Note, Water and Sanitation Program – Africa, World Bank, Nairobi.

Chilton, P. J. & Foster, S. S. D. (1995) Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa. *Hydrogeology Journal*, **3**, 36-49.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W. T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., Sarr A., & Whetton, P. (2007) Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed.

by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller) Cambridge University Press, Cambridge, UK.

De Vries, J.J. & Simmers, I. (2002) Groundwater recharge: an overview of processes and challenges. *Hydrogeology Journal,* **10**, 5-17.

Demlie, M., Wohnlich, S., Wisotzky. F. & Gizaw, B. (2007) Groundwater recharge, flow and hydrogeochemical evolution in a complex volcanic aquifer system, central Ethiopia. Hydrogeology Journal, **15**, 1169-1181.

Edmunds, W. M. 2008. Groundwater in Africa – Palaeowater, climate change and modern recharge. In: Adelana S. M. A. & MacDonald A. M. Applied Groundwater Studies in Africa. IAH Selected Papers in Hydrogeology, Volume 13, CRCPress/Balkema, Leiden, The Netherlands, 305-322.

Eilers, V. H. M., Carter, R. C. & Rushton, K. R. (2007) A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria. *Geoderma*, **140**, 119-131.

Foster, S. S. D. (1984) African groundwater development – the challenges for hydrogeological science. In: *Challenges in African Hydrology and Water Resources, Proceedings of the Harare symposium, July 1984*. IAHS Publication 144.

Foster, S. S. D., Tuinhof, A. & Garduño, H. (2008) Groundwater in Sub-Saharan Africa – A strategic overview of developmental issues. In: Adelana S. M. A. & MacDonald A. M. Applied Groundwater Studies in Africa. IAH Selected Papers in Hydrogeology, Volume 13, CRCPress/Balkema, Leiden, The Netherlands, 9-21.

Gale, I.N. (2005) Strategies for managed aquifer recharge (MAR) in semi arid areas. UNESCO, Paris.

Giordano, M. (2005) Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: a first-cut assessment. *Hydrogeology Journal*, **14**, 310 – 318.

Guiraud, R. (1988) L'hydrogeologie de l'Afrique. *Journal of African Earth Sciences*, **7**, 519-543.

IWMI (2007) *Costs and performance of irrigation projects: a comparison of sub-Saharan Africa and other developing regions.* Research Report 109, International Water Management Institute, Colombo, Sri Lanka.

JMP (2008). *Global water supply and sanitation 2008 report.* Joint Monitoring Programme WHO/UNICEF. World Health Organization: Geneva.

Lerner, D. N., Issar, A. & Simmers, I. (1990) Groundwater recharge; a guide to understanding and estimating natural recharge. International Contributions to Hydrogeology **8**, Heise, Hannover, Germany.

Kulkarni, H., Deolankar, S. B., Lalwani, A., Josep, B., Pawar, S. (2000). Hydrogeological framework of the Deccan basalt groundwater systems, west-central India. *Hydrogeology Journal,* **8**, 368-378.

MacDonald, A. M., Calow, R. C., Nicol, A. L. Hope, B. & Robins, N. S. (2001) Ethiopia: Water Security and Drought. British Geological Survey Technical Report WC/01/02.

MacDonald, A. M., Davies, J., Calow, R. C. & Chilton, J. (2005a) *Developing groundwater: a guide for rural water supply*. ITDG Publishing: Rugby, UK.

MacDonald, A. M., Kemp, S. J. & Davies, J. (2005b) Transmissivity variations in the mudstones. *Ground Water,* **43,** 259–269.

MacDonald, A. M. & Calow, R. C. (2007) Drought and community water supplies. *Waterlines* **26** (1) 14 -16.

MacDonald, A. M., Davies, J. & Calow, R. C. (2008a) African hydrogeology and rural water supply. In: Adelana S. M. A. & MacDonald A. M. Applied Groundwater Studies in Africa. IAH Selected Papers in Hydrogeology, Volume 13, CRCPress/Balkema, Leiden, The Netherlands, 127-148.

MacDonald, A. M., Barker, J. A. & Davies, J. (2008b). The bailer test: a short effect pumping test to assess borehole success. *Hydrogeology Journal*, **16**, 1065-1075.

Moore, P., Marfin, A., Quenemoen, L., Gessner, B., Ayub, Y., Miller, D., Sullivan, K. & Toole, M. (1993) Mortality rates in displaced and resident populations of central Somalia during 1992 famine. *The Lancet*, **341**, 935-938.

Moriarty, P. & Butterworth, J. (2003) *The productive use of domestic water supplies: how water supplies can play a wider role in livelihood improvement and poverty reduction*. IRC International Water and Sanitation Centre, Delft, The Netherlands.

New, M. & Hulme, M. (1997) A monthly rainfall dataset for Africa for 1951 to 1995. University of East Anglia, Norwich, UK.

New, M., Hulme, M. & Jones, P. D. (1999) Representing twentieth century space-time climate variability. Part 1: development of a 1961-90 mean monthly terrestrial climatology. *Journal of Climate*, **12**, 829-856.

Nicol, A. L. (2001) Adopting a Sustainable Livelihoods Approach to Water Projects: Implications for Policy and Practice. *ODI Working Paper, 133*, London.

Pritchard, M., Mkandawire, T. and O'Neill, J. G. (2008) Assessment of groundwater quality in shallow wells within the southern districts of Malawi, *Physics and Chemistry of the Earth,* doi:10.1016/j.pce.2008.06.036.

Persits, F., Ahlbrandt, T., Tuttle, M. Charpientier, R., Brownfield, M. & Takahashi, K. (1997) Maps showing geology, oil and gas fields and geological provinces of Africa. *USGS Open-file report 97-470A.*

Reedman, A., Calow, R. C. & Bate, D. (2002) The value of geoscience information in less developed countries. *British Geological Survey Commissioned Report CR/02/087N.*

Robins, N. S., Davies, J., Farr, J. L. & Calow, R.C. 2006. The changing role of hydrogeology in semi-arid southern and eastern Africa. *Hydrogeology Journal*, **14**, 1481-1492.

Rueedi, J., Brennwald, M.S., Burtschert, R., Beyerle, U., Hofer, M. & Kipfler, R. (2005) Estimating the amount and spatial distribution of groundwater recharge in the Iullemmeden basin (Niger) based on ^{3}H, ^{3}He and CFC-11 measurements. *Hydrological Processes*, **19**, 3285-3298.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, **20**, 3335-3370.

Sheffield, J. & Wood E.F. (2008) Global trends and variability in soil moisture and drought characteristics 1950-2000, from observation-driven simulations of the terrestrial hydrologic cycle. *Journal of Climate,* **21**, 432-458.

Taylor, R. G., & Howard, K. (2000) A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: Evidence from Uganda. *Hydrogeology Journal*, **8**, 279-294.

Taylor, R. G., Tindimugaya, C., Barker, J.A., Macdonald, D.M.J. & Kulabako, R. (2009) Convergent radial tracing of viral and solute transport in gneiss. *Ground Water*. DOI: 10.1111/j.1745-6584.2008.00547.

Thornton, P. K., Jones, P. G., Owiyo, T. M., Kruska, R. L., Herero, M., Kristjanson, P., Notenbaert, A. & Bekele, N. (2006) Mapping Climate Vulnerability and Poverty in Africa. Report to the Department for International Development, ILRI, Nairobi.

UNEP (2000) African population database 2000. United Nations Environment Programme. Nairobi, Kenya.

UNESCO (1991). *Africa Geological Map Scale (1:5,000,000). 6 Sheets*. UNESCO, Paris.

United Nations (2000). *United Nations Millennium Declaration.* United Nations General Assembly, A/RES/55/2. United Nations. New York.

United Nations (2006) The Millennium Development Goals Report. United Nations, New York

UNTCD (1988) *Groundwater in North and West Africa.* Natural Resources/Water Series, **18**, United Nations: New York.

UNTCD (1989) Groundwater in Eastern, Central and Southern Africa. Natural Resources/Water Series, **19**, United Nations: New York.

Van Dongen, P. & Woodhouse, M. (1994) *Finding groundwater: a project manager's guide to techniques and how to use them*. Technical Report, UNDP-World Bank Water and Sanitation Programme, World Bank Washington DC.

WHO (2004) *Making Water a Part of Economic Development: The Economic Benefits of Improved Water Management Services*. World Health Organisation, Geneva.

WHYMAP 2008. *Groundwater resources of the world.* BGR/UNESCO, accessed at: http://www.whymap.org .

Wright, E. P. (1992). The hydrogeology of crystalline basement aquifers in Africa. In: *The hydrogeology of crystalline basement aquifers in Africa* (ed. by E. P. Wright & W. Burgess), 1-27. Geological Society London Special Publications, **66**.