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in the context of Developing and Transition Countries

Groundwater theory

Bern University of Applied Sciences, July 2007

Groundwater theory

This paper has been prepared by using the following documents:

- Developing Groundwater, Alan MacDonald, Jeff Davis, Roger Calow, and John Chilton, BGS, ITDG Publishing, 2005
- Drilling Boreholes for Handpumps, Peter Wurzel, SKAT, 1997
- Technology Options for Rural Water Supply, Karl Erpf, Erich Baumann, Skat, 2005

The author would like to thank for the permission to quote from these documents.

Erich Baumann, Skat
31 July 2007

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1 Groundwater- a precious resource

The importance of groundwater is often overlooked. It is a mysterious resource – well hidden in the ground. However, some 97 per cent of all freshwater found on the Earth is stored underground (excluding frozen water in glaciers).

Table 1: Water Resources

Water source	**Water volume (cubic Km)**	**Total water (percent)**
Oceans	820,700,000	97.24%
Icecaps + Glaciers	18,000,000	2.14%
Groundwater	5,200,000	0.61%
Fresh-water lakes	78,000	0.009%
Inland seas	65,000	0.008%
Soil moisture	41,000	0.005%
Atmosphere	8,000	0.001%
Rivers	1,000	0.0001%
Total Water Volume	**844,000,000**	**100%**

Over 1.5 billion people depend on it for their drinking water, and many more will in the future if the Millennium Development Goals are to be met. The resource is naturally fairly resistant to drought, storing up water in times of plenty, and releasing it in times of need; also the quality of the water tends to be good and is much less vulnerable to contamination than surface water. However, the resource is not invulnerable: with the ability to pump out huge quantities of water, and the advent of particularly persistent contaminants, the resource needs to protected and managed.

The below Table 2 summarises the advantages of groundwater for rural water supply, with some qualifications.

Table 2: Advantages and Limitations of Groundwater

Advantage of Groundwater	Qualifying limitations
Often available close to where it is needed	Considerable effort may be needed to locate suitable sites
Can be developed relatively cheaply and progressively to meet demand with lower capital investment than surface water	Resource constraints in the more difficult areas make cost considerations an important factor in many developing countries
Generally has excellent natural quality and can usually be drunk with no treatment	Chemical pollution (arsenic, etc) is more often observed
Generally has a protective cover provided by the soil and unsaturated zone	The threat of pollution from human activities needs to be taken into account

In this paper some of the basics of groundwater are covered and the main environments in which groundwater occurs are explained. The paper concludes with a description of the main methods how groundwater resources can be accessed and exploited.

2 Groundwater in the hydrological cycle

Groundwater is part of the Earth's natural hydrological cycle (see Figure 2.1). The cycle is driven by the energy of the sun and takes water from the large reservoir of the oceans and transfers it through the atmosphere back to the oceans through various routes.

Precipitation falling on the land surface represents the source of fresh water. Some of it flows along the surface to streams or lakes, some of it is used by plants, some evaporates and returns to the atmosphere, some sinks into the ground. Under the influence of gravity, continues moving downward until it forms a groundwater reservoir. The rocks that store and transmit groundwater are called aquifers. Groundwater is rarely static, but flows underground slowly towards rivers or the sea until it returns to the surface, sometimes several tens of thousands of years later. Rocks that do not easily transport groundwater (such as clays) are known as aquitards. The natural hydrologic cycle has been modified by human activity: rivers are, dammed, water used for irrigation and groundwater abstracted.

The quantity of water entering the groundwater reservoir, known as recharge, depends on the soil type, rainfall amount and rainfall intensity. In some areas of the world, people face serious water shortages because groundwater is used faster than it is naturally replenished.

1. Spring (back-stowing spring)
2. Spring (gravity spring)
3. Spring (artesian spring)
4. Borehole (deep well)
5. Borehole (shallow well)

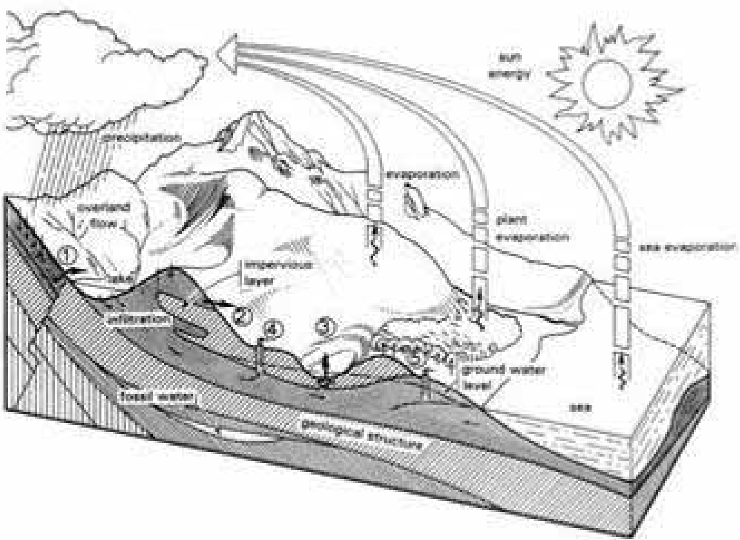


Figure 1: Groundwater in the hydrological Cycle

3 Groundwater: basics and definitions

Since groundwater is stored and transmitted by rocks, the resource can only be understood with some knowledge of geology. The term hydrogeology means “water in rocks”. Some basic geology is given in Box 1, and more detailed discussions are given later.

Box 1: Geology basics: the different types of Rocks

Sedimentary Rocks are formed by deposition of material, usually under water from lakes, rivers and the sea. In unconsolidated granular material, such as sand and gravels, the spaces between the grains are called voids or **pores**. These may become consolidated physically by compaction and chemically by cementation to form typical sedimentary rocks such as **sandstones** (sand and gravel), **limestones** (fossil shells), and **mudstones** (clay). The process of consolidation considerably reduces the pore spaces between grains.

Igneous Rocks are formed from molten geological material rising from great depths and cooling to form crystalline rocks. Igneous rocks that cool below the surface can occur in huge bodies to form rocks like **granite**. Igneous rocks that cool at the land surface are formed from various types of volcanic eruptions and include lavas and ashes. Most ingeous rocks are strongly consolidated and, being crystalline, usually have no pores between grains.

Metamorphic Rocks are formed by deep burial, compaction, melting, alteration or re-crystallisation of igneous or sedimentary rocks during periods of intense geological activity. Metamorphic rocks include **gneisses** and **slates**. They are normally consolidated with few pore spaces in the matrix between the grains.

Groundwater is stored within the pore spaces and fractures in rocks. The proportion of voids in a rock is the porosity and is generally expressed as a percentage. Where the pores are joined up and water can flow easily and the rocks are said to be permeable. The rock characteristics determine how much groundwater can be stored and how productive an aquifer is. Unconsolidated granular sediments, such as sand or gravel contain large amounts of pore spaced between the grains. The water content in these aquifers can exceed 30% of their volume. However, the porosity progressively reduces both with the proportion of finer materials such as silt or clay and with consolidation. In highly consolidated sedimentary rocks, the porosity may reduce to less than 10%. In crystalline rocks, such as igneous- and metamorphic rocks, groundwater is found only in fractures and rarely exceeds 1% of the volume mass. If the rocks are soluble (such as limestone) water washes the fractures out forming fissures and caverns. Even then the total storage is relatively small with unconsolidated aquifers.

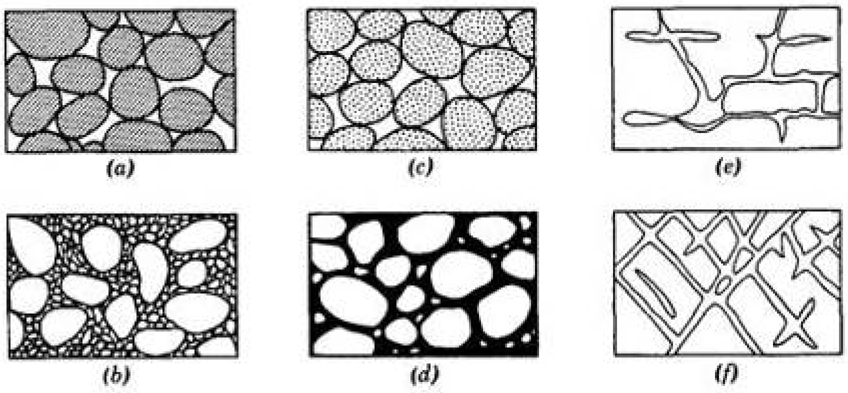


Figure 2: Rock Texture and Porosity for Aquifer

Examples of rock interstices and the relation of rock texture to porosity.

a) Well-sorted sedimentary rock having high porosity,
b) Poorly-sorted sedimentary rock having low porosity,
c) Well-sorted sedimentary deposits consisting of pebbles that are themselves porous so that the deposit as a whole has a very high porosity,
d) Well-sorted sedimentary deposit where porosity has been diminished by the deposition of mineral in the interstices,
e) Rock rendered porous by solution,
f) Rock rendered porous by fracturing.

(after Meinzer)

The deeper the rocks are the more compressed they become, and fractures close up. Some groundwater has been found at a depth of 10km. Generally usable groundwater for rural water supply can be found at less than 50m, to sometimes 100m depth. At this level groundwater can be practically and economically exploited.

When you dig or drill a hole in an aquifer, at a particular level water begins to flow in. The depth of that water is called the **water table**. Above the water table is the **unsaturated zone** where water still occurs but the pores are generally not fully filled with water.

All freshwater found underground must have had a source of **recharge**. This is normally precipitation (rainfall or snowmelt), but can also sometimes be seepage from rivers, lakes or canals. The recharge typically travels vertically downwards through the unsaturated zone to the water table. Once below the water table groundwater can flow horizontally, according to pressure gradients, until water reaches the land surface where it flows from the ground as springs or seepages. The outflow of the aquifer matches the recharge.

Shallow aquifers in recharge areas are generally **unconfined**, that is the water table is within the aquifer and at atmospheric pressure (see Figure 3). Groundwater, however, is often confined by low permeability rocks (an aquitard). Under confined conditions water may be encountered under pressure, and when wells are drilled, water rises above the top of the aquifer, sometimes even above ground surface, to a level called the potentiometric , surface.

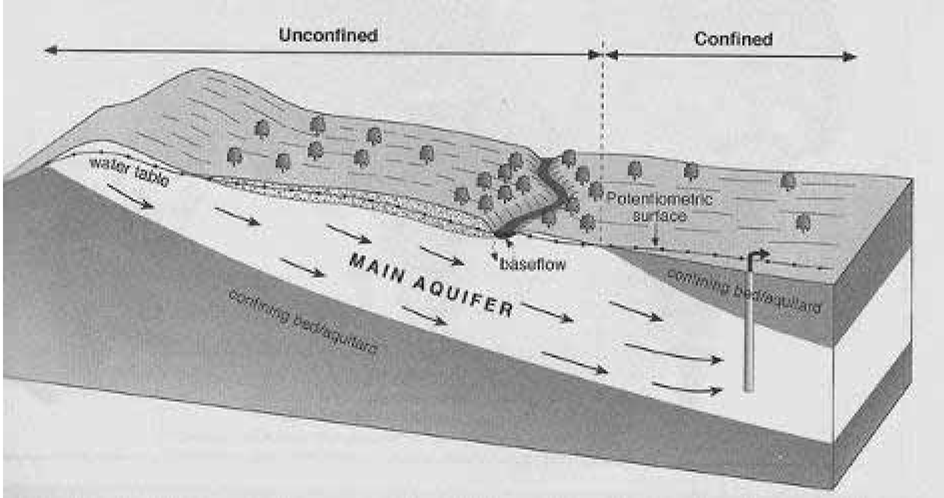


Figure 3: Groundwater System

The ability of an aquifer to transmit groundwater is usually described by its hydraulic properties, hydraulic conductivity, thickness, porosity, transmissivity and storage coefficient. **Porosity** is the total void space within a rock and, therefore, usually defines the total amount of groundwater stored in an aquifer. The **hydraulic conductivity** of a rock (measured in m/day) describes the velocity that groundwater would flow through the rock if there was a pressure gradient of 1 m per metre. **Transmissivity** (measured in m^2/day) describes the ability of an aquifer to transmit volumes of ground- water and is calculated by multiplying the hydraulic conductivity by the aquifer thickness. The **storage coefficient** is a truer measure than porosity of the amount of groundwater stored in an aquifer. It is defined as the amount of groundwater released from storage within the aquifer when the water table falls by 1 m. Pumping tests are the most common method for measuring hydraulic properties, and give estimates of the storage coefficient and transmissivity.

Water stored in aquifers is almost always of excellent natural microbiological quality and generally adequate chemical quality for drinking. Nine major chemical constituents (sodium, calcium, magnesium, potassium, bicarbonate, chloride, sulphate, nitrate and silicon) make up 99% of the mineral content of groundwater. The proportion of these elements reflects the geology and history of the groundwater. Minor or trace elements make up the remaining 1% of the total, and their presence (or absence) can occasionally give rise to health problems and make the water unfit for human or animal use.

Pollution of groundwater is a serious environmental concern. The turnover time of a groundwater reservoir is measured in years if the reservoir is small, and in hundreds of years if it is large, because the ratio of recharge to the volume stored is small. Conversely, a surface water dam has a turnover time of only months (small dam) to tens of years (large dam) because the mean annual run-off into the dam is in the order of the total volume stored. Therefore, if a dam becomes polluted (and action to stop the pollution is taken) it will clear within a comparatively short time.

Not so with a groundwater reservoir. If a groundwater reservoir becomes heavily polluted, in practical terms it remains polluted forever! This danger cannot be over-emphasised. Several of the large groundwater reservoirs of the USA now showing nitrate pollution are forever ruined.

There is an ongoing project to provide a simplified hydrogeological map of the world (the web address is www.iah.org/whymap). Figure 4 shows that the world is divided into three types of environment: (1) major aquifers; (2) areas with important by complex aquifers and (3) areas of low permeability with local minor aquifers.

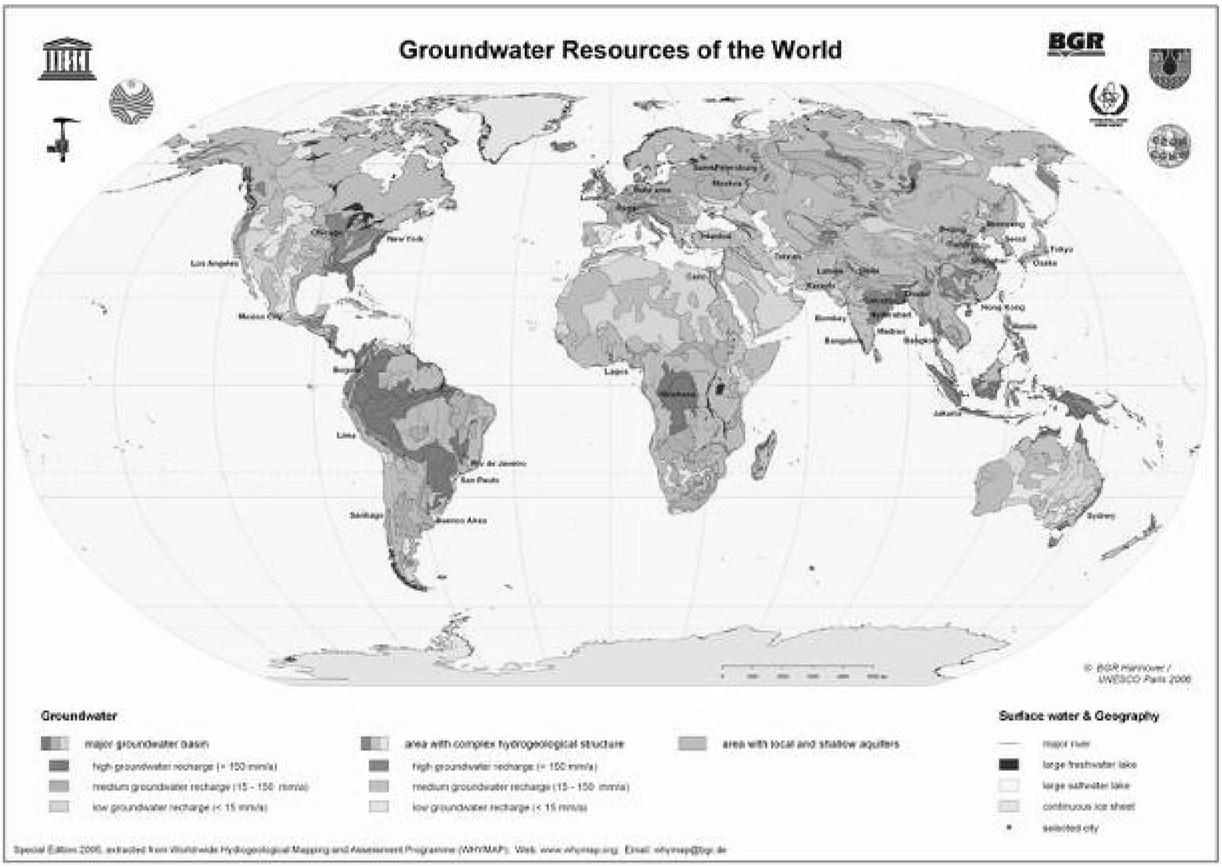
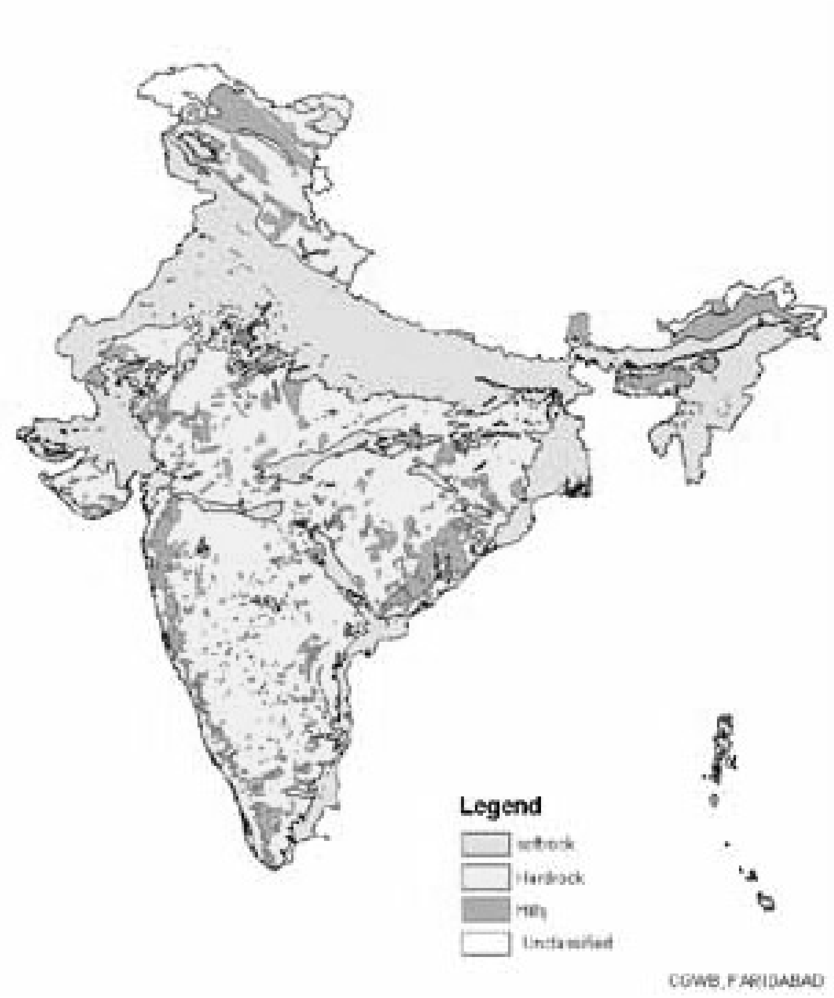


Figure 4 Hydrogeological Map of the World

4 Different hydrogeological environments

4.1 Overview

As discussed above, the availability of groundwater depends primarily on the geology. Although almost all geological materials contain some water and many different rocks can form useful aquifers, it is possible to develop a summary of the most common aquifer types and hydrogeological environments (Annex 1). Such a broad classification inevitably involves some simplifications of the true breadth of subsurface geological variation and complexity: many hundreds of scientific papers have been written on each environment, and some workers have devoted their lives to understanding just one environment. That being said, a brief summary of each environment and subdivision is given below. Figure 5 shows the distribution hydrogeological environments across India.



CGWB, FARIDABAD

Figure 5 Hydrogeological Map of India

Table 3 The groundwater potential of the main hydrogeological environments

	Hydrogeological sub-environment	**Description**	**Groundwater** **Potential average yield (lt/sec)**	**Groundwater targets**
Crystalline basement rocks	Highly weathered and/or fractured basement	Ancient crystalline and metamorphic rocks can be highly fractured. They can also decompose to form a mantle of weathered material tens of metres thick which can be gravelly and fractured	Moderate 0.1-1	Fractures at the base of the deep weathered zone Vertical fracture zones
	Poorly weathered or sparsely fractured basement	Ancient crystalline and metamorphic rocks, where they have not been weathered or fractured. Groundwater may be very difficult to find	Low 0.1-1	Widely spaced fractures and localized pockets of deep weathering
Consolidated sedimentary rocks	Sandstones	Sands and gravels that have been compacted and are often cemented to form consolidated rocks. The degree of consolidation generally varies with age	Moderate ~ High 1-20	Coarse porous or fractured sandstone
	Mudstones and shales	Silt and clay that has been consolidated. More consolidated mudstones can be fractured; softer mudstones tend not to be fractured. Often interbedded with sandstone or limestone layers	Low 0-0.5	Hard fractured mudstones Igneous intrusions or thin limestone/sandstone layers
	Limestones	Remains of shell fragments, aquatic skeletons and reefs that were deposited in seas and cemented to form consolidated rocks. These rocks are slightly soluble in rainwater, therefore fractures can be enlarged to form well developed conduits and fracture systems (karst features)	Moderate- high 1-100	Fractures and solution-enhanced fractures (dry valleys)
	Recent coastal and calcareous island formations	Corallimestones and shell banks found in coastal areas and coral islands. Often loosely cemented with high porosity and permeability	High10-100	Proximity of saline water limits depth of boreholes or galleries. Highpermeability results in water table being only slightly above sea level

Unconsolidated sediments	Major alluvial and coastal basins	Sands, gravels and clay deposited by major rivers, deltas or in shallow seas. These deposits can be kilometres thick. Sands and gravels have both high porosity and permeability	High 1-40	Sand and gravellayers
	Small dispersed deposits, such as river valley alluvium and coastal dunes deposits	Alluvium is found near many modern-day rivers. Very mixed and can comprise cobbles, gravels, sands, silts clays and mixtures. Coastal deposits are usually sandy due to the high energy environment of deposition	Moderate 1-20	Thicker, well-sorted sandy/gravel deposits Coastal aquifers need to be managed to control saline intrusion
	Loess	Windblown deposits comprising fine sand and silt. Generally has low permeability and is only several metres thick -but can be extensive and thick in some areas (e.g. eastern and central Asia)	Low- Moderate 0.1-1	Areas where the loess is thick and saturated, or drains down to a more permeable receiving bed
	Valley deposits in mountain areas	In mountainous areas valley sides and bottoms can be filled with poorly sorted rock fragments, sands gravels and cobbles. Where the mountains are (or have been) volcanic, they can also contain ashes and volcanic debris, ashes and lava flows	Moderate-High 1-10	Stable areas of sand and gravel; river-reworked volcanic rocks; blocky lava flows
Volcanic Rocks	Extensive volcanic terrains	Lava flows from volcanoes which can form extensive plateaus, sometimes dissected to form mountainous terrains. Offen volcanic terrains are made up of layers of lava and pyroclastic rocks (volcanic material, commonly ash, which is blown into the atmosphere by explosive volcanic activity). Can form complex multilayered aquifers	Low- High Lavas 0.1-100	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 and pyroclastic rocks 0.5-5	Ashes are generally poorly permeable but have high storage and can drain water into underlying layers

4.2 Crystalline basement rocks

Crystalline Rock - this is a solid, dense rock where groundwater is stored in joints, crevices, and cracks. Crystalline basement rocks are present over large parts of Africa and Asia. They comprise ancient igneous and metamorphic rocks over 550 million years old. Unweathered basement rock contains negligible groundwater, but significant aquifers develop within the weathered over- bedrock (Wright and Burgess 1992).

Because these ancient rocks occupy stable continental shield areas, there has been plenty of opportunity for prolonged periods of weathering, and the zone of weathering tends to be better developed and thicker in tropical regions where such processes are more active. As a result, the weathered zone can be as much as 60 m thick, but more commonly in the range of 20m to 30m. Below this zone the rock becomes progressively less weathered and more consolidated until fresh fractured bedrock is reached (see Fig.6)

Porosity generally decreases with depth; permeability, however, has a more complicated relationship, depending on the extent of fracturing and the clay content see Figure 7). In the soil zone, permeability is usually high but groundwater does not exist throughout the year and dries out soon after the rain ends. Beneath the soil zone, the rock is often highly weathered and clay rich, so 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.

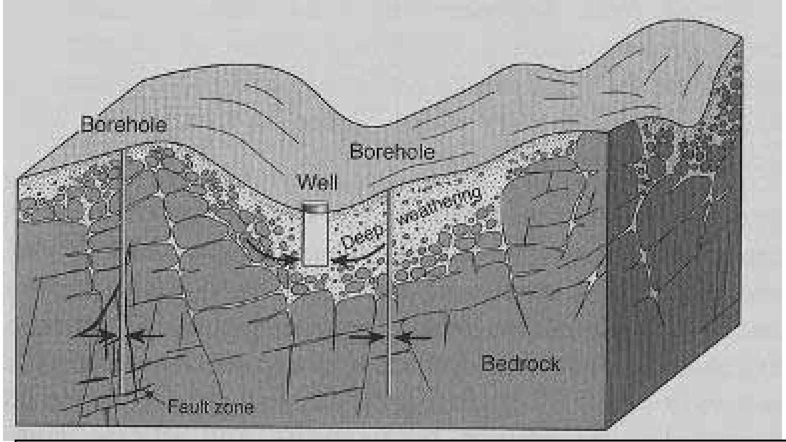
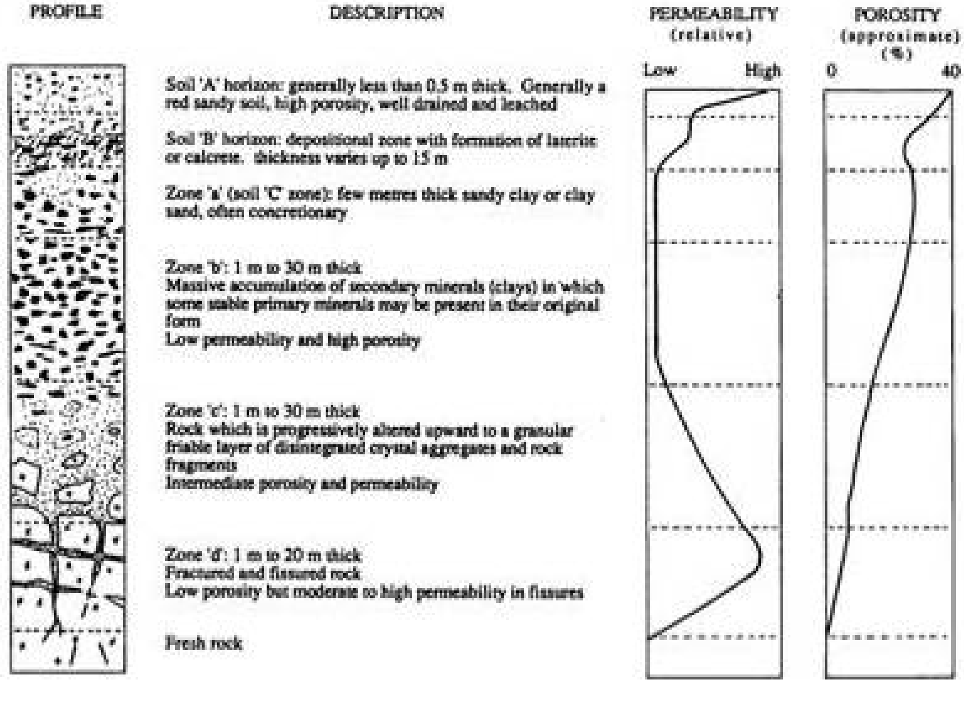


Figure 6 How Groundwater occurs in weathered basemen



Soil 'A' horizon: generally less than 0.5 m thick. Generally a red sandy soil, high porosity, well drained and leached

Soil 'B' horizon: depositional zone with formation of laterite or calcrete. thickness varies up to 15 m

Zone 'a' (soil 'C' zone): few metres thick sandy clay or clay sand, often concretionary

Zone 'b': 1 m to 30 m thick
Massive accumulation of secondary minerals (clays) in which some stable primary minerals may be present in their original form
Low permeability and high porosity

Zone 'c': 1 m to 30 m thick
Rock which is progressively altered upward to a granular friable layer of disintegrated crystal aggregates and rock fragments
Intermediate porosity and permeability

Zone 'd': 1 m to 20 m thick
Fractured and fissured rock
Low porosity but moderate to high permeability in fissures

Fresh rock

Figure 7 Vertical profile through regolith showing variation of weathering, storage capacity and permeability (after Acworth 1987 quoted by Barker et al in Wright and Burgess 1992)

Deeper fractures within the basement rocks are also an important source of groundwater particularly where the weathered zone is thin or absent.

4.3 Consolidated sedimentary aquifers

Sedimentary rocks comprise sandstone, limestone, siltstone and mudstone: rocks formed from fragments of pre-existing material (see Box 2.1).

The most productive aquifers are found within sandstones and limestones. Mudstones are less productive group but unfortunately they make up more than half of all sedimentary rocks. Figure 8 summarizes how groundwater, can occur in sedimentary areas.

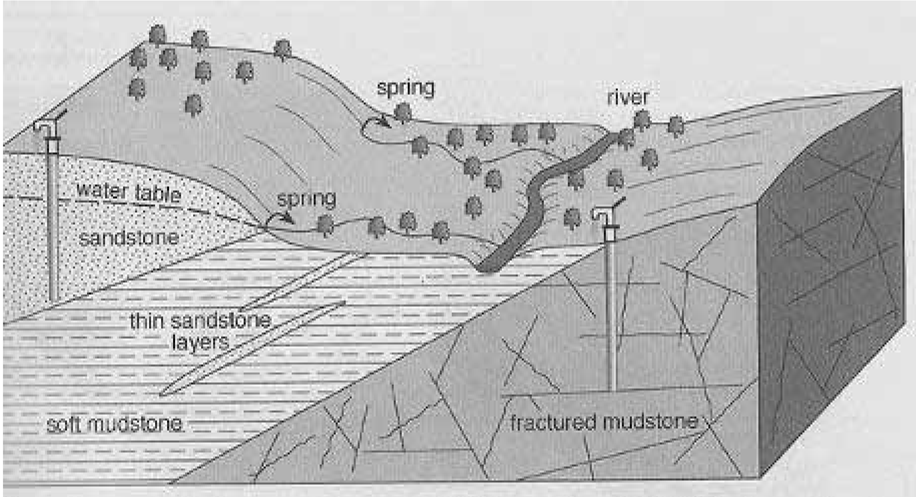


Figure 8 How groundwater occurs in sedimentary areas

Younger **sandstones** usually retain a primary porosity (the pore spaces between sand grains). These rocks contain large resources of groundwater and also allow groundwater to move easily throughout the rocks - they are excellent aquifers. In older, more-cemented formations, the primary porosity is highly variable and, depending on the degree of cementation, may not exist at all. In these cases it is the secondary (fracture) porosity which provides the aquifer permeability and storage and groundwater occurs in a similar way to crystalline basement rocks. Sandstone aquifer are important sources of water in Western Europe and North America, in North Africa (the Nubian sandstone), Southern Africa (the Karroo sandstone), in northern India (Tertiary sandstones), in South America (the Guarani complex) and in Australia (the Great Artesian Basin).

Limestones are widespread and can be prolific aquifers. They are particularly important in China where they cover an area of 2.2 million km^2. Limestones generally have little usable primary porosity, and water is stored and transmitted in fractures. Because they are soluble, many of the fractures are enlarged by dissolution to form conduits centimetres or even metres across (see Figure 9).

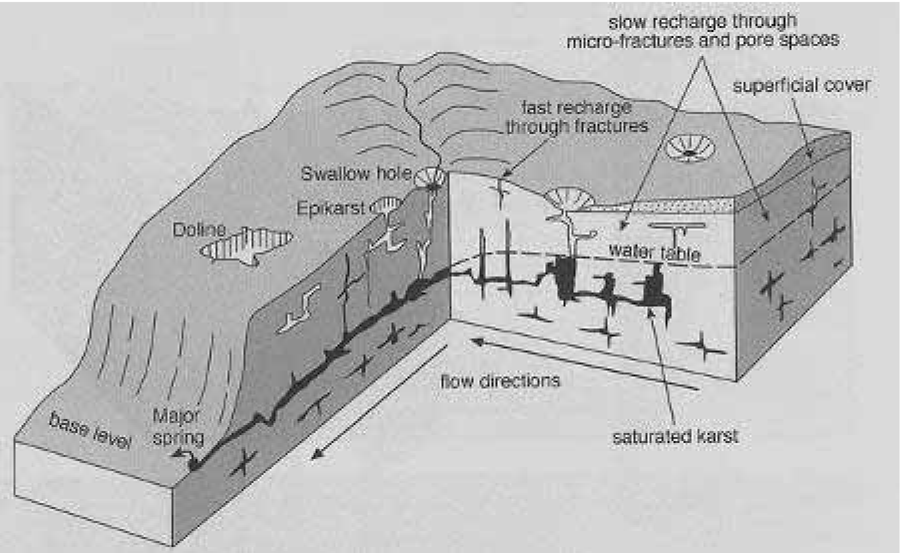
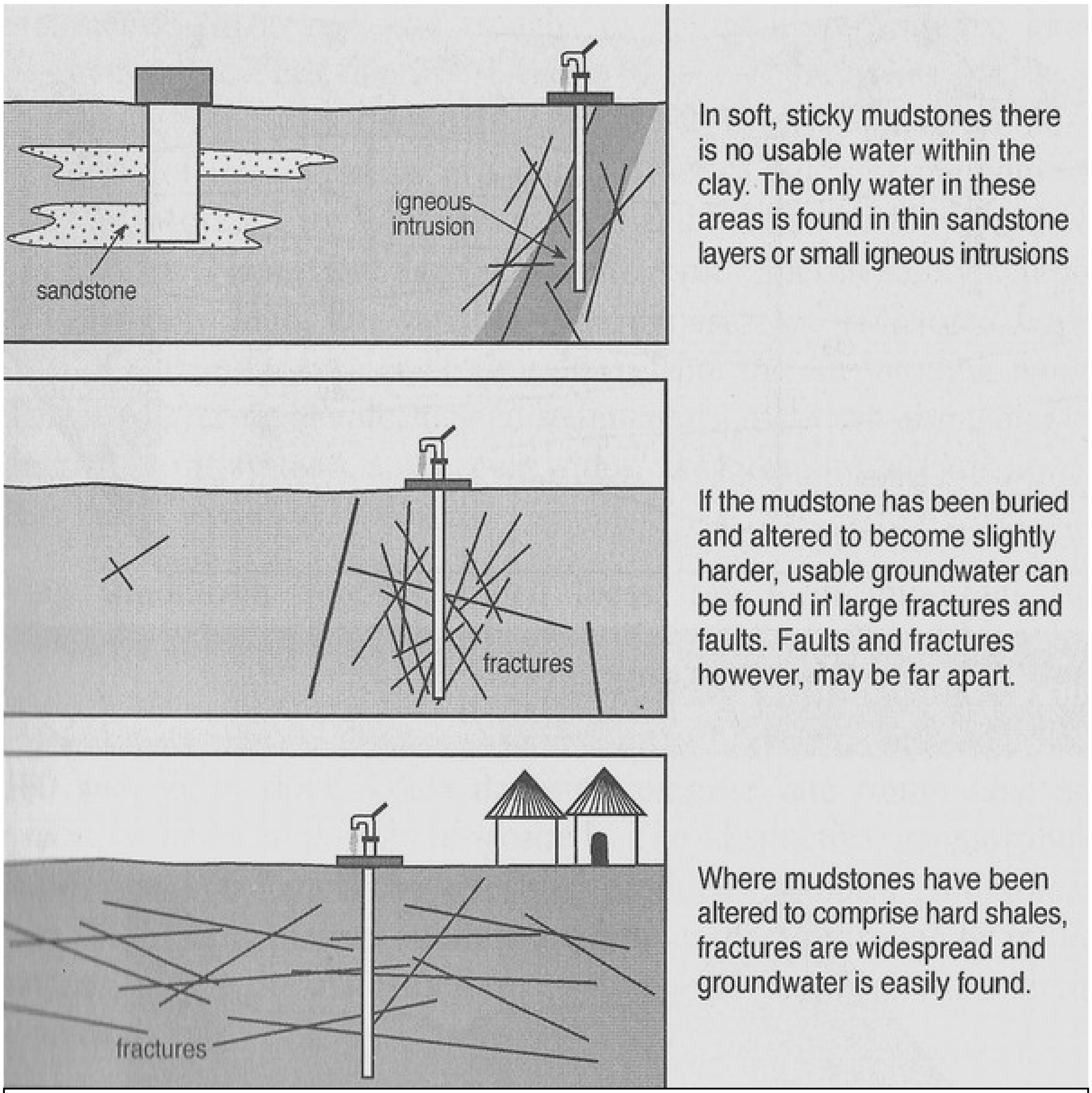


Figure 9 Groundwaterflow in Karst Limestones

This is usually called karst. Karst limestones are unpredictable environments to work in. Boreholes drilled several metres apart may have very different yields. Also borehole yields can vary considerably throughout the year. Large springs are common in karst limestone environments.

Although **mudstone** and siltstone are poor aquifers, small amounts of groundwater can often be found in these environments with careful exploration (see Figure 10).



In soft, sticky 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, 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 10 Groundwater occurrence in Mudstones

Mudstones are clays that have become consolidated through compaction and heating. The pore spaces are too small for water to move through easily, so usable groundwater is only found in fractures. In soft mudstones there are no open fractures, and groundwater can only be found if there are thin interlayers of sandstone or limestone. Where the mudstone is slightly harder, fractures can remain open and usable groundwater resources exist. Mudstones are the most common sedimentary rock and are found throughout the world.

4.4 Unconsolidated sedimentary aquifers

Unconsolidated sediments are deposited in different environments such as rivers and deltas by various combinations of physical processes. The sediments are all relatively young and as the name suggests, the material is still loose and groundwater is stored and transmitted through pore spaces, not fractures. They comprise a range of materials, from coarse gravel and sand to silt and clay. At one end of the scale are extensive sequences of coastal, river and deltaic alluvium, sometimes hundreds of metres or even kilometres thick. At the other end of the scale can be a thin covering of alluvium next to a small river.

Major alluvial and coastal basin sediments form some of the most important aquifers in the world, in which very large volumes of groundwater are stored and from which large quantities of water are pumped for water supply and irrigation. Examples include the Lower Indus, Ganges Brahmaputra, Mekong, Tigris-Euphrates and Nile valleys. Aquifers in unconsolidated strata are rarely simple homogeneous systems but typically consists of alternating permeable layers of productive sands and gravels separated by less permeable aquitard layers of clay and silt (Figure 11).

The shallow aquifers are easiest and cheapest to exploit, but are likely to be the most vulnerable to pollution. The presence of aquitards may produce complex groundwater flow patterns, but the permeable horizons may still have a degree of hydraulic continuity, such that pumping from one layer will affect the others, producing significant vertical head gradients and leakage.

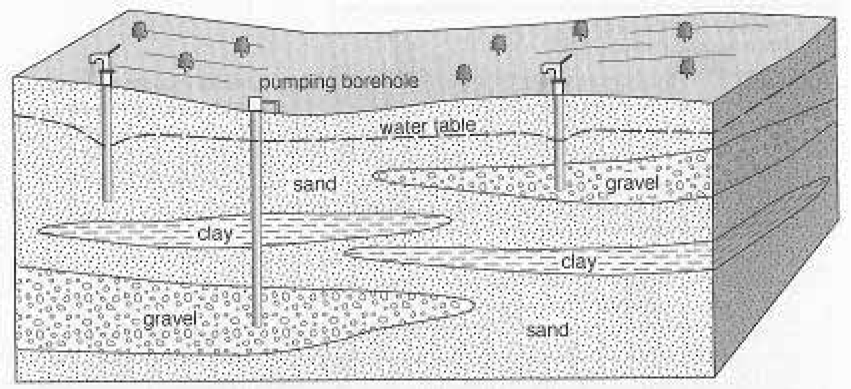


Figure 11 Groundwater occurrence in alluvial Basins

Deeper groundwater in thick alluvial sequences is derived from recharge several hundred to several thousand years ago, and the term fossil has sometimes been used to describe deep, old groundwater.

Small riverside alluvium and other deposits can form locally important aquifers. Shallow floodplains, less than 100 m wide and with less than 10 m thickness of sediments can be a valuable resource, particularly where the underlying bedrock has little potential for groundwater (Carter and Alkali 1996). In these deposits groundwater is close to the surface, so pumping lifts are shallow, also the proximity to the rivers offers a reliable source of recharge (Figure 12).

In southern Africa, sand-rivers are important sources of water for domestic use and stock watering. These rivers rarely contain surface water, but the thick sediment within the river channel can contain significant quantities of groundwater.

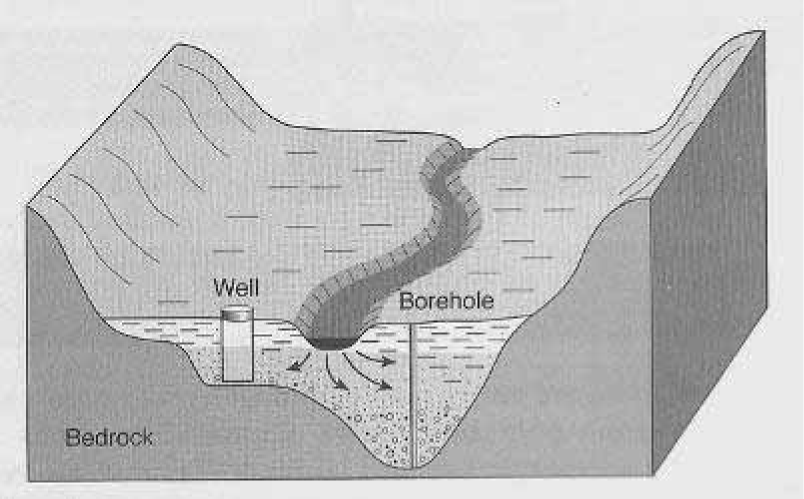


Figure 12 Groundwater occurrence in Riverside Alluvium

5 Accessing groundwater

There are many different ways of accessing groundwater from tapping water from springs to drilling deep boreholes, or even horizontal boreholes. In many cases, the methods used to access groundwater depend on the nature of the resource itself; for example shallow hand-dug wells cannot readily be used to access groundwater that is more than 25 m below the ground surface. However, in some hydrogeological environments, different methods can be used, and in those cases other factors, such as cost or community wishes can be given a higher priority.

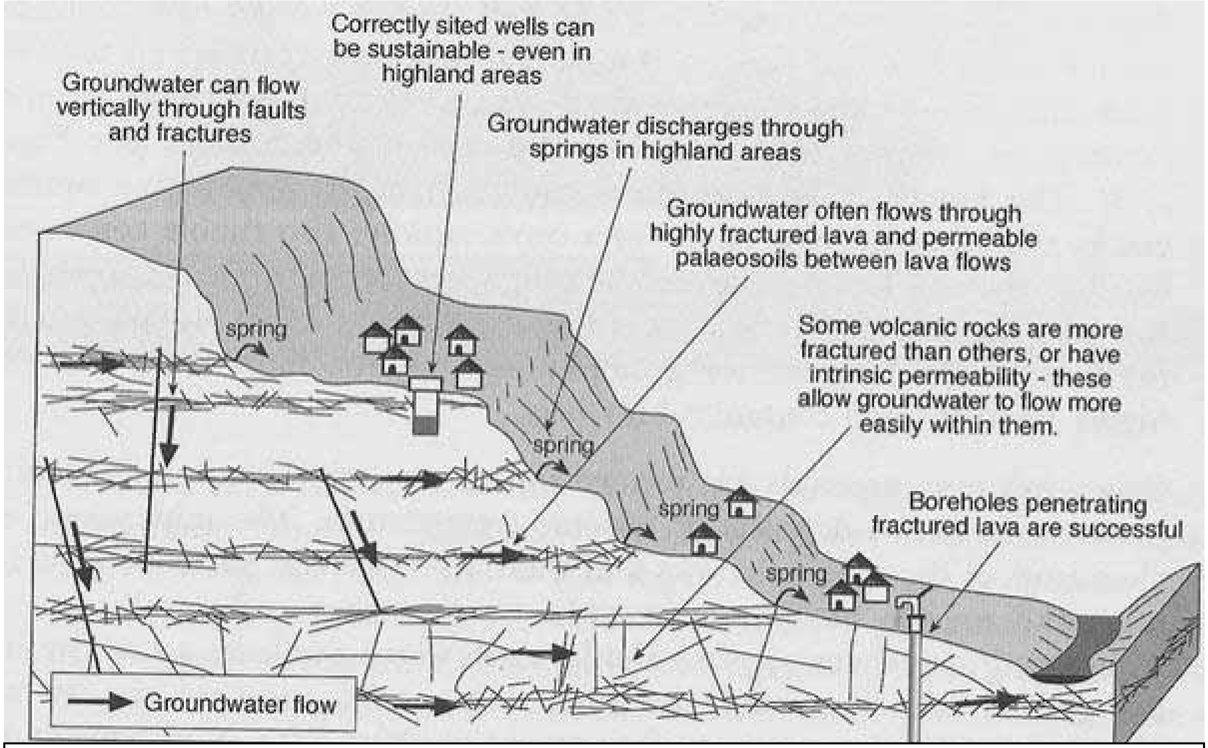


Figure 13 How Groundwater can exist in Volcanic Terrains

Below we describe some of the many methods used to access groundwater - some of them are not now used very often. The three most common are boreholes, hand-dug wells, and springs. Pumping methods are not described there are several other manuals and resources which go into detail about pumps.

5.1 Springs

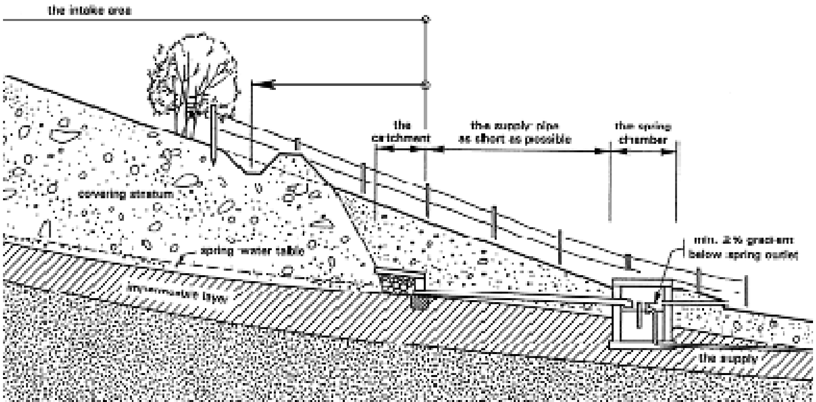


Figure 14 Improved Spring

A spring is a place where groundwater flows naturally from the rock or the soil onto the land surface; it is essentially an overflow from the aquifer. No equipment is required to make a spring -it is there already. Springs are dependent on the nature and relationship of rocks, especially the layering of permeable and impermeable rocks, the presence of faults, the position of the water table and changes in slope. The yield of springs also varies enormously, from mere seepages of less than 0.1l/s to huge flows of thousands of litres per second.

Springs can be highly vulnerable to contamination (particularly from activity around the spring itself) and susceptible to drought or even several months with no rainfall. To try to protect the spring, and maximize the yield from it, a collection chamber can be built away from the eye of the spring and the water collected from a controlled tap (see Figure 14).

The catchment has to be protected to prevent a spring from becoming polluted. The area just above and up-stream of the catchment needs particular care. The size of the protection zone depends on the thickness and nature of the covering stratum. It is recommended that the protected area must not be smaller than 10 m. Within this area, no farming, no domestic animal grazing, no rubbish pit etc. are allowed. The area just above the catchment should be planted with grass and outside of the radius of about 10 m; the protection zone should be afforested.

Excavation and construction of the catchment should be carried out during the peak of the dry season, in order to obtain the most reliable springs.

Nevertheless, the catchment has to be designed in such a way that it can cope with the peak flow in the rain season

Figure 15 Spring

5.2 Hand-dug wells

Construction of a Dug-well is most probably the oldest technique for extracting water from the ground. Wells have been dug to access groundwater for millennia. Wells are dug by hand, and therefore need to be constructed in soft material, such as weathered basement, sands and gravels, or limestone and chalk. They are generally less than 20 m deep and 1-2 m in diameter, although there are several instances of wells more than 100 m deep or with a diameter of more than 4 m. Little or no specialized equipment is required to construct a well- just something to dig with, and a way of getting the spoil out of the well. Wells often need to be lined to keep them open. Bricks, stones, concrete rings, steel and even tractor tyres have all been used as lining materials. Like springs, hand-dug-wells are vulnerable to contamination from activity around the top of the well. In an attempt to minimize this, hand-dug wells are generally improved by installing a concrete apron around the top (Figure 1xx). In addition to constructing a well cover, it is important to erect a good fence of locally available materials (wood or stones), to keep the animals away from the water point.

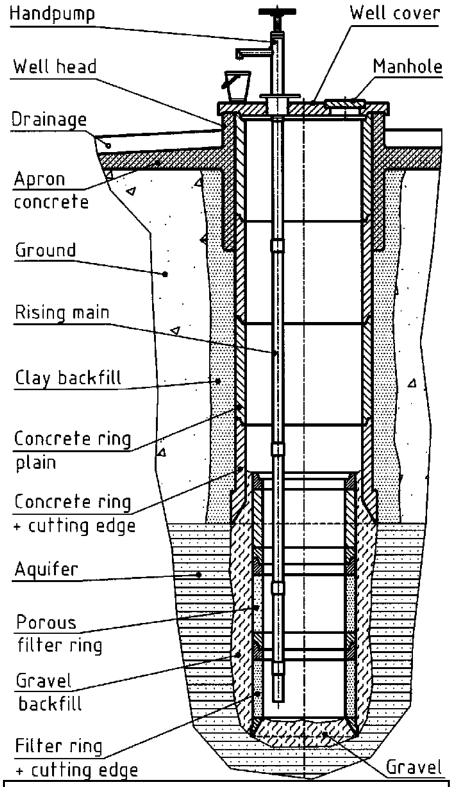


Figure 16 Dug Well

The advantages (compared to boreholes):

- The level of community involvement is very high,
- Skilled labour is not required besides supervision by a specialist.

- Te cost for constructing a dug-well is low and most of the construction materials are available locally,
- Water can continue to be drawn from the well equipped with a handpump, even if the pump fails (manhole),
- The storage capacity allows wells to produce sufficient water even when the aquifer permeability is very low,
- Reliable maintenance of a well requires little technical skill.

The disadvantages (compared to boreholes):

- Hand dug-wells are usually shallow and thus can tap only the upper levels of the aquifer, where water level fluctuations might be relatively large,
- The technology is only suitable for soft geological formations and shallow water tables, restricting it to specific areas and regions, even though there are very deep wells constructed in hard rock by using explosives. Such methods are time consuming and require special skills.
- The construction time is normally quite long
- Dug-wells are susceptible to bacteriological contamination, especially those without a tight well cover. If used with a handpump this risk can be minimised.
- In general, a shallow water table means large water fluctuations with the possibility that the well is drying up during any drought period (deepening or horizontal drilling can improve yield),
- Risk to workers such as collapse of the excavation, items being dropped down the well and suffocating by dangerous gases from the soil or internal combusting engines. A petrol or diesel engine for dewatering the well during construction should never be used inside or close to the well (need for supervision of an experienced specialist).

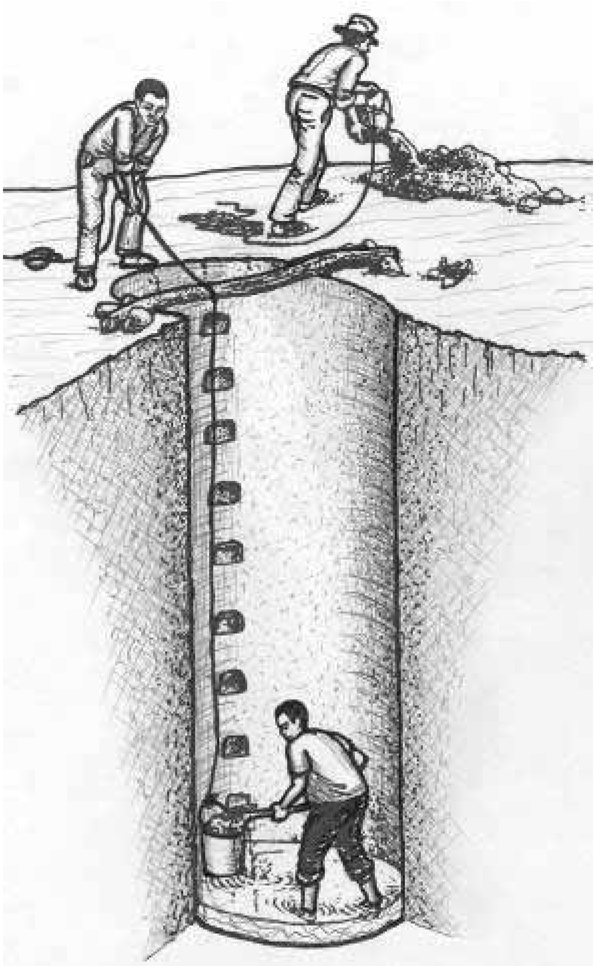


Figure 17 Digging a Well

5.3 Boreholes

A borehole is a narrow-diameter tube drilled into the ground at a controlled angle (usually vertical). This is the most common type of water source used on rural water supply projects. Boreholes started to be constructed in earnest with the invention in the nineteenth century of the steam-driven drilling machine. Nowadays, powerful diesel-driven rigs are used to construct boreholes, although in some places hand drilling can be effective (see Chapter 6). Boreholes for rural water supply are generally drilled to a depth of between 20 and 100 m, although in some situations where the aquifers are very shallow or very deep they can lie outside this range. They are often between 100 and 300mm in diameter. In Asia they are often referred to as tube wells, and by Americans just as wells.

Manual Drilling

Sludging Method

Sludging is a traditional method used widely in Bangladesh, whereby a tube well is directly sunk into soft ground, usually in silt or sand deposits of a river basin.

The system is similar to the well jetting process, whereby in the sludging method the water used for transport of sand and mud is lifted up the drive pipe.

Next to the place where the well will be sunk, a small pond is prepared and filled with water.

A scaffold is erected, so that the operator is able to reach the end of the pipe.

A hollow pipe of steel or bamboo (drive pipe) is moved up and down in the borehole, while a one-way valve provides a pumping action.

The palm of the operators hand is building this valve, sealing the pipe end during the up-stroke and releasing the muddy water during the down-stroke.

The up and down stroke is made by one or two labourers, connecting a short piece of pipe to the drive pipe and using it as a lever.

A newer development is the “Rota Sludge” method. In this technique a second operator turns the drill pipe in a twisting motion during the down-stroke. This allows cutting through harder soil.

Figure 18 Sludging

Well Driving Method

In certain soil conditions or with loose soil or sand, rising mains (with attached drive point and screen) can be driven directly into the ground.

However, it is more common to sink first a well casing with this system and removing the material in the pipe by hand-augering or bailing, before the rising main is lowered. For driving pipes directly into the ground, the top pipe needs to be protected by a drive cap.

Smaller pipes might be possible to be driven by a sledge hammer, but because of the limited driving force, only limited depths can be achieved.

For greater depths, a specially designed striker with weight can be used, which is guided on the inside or outside of the pipe and can be operated by hand.

Another system is to operate the striker by a rope attached to a pulley, by lifting and dropping down the striker to the drive cap.

Figure 19 Well Driving

Larger pipes are usually driven by air, steam or hydraulic operated strikers.

Special guiding devices should be used to prevent tilting of the pipe during the driving process.

Hand Drilling Methods

Hand operated drilling of shallow water wells is usually done with different augering or bailing tools, whereby the soil conditions sets its demand what type of boring tool be applied.

Survey Drilling

Survey drilling is mostly made with “Hand Auger Equipment” that is best suitable for soil research.

By applying such equipment, a depth of 8 to 10 m can realistically be achieved.

The maximum boring depth strongly depends on various factors such as: depth of the groundwater, the soil profile, and the characteristics of the material the auger has to pass through.

Most used auger types are: Edelman auger, Riverside auger, Stony soil auger, Spiral auger, Stone catcher and Gorge auger.

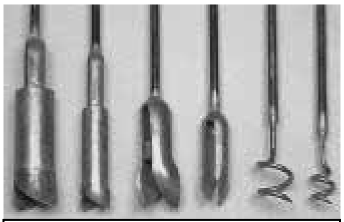


Figure 20 Augering Tools

Borehole Augering

Drilling tools for hand augering of water wells for a well depth of 20 to 25 m requires more sophisticated equipment and additional manpower. For operating this equipment, a heavy lifting set (tripod with a hand winch), a casing tube for easy lifting of filled augers and sturdy auger tools.

Most used auger types are:

Heavy riverside auger,

Stony soil auger, Chisel auger, Stone catcher and Flight auger.

Additional tools are used for installing the casing tube such as Casing tool clamp and Notched casing shoe.

Figure 21 Augering (Note: the men provide the weight and the women provide the labour)

Borehole Bailing

Borehole bailing is another common system of “drilling” a shallow well. The bailer is a hollow stainless steel tube with a one-way valve at the lower part. By pounding the bailer rapidly to the ground, loose material will collect in the bailer.

The bailer is also operated inside the casing tube and whenever the bailer has moved beyond the casing, it is lifted for emptying so that the casing tube can be pushed deeper into the ground by turning.

Bailing is often combined with augering and can also be used for developing existing wells, whereby the bailer is used to remove silt that has settled at the end of an existing borehole.

Figure 22 Bailer

Stone-hammer Method

The stone hammer method developed by EMAS in Bolivia is a low-cost drilling method that can be used in sedimentary soils without stones.

The hammering movement is articulated by on operator pulling a rope, which is laid over a pulley wheel on a steel mast and directly connected to the drill pipe.

Another operator is guiding and turning the top handle of the drill pipe and a third person is constantly pumping water through a hose connected to the drill pipe.

The pumped water is pressed down the drill pipe and is released through the holes in the drill bit, where it washes the mud and loosened soil to the surface.

Depending on the soil conditions, holes to a depth of 30 to 50 m can be achieved.

Rapid Well Jetting

Figure 23 Well Jetting

The Rapid Well Jetting is a method that can be used in sandy ground and in alluvial soil. The jetting pipe is inserted into the casing pipe and screen pipe, which has a valve mechanism at the lower end to seal the casing after jetting has stopped and to avoid sand intrusion. A small portable petrol driven pump is used for generating the jetting stream. The same motorized pump can be used to developing the newly installed well by pumping water in the opposite direction (from the well).

In ideal conditions the jetted water forces its way downwards, allowing the pipe to penetrate the ground. The direction of the back flow is upwards, along the outside of the well casing. This water keeps the sediment from closing again around the pipe and jamming it.

Limitations include the difficulty of jetting through coarse sand and fine gravel formations. In these layers the force of the jetting water is lost because of the quantity that disperses into the formation. When this takes place, the water flow up on the outside of the pipe is lost and the sediment jams the pipe in the hole.

Hard clayey sand layers are also difficult to penetrate; this is presumably because the jet of water is not strong enough to disturb cohesive sediments.

In favourable formations the technique has only been able to deepen wells to 7 or 8 m below ground (4 or 5 m below the water table), but this is enough for the special conditions along coastlines and rivers.

Motorized Drilling Methods

Well Jetting

Well Jetting is a method in which a high velocity stream of water is used for excavating a hole in relatively soft ground. Water is pumped under high pressure through a pipe, which is sinking into the ground.

Material like soil and sand that has been loosened by the water stream is then washed on the outside of the pipe towards the surface.

Usually a small pond is built to separate the water and the excavated material, so that the water can be reused for jetting.

The limitations of this technique are given by the material of the ground that needs to be penetrated (unconsolidated formations) and the velocity and pressure of the pumped water.

Lightweight Drilling Methods

In places where not large diameter boreholes in very hard rock layers are required, the lightweight drilling methods are increasingly attractive.

Considering the costs for choosing minimal hole diameters, the flexible transport and the easy operation of a light weight rotary rig mounted on a small truck or a trailer and the transport costs for lightweight equipment like PVC casings instead of steel casings can reduce the cost for a borehole considerably, without compromising on drill pipe the quality.

Figure 25 Small Drill Rigs

Figure 24 Small Rotary Rig

The development of the “Down the hole hammer” has made penetrating hard rock for lightweight drill rigs normal.

With this method the required power is directly delivered to the hammer by compressed air and therefore the use of a heavy drill rig with sufficient hydraulic power is not anymore required.

Heavy Drilling Methods

Drilling methods using machine-mounted rigs are essentially of two types, the percussion drill method (cable tool) and the several rotary drill methods.

Percussion Drill Method

Drilling is accomplished by the regular lifting and dropping of a drill bit mounted on drill stems, which is connected to the steel cable that runs over the pulley wheel at the end of the mast. The up and down movement is made by a mechanism mounted on the truck.

The drill bit, which does the actual drilling, is essentially a chisel. It can weight up to 1 to 2 tons and is variously shaped for drilling in different rock formations.

The drill bit is worked up and down in the borehole, pulverising the rock until 1-2 m of loose material fills the hole. The cuttings are removed from the borehole by a bailer.

Percussion rigs are able to drill holes of Ø100 to 400 mm through consolidated rock materials to depths in excess of 600 m.

Figure 26 Percussion Rig

Rotary Drill Method

This method is the most used technique for drilling large boreholes. Cutting of rocks is achieved by rotating bits of various types and the power delivered to the bits is made by a rotating hollow steel tube. Pre-mixed mud is forced down the drill pipe and out of the bit and forcing the broken rock fragments to the settling tank at the surface.

The mud is also supporting the borehole wall and minimises the fluid loss into the aquifer.

Therefore casings during the drilling operation are rarely needed.

Before installing the casing pipes, the borehole needs to be cleaned (developed) efficiently from mud that reduces the permeability of the aquifer.

The performance of large Rotary drill rigs are similar to those of the Percussion drill rigs, but this technique is more complex and therefore the equipment is expensive and operation difficult.

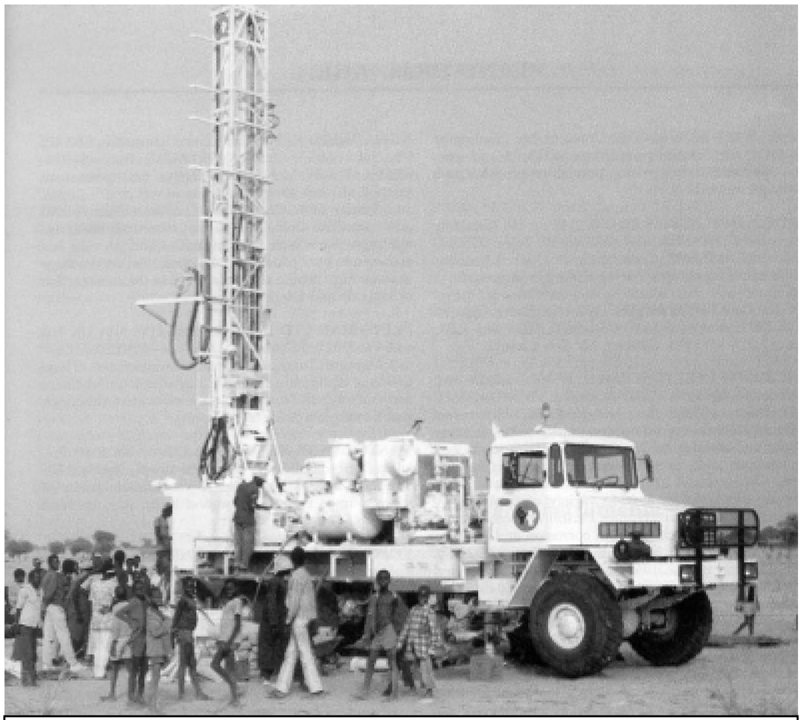


Figure 27 Heavy Duty Rotary Rig

Rotary Percussion Method

This recent developed technique is a combination of a rotary drilling with percussion drilling. A pneumatic hammer is delivering 10 to 15 impacts per second to the “Down-the-hole hammer”.

Very fast penetration rates are achieved with this system and because of the percussion is generated by the separate air compressor; smaller rigs can be used for drilling (see also “Lightweight Drilling Methods”).

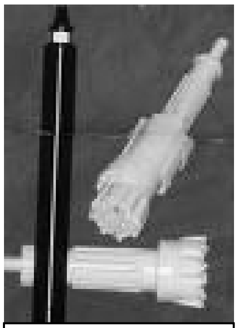


Figure 28 DTH Hammer

Boreholes have several advantages:

- they are quick to construct, if the right equipment is available
- they can be drilled deep and can therefore tap deeper, often more sustainable, groundwater
- they can be drilled in very hard rock
- effective sanitary seals can easily be constructed.

However, borehole drilling is expensive, and requires a specialized drilling rig, which is expensive to maintain and run. A well-trained crew is required to drill boreholes and it is difficult to involve communities directly in the process.

5.4 Further methods to assess groundwater

A collector well (or Ranney well as it is sometimes known) is a well that has been modified by drilling horizontal boreholes radially below the water table. Collector wells have proved more drought resistant than unmodified hand- dug wells or individual boreholes.

A Qanat (foggara, karez or kanat) is an ancient, sophisticated way of abstracting groundwater and transporting it to the point of demand. A qanat comprises a mother well, usually in alluvial deposits at the edge of a mountain, and a gently inclined underground channel which allows the groundwater to flow downhill from the edge of the mountains to the village.

An infiltration gallery is a horizontal drain constructed to abstract shallow groundwater they are particularly useful for abstracting water from alluvium, windblown deposits or sand rivers. They are simply, constructed by excavating a trench to 2-3 m below the dry season water table. To do this, the sides may have to be shored up with timber and a dewatering system installed. Plastic drainage pipe is then put in the trench and surrounded by washed gravel, before backfilling the trench. A sump is then located at either of the trench from which the water is pumped.