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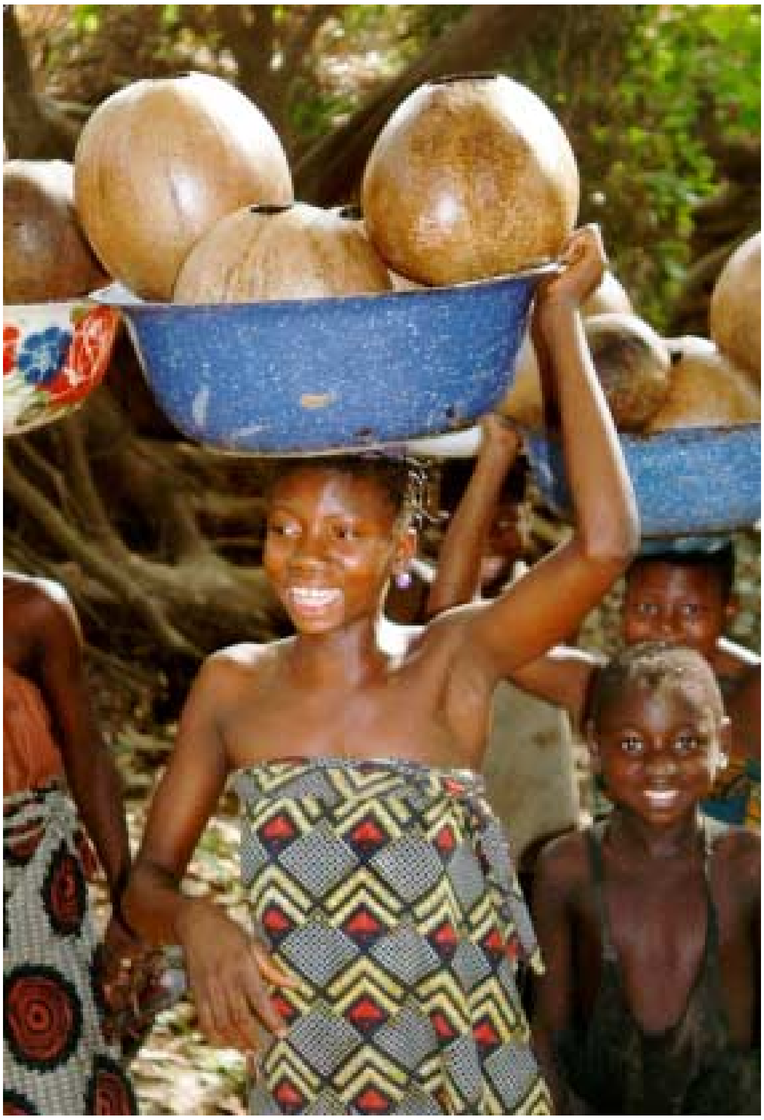
Overseas Geology Series

A brief review of groundwater for rural water supply in sub-Saharan Africa



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A brief review of groundwater for rural water supply in sub-Saharan Africa

A M MacDonald and J Davies

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Front cover illustration: collecting water in Benue State, Nigeria.

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Technical Glossary

Agglomerate	A volcanic rock made of angular pieces of rocks from explosive volcanic eruptions.
Aquifer	A rock formation that contains sufficient groundwater to be useful for water supply.
Basalt	A black igneous rock, normally the major component of lava flows.
Borehole	A cylindrical hole, usually greater than 20 m deep and 100 mm in diameter constructed by a drilling rig to allow groundwater to be abstracted from an aquifer.
Geophysics	Techniques which measure the physical properties of rocks without the expense of drilling boreholes. In favourable circumstances, results from geophysics surveys can be used to infer the presence of groundwater.
Ground conductivity	A simple geophysical technique which measures the bulk electrical conductivity of the ground by inducing and measuring electrical currents with two coils.
Palaeosoil	An ancient soil that is often preserved on being buried by lava.
Porosity	The ratio of void space in rock to the total rock volume – expressed as a percentage. Rocks with high porosity can store greater volumes of groundwater.
Pyroclastic rock	Generic term used for rocks formed by explosive volcanic eruptions.
Permeability	Rate of groundwater flow through a cross-section unit area of aquifer under a unit pressure gradient. Permeability is higher when there are interconnected fractures.
Resistivity	A well-established geophysical technique that gives a depth profile of the electrical resistivity of rocks at a site by passing electric currents though the ground.
Sandstone	A rock that is made from cemented sand grains, usually has a high potential for groundwater supplies.
Shallow well	A large diameter (usually greater than 1 m diameter) hole, dug to less than 20 m depth to access groundwater.
Siltstones and mudstones	Fine-grained rocks made of mud and or very fine-grained particles, which usually have low potential for groundwater supply.
Success rate (borehole drilling)	Imprecise term, normally taken as the number of successful boreholes divided by the total number of boreholes drilled – expressed as a percentage. However, different organisations have different measures for denoting a successful borehole.
Weathered zone	A layer of rock beneath the soil zone which has been altered by physical breakdown or chemical decomposition.
Yield	The volume of water provided by a well or borehole, measured in m^3/d or l/s.

List of Abbreviations

UNSA	Unconsolidated sedimentary aquifer
DFID	Department for International Development
BGS	British Geological Survey
NGO	Non Governmental Organisation
UNEP	United Nations Environment Programme
UNTCD	United Nations Technology Co-operation Department
SSA	Sub-Saharan Africa
ESRI	Environmental Systems Research Institute

Executive Summary

Groundwater has proved the most reliable resource for meeting rural water demand in sub-Saharan Africa. There are four main hydrogeological environments in SSA. Each of these broad categories requires different methods for finding and abstracting groundwater.

1. Crystalline basement occupies 40% of the land area of SSA; 220 million people live in rural areas underlain by crystalline basement rocks. Groundwater is found where the rocks have been significantly weathered or in underlying fracture zones. Borehole and well yields are generally low, but can be sufficient for rural demand.

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. Groundwater is found within palaeosoils and fractures between lava flows. Yields can be high, and springs are important in highland areas.

3. Consolidated sedimentary rocks occupy 32% of the land area of SSA and sustain a rural population of 110 million. Significant groundwater is found within sandstones and limestones, which can be exploited for urban as well as rural supply. Mudstones however, (which account for about 65% of all sedimentary rocks) contain little groundwater, and careful study is required to develop water for community supply.

4. 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. Groundwater is found within sands and gravels.

Groundwater has excellent natural microbiological quality and generally adequate chemical quality for most uses. However problems can arise from the chemistry of groundwater in some circumstances, for example: high sulphate in some parts of the weathered basement and mudstones; hardness in limestone aquifers or sandstones cemented with carbonate material. Minor and trace constituents which make up about 1% of the solute content of natural waters can also sometimes lead to health problems or make the water unacceptable for human and animal consumption. For example: high fluoride in some volcanic aquifers; elevated iron and manganese where conditions are anoxic; high arsenic in some unconsolidated sediments and the lack of iodine in aquifers far from the sea.

Research and experience in some of these hydrogeological environments have enabled standard techniques to be developed for finding and abstracting groundwater. Geophysical techniques in particular have proved useful in many environments for siting wells and boreholes. However, much is still not known about groundwater in Africa. Some issues that demand more attention are:

- the age, recharge and sustainability of groundwater supplies in basement areas, particularly during drought;
- the existence of groundwater in poorly weathered crystalline basement and mudstone areas;
- sustainability of groundwater supplies from upland volcanic aquifers;
- overexploitation of groundwater in sedimentary basins;
- variations in natural quality and contamination of groundwater;
- appropriate (technical, economic and social) choice of water technology.

Co-ordinated groundwater research and data collection has become more difficult in SSA due to decentralisation and demand responsive approaches to the provision of rural water supplies. Information is rarely collected from the many thousands of boreholes drilled each year, with the result that the same costly mistakes are made time and again. However techniques are available to allow local institutions to collect high value data from ongoing drilling for little additional cost. The use of these techniques could allow local institutions to assess the nature of groundwater resources in their areas and, with proper documentation and networking, increase the knowledge base of groundwater in Africa. Budgets for groundwater research in Africa could then be targeted to issues that cannot be addressed by improved data collection from ongoing drilling. Such a scenario will only occur with the dissemination of simple techniques in groundwater resource assessment to those involved in rural water supply, and when the benefits of such assessments are seen within individual water projects.

1. INTRODUCTION

Groundwater is well suited to rural water supply in sub-Saharan Africa (SSA). The characteristics of groundwater differ in a number of ways from surface water. Since groundwater responds slowly to changes in rainfall, the impacts of droughts are often buffered (Calow *et al.,* 1997). In areas with a long dry season, groundwater is still available when sources such as rivers and streams have run dry. Groundwater is generally microbiologically uncontaminated and to a certain extent naturally protected from pollution. The resource is relatively cheap to develop, since large surface reservoirs are not required and water sources can usually be developed close to the demand (UNEP, 1996). These characteristics make groundwater well suited to the more demand responsive and participatory approaches that are being introduced into most rural water and sanitation programmes.

Where groundwater is readily available, wells and boreholes can be sited using mainly social criteria qualified by simple hydrogeological considerations. However, problems arise in areas where communities are underlain by difficult geological conditions, where groundwater resources are limited and hard to find. In these areas, simple 'rule of thumb' criteria are not sufficient to site sustainable wells and boreholes, and following an exclusively social approach, with minimal technical input, can lead to many dry wells and boreholes.

To have successful and sustainable rural water supply projects it is essential to understand the hydrogeological environment of the project area. Different methods are required for developing groundwater in different areas. For example, in some rock types dug wells are appropriate; in others, only boreholes will be sustainable. The hydrogeological conditions determine the technical capacity required for both finding and abstracting groundwater.

2. GROUNDWATER IN AFRICA

The availability of groundwater depends primarily on the geology. Groundwater is stored within pore spaces and fractures in rocks. Where the pores or fractures are interconnected, groundwater can flow easily and the rocks are said to be permeable. Fractured or porous rocks (such as sandstones and limestones) therefore have a high potential for groundwater development. The availability of groundwater also depends to a certain extent on the volume and intensity of rainfall. However, research suggests that recharge to groundwater can occur even in arid parts of Africa. Since the volume of groundwater abstracted for rural domestic water supply is generally low, recharge to the aquifers is less important than the geology in determining initial yields, but very important in determining sustainability.

The hydrogeology of SSA has been classified according to geological environment (see Figure 1). The classifications have been chosen and simplified in this way to reflect the different manner in which groundwater occurs, and the different techniques required for siting wells and boreholes. The four provinces are: Precambrian "basement" rocks; volcanic rocks; unconsolidated sediments; and consolidated sedimentary rocks. In basement rocks, groundwater generally occurs in the top few metres of weathered rock; in volcanic rocks, groundwater occurs in highly permeable zones between lava flows. Consolidated sediments contain groundwater in the pore spaces of sandstones or fractures and weathered zones within limestones. Unconsolidated sediments occur throughout Africa in valleys in addition to the large areas shown in Figure 1; groundwater is found within sands and gravels. Each province is discussed in more detail in the next section.

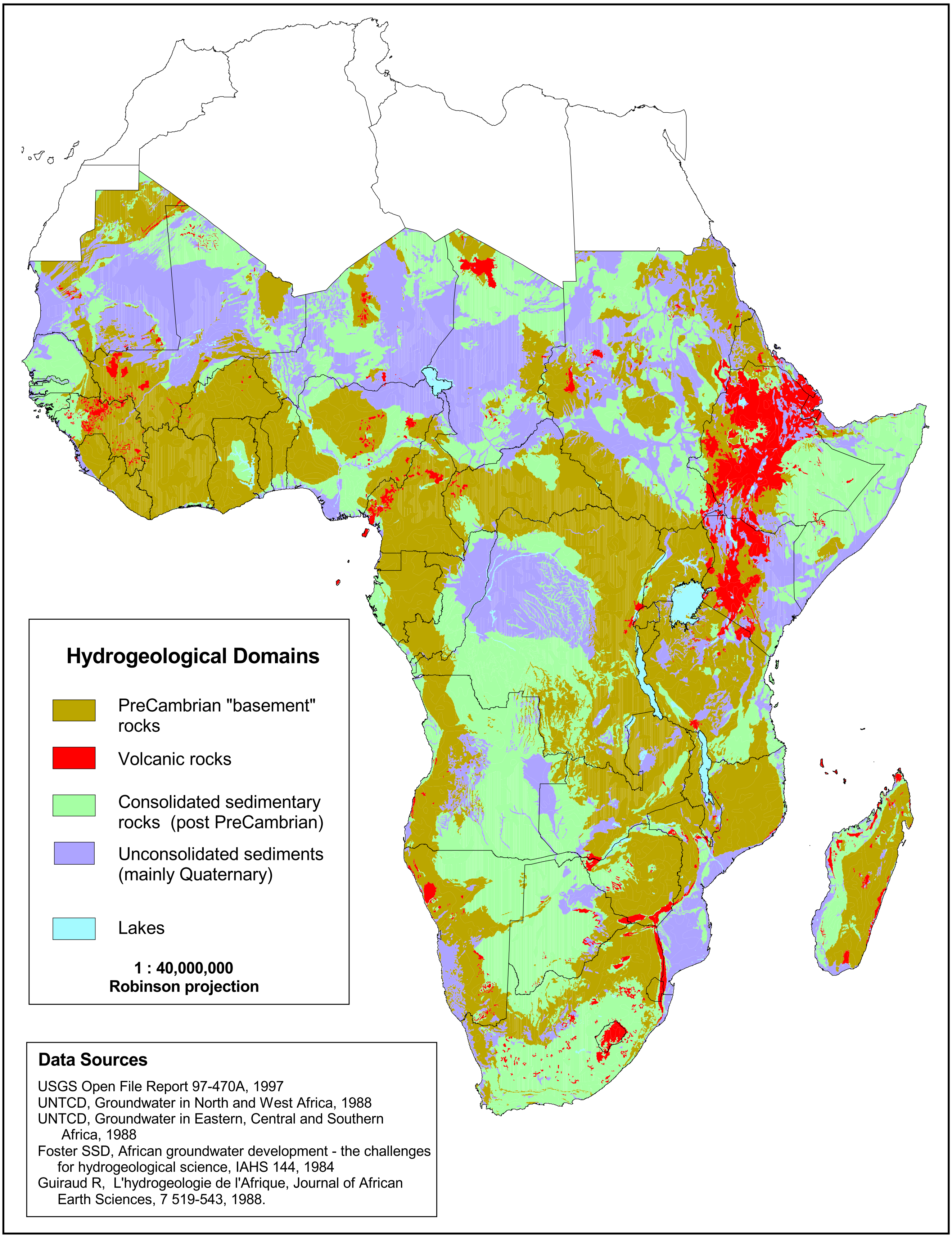

Figure 1 The hydrogeological domains of sub-Saharan Africa.

Groundwater has excellent natural microbiological quality and generally adequate chemical quality for most uses. Nine major chemical constituents (Na, Ca, Mg, K HCO_3, Cl, SO_4, NO_3 and Si) make up 99% of the solute content of natural groundwaters. The proportion of these constituents reflects the geology and history of the groundwater (Foster *et al.*, 2000). Minor and trace constituents make up the remaining 1% of the total, and their presence (or absence) can occasionally give rise to health problems or make them unacceptable for human or animal use (Edmunds and Smedley, 1996). Health problems are associated with elevated concentrations of arsenic and fluoride, or the deficiency of iodine. In some places the total salt content of the water is high and makes the water unsuitable for drinking. Quality problems particularly associated with the different hydrogeological environments are discussed in the individual sections

Figure 1 shows the geographical distribution of the four hydrogeological environments of SSA. Basement rocks form the largest hydrogeological province, occupying 40% of the 23.6 million square kilometres of SSA (Figure 2); volcanic rocks are the smallest hydrogeological province with only 6% of the land area.

The relative importance of the hydrogeological provinces 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 prohibitively expensive and difficult to manage. Using data from the World Bank (2000) and ESRI (1996), an approximation was made of the distribution of rural population throughout SSA. Of these a large proportion of rural populations that live upon the major rock groups: up to 220 million people on the Precambrian basement; 45 million on volcanic rocks; 110 million on consolidated sedimentary rocks and 60 million on unconsolidated sediments (Figure 2), will be dependent upon water supplies obtained from these formations.

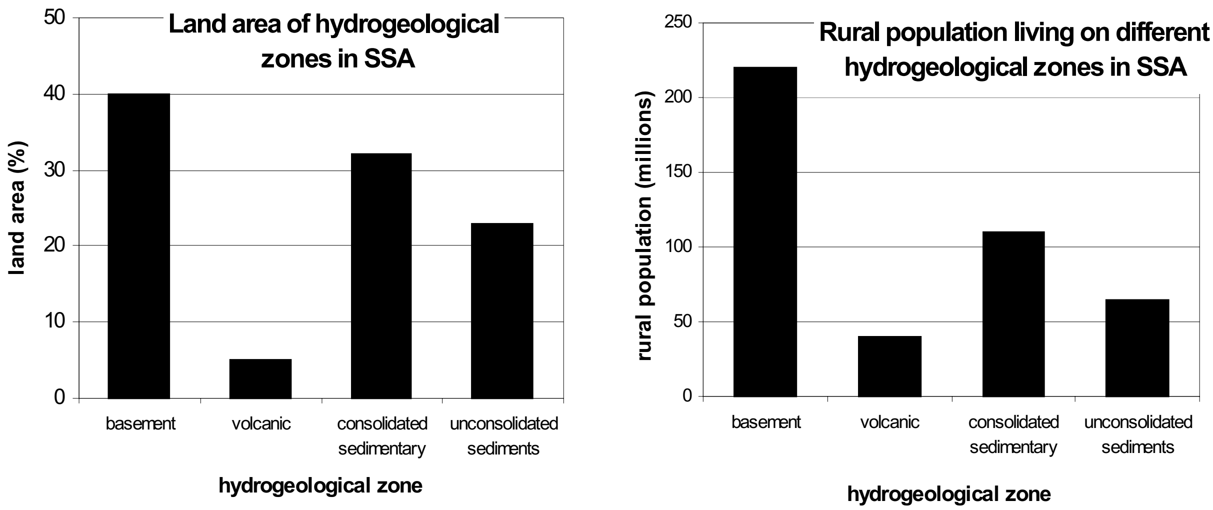

Figure 2 The land area and rural population of the different hydrogeological zones of SSA.

3. PRECAMBRIAN BASEMENT

Precambrian basement rocks occupy 40% of the land area of SSA. They comprise crystalline and metamorphic rocks over 550 million years old[1]. Unweathered basement rock contains negligible groundwater. Significant aquifers however, develop within the weathered overburden and fractured bedrock Four factors contribute to the weathering of basement rocks (Jones, 1985; Acworth, 1987; Wright and Burgess, 1992):

- presence and stress components of fractures;
- geomorphology of the terrain;
- temperature and occurrence of groundwater;
- mineral content of the basement rock.

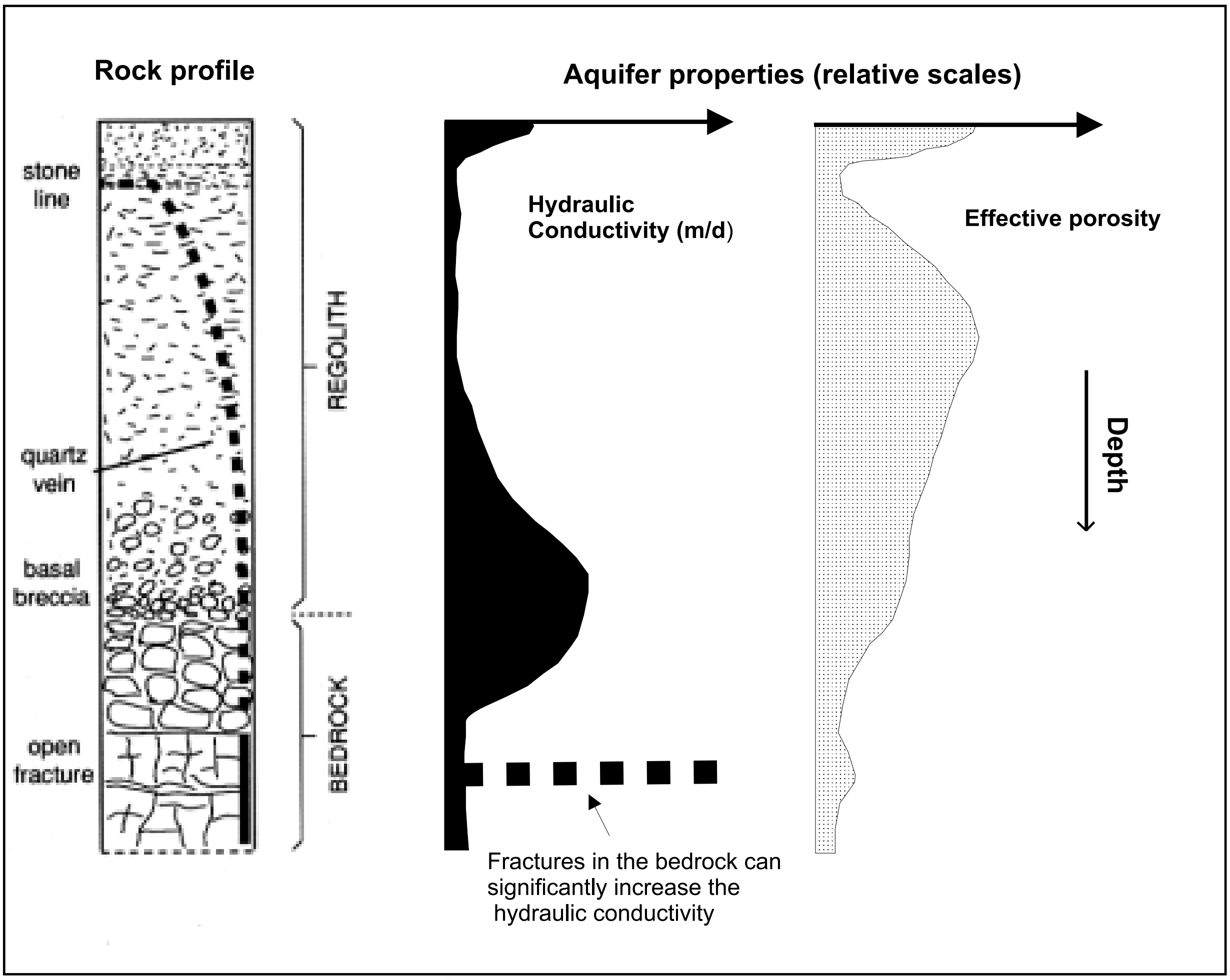

Figure 3 The variation of permeability and porosity with depth in basement aquifers (based on Chilton and Foster, 1995).

[1] To construct the map, unmetamorphosed sedimentary rocks of Precambrian age were also included with basement rocks. There are few of these rocks in Africa, and their hydrogeological properties are between basement and consolidated sedimentary rocks.

The resulting weathered zone, can vary in thickness from just a few metres in arid areas to over 90 m in the humid tropics. Permeability and porosity in the weathered zone are not constant but vary throughout the profile (Figure 3). Porosity generally decreases with depth; permeability however, has a more complicated relationship, depending on the extent of fracturing and the clay content (Chilton and 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 up to one or even five litre/s. Sands and gravels eroded from basement rocks and deposited in valleys can also be important sources of groundwater, these are discussed in Section 6. 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. The deeper the weathering, the more sustainable the groundwater. However, due to the complex interactions of the various factors affecting weathering, water-bearing horizons may not be present at all at some locations.

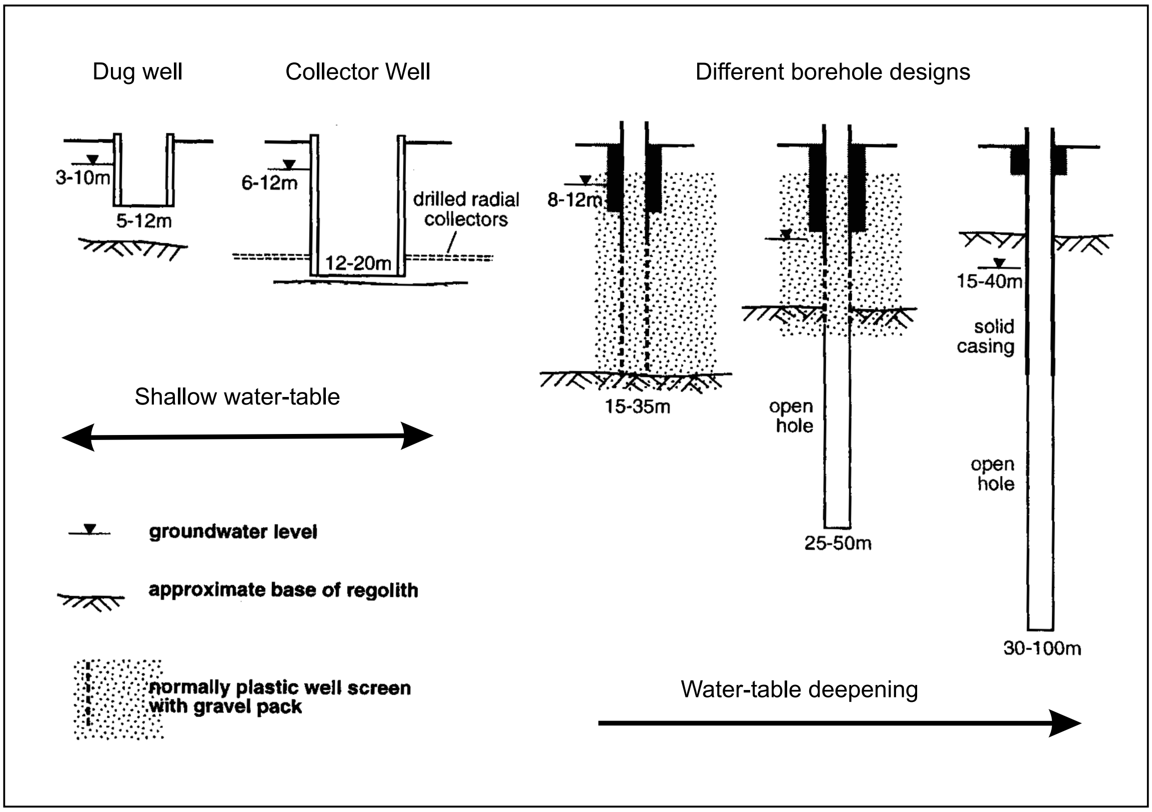

Figure 4 **Different designs of wells and boreholes for basement, depending on the hydrogeological conditions (from Foster *et al.,* 2000).**

Various techniques have been developed to try to locate favourable sites for the exploitation of groundwater resources within basement rocks. These include remote sensing (Lillesand and Kiefer, 1994) geophysical methods, and geomorphological studies (McNeill, 1991, Wright and Burgess, 1992; Taylor and Howard, 2000). Geophysical surveys using combined resistivity[2] and ground conductivity[3] surveys have often been found useful in siting wells and boreholes. These can often be successfully interpreted with simple rules of thumb.

Different methods have been used to abstract groundwater from basement aquifers. The most common are boreholes and dug wells (see Figure 4). Collector wells have also been used with much success, although their distribution is at present fairly limited (British Geological Survey, 1989; Ball and Herbert, 1992). Each of these abstraction methods has their own advantages and limitations. Boreholes are quick to drill, can penetrate hard rock easily and can be drilled to depths of 100 m. However, drilling is expensive and can limit the participation of communities. Boreholes are necessary in basement areas for abstracting water from deep fracture zones. Dug wells are best used to exploit aquifers within thick, near surface zones of weathering. The main advantage of dug wells is that they can store a large amount of readily accessible water. Wells also have a large internal surface area, which maximises seepage from the aquifer. Little specialist equipment is required for their construction (Watt and Wood, 1979) and once completed, a pump is not essential to abstract water. However, it is difficult to construct hand dug wells in hard rock; also, since they are shallow, they can sometimes fail at the end of the dry season when groundwater levels fall.

Collector wells have been designed to maximise the yield from the base of the weathered zone (British Geological Survey, 1989). A collector well consists of a large diameter central shaft with horizontal radials penetrating the surrounding aquifer. These radials are positioned to penetrate the high permeability zone at the base of the weathered profile. The resulting well has a large storage, but

Box 1 Summary of main characteristics of crystalline basement aquifers.

1. Crystalline basement covers 40% of the landmass of SSA and supports 220 million rural inhabitants.
2. The occurrence of groundwater depends on the existence of a thick weathered zone (the upper 10 - 20 m) or deeper fracture zones. Much of the weathered basement has been weathered or fractured.
3. Groundwater in the shallow weathered zone can be exploited with dug wells and collector wells; groundwater in the deeper fracture zones can only be exploited using boreholes.
4. Good sites for wells and boreholes can be found using ground conductivity (EM34) and resistivity
5. Groundwater is generally of good quality (occasional elevated sulphate, iron or manganese), but is vulnerable to contamination.

Issues requiring more research:

- sustainability of groundwater from basement aquifers, particularly during extended drought periods;
- the vulnerability of shallow aquifers to pollution, particularly with the rapid increase of onsite sanitation and intensification of agriculture in some areas;
- the relative performance and operational costs of boreholes, wells, family wells and collector wells;
- the frequency of occurrence of groundwater in deep fractures where the weathered zone is thin or absent.

[2] 'Resistivity' is a well established geophysical technique which gives a depth profile of the electrical resistivity of the rocks by passing electrical currents through the ground at various electrode spacings.

[3] 'Ground conductivity' is a simple geophysical technique which measures the bulk electrical conductivity of the ground by inducing and measuring electrical currents in the ground with two coils. Equipment such as EM34 and EM31 are often used.

also a high seepage rate and therefore provides a higher sustainable yield (Macdonald *et al*., 1995). However, collector wells are more expensive to construct than hand dug wells and require a specialist horizontal drilling rig. Other, less expensive methods of constructing radials would make collector wells more easily replicable.

Groundwater in basement aquifers is generally young and has low solute concentrations. However, high sulphate can occur due to the weathering of the basement rocks. Elevated iron and manganese can also occur where conditions are reducing (i.e. oxygen has been removed from the water). These are not damaging to health but can make the water taste unpleasant, or become coloured. Since groundwater in crystalline basement tends to be shallow, it is vulnerable to contamination. Pit latrines and irrigation returns can increase the nitrate concentrations in the groundwater. Where pit latrines are close to shallow wells, microbiological contamination can sometimes occur.

4. VOLCANIC ROCKS

Volcanic rocks occupy only 6% of the land area of SSA and are mostly confined to east Africa. However, despite their small size, they are 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 Ethiopia. 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) and Vernier (1993). Volcanic rocks are important aquifers in India and have been extensively studied there (Kulkarni *et al,*. 2000).

Most of the volcanic rocks in SSA were formed in three phases of activity during Cenozoic times, associated with the opening of the East African rift valley. 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 (ancient fossilised soils). 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 5 shows aspects of groundwater flow in highland volcanic areas.

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

- thick paleosoils 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.

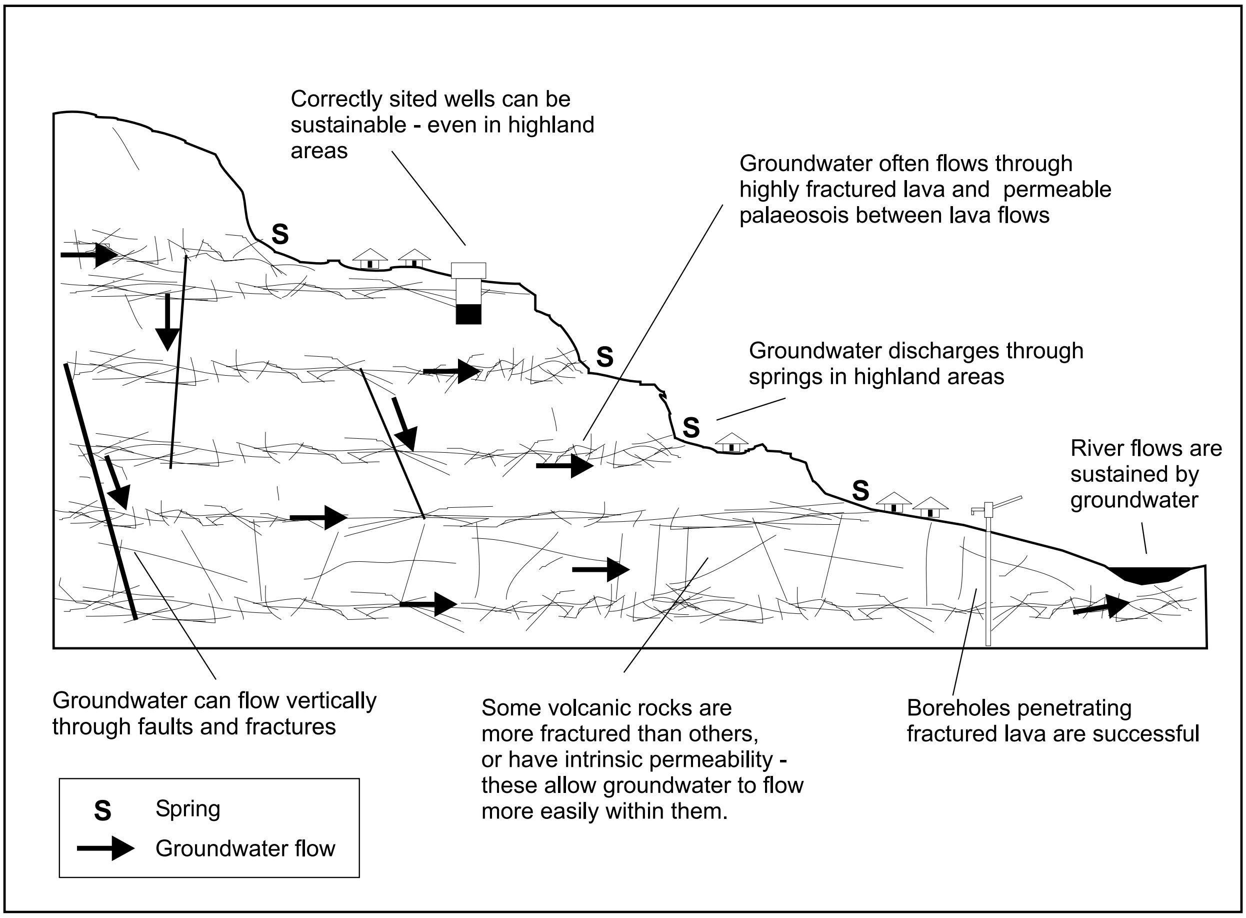

Figure 5 Cross section of groundwater flow in highland volcanic areas.

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. Analysis of 128 springs issuing from fractured lava flows in the Ethiopian Highlands indicated spring yields of 1 – 570 l/s (Aberra 1990). Springs, especially at higher altitudes can be more susceptible to drought failure than boreholes (Calow *et al.,* 2000).

The quality of groundwater can sometimes 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. Ashley and Burley (1995) found many health problems associated with high fluoride concentrations in volcanic rocks in the Ethiopia Rift valley, and high-fluoride groundwaters are common in the rift valley regions of Kenya and Tanzania.

Box 2 Summary of main characteristics of volcanic rocks.

1. Volcanic rocks cover only 6% of the landmass of SSA, but underlie drought prone and poverty stricken areas in East Africa; 45 million rural people live on these rocks.
2. Groundwater occurs in zones of fracturing between individual lava flows and within volcanic rocks which have been themselves highly fractured or are porous.
3. Yields can be highly variable, but are on average sufficient for rural domestic supply and small scale irrigation.
4. Groundwater in mountainous areas can be exploited though springs, wells and boreholes. Where the rocks are hard and the fracture zones deep only boreholes are possible.
5. Geophysical methods are not routinely used to site boreholes and wells, but may be valuable in certain circumstances.
6. Groundwater quality can sometimes be poor due to elevated fluoride concentration.

Issues requiring more research:

- the sustainable groundwater resources available in small upland aquifers, particularly in mountain areas of Ethiopia;
- it appears that the groundwater potential is highly dependant on the geology, however little geological mapping has been undertaken in volcanic areas;
- the relative performance and sustainability (particularly during drought) of springs, boreholes and wells;
- the difference in fracturing (and therefore groundwater potential) in different types of volcanic rocks;
- groundwater quality remains a concern in volcanic rocks and should be tested as part of all rural water supply programmes.

Geophysical techniques have sometimes been used in volcanic terrain to site boreholes, but few guidelines have been developed. Remote sensing techniques could be valuable for detecting different geological units and identifying fracture zones. Boundaries between volcanic rocks and sedimentary rocks could be easily identified with magnetic methods. Ground conductivity methods (e.g. using EM34 equipment) can be used to locate vertical fracture zones. Resistivity methods have been used to locate vertical and horizontal fracture zones in East Africa. 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.

5. CONSOLIDATED SEDIMENTARY ROCKS

Consolidated sedimentary rocks occupy 32% of the land area of SSA (Figure 1). Approximately 110 million people live in rural areas underlain by these rocks. Sedimentary basins can store considerable volumes of groundwater. In arid regions, much of the groundwater can be non-renewable, having been recharged when the area received considerably more rainfall. The presence of groundwater in consolidated sedimentary rocks is not guaranteed, but is dependent on their nature.

Sedimentary rocks comprise sandstone, limestone, siltstone and mudstone: rocks formed from fragments of pre-existing material. They tend to be deposited in large basins which can contain several kilometres of sediment. Examples are the Karroo, and Kalahari sediments of Southern Africa (Truswell, 1970), sediments within the Somali basin of East Africa and the Benue Trough of West Africa (Selley, 1997).

In general, sediments become consolidated with age: circulating fluids redistribute minerals to form cement, which binds the sediment together. For the purposes of the simplified map shown in Figure 1, sedimentary rocks deposited before Quaternary times are assumed to be mainly consolidated; sedimentary rocks of Cambrian and Precambrian age are included with the Precambrian basement since they are generally well cemented or recrystallised. The groundwater potential of sedimentary rocks is dependent on both the type of sediment, and the nature of the cement binding the sediments together. Sandstones have the highest potential for groundwater, since they have large pore spaces, which can contain significant groundwater. High yields can also be found in fractured and karstic limestone. However, groundwater can be difficult to find in mudstone and siltstone. Figure 6 illustrates how groundwater occurs in consolidated 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 Karro sandstones of southern Africa (Interconsult, 1985)). 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 rock immediately surrounding the community and to a depth of less than 100 m are usually considered.

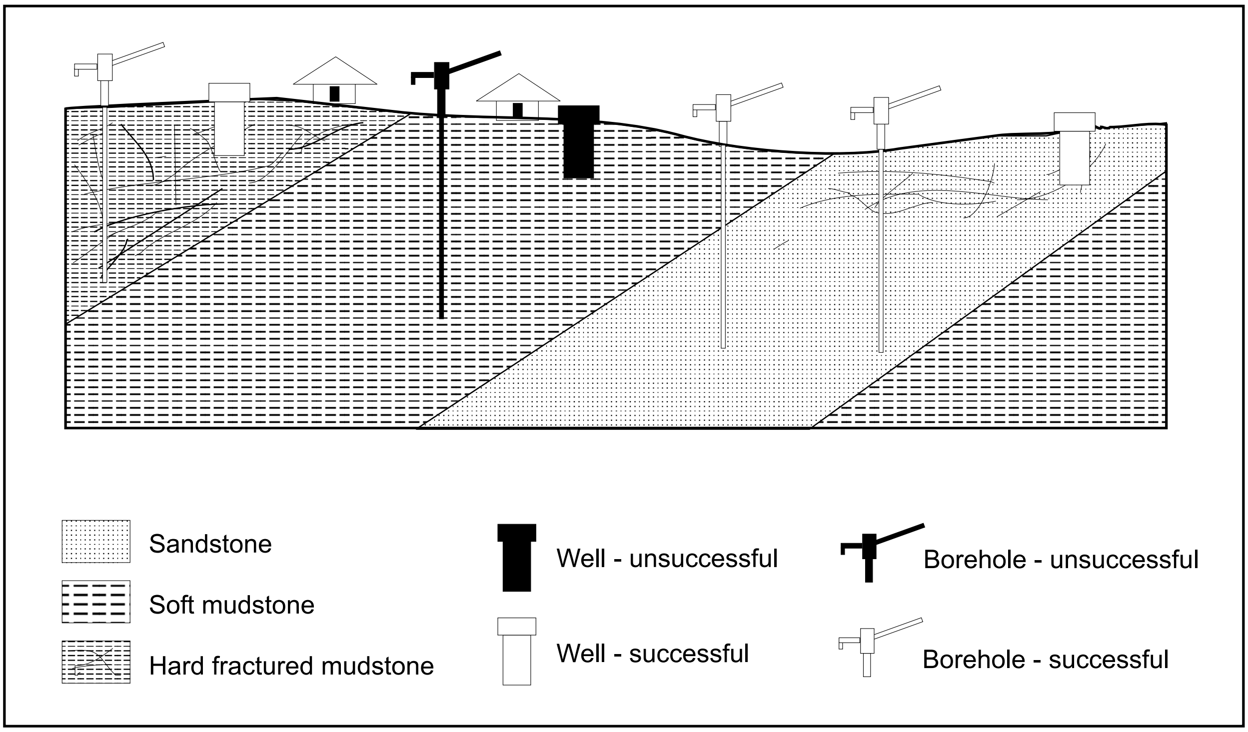

Figure 6 Groundwater occurrence in consolidated sedimentary rocks.

Box 3 Summary of main characteristics of consolidated sedimentary rocks.

1. Consolidated sedimentary rocks cover 32% of the landmass of SSA, 110 million rural people live on these rocks.
2. Consolidated sedimentary rocks comprise sandstone, limestone and mudstone and often form thick extensive sequences.
3. Sandstone often contains large amounts of groundwater, particularly where fractured or friable. Limestone can also contain significant groundwater.
4. Mudstone, which may comprise up to 65% of all sedimentary rocks are poor aquifers, but groundwater can still sometimes be found in harder more fractured mudstone.
5. Where aquifers and groundwater levels are shallow, wells can be used. However where the aquifers are deep, boreholes must be used and need to be carefully constructed and gravel packed to avoid ingression of sand.
6. Geophysical methods can easily distinguish sandstone from mudstone and between hard and soft mudstone. Where sandstone or limestone aquifers are extensive and/or shallow, carefully siting is often not required for domestic water supplies.
7. Groundwater quality is generally good, but can be saline at depth, or have localised elevated sulphate, iron or manganese.

Issues requiring more research:

- recharge and overexploitation of groundwater from large consolidated sandstone basins, e.g. the Karroo;
- the existence and development of groundwater in low permeability consolidated sedimentary rocks, such as mudstone and siltstone.

Although mudstone and siltstone are poor aquifers, groundwater can often be found in these environments with careful exploration. Studies in Nigeria showed that where the mudstone was soft, 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 (Davies and MacDonald, 1999). It is estimated that 65% of all sediments are mudstone (Aplin *et al.,* 1999); therefore, up to 70 million people may live directly on these mudstone areas.

Geophysical techniques can be used to identify good aquifers. Sandstone can easily be distinguished from mudstone using ground conductivity or resistivity methods (Interconsult 1985, Davies and MacDonald, 1999). Similarly, harder mudstones can also be distinguished from soft mudstone. 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. Where aquifers are deep, boreholes are the best method for developing groundwater. However, fine sands can clog borehole screens, so the boreholes need to be carefully constructed and gravel packed. If the aquifers and groundwater levels are shallow, dug wells can be constructed.

Groundwater quality from sandstone aquifers is generally of good quality. Occasionally water can be hard (elevated HCO_3) if the sandstone is cemented with carbonate cements, or have high iron and manganese where the groundwater is deep and anoxic. In limestone aquifers, groundwater can again be hard, but is otherwise of good quality due to the slightly alkaline pH. Where water can be found in mudstones, high sulphate, iron and manganese are sometimes found. Saline water is sometimes found in consolidated sedimentary rocks, particularly at depth, due to the dissolution of thin layers of evaporite, or the concentration of salts due to water evaporation.

6. UNCONSOLIDATED SEDIMENTS

Unconsolidated sediments form some of the most productive aquifers in Africa. They cover approximately 22% of the land surface of SSA (Figure 1). 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, Zaire and Mozambique and in the coastal areas of Nigeria, Somalia, Namibia 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 be unconsolidated. Aquifers within unconsolidated sediments are known as "unconsolidated sedimentary aquifers", or UNSAs for short.

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. For a good review see Mathers and Zalasiewicz (1993). Significant groundwater is found within sands and gravels. Groundwater storage and flow is through the pore spaces of the sediment.

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 7). Manley and Wright (1994) discuss groundwater occurrence within the fine-grained sediments of the Okavango Delta in NW Botswana. In Nigeria studies have been undertaken of groundwater resources of the Chad Basin system (Barber, 1965).

Small UNSAs are found throughout SSA. On basement, volcanic and consolidated sedimentary rocks, UNSAs can be found in valleys, deposited by current 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. Davies *et al.,* 1998) and Zimbabwe. 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 and 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. Remote sensing techniques such as satellite imagery and aerial photography can also be used to provide information on the distribution of sedimentary systems. An extensive review of groundwater in UNSAs was carried out by the BGS in the mid 1990s. Within this review, Peart (1996) discusses the use of geophysical methods and Marsh and Greenbaum (1995) the application of remote sensing to groundwater exploration.

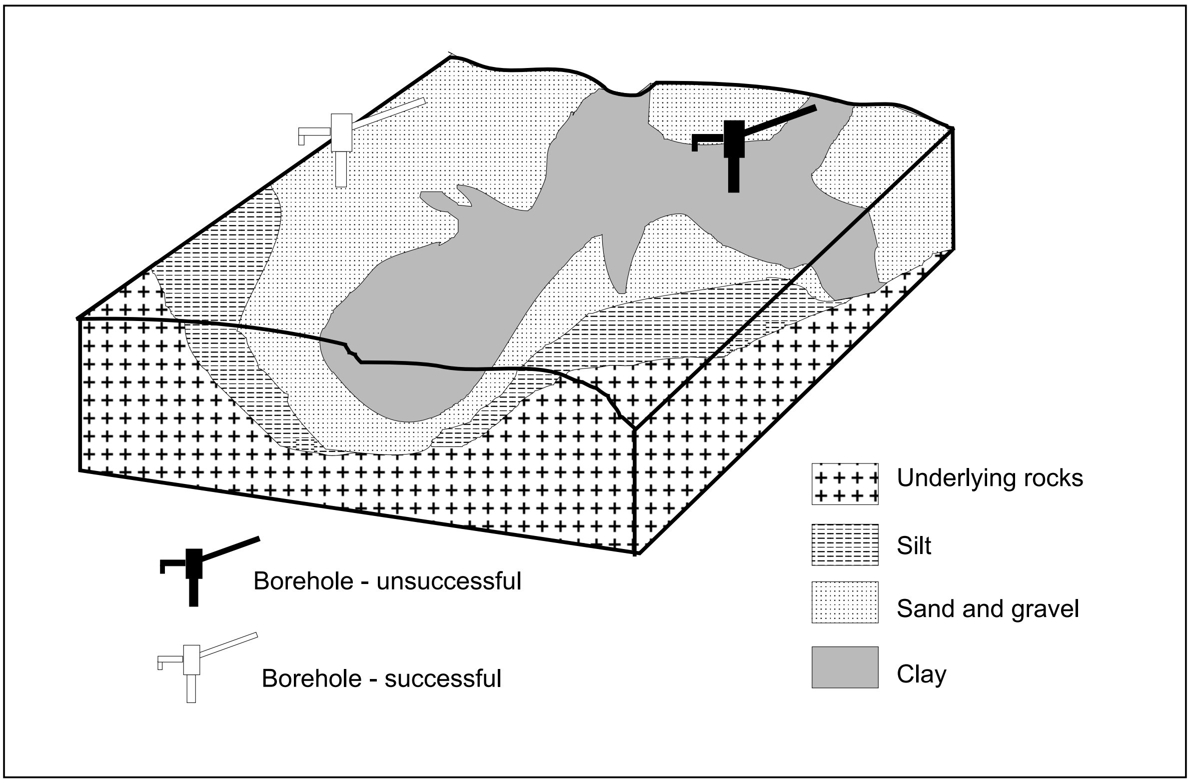

Figure 7 Groundwater occurrence in unconsolidated sedimentary rocks.

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. Deep boreholes can collapse due to the loose sediment, therefore drilling must be carried out carefully. Also, the borehole screens and gravel pack must be constructed to stop sand and silt getting into the borehole and damaging the pump. Digging wells in soft sediment is not difficult. However, special construction techniques must be used to avoid the well collapsing. Herbert *et al.* (1998) developed the application of collector well systems for abstraction of water from sandriver systems. Hand drilling is often possible in UNSAs where the aquifer and groundwater levels are shallow. These can considerably reduce the cost of exploration.

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 (www.bgs.ac.uk/arsenic). Elevated iron concentrations are more widespread than arsenic and, although of little health concern can make the water taste bitter and cause problems with pumps and well screen. Small shallow UNSAs are vulnerable to contamination from surface activity and pit latrines. Since groundwater flow is through pores rather than fractures the risk is generally more of chemical contamination (e.g. elevated nitrate) than microbiological.

Box 4 Summary of main characteristics of UNSAs.

1. Unconsolidated sediments cover 22% of the landmass of SSA, at least 60 million rural people live on these sediments, but many more live close to small UNSAs associated with river valleys.
2. UNSAs comprise a range of material from coarse gravel to silt and clay. Groundwater is found within gravel and sand layers.
3. Yields from thick deposits of sand and gravel can be high, sufficient for domestic supply and agricultural irrigation.
4. Where aquifers and groundwater levels are shallow, wells can be used and boreholes installed using hand drilling. However where the aquifers are deep boreholes must be used and need to be carefully constructed and gravel packed to avoid ingression of sand.
5. Geophysical methods can easily distinguish sand and gravel layers and can be used to indicate the thickness of UNSAs. In large UNSAs, little siting is required.
6. Groundwater quality problems can occur in UNSAs due to natural geochemistry and contamination, such as high iron, arsenic and elevated nitrate.

Issues requiring more research:

- groundwater quality from unconsolidated sediments;
- recharge and overexploitation to large UNSAs (e.g the Chad Basin);
- vulnerability of groundwater supplies to contamination.

7. IMPLICATION FOR GROUNDWATER DEVELOPMENT AND RESEARCH

The basic models for how groundwater occurs in the various hydrogeological environments have been presented above. These models have been developed from research and experience both in Africa and other similar hydrogeological areas worldwide but there are still significant uncertainties and unknowns. A summary of groundwater resources and development in each of these hydrogeological environments is given in Table 1. Indicative costs of developing a groundwater source are given to help reflect the implications for rural water supply of the varying hydrogeological conditions and the current knowledge base of different aquifers. The technical capacity required to develop groundwater also changes with the hydrogeology; in some environments little expertise is required, while in others considerable research and money is required to develop groundwater.

There are many exceptions to the general models and there are areas in each of the hydrogeological environments where groundwater is not easily found. More research and experience is required to help refine the models and shed light on the groundwater potential of different environments. Two of the most widespread problematic areas are poorly weathered basement rocks and sedimentary mudstones. Research into the potential for groundwater in these rocks types is limited, and water projects in these areas are rarely successful.

Figure 8 shows the number of research papers published on different rock types in Africa. Unfortunately, due to the key words available, it is not possible to distinguish consolidated and unconsolidated sediments. Generally, the number of papers published reflects the importance of the aquifer as shown in Figure 2. However, most of these papers refer to areas of successful groundwater supply where groundwater potential is high. The difficult areas within each are rarely studied. This is shown by the example of sedimentary rocks. Although mudstone and shales probably account for

65% of sedimentary rocks, only 10% of the sedimentary rock papers refer to mudstone. The same pattern is found in other hydrogeological environments, where the difficult areas are rarely studied.

Decentralisation and the promotion of demand-responsive approaches to service provision have significant implications for building knowledge of groundwater in Africa. In particular, local institutions - including local government and NGOs - are now tasked with providing technical support for community initiated and managed services. 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. Without this knowledge, local institutions risk making poorly informed decisions.

Addressing the knowledge deficiencies of hydrogeology in SSA has significant cost implications. Appropriate levels of investigations should be used for different environments. Simple cost-benefit analysis can help here, 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.

There are social arguments, as well as the economic one described above, for concentrating financial resources on the difficult areas. If water projects were judged only on the costs of individual boreholes, then water projects should all be concentrated to areas where it is easy to find groundwater. However, the areas where sustainable groundwater sources are hard to find often have the greatest problems with health and poverty. Helping to solve water problems in these areas may have much larger benefits than in areas where it is easier to find water.

However, increasing knowledge of groundwater resources need not be prohibitively expensive. By far the cheapest method is to collect information from ongoing drilling programmes. In 1984, Foster anticipated the cost implications of failing to maximise information from these sources:

> "If inadequate provision is made for the collection, verification, registration and archiving of the hydrogeological data from all these boreholes, a major and unnecessary loss of investment ……. will have occurred, since the cost of obtaining the equivalent data by drilling investigations boreholes will be very high." (Foster, 1984).

In 2000 we are now in the situation where many thousands of boreholes have been drilled in SSA and little knowledge gained from them. As a consequence, the same costly mistakes are made time and again. To gain the same information that could have been routinely collected during ongoing drilling requires significant investment in exploratory drilling and testing. Even now, in the new decentralised regime, techniques and methods are available that could be used to collect useful information from ongoing drilling. The use of these techniques could allow local institutions to assess the nature of groundwater resources in their areas and, with proper documentation and networking, increase the knowledge base of groundwater in Africa. Budgets for groundwater research in Africa could then be targeted to issues that cannot be addressed by improved data collection from ongoing drilling. Such a scenario will only occur with the dissemination of simple techniques in groundwater resource assessment to those involved in rural water supply, and when the benefits of such assessments are seen within individual water projects.

Hydrogeological Domains	Hydrogeological Sub-Domains	Groundwater Potential	Average Groundwater Yields	Groundwater Targets	Cost Effective Survey Methods	Available Technology	Costs* and technical difficulty** of developing groundwater sources	
							Rural Domestic Supply	Small Scale Irrigation
Basement Rocks	Highly weathered and/or fractured basement	Moderate	0.1- 1 l/s	Fractures at the base of the deep weathered zone	Simple geophysics such as ground conductivity and resistivity.	Wells Boreholes Collector wells	£ - ££ # - ##	££ - £££ ## - ###
	Poorly weathered and/or sparsely fractured basement	Low	0.1 l/s	Widely spaced fractures and pockets of deep weathering	Remote sensing with geophysics, such as ground conductivity and magnetic profiling.	Boreholes	£££ ###	Generally not possible
Volcanic Rocks	Mountainous areas	Moderate	0.5 – 5 l/s	Horizontal fracture zones between basalt layers. More fractured basalts	Remote sensing with geophysics, such as ground conductivity and resistivity. In some areas no siting is required.	Boreholes Springs and wells.	£ - ££ # - ###	£ - ££ # - ###
	Plains or plateaux	Moderate	0.5 – 5 l/s	Horizontal fracture zones between basalt layers. More fractured basalts	Remote sensing with geophysics, such as EM34 and resistivity. In some areas no siting is required	Boreholes	££ - £££ # - ###	££ - £££ # - ###
Consolidated sedimentary rocks	Sandstones	Moderate - High	1 – 20 l/s	Porous or fractured sandstone	Often not required. Where needed, remote sensing, resistivity and electrical conductivity.	Boreholes Wells	£ - ££ # - ##	£ - £££ # - ##
	Mudstones	Low	0 – 0.5 l/s	Hard fractured mudstones; igneous intrusions or thin limestone/sandstone layers	Geophysics generally required, electrical conductivity, resistivity and magnetic profiling.	Boreholes	££ - £££ ## - ###	Generally not possible
	Limestones	Moderate	1-10 l/s	Karstic and fractured limestones	Geophysics may be required to locate fracture zones and saline intrusions in coastal zone	Boreholes	££ - £££ ## - ###	£ - £££ # - ##
Unconsolidated sediments	Large basins	Moderate - High	1 – 20 l/s	Sand and gravel layers	Often not required. If alternating with clays then geophysics can be used (resistivity or electrical conductivity).	Boreholes (hand drilling possible)	£ - ££ # - ##	£ - £££ # - ##
	Small dispersed deposits, such as riverside alluvium	Moderate	1 – 20 l/s		Geophysics (EM34 and resistivity) can identify where the deposits are thickest.	Boreholes (hand drilling possible).	£ - ££ # - ##	£ - £££ # - ##

*The approximate costs of siting and constructing one source, including the "hidden" cost of dry sources: £ = < £1000; ££ = £1000 to £10 000 and £££ = > £10 000.

** The technical difficulty of finding and exploiting the groundwater is roughly classified as: # = requires little hydrogeological skill; ## = can apply standard hydrogeological techniques; ### = needs new techniques or innovative hydrogeological interpretation.

Table 1 **Summary of hydrogeological conditions and the cost of developing groundwater sources in sub-Saharan Africa.**

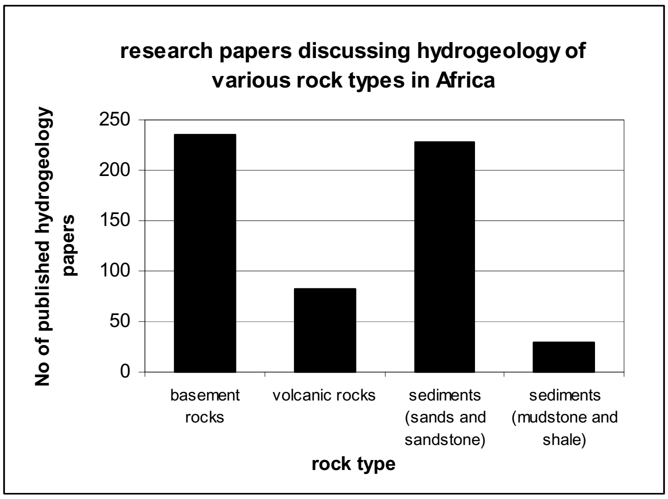

Figure 8 **Research papers published on the hydrogeology of different rock types in Africa. (Note it was not possible to distinguish consolidated sedimentary rocks and UNSAs).**

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(Note: key papers are in bold type)

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