African hydrogeology and rural water supply

Alan M. MACDONALD[1], Jeff DAVIES[2] & Roger C. CALOW[2]

[1]British Geological Survey, West Mains Rd, Edinburgh, EH9 3LA, UK, tel +44 131 650 0389, amm@bgs.ac.uk

[2] British Geological Survey, MacLean Building, Wallingford, Oxfordshire, OX10 8BB, UK.

Abstract

The widespread development of groundwater is the only affordable and sustainable way of improving access to clean water and meeting the Millennium Development Goals for water supply by 2015. Current approaches to rural water supply, in particular demand driven approaches and decentralisation of service delivery have many benefits to the overall efficacy and sustainability of water supplies, however, problems arise when projects do not take into consideration the nature of the groundwater resources. Different approaches and technologies are required depending on the hydrogeological environment. Sub-Saharan Africa (SSA) can be divided into four hydrogeological provinces: (1) The crystalline basement occupies 40% of the land area of SSA and supports 235 million rural inhabitants. (2) Volcanic rocks occupy 6% of the land area of SSA, and sustain a rural population of 45 million, many of whom live in the drought stricken areas of the Horn of Africa; (3) Consolidated sedimentary rocks occupy 32% of the land area of SSA and sustain a rural population of 110 million: (4) Unconsolidated sediments occupy 22% of the land area of SSA and sustain a rural population of 60 million. Hydrogeological expertise can have significant benefit to rural water supplies by increasing capacity throughout projects by effectively transferring knowledge; by providing authoritative benchmarking, by focused research and by providing accessible advice to planners and policy makers

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Introduction

At least 44% of the population in sub-Saharan Africa (some 320 million people) do not have access to clean reliable water supplies (JMP, 2004). The majority of those without access (approx 85%) live in rural areas where the consequent poverty and ill health disproportionately affect women and children (DFID, 2001; JMP, 2004). In response, the international community has set the Millennium Development Goals (MDGs) which commit the UN membership to reduce by half the proportion of people who are unable to reach, or afford, safe drinking water by the year 2015 (United Nations, 2000). Poverty reduction and sustainable development are now given highest priority.

In this context, the need for sustainable development and management of groundwater cannot be overstated. Across large swathes of Africa, South America and Asia, groundwater provides the only realistic water supply option for meeting dispersed rural demand – alternative water resources can be unreliable and expensive to develop (Foster *et al.*, 2000; MacDonald *et al.*, 2005).

Yet many projects spend large amounts of money installing water sources without trying to understand the groundwater resources on which these sources depend. As a result, many supplies are unsuccessful or perform poorly (Robins *et al.*, 2006). Successfully developing groundwater resources sustainably and cost-effectively on the scale required to help achieve the Millennium Development Goals is not trivial. The challenge is more than just providing extra drilling rigs to the worst-affected countries: technology, software and hardware must all be appropriate to the nature of the groundwater resources in the project area.

In this paper we discuss the groundwater resources in sub-Saharan Africa (SSA) in the context of rural water supply: finding and developing groundwater resources to sustain community hand pumps. An extended reference list is given to help follow up technical aspects of the hydrogeology of Africa, which are not discussed in detail here.

Groundwater resources in sub-Saharan Africa

The availability of groundwater resources in sub-Saharan Africa depends critically on the geology, the history of weathering faulting, and the recharge to groundwater.

Figure 1 shows the average annual rainfall across sub-Saharan Africa based on data from New & Hulme (1997). This clearly demonstrates the arid areas, where groundwater recharge is limited and erratic. However, there is no simple direct relationship between average annual rainfall and recharge, and significant recharge (10 - 50 mm) can occur where annual rainfall is less than 500 mm (Edmunds & Gaye, 1994; Butterworth, 1999; Edmunds *et al.*, 2002). Climate change will significantly alter patterns of rainfall and recharge across Africa. Climate models predict that the number of drought episodes in Africa will increase, particularly in Sahel areas, and the number of people affected by sever drought will grow (Hulme *et al*., 2001; Magrath & Simms, 2007). Rural water supply, however, does not require large quantities of recharge, and a simple mass balance indicates that recharge of 10 mm per annum would support community boreholes (5 m^3/d or 0.17 l/s) with hand pumps at a spacing of 500 m across Africa.

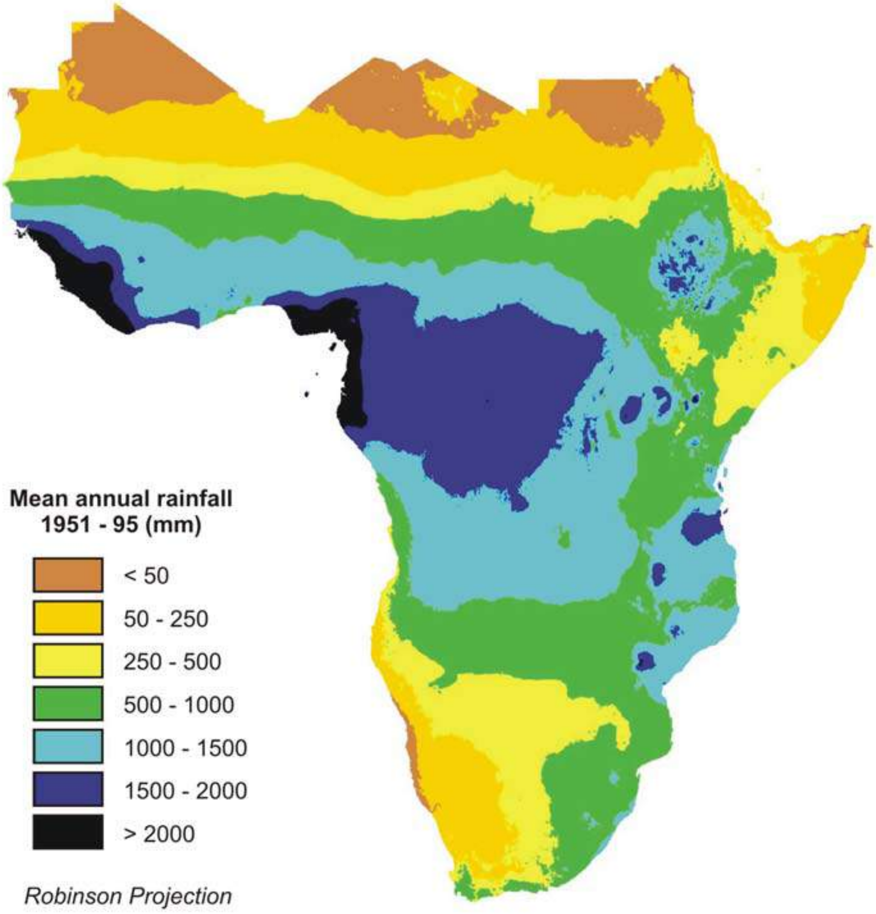

Figure 1 **Average annual rainfall for sub-Saharan Africa for the period 1951 – 1995. Produced from data from New & Hulme (1997).**

A simplified hydrogeological map is shown in Figure 1 based on a synthesis of studies (Foster 1984; Guiraud 1988; UNTCD 1988; UNTCD 1989; MacDonald & Davies 2000) and using the 1:5,000,000 scale geological map of Africa as a base (UNESCO, 1991; Persits *et al.*, 1997). The classifications reflect the different manner in which groundwater occurs, constrained by the geological information available at this scale throughout SSA. The four different environments are: Precambrian "basement" rocks; volcanic rocks; unconsolidated sediments; and consolidated sedimentary rocks. Basement rocks form the largest hydrogeological environment, occupying 40% of the 23.6 million square kilometres and volcanic rocks are the smallest hydrogeological environment with only 6% of the land area (see Table 1). This basic division forms the basis for the rest of this paper.

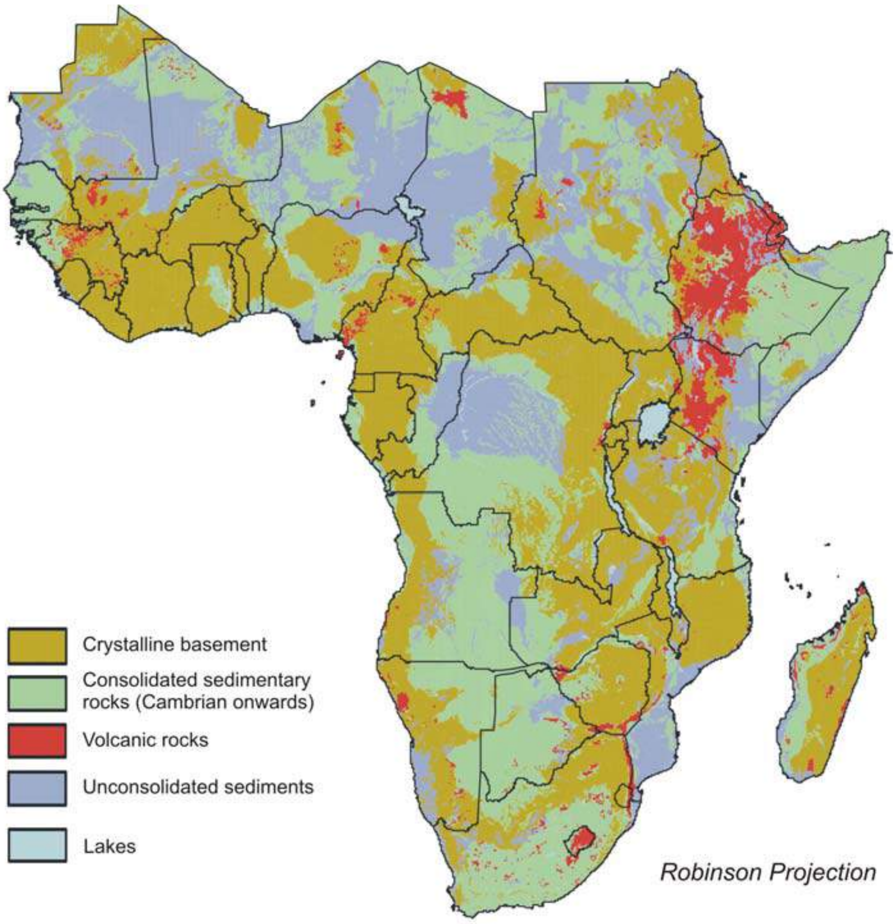

Figure 2 The hydrogeological environments of sub-Saharan Africa (from MacDonald & Davies, 2000, MacDonald *et al.*, 2005).

The potential of each hydrogeological environment to contribute to rural water supply is best indicated by the rural population living in each one. As discussed above, the rural communities are most dependent on local resources for water supply, since transportation is often prohibitively expensive and difficult to manage. Using spatial data from ESRI (ESRI, 1996) and statistics from the World Bank and the WHO/UNICEF Joint Monitoring Programme (JMP, 2004), an approximation was made of the distribution of rural population throughout sub-Saharan Africa. The results are shown in Table 1. Basement rocks support the largest population (235 million) and volcanic rocks the least (45 million). However, despite, the relatively low number of people living in hydrogeological volcanic areas, they are particularly important since they are home to some of the poorest and most drought prone people in Africa.

Table 1 The land area of each hydrogeological environment shown in Figure 2, and and estimate of the rural population living on each (ESRI, 1996; World Bank, 2000; JMP, 2004)

Hydrogeological Environment	*land area (%)*	*rural population (millions)*
Basement rocks	40	235
Consolidated sedimentary rocks	32	120
Volcanic rocks	6	45
Unconsolidated sediments	22	70
Total	**100 %**	**470**

Hydrogeological environments

In this section each of the hydrogeological environments are described with references to key publications on each. Table 2 provides a summary the groundwater potential for each environment.

Before discussing each hydrogeological environment it is important to define what constitutes an aquifer in the context of rural water supply. If we assume that a borehole is to supply a minimum of 5 m^3/d to be successful, and that recharge is not a constraint (see above), then the minimum aquifer properties can be estimated that would give a successful source. Modelling indicates that transmissivity is the key limiting factor and that generally transmissivity >1 m^2/d will give a successful borehole (MacDonald *et al.*, 2008).

Table 2 A summary of the groundwater potential of the African hydrogeological environments (modified from MacDonald *et al.*, 2005).

	Hydrogeological Sub-Environment	GW potential & average yields	Groundwater Targets
Crystalline basement rocks	Highly weathered and/or fractured basement	Moderate 0.1- 1 l/s	Fractures at the base of the deep weathered zone. Sub -vertical fracture zones.
	Poorly weathered or sparsely fractured basement	Low 0.1 l/s – 1 /s	Widely spaced fractures and localised pockets of deep weathering.
Consolidated sedimentary rocks	Sandstone	Moderate – High 1 – 20 l/s	Coarse porous or fractured sandstone.
	Mudstone and shale	Low 0 – 0.5 l/s	Hard fractured mudstones Igneous intrusions or thin limestone / sandstone layers.
	Limestones	Moderate – high 1-100 l/s	Fractures and solution enhanced fractures (dry valleys)
	Recent Coastal and Calcareous Island formations	High 10 – 100 l/s	Proximity of saline water limits depth of boreholes or galleries. High permeability results in water table being only slightly above sea level
Unconsolidated sediments	Major alluvial and coastal basins	High 1 – 40 l/s	Sand and gravel layers
	Small dispersed deposits, such as river valley alluvium and coastal dunes deposits.	Moderate 1 – 20 l/s	Thicker, well-sorted sandy/gravel deposits. Coastal aquifers need to be managed to control saline intrusion.
	Loess	Low – Moderate 0.1 – 1 l/s	Areas where the loess is thick and saturated, or drains down to a more permeable receiving bed
	Valley deposits in mountain areas	Moderate – High 1 – 10 l/s	Stable areas of sand and gravel; river-reworked volcanic rocks; blocky lava flows
Volcanic Rocks	Extensive volcanic terrains	Low - High Lavas 0.1 – 100 l/s Ashes and pyroclastic rocks 0.5-5 l/s	Generally little porosity or permeability within the lava flows, but the edges and flow tops/bottom can be rubbly and fractured; flow tubes can also be fractured. Ashes are generally poorly permeable but have high storage and can drain water into underlying layers.

Precambrian basement

Precambrian basement rocks occupy 40% of the land area of SSA and support approximately 235 million rural inhabitants. They comprise crystalline igneous and metamorphic rocks over

550 million years old (Key, 1992). Unweathered and non-fractured basement rocks contain negligible quantities of groundwater. Significant aquifers however, develop within the weathered overburden and fractured bedrock.

The geology of Precambrian Basement areas is complex, reflecting the long history that the environment has been subjected to. Although Precambrian basement terrains largely comprise crystalline igneous and metamorphic rocks, there are also areas of metamorphosed consolidated sediments comprising sandstones, conglomerates, shales and mudstones in west. Two notable examples are the Voltaian Sediments of Ghana and the Transvaal, Waterberg and Ventersdorp Groups in southern Africa.

Five factors contribute to the weathering of basement rocks (Jones 1985; Acworth, 1987):

- tension and stress fractures;
- geomorphology of the terrain; e.g. weathering along fracture controlled valleys, formation of inselbergs
- temperature and occurrence of groundwater controlling the depth and nature of weathering
- mineral content of the basement rock
- the palaeo-climates experienced by the near surface deposits.

The resulting weathered zone can vary in thickness from just a few metres in arid areas to over 90 m in the humid tropics. Historical erosion surfaces may also be important in preserving ancient weathered surfaces. Figure 3 summarise the permeability and porosity profiles for the weathered zone. Porosity generally decreases with depth; permeability however, has a more complicated relationship, depending on the extent of fracturing and the clay content (Wright & Burgess, 1992; Chilton & Foster, 1995). In the soil zone, permeability is usually high, but groundwater does not exist throughout the year and dries out soon after the rains end. Beneath the soil zone, the rock is often highly weathered and clay rich, therefore permeability is low. Towards the base of the weathered zone, near the fresh rock interface, the proportion of clay significantly reduces. This horizon, which consists of fractured rock, is often permeable, allowing water to move freely. Wells or boreholes that penetrate this horizon can usually provide sufficient water to sustain a handpump.

Deeper fractures within the basement rocks are also an important source of groundwater, particularly where the weathered zone is thin or absent. These deep fractures are tectonically controlled and can sometimes provide supplies of 1 - 5 l/s. The groundwater resources within the regolith and deeper fracture zones depend on the thickness of the water-bearing zone and the relative depth of the water table. In general terms, the deeper the weathering, the more sustainable the groundwater. However, due to the complex interactions of the various factors affecting weathering (an in particular the presence of clay in the weathered zone), water-bearing horizons may not be present at all at some locations.

Various techniques have been developed to locate favourable sites for the exploitation of groundwater resources within basement rocks. These include remote sensing (Lillesand & Kiefer, 1994) geophysical methods (Beeson & Jones, 1988; McNeill, 1991; Carruthers & Smith, 1992) and geomorphological studies (Taylor & Howard, 2000). Geophysical surveys using combined resistivity and ground conductivity (EM) surveys have often been found useful in siting wells and boreholes (see Table 3). These can often be successfully interpreted by using simple guidelines, (MacDonald *et al.*, 2005). Although groundwater is generally abstracted th5rough boreholes and wells, more sophisticated systems, such as collector wells have also been used with success, (Ball & Herbert, 1992; Lovell, 2000).

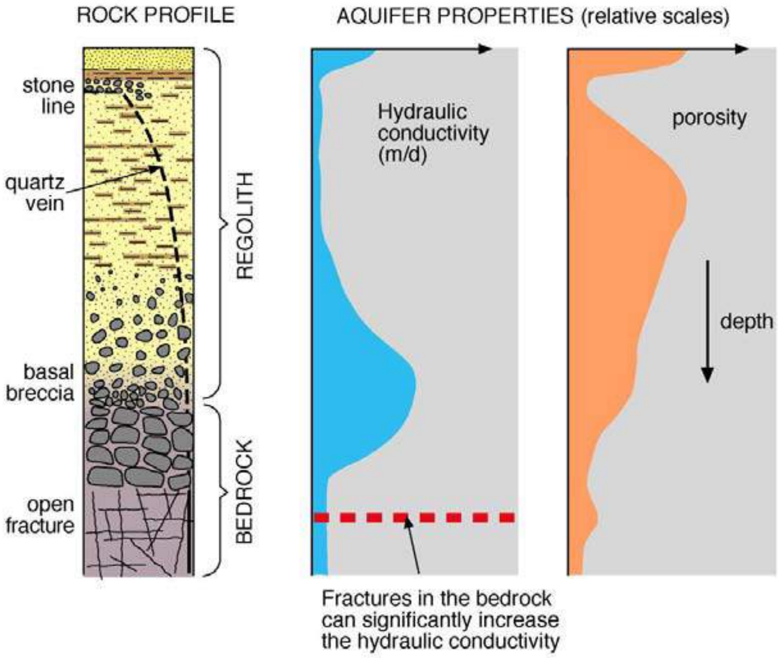

Figure 3 Schematic diagram of the variation of permeability and porosity with depth in the crystalline basement (adapted from Acworth, 1987; Chilton & Foster, 1995).

Table 3 A summary of common geophysical investigations used in rural water supply projects (see Milsom (2002) for more details).

Geophysical technique	What it measures	Output	Usual maximum depth of penetration	Comments
Resistivity	Apparent electrical resistivity of ground	1-D vertical geoelectric section; more complex equipment gives 2-D or 3-D geoelectric sections	100 m	Can locate changes in the thickness and nature of the weathered zone and differences in geology. Also useful for identifying thickness of sand or gravel within superficial deposits. Often used to calibrate FEM surveys (see below). Slow survey method and requires careful interpretation.
Frequency domain Electro-Magnetic methods (FEM)	Apparent terrain electrical conductivity (calculated from the ratio of secondary to primary electromagnetic fields)	Single traverse lines or 2D contoured surfaces of bulk ground conductivity	50 m	Quick and easy method for determining changes in thickness of weathered zones or alluvium. Interpretation is non-unique and requires careful geological control. Can also be used in basement rocks to help identify fracture zones.
Transient Electro-Magnetic methods (TEM)	Apparent electrical resistance of ground (calculated from the transient decay of induced secondary electromagnetic fields)	Output generally interpreted to give 1D resistivity sounding	150 m	Better at locating targets through conductive overburden than FEM, also better depth of penetration. Expensive and can be difficult to operate.
Very Low Frequency (VLF)	Secondary magnetic fields induced in the ground by military communications transmitters.	Single traverse lines, or 2D contoured surfaces.	40 m	Can locate vertical fracture zones and dykes within basement rocks or major aquifers
Ground penetrating radar (GPR)	Reflections from boundaries between bodies of different dielectric constant	2D section showing time for EM waves to reach reflectors	10 m	Accurate method for determining thickness of sand and gravel. The technique will not penetrate clay, however, and has a depth of penetration of about 10 m in saturated sand or gravel.
Seismic refraction	P-wave velocity through the ground	2-D vertical section of P-wave velocity	30 m	Can locate fracture zones in basement rock and also thickness of drift deposits. Not particularly suited to measuring variations in composition of drift. Fairly slow and difficult to interpret.

Magnetic	Intensity (and sometimes direction) of earth’s magnetic field	Variations in the earth’s magnetic field either along a traverse or on a contoured grid	100 m	Can locate magnetic bodies such as dykes or sills. Susceptible to noise from any metallic objects or power cables.

Volcanic rocks

Volcanic rocks occupy only 6% of the land area of SSA and are found in east and southern Africa where they can form important aquifer systems. In total, about 45 million people are dependent on volcanic rocks for rural groundwater supplies, and they underlie much of the poorest and drought stricken areas of SSA. The groundwater potential of volcanic rocks varies considerably, reflecting the complexity of the geology. There have been few systematic studies of the hydrogeology of volcanic rocks in Africa, although good site studies are given by Aberra (1990), Vernier (1993), Demlie *et al.* (2007) Kebede *et al.* (2007). Volcanic rocks are important aquifers in India and have been extensively studied there (e.g. Kulkarni *et al.*, 2000).

The volcanic rocks in SSA were formed during three phases of activity during Cenozoic times, associated with the opening of the East African rift valley and an earlier Late Karoo (Jurassic) phase. These events gave rise to a thick complex sequence of lava flows, sheet basalts and pyroclastic rocks such as agglomerate and ash. Thick basalt lava flows are often interbedded with ash layers and palaeosoils. The potential for groundwater depends largely on the presence of fractures. The top and bottom of lava flows, particularly where associated with palaeosoils, are often highly fractured and weathered; towards the middle of the lava flows, the basalt tends to be more competent and less fractured. Figure 4 shows aspects of groundwater flow in highland volcanic areas in Ethiopia. In southern Africa, large volumes of flood basalts erupted from centres in present day Lesotho, SE South Africa, Mozambique, western Zimbabwe and north-eastern Botswana. These thick extrusive sequences of basalts and ash deposits were associated with the intrusion of extensive dolerite ring and dyke swarm complexes within the present day regions of south-eastern South Africa, southern Zimbabwe and north eastern Botswana (TAMS, 1996; Woodford & Chevallier, 2002).

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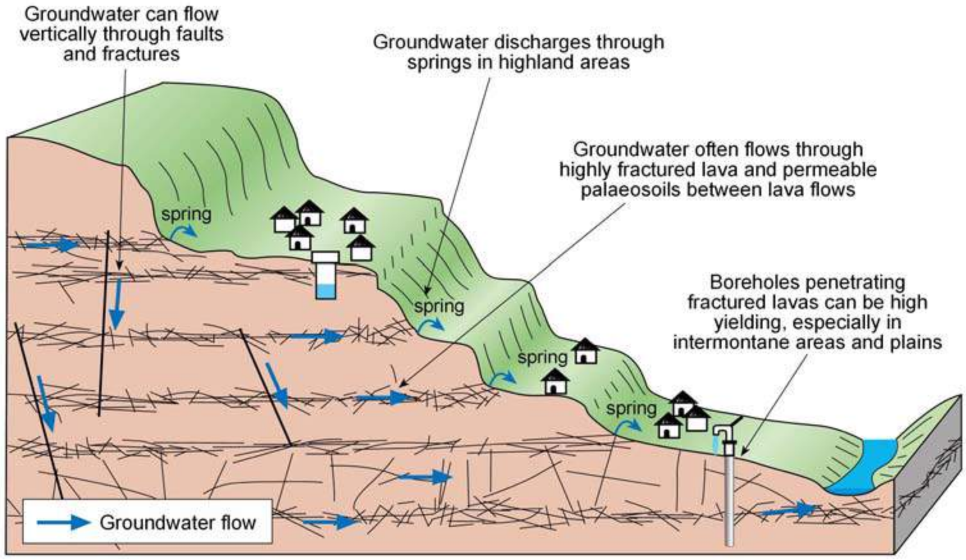


Figure 4 Groundwater occurrence in volcanic rocks.

The most important factors for the development of aquifers within volcanic rocks are given below (Kehinde & Loenhert 1989; Vernier 1993):

- Thick palaeosoils or loose pyroclastic material between lava flows are often highly permeable;
- joints and fractures due to the rapid cooling of the tops of lava flows provide important flow pathways;
- contact between lava flows and sedimentary rocks or earlier volcanic material such as domes etc. are often highly fractured and contain much groundwater;
- gas bubbles within lava flows, and porosity within ashes and agglomerates can provide significant groundwater storage.

Fractured lava flows can have very high permeability, but yields exhibit large variations with average values from boreholes about 2 l/s (UNTCD, 1989), which is more than adequate for rural domestic water supplies. Boreholes are generally more suitable than hand dug wells, since the fracture zones with significant groundwater are often deep. However, in Kenya, where the volcanic rocks form vast tablelands, the groundwater can be shallow, and sometimes exploited by dug wells. Dug wells can also be used in mountainous areas, where aquifers are small and water-levels sometimes shallow. Springs are common in volcanic rocks, particularly in highland areas. The interconnected fractures and cavities found in the lava flows provide rapid discrete flow paths for groundwater, which often discharge as springs at impermeable boundaries. Springs, particularly at higher altitudes can be more susceptible to drought failure than boreholes (Calow *et al.*, 2002).

The quality of groundwater can be a problem in volcanic rocks. Fluoride concentrations are sometimes elevated and concentrations in excess of 1.5 mg/l can lead to health problems such as dental or skeletal fluorosis. High fluoride groundwaters are common in the rift valley regions of Kenya and Tanzania (e.g. Ashley & Burley, 1995; Reimann, 2003).

Geophysical techniques have sometimes been used in volcanic terrain to site boreholes, but few general guidelines have been developed. Remote sensing techniques may be valuable for detecting different geological units and identifying fracture zones but have not been widely applied. Boundaries between volcanic rocks and sedimentary rocks could be easily identified with magnetic methods. Resistivity methods have been used to locate vertical and horizontal fracture zones in East Africa (Drury et al., 2001). However locating deep horizontal fracture zones (such as the boundary between lava flows) can be difficult using geophysics, and boreholes may have to be drilled relying solely on experience from previous drilling in the area.

Consolidated sedimentary rocks

Consolidated sedimentary rocks occupy 32% of the land area of SSA (Figure 2). Approximately 135 million people live in rural areas underlain by these rocks. Sedimentary basins can store considerable volumes of groundwater, but in arid regions, much of the groundwater can be non-renewable, having been recharged when the area received considerably more rainfall. Also, sedimentary rocks are highly variable and can comprise low permeability mudstone and shale as well as more permeable sandstones and limestones Examples of large sedimentary basins in sub-Saharan Africa (Figure 5) are the Karoo (tillite, mudstone, sandstone and conglomerate), and Kalahari Basin sediments (mudstone and sandstone with uncompressed cover sediments of poorly consolidated muds, silts and sands with associated consolidated evaporate sediments such as calcrete and silcrete) of Southern and Central Africa (Truswell, 1970), sediments within the Somali basin of East Africa and the Benue Trough of West Africa (Selley, 1997).

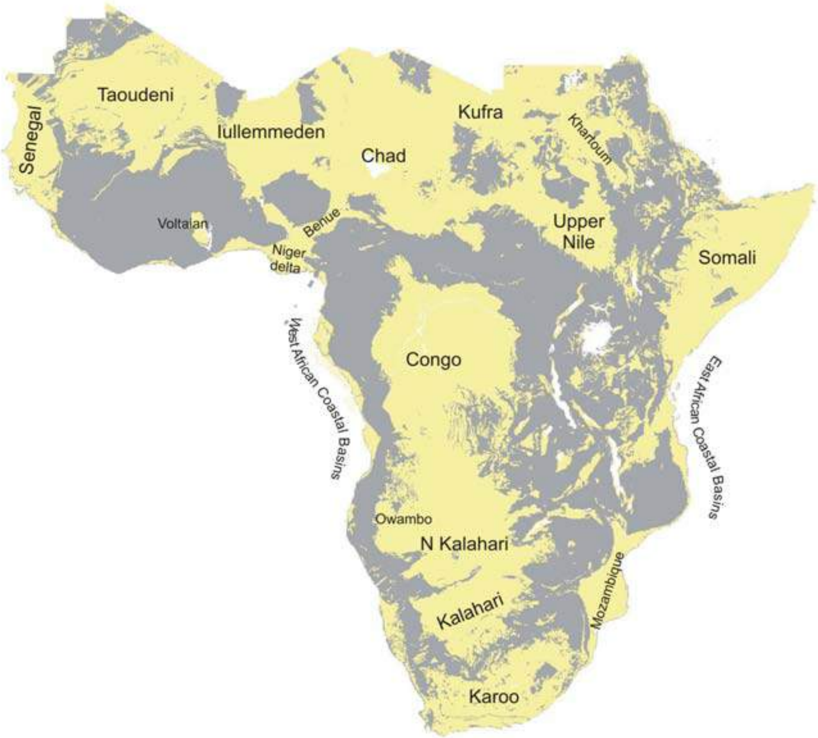


Figure 5. The location of large sedimentary basins in sub-Saharan Africa.

For the purposes of creating the simplified map shown in Figure 2, sedimentary rocks deposited before Quaternary times are assumed to be mainly consolidated. Figure 6 illustrates how groundwater occurs in consolidated sedimentary rocks.

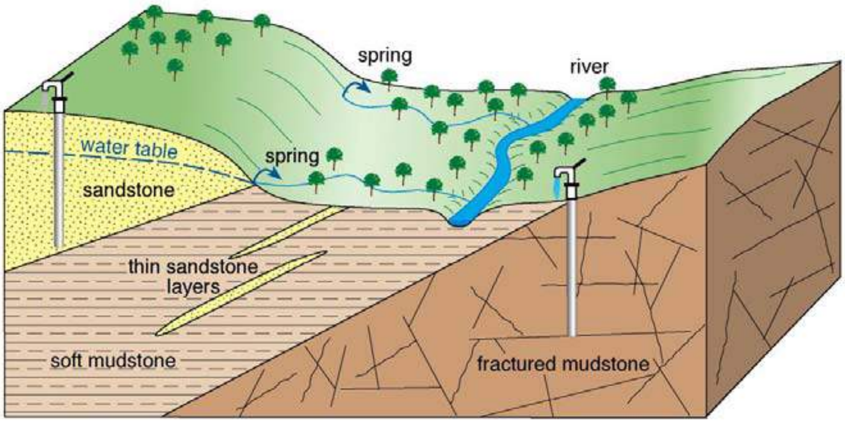
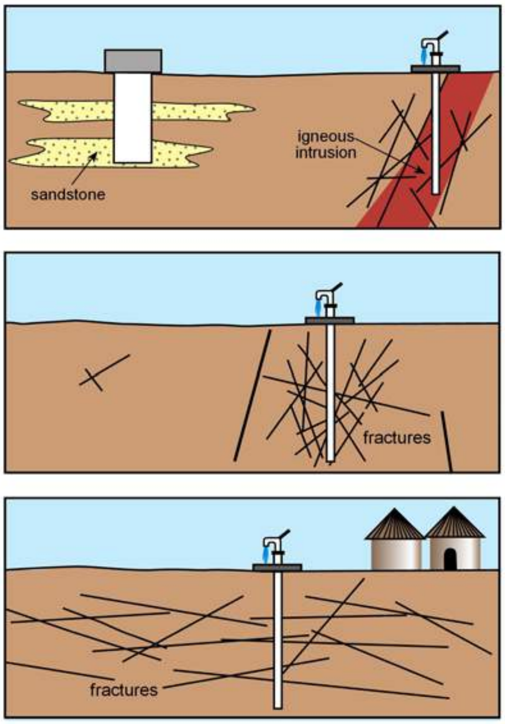


Figure 6. A schematic diagram illustrating how groundwater for rural water supply can exist within sedimentary rocks.

Consolidated sandstone and limestone contain significant groundwater. Shallow limestone aquifers are often vulnerable to saline intrusion and pollution (e.g. the limestone aquifers along the East African coast). Carefully constructed deep boreholes into thick sandstone aquifers can provide high yields (e.g. Middle and Upper Karoo sandstones of South Africa, Botswana and western Zimbabwe (Interconsult, 1985; Woodford & Chevallier, 2002; Cheney *et al.*, 2006). Yields are highest where the sandstones are weakly cemented or fractured. This makes the aquifers highly suited to large-scale development for reticulated urban supply, industrial uses and agricultural irrigation. However, rural water supply generally relies on shallow boreholes or wells close to communities. Only rocks immediately surrounding the community and to a depth of less than 100 m are usually considered. In large sedimentary basins, where modern recharge is limited, water-levels can be deeper than 50 m, and therefore difficult to abstract using a handpump. More sophisticated approaches may be required for rural water supply in such areas requiring deeper boreholes, header tanks and distribution systems.

Although mudstone and siltstone are poor aquifers, groundwater can often be found in these environments with careful exploration. Studies in Nigeria showed that where mudstone is soft and dominated by smectite, negligible groundwater exists; in slightly metamorphosed mudstone, where the rocks have been altered to become harder, fractures can remain open and usable groundwater can be found (MacDonald *et al.*, 2005). Similar problems have been encountered in the fine grained aeolian and fluvially deposited Karoo age sediments (as in south Africa and Lesotho (Sami, 1996)). It is estimated that 65% of all sediments are mudstone (Aplin *et al.*, 1999); therefore, up to 75 million people may live directly on these mudstone areas. Figure 7 illustrate how groundwater exists in mudstone areas.



In smectite rich mudstones there is no usable water within the clay. The only water in these areas is found in thin sandstone layers or small igneous intrusions

If the mudstone has been buried and altered to become slightly harder (mixed layer I/S clays), usable groundwater can be found in large fractures and faults. Faults and fractures however, may be far apart.

Where mudstones have been altered to comprise hard shales, fractures are widespread and groundwater is easily found.

Figure 7. Groundwater occurrence in mudstone areas (after MacDonald *et al.*, 2005).

Geophysical techniques can be used to identify good aquifers. Sandstone can easily be distinguished from mudstone using ground conductivity or resistivity methods (e.g. Interconsult, 1985; Bromley *et al.*, 1996). Similarly, harder mudstones can also be distinguished from soft mudstone (MacDonald *et al.*, 2001). In areas where large sandstone or limestone aquifers are present, little or no detailed siting is required for rural domestic supply; boreholes can be drilled anywhere. Occasionally, if the aquifers and groundwater levels are shallow, dug wells can be constructed.

Unconsolidated sediments

Unconsolidated sediments form some of the most productive aquifers in Africa. They cover approximately 22% of the land surface of SSA (Figure 2). However, this 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 throughout Africa. Examples of extensive deposits of unconsolidated sediments are found in Chad, Congo and Mozambique (the amalgamated deltas of the Save, Zambezi and the

Limpopo) and in the coastal areas of Nigeria (Niger Delta), Ghana, Somalia, Namibia, Madagascar and Kenya. There is no clear dividing line between unconsolidated sediments and consolidated sedimentary rocks, as the time taken for consolidation can vary. However, for most purposes it can be assumed that sediments deposited in the past few million years (during Quaternary and late Neogene times) will remain unconsolidated. Unconsolidated Sedimentary Aquifers are often described as UNSAs.

Unconsolidated sediments comprise a range of material, from coarse gravel and sand to silt and clay. They are deposited in different environments such as rivers and deltas by various combinations of physical processes. Large unconsolidated sedimentary basins can store large amounts of groundwater. Guiraud (1988) describes several of the major UNSAs in Africa. As with consolidated sedimentary rocks, where the basins are now in arid regions, the water they contain may not be currently renewable. The size and physical characteristics of the aquifer depend on how the sediment was deposited. Sand and gravel beds can be continuous over hundreds of kilometres, but are often multi-layered, with sands and gravels interbedded with silts and clays. Depending on the depositional environment, the structure of the aquifers can be highly complex, with sediments changing laterally within a few metres (see Figure 8).

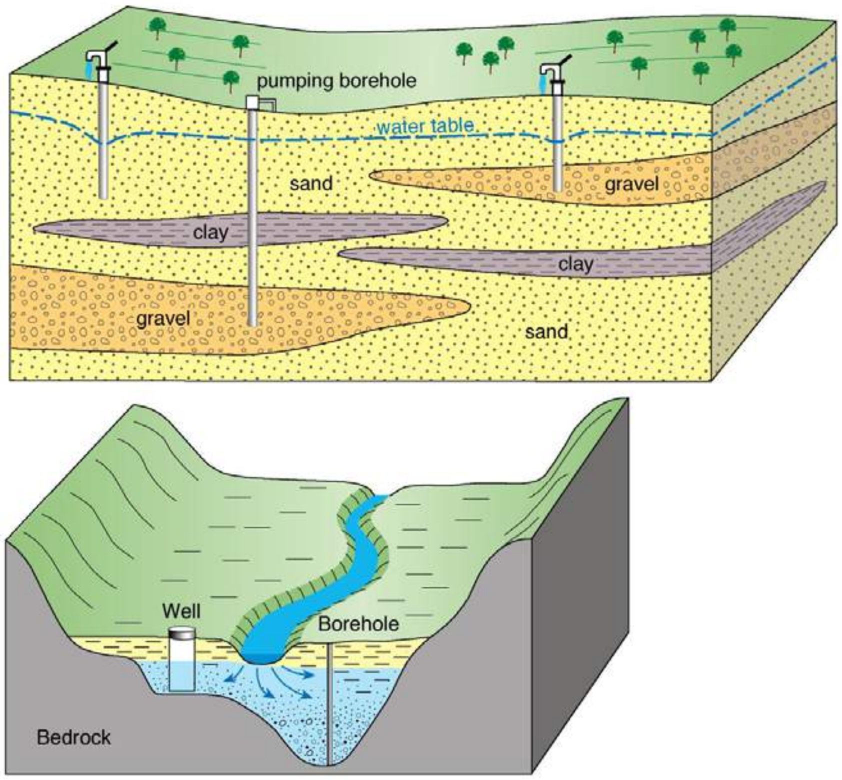


Figure 8 Groundwater occurrence in large unconsolidated sedimentary basins (top) and small unconsolidated valley deposits (bottom).

Small UNSAs are found throughout SSA. On basement, volcanic and consolidated sedimentary rocks, UNSAs can be found in valleys, deposited by present day rivers. Here, groundwater is close to the surface, so pumping lifts are small; also the proximity to the rivers offers a reliable source of recharge. In southern Africa, sand-rivers are important sources of water for domestic and stock watering use. Research into the occurrence of groundwater in sand rivers has been undertaken in Botswana (e.g. Wikner, 1980; Herbert et al., 1997; Davies *et al.*, 1998), Namibia (Jacobson, *et al*., 1995), South Africa (Clanahan & Jonch, 2005) and Zimbabwe (Owen, 1989). These rivers rarely contain surface water, but the thick sediment within the river channel can contain significant groundwater. In northern Nigeria, shallow floodplains known as fadamas, are important sources of groundwater (Carter & Alkali, 1996). These floodplains may be several kilometres wide and can contain 10 m of sands and gravels. They rely on annual flooding for recharge.

Where the structure of UNSAs is complex, geophysical techniques can be used to distinguish sand and gravel from clay. Ground penetrating radar, shallow conductivity and resistivity surveys are all routinely used in groundwater exploration in UNSAs. Ekstrom *et al.* (1996) describe the application of resistivity to find groundwater in river alluvium in SW Zimbabwe; Davies *et al.* (1998) used shallow seismic refraction to investigate sand rivers in NE Botswana and MacDonald *et al.* (2000) describe the use of ground conductivity and ground penetrating radar for locating groundwater in alluvium and blown sands. Remote sensing techniques such as satellite imagery and aerial photography can also be used to provide information on the distribution of sedimentary systems.

UNSAs are easy to dig and drill, so exploration is rapid and inexpensive. Where groundwater is shallow, simple hand drilling is often effective. Where boreholes have to be deeper, drilling can be more problematic. Groundwater quality problems can occur in UNSAs due to natural geochemistry and contamination. Problems can arise where groundwater is developed from such sediments with little regard to the water chemistry.   High arsenic concentrations in groundwater within Bangladesh and India were undetected until the local population developed symptoms of arsenic poisoning (Kinniburgh *et al.*, 2003).

Discussion: using appropriate groundwater knowledge

The premise of this paper is that knowledge of groundwater resources and hydrogeological expertise is fundamental to successful and sustainable rural water supplies. The technical capacity required to develop groundwater resources differs with the hydrogeology: in some environments little expertise is required, while in others considerable research and money is required to develop groundwater. In this discussion we highlight four areas where hydrogeological expertise can be focussed to maximise the benefit to rural water supplies. (1) existing knowledge transfer; (2) benchmarking; (3) researching difficult areas; and (4) providing accessible advice to planners and policy makers

Knowledge Transfer

Implementers of rural water supply programmes (those tasked with siting water points, designing boreholes/wells, assessing yield, quality and sustainability) form a varied group with a wide range of skills and disciplines. They may be water engineers, geologists, geophysicists, hydrogeologists or general technicians. Trained and experienced groundwater specialists are rare. Therefore, there is a pressing need for groundwater development skills to be made more widely available within rural water supply projects. This could be achieved in a number of ways:

1. Developing manuals designed specifically for the issues surrounding rural water supply (e.g. MacDonald *et al.*, 2005).
2. Producing groundwater development maps that indicate the availability of groundwater resources, and the techniques required to find and develop groundwater in different areas.
3. Running regular incountry training courses and workshops, where the useful skills can be developed and lessons shared from different projects
4. Creating local, regional and worldwide networks to provide a pyramid of support to the project staff undertaking the work.
5. Investing research into developing new simple but effective techniques for use by project staff on rural water supply.

To be able to transfer knowledge, that knowledge first needs to be available. However, decentralisation and the promotion of demand-responsive approaches to service provision have had significant implications for building knowledge of groundwater in Africa. In particular, local institutions - including local government and NGOs. While this move has many benefits and promises greater sustainability, decentralisation has been to the detriment of national databases, national knowledge and control over borehole drilling and construction standards. As a consequence, knowledge of groundwater resources is not growing or even being maintained in much of SSA. This new reality will need to be embraced and new methods and possibly institutions developed to ensure that data is captured from ongoing projects and transformed to information which can be assimulated as knowledge by those who need it.

Benchmarking

As the provision of rural water supply becomes increasingly decentralised, budget holders (who are often based in district or local government) have little knowledge about the complexities of hydrogeology and groundwater investigations. This makes it difficult for them to judge whether a drilling success rate is justified due to difficult terrain, or whether a project is over specified in easy terrain. Knowledge of local hydrogeology and the business of groundwater development is required to be able to make informed decisions about designing and managing projects.

Simple cost-benefit analysis can help if data are available on drilling costs and success rates ‘with’ and ‘without’ different levels of investigation. As noted in Farr et al. (1982) the use of a particular search technique is only justified if it increases the chances of subsequent boreholes being successful, such that the overall saving in drilling costs (through drilling fewer unsuccessful boreholes) is greater than the cost of the search. In some environments, where groundwater is readily available, expensive methods may not be justified. In other environments, however, seemingly expensive methods or studies may be entirely justified by long term savings in drilling costs.

Therefore, it is fundamental to the success of decentralised programmes that the local governments have sufficient hydrogeological expertise. Hydrogeologists can be of value in a number of ways:

1. Facilitating the acquisition of the knowledge and skills required by the decentralised bodies to manage contractors. This may be through the various methods described in the section on “knowledge transfer” above.

2. Providing authoritative guidelines against which proposals, projects and contractors can be assessed. This “benchmarking” role is increasing in importance and visibility within the development community.

Research in complex areas

Areas where sustainable groundwater sources are hard to find often have the greatest problems with health and poverty. In these areas, women have to walk further to find water and waterborne diseases such as guinea worm are more common. Helping to solve water problems in these difficult areas may have greater impact on reducing poverty in sub-Saharan Africa than drilling many more boreholes in areas where it is relatively easy to find water.

By effectively disseminating techniques to project staff in areas where it is relatively easy to find groundwater, hydrogeological expertise and research budgets can focus on more difficult areas where groundwater occurrence is not well understood and rural water supplies rarely effective. Some issues that demand more research are:

- the age, recharge and sustainability of groundwater supplies in basement areas, particularly during drought; this will become increasingly important with a changing climate;
- the existence of groundwater in areas where groundwater is difficult to find (e.g. poorly weathered crystalline basement and mudstone areas), and developing techniques that can be used by project staff in these areas to find groundwater and develop rural water supplies;
- identify and understanding the constraints on rural water supply caused by natural groundwater contaminants, such as fluoride and arsenic;
- matching more closely technologies for accessing groundwater (wells, boreholes, springs, collector wells) with the hydrogeological environment and socio-economic conditions to maximise yield and sustainability, and minimise costs;
- examine the risks to rural water supply caused by the increase in onsite sanitation.

Informing policy

Many of the current pillars of rural water supply policy stem from a change in thinking about the value of water and a recognition that centralised approaches to service delivery are unsustainable. A key objective of policies is the provision of potable water on a continuous basis: security of supply across seasons and between wet and dry years is essential if health and poverty alleviation benefits are to be met and sustained. Central pillars of modern policy include: treating water as a social and economic good; using demand responsive approaches which allows consumers to guide investment decisions; moving from community participation to community management; embedding rural water supply in larger initiatives which include sanitation and hygiene promotion; decentralizing service delivery; and recognising the broader livelihood benefits of rural water supply rather than concentrating only on public health.

These approaches have many benefits for improving rural water supply in Africa, however, they rely on informed decisions being made on technology choices and approaches. Unfortunately, this is rarely true. As discussed above, capacity rarely exists within projects to advise communities on the most appropriate approach to use in their particular community. Therefore, hydrogeologists have much to offer in influence how policies are translated into workable approaches on the ground. Only with determined interdisciplinary approaches will interventions be effective and sustainable.

Conclusions

Groundwater is central to helping sub-Saharan Africa meet the Millennium Development Goals for water supply. Rocks with poor aquifer properties ($T \sim 1$ m^2/d and $S \sim 0.001$) will generally still support a village borehole with a handpump. The current approaches to rural water supply, in particular demand driven approaches, community participation and poverty focus have many benefits to the overall efficacy and sustainability of water supplies. However the underlying presumption that groundwater is ubiquitous, or can easily be found at each site is dangerous and my lead to many failures.

Crystalline basement occupies 40% of the land area of SSA; 235 million people live in rural areas underlain by crystalline basement rocks. Volcanic rocks occupy 6% of the land area of SSA, and sustain a rural population of 45 million, many of whom live in the drought stricken areas of the Horn of Africa. Consolidated sedimentary rocks occupy 32% of the land area of SSA and sustain a rural population of 110 million. Unconsolidated sediments occupy 22% of the land area of SSA and sustain a rural population of 60 million. They are probably more important than these statistics suggest since they are present in most river valleys throughout Africa.

Hydrogeologists have a key role in helping to meet the Millennium Development Goals, but must learn to work within the existing policy framework which gives social and economic factors a higher priority than groundwater resources. The four main areas of work for hydrogeologists are: 1) communicating techniques and knowledge to those responsible for siting and developing groundwater supplies; 2) benchmarking the expected expertise and quality for different hydrogeological environments; 3) researching complex areas, where little is known about groundwater resources; and 4) providing accessible and appropriate advice to policy makers. The hydrogeological community can help to reduce poverty in sub-Saharan Africa. The most pressing task is to communicate what we know to the people who need to know it.

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