TECHNICAL REVIEW

BOREHOLE DRILLING AND REHABILITATION UNDER FIELD CONDITIONS

COMITE INTERNATIONAL GENEVE

ICRC

REFERENCE

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Credits
Consallen Group Sales Ltd: Fig. 4
Dando Drilling Rigs: Fig. 7
GeoModel, Inc.: Fig. 18
Geovision: Fig. 19
Andrea Guidotti/ICRC: Fig. 9 (top)
Los Alamos National Laboratory: Fig. 8 (right)
Thomas Nydegger/ICRC: Fig. 6 (cover, abstract)
OFI Testing Equipment, Inc.: Fig. 11
PAT-DRILL: Fig. 5
Sameer Putros/ICRC: Fig. 8 (left), Fig. 9 (bottom)
D. Soulsby/ICRC: Figs 1, 2, 3, 10, 12-17, 20, Annexe 3

FOREWORD

This technical review presents and synthesizes an impressive amount of practical experience in the field of borehole drilling and rehabilitation.

David Soulsby – author of this publication and a seasoned geologist/geophysicist/water engineer – strikes the right balance between theoretical and practical knowledge while adopting the approach of a scholar/practitioner. There is no doubt that his work will greatly help the ICRC's Water and Habitat engineers address technical dilemmas under difficult field conditions.

However, the ICRC's field experience reveals that in water-stressed regions afflicted by armed conflicts or rising tensions, there are no easy answers. This said, sustainability for the people benefiting from water projects can be reached when a cost-effective solution is part and parcel of a comprehensive analysis putting the dignity and the needs of the community at the centre while addressing wider environmental concerns.

This is an important contribution to the Water and Habitat unit's efforts to promote good field practices within its staff and amongst other humanitarian players.

I am extremely grateful to two successive Chief Hydrogeologists, Mr Jean Vergain who initiated this valuable work and Mr Thomas Nydegger who provided invaluable guidance throughout the editing of the Review. Finally, I wish to extend my thanks to Ms Anna Taylor who gave constructive advice as a reviewer and structured the final version of the manuscript.

Robert Mardini
Head of the Water and Habitat Unit

ABSTRACT

Boreholes are one of the best means of obtaining clean water in field conditions. However, constructing, or repairing, boreholes requires specialized knowledge and technical expertise, much of which can be gained from the standard literature; but field operations in remote areas or in difficult conditions often require flexibility and imagination in avoiding and solving technical problems. This review is intended as a decision-making tool to assist in making cost-effective choices between borehole drilling methods, and in deciding whether to drill new boreholes or rehabilitate existing sites. The end result should be a cost-effective facility capable of supplying potable water for many years.

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GLOSSARY

Aquifer	A subsurface rock or sediment unit that is porous and permeable and contains water. In an aquifer, these characteristics are highly developed: useful quantities of water are stored and transmitted.
Confined	An aquifer that is bounded above and below by impermeable rock or layers of sediment. There may or may not be enough pressure in the aquifer to make it an 'artesian aquifer (piezometric level above ground level).'[1]
Perched	Usually, an unconfined aquifer that is resting on an impermeable layer of limited extent surrounded by permeable formations or surmounting another unconfined aquifer.
Unconfined	An aquifer that is not overlain by an impermeable rock unit. The water in this aquifer is under atmospheric pressure. This kind of aquifer is replenished by rainfall in the area of its watershed or by infiltration from a river.[1]
Bedrock	Solid rock present beneath any soil, sediment or other surface cover. In some locations it may be exposed on the surface of the Earth.[1]
Formation	A laterally continuous rock unit with a distinctive set of characteristics that make it possible to recognize and map from one outcrop or well to another. The basic rock unit of stratigraphy.[1]
Host	The rock formation containing the water. The rock and the water together form an aquifer.

1 Adapted from "Geology dictionary" at http://geology.com.

Fracture	Any local separation or discontinuity plane in a geologic formation, such as a joint or a fault that divides the rock into two or more pieces. Fractures are commonly caused by mechanical stress exceeding the rock strength. [2]
Groundwater	Water that exists below the water table in the zone of saturation. Groundwater moves slowly and follows the water table's slope.[1]
Igneous	Formed by the crystallization of magma or lava.
Impervious	Impermeable. An impervious layer is a layer of rock, sediment or soil that does not allow water to pass through. This could be caused by a lack of pore space, or by pore spaces that are not interconnected or that are so small that water molecules have difficulty passing through.[1]
Joints	A fracture in rock along which there has been no displacement. [1]
Lithology	The study and description of rocks, including their mineral composition and texture. Also used in reference to the compositional and textural characteristics of a rock.[1]
Metamorphic	A term used to describe a rock whose mineral content, textures and composition have been altered by exposure to heat, pressure and chemical actions, usually in the course of tectonic burial and/or magmatic activity.[1]
Mudstone	A sedimentary rock composed of clay-sized particles but lacking the stratified structure that is characteristic of a shale.[1]

2 Entry on "fracture (geology)" in Wikipedia at www.wikipedia.org.

Permeability	A measure of how well a material can transmit water. Materials such as gravel, that transmit water quickly, have high values of permeability. Materials such as shale, that transmit water poorly, have low values. Permeability is primarily determined by the size of the pore spaces and the degree to which they are interconnected. Permeability measures are expressed in units of velocity, such as centimetres per second.[1]
Pores	Voids in a rock including openings between grains, fracture openings and caverns.[1]
Porosity	The volume of pore space in rock, sediment or soil. Usually expressed as a percentage.[1]
Sandstones	Sedimentary rock composed of sand-sized particles (1/16 to 2 millimetres in diameter) consolidated with some cement (calcite, clay, quartz).[1]
Shales	Thinly laminated sedimentary rock made of tiny clay-sized sedimentary particles.
Unconsolidated	Poorly cemented or not at all (in reference to sediments).
Wadi	A stream that fills up after rainfall, but which is usually dry the rest of the time.
Weathered	Earth rocks, soils and their mineral content which have undergone decomposition as a result of direct contact with the planet's atmosphere, water, light, frost and heat.[1]

Boxes with this formatting highlight experiences from the field or practical suggestions.

Boxes with this formatting contain information critical for successful operations or for the safety of staff.

1. INTRODUCTION AND EXECUTIVE SUMMARY

The International Committee of the Red Cross (ICRC) is an impartial, neutral, and independent humanitarian organization. Its mission is to protect the lives and dignity of victims of war and internal conflict and to provide them with assistance. Through its Water and Habitat Unit, the ICRC provides water and sanitation in dozens of countries and conflict zones throughout the world, meeting the needs of millions of people. The Water and Habitat Unit has drilled or rehabilitated hundreds of boreholes, sometimes employing contractors and sometimes their own machines.

This technical review is aimed at project coordinators, water engineers, and technicians. It is intended to be of assistance to everyone, from planners in offices to on-site personnel, in the making of technically correct and cost-effective decisions in the field when the drilling or rehabilitation of boreholes is required. An attempt has been made to orient the contents towards problems that might be encountered in the field. Nevertheless, some consideration of theoretical information has been necessary, because engineers will not be able to function without it. The authors hope that they have struck a balance between the practical and the theoretical, a combination that is required in professional water engineers.

The review begins with an overview of the benefits of utilizing groundwater and a consideration of various drilling methods, in Sections 2 to 4. Techniques are compared and details of the drilling equipment associated with each are provided to assist the user in selecting appropriate equipment.

The review focuses on mud and air rotary drilling, as they are the most common methods of borehole drilling found in the field. Details on borehole construction, design and development using these two methods are found in Sections 5 and 6. Construction costs are considered in Section 7. Key factors influencing borehole deterioration and aspects of monitoring and maintenance are outlined in Sections 8 and 9. When borehole deterioration reaches a stage where production is severely hampered, rehabilitation becomes unavoidable: this subject is treated in Section 10. Finally, Section 11 deals with issues that might arise while working with contractors and with minimizing the unpredictability of that aspect of drilling.

2. GROUNDWATER AND THE ADVANTAGES OF BOREHOLES

Easy access to safe, potable water is a basic human need, important for health and quality of life. A statement like this is regarded now as being something of a cliché. However, it must be said that even with the growing prevalence of water shortages throughout the world, a reliable water supply is still taken for granted, with no real thought about its sustainability and quality. This attitude is most starkly evident in areas where there is a reliance on water from boreholes, which, it is assumed, will keep on producing – at the same rate – continuously and forever. Groundwater is out of sight, and hence, largely out of mind, but it is one of the best sources of water that man has been able to utilize.

If water is not flowing visibly along a dry wadi, it may be moving unseen, slowly, through the sediment, and can be accessed by digging a well in the riverbed – a fact well known to many elephants.

2.1 Exploiting groundwater

The principal source of inland groundwater is rainfall. A proportion of rain falling on the ground will percolate downwards into an aquifer if the conditions are right. A great deal of rain water ends up as run-off in streams and rivers, but even here there is often a direct hydraulic connection with a local aquifer. Indeed, in arid areas with ephemeral streams, high groundwater levels may be able to sustain surface flow along drainages.

It is obvious that a hole dug or bored into a saturated 'sponge' will release water from storage. This water can be sucked or pumped out, and all being well, more water will enter the hole to replace that which has been withdrawn. This is the basic principle behind a water borehole.

2.1.1 Geological constraints

The Earth's crust has often been compared to a sponge, in that it can soak up and hold water in pore spaces, fractures and cavities. This ability to store water depends very much upon geological conditions and on the host formation. For example, fresh, unfractured, massive granite – a crystalline rock – has virtually no space available for water, whereas unconsolidated, or loose, river gravel and highly weathered cavernous limestone can store large quantities of groundwater and are capable of releasing it relatively freely. Sandstone and mudstone may be able to hold significant groundwater resources, but because of differences in grain size – and hence porosity – will release it at different rates. One may be a good aquifer, the other a poor one. The rate at which water flows through a formation depends on the permeability of that formation, which is determined by the size of pores and voids and the degree to which they are interconnected. Permeability and porosity should not be confused, porosity being the ratio between the volume of pores/voids to the bulk volume of rock (usually expressed as a percentage). Table 1 provides a range of porosities and permeabilities for common soil profiles.

The three principal characteristics of aquifers are transmissivity, storage coefficient, and storativity. Transmissivity is a means of expressing permeability, the rate at which water can flow through the aquifer fabric. Storage coefficient and storativity express the volume of water that can be released from an aquifer.

Hydrogeology is the science of groundwater, and it is the job of a hydrogeologist to assess the groundwater resources in any given area. This is accomplished through

Table 1. Typical porosities and permeabilities for various materials (various references)

Lithology	Porosity (%)	Permeability (m/day)
Clay	42	10^{-8}–10^{-2}
Silt/Fine sand	43–46	10^{-1}–5
Medium sand	39	5–20
Coarse sand	30	20–100
Gravel	28–34	100–1000
Sandstone	33–37	10^{-3}–1
Carbonate (limestone, dolomite)	26–30	10^{-2}–1
Fractured/Weathered rock	30–50	0–300
Volcanics (e.g. basalt, rhyolite)	17–41	0–1000
Igneous rocks (e.g. granite, gabbro)	43–45	$<10^{-5}$

the use of maps (topographic, geological), satellite images, aerial photos, field observations (geological mapping, vegetation surveys, etc.), desk studies (literature, field reports, etc.) and ground geophysics. Ground geophysical surveys are now quite effective in locating water-bearing formations at depths down to around 100 metres. Methods include resistivity (vertical electrical profiling), natural-source self-potential and electromagnetic methods (such as VLF), magnetic methods, and micro-gravity surveying.

2.1.2 Borehole siting

Choosing a borehole site is a critical part of the process of providing a safe and reliable supply of groundwater. The best sites are those in which catchment (natural water input) may be maximized. Such locations are not necessarily those that receive the highest rainfall (which may occur in upland watersheds). 'Bottomlands' – such as river valleys and lake basins – tend to be areas of maximum catchment, as both surface water and groundwater migrate towards them under gravity. Fracture zones, although not always directly related to bottomland, can also be good reservoirs for groundwater, and may be located by ground observation or satellite images/aerial photographs, and by geophysical methods.

Another aspect of borehole siting that demands careful consideration in populated areas is the potential for contamination by cattle and pit latrines or other waste disposal facilities. Because near-surface groundwater migrates downslope, a shallow dug well or a borehole tapping shallow groundwater should be sited as far away as possible (while bearing in mind the human need for proximity to a source of water) and upslope of potential sources of pollution (latrines or sewage pipes, for instance). Deeper aquifers confined by impermeable layers are at less risk of contamination from surface pollutants. One final consideration is the nature of the shallow aquifer. If the host formation is made of fine or medium-grain-sized sand, it will act as a natural filter for particulate pollutants, whereas fissured limestone, with a high rate of water transmission (transmissivity) will carry away pollutants faster and to greater distances from the source. It is estimated as a rule of thumb that most micro-organisms do not survive more than 10 days of transportation by underground water.

2.1.3 Types of geological formation

Figure 1 shows a hypothetical geological situation in which different sources of groundwater may (or may not) be tapped by dug wells or boreholes (also called 'tube wells').

A) Perched aquifers

At site A, a shallow dug well may provide a little water from a 'perched' aquifer in the weathered zone above relatively impervious (low porosity) mudstones. If this well was extended into the mudstones it might produce very little additional water. A perched aquifer is normally limited in size and lies on an impervious layer higher than the area's general water table.

B) Shallow unconfined aquifers

The term 'unconfined' refers to an aquifer within which the water is open to atmospheric pressure: the so-called

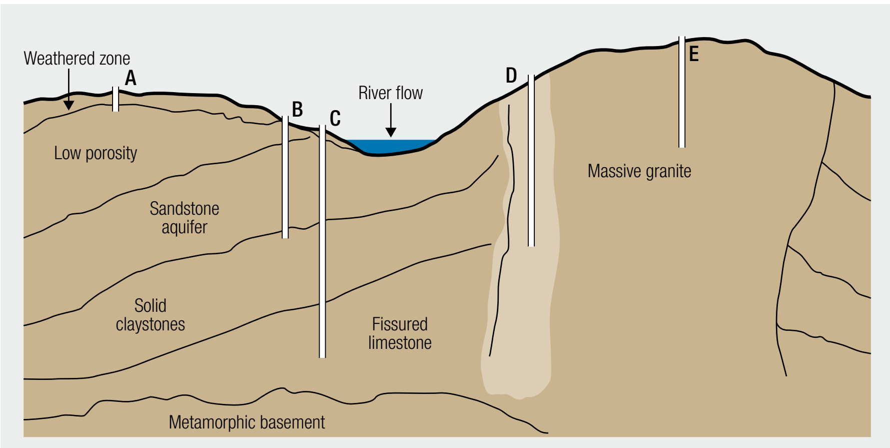


Figure 1. A hypothetical hydrogeological scenario

piezometric surface (pressure head level) is the same as the static water level (SWL) in the borehole. At site B, a borehole extracts water from an unconfined sandstone aquifer, the SWL of which is somewhat lower than the level of flow in the river. This sandstone aquifer is in a good catchment area because of recharge from the river.

C) Confined aquifers

A 'confined' aquifer may hold groundwater under greater pressure, so that when punctured by a borehole, the SWL rises to the higher piezometric level. If the piezometric surface happens to be above ground level (which is not uncommon), water will flow out of the borehole by itself: this is known as 'artesian water.' Deep borehole C intersects the sandstone aquifer and a deeper confined aquifer in fissured limestone; because of overpressure in the limestone aquifer, the SWL in C may be at the same or higher elevation than in B. The limestone aquifer may have no source of replenishment; so the water in it is ancient, or 'fossil,' and could be exhausted if over-exploited.

D) Fracture zone

Borehole D, which has been drilled into fractured granite (shaded area), finds water held in the fracture zone. Fracture zones develop during geological times as a result of the severe mechanical stress, caused by tectonic movements, that is exerted on non-plastic formations.

E) Hydrogeological basement

Site E, a borehole sunk into massive granite on top of a hill, is dry. In this situation, it would be a waste of time and money to extend a deep borehole (such as C) into the metamorphic basement, which is generally known as the 'hydrogeological basement' or 'bedrock.' The bedrock marks the level below which groundwater is not likely to be found.

2.2 Groundwater extraction

A water borehole is not just a hole in the ground. It has to be properly designed, professionally constructed and carefully drilled. Boreholes for extracting water consist essentially of a vertically drilled hole (inclined and horizontal boreholes are rare and will not be discussed here), a strong lining to prevent collapse of the walls, which includes a means of allowing clean water to enter the borehole space (screen), surface protection, and a means of extracting water. Drilling by machine is an expensive process, and boreholes require professional expertise for both their design and their construction. There are, however, compensations: this method of extracting water has a number of significant advantages.

The common alternatives to drilled boreholes, available to everyone with basic knowledge and simple tools, are surface water sources, springs, and dug wells. Where shallow groundwater emerges at a seepage site or at a spring, water catchment systems can be constructed to provide water of reasonable quality. Catchment boxes, that include sand or stone filters, and collector sumps are extremely effective means of collecting water. Gravity may be used to effect pipe network distribution from upland springs. Shallow dug wells usually exploit near-surface groundwater. Wells down to a depth of five metres are relatively simple to construct (given time and willing local labour), and there are many publications describing this process. Furthermore, because of their relatively large diameter, wells provide valuable storage volume. The water supply can be protected by lining the well, covering it with a lid, and fitting a hand-pump to it.

However, dug wells, and surface water catchment in general, are very vulnerable to contamination caused by agricultural activities, animals, poor sanitation and refuse. In addition, surface or shallow groundwater catchment is vulnerable to poor rainfall and declines in water level caused by drought, because it usually taps the top of the aquifer. Borehole water, by contrast, often requires no treatment and is less susceptible to drops in water level during periods of drought or limited rainfall.

2.2.1 Advantages of drilled boreholes

If they are properly designed and maintained, drilled boreholes:

- Are less vulnerable to drought or drops in water level when drilled into deep water-bearing formations
- Can be designed to exploit more than one aquifer (when individual aquifers are vertically separated and not hydraulically connected)
- Are less vulnerable to collapse
- Are less vulnerable to contamination
- Are, if properly sited, capable of producing large yields; so, mechanically or electrically powered pumps can be used
- Are amenable to quantitative monitoring and testing, which enables accurate assessment of aquifer parameters (as in aquifer modelling), water supply efficiency, and optimal design of pump and storage/distribution systems
- Can be used to monitor groundwater levels for other purposes, e.g. environmental studies or waste disposal

2.2.2 Disadvantages of drilled boreholes

- High initial material costs and input of specialized expertise, i.e. construction, operation, and maintenance may require skills and expensive heavy equipment
- Vulnerable to irreversible natural deterioration if inadequately monitored and maintained
- Vulnerable to sabotage, can be irreparably destroyed with little effort if inadequately protected
- Require a source of energy if water extraction pumps are used (unlike gravity feed systems)
- Do not allow direct access, for maintenance or repairs, to constructed parts that are underground

3. METHODS OF DRILLING BOREHOLES

Once a suitable site has been selected and borehole drilling decided on, the proper drilling method must be chosen.

Another primary consideration in project planning is the availability of existing water sources and water points. There may be completed dug wells and boreholes already in the area. Are they in use? If not, can they be rehabilitated to augment water availability or to reduce the cost of the programme? Drilling equipment, such as compressors, can be used to bring disused boreholes back into use; the question of rehabilitation will be addressed in Section 10 of this review. This section outlines the factors that must be considered when choosing a drilling method.

3.1 Common drilling methods

Essentially, a drilling machine consists of a mast from which the drilling string components (tools plus drill pipes or cable) are suspended and, in most cases, driven. Modern systems are powered rotary-driven, but it is probably worth a short digression to describe some methods of manual drilling for water. Simple, low-cost methods include:

A) Hand-auger drilling

Auger drills, which are rotated by hand, cut into the soil with blades and pass the cut material up a continuous screw or into a 'bucket' (bucket auger). Excavated material must be removed and the augering continued until the required depth has been reached. Auger drilling by hand is slow and limited to a depth of about 10 metres (maximum 20 metres) in unconsolidated deposits (not coarser than sand), but it is a cheap and simple process.

B) Jetting

A method whereby water is pumped down a string of rods from which it emerges as a jet that cuts into the formation. Drilling may be aided by rotating the jet or by moving it up and down in the hole. Cuttings are washed out of the borehole by the circulating water. Again, jetting is useful only in unconsolidated formations and only down to relatively shallow depths, and would have to be halted if a boulder is encountered.

C) Sludging

This method, which may be described as reverse jetting, involves a pipe (bamboo has been successfully employed) being lowered into the hole and moved up and down, perhaps by a lever arm. A one-way valve (such as someone's hand at the top of the pipe) provides pumping action as water is fed into the hole and returns (with debris) up the drill pipe. There may be simple metal teeth at the cutting end of the pipe, and a small reservoir is required at the top of the hole for recirculation. The limitations of sludging are similar to those of the previous two methods, but it has been used effectively in Bangladesh.

These manual shallow drilling techniques might be used as low-cost alternatives in groundwater investigations for dug well sites, particularly if geophysical surveys prove to be ineffective, unavailable or impracticable because of ground conditions. In such instances, when the drilling is done solely for the purpose of prospecting, only small holes are drilled, rapidly.

D) Percussion drilling

Drilling by percussion is done by simply dropping a heavy cutting tool, of 50 kilograms or more, repeatedly in the hole. This may well be the original method of drilling for water, pioneered by the Chinese (probably using bamboo) 3000 years ago or more. The drilling tools are normally suspended by a rope or cable; and – depending on the weight of the drill string, which, for manual operation, is obviously limited – it is possible to drill to considerable depths in both soft and hard formations. Basic percussion drilling systems are still widely used in Pakistan to drill shallow boreholes for hand-pumps. They consist of a strong steel tripod, cable and power winch, percussion tools, and a baler. These systems are seriously hindered when the ground is hard, and can accidentally change direction along weaker zones, causing boreholes to become crooked or tools to jam. Unconsolidated materials, although easy to drill with cable tool, become very obstructive when boulders are present. Sticky shales and clays are also difficult to penetrate with cable tool rigs, and loose sand tends to collapse into the hole almost as fast as it can be bailed.

E) Rotary drilling and down-the-hole hammer (DTH)

Most borehole applications in the field will require rotary drilling. True rotary drilling techniques allow much deeper boreholes to be constructed, and use circulating fluids to cool and lubricate the cutting tools and to remove debris from the hole. Circulating fluids usually take the form of compressed air or of pumped water with additives, such as commercial drilling muds or foams (see Section 5).

The down-the-hole hammer is a further development of the rotary method.

Table 2. Comparison of drilling methods

	Advantages	Disadvantages
Manual construction (Hand dug wells and hand drilling)	Simple technology using cheap labour	Shallow depths only
Percussion drilling	Simple rigs, low-cost operation	Slow, shallow depths only
Rotary drilling, direct circulation	Fast drilling, no depth limit, needs no temporary casing	Expensive operation, may need large working space for rig and mud pits, may require a lot of water, mud cake build-up may hamper development
Rotary DTH, air circulation	Very fast in hard formations, needs no water, no pollution of aquifer	Generally not used in soft, unstable formations, drilling depth below water table limited by hydraulic pressure
Rotary, reverse circulation (not described in text)	Leaves no mud cake, rapid drilling in coarse unconsolidated formations at large diameters	Large, expensive rigs, may require a lot of water

Figure 2. A mud rotary machine working in eastern Zimbabwe, 1996. Note the mud pits dug nearby.

Figure 3. Air rotary machine developing a successful borehole, South Africa, 1989

4. DRILLING EQUIPMENT

Once a drilling method has been selected, you must decide on the type of drilling equipment or rig that best suits your situation. This section discusses the various types of rig available and their suitability, and also provides an overview of drilling rig parts.

4.1 Choosing a drilling rig

The type of rig chosen may be determined on the basis of the site geology, the anticipated depths of the boreholes, and their expected diameters. Access is an important consideration. All drilling machines, except the smallest units capable of being dismantled and reassembled on site, require transportation: a road may have to be cut through bush to reach a location. For the largest truck or trailer-mounted rigs this can be a significant problem during rainy seasons in remote areas. Heavy rigs are notorious for becoming stuck in mud, and in such difficult conditions they should be used only if rain is not expected, or if there are means of pulling the rig out of trouble. Because low-lying areas often provide good drill sites, a rig may have to labour up a steep slope when it leaves. Rutted dirt roads may have to be covered with stones to facilitate traction.

Percussion rigs will not often be encountered these days in water borehole deep drilling; they are more useful in shallow site investigations or exploration. Some years ago, this writer saw an old cable tool percussion machine mounted on a large trailer, drilling exploration holes around an opencast manganese mine at Hotazel on the Western Cape in South Africa.

4.1.1 Percussion drilling

Mechanical winching obviously improves the effectiveness of percussion drilling (light cable tool rigs), and a number of useful choices are available. One example is the Forager 55 cable-trailer rig (Figure 4): weighing only 400 kilograms, it can be transported easily to inaccessible sites. The tripod frame can be erected by one person; and the heart of the system is a small free-fall winch, which hoists and drops the tool-set to drill the hole. Power can be provided either mechanically or hydraulically, although the supplier doesn't recommend the latter for use overseas. However, this kind of rig is not adapted to hard formations or sediments containing blocks. In collapsible formations, the drilling depth is limited by the hauling capacity of the equipment used to retrieve the temporary casing that maintains the walls of the hole. The unit and its accessories are available from the Consallen Group in the UK (Product reference 1, Annex 7).

4.1.2 Heavy duty cable tool

Heavy-duty cable tool percussion drilling rigs are truck or trailer-mounted and powered by a large diesel engine driving a cable winch. To add extra weight and drilling power, a 'sinker' – or heavy solid steel bar – is fitted above the chisel-like cutting tool. This usually improves borehole straightness and verticality. Percussion rigs allow operators to vary the number of strokes per minute and the length of each stroke, to optimize penetration in hard or soft rock conditions. By adding water, cuttings are removed from a percussion-drilled borehole in the form of a slurry and by means of a 'bailer' (heavy steel tube with a non-return 'clack' valve at the bottom). Softer, unstable formations such as sands or clays may require a combined hollow cutting and bailing tool.

Figure 4. The Forager 55 cable-trailer rig in use

4.1.3 Rotary drilling

Industrial rotary rigs are truck or trailer-mounted, but small and extremely powerful machines (see below), often cost-effective for humanitarian projects, are also on the market. One example is the Eureka Port-a-Rig, which can be transported by a pick-up truck in component form and assembled on site. The basic unit weighs about 500 kilograms and is driven by a 4-kw engine, with top drive and mud or air flush. A small 7-bar compressor, mounted on a small trailer, is available. The Eureka is capable of drilling to 50 metres (Product reference 2, Annex 7).

Operating a PAT 201 in South Sudan for a Dutch NGO, this writer had to erect a gantry consisting of three telephone poles (two uprights and one cross-beam) from which a 5-tonne chain block was suspended. On one or two occasions, the chain block, pulling on the engine mounting, was able to free the drill pipes and drag bit, which had become jammed when the borehole collapsed.

The smallest rotary drilling system of which this writer has first-hand experience is the PAT 201. The system is powered by a small petrol engine in a mounting that can slide up and down a three-legged mast. It is recommended only for mud drilling in alluvial conditions, but this writer can confirm that the PAT 201 is indeed capable, as the manufacturers

Figure 5. A PAT 301 drilling rig

claim, of drilling to 60 metres. However, there is little power available for 'pull back' (just a small hand-winch), which is the main limitation of small rigs.

The PAT Company (Product reference 3, Annex 7) produces a range of small to medium-sized drilling rigs: the 201, 301 (shown in Figure 5), 401, and the 501, all of which use 3-metre drill pipes. The PAT 301 and 401 operate hydraulically and may be towed or carried by a light pick-up, such as a Land Cruiser. Both can use water/mud or compressed air flushing and are capable of drilling to depths of 150 or 200 metres at diameters of up to eight or nine inches. Mud pumps are available for PAT rigs, and compressors of up to 7 to 12-bar capacity can be supplied for the larger rigs. In size and capability, the 501, a unit mounted on a 6½-tonne truck, falls between small portable machines and large industrial drilling rigs, which are generally custom-built.

Needless to say, the dangers inherent in using high-pressure air systems require that pressure hoses and couplings be of the correct rating and in good condition. This is especially important when working in remote areas where access to emergency medical care may be many hours' drive away.

Circulation systems require a pump to drive the fluid: in the case of mud-rotary drilling, a mud pump, and for air systems, a compressor. Conveniently sized units are available for the smaller rigs: for example, PAT produces a small mechanical mud pump for the 201 portable rigs. Large rigs

Figure 6. ICRC PAT 401 in action, northern Uganda, 2008

use industrial-scale units. Mud pumps are essentially simple sludge pumps based on pistons, impellors, or helical stators. For compressors, manufacturers specify the pressure a unit may develop in terms of 'bar' or 'psi' (pounds per square inch), where 1 bar = 100 kPa, (1 Pa = 1 N/m^2). Heavy-duty (industrial plant) units can develop pressures of 20 bar – and it is pressure that delivers power to a down-the-hole (DTH) hammer – making for a faster penetration rate. Pressure also lifts cuttings to the surface: for instance, a 7-bar compressor would be required to lift a 60-metre column of water from the bottom of a hole. Because the production of compressed air is a notoriously inefficient process, the compressor might dominate a drilling set-up in terms of size, cost, and maintenance problems.

Many contractors construct their own machines using, for example, particular makes of truck chassis, engine or compressor, for which spare parts are readily available.

The budgets of aid organizations seldom permit the purchase of industrial-sized drilling machines, but it is these that will normally be used if a drilling contractor is hired for a project. Large drilling rigs can be bought 'off the shelf' by commercial operators: the Atlas Copco machines and the Dando company, which manufactures the extremely successful Watertec 24 rig shown in Figure 7, will be familiar names to many drillers and hydrogeologists. The W24, a typical example of this type of machine, has a 'pull back' of 24,000 kilograms and can drill to depths greater than 700 metres with bit diameters of up to 17½ inches. It was developed specifically to cope with the harsh conditions encountered in Africa and in Arab countries. The W24 is one of many rigs that can be adapted for air or mud circulation as required.

Figure 7. The Dando Watertec 24 drilling rig

4.2 Drilling rig components

4.2.1 Drill bit

No single type of drill bit can cope with all possible drilling conditions and formations. Some typical examples are shown in Figure 8. Drag bits consist of three or four serrated blades that shear the formation when the bit is rotated; they can penetrate softer formations such as poorly consolidated or stiff clays and mudstones rapidly. Roller cone bits (or tricone rock bits), which can be used with air or liquid flushing, are popular with the oil industry. They can be used to penetrate both soft and relatively hard formations.

Figure 8. Two common types of drill bit: left, two drag bits; right, a roller cone bit.

4.2.2 Hammer

In air-circulation drilling, if a formation is too hard for penetration by a drag bit, a DTH hammer is generally employed. This tool was developed for the mining and quarrying industry. The 'business' end – the button bit – is studded with hemispherical tungsten carbide 'buttons,' and with channels built in to allow the passage of compressed air. When the hammer is pressed against the ground, the bit is forced into a pneumatic hammer action (like a road drill) by compressed air fed down the drill pipes. Then, as the tool is rotated in the hole, the buttons act across the entire base of the borehole. Most hammers rotate at speeds of 20 to 30 revolutions per minute, and blows can be struck at rates of up to 4000 per minute. Debris is normally flushed (blown)

Anyone familiar with drilling contractors' operations in the field will know the extent to which downtime can adversely affect the schedule of a project. Problems commonly arise in hydraulic systems and compressors that might have been inadequately maintained because of the pressure of work.

Figure 9. DTH hammer button bits. The hammer body, into which it slides, is not shown.

out of the hole at the end of each drill pipe. DTH hammers are most effective in hard rock formations such as limestones or basalts; soft, fine-grained formations tend to clog the air ducts or jam the piston slides.

Nonetheless, DTH hammers are extremely cost-effective and hence very popular with commercial drillers.

In remote locations, and when the pressure of work is heavy, hammer maintenance can easily be overlooked, to the detriment of a project's schedule.

5. BOREHOLE CONSTRUCTION

Once the drilling method and the equipment have been chosen, you will be required to observe and monitor the construction of the borehole. You may also be charged with the responsibility of supervising (in terms of quality control) the drilling of boreholes by your colleagues or by external drilling contractors. Quality control of drilling operations requires knowledge and confidence, which are acquired only by experience; but a cooperative contractor (sympathy would be too much to expect!) can make a job easier, and even enjoyable. This section outlines key considerations for borehole construction using the mud and air rotary drilling methods.

5.1 Construction considerations

Large drilling rigs are equipped to ensure that a borehole is started true and vertical. Maintaining verticality and straightness can be difficult during the early stages of drilling, but as the drill string weight increases, this problem tends to dissipate unless highly heterogeneous drilling conditions are encountered (in the form of boulders or cavities). Straightness is particularly important for water boreholes in which long strings of casing and screens may have to be installed with a gravel pack filter (see Section 6.3.2).

Non-vertical or inclined drilling is used mostly in oil and mineral extraction. Tools used for water boreholes are not suited to inclined drilling.

As drilling proceeds, drill pipes are screwed together. It should be noted that two of the three bits shown in Figure 8 have conical screw threads. This allows tools and pipes to be rapidly attached and screwed together on the rig. A blast of air is sent through each pipe to remove blockages, and the string is tightened with heavy-duty spanners on the rig. Taller drill masts can obviously handle longer drill pipes – six metres is the normal length, except for smaller rigs (see above) – which speeds up bit lowering ('tripping-in') and raising ('tripping-out') times.

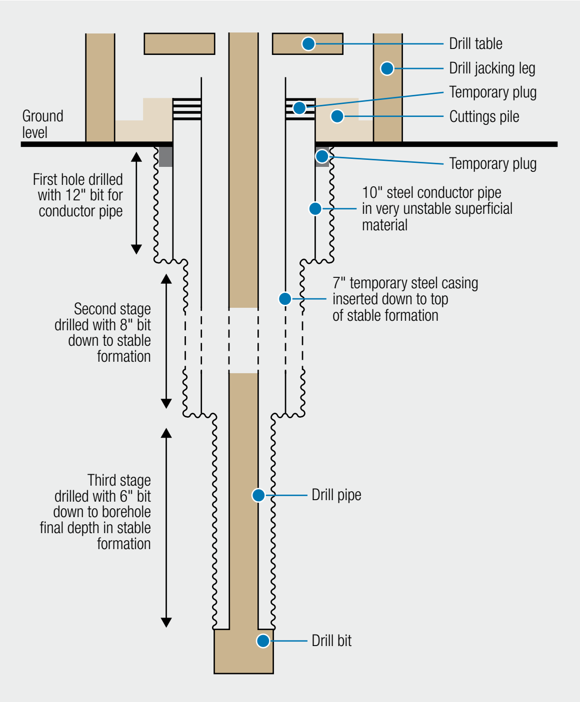


Figure 10. Schematic section of an example of temporary borehole completion (not to scale).

Reaming – the enlarging of an existing hole – can be carried out either with a drill bit of any kind or with specially designed reaming tools. Drilling companies often devise tools for special use, sometimes in the field, and they are often very ingenious.

It should be borne in mind that after drilling has begun, the sides of the upper part of the borehole are likely to suffer erosion by circulation fluid and cuttings, which causes an irregular enlargement of the borehole, reducing up-hole fluid (air or mud) velocity. This can be dealt with by installing conductor pipe as described below.

As drilling proceeds, the amount of water leaving the borehole will – it is hoped – be seen to increase, reaching

> Objects lost in the hole can often be 'fished' out using existing equipment (such as pipe screw threads) or with specially adapted tools. But drillers should always take great care to prevent this kind of occurrence, as minor accidents are potentially very costly in terms of time and equipment.

a point at which it becomes clear that the borehole will provide the required supply. Even then, the borehole may have to be deepened further to provide sufficient pumping drawdown (see Section 6.3.2). However, if the borehole is found to be wanting, it may be advisable to stop drilling early (unless a hand-pump is acceptable at that location) or carry on in the hope of a greater water strike (here some knowledge of local geology would be very useful). If fragments of ancient, hard metamorphic or igneous basement rocks, such as gneisses, schists, and granites start appearing in the cuttings, and the penetration rate decreases significantly, the 'hydrogeological basement' has, in all likelihood, been reached and it would probably be futile to continue to deepen the hole.

If a manufactured dip meter cannot be obtained, one can be fashioned simply, with about 100 metres of ordinary twin-core domestic lighting flex and a cheap electrical test meter (with a resistance – Ω – scale). Connect one end of the cable to the meter and lower the free end with bared wires, which may be weighted with a piece of metal, into the borehole. When the bare wires touch the water, the meter will register a current. When that happens, mark the cable, pull it out, and measure the length from the bared end to the mark.

Penetration rate through each zone or formation in the borehole may be determined simply by timing the progress of one drill pipe or a fixed distance marked by two chalk marks on the drill pipes as they pass through the table. Penetration rate can provide an estimate of formation consolidation or hardness, and also show precisely when an aquifer was crossed.

The question, then, is: When to stop drilling? The supervisor normally has an idea, from the project specifications, of how much water is required from a borehole; a hand-pump, for instance, does not demand a large supply (0.5 litre/sec is more than enough), whereas a motor pump supplying a storage tank for a village, a refugee camp, or a facility such as a school requires a significantly greater yield.

When drilling is finally stopped by the supervisor (who normally bears this responsibility), it is advisable to allow a few minutes for the water level in the borehole to recover and to then measure it with a cable dip meter.

Field hydrogeologists and water engineers working on borehole drilling projects in the commercial or humanitarian sectors are most likely to encounter rotary drilling machines (of whatever size) using mud circulation or compressed air. For this reason, the discussion in this review is limited to those techniques most commonly used in water borehole drilling: mud rotary and air rotary, as cable-percussion drilling, auger drilling, and other methods are becoming increasingly rare.

5.1.1 Mud rotary drilling

Besides the cooling and lubrication of drilling bits, which has already been mentioned, the addition of special muds or other additives to circulating water provides the following significant advantages when drilling in unstable formations:

- By using fluids of a density higher than that of water itself, significant hydrostatic pressure is applied to the walls of the borehole, preventing the formation from caving in
- The liquid forms a supportive 'mud cake' on the wall of the borehole, discouraging the collapse of the formation
- The liquid holds cuttings in suspension when drilling is halted for the addition of drill pipes
- The liquid removes cuttings from the drill bit, carries them to the surface, and deposits them in mud pits (see below)

Drilling mud – a partially colloidal suspension of ultra-fine particles in water – fulfils these functions by virtue of its properties of velocity, density, viscosity, and thixotropy (ability to gel or freeze when not circulated). Water by itself exerts hydrostatic pressure at depth in a borehole, but at shallow depths this may not be sufficient. Among additives for increasing the density of water, salt is one of the most convenient; but one of the most widely used is a natural clay mineral known as bentonite (calcium montmorillonite), which swells enormously in water. A slurry consisting of water and bentonite combined in the proper proportions has a higher viscosity than water and forms a mud cake lining in the borehole. However, a major disadvantage is that the mud needs to be mixed and left for some 12 hours before use to allow the viscosity to build up.

The normal bentonite mud mix is 50 kilograms per cubic metre of water (a 5% mix), or 70 kilograms per cubic metre, if caving formations are expected.

Natural polymers provide a more practical solution for water boreholes, but they are relatively expensive, so should be used with care. One example of such a polymer, used in oilfield and water drilling, is guar gum, an off-white coloured powder extracted from guar beans. It is an effective emulsifier used in the food industry, so is biodegradable, and will lose its viscosity naturally after a few days. Polymers are best mixed by sprinkling the powder into a jet of water, to prevent the formation of lumps. The polymer mud should be mixed during the setting-up stage – a minimum of 30 minutes is usually required – so that it has time to 'yield' (build up viscosity).

However, this writer found that, at daily temperatures of between 38 and 42 degrees Celsius or more in Sudan, guar gum mud (a particular brand purchased in Nairobi) did not last more than a day: decomposition and loss of viscosity began the next day.

The normal mix for guar gum polymer is one kilogram per cubic metre of water; for drilling in clay formations, use up to 0.5 kilogram per cubic metre, and for caving formations, use one to two kilograms per cubic metre.

Besides the usual mud properties, polymer drill fluids also coat clay cuttings, preventing the formation of sticky aggregates above a drill bit (known as 'collars'), which can hold up drilling while they are removed (a simple remedy for clay aggregation is to add salt to the drilling fluid). Another advantage of polymers is that they make it possible, when it is clay that is being drilled through, to distinguish genuine formation samples from the mud. Degradation of polymer muds is accelerated by high ambient temperatures, acidity, and the presence of bacteria (using the polymer as a food source): polymer-based mud might last only two or three days in tropical conditions, and can cause bacterial infection of the borehole.

It could be that natural polymer powders have a limited shelf life, and this should be checked before purchasing stock from a supplier. Food-grade bacterial inhibitors have been used as additives to prevent the breakdown of polymer-based muds. When using polymers, observe the manufacturer's guidelines. Foaming agents are also widely used as drilling fluid additives, normally in air drilling (see Section 5.1.2).

A) Checking the viscosity of drilling mud

Every mud additive (bentonite, mud, salt, etc.) must be mixed into the circulating water to provide the correct viscosity. This can be done initially in a specially prepared pit (see Figure 12), but as drilling proceeds, and especially if groundwater is struck, the mud will become diluted, and more mud or additive powder will have to be added. Too low a viscosity may result in fluid seeping into the formation, and it may later be difficult to remove the fine mud particles from the wall of an intersected aquifer, reducing the efficiency of the borehole (see Section 6.2). 'Thin' mud may also cause cuttings to fall back onto the drill bit, causing it to stick in the hole. The viscosity of drilling mud can be easily and frequently checked by means of a simple viscometer known as a Marsh funnel. This is a rugged plastic funnel, with a built-in screen or strainer to filter out lumps as the mud sample is poured in (shown in Figure 11; for details regarding its purchase, see Product reference 4, Annex 7).

Figure 11. The Marsh funnel viscometer. Top, built-in funnel screen. Bottom, 1000 ml plastic measuring jug with one-quart (946ml) mark.

Marsh funnel viscosity is reported as the time in seconds required for one full quart (946 millilitres) of drilling mud to flow out of the funnel. The funnel is filled through the screen with a fresh mud sample up to a quart mark, or to the level of the built-in screen, while blocking the outlet with one finger. Allow the mud to run down into a quart-graduated or marked container and time the flow for one quart of mud. Remember also to note the ambient or mud temperature at the time of the measurement.

Extremely porous or fissured formations can cause a loss of drilling fluid (mud); it is possible that the entire mud

Typical Marsh funnel times required for common drilling conditions	
Normal drilling mud	35 to 45 seconds
Medium sand	45 to 55 seconds
Coarse, permeable sands	55 to 65 seconds
Gravels	65 to 75 seconds
Coarse gravels	75 to 85 seconds
Zones of high permeability	60 to 80 seconds
Partial loss in water-bearing zones	100+ seconds
Caving sand may also need a high viscosity mud.	
Note: One quart of clean water normally runs out of a Marsh funnel in 25.5 seconds, one litre in 27 seconds.	

circulation might disappear into a cavity. This could put a stop to drilling altogether, if increasing fluid viscosity by adding more additive has no effect. If the area from which fluid is being lost is not likely to be part of an aquifer, fibrous materials such as sawdust, dried grass, or cow-dung could be introduced into the mud, while ensuring that a pumpable circulation is maintained. Such additives can block large pores and cavities permanently, which is why they should not be used to cure losses in a water-bearing zone.

An alternative method is to add foaming agents, essentially soaps or detergents and biodegradable surfactants. Household detergents such as washing-up liquids and cold-water laundry soap powders are quite effective, if professional drilling additives are not available. A combination of drill mud and foaming agent can produce a mixture whose consistency resembles that of men's shaving cream; this is extremely effective at blocking cavities and lifting material out of a borehole, especially if air can be introduced, even with a small compressor. A mix of about 5% foaming agent and 1% polymer mud produces a fairly viscous foam.

Note: A stiff foam takes up more space and its use might necessitate larger settlement pits than originally envisaged.

B) Mud pits

To mix the mud, as described previously, mud pits are required. This can be combined with a 'suction pit' or sump from which a mud pump will take the circulation supply.

Second, a larger, 'settling' pit is essential, in which mud returning to the surface from the borehole's annular space will be allowed to drop its load of drill cuttings. The two pits and the borehole are usually connected by shallow channels or ditches and a weir; a typical arrangement is shown schematically in Figure 12. Mud pits are most commonly dug in the ground alongside the rig, but some contractors can supply steel tanks, which are their equivalent. If dug in soft soil, pits may be lined with plastic sheeting, clay or cement. Mud circulation through pits must be slow and steady, to settle the cuttings and to make collecting formation samples (normally taken from a channel close by the borehole) easier. The mud pump inlet and strainer are held by rope above the bottom of the suction pit, so that mud that is as clean as possible can be recirculated into the borehole via the drill pipes. Optional extra 'swirl pits' may be included between the borehole and the settling pit to

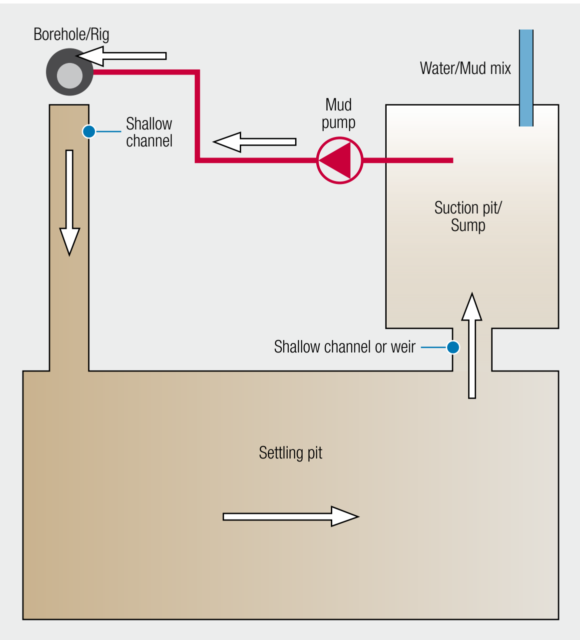


Figure 12. Schematic plan view showing mud pits and mud circulation (anti-clockwise white arrows). Not drawn to scale.

further aid settlement of debris. The capacity of the suction pit should be roughly equal to the volume of the hole being drilled; the capacity of the settlement pit should be at least three times that.

To roughly calculate pit volumes, given hole diameter D in inches (drill bit size):

Borehole volume and suction pit volume = $D^2H/2000$ in cubic metres (or $D^2\ H/2$ in litres), where H is depth of hole in metres.

Settlement pit volume should be ~$0.002D^2H$ cubic metres (or $2D^2H$ litres).

If borehole diameter changes, adjust calculations accordingly.

The suction pit should be constructed as an approximately equal-sided cubic space; the settling pit should be approximately two to three times as long as it is wide and deep (e.g.. 2 × 1.5 × 1 or 3 × 1 × 1 m).

The greyscale gradations show progressive settlement of drill cuttings up from the borehole annular space (dark ring) through the system, from dark grey (loaded mud) to pale grey (clean mud). The mud pump and mud hoses back to the drill pipe are shown in red. The yellow marker shows the area from which borehole cuttings samples should be obtained. The water/mud mix inlet is shown in blue.

C) Return fluid velocities

For mud rotary drilling, up-hole (return) fluid velocities should be within the range 15 to 30 metres/minute.

The minimum capacity for a circulation pump can be calculated from the formula Q = 7.5 (D2 – d2) where Q is up-hole flow rate in litres/minute for any combination of drill bit diameter D and drill pipe diameter d (both expressed in inches).

Table 3. Mud rotary: Circulation fluid flow rates for a range of drill bit and drill pipe sizes

Borehole (drill bit) diameter		Drill pipe diameter					
		58 mm (2¼")		75 mm (3")		88 mm (3½")	
		Fluid flow litres/min		Fluid flow litres/min		Fluid flow litres/min	
		Min	Max	Min	Max	Min	Max
75 mm	3"	30	60	—	—	—	—
90 mm	3½"	54	108	25	50	—	—
100 mm	4"	82	164	55	110	25	50
125 mm	5"	150	300	120	240	100	200
140 mm	5½"	180	380	160	320	135	270
150 mm	6"	230	460	200	400	175	350
200 mm	8"	450	900	415	830	390	780
250 mm	10"	700	1400	685	1370	650	1300

Table 3 shows the maximum and minimum fluid flow rates in litres/minute for various borehole (drill bit) diameters; maximum flow rates are about double the minimum.

On successful completion of a borehole, mud cake, foam or other additives (if used), and all drilling debris must be washed out from the borehole. This is the development stage and is covered in Section 6.2. Suffice to say here that drilling muds often require other additives to effect their dispersal.

5.1.2 Compressed air rotary drilling

Using compressed air as the circulation medium does away with having to prepare and inject liquids into a borehole (although water and additives may be introduced for special purposes). In some cases, the use of air drilling may be essential: for example, when constructing observation holes for pollution studies, where groundwater contamination should be kept to a minimum. Even then, a formation may become contaminated by oil particles from the compressor. The principal features of air drilling may be summarized as follows:

The use of a low-density circulation medium (air) requires high fluid velocities to lift debris out of the borehole. Thus, for large-diameter boreholes, large-capacity compressors are required (see Table 4).

Dry formations present few obstacles for air drilling, but a water strike at depth requires that the air pressure overcome hydrostatic pressure to a significant degree, to operate the DTH hammer and carry water and cuttings to the surface. Damp formations can, however, cause problems, such as the accumulation of sticky cuttings above the drill bit (like the clay 'collar' referred to earlier).

Air provides very little protection from borehole collapse, other than dry or damp pulverized rock powder that smears the wall of the borehole. Because softer formations are easily eroded, it is vital to protect the looser upper section of the borehole by inserting a suitable length of steel tubing known as a 'conductor pipe,' which is a little larger in diameter than the drill bit used when 'spudding in' (the very moment drilling starts at surface level). The conductor pipe should protrude a little above ground level – but not so much that it interferes with the rig drilling table – leaving space for cuttings to blow clear. Boreholes are drilled with larger bits at first, reducing diameter at depth, after installing temporary steel casing (protective lining inserted inside the conductor pipe) to protect areas of unstable

Table 4. Air drilling: Maximum drill bit sizes for a range of compressor capacities and drill pipe sizes

Compressor capacity			Maximum borehole (drill bit) diameter					
m^3/min	litres/sec	ft^3/min	Drill pipe diameter 58 mm (2¼")		Drill pipe diameter 75 mm (3")		Drill pipe diameter 88 mm (3½")	
3	50	100	85 mm	3"	—	—	—	—
5	80	175	100 mm	4"	115 mm	4½"	125 mm	5"
7	120	250	115 mm	4½"	125 mm	5"	140 mm	5½"
10	175	375	125 mm	5"	140 mm	5½"	150 mm	6"
13	210	450	140 mm	5½"	150 mm	6"	165 mm	6½"
17	280	600	150 mm	6"	165 mm	6½"	175 mm	7"

formation. Typically, the drilling of a borehole by the air rotary method may consist of three stages of varying diameter, as shown in Figure 10.

While air drilling, up-hole airflow rates should be within the range 900 to 1200 cubic metres/minute.

The required compressor capacity can be calculated from the formula $Q = ½(D^2–d^2)$ in cubic metres/minute (with D and d again being expressed in inches).

Temporary casing may be particularly difficult to insert through a horizon containing stones or boulders (such as coarse river channel deposits), but unfortunately such formations often host good aquifers. DTH hammers can break hard rock boulders (or partially fragment them), but there is always the risk of the hammer diverting and becoming wedged, or lumps of rock falling behind the bit and jamming it in the hole. The best way to deal with boulders is to install a simultaneous casing system, which is supplied by most DTH hammer manufacturers. This allows steel casing to be pushed or pulled down a borehole, directly behind the hammer, to prevent the walls from caving in. The hammer has a large diameter bit that is used to make the hole for the casing; the bit can be mechanically reduced in size and retrieved through the casing. Such systems require rigs with strong masts and the power to handle heavy casing insertion in difficult drilling conditions.

Cuttings samples during air drilling are usually obtained by pushing a shovel under the drill table alongside the conductor pipe. As the samples are blown out, rock fragments collect around the conductor pipe and some land on the shovel. At the prescribed sampling interval, the shovel is withdrawn with the fresh sample. Drillers often need to be reminded to collect these samples.

During air drilling, foams can be added through the drill pipes to eliminate dust emerging from a dry hole, to keep the borehole clean, and to prevent fine particles from clogging any small water-bearing fissures that may be intersected. Furthermore, soap bubbles help lift debris out of the borehole. However, foams do not provide any hydrostatic support for collapsing boreholes; they also make it difficult to collect samples at any drill depth.

However, drillers often forget to make these chalk marks. The supervisor must keep count of the number of drill pipes going into the hole. The total length of these, plus the length of the drill bit, is the correct depth (beware of drill pipes of slightly differing lengths).

5.2 Borehole logging

For a borehole to be properly logged, the driller and supervisor need to know its exact depth at all times. This is necessary for the calculation of drilling charges, and while designing the borehole (see Section 6). First, make a note of the length of the drill bit and of any other tools that may be used to drill the hole. Put the bit on the ground and make a chalk mark, '0,' on the first drill pipe against a suitable fixed point on the rig and at a known height above ground level, such as the drilling table (which centralizes the drill pipes in the hole). From then on, marks can be made on the drill pipe at regular intervals – say, every half metre – to record the depth of drilling and to assist in the logging of penetration rates.

A) Formation samples

Formation samples need to be obtained as drilling proceeds: the usual sampling interval is one metre. These are obviously highly disturbed samples, having been sheared or broken from their parent formation, so should not be used to infer characteristics such as bedding, texture, porosity, or permeability. There will be a slight delay as formation fragments are lifted to the surface by the circulating mud, but a rough estimate of the up-hole velocity should enable one to calculate the actual depth at which cuttings were derived. Keep in mind that if mud viscosity is too high, or if formation collapse occurs (viscosity too low), some fragments could return to the borehole, with the potential of causing confusion. Cuttings obtained from the shallow mud channel near the borehole (see Figure 12) should be washed in water to remove mud, and laid out in order (by the depth at which each was acquired) on the ground or in a sample box with separate compartments for each sample. They can then be logged by the supervisor or site geologist and bagged if required. Samples should, of course, be labelled correctly with all information relevant to the job in hand.

The main attributes of a borehole log are accuracy and consistency; a good set of logs can be a useful resource when planning future drilling programmes. Drillers must keep their own logs and notes and, as is often stipulated in contracts (see Section 11), these should be accurate; however, in practice, they cannot always be relied upon, especially if the supervisor is absent from the site for a period. All geological samples and water strikes should be logged by the drillers and the supervisor, as this important information will be required for designing the borehole and the equipment to be installed.

Full borehole logging may also include geophysical logging, which is normally carried out only after a well has been completed. These systems are briefly described in Section 6.3.3.

Annex 1 gives a typical example of a drilling log sheet, which is applicable for both mud and air drilling, and which should be kept by the supervisor. The driller's log should also include information on drilling or other work time, standing (waiting) time, and downtime (breakdowns).

Water strikes made during mud rotary drilling are usually indicated (unless they are very minor) by a rapid dilution of the mud mix. Intersection of an aquifer during air drilling is much more obvious, as the machine will begin blowing out damp fragments of rock instead of dry dust.

6. BOREHOLE DESIGN, DEVELOPMENT, AND COMPLETION

Having drilled a borehole to the required depth, the supervisor should be armed with the following information:

- The depth of the borehole
- A lithological log of the borehole
- Borehole diameter(s) and depths of any diameter reduction
- Depths of water strikes (if any)
- Penetration rate log
- Approximate static water level in the borehole (or some indication of what this might be)

All this data should appear on the borehole log sheet (see Annex 1), and should be used while designing the borehole. Some idea of the final design should already be in the mind of the supervisor when he or she is selecting drilling diameters. For example, if the borehole is required for a hand-pump, a large-diameter hole would be unnecessarily expensive; and only one size of bit – possibly two at most, because hand-pumps make lifting from great depths very hard work – will be needed.

6.1 Borehole construction design

As water is pumped out of a borehole, the water level in the hole falls. It may fall by an amount known as the 'pumping drawdown,' which eventually stabilizes for that rate of extraction. If the water level does not stabilize and continues to drop until the borehole is 'dewatered,' the hole is being over-exploited. In this discussion it is assumed that boreholes are designed with the intention of maximizing yield and efficiency, the normal requirements for everything other than hand-pump-equipped holes.

- The maximum yield of a borehole is defined as that yield which the borehole can sustain indefinitely before drawdown exceeds recharge from the aquifer.
- Borehole efficiency is technically defined as the actual specific capacity (yield per unit of drawdown: say, litres per second per metre) divided by the theoretical specific capacity, both of which can be derived from a pumping test. Specific capacity declines as discharge increases.

Once all the lengths of temporary casing and conductor pipe installed during drilling have been removed by the drillers, the depth of the borehole should be checked by a weighted plumb-line, in order that an accurate construction design may be drawn up.

6.1.1 Borehole casing

Boreholes are constructed by inserting lengths of protective permanent casing. These are lowered or pushed into the hole by the drilling rig to the required depth; the lengths of casing may be joined together by means of screw threads, flange-and-spigot, gluing, riveting, or welding. Casing normally extends up to the surface, with a certain amount (say 0.7 metre) standing above ground level. Lengths of casing may be obtained in mild steel, stainless steel, and plastic (such as uPVC, ABS, polypropylene, and glass-reinforced plastics). Plastic casings are more fragile and deformable than steel casings (especially the screw threads), and so should be used mainly for low-yield and shallow boreholes. The casing should be capable of withstanding the maximum hydraulic load to which it is likely to be subjected, that is, about 10 kilopascals (kPa) for each metre that extends below the water level down to the maximum expected drawdown. Table 5 gives a few typical values of casing collapse strength (Clark, 1988), but because of the number of variables, it is advisable to consult manufacturers' specifications.

Because of their fragility, plastic casings should be stored and shipped with care. Stack the materials properly in shade (not direct sunlight) because the plastic is susceptible to degradation and deformation by heat and to degradation by natural ultraviolet radiation. In very cold (sub-zero) conditions, PVC becomes brittle.

Table 5. Typical casing collapse strengths

Casing material	Casing wall thickness	Collapse strength
uPVC	12.4 mm	660 kPa
Polypropylene	12.7 mm	690 kPa
Glass-reinforced plastic	6 mm	690 kPa
Mild steel	9.4 mm	11.1 MPa

Steel casing is available in a variety of grades and weights. Low-grade casing can be used for shallow tube-wells, but heavy-duty, high-grade steel should be used for deeper boreholes (especially those more than 200 metres deep) and when ground conditions hamper insertion (such as coarse gravel/boulder formations). Special types of casing that can resist aggressive waters are also obtainable, but

A drilling contractor might arrive on site with a number of odd lengths of steel casing, which the drillers would attempt to weld together. In such instances, beware of the drillers using, or having used, angle grinders to cut the casing, which might, as a result, be left without very straight or square ends. This writer has observed drillers attempting to weld together steel casings with a significant gap between adjacent sections: this resulted in breakage at the inferior weld in the borehole. Check also that the drillers are using the correct type of welding rod: if mild steel/mild steel, mild steel/stainless steel, or stainless steel/stainless steel joints are required, different types of welding rod may be necessary. Using the wrong welding rods could cause parting of the casing in the borehole.

stainless steel is the best means of combating corrosion. Casing is usually supplied in standard lengths already equipped with screw threads or other jointing methods.

6.1.2 Borehole well screens

When a borehole has been dug alongside a water-bearing zone, the casing installed in it must have apertures that allow water to enter as efficiently as possible while holding back material from the formation. These perforated sections are known as borehole or well screens; they come in sizes and joints similar to casing, so can be interconnected with suitable plain casing in any combination, or 'string.' Screens can also be obtained with a variety of aperture (slot) shapes and sizes, from simple straight slots to more complex bridge slots and wire-wound screens made with V-cross section wire. Screen slots should be of a regular size, aperture, and shape because they might have to efficiently prevent all particles of a certain size from getting through. Plain plastic casing can be easily slotted with a saw or special slotting machine, but beware again of drilling contractors cutting irregular, messy slots in steel casing with grinders or oxyacetylene torches. The open area of factory-made plastic screens commonly exceeds 10% of total surface area, but rough-cut holes in mild steel casing rarely take up more than 2 or 3%. Screen slots should be slightly smaller than the average grain size of the aquifer fabric, and should allow water to enter the borehole at a velocity within the range 1 to 6 centimetres/second (0.01

to 0.06 metre/second). Entrance velocity is defined as the discharge rate of the well divided by the effective open area of the screen. Too high an entrance velocity may lead to screen incrustation, excessive well losses, and other damaging consequences of turbulent flow conditions.

A) Formula to calculate the open area of a screen

Open area of screen per metre of screen in cm^2 = l × w × n/10, where l is length of slot in cm, w is width of slot in mm, and n is number of slots per metre length.

For example, a minimum screen open area of 100 cm^2 provides, roughly speaking, the minimum entrance velocity for a yield of about 0.3 litres/second (about 4 gallons/minute). In practice, additional screen lengths should be included to allow for variations within the aquifer (which is unlikely to be homogeneous) and in the borehole (see Table 1).

The most efficient well screens are the well-known 'Johnson screens' – continuous-slot types manufactured with V-wire wound spirally around a cage of longitudinal support rods. The whole structure may be composed of stainless steel or low-carbon galvanized steel. These wire windings have been constructed such that the slots widen inwards, which significantly reduces rates of screen clogging, as illustrated in Figure 14. The effective open areas of Johnson screens are more than twice that of conventional slots, which allows

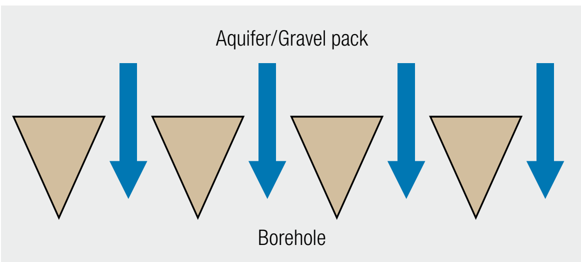


Figure 13. Water flow through a V-wire screen

more water to enter per length of screen. Slot sizes of 0.15 to 3 mm, diameters of 1½" to 32", and screen lengths of 3 metres and 6 metres are available. The different grades of screen are suitable for a variety of borehole depths; the ends are plain (for welding) or screw-threaded (Product reference 5, Annex 7). Johnson screens allow yields of about 5 to 6 litres/second per metre length, so that a 6-metre-length can give about 30 to 35 litres/second and a 12-metre-length twice as much.

Most projects, and especially those involving shallow or low-yield boreholes, require only basic PVC casing and screens to be installed. Table 6 provides pumping rate, borehole diameter, and screen opening data; recent quoted prices for various sizes of casing and screen are provided in Annex 2.

Table 6. Casing diameters and screen openings

Expected pumping rate (litres/sec)	Borehole diameter (inches)	Minimum screen opening (cm^2)
0.3	6	100
0.5	6	180
0.8	6	300
1.0	6	400
1.5	6	500
2.0	6	750
2.8	6	1000
4.2	6	1500
5.6	8	2000
7.0	8	2500
8.3	8	3000
11.0	10	4000

6.1.3 Gravel pack

After the casing and screen string have been inserted, natural material will tend to fall from the walls of the borehole into the annular space, forming a natural backfill or 'gravel pack' that helps to filter incoming water. The screen slot sizes should be such that only the finer content of this backfill is allowed into the borehole; this can be washed out during development, leaving the coarser portion behind to act as a filter. Thus, an aquifer is suitable for the development of a natural gravel pack if it is coarse-grained and poorly sorted, as many alluvial gravels are (a relatively rare situation). A borehole drilled into an unstable aquifer formation, or into one that is well sorted, and with a high proportion of fines (which would be apparent from the drill samples), will require an artificial gravel pack around the screens. When the only screens available on site are of a slot size larger than the average grain size of the aquifer, then a gravel pack should be installed. Unfortunately, time and other constraints do not normally allow a detailed grain-size analysis of the aquifer fabric to be carried out in the field; so, a degree of intuition is required here. If there is any uncertainty, instal an artificial gravel pack.

A) Artificial gravel pack

Ideally, an artificial gravel pack should consist of clean, rounded, quartz 'pea' gravel supplied in bags; grains the size of small household peas are generally suitable. Coarse, well-worn river sand is often ideal; the grains should be a little larger but no more than twice the screen slot size. Being smooth and spherical, the grains should run easily down into the annular space without clumping and leaving gaps of air (a little water often helps).

The standard practice is to produce a 3 to 4-inch wide annular space for the gravel pack (say, a 6″ screen in a 12″ hole); the casing/screen string must be centred in the borehole. Most boreholes are not perfectly straight, so the casing will almost invariably be in contact with the wall in some places unless it is centralized. This is achieved by

Many contractors will bring on site whatever they consider to be suitable gravel, which may be irregular stone chippings or 'building aggregate.' It is then up to the supervisor to decide on the acceptability of this gravel, given such factors as remoteness of location and availability of better materials. If the only material available is concrete-type aggregate and the borehole annular space is narrow (less than 3 inches), consider, if at all possible, the use of a smaller screen slot size without the gravel pack.

using manufactured centralizers (such as flexible 'wings') or some other suitable alternative. Unfortunately, in developing countries, few drilling contractors bother to provide centralizers, even if they have heard of them. It is extremely difficult – if not impossible – to fashion effective casing centralizers in remote locations. Section 11 of this review suggests that project organizers or supervisors should attempt to familiarize themselves with the competence of bidding contractors to ensure that the successful firm will be familiar with and willing to offer essential technical components.

Before pouring gravel pack material into the annular space, which must be done smoothly and without haste, calculate the volume of annular space (it is reassuring to see that the correct volume of gravel has been installed). Again, an accurate log of borehole size changes is required here. Pouring gravel pack into a borehole with a high water level usually results in displaced water rising in the hole and overflowing. Water overflow will abruptly stop as the screen becomes covered by gravel. Continue to pour gravel until you are certain that the top of the pack is well above the top of the screen.

Annular volume between borehole diameter D and casing/screen diameter d (D and d both in inches), length L (in metres) = ~½L(D^2–d^2) in litres.

Thin gravel packs (less than 50 mm, or 2", thick) may be installed to act as a formation stabilizer only in conditions such as those associated with a fractured or slightly weathered consolidated aquifer. It should also be noted that gravel packs greater than 150 mm (6") thick will make borehole development more difficult, especially if a drilling mud lining has to be removed.

Introducing a natural or artificial gravel pack into a borehole will reduce the effective open area of the screen, because now the open area (porosity) of the system at the aquifer/screen interface will be limited by that of the packing in the annular space rather than the screen. Well-rounded grains of uniform size (as in the 'ideal' gravel pack) have among the highest primary porosities (around 40%) and permeabilities (20 or more metres/day) in unconsolidated sediments; in practice, the figures are probably much lower. The effective open area of the adjacent aquifer is more likely to be around 10%. The result is that one should assume the effective open area of a screen, even with a gravel pack of good quality, to be roughly half the actual

Table 7. Choice of screens and gravel pack for various ground conditions

Aquifer characteristics Physical/Chemical	Crystalline (narrow fissures or joints)	Consolidated (small voids/ porosity)	Unconsolidated	Stable but with fissures/ Caverns
Thin (<100m)	No screen or gravel pack normally required (open hole). Screen plus formation stabilizer might be necessary if formation fractured.	No screen or gravel pack normally required (open hole). Screen plus formation stabilizer might be necessary if formation fractured.	Screen with high open area and gravel pack required. Might develop natural gravel pack if aquifer homogeneous.	Screen with high open area. Gravel pack required if caverns contain loose sediment.
Thick (>100m)	Long screen with small open area (10%). No gravel pack (except, possibly, formation stabilizer if formation fractured).	Long screen with small open area (10%). No gravel pack (except, possibly, formation stabilizer if formation fractured).	Long screen (or multiple screens) and gravel pack required. Might develop natural gravel pack if aquifer homogeneous.	Long screen (or multiple screens) and gravel pack required if caverns contain loose sediment.
Deep (>200m)	No screen or gravel pack required (except, possibly, formation stabilizer if formation fractured).	No screen or gravel pack required (except, possibly, formation stabilizer if formation fractured).	Strong (steel) casing/ screens and gravel pack required. At depth, a natural gravel pack might be less likely to develop.	Strong (steel) casing/screens and gravel pack required if caverns contain loose sediment.
Corrosive water (e.g. high salinity, low pH, high temperature)	As above, but use plastic or stainless steel casing/ screen(s).	As above, but use plastic or stainless steel casing/ screen(s).	As above, but use plastic or stainless steel casing/ screen(s).	As above, but use plastic or stainless steel casing/ screen(s).
Encrusting water (e.g. iron/ carbonate enriched)	As above, but use high open area screen (s) to reduce entrance velocities.	As above, but use high open area screen (s) to reduce entrance velocities.	As above, but use high open area screen (s) to reduce entrance velocities.	As above, but use high open area screen (s) to reduce entrance velocities.

screen open area. The recommended minimum actual open area of any installed screen is around 10%.

The essence of borehole design is deciding the combination of plain casing and screens to be inserted and the type of screen to be used, and whether a gravel filter pack (or thin formation stabilizer) is required. Table 7 attempts to summarize these decisions for a variety of ground conditions that are likely to be encountered during drilling. An 'open hole' design is one in which no screen or gravel pack is used in the area of the aquifer, but all boreholes that this writer has encountered have required casing, to at least stabilize the superficial soils or weathered zone (regolith). Open holes are suitable mainly for hand-pumps, because of the danger of a powerful motor pump sucking in debris even from a stable hard rock formation. If a stable formation is encountered some way below a water strike, reducing the penetration rate, some extra borehole depth, to act as an open-hole sump, can be created a little more quickly by reducing drill bit size.

6.1.4 Pump selection

One also needs to consider what type of pump is to be used in the borehole as well as its size and the casing and screen diameters needed to house it. Relatively low-yield boreholes intended for hand-pumps with submerged pistons are rarely more than 30 metres deep and need not be of large diameter (4 inches can be enough). Certain types of hand-pump can be fitted with counterweighted operating handles, to make drawing from deeper water levels less exhausting (mainly for women in developing countries). Mechanical reduction of the submerged piston stroke can make drawing water easier, but as less water is drawn by each stroke of the pump, filling a container takes longer. Shallow boreholes often tap weathered zone aquifers above hard, impervious clays or bedrock (such as granite); the schematic diagram in Annex 3A shows how a typical example might be completed with a hand-pump. The standard practice is to place the pump inlet slightly above the upper end of the screen. For hand-pumps, this does not matter much: in the example shown in Annex 3A, the pump inlet could be lowered into the upper part of the open hole/sump (by attaching extra pipes) if there is a significant fall of static water level in the borehole because of prolonged drought.

More powerful types of pump, such as electric submersibles and rotary positive displacement pumps, must always be installed inside protective plain casing: screens are not appropriate for this purpose. The internal diameter of the pump chamber should be at least 5 centimetres (about 2 inches) greater than the external diameter of the pump.

6.1.5 Sealing the borehole

The borehole structure must be sealed at the top of the casing with a 'sanitary seal' (Section 6.3.1); it can also be sealed at the bottom to completely eliminate the possibility of material entering through any means other than the screen(s). With plastic casing this can be done by attaching a 'closing cap' to the bottom end.

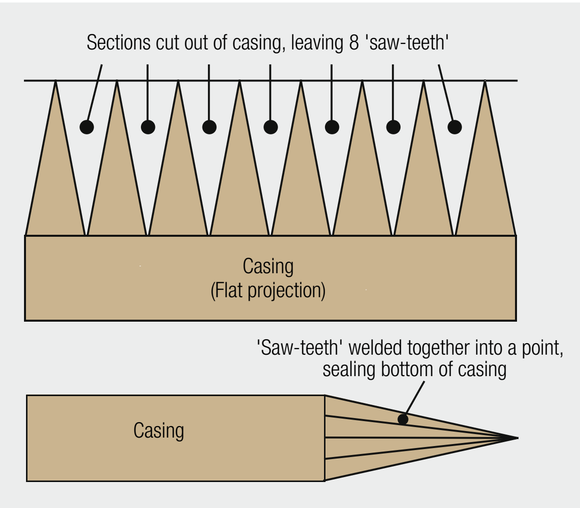


Figure 14. Sealing the bottom end of mild steel casing by the welded 'saw-teeth' method. Typical length of teeth 0.5 to 1m.

Before installation, a string of mild steel casing/screen can be sealed at the base by the following method (see Figure 14): at the intended bottom end of the string, first mark out a regular and long 'saw-tooth' pattern around the circumference (usually eight 'teeth,' typically 0.5 to 1 metre long); cut out the triangular sections with their apexes pointing upwards (in terms of the borehole); hammer the saw-teeth on the casing to a sharp point; and weld the edges of the teeth together to seal the casing.

A problem this writer has witnessed on a number of occasions when contractors were unable to provide a closing cap for plastic casing, but nonetheless wrongly assumed that the casing was sitting firmly on the bottom of the borehole: lost gravel pack had to be blown out of the hole and the casing pressed down harder (risking breakage) before new gravel could be poured. At one site in northern Uganda, this had to be done twice.

It will be readily seen that producing a point at the lower end will assist lowering of the casing into the borehole, especially if difficult drilling conditions such as coarse gravels, stones, or boulders are encountered. Furthermore, closing off the casing ensures that gravel pack material cannot enter the borehole from the annular space.

6.1.6 Examples of borehole design

A) Homogenous aquifer

In Figure 1, hypothetical borehole site B has been drilled into a partly consolidated, relatively homogeneous sandstone aquifer that would require a full artificial gravel pack. To provide additional dynamic drawdown, the pump inlet has been placed in a short section of plain casing between two lengths of screen. High-powered pump inlets should always be placed above the upper end of a screened area, or within a section of plain casing between screens (pump chamber, shown in Annex 3B). Fast water flow into a pump should never be straight through the screen, as the adjacent high entrance velocity will cause rapid screen erosion or incrustation. Furthermore, water flowing upwards past and through a submerged pump has a greater cooling effect on the moving parts. Also, there will be less risk of sucking in damaging particles.

B) Exploiting two aquifers

Annex 3C shows the borehole design suggested for hypothetical borehole site C in Figure 1, intersecting and exploiting two aquifers. We may assume that, on the basis of geological information, this site was selected as a potentially high-yield and relatively deep borehole; the drilling contractors would have been instructed to make mild steel casing and Johnson screens available for its completion. The presence of a significant cavity with loose infilling sediment (such as lateritic pea gravel) within the deeper fissured limestone aquifer would have confirmed the necessity for this section to be cased and screened, and may even have led to the termination of drilling. Caving infill would have been sampled as drilling came to an end, and the screen chosen would have had a slot size small enough to exclude most of the material. If, as in this example, a casing size reduction is deemed advantageous, size reducers can be manufactured on site by cutting and welding mild steel casing (as with sealing points, Figure 14). This design would permit a high-yield submersible pump to be installed just above the casing reducer. The dynamic drawdown, or pumping level, must now be considered. A screen section might have to be installed above the pump, but the water level during pumping must not be allowed to drop below the top of the upper screen. This avoids aeration of the upper section of the screen and of the adjacent aquifer, reducing the risk of screen incrustation by iron in the water. A good design should incorporate an adequate length of plain casing down to the top of the first screen, another test of the judgement and experience of the designer or supervisor.

C) Borehole in a fracture zone

An example of borehole construction in fractured rocks is illustrated by hypothetical site D in Figure 1, the proposed design for which is shown in Annex 3D. Drilled into fractured but stable granite, this borehole could be completed as an open hole. It is not likely to be a strong borehole, but as fracture zones can be unpredictable in terms of water production (often the more fractures intersected, the better the yield), it might be worth installing a string of PVC casing/screen in the event that a powered pump can be fitted. Here, a relatively small screen slot size with no gravel packing is probably enough. Sufficient pumping drawdown has, one hopes, been provided by extending blank casing further down into the water zone (choice of pump will be determined by the results of the pumping test).

More information about the yield of a newly drilled borehole will be obtained during the development stage.

> One may pose this question: How can a borehole designer guess what type of pump will be needed before a particular borehole has been properly tested? During the drilling of the borehole, the amount of water being blown out by air or diluting the circulation mud will indicate to the supervisor whether it is likely to be a 'good' borehole. Experience contributes much to this process; in designing borehole constructions, one must often trust intuition.

6.2 Borehole development

At this stage, it might seem almost impossible that clean, potable water could emerge from the mess being pumped out of a new borehole, but provided it has been properly constructed, good water will indeed appear. Whether a borehole has been drilled using mud or air circulation, it will have to be cleaned out. After the installation of the permanent casing, screens, and gravel packs (if any), dirty water, mud, crushed rock, oil (from the drilling machinery), and perhaps other debris will be left in the hole. Development can also repair damage done to the adjacent aquifer by the drilling process, develop the aquifer (increase transmissivity), and enhance the performance of the borehole.

As stated by Driscoll in *Groundwater and Wells*, "Development has two broad objectives: (1) repair damage done to the formation by the drilling operation so that the natural hydraulic properties are restored, and (2) alter the basic physical characteristics of the aquifer near the borehole so that water will flow more freely to a well." [1]

Drilling tools smear crushed rock and clay all over the walls of the borehole, and the drilling process forces dirty water and clay into the rock matrix around the hole, sealing off many water entry points from the aquifer. If these matters are not remedied, the borehole's performance will be very poor; it should also be noted that the filthy water that would be pumped out – were things to be left unaltered – would damage a pump quickly. Mud rotary drilling leaves a cake of firm clay ('mud cake') on borehole walls, often of a thickness up to one centimetre, which can effectively choke aquifers. Removal of this layer is not easy, requiring 'violent' or 'aggressive' methods, and should not be hurried or abandoned prematurely. Moreover, since mud-caked walls will have been partly isolated from the borehole internal space by casings, screens, and possibly even gravel packing, cleaning up will be even more difficult.

1 F. G. Driscoll, reference No. 5, Annex 7.

Development also encourages a gravel filter pack to settle properly, eliminating voids, which may necessitate topping up the gravel pack a little. The process should continue until the water being discharged from the borehole is, in the judgement of the supervisor, as clean as possible. Small particles of sand might occasionally issue from the borehole, but cloudiness (turbidity) of the water should have disappeared before development is stopped. Excessive production of sand might be caused by voids in the gravel packing or by damaged casings or screens. Turbidity is generally caused by colloidal clay or micro-organic particles; and can, in the latter case, result in unpleasant tastes and odours and in organic growths like slimes.

6.2.1 Development methods

In most cases, development entails the surging and blowing of compressed air; the process may be helped along by the use of additives, which can assist in breaking down drilling mud.

A) Mud dispersants

Bentonite-based muds are particularly difficult to remove; organic polymers are biodegradable and, in theory, are destroyed by bacteria with which wells can be seriously infected. Chlorine-rich compounds are effective mud dispersants, as well as bacterial disinfectants. Calcium hypochlorite (HTH or High-test hypochlorite) can be used as a mud dispersant; for rapid breakdown of guar gum, use a hypochlorite solution (12% chlorine) at about 0.4% mix in water. For slow dispersal, a weak solution of hydrogen peroxide may be used.

Bentonite is more efficiently dispersed using polyphosphate compounds like Calgon (brand name for water softener). This chemical consists of granular or powdered sodium hexametaphosphate, a hygroscopic (water attractant) material that destroys the cohesiveness and plasticity of clay particles. Granular Calgon should be dissolved in hot or boiling water (about one kilogram of the

Before opting for acidization, try to ensure the following: that the contractor possesses the necessary equipment and experience; that acids are available locally, and that the spent acid can be disposed of safely (contractors should comply with hazardous waste disposal/pollution control regulations).

chemical in 40 to 50 litres of hot water): the usual dosage is 10 to 50 kilograms of Calgon per cubic metre of water estimated to be in the borehole. Try to leave the dispersant in the hole overnight to allow the solution time to permeate into aquifer formations. Higher concentrations are needed to remove the more resistant mud cakes. Leftover mud is more easily removed when the borehole is washed out.

B) Acid treatment

Development of wells drilled into calcareous (limestone, chalk, or dolomite) formations can be aided by the use of certain acids (such as hydrochloric acid, HCl) that dissolve pulverized carbonate smear on borehole walls. Acid treatment can widen and clean carbonate aquifer fissures even when they are tens of metres away from the borehole.

Borehole acidization during rehabilitation is discussed in Section 10.2.2 as well.

C) Surging

The technique of surging (or surge pumping) consists of forcing water up and down a borehole and, more importantly, back and forth through the screens, gravel pack, and adjacent aquifer matrix. Many textbooks on this subject state that surging can be done mechanically, using a piston-like surge block or bailer, but this writer has never seen a surge block being used. Surging can also be conducted with pumps, but this is not advisable because of the possibility of damaging debris entering the pump. Furthermore, a powerful pump could dewater a borehole if the screen is blocked by mud cake and cause the screen to collapse inwards as a result of hydraulic pressure in the annular space. In practice, surging is almost invariably accomplished using compressed air – that is, air-lift pumping using the drill pipes on the rig (with the drill bit removed) and a compressor.

D) Blowing yield

Between bouts of surging, air is blown into the borehole and its pressure adjusted so that the outflow of water is

Figure 15. Measuring the blowing yield of a newly drilled borehole

more or less equal to the inflow: this is known as the 'blowing yield.' Measurement of this flow gives an indication of the performance of the borehole, and helps to design a subsequent pumping test (see Section 6.3.2A). Blowing yield can be easily measured if the drillers arrange that all the water (in practice, most of the water) being ejected from the casing can be led along a shallow channel or pipe in the ground into a measuring device, such as a bucket in a pit or a V-notch weir. Filling of a bucket of known volume can be timed to give the discharge, which, in the opinion of this writer, is a much simpler and more reliable method, less prone to error. A V-notch is an opening or weir in the form of an inverted triangle in the side of a tank or reservoir; it is used to determine surface-water flows. Water whose discharge is to be estimated is allowed to flow over the notch weir, and the rate of flow can be calculated by measuring the depth of the water over the apex of the notch. Various publications and websites give rates of flow tables for notches of different apex angles (the most common is 90°).

E) Air-lift pumping

Basic air-lift pumping suits well development because it does not involve mechanical parts, which can be damaged by debris. The air line from a compressor may or may not be inside a rising main with a discharge outlet, and the end of the air line is at such a depth that at least 50% of its length is submerged in the borehole water (Figure 16). Pumping can be stopped and started at intervals by shutting off the air supply at the compressor, which induces surging. Violent releases of pressure pull water in through the screen (and gravel pack); then, when the valve is closed, pressure rises to force water back out through the screen. So the pump/non-pump (back and forth) cycle acts like a surge block, and material is effectively loosened and removed from the borehole/aquifer boundary. Normally, the drill pipes are lowered to the bottom of the borehole and surging commences from there, with dirty water being blown vigorously out of the casing at the surface. The pipes should be raised and lowered at intervals so that different parts of the screen are subjected to surge action.

F) Jet washing

After the mud drilling of what may be a low-yield borehole, or if there is no compressor, another method that may be used is jetting: washing of the well face with high-pressure water jets. The mud pump or a separate jetting pump is used to inject clean water into the borehole down the drill pipes from a source such as a river, lake, bladder tank, or mobile bowser. At the bottom of the drill string is a jetting nozzle tool, which produces the high-pressure jets; ideally this can be raised, lowered, and rotated in the borehole. The jets are directed horizontally at the screen slots or the borehole wall. This method can be used alongside an air percussion rig, but a separate jetting rig will be required, either piped into the drill string, or with a separate injection pipe lowered down the borehole. Jetting is an effective cleaning system for screens and sections of open hole, but is less effective at penetrating the aquifer matrix than surging. Of course, a blowing yield cannot be obtained from jet development, because water is being pumped into the borehole.

G) Mechanical cleaning

Mechanical methods of cleaning boreholes, such as brushes and scratchers, are rarely used because of the possibility of damaging a screen. However, an open hole in a stable, hard rock formation could theoretically be cleaned first by wall scratching to loosen a particularly intractable mud cake, then by surging or jetting. Wall scratchers may be fashioned from rings of steel, with spokes of springy metal welded radially around the outer circumference. The ring of spokes resembles, and acts like, a flue-brush, scraping the borehole walls as it is lowered and rotated on the end of the drill string.

If there are no serious technical difficulties during borehole construction, on-site work, including development, normally takes around a week.

6.3 Borehole completion

6.3.1 Sanitary seal

With borehole cleaning completed, the final job is the construction of a sanitary seal, which, as the name suggests, seals the borehole from surface contamination. This should also be the responsibility of the drilling contractor, and written into the work agreement. At least the uppermost two metres or so of annular space (probably that section formerly protected by the conductor pipe during drilling) should be cleaned out and dug into a fresh larger hole – perhaps square in shape – surrounding the permanent casing. Below this, the borehole annular space above the gravel pack will have been backfilled with a plug of ordinary gravel, chippings, bentonite granules, or even just cuttings from the borehole. The fresh hole for the sanitary seal can then be filled with concrete grout up to, or preferably slightly above, ground level (see construction diagrams, Annex 3). For boreholes with high static water levels, capped by permeable superficial soils, little more can be done other than to take care not to spill wastewater around the borehole. Finally, the supervisor should confirm the completed borehole's total depth and static water level with a plumb line and a dip meter. Then the top of the casing must be sealed with a locked cap or welded plate, on which the borehole identification number may be inscribed.

6.3.2 Pumps and test pumping

After drilling has been completed and the sanitary seal put in place, borehole test pumping is carried out. It has the following objectives:

- To measure the performance of the borehole
- To determine the efficiency of the borehole, or variation of its performance under different rates of discharge
- To quantify aquifer characteristics, such as transmissivity, hydraulic conductivity, and storativity.

In remote locations, a supervisor or hydrogeologist may require some indication of a borehole's performance if the type of pump to be installed has not yet been determined. Blowing-yield during development will tell the supervisor that a particular borehole has the potential for good production. Low-yield boreholes (less than 0.5 litre/second) will require only a hand-pump for extraction and do not need to be tested, and time should not be wasted doing this. Boreholes of very low yield (less than 0.2 litre/second), but with high water levels (say, 10 metres or less) may not be suitable for long-term water supply, but can give an indication that groundwater exists in the area, which could be exploited by dug wells. Here, community participation should be encouraged.

Another common alternative (which this writer has often encountered in southern Africa) is for contractors to provide a trailer-mounted small-car engine/gearbox combination, which drives a Mono pump shaft drive head fixed on top of the borehole. Pump speed is controlled by engine speed and gear selection.

It is assumed for the purposes of this discussion that the borehole in question is isolated in terms of distance from other producing wells or boreholes, that there are no observation wells in the immediate area, and that there is no previous relevant information concerning test pumping or aquifer characteristics. The supervisor has only a drilling log, blowing yield, and his own knowledge and experience to call upon. In such situations, it is possible to design a simple test-pumping programme using the blowing yield as the assumed maximum safe extraction rate. Basic single-well pumping tests involve pumping at a variable and/or constant rate and measuring changes ('drawdown') in water level during pumping and recovery. Recovery is the rate at which the water level in the borehole rises ('recovers') back to static water level once the pump has been switched off. More information can be obtained if measured variable discharge rate (or 'step drawdown') and constant discharge rate tests are conducted, as the one test complements the other.

Both step and constant discharge tests evaluate borehole performance, but the constant discharge test can provide information on long-term well performance, aquifer characteristics, and even aquifer geometry. When the only information required is whether a particular pump can produce from a particular borehole on a sustained basis, a simple test – running that pump (preferably at a rate below that of the blowing yield) in the well – is all that is needed; but beware of over-pumping. This 'test' will not provide any information about the borehole or the aquifer if pumping drawdown levels are not recorded. Drawdown measurements during pumping and recovery phases are made according to a logarithmic time scale in minutes (see Annex 4).

A) Test pumping

Test pumping generally requires that the pumping rate be controlled fairly easily and accurately. The two commonest methods are: using an electric submersible pump, with valve control of the discharge pipe at the surface, or using a mechanical rotary pump (such as the well-known 'Mono pump'), driven by an engine from the surface. Both types would be lowered into the borehole at the end of a rising main to the intended pumping level in the hole.

Electric submersible pumps, many of which run only on a 3-phase AC supply, require a suitable generator and control system (switching, safety cut-outs, etc.). As they are essentially constant-discharge pumps, the pumping rate must be controlled by a valve (or valves): a uni-directional globe valve designed for regulating flow is required (as opposed to the frequently used gate valve, which is really just an on/off tap, not recommended for use in flow control).

Mechanical pumps are driven by a shaft from the surface, which, in turn, is driven via a gearbox and a propeller shaft

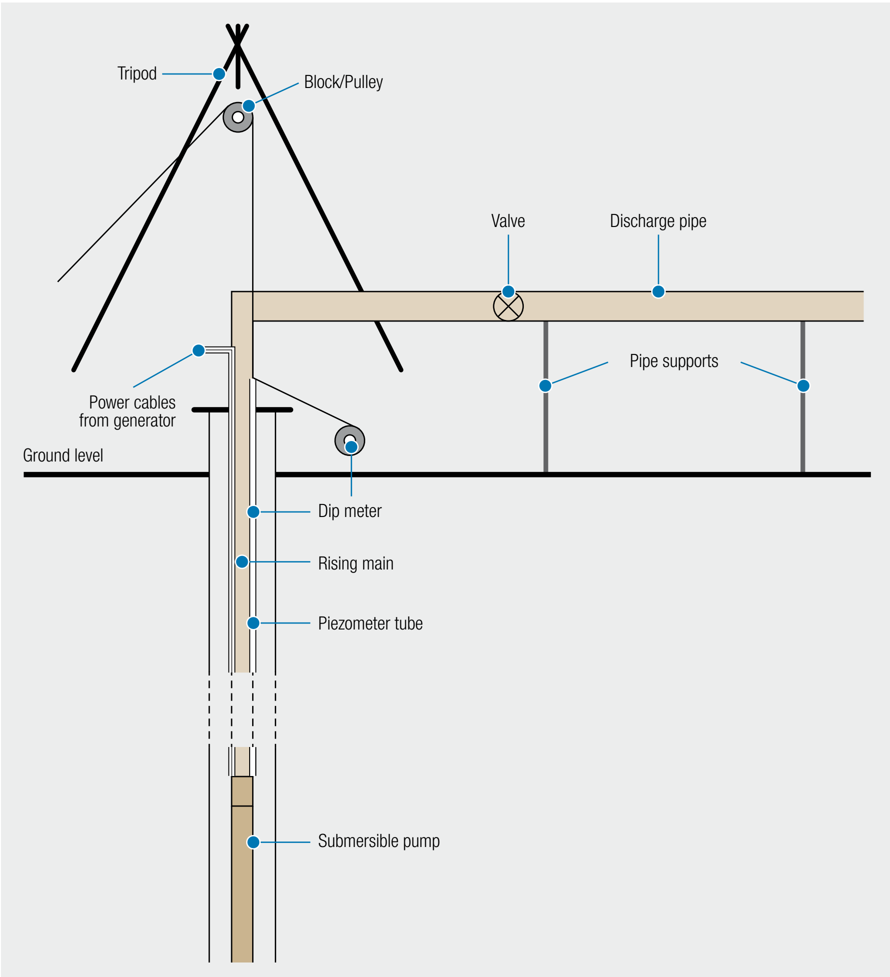


Figure 16. Typical test-pumping set-up (shown with electric submersible pump). Not to scale.

or by belts from an engine. Here, the engine speed or gearing can be changed to vary the rotation speed (and discharge) of the pump. Many drilling or test-pumping contractors provide either or both systems. They may, for example, offer different sizes of submersible, one of which might match the blowing yield of the borehole.

In all cases, pump and galvanized pipe rising main sections are lowered into the borehole by means of a strong steel tripod support, with steel cable, pulleys, a chain block, or a winch. For water levels to be easily measured during the pumping and recovery phases of the test, a flexible plastic pipe called a 'piezometer tube,' open at the lower end, can be attached (e.g. by cable ties, adhesive tape, or binding wire) to the rising main as it is lowered into the hole. A dip meter cable is introduced down this pipe, to record changes in water level. Discharge during the test can be measured by means of bucket timing or with a flow meter built into the discharge pipe. Water pumped out should be directed downslope and well away (more than 100 metres) from the pumped borehole. Figure 16 shows a schematic of a typical test-pumping set-up and Figure 17 a rig in operation in Zimbabwe.

Figure 17. A test-pumping rig in operation (it consists of a belt-driven mechanical rotary (Mono) pump), Zimbabwe

Switching between connected steps (without stopping the pump) to an increased discharge should be accomplished as quickly and as smoothly as possible. This can be ensured by carrying out a practice session – before the test proper is begun – to make sure everything is worked out, such as engine speeds or valve settings. All tests after a previous pumping period should begin only after the drawdown has recovered closely the original static water level. Disconnected steps (between which the pump is stopped) may be used if the borehole is allowed to recover between steps.

B) Step tests

If the blowing yield has been measured at a rate Q litres per second, you might want to conduct a step test in this way: pump the borehole first for an hour at Q/4 litres per second (step 1 discharge q1), for another hour at Q/2 litres per second (step 2 discharge q2), for a third hour at ¾Q litres per second (step 3 test discharge q3) and, finally, for a fourth hour at 1.25Q. The fourth step (discharge q4) is intended to slightly over-pump the borehole. The test should be stopped if the drawdown approaches the pump inlet.

After this basic step test, if the borehole stabilizes with a dynamic drawdown some way above the top of the screen at discharge q3, but not at q4, then the blowing yield, Q, is probably the best production level. However, depending upon demand, a production yield of q3 might be safer, as that takes account of any possible future fall in water levels or borehole deterioration. If the dynamic level stabilizes just above the screen at q3, then a production rate of q2 (or a little more) might be more appropriate.

C) Constant discharge test

Once the production level has been estimated from this test, it should be confirmed by pumping the borehole at the constant discharge for a minimum of 24 hours (high-yield production holes are run for 48 hours). This is called a constant discharge test. As the test proceeds, drawdowns should be regularly measured. At the end of the test, as soon as the pump is switched off, water levels should be monitored as they recover (to the static water level). If the pumping level stabilizes at a safe level above the screens and pump inlet, this may be the appropriate production yield. An example of a borehole test log sheet is provided in Annex 4. Many publications deal with the analysis of borehole pumping test data, and their applicability to aquifer modelling. Even if a particular drilling programme does not require such analyses, the field data should be regarded as a valuable resource and retained, because they may be needed in the future. For instance, one of the boreholes may suffer a loss of efficiency and need to be rehabilitated; the results of a post-rehabilitation pumping test can then be compared with the original test, to assess the degree of permanent deterioration.

D) Checking verticality

After the testing equipment has been removed, a check of borehole verticality ('plumbness') and alignment ('straightness') should be conducted. This is usually done by inserting and lowering into the hole a perfectly straight, 12-metre-long steel rod or pipe, the external diameter of which should be a maximum of 13 mm (about 0.5 inch) less than the inner diameter of the main or longest section of casing (i.e. in which the pump will be housed, unless a hand-pump is to be installed).

E) Disinfection

Finally, assuming that it has passed the tests above, the borehole should be thoroughly disinfected with a chlorine-rich solution, such as HTH, leaving a concentration of residual chlorine of 50 milligrams/litre for at least four hours. Table 8 gives the quantity of chlorine compound to

Table 8. Quantity of chlorine compound to produce a 50 mg/l solution in 20 m of water-filled casing[2]

Casing diameter (inches)	Volume per 20 m (m^3)	65% HTH (dry weight)* (g)	25% Chloride of lime (dry weight)* (g)	5.25% Sodium hypochlorite (Jick, eau de javelle) (liquid measure)
2	0.04	3.74	9.31	0.04
4	0.16	12.98	37.18	0.20
6	0.36	37.18	74.10	0.39
8	0.65	55.80	129.84	0.66
10	1.01	74.10	204.59	1.11
12	1.46	111.48	297.70	1.57
16	2.59	204.59	520.66	2.49
20	4.05	316.07	799.34	4.20
24	5.84	445.90	1171.15	5.70

* When powder is used, it should first be put in solution in a water container before being introduced into the borewell.

2 Adapted from F. G. Driscoll, reference No. 5, Annex 7

be added to 20 metres of water-filled casing for various diameters. The borehole may then be re-sealed with the locked cap or welded plate.

6.3.3 Geophysical logging

Information about structural features and geological formations in a borehole can be remotely obtained by geophysical borehole logging techniques. The object of well logging is to measure the properties of the undisturbed rocks and fluids they contain. Geophysical logs can provide information on lithology, the amount of water in a formation, formation density, zones of water inflow, water quality, and other *in situ* parameters that cannot be derived from highly disturbed drilling samples. A suite of geophysical log data, including deep-penetration methods, will more or less complete the technical description of a borehole, but geophysical logging is a specialized field best left to geophysical contractors or hydrogeological consultants. A logging unit consists of a power supply, a receiver/data processing unit, and a cable on a powered winch that lowers special sensor probes ('sondes') into the borehole to measure various properties. The cable contains multiconductors that transmit signals to the receiver console. Data, processed by computer, can be shown as a geophysical record on a graphic display, which should consist of a number of different structural, formation, and fluid logs. Specialized software packages enable manipulation, interpretation, and comparison of data. Multiple-sonde geophysical ('suite') logging can provide a substantial amount of information about the sub-surface conditions in and around a borehole.

7. DRILLING/ CONSTRUCTION COSTS

The demands of commercial competition mean that drilling contractors are often reluctant to quote prices unless one can provide specific details of geological conditions and anticipated borehole depths at potential sites. They may, for instance, request that a hydrogeological site survey be carried out beforehand. For this preliminary work, one should try to employ an independent consultant rather than one offered by – or affiliated with – a drilling contractor. At United Kingdom rates, this might amount to between 200 and 300 pounds per day – the length of the job depending on the size or complexity of the site – in addition to the costs of hiring any surveying equipment that may be needed.

Drilling contractors, at least in the U.K., are never slow to point out that boreholes can cut water costs by up to 80% and that the cost of borehole water is only around two to three pence a cubic metre, compared to £1 in some areas for normal supplies (quoted by W.B. & A.D. Morgan, of Powys, U.K.). However, while researching for this review, this writer found great difficulty in obtaining quotations from drilling companies, but a few examples gleaned from the Internet are provided here.

Drilling contractors normally charge on a system of units of time and materials used. A fixed rate for borehole drilling might be offered only if the contractor is very familiar with the location in question and knows exactly what to expect. Quoted prices will normally include basic PVC casing/screens; gravel packs might be extra, and pump installation will also be an additional expense. A typical fixed-rate cost, regardless of borehole depth, has been obtained from the United States: of around 15,000 US dollars (including PVC casing/screen). In Nigeria, a Lagos real-estate adviser quotes a cost of 350,000 Nigerian naira per borehole (industrial, heavy-duty drilling; probably includes PVC casing/screen, but not pump), which converts to only around US$ 3,000 at current rates (2008).

In another African example, Water Africa Services Ltd of Nairobi, Kenya, bidding for the drilling of 10 boreholes in Jonglei, South Sudan (commencing 2009), quoted an overall price of US$ 146,960 (including casings/screens, but not pump). This contract is for the Ministry of Co-operatives and Rural Development, Juba.

Large-donor programmes, such as those funded by the World Bank, which is supporting most of the borehole drilling currently taking place in Malawi, are also willing to pay up to US$ 15,000 per borehole. As governments in developing countries are often not footing the bill for drilling projects, it is not necessarily in their interest to reduce such costs. Actual drilling costs do not normally take into account the need for community participation at all stages: from site selection to drilling, pump installation, and utilization. Each of these phases might require skills in community mobilization and training.

In northern Pakistan, drilling systems operated by local small contractors are still being used to drill shallow boreholes for hand-pumps. These operators charge only around 500 rupees, approximately £4 sterling, per metre of drilling. Costs of casings and pumps would be additional. Rates for dug wells are around 1000 rupees per metre. A recent UK quotation for casing and screen prices is included as Annex 2.

7.1 Buying a rig

Depending on the scope of the drilling programme planned, it might be tempting to consider buying a rig to avoid depending on contractors and to try to make the best of the available budget.

Industrial commercial rigs are usually beyond the reach of humanitarian agencies, but portable rigs are affordable and their prices range from US$ 10,000 to US$ 100,000 approximately. This makes them a tempting option.

However, if an agency is planning to invest in a small rig (of the PAT or Eureka type, for example) a thorough economic analysis must be performed beforehand.

Buying a rig and bringing it to your warehouse only represents a small part of the costs involved.

A stock of spare parts and consumables has to be kept and maintained. A logistical chain is needed to supply the drilling campaign. Vehicles are indispensable for the transportation of water, material and staff, and sometimes even for security. Qualified drillers have to be found and trained, including a number of replacements. If the agency does not have a single employee who is knowledgeable in drilling, any planning for a drilling programme should be put off until a consultant has been hired. Very often, applications for drilling permits have to be made, and the drilling agency sometimes has to be registered as such. Once a drilling campaign has started, interrupting it is very expensive; everything must be done to try and avoid that situation.

Finally, there is the choice of doing it yourself, as it were. This will depend on your capacity (available skills) and the scale of the drilling programme (the number of boreholes and the possibility of continuing to use the rig for other programmes). After a certain number of boreholes to be calculated, the initial investment and effort is profitable.

7.2 Success rates

Possible success rates also have to be factored into a drilling project cost equation. Most professionals judge a borehole success rate of 70 to 80% to be satisfactory.

Indeed, the manager of a South African groundwater consultancy, who employed this writer as a hydrogeologist in Zimbabwe during the 1980s, admitted that he deliberately kept success rates down to these levels, in order that their work not give the appearance of being too easy!

A drilling programme of 30 deep boreholes was also completed in the same area with a success rate of 94%. In both projects, drilling locations were determined by detailed site surveys that included geophysical exploration. The shallow wells (average depth: 21 metres) cost around US$ 5,000 each; the deeper boreholes (average depth: 46 metres) cost around US$ 10,625 each. The drilling was done with a PAT 301 rig.

Clearly, drilling is made much more economical when the smaller types of rig are used: one quotation for a hole (depth or design unspecified) drilled by a Eureka Port-a-Rig (see Section 3.1) was about US$ 3,000.

As mentioned near the beginning of this review, a water supply project could be significantly augmented – and its costs significantly lowered – by locating existing boreholes in the project area and, if at all possible, bringing them back into use.

In 2006, a total of 80 shallow boreholes were drilled by TGS Water Ltd of Kampala in the districts of Oyam, Apac, Dokolo, and Lira in northern Uganda. The holes were drilled to reach shallow resistant formations, so were apparently exploiting near-surface aquifers in the weathered zone. Here, borehole success rate was 71%.

8. BOREHOLE DETERIORATION

Nothing lasts forever, and water wells are no exception. The life expectancy of a production borehole will be limited if it was incorrectly designed or not constructed for maximum efficiency, or if it has been over-pumped. Many production wells are seldom monitored or maintained; they are neglected until a problem arises. But if a borehole is properly designed, constructed with the correct materials, and given regular attention, it can produce water for 50 years or more.

Common causes of borehole deterioration or failure include the following:

A) Water level drawdown

Production from a borehole or a well field can decline because of a drop in the water table, which might be due to natural causes such as drought, but also to well deterioration and over-pumping (excessive drawdown). A drop in the water level can result in submersible pumps shutting off automatically.

B) Mechanical failure

Pumps eventually lose their effectiveness as parts become worn, corroded, or clogged, and borehole screens become partly blocked by damaging organic and inorganic accumulations and scale deposits. If pumps are not turned off before they begin sucking in air, they will be irreparably damaged. Decline in or loss of production can be at least partly (if not mostly) remedied by a programme of well maintenance and rehabilitation.

C) Incrustation

Most ground waters are only mildly corrosive, if at all, so corrosion is not usually a problem if good-quality plastic and steel (such as stainless steel) casings and screens have been installed. The main cause of deterioration is the build-up of incrustations around screen openings, which reduce borehole efficiency. As a borehole is pumped, pressure is reduced by the local drawdown, and water velocity and turbulence around the borehole increase. In this agitated zone, carbon dioxide gas is released from the water, which reduces the solubility of certain compounds in the water, such as calcium carbonate. Incrustation is mainly the result of the precipitation of insoluble carbonates, bicarbonates, hydroxides, or sulphates of calcium, magnesium, sodium, manganese, or iron. However, these deposits are rarely composed of a single mineral. Normally, the level of dissolved iron in groundwater is low, but slight changes in water chemistry, such as acidification due to dissolved carbon dioxide or organic matter (humic acids) can result in higher iron concentrations (up to tens of milligrams per litre). Iron will remain in its soluble (ferrous) state unless there is a rise in the pH (alkalinity, equivalent to reduction of acidity) or Eh (redox potential) of the water. Increased oxygenation of the turbulent zone can initiate iron precipitation by oxidation from the ferrous (soluble Fe2+) to the ferric (insoluble Fe3+) form in the screen area. Serious mineral deposition can occur at the top of screens, which become exposed to air owing to excessive drawdown. Inorganic silts and clays often add to the problem, but organic deposits can also be involved. Oxidation of ferrous to ferric iron at the borehole boundary can encourage the growth of certain bacteria. Organic slime formation by species of iron bacteria is a result of the life cycle of such organisms. They inhabit groundwater by metabolizing ammonia, methane, or carbon dioxide, again changing iron into deposits of insoluble salts (mainly hydroxide), which worsens incrustation.

Iron biofouling is a complex process influenced by interactions between the aquifer environment and the borehole structures. Microbial matter consists of filamentous cell colonies, mats, and slime sheaths (which cells secrete for protection), often of a sludgy consistency, but able to harden with age. Such incrustations impair hydraulic efficiency and specific capacity, clogging pipes, filter packs, screens, and pumps. They can cement a gravel pack into something akin to concrete. They encourage corrosion and reduce water quality, but remedial measures are likely to be less effective once hardening has occurred. If an incrustation has aged and recrystallized it will be extremely difficult to loosen and remove.

D) Corrosion

The most common corrosion process is electrochemical, in which iron (or another metal) is dissolved and re-precipitated as a hydroxide deposit. Corrosion in a water well most often occurs at localized physical imperfections on metal pipes and screens; the process can be encouraged by high salinity, high temperatures, oxygen, carbon dioxide, hydrogen sulphide, and organic acids (from peat or pollution). Corrosion can perforate metal screens and casings, weakening the structure and allowing pollutants (or even gravel pack material) to enter the borehole. As has been mentioned before, incrustation or corrosion can be slowed down by installing screens with the greatest possible slot area, to reduce pumping rates and inlet velocities, and by periodic cleaning or redevelopment of the borehole.

9. BOREHOLE MONITORING

This section contains a brief review of techniques that enable detailed evaluation of a borehole. Additional information can be found in the references listed in Annex 7B.

Continuous monitoring of borehole performance can be cost-effective, helping to detect any problems before they become serious. Maintenance programmes should consist of regular field visits, water sampling (for chemical/microbial analyses), water level measurements, and routine monitoring by simple step-drawdown tests. The data collected can be compared with those obtained when the well was new or last monitored. A regular testing schedule consisting of a basic step-drawdown test every year is sufficient, with maintenance carried out if there is any sign of deterioration. Low-risk areas (in terms of borehole incrustation or corrosion) may require maintenance work only every few years. It is prudent to erect a lockable fence around the borehole to prevent tampering and accidental or malicious damage. Table 9 sets out the symptoms to be noted in a monitoring programme, along with causes and suggested remedial actions.

Local staff should be recruited and trained in the monitoring of boreholes, and in the repair of pumps (especially hand-pumps), particularly in those areas where the failure of the water supply would have the most serious consequences. This would apply most to boreholes supplying settlements or institutional facilities in remote arid or semi-arid regions of the world and in places where rapid borehole deterioration is a possibility.

A) Water quality monitoring

Chemical analysis of the bore water should indicate the potential for damage to borehole structures. The physical condition of the abstraction system at a borehole may give an indication of developing conditions within the borehole itself. If unusual and significant corrosion or incrustation is taking place among borehole headwork structures, the same is likely to be happening inside the

Table 9. Borehole monitoring: Symptoms, causes, and remedies

Monitored symptom	Causes	Remedial action
Regional fall of groundwater level	Regional factors, e.g. earth movements, drought, large-scale abstraction, extensive deforestation	Lower pump inlet Deepen borehole Drill new (deeper) borehole
Localized fall of groundwater level	Over-pumping Blocked screens or gravel pack	Check/compare earlier test pumping data Reduce pumping rate Rehabilitate: inspect screens, surge-develop to clean screens and gravel pack.
Change in water quality (chemical)	Chemical pollution Saline influx Aquifer mixing	Analyse water; if hazardous, shut down borehole production and reassess situation.
Change in water quality (biological)	Pollution Change in water chemistry	Analyse water. If hazardous, shut down borehole production. If temporary, pump out water and disinfect borehole.
Unusual corrosion/incrustation of borehole headworks equipment	Water quality, e.g. carbonate (hard water), acidic water, iron bacteria	Remove pump, inspect borehole. Rehabilitate
Reduction of yield (pumping level unchanged)	Pump faulty Piping blocked (incrustation)	Remove and inspect pump Inspect piping; replace if necessary.
Unusual noise or vibration (submersible pump)	Damaged/faulty pump	Remove and inspect pump Inspect borehole

borehole. Water quality monitoring is particularly important if boreholes are close to densely populated areas or in coastal zones. Pollution (chemical or biological) may be caused by the former; in coastal areas there is the possibility of intrusion by salt water, from a fluctuating fresh water/sea water transition zone. In the latter case, of course, simple tasting will confirm the problem, but regular conductivity or total dissolved solids (TDS) analysis will provide predictive data.

Distilled water has a conductivity of 1 µS/cm,

good fresh water <200 to 500 µS/cm,
and saline water >6,000 µS/cm
(S = Siemen, 1 Ω^{-1}).

The equivalent TDS classification is:

fresh water 0 to 1,000 mg/l;
brackish water 1,000 to 10,000 mg/l;
and saline water 10,000 to >100,000 mg/l.

Reference 11 in Annex 7B gives details of a report, published by CIRIA, which provides best-practice guidance on the monitoring, maintenance and rehabilitation of boreholes equipped with hand-pumps.

Borehole monitoring should include regular step-drawdown tests, which can be further analysed to determine the basic hydraulic parameters of aquifers. Drawdown in a borehole is essentially the sum of losses due to movement of water from the aquifer into the borehole space. Mathematical analysis of step-test data allows these losses to be determined, along with the relationship between drawdown and discharge for the borehole under test. From these data, an indication of the efficiency of the borehole (and hence of any reduction of efficiency over time) can be obtained.

10. BOREHOLE REHABILITATION

Rehabilitation is the action taken to repair a borehole whose productivity has declined or that has failed through lack of monitoring and maintenance of the pump and/or well structure. This is often a financial problem, or a logistical one – a function of remote location and, possibly, of conflict preventing easy access. Surface pumps, such as wind-pumps or hand-pumps, often fail for purely mechanical reasons – broken rods or corroded risers, for instance – and disused boreholes silt up or have objects dropped into them. Unfortunately, if a borehole has become tightly blocked by hard debris, such as stones and pieces of metal (a not uncommon occurrence), it is probably totally lost. Existing boreholes are likely to be well sited in terms of usage, since they must originally have been drilled for a purpose. Therefore, it is almost always advantageous to rehabilitate them.

It can be reckoned as a rule of thumb that a simple rehabilitation (no casing replacement) will cost around 10% of the price of a new borehole.

10.1 When to rehabilitate

All pre-existing boreholes within a project area should be inspected for the possibility of rehabilitation, unless they are on privately owned land. The extra water might not be needed, but as boreholes provide access to groundwater, they could be used as observation holes for monitoring local water levels. Abandoned boreholes may act as pathways for the contamination of an aquifer, or enable the mixing of ground waters of differing quality from separate aquifers. They might also present a physical hazard to, say, local children, especially if they are of large diameter and open. Redundant boreholes are potentially useful as groundwater monitoring points, even if they cannot be rehabilitated for production; but holes that are beyond repair should be backfilled using clean, inert, non-polluting materials such as gravel, sand, shingle, concrete, bentonite, rock, or cement grout.

A borehole that has, for some time, stood unprotected – by a top casing cap or a surface installation – will almost certainly have been lost because of, say, objects being dropped into it by children. If a blockage can be reached from the surface it should be probed with a strong metal bar to get an idea of its solidity. Loose fine material might be removable using compressed air (see below); if this can be done, full rehabilitation might be a possibility. If the borehole was protected by a cover and is apparently clear, it should be checked for depth by plumb-line dipping, for static water level by dip meter, and for method of construction and internal condition by means of a closed-circuit television (CCTV) borehole camera.

Before carrying out rehabilitation, it is advisable to sample and analyse the local groundwater (if possible) to ensure that it is not unduly chemically aggressive.

10.2 Rehabilitation methods

The basic rehabilitation process should consist of the following principal stages in this order:

- Collection of archives and information (from water authorities, drilling companies, aid organizations, etc.) on the borehole design
- Inspection by CCTV
- Breaking-up of clogging deposits and incrustations
- Removal of silt and debris by surging and airlift clearance pumping
- Borehole disinfection
- Step-drawdown test

10.2.1 Inspection by CCTV

Prior to commissioning a CCTV inspection, efforts should be made to locate borehole design and construction details, as that may save a lot of time. However, in some countries archives of borehole design might be hard to find.

Figure 18. Casing damage as seen through a CCTV borehole camera

However, in tropical countries, for example, a relatively warm camera inserted into a borehole may develop condensation on the inner surface of the lens when it is lowered into cold water, obscuring the view.

Figure 19. A CCTV borehole camera

Typically, rehabilitation might consist of an initial CCTV run before desilting by conventional air surging. A second CCTV inspection should then be carried out to check the efficacy of the desilting operation and to obtain a clearer picture of down-hole conditions. All CCTV runs should be logged in detail and videotapes of the inspection retained for future reference.

A CCTV video survey enables full inspection of the inside of a borehole to be carried out, from top to bottom, in 'real time.' Side views allow casing or screen condition to be observed at accurate, recorded depths. With information of this quality, problems can be identified and complete rehabilitation of a borehole planned. Construction details can be observed directly and compared with the original log, if one is available. Objects or debris dropped into a hole can be inspected and the possibility of removal assessed. Water cascades, and to a certain extent, water quality (chemical precipitates, turbidity), can be viewed on a television monitor.

Some very sophisticated borehole video camera systems are now available on the market. Shaped to fit easily into a borehole, the best models are fully submersible with depth-marked cables on a powered or hand-cranked winch or with automatic depth recording. Many models have built-in lighting, variable pan-and-tilt angles, and different look directions, which means that clear views directly down and to the sides of the borehole are possible. Video monitors are usually provided in a camera package; a video recorder may be optional. The GeoVISION Deluxe (Product reference 6, Annex 7) is an example of a good borehole camera system.

And if the water in a borehole is very turbid, back-scattering from the lighting system can swamp an image. Nonetheless, a borehole camera system is an invaluable tool when a rehabilitation programme is being contemplated. Once a borehole has developed incrustations or corrosion problems it needs to be rehabilitated or treated by mechanical, chemical, or other means (such as those used in development) to recover its lost production capacity, but no single treatment is suited to all wells.

10.2.2 Breaking up of clogging deposits and incrustations

It is usually difficult – if not impossible – to remove old casings or screens to clean or replace them, so other methods often need to be used.

Screens can be cleaned using a rotating wire brush or scratcher, but they may have been weakened by corrosion, so care should be taken not to worsen their condition. Borehole restoration methods are similar to those used in development, except that incrustations have to be broken up and removed.

A) Water jetting

If it is done systematically, water jetting at high pressures can be a particularly effective means of de-clogging and cleaning the internal surfaces of boreholes. A jetting nozzle on the end of a length of high-pressure air hose or pipe is required. Test trials have shown that nozzle exit pressures of 17,000 kPa (for a 1.5 to 2″ nozzle, positioned about 1″ from the screen) will be effective on most occasions. In unlined boreholes, the jetting pressure limit is around 40,000 kPa. To avoid damage to plastic screens, pressures greater than 20,000 kPA should be avoided, because very high pressure jetting (greater than 30,000 kPa) can cut through plastic casing. Steel casing can withstand pressures of up to at least 55,000 kPa, and the screens that best respond to jetting treatment are those with high open areas and continuous slots, such as wire-wrap types like Johnson screens.

B) Air-burst technology

Air-burst technology is a new and patented technique of borehole rehabilitation: it entails using small volumes of an

Furthermore, unless the borehole in question is of relatively large diameter (say, 10 inches or more) and does not contain screens, it is not advisable – because of the possibility of causing damage inadvertently – to lower drilling rods into it from a drilling rig brought onto the site.

inert gas to generate high-intensity 'pressure-pulses' in selected zones inside a well.

The pulses, from a special tool, create air bubbles and high-frequency acoustic shocks that shatter mineral and organic films and incrustations on the borehole walls and screens. Gas bubbles surge water into and out of the formation adjacent to the tool, displacing sediment, incrustation debris, and fragments of biofilm, which are washed into the borehole, and can later be cleaned out by conventional air-lifting.

Air-bursting can develop every part of the borehole structure with multiple and adjustable bursts of energy adaptable to any diameter, design, or age of borehole. However, it is a specialized technique probably more appropriate for severely deteriorated high-performance boreholes in commercial or utility production well fields.

C) Acidization

For seriously affected boreholes, a combination of physical and chemical methods might be most effective. Acidization (mentioned in Section 6.2.1B) can remove carbonate incrustations and ferric hydroxide deposits in their early non-cemented stage.

Hardened iron deposits would require physical breaking up by the methods described above. A 30% sulphamic acid solution to the volume of the screened or open section to be cleaned can be used for 15 to 24 hours, with the water in the borehole being periodically agitated by air that is blown in.

D) Hydrofracturing

Old boreholes drilled into low-yield formations, such as Precambrian crystalline rocks, can be stimulated by a process known as hydrofracturing.

The technique can be applied only to open, uncased sections such as might occur towards the bottom of a hole.

First, a CCTV or down-hole geophysical log must be run to assess the suitability of the borehole to such treatment. The section to be worked should already be fractured to a certain extent, and must be isolated using some kind of packer. This might consist of a series of rubber seals that can be expanded in the borehole by a hydraulic ram or by compressed air from the surface.

An injection pipe runs down the centre of the packing system. High-pressure water is injected into the borehole in order to create or enlarge the fractures. Sand can be added to the water to keep open ('prop') newly developed fractures.

Reports indicate that yield increases of 20 to 80% have been achieved using hydrofracturing. Depending upon the nature of the formation, injection pressures of 35 (soft) to 140 (hard) bar are used. After treatment, water and debris are air-lifted out in the normal way.

10.2.3 Relining

A borehole seriously affected by corrosion – that is now pumping out sediments – can be restored only by partial or total relining. The necessary course of action may be decided only after a borehole camera survey, or a geophysical logging programme, has determined the extent of the damage or deterioration. Down-hole logs might contain indications (water temperature, conductivity, flow, resistivity, or casing collar logs; see Section 6.3.3) of holes in casing.

Any new casings or screens that are installed should be of corrosion-resistant materials to avoid a repetition of the original problem. A new lining will be of smaller diameter, so the new pump will have to be chosen with this in mind.

Corroded screens should not be relined if at all possible, because concentric screens create turbulence and abrasion, and fragments of corroded metal could be sucked into the borehole during pumping.

> Two sets of concentric screens would severely reduce the performance of a borehole, but if a hand-pump is the intended means of extraction, this may not matter very much.

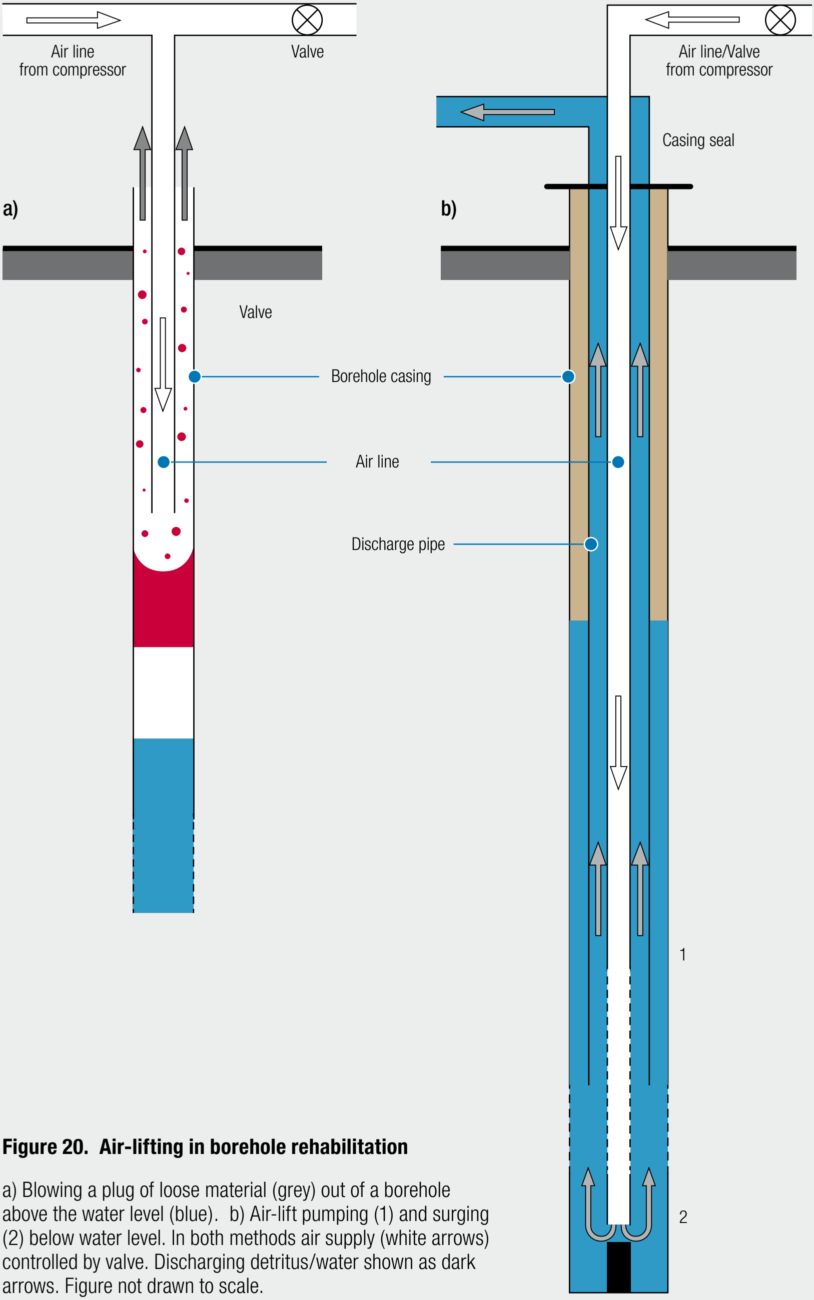


Figure 20. Air-lifting in borehole rehabilitation

a) Blowing a plug of loose material (grey) out of a borehole above the water level (blue). b) Air-lift pumping (1) and surging (2) below water level. In both methods air supply (white arrows) controlled by valve. Discharging detritus/water shown as dark arrows. Figure not drawn to scale.

Although it can be extremely difficult, corroded screens should be removed and replaced by new corrosion-resistant materials. Any attempt to do this would involve bringing a large drilling rig on site and using its pulling power to remove the old casing string.

Any lost gravel pack material can be blown out. With new casings installed, the borehole can be developed in the usual way.

New casings and screens can be protected from corrosion under water by means of sacrificial electrodes (cathodic protection). Sacrificial anodes of a metal that is higher in the electromotive series (relative tendency to oxidation) than steel – such as magnesium and zinc – are attached and corrode in preference to the protected metal of the casing. Such systems are used to protect ships, underwater pipe-lines, and pump installations, but are rarely applied to borehole casings or screens.

Techniques for the removal of clogging deposits and incrustations include high pressure surging, jetting, air-lift pumping, air-bursting, and chemically assisted dispersion. Periodic rehabilitation, which ought to be carried out on a regular basis, can remove deposits before they harden with age.

Typical workouts like this might consist of employing a truck or trailer-mounted compressor of the type normally used during drilling (minimum capacity 7 bar-100 psi). The most commonly used air-lift pumping set-ups are shown in Figure 20. This illustrates the options for removing a shallow, loose blockage above the water level with the casing open (a), and for air-lift clean-out below the water level with a discharge pipe inside the sealed casing (b, 1). For blowing and surging, the air line is lowered so that the end is below the bottom of the discharge pipe (b, 2). Air blowing/surging and clean-out should be carried out alternately and each process repeated five to six times, or until the borehole water is clean.

During a project in Ghana (Nampusuor, 2001), airlifting was employed to rehabilitate a number of boreholes fitted with hand-pumps, each less than 50 metres deep. The estimated cost of the job was between US$ 800 and US$ 1000 per borehole when using a contractor (including a step-drawdown test), and it took about 24 hours per hole. Costs could be reduced if an organization carried out such work in-house.

In addition to air surging, a drilling rig can be used to redesign an uncased borehole or one from which linings have been pulled out. A borehole can be reamed or deepened to intersect more of the aquifer or to provide greater available drawdown. Shallow dug wells can also be rehabilitated using a drilling rig. When the water level drops below the bottom of a well, the well runs dry. If the structural integrity of the well (its sidewall and surface structure) is sound, a rig can be brought in to drill a borehole through the base of the well and further into the shallow aquifer (or even deeper, but it may be better to drill a completely new borehole if this is desired). The borehole can, if necessary, be cased and screened by the methods described above, and a hand-pump mounted on the dug well slab with risers extending down into the borehole.

10.2.4 Borehole sterilization

Boreholes affected by iron incrustation should be sterilized by chlorination between the clean-out pumping and the step test, to destroy ubiquitous iron bacteria to and delay re-infection of the well. Granular HTH can be dissolved and added so as to leave about 50 milligrams per litre of residual free chlorine in the borehole water. Mixing the solution in the borehole can be done by blowing with the air line used for the air-lift pumping. The concentration should be monitored using a water testing kit such as the Oxfam-DelAgua. The borehole can then be pump tested.

10.2.5 Step-drawdown testing

A step-drawdown test will indicate whether rehabilitation has been successful; it can also serve as a new baseline against which future well performance can be measured.

Test pumping of a rehabilitated borehole will also help to re-establish normal groundwater flow and remove remaining silt particles.

10.2.6 Mechanical repair

Many boreholes lie disused because pumps have broken down or because of the lack of necessary expertise or spares. In the case of hand-pumps, this can be relatively easy to fix: all that is needed is a set of standard tools with which to remove the pump handle, chain, riser pipes, rods, and piston, for inspection and repair or for replacement.

Pumps and risers on deeper boreholes might require a tripod and a vehicle with a winch for removal. If at all possible, a borehole should be inspected by video camera once a pump has been removed (see above).

In southern Darfur, this writer organized – with the ICRC – a mobile hand-pump repair team using two vehicles and two mechanics (plus local helpers at each village). Five full sets of India Mark II hand-pump spares, along with new riser pipes, rods and tools were carried in a pick-up truck. The team moved from village to village, locating and repairing disused hand-pumps on shallow boreholes.

11. WORKING WITH CONTRACTORS

For a particular water supply project, planners must decide whether to use commercial drilling contractors or invest in machines and experienced staff (see Section 7.1)

If the financial analysis concludes that a contractor must be hired, a few steps must be followed to avoid later surprises.

Contractors are generally – but not always – very dedicated professionals, but they represent commercial firms with their own specific constraints, stresses and attitudes to risk-taking. Being aware of this helps to look at a project from their point of view and to anticipate some of their actions.

11.1 Selecting a contractor

Working with drilling contractors can be either interesting or frustrating. Because a great deal of frustration can result from confusion over what is demanded of contractors, the technical specifications and the terms of the contractor's employment should be clearly defined from the outset. As there might be a number of drilling organizations submitting bids for a work project, the staff responsible for letting contracts will have a number of factors to consider:

- Has the drilling company a good reputation?
- Can the company provide details of a similar contract recently completed successfully, or references from the employers?
- Is the company on a list of approved drilling contractors? Does it belong to a professional organization (such as the British Drilling Association in the U.K.)?
- Does the company possess the equipment necessary to fulfil the demands of the contract, and is the equipment in a good state of repair? (Here, a visit to the driller's yard with an experienced, impartial engineer will be useful.)
- Does the company possess adequate maintenance and backup facilities to provide for plant breakdowns, and is that backup efficient?

- Is the company's yard or depot clean and well run? (This will give an indication of their standards of work.)
- Check on staff employed by the company: Are they sufficiently experienced or qualified?

11.2 Contract documentation

Borehole drilling contracts are much like other commercial agreements in, say, the civil engineering sector. But drilling is a specialized field requiring clearly defined technical objectives and methods that should incorporate a degree of flexibility.

A basic drilling contract between client and contractor should contain specific clauses and technical specifications: an example is provided as Annex 5. The supervisor or client representative must make himself or herself thoroughly familiar with these requirements. With detailed specifications in hand, he or she should be able to react quickly (if not always amicably) to any work disputes and bring them to an end.

Work/charge sheets for drilling contractors should list all that is required for the fulfilment of the clauses and technical specifications contained in the contract; these are listed in Annex 6.

ANNEXES

Annex 1. Example of a drilling log sheet

Annex 2. Recent quoted prices for casings and screens

Annex 3. Examples of borehole completion designs (not to scale):

- Annex 3A: Borehole completion for hand-pump in a shallow, weathered zone aquifer
- Annex 3B: Borehole construction for partly consolidated sandstone aquifer (as in Figure 1, hypothetical site B)
- Annex 3C: Borehole construction for combined sandstone and limestone aquifers (as in Figure 1, hypothetical site C)
- Annex 3D: Borehole construction for aquifer in granite fracture zone (as in Figure 1, hypothetical site D)

Annex 4. Example of test pumping data sheet

Annex 5. Basic drilling contract: Clauses and specifications

Annex 6. List of items on contractor work/charge sheets

Annex 7. Product references and further reading

Annex 1. Example of a drilling log sheet

[NAME OF ORGANIZATION]	DRILLING LOG SHEET	Page .... of ....
[PROJECT/CONTRACT]	CONTRACTOR/DRILLER:	
Borehole No.:	Location/Co-ordinates:	Elevation:
Drill machine:	Mud/Air:	Supervisor:
Start date:	Completion date:	Completion depth:

Borehole Data			Drilling penetration rate (units)	Marsh funnel viscosity (sec)	Casing, screens, filter gravel pack installed	Other information or remarks
Depth (m, ft)	Lithology from samples	Water strikes				

Annex 2. Recent quoted prices for casings and screens

(Provided by BOODE UK Ltd (Waterwell Systems))

1. PVC Casing and Screens

a) PVC Casing and Screen (4″) 113mm OD × 103mm ID × 2.9m lengths × C-type flush butt joints with trapezoidal threads
   Casing at: £23.11 per length
   Screen at: £31.92 per length

b) PVC Casing and Screen (6″) 165mm OD × 155mm ID × 2.5m lengths × B-type external upset joints with trapezoidal threads
   Casing at: £35.66 per length
   Screen at: £47.90 per length

c) PVC Casing and Screen (8″) 225mm OD × 203mm ID × 5m lengths × C-type flush butt joints with trapezoidal threads
   Casing at: £168.33 per length
   Screen at: £204.92 per length

d) PVC Casing and Screen (12″) 315mm OD × 299mm ID × 5m lengths x B-type external upset joints with trapezoidal threads
   Casing at: £200.95 per length
   Screen at: £245.17 per length

2. Stainless Steel Casing and Screens

a) Johnson's (12") 323.9mm OD × 305.5mm ID 304L stainless steel wedge wire wound well screens × 5m lengths × 1mm slot size × 9.3 bar collapse resistance × weld ring and collar connections at: £1,114.00 per length

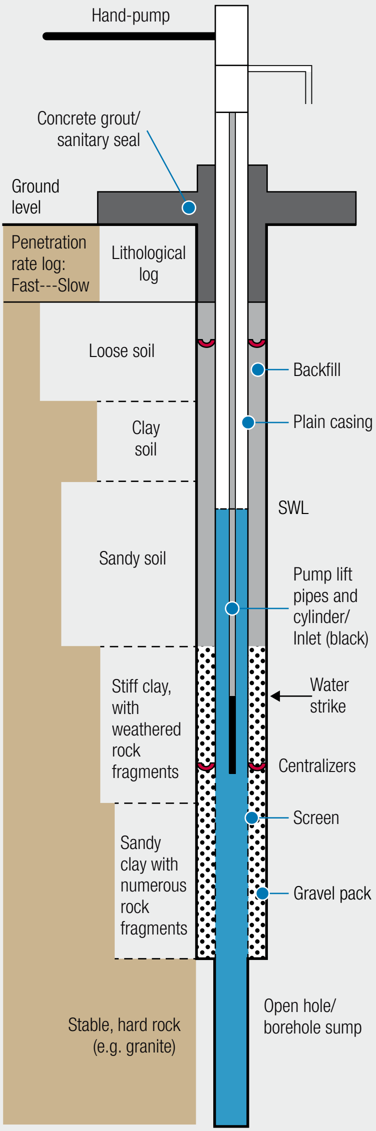
b) Johnson's (10") 273.1mm OD × 256mm ID 304L stainless steel wedge wire wound well screens × 6m lengths × 0.5mm slot size × 17.4 bar collapse resistance × weld ring and collar connections at: £1,209.00 per length

c) Johnson's (10") 273.1mm OD × 4.19mm wall thickness 304L stainless steel casing × 3m lengths × API male and female connections at: £1,185.00 per length

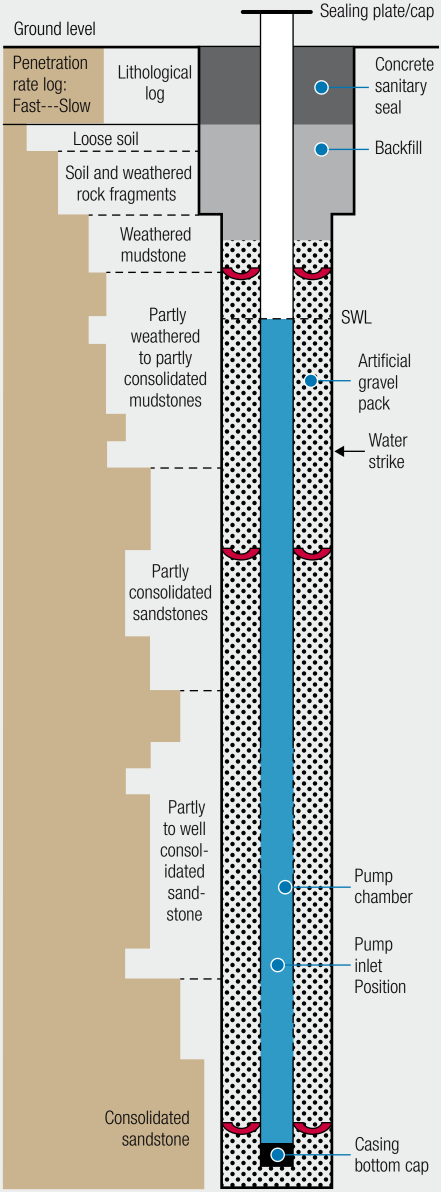
d) Johnson's (7 5/8") 193.7mm OD × 3mm wall thickness 304L stainless steel casing × 6m lengths × weld collar connections at: £822.00 per length

Annex 3. Examples of borehole construction designs (not to scale)

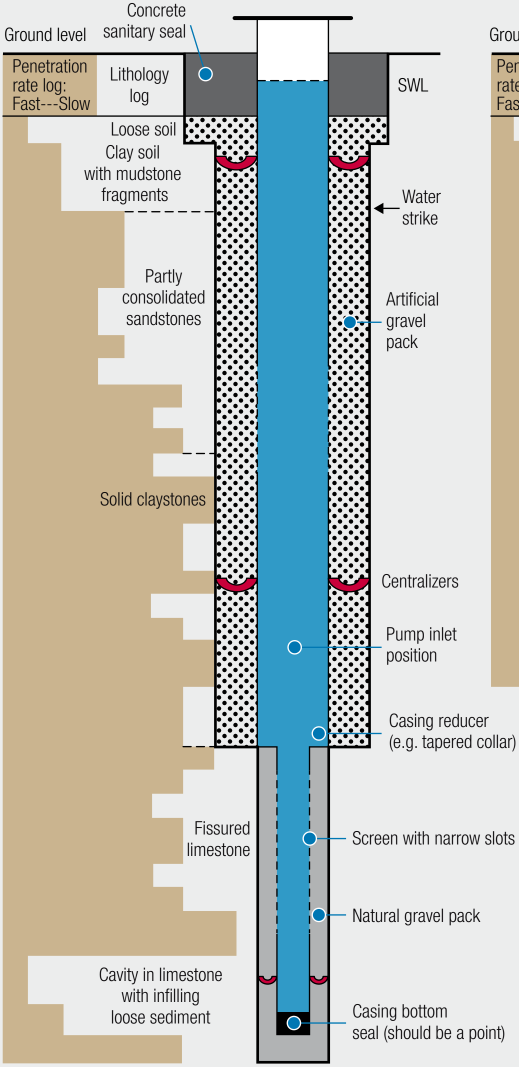
Annex 3A: Borehole completion for hand-pump in a shallow, weathered zone aquifer



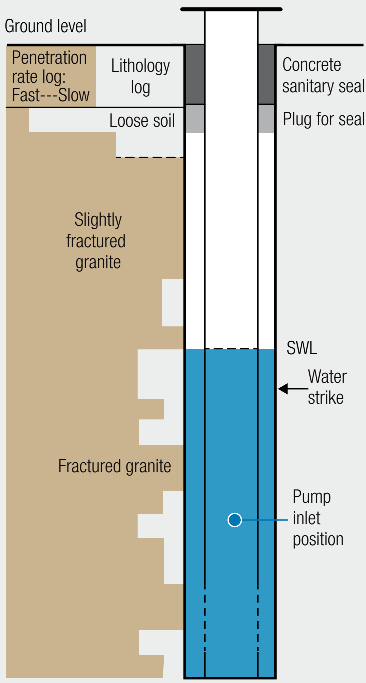
Annexe 3B: Borehole construction for partly consolidated sandstone aquifer (as in Figure 1, hypothetical site B)



Annexe 3C: Borehole construction for combined sandstone and limestone aquifers (as in Figure 1, hypothetical site C)



Annexe 3D: Borehole construction for aquifer in granite fracture zone (as in Figure 1, hypothetical site D)



Annex 4. Example of test pumping data sheet

[NAME OF ORGANIZATION]		STEP DRAWDOWN TEST DATA SHEET
[PROJECT/CONTRACT]		CONTRACTOR:
Borehole No.:	Location/Co-ordinates:	Elevation:
Borehole New/Rehabilitated	Borehole Depth:	Static Water Level:
Test Pump Type:	Pump Inlet Depth:	Test Datum:
Existing Pump:	Test Supervisor:	Test Date:

Pumping Time (min.)	PHASE 1 (1 hour) Drawdown (m)	Discharge (units)	PHASE 2 (1 hour) Drawdown (m)	Discharge (units)	PHASE 3 (1 hour) Drawdown (m)	Discharge (units)	PHASE 4 (1 hour) Drawdown (m)	Discharge (units)	Recovery (Residual drawdown) (m)
0.5									
1									
1.5									
2									
2.5									
3									
4									
5									
6									
7									
8									
9									
10									
12									
15									
20									
25									
30									
40									
50									
60									
70									
80									
90									
100									
120									

Remarks:

Note

For 24-hour constant discharge test drawdown measurements, use pumping times as for step test plus: 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1440 minutes.

For 48-hour constant discharge test, use pumping times as for step test plus: 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400, 2500, 2600, 2700, 2800, 2880 minutes.

For recovery (residual drawdown) measurements after pumping stops, use same time intervals, continuing with readings every 100 minutes after 2800 until water level has recovered to within 20 centimetres of original static water level.

Annex 5. Basic drilling contract: Clauses and specifications

A. General Clauses

A.1

The purpose of the contract is the construction of boreholes for potable water supplies for the settlements (or camps).

The Contractor will carry out the specified drilling works and provide proper machinery, implements, tools, materials, and labour for due construction of the boreholes, their development and test pumping. He will also provide the casings, screens, and gravel filter pack materials according to the quality specifications given hereunder.

A.2

The Client will provide all available information about the surface and hydrogeological conditions at each drilling site. This information does not hold the Client responsible for local variations in conditions at specific drilling sites or for particular problems the Contractor may face while carrying out his work.

A.3

The Client will indicate the drilling sites and provide the required permits for access to land where the contract is to be carried out.

The Contractor will be responsible for all damages occurring outside the allocated land.

The Contractor will clear all debris of any kind, and leave the land, as far as it is possible, in its original condition once the borehole has been completed, developed, and tested.

A.4

If the Contractor is not able to complete the drilling or has to abandon the borehole owing to loss of tools or any other accident or contingency, he should remove the casing or drive pipes already placed in the hole and refill it with clay or concrete, at his own expense. All material extracted from such holes, after back-filling them, will be considered the property of the Contractor. In this case the Client will not pay for any of the work carried out, and will authorize in advance the drilling of a new hole, at a site near the abandoned one.

B. Technical Specifications

B.1 Boreholes

B.1.1 Information concerning each borehole

The Contractor will supply a detailed borehole log, in which all relevant information on drilling rate, well casings, and other construction operations will be accurately recorded.

The Contractor will also annotate all information pertaining to the appearance of water strikes and aquifers, types of strata found, and formation sampling details.

B.1.2 Casing and diameters

The drilling of each hole will be carried out according to the requirements of these specifications, using the proper drilling tools, drive pipes, casing pipes, gravel packs, and sanitary protection, based on the real characteristics of the aquifer formation(s). The casing pipe and sanitary protection (seals) should isolate the aquifers from other formations considered unsuitable for production of potable water.

The borehole design is to be authorized by the Client (or the Client's representative on site) before casing pipes and screens are installed in the well.

B.1.3 Pipes, screens, and artificial gravel packs

The Contractor will supply all pipes, screen filters, and fittings for the proper casing of the wells at the agreed price.

An artificial, properly graded gravel pack will be placed in the annular space between the borehole wall and the outer face of the casing/screen. Proper techniques should be used for the accurate placing of this pack on site. The gravel to be used should be clean, and well rounded. The grains should be hard and of alluvial origin, and in size between 0.5 and 2.5 centimetres diameter. This gravel must be approved by the Client.

B.1.4 Drilling equipment and depth of drilling

The Contractor will use drilling equipment capable of drilling down to the required depths. The use of cable tool, rotary, or down-the-hole hammer (air percussion) rigs is acceptable. Any borehole depths indicated to the Contractor prior to drilling should be regarded as tentative and for guidance only.

If the actual characteristics of the boreholes to be drilled justify any change in these specifications, the Contractor will request the authorization of the Client for such changes to be made. These communications will be made verbally and shall be correctly recorded by the Client.

Once changes in borehole depth have been authorized by the Client, a proper price adjustment will be made in accordance with the final depth of the borehole and the unit price rendered by the Contractor in his original proposal.

B.2 Borehole completion and test pumping

B.2.1 Pumping tests

Once the borehole construction is completed, the well will be developed by treatment with suitable mud dispersant additives (if required) and hydraulic surging (by means of a surging piston/block or compressed air). Immediately after these operations are completed, and the borehole water is certified clean by the Client, the pumping unit can be introduced into the well.

The Contractor will provide a test pumping unit capable of discharging 50 per cent more water, at the borehole's pumping water level, than the maximum yield indicated for each borehole.

The Contractor will communicate (…… days in advance) the date the pumping test is to be carried out. Test pumping of the borehole is to be performed in accordance with 2.2.1.1.

B.2.1.1 The pumping test

The test will consist of continuously pumping the borehole at the maximum yield specified (or at any other previously defined rate(s), according to the results of the drilling work) between the Contractor and the Client. The duration of this test will be ……hours. Measurement of dynamic water levels will be performed according to the logarithmic time-scale schedule normally used for test pumping water wells.

B.2.1.2 Other specifications

The Contractor will remove all pumped water in such a way that no surface ponding occurs at distances less than 100 metres from the borehole. The Contractor will provide all the necessary materials for this purpose.

The Contractor will provide all necessary equipment (such as weirs, pipes, or meters) for the proper measurement of discharge rates and water levels.

B.2.2 Borehole yield

After the pumping tests have been carried out, the Client will decide the recommended production yield for each borehole, according to the test results, appropriate hydrogeological techniques, and the actual needs.

B.3 Borehole verticality (plumbness) and alignment

B.3.1 Tests

The borehole will be tested for plumbness and alignment by means of a 12-metre-long, perfectly straight, steel rod or pipe that will be introduced along the whole well. The external diameter of this will, at the most, be 13 millimetres less than the well casing's inside diameter. This item will be supplied by the Contractor.

B.3.2 Minimum requirements

The test item, described in B.3.1, should pass easily through the whole borehole, or through the main section of casing that will contain the production pump and rising main. Loss of plumbness of the well axis should never be more than two-thirds of the inside diameter of casing. If these minimum requirements are not met in the borehole, the Contractor will, if possible, correct the defects. Otherwise, the Client is at liberty to reject the well and no payments will be made for its drilling and completion. This check should be made before or after test pumping of the borehole.

B.4 Protection of water quality, disinfection, and sampling

B.4.1 Contractor responsibility

The Contractor will take utmost care to avoid physical, chemical, or bacterial contamination of the well water during the construction process. Where water is polluted owing to the Contractor's neglect, he will be obliged to carry out all necessary remedial operations, at his own cost, in order to remove such pollution from the well.

B.4.2 Well sterilization

Once the borehole has been completed and tested, the Contractor will disinfect the well with a chlorine solution yielding at least 50 mg/l of active chlorine in all parts of the well.

The chlorine solution for this purpose may be prepared by dissolving calcium hypochlorite, sodium hypochlorite, or gaseous chlorine, in water. The chlorine solution should stay in the borehole for at least four hours, at the specified concentration.

B.4.3 Formation samples

The Contractor will keep a complete record of the formation samples taken during the drilling operations, in properly packed and identified sample bags, and will make these available to the Client upon his request.

The Contractor will take at least one sample every three metres of drilling, unless a change in geological formations is observed by the driller. In such cases, additional samples should be taken. The minimum weight of each sample should be 500 grams.

For each sample not taken, the Contractor will be fined a penalty amounting to 1% of the total value of the borehole, and this will be deducted from the final payment. If the total amount of samples missed is more than 15% of the specified number, the borehole should be started again and the Client will not make any payments for the work already done.

B.4.4 Water samples
The Contractor will take two water samples for laboratory analysis, after completion of the long-duration (constant discharge) pumping test. One sample will be used for physical and chemical analysis, and this should be placed in a clean and properly sealed plastic or glass container. Its volume should not be less than five litres. The second sample will be used in a bacteriological analysis. It should be collected in triplicate, in sterilized, properly sealed, and protected containers. The volume of such containers should not be less than 100 millilitres. The samples will be handed to the Client as soon as they have been collected.

B.4.5 Sand particle content in pumped water
The water drawn out of the borehole will be acceptable if it has a sand particle content of less than three grams per cubic metre. Should this limit be exceeded, the Contractor will make all necessary adjustments to the well structure, at his own expense, in order to meet this specification.

B.5 Finishing works

B.5.1 Temporary cap
The Contractor will pay close attention to the due protection of the borehole against entrance of water or other pollutants while drilling or after completion of the borehole. For this purpose, he will provide a temporary cover or cap to be placed atop the borehole casing at any time the drilling rig is not in operation. This cover will also be placed after the borehole has been completed.

B.5.2 Sanitary seal
All the boreholes that have been successfully completed and tested should have proper sanitary seal protection built of concrete.

This protection will be placed a minimum of two metres below the ground to 0.25 metre above the ground and will occupy all the annular space between the borehole wall and the outside of the casing/screen.

Annex 6. List of items on contractor work/charge sheets

Drilling Contractors	
Moving onto site	km
Setting up	Each set up
Dig mud pits	hours
Drilling mud	kg mud
Drilling at diameter X”	m
Drilling at diameter Y”	m
Drilling at diameter Z”	m
Fabricate casing point	Each fabrication
Drilling with foaming agent	kg agent
Instal casing/screen/centralizers	m
Fabricate reduction collar	Each fabrication
Instal gravel pack	kg, bag, or cubic m
Backfill	Each job
Pour chlorine/Calgon	kg chlorine/Calgon
Acidization	Per job
Development (blowing/surging/jetting)	hours
Mechanical cleaning	hours
Sanitary seal	hours
Borehole cap	Each item
Formation sampling	Per job
Water sample	Each sample
Standing time (to contractor)	No charge
Standing time (to client)	hours
Downtime (to contractor)	No charge
Fishing (to contractor)	No charge
Plumbness/alignment check	Each check
Clean up site (to contractor)	No charge

Test Pumping Contractors	
Moving onto site	km
Setting up	Each set up
Instal/Remove pumps and rising main (including outlet pipe)	m
Pumping, step test/measure drawdown	hours
Recovery after steps/measure drawdown	hours
Pumping constant discharge	
Test/Measure drawdown	hours
Recovery after constant discharge	
Test/Measure drawdown	hours
Water sample	Each sample
Standing time (to contractor)	No charge
Standing time (to client)	hours
Downtime (to contractor)	No charge
Disinfection	Per job
Clean up site (to contractor)	No charge

Annex 7. Product references and further reading

A. Product references

1. Consallen Group Sales Ltd, P.O. Box 2993, Sudbury, Suffolk CO10 0ZB, UK.
Tel/Fax: +44 (0) 1787-247770; e-mail: sales@consallen.com.

2. Eureka UK Ltd, 11, The Quadrant, Hassocks, West Sussex, BN6 8BP, UK.
Tel: +44 (0) 273 846333, Fax: +44 (0) 273 846332.

3. Promotion of Appropriate Technology Co. Ltd, 44/5 Soi Atit, Wutakard Road, Chomthong, Bangkok 10150, Thailand. Tel: +66 (0) 2 476-1845, (0) 2 476-5313, Fax: +66 (0) 476-5316; e-mail: pat@pat-drill.com.

4. Marsh Funnel Viscometer: OFI Testing Equipment, Inc.,
1006, West 34th Street, Houston, Texas, 77018, U.S.A.
Tel: 713 880 9885, 877 837 8683, Fax: 713 880 9886, www.ofite.com.

5. Johnson Screens (India) Ltd, e-mail: sales@johnsonscreensindia.com.

6. Marks Products Inc., 1243 Burnsville Road, Williamsville, Virginia, 24487-9611, U.S.A.
Tel: 800-255-1353, www.geovision.org.

B. Further reading

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2. Ball, P. *Drilled Wells*. Swiss Centre for Development Cooperation in Technology and Management (SKAT), 2001.

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9. Nampusuor, R. *Report on Innovations in Borehole Rehabilitation*, Report for the CWSA/ CIDA Community Water Project Upper Regions, Ghana, 2001.

10. Roscoe Moss Company. *Handbook of Ground Water Development*, Wiley-IEEE, 1990.

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MISSION

The International Committee of the Red Cross (ICRC) is an impartial, neutral and independent organization whose exclusively humanitarian mission is to protect the lives and dignity of victims of armed conflict and other situations of violence and to provide them with assistance. The ICRC also endeavours to prevent suffering by promoting and strengthening humanitarian law and universal humanitarian principles. Established in 1863, the ICRC is at the origin of the Geneva Conventions and the International Red Cross and Red Crescent Movement. It directs and coordinates the international activities conducted by the Movement in armed conflicts and other situations of violence.

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