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**The Potential of Bucket Bored Wells for Rural Water
Supply in Developing Countries**

Robert James Summers, B.A.

A thesis submitted to the Faculty of Graduate Studies and Research as partial fulfillment
of the degree of

Master of Arts

Department of Geography
Carleton University

Ottawa Ontario

July 27, 1998

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**“THE POTENTIAL OF BUCKET BORED WELLS FOR RURAL
WATER SUPPLY IN DEVELOPING COUNTRIES”**

Submitted by Robert Summers , B.A.
In partial fulfillment for the requirements for
The degree of Master of Arts

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July 27, 1998

Abstract

A supply of safe reliable water is of great importance to the development of rural societies in developing countries. Groundwater is often a source of such water. Development projects have tended to focus on either hand dug or machine drilled wells to exploit this groundwater. This focus has limited the ability of projects to adapt to different social and physical environments. Projects should consider a greater variety of more appropriate well construction techniques. One such technique is bucket boring of wells. Bucket boring has been used in industrialized countries for more than a century. Bored wells may be an appropriate technology for development projects. They have many attributes that make them superior to hand dug wells and drilled wells in a variety of social and physical environments. The use of bucket boring as a well construction technique should be considered in all rural water projects in developing countries.

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Chapter 1: Introduction

Water is vital for survival. In rural areas of developing countries its provision can mean the difference between life and death, or more commonly, between sickness and health. Currently more than 1.1 billion people lack access to safe drinking water in the developing world (UNICEF, 1998). In many areas, the safe water that people require is directly below them. Unfortunately accessing that water, and keeping it 'safe' can be a difficult thing.

Groundwater is often seen as a thing of mystery, a mysterious source of water which is safe and abundant. To access groundwater it is most often necessary to construct a water well. Water well construction techniques have varied throughout time and place. Different methods of construction have developed as people have adapted techniques to deal with particular biophysical and social environments.

In rural areas of developing countries, water supply is often of poor quality and can be responsible for the spread of disease. Development agencies and governments often perceive water well construction as a means to supply rural populations with safe reliable water. Construction methods adopted by development agencies have not shown the same diversity as that found in private well construction. Hand dug wells and machine drilled wells have tended to be the dominant construction methods used within these programs. It is the contention of this thesis that the current focus on hand dug and drilled wells is inappropriate. This thesis focuses on one particular well construction technique, bucket boring of wells, and its potential for use in development programs.

Bucket boring of water wells is a construction technique which creates a large diameter well, similar in function to a hand dug well, but without many of the shortcomings. This large diameter allows for the exploitation of low transmissivity aquifers (aquifers with a low flow rate) of shallow (up to 7 m) and moderate depths (up to 50 m) which could not be exploited through the use of drilled or punched wells. These wells, though similar to a hand dug well, provide greater aquifer penetration and sedimentation resistance, thus making them more reliable. Bucket boring has been used in North America and Europe for over a century. There are specific geologic settings where it is the only technique that can be employed effectively to exploit groundwater.

It is contended in this thesis that bored wells are, in many cases, a more appropriate technology than those technologies currently employed in development projects. Bucket boring has certain characteristics, which make it more favorable in particular biophysical and social environments. As noted above, certain hydrogeologic situations favor bored wells. Also, bored wells are more resistant to drought and sedimentation than hand dug wells. Bored wells can make use of handpumps in regions where drilled wells cannot. The process of bucket boring is simpler than drilling and may be more acceptable to local people. The inclusion of bored wells as an option for well construction greatly expands the physical locations where a well may be sited, thus allowing for greater responsiveness for local social and logistical concerns. Although modern bucket boring rigs use fossil fuel engines, traditionally rigs have made use of animal power (horses); this may have application in developing countries. Effectively, bucket boring is another tool which can be used

to exploit groundwater. By including this technology as a potential method of constructing water wells, projects become more flexible and responsive to local environments. The result of this is an increased potential for greater sustainability of water projects.

In North America, bucket boring methods have tended to be relegated to areas where drilled wells are not functional. These areas range from small areas of less than a square kilometer to much larger areas of thousands of square kilometers. Much of Saskatchewan and approximately half of Iowa are quite dependent upon bored wells as a water source. Because its use has typically been regional and because the technology involved has changed little over time, bucket boring receives little attention in water well literature. Knowledge of bucket boring techniques appears to be confined to individuals in the water well industry within those regions where it is commonly used. Water engineers and drillers who have not worked in these regions tend to have little or no knowledge of bucket boring.

Because of the above, bucket boring is almost unknown in the development community. In discussions with dozens of individuals involved in water supply in developing countries, only two had any knowledge of the existence of bucket boring techniques. One had experience with bucket boring in Alberta (McPherson, 1992), while the other had experience in Saskatchewan (Fitzgibbon, 1998). In a rather thorough search of development literature, I did not come up with a single reference to bucket boring. Through a major supplier of bucket boring rigs, I know of two separate projects in Africa which employed the use of bucket boring (Collins, 1997), one

project was in Ethiopia, the other in Algeria. The records of both are scarce, due to war and poor record keeping.

The first purpose of this thesis is to examine the potential for bored well usage in water supply projects in rural areas of the developing world. Information has been gathered to determine if bored wells fit the requirements of the developing world. Both the biophysical aspects of bored water well construction as well as the social aspects of water well projects are considered. Information was gathered from a variety of sources, including discussions with professionals in the water well field, primary data sources (such as well logs), books, journals and other academic publications. This research, combined with my own personal experience, is the base behind the thesis. I am a journeyman water well driller in Alberta, Canada, and have experience on boring rigs, direct circulation mud rotary rigs, and direct circulation air rigs with down the hole hammers. I have brief experience with percussion rigs and reverse circulation rotary rigs. My family has been in the business of constructing water wells for four generations. In addition to those individuals directly referenced in the text, I have spoken with a number of water well drillers, borers, engineers and other related professionals regarding the process of bucket boring and its application in the developing world.

The second major purpose of the thesis is to educate all levels of workers in the water sector about bored wells, their construction, and their characteristics. There has been little information recorded about bored wells and most information which is available is out of date and inaccurate. Although not a manual for bored well construction, this thesis should provide the reader with an adequate understanding of

the methodology and technology used. Water engineers may find certain aspects of the thesis to be at a basic level, but it is expected that they will find other sections useful. An individual with no experience in the water industry may find that some sections presume a basic understanding of groundwater supply. For these people, a comprehensive text such as Driscoll's *Groundwater and Wells* (1988) may be a useful reading companion.

The main body of the thesis is structured into seven chapters. Chapter two is an introduction to the most common methods of well construction. It is centered around the distinction between large diameter wells and small diameter wells. At the end of the chapter is a clarification of the terms used throughout the rest of the document. Chapter three is a description of modern bucket boring techniques. Much of the information is from my own experience on bucket boring machinery. This chapter should give readers a clear understanding of bucket boring equipment, techniques, applications, and limitations. Chapter four is a look at the use of animal powered boring machines. These machines were a mainstay of water well construction throughout the latter part of the 19th century and into the first part of this century. The premise in chapter four is that these machines are a simple technology which may offer an appropriate method of well construction for the developing world. Much of the information in this chapter came from discussions with former operators of animal powered boring machines. Chapter five discusses how water well construction techniques relate to the physical environment in which they are used. This includes an examination into how groundwater geology and weather patterns should influence the choice of well construction. Chapter six is a brief look at water

prospecting and its relevance to bored wells. Chapter seven is an examination of social issues which are pertinent to the choice of well construction technique employed. This includes a look at appropriate pumping technologies. Lastly, chapter eight looks at some real world situations which are relevant to the entire thesis. This is done so that some of the theory presented in the paper can be demonstrated in reality. Chapter nine is a summary of the thesis and conclusions.

Although the premise of the thesis applies to many areas in the developing world, the reader will notice that most examples of situations relate to Africa. This is done for two reasons. First to give a certain focus to the thesis arguments and second because water projects in Africa have been exceptionally prone to failure. Africa, in general, does not have a well developed private water well industry (which much of the developing world has) and water well construction is done mostly by governments and organizations.

Chapter Two: Water Well Construction and Typology

Water wells all share the similar function of tapping groundwater, but there are a number of characteristics which change from well to well. Diameter, depth, formations encountered, casing style, perforation style, storage capacity, and flow rate are probably the most significant variables used to describe a well. These variables affect the working of a well and are interdependent upon one another. The diameter and depth of a well affect both the flow rate and the storage capacity. The formations encountered affect the decision of what kind of casing and perforations to install. The flow rate of a well is a result of all of the above.

Well typology tends to be based upon the method of producing the well. Wells can be constructed in a variety of ways. Most methods can be classed as being one of the following: dug, drilled, punched, or bored. This is only a very broad overview because there is a much greater breakdown within each of these categories.

The purpose of this chapter is to categorize and explain the techniques commonly used to produce wells in the developing world. A second purpose of this chapter is to standardize the use of terminology for the remainder of the thesis. This is done because there is no official nomenclature of water wells and water well construction techniques. This can lead to confusion when reading from one document to another. What is termed a borehole in one article may be referred to as a drillhole or tubewell in another.

The type of well design and construction technique to use in any particular situation is decided by a number of factors. A decision is usually made which takes into account the physical possibilities, the water needs of the users, and the costs involved. How different well construction methods relate to these issues will be discussed when descriptions of the differing well and construction techniques are given.

Costs for each method of construction will vary greatly between locations and projects. Because of this, and the lack of actual data on bored well construction costs in the developing world, costs will be dealt with in a non-specific manner in this thesis. More specific costs could be determined when examining a particular area and project prior to the implementation of a project.

Although a variety of construction techniques exist, the two most common methods currently used are dug wells produced by hand and machine drilled wells. Drilled wells are common throughout the world. They have achieved popularity in developed countries due to the ability of drilling rigs to penetrate most strata. Although they are used in the developing world, their high costs and complex nature make their operation difficult in many areas. Hand dug wells are generally used only in developing countries, where labour is relatively inexpensive compared with the costs involved in running expensive drilling rigs. Hand dug wells are often touted as a more appropriate technology than modern drilling methods.

Large Diameter Wells

There is no specific measure that indicates that a well is considered *large diameter*. The reference comes mostly due to the fact that well diameters tend to cluster into two categories. The diameter of most wells falls either between about 50 to 200 mm or 600 to 1500 mm. Those which fall into the first category are considered to be small diameter wells. Those in the second category are referred to as large diameter wells. In terms of relative frequency, few wells fall in the area between these nodes. This, very unofficial system, is commonly used in discussing wells. For the purpose of this thesis, those wells with a diameter of 600 mm or more will be considered large diameter. Those with diameters under 200 mm will be considered small diameter. Wells which fall between these values will be considered to have a medium diameter.

Hand digging, machine boring, and reverse circulation rotary drilling are the three most common methods of constructing a large diameter well. Wells have been dug by hand for thousands of years throughout the world. Bucket boring is a technique that has been used for over a century, first using animal power, then using machines powered with fossil fuel engines (Eberle and Persons, 1979: 10-17). Reverse circulation rotary drilling is a more recent technology. This is an expensive endeavor which is used in areas where wells with extremely large pumping rates are required. As reverse circulation rotary techniques are so costly, there is little call for them in rural development programs.

Large diameter water wells are capable of storing great amounts of water. This gives them a specific advantage over small diameter wells. Clark (1988: 23), speaking specifically about hand dug wells, notes that these wells are invaluable in marginal aquifers (aquifers with low transmissivity) because of their ability to act as a self filling reservoir. The aquifer can leak continuously into the well in order to fulfill a peak demand period which may be much larger than what the aquifer may be able to instantaneously provide. Blankwaardt (1985: 3), Watt and Wood (1978), DHV consulting (1977), and Brush (1979: 12, 19) also note this benefit of large diameter wells. The deeper and wider the well, the greater its reservoir potential becomes. With regard to both high production wells and those wells making use of marginal aquifers, the greater intake surface area that large diameter wells have, results in another advantage over small diameter wells. A larger intake area improves the flow of water into the well. The general rule regarding well diameter and water inflow is that for every doubling of the diameter, the water flow will increase by ten percent (in an unconfined aquifer) (Driscoll, 1986: 450). This would mean that if a 100 mm well had a flow of 240 litres per hour then a 1600 mm well of the same depth would have a flow of about 350 litres per hour. In marginal areas, or areas where high production is needed, this difference could be very significant. The ability to collect and store water, along with the improved water flow into a large diameter well, makes the use of bored or hand dug wells quite viable in many areas where small diameter wells are ineffective.

In developing world applications a large diameter well also has advantages relating to pumping systems. Where there is concern over pump breakdowns it is

quite possible to install more than one pump on a large well and there is even room for an access hatch for bucket use if pumping systems fail (IRC, 1988: 72). Another advantage of large diameter wells is the prevention of turbulence when pumping. Uphole velocities and turbulence become more severe the smaller the diameter of a well. This turbulence can lead to corrosion, encrustation, and siltation problems. These issues will be discussed further in Chapter seven, which deals with social and logistical issues of water wells (including pump maintenance).

There are some disadvantages to large diameter wells. The first of these is the effort and expense involved in lining them. This is especially significant in developing countries. The per foot cost of large diameter wells is higher than small diameter wells. It is important to note though that large diameter wells are generally much shallower than most small diameter wells. There is also an additional cost involved in sealing and covering large diameter wells. Lastly, these wells generally are limited in depth. Few hand dug wells surpass 30m in depth (Brush, 1979: 20) and few bored wells surpass 50m (Gus Pech, year unknown). In comparison, the maximum depth of rotary drilling is basically determined by the equipment. Typical equipment used for water well construction is capable of depths over 250m.

Dug Wells

Dug wells can be produced either by machine or by hand. A dug well is a well in which material has been removed through a direct mechanical process. This simply means they have in some manner been dug. Most dug wells are excavated by hand, but in some circumstances backhoes or other mechanized equipment are used. Hand dug wells were the most common type of well throughout the world until at least the

mid-1950's (Tolman, 1937: 393; Wagner 1959: 68.). In developing countries hand dug wells are still the most common source of groundwater exploitation (Clark, 1988: 23). S.B. Watt and W.E. Wood (1977) have written what is probably the most comprehensive manual on hand dug wells. Other sources that are very useful are publications on water wells written during the time that hand dug wells were still being constructed regularly in industrialized countries (such as Wagner and Lanoix, 1959). Most recent publications on groundwater and wells give little more than a brief mention of hand dug wells if they mention them at all.

Presently in industrialized countries, most wells are constructed using more complex methods. It is becoming less and less common to see dug wells being constructed. This is mostly due to the introduction of different drilling techniques, the cost of labour, the licensing of water well drillers, and the specialization of companies in drilling water wells. It is now far more common for a well to be constructed by a licensed water well driller using a rig designed for that purpose, than it is for an individual to dig his own well.

The tools used to dig a hand dug well usually consist of shovels, pails, ropes, chisels, picks, a tripod, and at times a pump. Hand dug wells are generally limited to formations which can be removed with such tools. This generally limits hand digging to unconsolidated materials or soft rock. Using picks, chisels, and at times explosives, hard layers can be penetrated, but this is extremely difficult and slow work. Rarely is more than a meter of hard rock removed by such methods (Wagner, 1959). It is important to note that hand dug wells are generally installed in areas where modern technologies that would make digging easier (power chisels, hydraulic rams, etc.) are

unavailable or very expensive. The techniques and technology used to construct hand dug wells has changed little through time.

Digging Methodology

After a workspace has been set up for digging a hole, excavation can begin. Workers, using shovels, dig a hole large enough for them to enter and work in. The excavators continue digging downwards, removing material with shovels. Once they are too deep to 'throw' material from the hole, pails are filled and removed from the hole from above by rope. The hole must be large enough for at least one man to work in. Watt and Wood (1977) suggest the minimum diameter for this is about 1200 mm. In material that will stand without caving, workers continue to dig the hole without any casing or well lining being installed. This procedure, although fairly common, is rather dangerous as all unconsolidated material poses a risk of caving. When caving is seen to be a problem, the hole is cased as it is dug.

Hand dug wells are generally cased using one of two methods; either with concrete rings set in from above, or by brickwork built up from the bottom (see Plate 2.1). Wooden casing was often used in North America and Europe quite successfully, but is seldom seen in developing countries today. When cement rings are used for casing, they are installed as the well is dug (or in some cases rings are poured inside the well). The excavators simply remove material below the bottom of the rings allowing them to slip down. This is known as caissoning (Wagner and Lanoix, 1959: 259). At times this method is employed in the lower section of a well (where caving may be problematic), while the upper section is lined by bricks and mortar or by cement rings poured within the well. Even in a well that is being cased as it is dug,

there is a danger of the rings separating while sliding down. If this happens, sediment can flow into the well, burying whomever is digging inside. In formations of very loose sediment hand digging is difficult as formation material flows up from the bottom of the casing faster than it can be dug. Where more than about 3 m of such material is encountered, it is unlikely that a hand dug well can be produced (DHV Consulting, 1978: 83).

Once water-bearing strata have been reached, excavation becomes difficult. If the water is entering the well at a very slow rate, it can be bailed out while digging. If water is entering the well at too great a rate to be bailed, a pump may be used. This is not an option in very loose sediment (sands and gravels) as caving will occur as water is removed from the well. Even in firm, unconsolidated water bearing materials (such as clay), the removal of too much water will result in the formation collapsing. In most situations, once water bearing formations have been encountered the excavators can dig no deeper. In some cases, the well is deepened further when the water table drops (during the dry season).

Water enters the well either from the bottom of the cased hole (usually through some form of gravel pack), or through the casing itself (through perforations, leakage between joints, or permeable casing). When dealing with fine sand, it is usually preferable for water to enter from the bottom of the hole as gravel layers provide a filtering system to prevent the well from silting in.

Plate 2.1: Hand dug well cased using bricks.

The major limitation of hand-dug wells is their lack of aquifer penetration (IRC, 1988: 72). Except in cases where advanced technology is used, hand dug wells are unable to proceed deep into an aquifer. Even in the best situations, rarely is penetration of up to 2 m reached (IRC, 1988: 72). When drawing from the top of an aquifer, only a fraction of available water production is attained. The inability to continue digging after an aquifer is reached also prevents the excavators from digging through one aquifer and into a second aquifer further down. Penetration to a second aquifer would be beneficial because a greater flow of water may be achieved. Fluctuating water tables often pose problems for hand dug wells. They often run dry during the times they are most needed (dry season, drought periods) (Walsh, Hulme and Campbell, 1988: 193). If this occurs, the well must be deepened. This may be extremely difficult if the well was dug by an outside group which is not in contact with those using it (as is the case in many development programs). These difficulties result in hand dug wells often being unpredictable and unreliable (Brush, 1979: 19).

Another factor limiting the depth of hand dug wells is the inability to penetrate hard rock. This is not to say that hard rock cannot be penetrated, but it is rarely done to any extent because of the great time and effort required. In many areas where there is little or no unconsolidated material, hand dug wells are not a viable option.

In unconsolidated sediment, hand dug wells face another drawback. They must be cased as they are dug. This is dangerous for the excavators and limits the quality of the design of the well.

Hand dug wells take a great deal of labour and time to dig. It is not unreasonable for a trained crew of men to take more than a month to complete a well (Brush, 1979: 20; Blankwaard, 1984: 4). It is also important to note that if wells are hand dug outside of the dry season, it is usually necessary that they be deepened during the dry season.

There are, however, a number of benefits in constructing hand dug wells. The most significant one relates to the low level of technology needed in digging. This results in a low cost for well construction in areas where labour is relatively cheap in relation to mechanized options. A well can be dug with simple tools and hand labour, so it is an attractive option in developing countries where labour is cheap and capital to invest in equipment is scarce. In addition to the issues involved in constructing a hand dug well, there are the advantages and disadvantages that are shared among all large diameter wells as discussed in the previous section.

Machine Dug Wells

As stated above, some dug wells are produced using more complex machinery such as backhoes. These wells are similar to hand dug wells, but generally are much more limited in depth. Few backhoes can dig beyond 5m. These wells share the advantages and disadvantages of hand dug wells. They are most common in the industrialized world in areas where a shallow water table makes it an inexpensive method of tapping groundwater. This method is becoming less common as environmental regulations tighten and water well drilling is being done only by those licensed to do so.

Bucket Boring

Bucket bored wells share a number of similarities to hand dug wells. They have a large diameter, usually from 600 mm to 1m. They generally, though not always, make use of aquifers in unconsolidated materials. Machine bored wells do not face the aquifer penetration problems of hand dug wells. The technique of boring also allows for well construction through harder materials, and materials which cause caving difficulty. The construction of bored wells will be discussed in detail in chapter three so the following is only a brief description.

Machine boring generally makes use of a rotating auger or more commonly, a bucket. The auger or bucket is turned in the hole until full, and then is pulled out and emptied. Modern bucket boring rigs, such as that produced by Caldwell, EZ Bore, or Gus Peck industries have telescoping kellys which raise and lower the bucket. Older rigs, driven by animals, used removable kelly sections to allow for the lifting and lowering of the bucket or auger. If a formation can be bulldozed or ripped, it can be removed by a bucket boring rig (Barr, year unknown: 88). Formations that have sufficient amounts of clay to act as a binding agent to stand up without support can be bored and casing installed after completion. Caving formations can be bored by caissoning cribbing down the well while boring or by keeping the hole full of fluid (water) while boring.

Using modern equipment, these wells are extremely quick to construct. Barr (year unknown) suggests that it is quite reasonable in favorable conditions to complete two or three wells up to depths of 30m in one day. My own experience suggests that

although this is quite possible, conditions generally dictate that one well a day with a single crew is a more realistic expectation.

The largest advantage that a bored well has over a hand dug well is its greater aquifer penetration. Bored wells also are superior in their casing and development methods. They are also a safer method of well construction (it is not necessary for individuals to enter the well). The most significant disadvantage of bucket boring of wells is the cost involved with using expensive equipment rather than manual labour for construction. Another disadvantage is the limited depth that these wells can attain. The disadvantages and advantages of bucket bored wells will be discussed in greater detail in the following chapter.

Small Diameter Wells

As stated above, small diameter wells for the purpose of this paper are those wells with a diameter of less than 200 mm. There are many methods used to construct such wells. Small diameter wells can be produced through percussion, drilling, or boring methods. All of these methods can be done by machine, or on a smaller scale, by hand. Drilling of water wells has become the most common method of producing water wells in the industrialized world. Hand drilling of wells is gaining popularity in the developing world due to its low cost and simplicity.

Small diameter wells have an advantage over large diameter wells in that they are cheaper to produce per meter. The major disadvantage of a small diameter well is the lack of storage and collection ability. For these wells to function, the aquifer they tap must be able to supply the peak demand of water whenever needed (DHV, 1979:

10). If at any one time, a pumping rate of 20 litres per minute is required of a well, the aquifer would need to be able to yield such an amount. If an aquifer which can supply the needed flow of water exists at a shallow to moderate depth, then a drilled well is most likely the least expensive method of well construction to employ. If such aquifers are not available at a shallow to moderate depth, it then becomes necessary to either drill deeper in the hopes of finding an aquifer with higher transmissivity or to install a large diameter well which can take advantage of a slower yielding aquifer. This choice has added dimensions in Africa where pumping technologies play a significant role in decision making. Deeper wells mean more complex pumps. This is often problematic in developing countries (DHV, 1978: 10).

Punched Wells

A punched water well is one that is produced through a punching (percussion) method. This method is also known as the cable tool method. The cable tool method of constructing water wells has been employed for more than 4000 years (Roscoe Moss Company, 1990: 145). This method consists of the raising and dropping of drilling tools with rope or cable to fracture and loosen materials. The fractured material is then mixed in a slurry with water (and possibly other drilling fluids) and is bailed out of the hole. Historically this method has been carried out in a variety of ways. Wells have been punched by hand, with individuals raising and dropping drilling tools either with rope or as a drill string (i.e. bamboo pipe, etc.). Animal power has also been used to punch wells. This is accomplished through the means of

simple drilling rigs. Mechanized drilling rigs making use of fossil fuels for power became very common in the early part of the 20th century (Tolman, 1937: 397).

Modern cable tool rigs have drill stems (drill tools) from 2m to 15m in length that weigh between 450 to 1400 kilograms. These tools are raised and dropped at a rate of more than 40 times per minute. Cable tool rigs are capable of producing wells from 75 to 600 mm in diameter (Hamill and Bell, 1986: 153). Most cable tool wells tend to be between 75 to 200 mm. Wells of great depth can be attained. Even with simple technology, the ancient Chinese were able to dig wells of almost 1000m in depth. However, construction of these wells often took two or three generations (Driscoll, 1986: 268). With modern technology, the depth limit that can be achieved by such a method is machine specific. Figure 2.1 displays the individual parts of a cable tool rig.

Cable tool rigs are still used in both industrialized and developing countries today. They are mostly used in areas where there is very little or no unconsolidated material above rock formations. This is because they are slow and inefficient in softer formations. The popularity of cable tool rigs has diminished greatly over the last half of this century due to the advance of rotary methods, which can produce similar holes in a great deal less time. Rotary drilling will be discussed in the next section.

Figure 2.1: Cable Tool Rig and Components

(Source: Roscoe Moss Company, 1990: 145)

Cable tool rigs are generally inferior to rotary drilling rigs in their efficiency and the time taken to drill a well. They have difficulty drilling through unconsolidated material, and tend to become slower and less efficient as the depth of the well increases. It is not uncommon to hear of a cable tool rig working on a 100m hole for more than a month. Another disadvantage is that in many circumstances these rigs are limited to using steel casing. This removes the possibility of using PVC casing; the result of which is the creation of inferior wells.

To their credit, under certain geological conditions, a cable tool rig can punch a hole rather quickly and effectively. These conditions are rather specific: areas consisting of hard rock formations such as hard shales and limestones or areas where rotary rigs experience loss of circulation (gravel, extremely fractured material).

The major reason the cable tool method continues to be employed rests with the costs involved. The equipment used is quite simple compared with rotary rigs leading to lower capital costs. Cable tool rigs also have lower *operating* costs when compared to rotary rigs. This includes fuel consumption, labour costs, and drilling supplies (Roscoe Moss Company, 1990: 149). Cable tool rigs are generally more durable and much easier to repair, making them an attractive option in many developing countries.

Drilled Wells

Drilled wells are produced using a rotary drilling technique. There are both hand drilled wells and machine drilled wells. All of these are small diameter wells,

which must rely on a direct flow of water out of the aquifer for water supply as they have very little storage capabilities.

Wells Drilled by Hand

Where they are hydrologically feasible, hand drilled wells are probably the most economical method of exploiting ground water. The term 'hand drilled well' generally covers all types of wells constructed either by boring or drilling wells by hand. Probably the best sources of information on constructing hand drilled wells are Bob Blankwaardt's *Hand Drilled Wells* (1984) and Brush's *Wells Construction: Hand Dug and Hand Drilled* (1979).

Although there are a number of specific techniques that one requires to construct hand drilled wells, the basic premise is rather simple. Through the use of either a small drilling bucket or auger, material is removed from the hole. The auger or bucket is rotated until full and then it is lifted either directly by hand or through the use of a simple tripod. To obtain greater depths, extensions are added while entering the hole and removed while coming out. Once the well is drilled, it is cased in a similar fashion to a machine drilled well. PVC casing is probably the easiest type of casing to use due to its light weight. Water well screens or slotted casing may be used in such wells as an intake.

Hand drilled wells can be extremely useful where unconsolidated or soft rock (soft sandstone or limestone) formations are found to supply reasonable amounts of water at depths up to about 30m (Brush, 1979: 15). They are relatively inexpensive to produce and maintain when compared with other methods of constructing wells (Blankwaardt, 1984: 4). They are, however, limited in depth though and cannot

penetrate harder layers. Also they will not function in slower aquifers as they do not have adequate collection and storage functions.

Machine Drilled Wells

Direct rotary drilling makes use of a drilling fluid (water, water mixed with additives, or air) to remove cuttings ground up at the bottom of the hole with a drill bit. Probably the best sources regarding machine drilled wells are Driscoll (1986) or the Roscoe Moss Company (1990). This method of drilling was designed during the 1920s for use in drilling seismograph holes, which were used in exploration for oil. In the 1930s, these types of rigs were being adopted for use in the water well industry (Driscoll, 1986: 279-280). Since then drilling methods have evolved to become the most significant manner of constructing water wells in the industrialized world. A well equipped drilling rig is able to work in a great variety of situations with success. The components of a drilling rig can be seen in Figure 2.2.

Figure 2.2: Direct Rotary Mud Drilling Rig

(Source: Roscoe Moss Company, 1990)

When drilling, a rig is performing two simultaneous functions, the first of which is the crushing and grinding up of material at the bottom of the hole. This is how the rig penetrates into formations. There are a number of different drill bits which are used to perform this function in different geologic conditions. The second function is the constant circulation of a fluid through the bit and back up the well. The essential functions of the drilling fluid are to lift the ground up material (cuttings) being created by the bit out of the hole, to stabilize the hole and prevent caving, and to cool and clean the bit (Driscoll, 1986: 286). It is very important that a driller understand the workings of both of these activities. Fluid viscosity, uphole fluid velocity, drill bit rpm, and the amount of weight set on the bit are all integral parts of the operation.

The drill bit is attached to the bottom of a string of pipes (drillstem). These pipes are hollow so as to allow fluid to circulate through them. The pipe is then attached either to a kelly or directly to a top drive system. In either case, the pipe is rotated in some manner (either direct drive or hydraulic). The rotation of the pipe carries down to the bit. The combination of the weight of the pipe and the rotating bit is the force, which causes the material in the hole to break down.

Unless air drilling is being used, drilling fluid (water or water with additives) is circulated. It begins in a settling pit (large tank often referred to as a mudpit). This fluid is then sucked into a large pump (mudpump) and pushed through hoses to a sealed swivel where it then enters the kelly and then the drill pipe. The fluid continues down the pipe, exits through the bit (picking up the cutting), and returns up the hole on the outside of the pipe and back into the settling pit. Here cuttings drop out of the

fluid due to their weight. The process continues as long as the drilling activity is taking place (see figure 2.2 on page 27).

The above method is very effective at maintaining high rates of drilling in unconsolidated formations, and in most sedimentary rock. It suffers however in very hard material such as metamorphic or volcanic rock. It is in these formations where cable tool (percussion) rigs have traditionally shown better performance. Over the last thirty years or so though, the introduction and improvements of down the hole hammers on drilling rigs has resulted in rotary drilling rigs being more effective to construct wells even in hard rock situations. It is important to note that this equipment is expensive to purchase and operate. It is also very specialized and would be hard to maintain in the developing world.

The down the hole hammer is an innovation which allows for a hammering action similar to that of a punching rig, but with a rate of 500 to 1000 blows per minute. This hammering action occurs along with the circulation and rotary benefits of rotary drilling (Hammil and Bell, 1986: 157). The hammer is mounted on the bottom of the drill stem in the same manner as a drill bit. It is activated by air which originates from a large air compressor mounted on the rig. The hammer pounds the material into such small cuttings that they are lifted out of the hole with the escaping air.

The advantages of drilling methods are numerous. This is the reason that they are widely used. Formation penetration is extremely quick in many materials. Wells of 100m can be sunk in a few hours under favorable conditions. Due to the use of drilling fluids to keep the hole from caving, a well can generally be drilled first and

cased after. This allows for the use of most casing types (PVC or Steel) and perforation methods (screens, slotted casing, etc.). With a well-equipped rig (down the hole hammer, high volume pumps and compressors) it is possible to drill through almost any formation to great depths. This allows for a great geologic range in which wells can be completed. The only areas where a well cannot be made are those areas where ample water supply for a small diameter well does not exist.

Another important drawback of rotary drilling methods are the high costs and complex technology involved. These rigs are costly, especially if air compressors, down the hole hammers, and high volume mudpumps are involved. The deeper the depth that the rig must be able to drill to, the greater the cost of the rig. The complexity of these rigs results in high maintenance costs and the need for highly trained individuals to operate them. Quite often inadequate drilling knowledge among drillers leads to poor quality wells. This results in lower well yields than could be possible, perhaps even resulting in 'dry wells' where adequate water sources actually exist to produce a well.

Terminology

Throughout the thesis the following terminology will be used when discussing wells. First, the technology used to create the well will be stated. This will generally be either stated as done by hand (human power augmented by simple tools), by animal power (simple rigs driven by animal traction), or by machine (fossil fuel driven technology). This will be followed by a descriptive term as to what method is used to create the well. Some examples of this are bored, dug, drilled, and punched. Next

will come a term that basically describes the diameter and possibly the depth of the well. If necessary (if it is unclear) the next term used in describing a well will relate to the strata from which it is taking its water. This could be consolidated sediment, basement complex rock, or unconsolidated sediment. Lastly, other descriptive terms that are necessary will be placed upon the end of the term. This could relate to the method of perforation, the type of casing, or the flow of the well. Note that when a well is screened it can be assumed (unless otherwise stated) that it is tapping an aquifer which is in unconsolidated sediment. Some examples of the well types could be as follows: A *hand-dug large diameter shallow well*, or a *machine drilled small diameter deep basement complex well*. When it is appropriate simpler terms will be used and generalities will be noted.

The terms relating to depth differ from text to text. Most often shallow wells are considered to be 7m or less. This is the approximate depth to which a suction pump can be used. For this thesis a shallow well will be considered to be 7m or less. A well of moderate depth will be from 7m to 50m in depth, and a deep well will be greater than 50m in depth.

When discussing different water well construction technologies the following terms will be used. An individual who operates a water well punching machine (cable tool rig) will be referred to as a water well puncher, the machine will be referred to as a punching rig. An individual who operates a rotary water well machine will be referred to as a water well driller, the machine will be referred to as a drilling rig. An individual who operates a water well boring machine will be called a water well borer, the machine will be termed a boring rig. The processes will be termed 'drilling',

‘punching’, and ‘boring’. This terminology is of significance because in much of the literature and in general conversation it is traditional to refer to individuals as ‘drillers’ and the process as ‘drilling’ regardless of what methodology is used (drilling, boring, or punching). That will be avoided here and the more direct notations discussed above will be used. When it is necessary to generally refer to all well construction people (drillers, borers, punchers, hand diggers, etc.) they will be referred to as well constructors.

Chapter 3: Modern Bucket Boring

History

Bored wells were a common method of well construction throughout the later part of the 19th century and into the early part of the 20th. By the mid 1940s though, punching rigs had become the dominant method of construction for water wells (Craig, 144-145:1947). At this time, methods were not yet developed to bore in caving ground. This resulted in poor aquifer penetration and unreliable wells. Since 1950, drilling machines have replaced punching rigs as the main type of water well rig being employed in industrialized countries, and boring methods have improved so that caving material is no longer a problem.

The decline in the popularity of bored wells in the early part of this century was a result of its inferiority to punching methods of the time. The inability of bored wells to obtain sufficient aquifer penetration along with the advent of improved punching methods resulted in punching methods usurping boring methods. Bored wells continued to be used in areas where aquifer penetration was not a problem and where small diameter wells (punched or drilled) were ineffective.

During the 1950s, rotary drilling techniques began to supplant punching methods as the mainstay of well construction. More recently combination rigs, using both rotary and 'punching like' methods (through the use of air hammers) have become quite significant. Throughout this period of time, though remaining less prevalent, boring methods have remained in use and have evolved. Sometime in the 1960s (if not before) the use of water to prevent unconsolidated material from caving

was introduced. Since then this methodology has been further improved through the use of polymers. This overcame the problems of caving material and obtaining aquifer penetration. Other improvements have been made which allow boring machines to penetrate harder material than previously possible. The adoption of hydraulics has greatly improved modern boring machines. Modern boring machines are efficient, effective ways to produce water wells.

Current Usage

With the ability to produce quality wells in an effective efficient manner, a question remains as to why bucket boring has remained secondary to drilling methods in the domestic water well industry. A quick survey of water wells in most of the industrialized world will show that the majority of wells produced in the last couple of decades are drilled wells. Presently, usage of bored wells tends to be limited to those areas where geologically (physically) they are superior in comparison to small diameter wells. In areas in which both bored wells and drilled wells will function effectively, drilled wells have begun to dominate. This implies that drilled wells in some way maintain a non-physical advantage over bored wells. I suggest four reasons why this has occurred in North America. The first of these relates to the historical situation where bored wells, due to certain drawbacks, were supplanted in many areas by punched or drilled wells. The second relates to the reputation of bored wells historically. The third reason relates to the economics of start up costs for water well companies. The last relates to the rise of reverse circulation drilling methods for large diameter wells.

As stated above, the methods used to bore water wells in the early part of this century did not allow for boring through caving material (Sparks, 1997). This often led to wells that were unreliable during dry periods (winter, etc). Another common problem among wells of this era was contamination due to poor well design. Few bored wells were sealed from surface contamination. As punching methods improved throughout the late 19th century and the early part of the 20th, they became a viable alternative to bored wells. Punched wells were more reliable at the time, and less prone to contamination (by virtue of their construction technique). Because of their superior quality and their ability to function in a greater variety of areas, punched wells displaced bored wells as the standard for water wells. Not long after, drilled wells replaced punched wells.

As a competing technology, bored wells lost a great deal of ‘momentum’ during much of the century. In a sense, the *initial advantage* bored wells had was overcome by a superior technology. This can be seen in the change in manufacturing of boring rigs. In the early part of the century there were over a dozen producers of water well boring machines (Collins, 1997). Presently, there are only two major manufacturers in the world (EZ Bore, Gus Pech). This small number of manufacturers of boring equipment means only two companies are actively promoting boring technology. In contrast, there are at least twenty major, and dozens of minor, manufacturers of water well drilling rigs, each promoting the use of drilling technology (Water Well Journal, 1996; Faison, 1998). This weakened “infrastructure” for boring technologies has not encouraged its growth. It has helped to prevent bored wells from ‘competing’ with drilled wells. Because of the momentum behind drilling

technology, it currently is more common in areas where geohydrologically both types of technology are adequate. This has left bored wells relegated to being used only in those areas where they are geologically superior to drilled wells.

Due to the problems (poor aquifer penetration, contamination problems) that were associated with bored wells historically, they became seen as ‘old technology’ and inferior to ‘modern’ small diameter wells. This description of bored wells was accurate at the time. Bored wells ‘earned a reputation’. Since that time bored wells have improved immensely. The reputation remains in many people’s minds though. It is often erroneously put forth that bored wells are unreliable and prone to contamination. I have heard this claim from a variety of people including water well constructors and customers. This attitude towards bored wells tends to persist in areas where they are not required as a source of water supply. People who have less contact with bored wells are more likely to be ignorant of them. I have not met a water well constructor or geologist who was well informed and experienced with bored wells who felt that they were problematic. It is most likely that this mis-information persists because there has been little need to challenge it. Bored wells are used where they are needed, and there is little incentive to push for their expansion into other areas.

A third factor that has led to the popularity of small diameter wells (mostly drilled) over large diameter ones relates to the supply side of the industry. The machines used for drilling water wells are commonly used in the mineral resources industry (petroleum and mining). The petroleum industry makes use of drilling machines for seismic testing (for oil and gas stores). These machines are also used in

drilling gas wells. The mining industry uses these machines for exploration and test holes. There are a number of uses for drilling rigs.

Boring rigs, on the other hand, have few uses other than drilling water wells. Excluding a few specialty applications such as methane recovery from landfill sites (Swanson 1997), they are not used outside of the water well industry.

The *minimum* cost of a new water well rig (boring or drilling) would be at least \$250,000 U.S (Faison, 1998). The most common purchasers of new drilling rigs tend not to be water well constructors dealing in domestic water supply, but rather companies doing work in the petroleum or mining industries, or companies dealing with industrial water needs. The need for modern, extremely dependable equipment creates a necessity for purchasing new equipment. This leaves their older machinery available for purchase at a greatly reduced cost.

It is not as imperative in the water well industry to have such modern equipment. The used equipment from other industries results in a supply of used drilling rigs for the water well industry. Used rigs tend to sell for prices which are a fraction of the cost of new rigs (Faison, 1998). This greatly lowers the cost of either starting or expanding a business. The water well drilling industry also benefits greatly from sharing similarities with the petroleum and mining industry. It benefits in decreased cost for equipment due to a surplus of used machines from those industries. It also benefits greatly from economies of scale for production of drilling muds, drilling bits, and assorted other supplies. Even the availability of experienced workers from these industries benefits the water well drilling industry. In addition companies with drilling rigs often are employed in the aforementioned industries as well as the

domestic water well industry. This increases opportunity for profit making. The water well *drilling* industry greatly benefits from its coexistence with the mineral resources industry.

Because of the above, the costs of both starting up and running a water well business is less when using drilling technologies rather than boring technologies. The result is that in areas where bored wells and drilled wells function equally well, drilled wells are the more economical type of well. Boring rigs tend to be more expensive to purchase and there is little opportunity to do work outside of the domestic water well industry. It is a stand-alone industry compared to the water well drilling industry. In areas where bored wells are necessary because drilled wells do not function, there is profitability in owning a boring machine (due to reduced competition from the drilling industry). This results in a significant boring industry being maintained in certain areas.

Lastly, the rise of reverse circulation drilling for large diameter holes has provided direct competition for boring equipment. Reverse circulation rigs can easily produce large diameter holes up to depths of over 300 m (Roscoe Moss Company, 1990: 144). This type of equipment is generally employed by large engineering firms for large projects (such as urban water supply). It is, however, far too costly to be considered for domestic water well construction. For depths up to 50m, bucket boring machines are far more efficient and economical than reverse circulation drilling. Nevertheless, the advent of these machines in the latter half of this century has resulted in a lower demand for bucket boring technology. Large drilling companies which in the past would have operated a boring machine now use reverse rotary

machines because their higher cost for shallow to moderate depth wells does not outweigh the advantage of being able to drill much deeper.

Published Information

Most published information on water well construction and design tends to focus on one of two areas. The first of these is a discussion about the most common or most modern methods and technologies being used in producing water wells. These processes tend to address the high-end corporate sector of the industry. They tend to be focused towards water engineers and large project situations. They discuss expensive technologies in the industry, the customers of which are usually corporations or governments. Some publications such as the *Water Well Journal* are aimed towards smaller scale contractors. These tend to discuss the methods used for drilling water wells, but rarely discuss other methods such as the boring of wells. There is simply very little information put out by the industry or by independent journals on the boring of water wells. This is due to the simplicity of boring methods, as well as its regional usage.

The second type of information available on water well construction comes from a very different source. It is development based. Journals such as *Waterlines* and *Source*, and books such as *Hand Dug Wells and Their Construction* by Watt and Wood (1979) address simple technology solutions to water supply problems. These sources are much more interdisciplinary than most references for well construction. They deal with the social, logistical, physical, and economic aspects surrounding the supply of water in developing countries. No articles that I have come across have discussed bored wells. When discussing well construction methods only a few options

are commonly mentioned. These are usually hand dug wells, machine drilled wells and at times, hand drilled wells. There are simply few people in development work who know about bucket boring and most likely none thus far have been focused upon it enough to write about it. It is a neglected area.

Bucket boring is neglected in both development and water well literature. The sparse information available regarding bucket boring is generally just recycled information from older articles and is inaccurate and out of date. Almost all mention of bucket boring comes with the absolutely inaccurate comment that bored wells cannot be used in caving material. This recycling of old information can be seen in the following example. In an article discussing boring technologies, many paragraphs of a 1979 article in *The Johnson Drillers Journal* (Larson, 1979) were directly copied from another article from the same journal in 1969 (Carr, 1969). The more recent article did not note that it was presenting old information and presented boring technology as it existed a decade earlier. In another example, the discussion of bucket boring in *Groundwater and Wells, 2nd Edition*, by Fletcher Driscoll (1986), is almost a direct reiteration of that presented in the first edition (Johnson, 1966) and of its predecessor *Ground Water: It's Development, Uses and Conservation* (Bennison 1947) also released by Johnson. The information provided did not reflect the improvements in boring technology or methodology. In contrast, the section on drilling rigs had been greatly enhanced to reflect how drilling methods had improved.

Because of the lack of recent literature on bucket boring, the major source of information regarding bored wells must come from individuals who are currently involved in the industry. As for published information, there tends to be some

available from government departments and research centers in areas where bored wells are common.

Modern Techniques and Equipment

The following is a discussion of modern boring methodology. I have included this as there has been little published on the subject. Most of the information is from my own experience and observations or has been gained in conversations with other water well borers. Methods vary from place to place, but the basics of bucket boring are the same. The methodology is best understood if observed, but it is hoped that the description below is sufficient to give those without that experience a general understanding of the process. It is also hoped that those more involved with water well boring may perhaps gain new insights.

Description of A Rig

Although there are some minor differences between models and brands, modern boring machines are generally very similar to one another. Boring rigs are rather simple when compared to drilling equipment and require less supporting equipment.

The typical components of a boring machine can be seen in Figure 3.1. Boring machines are most often truck mounted, and powered either by the motor of the truck or by a separate engine mounted with the rig. The motor, directly or indirectly, (through a hydraulic system) powers the drawworks (large winches) and the table drive. The rig has a large mast (derrick) that is lifted hydraulically. When the mast is laying down (traveling position), on it rests the kelly. The kelly appears as a long

section of square metal tubing (8-12 meters in length). The kelly is usually made up of three tubular sections, each fitting within the others. This is done so that the kelly can be 'telescoped' to a distance three times its length (see Figure 3.2). The telescoping kelly allows the rig to reach great depths easily. Fitted around the outside of the kelly is the kelly drive (yolk). The kelly drive can slide up and down the kelly (or more accurately the kelly can slide through the kelly drive). The kelly drive locks into the rotary table and transfers rotary power to the kelly (the kelly then transfers this to the bucket). When standing, the kelly hangs down from the mast. It is held by a cable, which goes over the top of the mast (the crown) and back down into the drawworks (winches).

The boring bucket is a round cylinder with auger-like drilling edges at the bottom. These edges make use of metal cutting teeth (the same as found on a backhoe). The entire bottom of the bucket is a hinged like a large trap door, so that cuttings may be dumped. The dumping arm is connected to the side of the rig and is hinged so it can be swung out from the truck. The rotary table consists of a large ring gear and a housing. The ring gear is driven either directly from the motor using a clutch system or through hydraulics.

Figure 3.1: Bucket Boring Rig

Figure 3.2: Telescoping Kelly

Lower section of telescoping kelly. Bottom picture has outer sections of kelly cut-away so as to see interior shaft. Center Shaft is solid.

Boring a Well

The following is a brief description of the basic method of boring a well. I have included it because such information is difficult to find in the literature. This is the type of operation that is usually shown visually (on site) or described in person. This is only a simple description and is not a manual of boring practices. The techniques involved in using such machinery are best learned through apprenticeship. In many ways it seems to be as much an art as a science. Much can be understood by the 'feel' of the ground and the sound of the machine. These things are not easily recordable.

Once a drilling site has been selected, preferably on level ground, the rig must be set up. The first aspect of this is leveling. This is often done using permanently mounted hydraulic jacks to set the rig level. If the ground is quite unlevel, it may be necessary to level the truck by 'digging in the wheels'. A level, stable rig is important for safety as well as good boring. Once level, the mast (derrick) can be lifted. Along with the mast, the kelly and kelly drive are lifted. With the kelly hanging, the derrick is set in position so that the kelly hangs plumb (it may also be necessary to adjust the leveling jacks). The kelly is then connected to the bucket, which is hanging in the rotary table (supported by a steel rod running through it which rests on the table). The bucket can then be lowered to ground level. As the bucket is lowered, the kelly drive is aligned so as to sit on the runners in the rotary table. The driller then engages the rotary table. The kelly drive slides around to slots in the table housing. When in the slots, the kelly drive is locked to the rotating table, thus turning the kelly, which transfers that rotation to the bucket below. The bucket then cuts into the ground and

begins boring. The bucket fills as it bores down. Once full, the bucket is lifted (usually with a slight rotation at first to lower the lift friction) out of the hole and up above the rotary table (see Plate 3.1).

There is great technique involved in controlling the digging of the bucket. It is very important that the borer understand the physics at work which lock the kelly, the table, and bucket to ensure adequate downward force on the bucket. Inexperienced drillers often misunderstand this. In one case in Ethiopia, it was observed that government employed borers working on a new Gus Pech boring machine did not understand this technique (Summers, 1998). This led to very poor boring speeds and ineffective use of the machine.

As the first bucket is being dug (or prior to), the helper (roughneck) usually will set up the dumping arm. This is a large hydraulically driven arm, which uses cables and pulleys to pull the bucket aside for dumping. Once the bucket is out of the hole, the helper hooks the dumping arm cable to it. It is then pulled aside by the arm and emptied (via the hinged bottom of the bucket) (Plate 3.2 and Plate 3.3). As it is brought back to the rotary table, the bucket is set on the side of the table closing the bucket door (Plate 3.4). The bucket is lifted, the dumping cable removed and it is then ready for another trip into the hole.

Plate 3.1: Boring Bucket, full of sediment, is brought out of well.

Plates 3.2 and 3.3: Bucket is pulled aside using dumping arm and is emptied.

Plate 3.4: Bucket is closed as it is set upon table.

When boring in unconsolidated material with enough clay content to prevent caving, the entire well is bored as described above. In unconsolidated sediment, which has the potential to cave, the method changes somewhat. As stated previously, this was one of the major problems faced by early water well borers. The first method used to overcome caving material was through casing the well as it was bored. In a method similar to that described in chapter two for hand dug wells, the hole was bored and cement cribbing was cased down behind it. This method is still in use in certain areas (Gus Pech Video, year unknown), but has been replaced in most areas by a method that makes use of fluid pressure.

The more modern method of dealing with caving material has been by filling the hole with water (Plate 3.5 and 3.6). Filling the hole with water creates pressure, which pushes outwards on the walls. This prevents caving. Originally this method required a large supply of water, but improvements in boring methodologies have reduced the volume of water required significantly. Water loss into formations (water would push out into the surrounding material) was the cause of large water needs. This problem has been dealt with through adding organic polymers (such as Revert[®]) to the water. The polymer forms a light gel in the hole, creating a film on the side walls and increases the density of the water to prevent water loss. Another benefit of the polymer is the increased pressure of the denser water (drilling fluid) on the walls of the well. After the well is finished, the polymer erodes. Chlorine can be used to remove the polymer quicker.

Plate 3.5: Bucket is down the hole and the kelly is locked into position. The rig is ready to bore out another bucket of material.

Plate 3.6: (above) hole is kept full of water to prevent caving. Plate 3.7: perforations are made using a tool made from a pick.

Drilling with fluid to prevent caving does have its limits. In flowing sand or in gravel it may not be possible to prevent caving. The only option available then is to use a liner (temporary casing) in the hole, or to case the hole as it is bored (most often with cement cribbing).

In certain areas, it is common to encounter large rocks or boulders when boring through unconsolidated sediment (especially in glacial deposits). There are a variety of ways of dealing with this problem. If the boulder is off to the side of the hole, one of three things must be done. The first option is to break or grind off the edge of the boulder. This can be done by hammering the bucket down on it (in an attempt to break it off), or by using a coring bucket to cut through it (this may not work if the rock slants into the hole; the coring bucket may simply slide off). A second option is that it may be possible to cause the boulder to fall into the bottom of the hole. This may be done by bumping it with the bucket or with a large auger. When at the bottom of the hole though, the boulder must be removed either by a clamshell bucket, an orange peel bucket, or an auger. A third option is to attempt to remove the boulder by making it fall on top of the bucket or auger. This is again done by bumping it, but this time from below. The auger can be useful here because the boulder (if small enough) may wedge into the spirals. It is usually, though not always, possible to remove a boulder. In the past, drillers often used dynamite sticks to blast boulders apart; however this is a difficult and dangerous procedure.

Consolidated sediments (sandstone, shale, limestone, etc.) can sometimes be bored using the regular bucket with special cutting teeth. When formations are too

hard to bore, it may be necessary to use a coring bucket. The coring bucket cuts into the formation in the same manner as a holesaw cuts into wood. Once the coring bucket has cored down into the bedrock, the core breaks off and is brought out of the hole inside the coring bucket. Almost any sedimentary rock can be removed using a boring machine with a coring bucket. This though is rather slow compared to drilling unconsolidated sediment. Speeds may average as slow as 15cm per hour. If a rig is expected to encounter the need to use coring buckets often, it is suggested that it be equipped with a pull-down system. The pull down system allows for more pressure (weight) to be put on the coring bucket. This greatly improves boring rates. Gus Pech Mfg. Co., has also developed a hydraulic powered percussion hammer to speed up the removal of consolidated formations. This option could be useful in areas where a great deal of rock is encountered.

The ability to bore into this rock is extremely significant because it may be employed in cases where an aquifer occurs directly above the bedrock. In this case, the additional storage gained by the coring bucket greatly improves what would have been available for a hand dug well which did not penetrate the rock (see Figure 3.3). This is a common situation in hand dug wells because consolidated sediment (limestones, sandstones, and shales) often halts digging by hand.

Unfortunately though, for most basement complex formations (basalt, slate, etc.) boring is not an option. Boring machines do not have the power to cut through such material. The only way to do so is with some sort of percussion method such as a downhole hammer.

Figure 3.3: Hand Dug Well and Bored Well
Encountering Consolidated Formation

Casing

There are a variety of casing types used in bored wells. The three most common materials in use today are galvanized corrugated culverts, PVC pipe, and cement rings (cribbing). Historically, wooden casing has also been used. Cement rings have been used in Africa for years in hand dug wells. The same rings can easily be used in bored wells. Cement rings were used in a bored well project in Ethiopia without problem (Summers, 1998). Most often a well is cased after it is bored, with the casing lowered from above. When using the cement ring method of casing, the rings are set on top of each other in the hole using a tool designed for that purpose. This can be done either above or below water. With PVC or galvanized casing, the casing is connected while being lowered into the well. The lower portion of the casing string is hung from the rotary table while the next joint of casing is lifted and connected. Most often these connections are made using coupler bands (Plate 3.8).

In situations where the well must be cased while it is bored (dry hole method for unconsolidated caving material), cement rings must be used. As the hole is bored (using a bucket which is just smaller than the inside diameter of the casing), cement rings follow behind. This method is known as caissoning. The small amount of 'edge' on the wall (the difference between the bucket diameter and the outside of the casing diameter) does not provide enough resistance to prevent the casing from 'sinking into the hole. If the material is fairly solid, the hole is usually bored prior to installing casing.

Plate 3.8: Casing is set into hole. Note the connection made by coupler.

The type of casing used in a bored well is related to three things: the availability (and cost) of each type, the chemical quality of the groundwater (with regards to corrosion and encrustation), and the method used to bore the hole (dry hole boring may require cement rings). In much of Africa, cement rings are already used to case hand dug wells. These rings could also be used in bored well construction. Galvanized steel is not as available and is perhaps more expensive. PVC has become more and more common in Africa. If a large operation were beginning, it may be feasible to find acceptable PVC casing produced in Africa.

The cement rings (cribbing) commonly used in Africa are often flat topped. They often rely on rebar guides formed into them for alignment (Plate 3.9). A far better system is a tongue and groove design. These were commonly used in North America prior to the implementation of PVC and galvanized steel casing. The change to tongue and groove cribbing would be a large improvement for well construction in both hand dug and bored well construction. The tongue and groove system offers better stability, better potential for sealing, and better potential for water filtration when joints are used as the well intake. This improvement can be made with minor alterations to the cement forms (see Figure 3.4). Construction of tongue and groove cribbing in Ethiopia can be seen in Plates 3.10 and 3.11.

Figure 3.4
Comparison of Cribbing Used
for Large Diameter Wells

Cribbing commonly used in development projects

Far superior design of Cribbing resulting in greater stability and easier sealing of surface joints. Also results in better filtering of sediment if joints are used as well intake. (Note: Constuction of this cribbing is no more compex than the above)

Plate 3.9: Cement cribbing which uses rebar to align itself. This is a poor design which is difficult to seal and results in contamination and sedimentation.

Plates 3.10 and 3.11: Construction of cement cribbing using forms. Note the tongue and groove design. Simple tripod is used for loading cribbing.

Well Intake and Contaminant Seal

For a well to be effective, it must have an intake section where water from the aquifer can enter. For bored wells there are three major methods of creating this: perforated casing may be used, the well may be constructed so that water may enter from the open bottom, or a water well screen may be used.

Perforated casing is an inexpensive, simple method of creating a water intake. Perforations are small holes that are put in the side of the casing to allow water through, but keep sediment out. When galvanized steel is used for casing, perforations are usually created using a special perforating tool. Most often this tool has been crafted out of another tool (such as a mining pick or ice pick). It has a thin, sharp end which creates a very thin v-like slot in the side of the culvert. It takes practice to get the proper 'weight' when using the tool, but the technique is relatively simple. If too large of slots are accidentally created, an individual with a hammer (and proper hearing protection) can go inside the culvert and 'close' the perforations to an appropriate width. The perforating of the casing is done while it is still lying on the ground (Plate 3.7).

PVC casing is usually perforated using a drill with a small bit, or a small rotary saw with a thin blade (.010"). It is very important when making perforations in PVC casing that the structural integrity of the material be maintained. The best method of perforating the casing should be developed through consultation with the supplier of the PVC casing. If that is not an option, it is advisable that small perforations be used and that they be as far from one another as possible.

Cement casing presents an interesting problem. It is very difficult to create perforations in it after it has been constructed. Perforations must then be built into a certain number of cement rings. There are some different methods to achieve this. The first method is by placing small steel rods through the form while the cement is still wet (through pre-drilled holes in the form). Once the cement has set enough that the holes will stay open, the rods are removed. This method works well, but is time consuming. A second method is to remove the forms from the cement while it is still 'green' (partially wet); rods can then be pushed through it and removed creating numerous holes.

Relying on pre-perforated cribbing can result in problems when a well must be cased as it is bored. The difficulty arises because it is necessary to determine when to insert the porous rings into the casing string to line up with the aquifer. In other words, you have to guess where the aquifer is going to be long before you reach it. In areas where the rig operator knows the conditions well, this is less of a problem.

A second method of creating a water intake for a well is through using *bottom entry*. This can be used on wells cased in PVC or galvanized steel, but it is mostly used in wells using cement rings. In this case, the well is completed without boring through the entire aquifer. It is completed so that water may enter through the bottom of the well. To prevent sediment from entering the well, a large gravel pack is used at the bottom. This gravel pack should be at least 1 to 2 meters thick and it should be made up of pea-sized gravel and coarse sand. The pump should be installed no closer than one meter from the gravel. This is a well design that should be used only when other methods are not available (i.e. non-perforated or porous cement rings). With a

proper gravel pack and a controlled outflow of water (limited pump volume), a water well designed this way can last for a very long time and is certainly an option.

Another issue with cement cribbing is the leakage, which occurs through the joints of the cement rings. As noted above, tongue and groove cribbing is far superior to flat topped cribbing for sealing. The top 3.5 meters of a well should always be sealed (Iowa State University, 1993). Cement rings can be sealed a number of ways. Grout or bentonite may be used between the rings to make a seal. If this is done carefully it works reasonably well. Rings of a soft rope (such as hemp) may be used to create a gasket-like seal. Sections of PVC and galvanized steel are generally more than 3.5 meters long, so there is no need to further seal them.

To further ensure the seal and to prevent contaminants from entering the water table alongside the well, the top 3.5 meters of the annulus (open space around the well) should be filled with impermeable material. This is best done using grout and is known as a sanitary surface seal. If grout is not an option, silty-clay taken from the well or from a local source should be used. Another method is the buried slab method (Iowa State university, 1993). This involves sealing the well 3.5 meters below the surface and installing smaller casing for that distance (reducing the casing diameter significantly; however this method takes away many of the benefits of bored wells (ease of access and maintenance) and should be unnecessary.

The last method of creating an intake for a water well is through the use of a continuous slot screen. The goal of all of the perforations discussed above is to allow water in, while keeping sediment out. Perforations must also be able to do this without becoming plugged up with silt. The most effective method of doing this is

with a continuous slot screen. A water well screen has a great deal of open area (space for water to enter into the well) so that it maximizes water flow into the well. It is designed so that all the fine material surrounding a well will come through the screen during well development, and none will come through after. The v-slot of the screen prevents it from becoming plugged up (Schreurs, 1990: 40-41). The installation of water well screens is most useful in wells completed in aquifers containing sand and/or silt. Using proper screens will result in improved well performance and well life. These screens are available in the U.S. and in Europe, and importation would often be justified through the production of silt-free wells which maximize aquifer production. The cost of these screens is minimized when low-carbon steel screens are used rather than stainless steel. The low-carbon screens often will perform almost as well as the stainless screens for a fraction of the cost.

Sand Pack (gravel pack) and Well Development

Once the casing has been installed, it is necessary to create a proper filtration pack around the outside of the perforations or screen. This can be done one of two ways: with a natural sandpack or an artificial sandpack. If an artificial sandpack is used, it will be necessary to have a supply of sand. That sand is then placed between the casing and the natural sediment. A natural sandpack makes use of the sediment surrounding the well intake. All that is required when using a natural sandpack is proper development of the formation (discussed below).

An artificial sandpack requires the addition of sand and/or gravel around the outside of the perforated area of the casing. For wells finished with perforations (rather than a screen), the sandpack should consist of coarse sand mixed with small

pea sized gravel. If a screen is used, a coarse sand will suffice. An artificial sandpack is preferred when dealing with aquifers consisting of very-fine to medium sand. The artificial pack will help guarantee that there will be no sediment entering the well. I would suggest that artificial packs be used whenever there is a good supply of appropriate sand available. The sandpack creates a filter around the outside of the well, which allows water to reach the perforations, but prevents finer material (silt) from entering.

Well Development

Once a well is cased and sandpacked (either with a natural or artificial pack), it must then be developed. Well development is one of the most important aspects of water well construction and is often the most neglected. Proper well development optimizes the performance of the well by improving flow and preventing the future entry of sediment into the well. An improperly developed well will result in sediment in the water and will lead to shortened well and pump life. Developing the water well is the act of reorganizing the sediment around the well intake. This is done with three basic goals: to remove fine sediment from the aquifer formation, to organize the sediment around the well intake to prevent future sediment movement, and to stabilize the formation around the well intake (Hamill and Bell, 1986: 185-186). Sediment is rearranged so that it is graded from large grain size close to the intake openings, to finer grain size away from the openings. The result of this is a filter that prevents the movement of fine sediment that could enter the well. The rearrangement of the sediment can be seen in Figure 3.5.

Figure 3.5: Cross Section of
Well Development

Sediment prior to well development.

Reorganized sediment after well development. Sediment acts as a filter now, preventing fine material from entering well with water.

Well development in unconsolidated aquifers is generally done using water movement to act upon the sediment surrounding the casing. This can be done a number of ways with differing levels of effectiveness (see Table 3.1). As stated above, improper development is a common problem among wells. Hand dug wells are rarely developed by any method other than over-pumping. Over-pumping is done by pumping water from the well at a much higher rate than it will be pumped in regular usage. This results in problems with sedimentation, pump wear and the plugging of the well intake. With modern boring rigs, surging with either a surge block or a bailer is the most common method of development. Surging is done by placing a large surge block (large disk which is close in size to the inside diameter of the casing) on the bottom of the kelly and moving up and down. This forces water rapidly both in and out of the perforations or screen and the formation.

The bailing method of well development combines surging and rapid water-removal. Bailing is a process through which a large bailing bucket (large cylinder with a one way valve on bottom) is rapidly lowered into the well, filled with water, then removed and emptied. Water from the well enters the bucket from the bottom. The bucket is emptied (dumped) when removed from the well. Large amounts of water can be removed very quickly using this method. In addition, the impact of the bailer, when it hits the water surface, forces water to flow through the perforations and back into the formation, thus resulting in a surging effect.

If there is a water truck available while developing the well, backwashing (filling the well with water to the top) and bailing is a very effective method of development. In unconsolidated sediment it is of utmost importance to properly

develop a well. This may take only a couple hours or it may take an entire day. At times it is necessary to allow the well to recover overnight before finishing developing. Plate 3.12 shows a well being pumped using a high volume pump. Often combining methods of development is most successful.

Advantages and Disadvantages

As discussed in chapter two, the large diameter of bored wells and hand dug wells give them certain advantages and disadvantages relative to other well designs. Due to their different methods of construction however, there are both advantages and disadvantages between the two. Increased aquifer penetration is the most significant advantage which bucket bored wells have over hand dug wells. Depth of penetration into an aquifer is the single most important variable in increasing yield and in increasing reliability of a well in times of low recharge (Harlan, Kolm, and Gutentag, 1989: 94-95; Larson, 1979: 5-7).

In its design and its workings, a bored well is superior to a hand dug well in every respect. Due to the precision that can be used in setting casing and determining aquifer location it is much easier to control perforations and to set screens. The ability to pass through an aquifer and complete the well below it, gives a benefit of added storage space and the ability to bottom the well in an impermeable layer. This forces all water entering the well to come through a sandpack and properly designed perforations (or well screen), greatly reducing the possibility of sand entering the well.

Table 3.1: Methods of Development Relevant to Large Diameter Wells

Method	Most Suitable for	Effective Range	Advantage	Disadvantage
Overpumping	Unconsolidated formations, Thin, relatively uniform, permeable aquifers. Often used in Hand Dug Wells.	Most effective over upper 25-50% of the screen length	Simple, Cheap, Easy.	Limited effective range. Does not overcome bridging by itself. Requires a pump with a greater capacity than the design discharge. Sand pumping may damage the pump
Rawhiding	Unconsolidated formations. Suitable for most situations. Often finish off with this technique when other methods used. Large diameter wells use a backwash variation, letting gravity force water backwards.	Upper portion of the screen	Simple, cheap, easy. More effective than straight-forward overpumping.	Limited effective range. May not completely eliminate bridging. Pump faces same requirements as above. Large diameter wells need a large volume of water available.
Surge Block	Unconsolidated formations. Suitable for most situations. Widely used with cable tool rigs and boring rigs.	Whole length of screen depending on technique adopted.	Simple, cheap, easy and effective.	Difficult to use with a rotary rig.
Bailing	Unconsolidated formations. Suitable for most situations. Widely used with boring rigs and cable tool rigs.	Whole length of screen.	Simple, cheap, easy and effective. Combines benefits of overpumping with surging.	Time consuming in slow well.
Dispersant chemical	Any formation. Used mostly with mud rotary rigs, but can be useful in clay formations.	Generally used in conjunction with jetting or backwashing.	Easy to use, improves other methods.	Not very effective when used by themselves.
Blasting or shooting	Consolidated formations. Commonly sandstones because acidizing is ineffective.	Depends on positioning of explosive, may be entire well.	Simple in theory. Can be very effective. Also cleans well face	Requires skilled, experienced personnel. Outcome may be unpredictable.
Acidizing	Consolidated formations. Usually limestones because they are most susceptible to acid attack, particularly if fractured.	Effective over submerged part of hole and surrounding aquifer	Can be very effective	Requires skilled, experienced personnel. Can be expensive and time consuming.

(Adapted From Hamill and Bell, 1986: 187)

Plate 3.12: Sediment laden water is pumped from a well helping to develop it.

There are other advantages as well. It is much quicker to begin and complete a well through boring than by hand digging. It is also much safer constructing a well from above than from within. This safety factor is important to consider. Entering a hole in the ground can be very dangerous. Even a hole being cased as it is dug can be deadly. It is possible for the casing to separate, allowing sand to pour into the hole and bury those inside. These safety aspects are generally not emphasized enough in the books on hand digging. In Brush's book he advocates the entering of an uncased hole of loose soil such as damp sand to a depth of 5m. This is by no means an advisable action. Damp sand is extremely dangerous and a hole consisting of it should not be entered to a depth of greater than about 1.5m. Even what Brush describes as firm soil could be dangerous.

The largest disadvantage of bored wells is the cost involved with using expensive equipment rather than manual labour. Many of these costs could be overcome if simple boring machines powered by animals were employed. This method is not as quick and powerful as using modern hydraulic rigs, but it is almost as effective at obtaining aquifer penetration and creates a well far superior to hand dug wells in almost every respect.

Another shortcoming of a boring operation is the inability to reach great depths. This, though, is only a disadvantage when deep wells are required due to the hydrology of an area. In cases where shallow or moderate depth wells are not an option (that being under 40-50m), neither is bucket boring. The other significant disadvantage with this method is its high cost per meter. This aspect of boring water

wells means that if an effective small diameter well can be produced in an area then that would be a less expensive alternative.

Chapter Conclusion

This chapter has been a further investigation into large diameter bored wells as they are produced by modern methods and technology. The first major point made in this chapter was that economic, historical, and social factors in industrialized countries have led to bored wells being used less often than they would be if only water needs and the geological reality was taken into account. These factors may be different in developing countries. The second part of the chapter examined the methodology of boring a well and the equipment used. This is something that has generally been ignored in most literature and it was described here to further the understanding of boring techniques. Perhaps the most significant point made in this section is that the modern methods that are used to bore wells are quite improved over past methods and result in wells that are safe, sediment free, long lasting, and reliable.

Table 3.2 Well Construction Methods

Method	Large Diameter		Small Diameter		
	Hand Dug	Machine Bored	Hand Drilled or Bored	Punched (Cable Tool)	Drilled with Down Hole Hammer
Practical Diameter Range	1000 mm and up	350 mm to 3000 mm.	50 mm to 175 mm.	50 mm to 300 mm	100 mm to 200 mm
Practical Depth limit	up to 30m.	up to 50 m.	up to 50 m	Capability of rig Usually more than 100 m.	Up to 500m with compressor boosters
Formation most effective in	Unconsolidated material	Unconsolidated material Soft Bedrock	Unconsolidated material Soft Bedrock	Rock formations	All
Formations that are problematic	Bedrock to hard rock, boulders, very loose sediment	All hard rock formations, especially volcanic or metamorphic rock; boulders can cause some difficulty	Hard Rock, Boulders	Soft formations, especially unconsolidated material	Zones with extremely high permeability, hard rock formations
Water Storage (Liters/meter)	Very High	High to Very High	Low	Low to Moderate	Low to Moderate
Level of Technology Involved	Simple to intermediate	Intermediate to Complex	Simple to Intermediate	Intermediate to Complex	Very Complex

Chapter 4: Animal Powered Well Machines

Appropriate Technology

The definition of ‘appropriate technology’ is greatly dependent upon what purpose the term is being used to promote and what issues those using the term are attempting to address. Appropriate technologies have been lauded as the solution to problems of social/political origin, of consumerist/environmental origin, and of economic/developmental origin (Kaplinski, 1990: 30–41). This issue in the developing world is most closely related to the environmental /developmental stream of ‘appropriate technologies’. It is in this respect that ideas such as simple water filters, VLOM handpumps, and VIP latrines have been employed in developing countries.

As noted, the definitions of ‘appropriate technology’ vary. Willoughby, in his book “Technology Choice, A Critique of the Appropriate Technology Movement” offers the following definition: “a technology tailored to fit the psychological and biophysical context prevailing in a particular location and period” (1990: 25). This definition works reasonably well for development work. I would suggest though, that a deductive element be added to that definition so that a technology is termed ‘appropriate’ only after it has actually shown to work effectively in a locale and over time. In addition, including the need for economic sustainability, which ensures that a technology is economically viable in an area, could further the definition. Regardless, the move toward appropriate technologies is an attempt to attain greater sustainability

of projects through considering the environment in which these technologies must function. The ultimate goal is efficiency and effectiveness of results.

In the developing world there are some general aspects of design which tend to make technology more appropriate. The WHO (1994: 14) state that appropriate technology for water and sanitation in the developing world is characterized by sociocultural appropriateness, affordability, ease of maintenance with the skills available in the agency or community, maximum use of locally available materials or spare parts, easily understood attributes, and technical efficiency.

Rural Water Supply

The appropriate technology movement has improved sustainability of water projects in developing countries. The most significant action, which has led to improvement, has been the introduction and refinement of the handpump. Handpumps are a technology, which derive from industrialized countries. Prior to industrialization, buckets, handpumps and wind pumps were the major method of removing water from water wells. For domestic situations, handpumps remained the most significant withdrawal method until replaced by electric pumps (this occurred around the middle of this century). Over the last few decades, handpump technology has been promoted for use in rural areas of developing countries. This is because handpumps are lower in cost to purchase and run, and are easier to maintain than other alternatives. Effectively, they result in more sustainable setups than electrical or fossil fuel driven pumps, and safer systems than bucket and rope systems.

Since the adoption of the handpump for development purposes, a number of advancements in its design have been made. A major goal of the water and sanitation

decade was to create a VLOM pump (Village Level Operated and Maintained). A number of pumps have been designed, produced and installed with VLOM characteristics. The promotion and adoption of appropriate technology in the application of pumping systems has resulted in significant improvement in project sustainability. This sustainability is best achieved when coupled with an appropriate education program.

Well Construction

The use of handpumps is an excellent example of both the need for and the success of appropriate technologies in development projects. Some work has been done on the use of appropriate technologies in the water well construction field, but its adoption has been slow at best. Rigs such as the Vonder rig, which is used for hand drilling of wells, are very successful, appropriate drilling technologies (Kinley, 1990: 15). Aid agencies though, have tended to favor either hand dug or machine drilled wells over other alternatives. This could be due to the propensity of water engineers to be attracted to what Okun (1982: 12) terms high technology. In discussing wastewater treatment Okun suggests that engineers tend to gravitate to more complex solutions, as that has been the focus of their education (1982: 13). Howe (1993) suggests a variety of reasons which result in aid projects adopting inappropriate technology. The most significant of these include corruption, lack of adequate research of needs, desire for 'modern' solutions, and an absence of an entire system perspective. With these problems one might surmise that the lack of work done on improving simple technologies may also be related to a lack of interest in the 'simple' solutions.

A perfect example of this lack of interest and adoption of simple technologies can be seen with hand drilled wells. Hand drilled wells are perhaps the cheapest, most effective method of constructing wells in certain geologies, yet they are seldom used. The same push for appropriate handpumps has not yet been shown with regards to well construction techniques.

In North America and Europe, hand dug wells were the earliest method of well construction. With the advent of simple machines and the use of animal traction though, came improved well construction technology. It is unknown when the first simple well drilling machines were produced. It is known that by the late 1800s animal powered machines were becoming a common method of producing water wells. By this time a division of labour had begun to take place. No longer did the process of digging a water well consist of gathering neighbors and hand digging a well. It became more common to hire someone to bore a well with a horse driven boring rig. This occurred because bored wells were superior to hand dug wells and could be produced more efficiently. Nearing the end of the 1800s, punching methods were also adapted to horse powered machinery, and some rigs were combination boring-punching rigs.

In the early part of this century, boring and punching rigs powered by either steam or fossil fuel engines became more common. Drilling rigs, which were being used in the oil industry, began to be used in the water well industry in the 1940s. From that point on, well construction machines became more complex and more powerful.

Animal Powered Water Rigs

Technology

The change from animal driven to engine driven rigs was a significant point in the evolution of water well rig technology. Animal powered rigs were simple in design; almost all repairs could be done by a blacksmith or a carpenter. Once engines were introduced, repairs and construction of these rigs became much more complex.

As stated above, the current 'appropriate' well construction technology used in development projects is hand digging. I suggest that it may be far more effective and productive to move further along the evolutionary path of water well construction techniques. Animal powered rigs are very compatible with the attributes of appropriate technology given by the WHO (as listed previously). Animal powered rigs offer the ability to produce much better quality wells at lower costs than hand digging. The technology is almost as simple as that used to produce hand dug wells. Animal powered boring and punching rigs could be built in developing countries. Almost all repairs on these machines could be done on-site, and those that cannot could be done in any town with either a blacksmith or a welder. Blacksmiths are relatively common in developing countries. One study in Mali estimated that there were over 2500 rural blacksmiths who were well versed at maintaining equipment for animal traction (Ker, 1995:chapter 10). The use of animal traction is common in many areas of the developing world. Where animal traction is not employed other alternatives such as using people to power such rigs may be an option.

Where animal traction is commonly employed there are local people who are well versed at caring for and training animals. Through using animal powered water

well rigs there would be far less dependence on imported machinery and labour than is the case for modern equipment. While hand digging technologies have many of the WHO characteristics, they do not meet the requirement of technical efficiency. The use of animal powered machinery for constructing water wells results in much better quality of wells at a lower cost than hand dug wells, without significantly increasing the complexity of the operation.

Both hand digging and hand drilling of wells require the use of simple equipment such as pulleys, tripods, and ropes. When combined, these items make up what could be seen as a simple digging rig. An animal powered water well rig is an evolution of this design, the differences being that it is trailer mounted, so as to be portable, and it makes use of reduction gearing to allow for increased power. The fact that it has historically been an animal providing that power on these machines is irrelevant. Many 'hand dug' well riggings have used animals to lift material out of the hole. If animal power was unavailable, an animal powered rig could be easily adapted to make use of human power.

Workings

Animal powered boring machines were commonly used in the prairies of Canada well into the 1950s. In fact, I know of one which was still being used to bore wells in the early 1990s. That rig was built around the turn of the century. The simplicity and ease of repair of these rigs often granted them useful life-spans of well over half a century (Summers, 1998; Sparks, 1997). Commonly, wells that were bored using these machines were cased using wooden cribbing. In later years though, the use of cement cribbing was adopted.

The machines, although different in design from one manufacturer to another, are all constructed very similarly (see Plate 4.1). Most are built upon a frame with four wheels. Attached to this frame is a large ring gear of cast steel. Resting freely upon rollers on the inside of the ring gear is the upper portion of the rig. The upper portion of the rig consists of a deck with a large hole in the center (for the bucket to pass through). Attached to this deck is a four pole mast. At the top of the mast is a pulley system (the crown). The drawworks (usually a single winch) are generally attached within the mast at about waist height for a man standing on the deck of the rig. The drawworks are connected to a cable, which goes over the mast and is used to lift and lower the bucket. The drawworks are powered by a driveshaft running down through the table and onto the ring gear. The deck is attached to a drive pole, which is then connected to an animal that drives the machine by walking in circles. When in operation the entire upper portion of the machine (deck, mast, drawworks, etc.) rotates. The ring gear remains stationary. As the deck rotates, the pinion gear at the bottom of the driveshaft is forced to rotate, thus powering the drawworks. The operator can then engage a clutch that will lift the bucket out of the well.

Plate 4.1: Animal powered boring rig. Built around 1900.

Also attached to the bucket, alongside the cable, is a square steel shaft. This shaft is similar to the kelly of the modern boring rig in that it is used to transfer the rotating power of the rig to the bucket. Shafts are only the height which the rig can lift (usually up to 3 m. in length) as they must be removed as the bucket is lifted, and added as the bucket is lowered. Once a bucket is lowered to the bottom of the well and is ready to start digging, the shaft is locked in place using a kelly lock. The kelly lock is similar to the kelly drive (or yolk) of modern machines in that it transfers rotation from the deck of the rig to the kelly (and subsequent shafts). Once at the bottom of the well and ready to dig, the rig operator commands the horse to begin driving the rig. The horse walks in a circle turning the upper portion of the rig. The rotating motion is passed through the deck, the kelly lock, and the shafts unto the bucket. Once the bucket begins to fill (approximately 20 cm to 30 cm of boring), the operator engages the drawworks and begins lifting the bucket. When the first shaft is fully above the deck floor, the operator disengages the drawworks by releasing the clutch (at the same time locking the drawworks in place by engaging a brake). He then orders his horse to stop. He and his helper remove the top shaft and place it down on the deck. The following shafts are removed in a similar fashion until the bucket is out of the well. Once out of the well, the bucket is swung aside using a small wooden crane and emptied. Lowering the bucket is basically the reverse procedure of raising it, except that the horse is left to rest as gravity provides the energy for the operation.

Similar to the methods described for modern boring operations in chapter three, well cribbing can be installed during the boring process or after. In the same manner discussed for modern boring equipment, water and polymers can be used to

retain caving material in the well. In addition to wood or cement cribbing, PVC and galvanized steel casing can also be used with animal powered boring machines, but the length of each joint would likely have to be reduced to a maximum of about 5 m.

Capability

Animal powered boring machinery retain many of the same advantages over hand dug wells which modern boring machines have. They can safely bore through caving ground, they can obtain good aquifer penetration, they produce sediment resistant wells, and they construct a well much quicker than hand digging methods. Though they have some of the similar advantages, these animal powered rigs are not as powerful as their modern counterparts. The maximum reasonable depth for these machines is about 30 m (Summers, 1998; Sparks, 1997). The diameter of a hole is limited to a maximum of about 1 m. These rigs have great difficulty with large boulders and most consolidated rock. They are most effective in unconsolidated sediments.

Although boring rates vary for these machines, a 20m. well on average, would take about two eight hour days to complete (Summers, 1998; Sparks, 1997). A 20m. hand dug well would take at least three weeks to complete (Blankwaardt, 1984: 4). Some projects report on wells taking as long as a year to complete by hand (Robson, 1991: 10-11). With very good boring conditions wells of up to 25m have been bored in a day using animal powered rigs (Sparks, 1997).

A comparison of animal boring technology, hand digging methods, and a simple drilling unit (the LS-100 drilling rig) can be seen in Table 4.1. The LS-100 is a small scale drilling rig which is relatively low-cost and is considered 'appropriate' for

development work. It is easy to see that animal powered bucket boring units offer many advantages of both alternatives.

Animal Traction

Animal traction is the use of animals to provide power for simple tools and machines. Most often used in the agriculture field, its use has been promoted as an appropriate technology for developing countries. In many areas of developing countries animal work is exploited significantly. This means that there is a support network in place for animal care. Items such as harnesses and collars are familiar to local people. There are a significant number of people who are well versed at working with animals. It is very practical to make use of animal work in developing countries instead of fossil fuel equipment. Small engine mechanics would be a rarity in a small African village, but there is a much greater likelihood of there being a local leather worker. Local people are often adept at caring for animals. In many areas of the developing world animals are available locally and do not need to be imported as other power sources would be.

Table 4.1: Comparison of Well Construction Techniques

Comparison Factor	Hand Digging	LS-100 Drilling rig	Animal Bored Well
Capital Cost	Low	Moderate	Low to Moderate
Technology	In-Place	New	Mix of New and In-Place Technology
Method	Established, Familiar, Traditional	Specialized training required	Specialized training required
Effort	Major effort bonds community	Onus on few drillers	Onus on few drillers (Unless human power is used to drive rig)
Time to Complete	Weeks or Months	Days	Days
Safety	Cave-in, falling rock hazards, digging in a deep hole.	Nobody in well	Nobody in well
Contamination	Poor annular seals; Casing/lid often leak; Shallow water may be contaminated.	Protected by sealed hole & continuous casing. Deep aquifers accessible (up to 33 m.)	Protected by sealed hole & continuous casing. Deep aquifers accessible (up to 33 m.)
Decontamination	Difficult	Easy	Easy
Water Storage	Large diameter provides storage reservoir to augment low yield	Cannot construct useful well in low yield aquifers	Large diameter provides storage reservoir to augment low yield
Water Supply	Well depth limited to 1-2 meters into water table.	Well screen 3-10 meters below water table	Well Screen can be placed as far below water table as necessary.
Limitations	Caving sand or hard rock	Cobbles or hard rock	Hard rock
Maintenance	Minimal equipment; readily available.	Spare parts may be difficult to acquire	Spare parts can be manufactured locally and easily substituted for.

(Adapted from LifeWater, 1998)

Traditionally the animals powering these rigs have been horses. Horses were used because they are relatively easy to train, they provide adequate power for the machine, and were a common animal where these machines had been used. These machines could be adapted for use with any animal that is used to pull a wagon or a plow. In some areas of the world, horses fair poorly due the presence of the tsetse fly. In these areas oxen and donkeys are often used for labour. A single ox would be sufficient to power a boring machine and could be trained to do so. At least two, and up to four, donkeys would likely be required to power the machine. A well-trained camel could easily power such a machine. In areas where animal traction is not commonly used, the use of humans as a power source would be a quite feasible alternative. Local people working in shifts could easily power such a machine. This would eliminate the need for animal care and training. There are a number of possibilities for powering these machines, all of them far more appropriate to the developing world than large diesel engines.

Modifications

Once adopted as an appropriate technology for developing countries, a great deal of research was done on handpumps. Modern knowledge and local concerns were combined with traditional handpumps to create pumps which fit the needs of the developing world. I suggest that the same could be done with animal powered water well rigs. Better steel, better bushings, and better fasteners would greatly improve the workings of a rig without compromising its ability to be repaired with local substitutes. Perhaps advances in design and craftsmanship could help improve other aspects of the rig for development work. Rigs could easily be constructed in

developing countries. The cost of producing such equipment would be low, perhaps even as low as the cost of a single borehole drilled with modern equipment.

Possibilities

E.F. Schumacher was perhaps the first individual to synthesize the ideas of appropriate technology. Within the framework of appropriate technology he discussed a move from the simplest of technologies to more productive ones which retain ‘appropriate’ qualities. He termed these ‘intermediate technologies’.

... an intermediate technology would be immensely more productive than indigenous technology (which is often in a condition of decay), but it would be highly cheaper than the sophisticated, highly capital-intensive technology of modern industry (Schumacher, 1973: 167).

The use of animal powered bucket boring machinery appears to fit directly within Schumacher’s statement. It is a proven method of creating water wells. The current move towards ‘appropriate’ well construction methods and equipment has become stagnant with the focus on hand dug wells. Animal powered machinery is immensely more productive than hand digging of wells and is much cheaper than modern drilling, boring, and punching techniques. Although further research needs to be done before the adoption of these techniques in water projects, the potential does appear to exist. Hand dug wells are a traditional method of well construction, but perhaps they are not the most appropriate method of well construction. They tend to be unreliable and ineffective. New alternatives should be examined. I suggest that

animal powered boring rigs are perhaps the most effective method of production which retain the simplicity of design needed in most developing countries.

Chapter 5: Hydrological, Geological, and Climatic Factors Affecting Wells

As noted in chapter two, determining what method of well construction should be used in a given situation is done by considering the physical possibilities, the water needs of the users, and the costs involved. This chapter deals with the physical possibilities and how they affect the choice of well construction methods. The focus will be on those physical situations which favor bucket boring techniques.

The physical reality in which water engineers and water well drillers must work within is directly related to the hydrologic cycle. The hydrologic cycle is the endless circulation of water between the ocean, the atmosphere, and the land (Freeze and Cherry, 1979: 1) (see Figure 5.1). To obtain water for human consumption and use, it is necessary to intercept water moving through the hydrologic cycle. Water wells are a method of intercepting this cycle as water moves through the ground.

The goal of a water well is to successfully intercept enough water moving through the ground to be of use to those constructing it. The goal of water well constructors and water engineers is to make use of the most appropriate technology for exploiting groundwater within the local conditions. In choosing an appropriate construction methodology for a water well, there are two major factors affecting groundwater flow which must be considered. The first of these is the geology of an area and the second is the influence of local weather patterns on groundwater. Knowledge of these two factors is of great significance in successfully intercepting and exploiting a significant amount of groundwater.

Figure 5.1: The Hydrologic Cycle

Groundwater Geology

The definition of an aquifer has been somewhat flexible in the past. Hydrologists have tended to define it as “a saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients” (Freeze and Cherry, 1979: 47). A second definition often used in the water well industry, relates more to the economic exploitation of groundwater: “A saturated bed, formation, or group of formations which yields water in sufficient quantity to be economically useful” (Driscoll, 1986: 61). The definition then is somewhat relevant to needs of those defining it. For the purposes of this thesis, the second definition will suffice. This is stated though with the realization that the definition then depends on the demands of the users and on the well type being used.

As stated above, the goal of a water well is to successfully intercept groundwater and exploit it. Sufficient amounts of groundwater are only found in aquifers. It is therefore necessary for a water well to intercept an aquifer to exploit groundwater.

There are three major features of groundwater geology which affect the distribution and the nature of aquifers and aquitards (impermeable layers). These are the lithology, the stratigraphy, and the structure of the geologic deposits and formations (Freeze and Cherry, 1979: 145). Lithology is the physical makeup of the geologic system. This includes the mineral composition, the grain size, and the grain packing of the sediments or rocks. The stratigraphy of a system is the layout of the system. It describes the geometrical and age relations between the various beds, lenses, and formations in geologic systems of sedimentary origin. Structural features

are the geometrical properties of geologic systems resulting from deformation after crystallization or deposition. These include such features as faults, folds, fractures, and cleavages (Freeze and Cherry, 1979: 145).

For the purpose of groundwater exploitation, formations can be seen as being one of three types: unconsolidated sediment, sedimentary rock, and hard rock (igneous and metamorphic rock).

Unconsolidated Material

Unconsolidated material consists of the debris of eroded rock. Most formations relevant to aquifer systems are the result of one of three different deposition methods: alluvial deposits (deposited by flowing water), aeolian deposits (deposited by wind action), or glacial deposits.

The grain size of alluvial deposits is very broad. Flood plain deposits may consist of extremely fine silt, whereas alluvial fan deposits may be coarse sand or gravel (Driscoll, 1986: 24). The level of sorting within such deposits can also vary depending on the deposition environment. The most significant aspect of alluvial deposits to water well constructors is the great variation in their lithology and stratigraphy. Each deposition area will have its own characteristics which water well constructors and engineers should be aware of. Alluvial deposits tend to lend themselves to a variety of well types. Coarser sediment (medium sand to gravel) are generally most efficiently exploited with small diameter wells. If adequate aquifers are available at a reasonable depth, hand drilled wells are probably the most cost effective method of installing a well in such a deposit (Blankwaardt, 1984: 2). For aquifers outside of the range of hand drilled wells, machine drilled wells function very

well. In situations where diesel or electrical pumps are going to be installed these aquifers can be exploited to great depths with drilled wells. Bored wells function effectively in a greater range of sediment than small diameter wells. They are often able to exploit water from much finer sediment (silty-clay) right up to coarse gravel. Often a small lens or layer of coarser material in clay or silt will supply a sufficient flow for a bored well (see Figure 5.2). Some clays are very well sorted and are not interrupted by courser material. These formations will not yield a sufficient amount of water for a well.

Aeolian deposits are created through wind action. They generally consist of fine to medium sand or silt, and have a fairly uniform texture. These deposits are considered to be moderately permeable (10^{-4} - 10^{-7} m/s) (Freeze and Cherry, 1979: 147). In clean medium grained sand deposits, small diameter wells are usually an effective option. In deposits of lower permeability, bored wells are often very successful.

Glacial deposits are of primary interest in Northern temperate regions and areas of higher elevation in the sub-tropics and tropics (Roscoe Moss Company, 1990: 13). Glacial till is generally a mixture of sand, silt, and clay. Permeability ranges from 10^{-6} to 10^{-12} m/s (Freeze and Cherry, 1979: 29). Sufficient aquifers can be found in some tills for small diameter wells, but bored wells prove to be more effective in most. Many glacial tills are virtually impermeable and therefore are not sufficient as an aquifer.

Figure 5.2: Small Aquifer of Sand and Silt Supplies
Well in Area Dominated by Clay

Small lens of sand and silt provides enough water to supply a large diameter well. The large amount of surface area between the lens (of sand and silt) and the silt laden clay allows enough water to leach through to provide the well.

Glaciofluvial deposits may be good aquifers. They are generally well sorted and well stratified coarse sediment (Roscoe Moss Company, 1990: 13).

Glaciolacustrine deposits are also well sorted, but can be formed of finer sediment which may result in aquitards. Loess is a wind blown sediment, which is associated with glaciation. It is usually very fine and generally does not result in good aquifers. It is rather common in these areas to see layering of all these glacial deposits (Roscoe Moss Company, 1990: 14). The result is often many aquifers interrupted vertically by a number of aquitards.

Sedimentary Rocks

Sedimentary rocks are simply consolidated sediment. Sandstone is a sedimentary rock which can demonstrate both primary (intergranular) and secondary (fissures and solution cavities) porosity and permeability which allow it to act as an aquifer. Limestone, dolomite, coal, and shale are relatively impermeable without secondary porosity and permeability. Primary permeability in sandstone ranges from being moderately permeable to impermeable (10^{-5} - 10^{-10} m/s) (Freeze and Cherry, 1979: 29). Strong aquifers can often be found in coarse or fractured sandstone. Wells can be bored, drilled, or punched in sandstone.

Carbonate rocks (limestone and dolomite) have fairly low primary permeability (10^{-7} or less for limestone). They are able, however, to gain secondary porosity through dissolution or fracturing. Dissolution is a chemical process in which water dissolves the carbonate rock, leaving behind cavities. These cavities often result in a 'pipeline' like system, which allows water to flow through them at relatively high rates. Fracturing is a physical process caused by stress or tectonic action. Fractures

also act as a ‘pipeline’ for water. Some limestones are easily bored with modern equipment while others are extremely hard and cannot be easily penetrated.

Coal and Shale are two sedimentary deposits that show almost no primary permeability (10^{-9} or less for shale) (Freeze and Cherry, 1979: 29). Shale tends not to make a good aquifer unless extremely fractured (Roscoe Moss Company, 1990). In many areas, beds of coal can be found within sedimentary sequences. Coal is often very fractured and may result in a very good aquifer. Most shales can be bored with modern equipment; some however may be more efficiently exploited through drilling methods. Coal aquifers can be exploited by any well construction method. Less permeable coal formations will lend themselves to bored wells rather than to smaller diameter methods.

Igneous and Metamorphic Rock

Hard rock (igneous and metamorphic rocks) usually have very little primary permeability (less than 10^{-11}) (Freeze and Cherry, 1979: 29). Secondary permeability can exist and may result in significant aquifers. These rocks may be fractured through a variety of different geologic activities. Lava flows and volcanic rock may contain secondary permeability caused during their formation. Hard rock aquifers can be exploited through punching or drilling (with the use of a down the hole hammer) methods. Finding exploitable aquifers in hard rock is difficult. It is generally only attempted in areas where other aquifers are unavailable (Driscoll, 1986: 42). Boring techniques are unable to penetrate hard rock. Most often though, in regions of hard rock there are significant valleys filled with unconsolidated material. In addition to this, in tropical environments, chemical weathering of rock and unconsolidated

deposits occurs rapidly, producing a zone of weathered material called saprolite (also known as laterite or ferricrete) (Lifewater, 1998a). This eroded bedrock often results in the formation of good aquifers, which may be exploited through the use of any type of well. Figure 5.3 represents the typical depth distribution of this eroded bedrock along with the normal availability of water within it. Figure 5.4 demonstrates in what areas in Africa saprolite is common.

The Physical 'Niche' of Bored Wells

Bored wells are generally best used in areas where there is a significant amount of unconsolidated material. They generally require a minimum of 7m of unconsolidated material (or soft sedimentary rock) to be effective. Modern methods allow for boring through clay, till, silt, and sand, without difficulty. Some very free flowing sands and gravels present a problem, especially if they are encountered at greater depths. Modern boring rigs also can bore through many consolidated materials. Soft sandstones and limestones can be bored using the bucket with special teeth, whereas harder materials can be bored using a coring bucket.

**Figure 5.3: Water Yield With Depth
(Weathered Zone Aquifers)**

(Data from Selby, 1985)

Figure 5.4: Weathered Zone (Saprolite) Aquifers in Africa

Source (Modified from Key, 1992)

Bored wells are generally limited to about 50m in depth. Therefore, to produce a well, a sufficient aquifer must be encountered within that depth. It is important to note that a sufficient aquifer for a bored well can flow much slower than that for a drilled well. An aquifer supplying 4 liters per minute will supply over 5700 liters a day in a bored well. If there is adequate storage space in the well for the 5700 liters (a storage of about 7m in well of 1m in diameter) then the well can allow for 5700 liters to be removed during a peak period. This would supply a pump running at 20 liters per minute for four and three quarter hours. This is from a very slow aquifer. If a drilled well were used in the same aquifer, it could only supply a maximum of 4 liters per minute to a pump (just over 1000 liters). When calculating the minimum acceptable aquifer flow level for a bored well, both flow and storage must be taken into account as well as average daily water demand. Peak demand is met through storage. When calculating flow for wells with little or no storage, only immediate flow is of importance.

The minimum requirement for any well is that an adequate aquifer be encountered within the range of the equipment used to get to it. In comparing bored wells to drilled wells, bored wells are much more limited in depth and penetration ability, but can be effective in much poorer aquifers (low producing, low permeable material). In relation to hand dug wells, bored wells have the advantage of much better penetration. The 'niche' for bored wells then, is in areas where hand dug wells do not achieve adequate penetration, and adequate aquifers for drilled wells are too deep to reasonably tap. This is the physical 'niche' where bored wells significantly outperform drilled and hand dug wells simply with regards to the physical situation. I

also suggest that there are non-physical advantages of bored wells, which make bored wells preferable to use in many more situations (this will be further discussed in chapters six & seven).

This physical situation or physical 'niche' occurs in certain geophysical conditions. As stated previously, bored wells are the most effective type of well used in aquifers found in mid to low permeable materials (about 10^{-5} m/s or less). These aquifers are generally made up of, but not limited to, clay, silt, fine to medium sand, glacial till, coal, fine to medium sandstone, or carbonates. More permeable materials (more than 10^{-5} m/s) such as medium to coarse sand, coarse sandstone, gravel, and fractured or dissolutioned sedimentary, metamorphic, or igneous rocks are generally more efficiently exploited with smaller diameter wells. Hand dug wells exploiting any type of aquifer can almost always be exploited more effectively, economically, and efficiently with either a small diameter well (hand drilled) or a bucket bored well.

This physical 'niche' often occurs alongside other options. An area excellent for a bored well may also be excellent for a drilled well of greater depth. An example can be seen in Figure 5.5. In making decisions in areas such as this, other considerations (cost, etc.) will play a significant role in what well construction technology is used.

There is vast array of areas where geologic conditions favor bored wells. In almost every region where a significant amount of unconsolidated material exists above bedrock, there exist areas where bored wells could be of significant use in exploiting aquifers. Later in this chapter a brief discussion of geologic areas in Africa will be introduced.

Figure 5.5: Location Where Both Bored Well or Deeper Drilled Well Would Be Effective

25 meter Bored well (left) is tapping low flowing aquifer and using storage capacity to supply water. 75 m Drilled well is tapping deeper sandstone aquifer. Both options will supply the necessary water requirements of the user. The decision of what type of well to construct then rests upon other factors (cost, social acceptability).

Water Quality

When presented with the argument that shallow wells have certain advantages in developing countries, a common response of people is to question the quality of the water which can be obtained at shallow to moderate depths. This concern may be the result of mis-information or perhaps the result of people's experience with inappropriately sealed wells. Pure water is not found in nature. All water, including rainwater, has some amount of 'impurities' (Roscoe Moss Company, 1990: 358-359). Different minerals and dissolved salts are generally what gives water its taste, texture, and colour. Groundwater tends to 'absorb' these solutes as it flows through material that has high concentrations of them. Shallower aquifers tend to have fewer total dissolved solids than deeper ones because they have passed through less earth. This does not imply that shallower aquifers are preferable because of this. In fact, there is little which can be stated as a 'rule' regarding dissolved solids in groundwater. Each area has specific characteristics and should be individually tested. Whereas shallow water may be preferable in one area, deeper water may be preferable in another.

The more direct concern regarding aquifers of shallow to moderate depth is the potential for contamination from above ground sources. Shallow aquifers are closer to above ground contamination than are deeper ones. This physical reality presents the concern that shallow and moderate depth wells could be contaminated more easily. In actual practice though, any well that is improperly constructed and located is more prone to contamination than a well that is properly constructed and located. This holds true regardless of the well type. A properly constructed bored well is as safe as a properly constructed drilled well (Iowa State University, 1993: 2). A study done in

Burkina Faso on water quality found that wells cased with cement cribbing were almost as free of contamination as deep wells. Both the wells cased with cement cribbing and the deep wells provided good protection against bacterial contamination (Guillemin et.al., 1991: 24-925).

Contaminants from above ground (including fertilizers, sewage, etc.) are filtered out as water passes through soil and sediment. Deep wells may tap solution channels or fractures in bedrock which act as direct channels from surface with little contaminant filtration (water is not purified in fractures or channels). The depth of deep wells is perhaps a false security for those who use them. An improperly sealed annulus around a drilled well can result in a 'pipeline' for surface contamination. The same is true for a bored well which is improperly sealed. Water contamination from above is much more a factor of the quality of well construction than it is of the depth of the aquifer which is exploited.

Weather Patterns

As groundwater supply is a part of the hydrologic cycle, it is affected by weather patterns. The hydrologic system, and weather patterns as a whole, is quite complex. The study of hydrology is a rather extensive discipline. Here I plan to discuss the very basics of the system as they apply to water engineers and water well constructors who are concerned with rural water supply in developing countries. I do not discuss long term forecasting of groundwater supply as it relates to recharge from precipitation. In recent years, with over-pumping of many major aquifers (such as in Mexico City, Bangkok, and the southern U.S.), issues of over-exploitation of groundwater have become of major importance. In most rural development situations

water withdrawal is not significant enough to warrant concern. Water engineers and water well constructors should be aware of the potential for over-pumping in areas they are working in, but unless significant water exploitation for urban populations, industry, or irrigation is occurring, or there is a very severe lack of recovery, there is little need to be concerned. Proper drawdown tests should be carried out to ensure that the well is not being pumped beyond its sustainable yield. For those carrying out drawdown tests on large diameter wells it should be noted that there has been considerable debate regarding calculations performed on such data. Herbert and Kitching (1981), Herbert et al. (1991), and Chachadi and Venkataramana (1991) are sources which offer some insight regarding this issue.

The most significant effect of weather on the supply of groundwater (as it pertains to water engineers, water well constructors, and the users of water wells) is its effect on the level of the water table. The vastness of most groundwater aquifers along with the buffering action of infiltration, creates a situation where groundwater levels tend to be relatively stable in non-polarized weather situations. Much of the developing world has very polarized weather patterns with long dry periods followed by short rainy ones. In northern climates there is little recharge in winter months when precipitation falls as snow, and open water freezes over. In both of these regions, there is commonly a seasonal variation in the water table. This can mean that wells may go dry or produce less in those months without rain. In developing countries, dry wells during dry seasons are a large problem. Water tables are commonly the lowest at the end of the dry season. Deeper wells are the simplest solution to this problem.

If this seasonal variation were the only effect the weather had on the water table there would be little concern regarding water supply. Hand dug wells could be dug or deepened nearing the end of the dry season and would then be a reliable source of water. Bored and drilled wells would simply need to ensure that they were deeper than the seasonally low water table. Unfortunately there is also precipitation variation *between* seasons. Most significant to the water table are seasons of low rainfall. This is more significant if it occurs over more than one season. The most severe situations of rainfall shortage, which occur, are droughts. In a drought, the water table can drop 3m or more (Driscoll, 1986: 53). Water tables subsided so significantly during the drought in Ethiopia in the late 1980s that hundreds of community wells went dry (Warner, 1985: 156). This lowering of the water table will often result in hand dug wells going dry regardless of what season they were dug in. A drought is the worst time for a well to go dry. A reliable source of water during a drought is invaluable to people. Often the water from such a source can be used for consumption as well as maintaining food sources, which would die without it (i.e. fruit trees, small gardens).

The effects of droughts and precipitation patterns are generally not long term (Freeze and Cherry, 1979: 230). Following a drought, water tables generally quickly return to their previous levels (Driscoll, 1986: 230). The natural system tends to return to equilibrium, which leads to a relatively stable water table over time. Human activity, which is large enough to affect the level of the water table, tends to be much longer lasting in its effects (Freeze and Cherry, 1979: 230). Long term weather pattern changes (such as desertification) also lead to long term changes in the water table (Driscoll, 1986: 53).

Bored Wells and Weather Resistance

In areas of very polarized weather patterns and in drought prone areas, wells must be constructed so that they are significantly below the water table. This will make them less susceptible to seasonal variability as well as to drought. The fact that bored wells obtain better aquifer penetration than hand dug wells makes them far more drought resistant than hand dug wells. Due to their large diameter, bored wells are also more drought resistant than small diameter wells which tap the same aquifer at the same depth. A lowering of the water table will lower the pressure of the aquifer, thus lowering the flow of water into the well. If this occurs at a scale where the production of the small diameter well drops below the required pumping rate of the well, the well cannot meet peak demand. The larger diameter of the bored well acts as a buffer against such situations. With regards to a comparison with deeper aquifer small diameter wells, bored wells can either be more or less drought resistant. This really depends on the characteristics of the two different aquifers being tapped. A bored well with a great deal of aquifer penetration (4m or more) would most likely withstand even the worst drought.

Some Examples of Geology Which Favors Bored Wells

Bored wells are regularly used in North America in those areas which fall within their geologic niche. As they have not been used often in developing countries, a question often arises as to their physical potential outside of North America. The following is a brief look at the physical potential for bored wells in Africa. It is only a very small survey of some of the potential areas for bored well usage and is by no means a complete picture. The goal of this section is simply to demonstrate that there

are significant areas where bored wells could be used in the developing world, not by any means to provide a survey of all areas.

Most of Africa consists of igneous and metamorphic rock from the Precambrian era, either outcropping or overlain by sedimentary rock and sediment. It is this sedimentary rock and sediment which is of primary interest for bucket boring methods. Different sediment formations were laid down in Africa throughout the Paleozoic, Cenozoic and Quaternary. These range from a variety of consolidated sediments (limestones, mudstones, shales, and sandstones) to unconsolidated materials (United Nations, 1973: 40-41). Figure 5.6 is a map showing the major hydrogeological outline of Africa. Those areas labeled as Coastal Basins or Sedimentary basins are areas where the majority of aquifers occur in unconsolidated or consolidated sediment. In much of this area, there exists significant shallow to moderate depth unconfined aquifers. The limestone plateau of Somalia and Eastern Ethiopia contains aquifers in both consolidated and unconsolidated material. It can be bored in most areas through the use of a coring bucket (Summers, 1997). Throughout the regions on the map designated as hard rock (fold areas, crystalline ridges, volcanic), there are significant shallow aquifers in residual overburden (saprolite) resulting from the weathering of the bedrock (Wright, 1985: 31). These areas also present the possibility of groundwater exploitation through bored wells.

Source (United Nations, 1988)

It is worth noting that the map is at a very small scale and is very general. The smallest region shown on the map is well over 15 000 km². Individual regions will have a rather varied hydrogeology. It would be necessary to survey specific areas to discover if there was adequate unconsolidated material or soft consolidated material containing adequate aquifers which would allow for boring operations. My own personal experience in the limestone plateau of Eastern Ethiopia has demonstrated to me that there is significant unconsolidated sediment and soft enough bedrock in that area for the successful operation of a bucket boring operation. Discussions with others in the water well field familiar with bucket boring have confirmed to me that there are conditions adequate for boring in many other regions of Africa (Fitzgibbon, 1998; Summers, 1997; Collins, 1997). This is backed up by descriptions of sedimentary deposits in academic literature (United Nation, 1988a; United Nations, 1988b; Heederik, 1984; Shazly et al, 1985; Davies and Goldburg, 1980; Afrodisis, 1980; Lloyd, 1990; Meijerink et al, 1997). Also confirming the presence of appropriate hydrogeological conditions for bored well construction is the prevalence of hand dug wells in Africa. In almost any area where hand dug wells are used, bored wells can also be used. In these areas, the use of bucket boring would almost always result in superior wells.

There is little question that there is physical opportunity for the exploitation of ground water through bored wells in Africa. The same could also be argued for most areas in the developing world. Boring rigs have been used in Thailand, Taiwan, South America, Lebanon, and Cambodia with good success (Gus Pech, year unknown). Hand dug wells have been used throughout the world. There is strong evidence

showing that the physical conditions required for bucket boring exist in developing countries.

Chapter 6: Groundwater Exploration

Water well construction, regardless of the technology used, tends to be a costly undertaking in many developing countries, particularly in Sub-Saharan Africa. The reasons for this are many, including the lack of an indigenous water well industry, the lack of an adequate infrastructure (Lloyd, 1990: 80), the difficulty in obtaining specialized equipment, the lack of trained workers, and in many areas the difficulty in locating aquifers. The latter concern is the focus of this chapter. Groundwater is often a very economic source of safe, reliable water. Often though, groundwater is difficult to find and to access. This search for aquifers is known as groundwater prospecting.

As noted in chapter four, an aquifer occurs below the water table in material which is porous and permeable enough to both hold and transmit water. In some areas of the world where aquifers are plentiful and test drilling is economical, the most effective manner of locating aquifers is through the drilling of test wells. Test wells are the most definite and accurate method of defining the limits and extent of aquifers. In areas where aquifers are less common and the likelihood of encountering an aquifer by chance is low, hydrologists, water engineers, and water well constructors use water prospecting in an attempt to further their chances of 'striking' water with each potential well they construct. These methods vary from remote sensing (using satellite imagery) to the ancient practice of dowsing.

The scope and detail of groundwater prospecting is directly dependent upon the objectives of the investigation. Most of the research regarding groundwater prospecting has been on large scale examination of regions. Efforts are made to map

the hydrogeological properties of regions, focusing mainly on large aquifer groups. This can be done through interpretation of data from existing wells, the drilling of new test wells, through geophysical methods (seismic, magnetics, gravitational, electrical, thermal), and through aerial photography. Such reconnaissance is generally only done when large scale water projects are being considered. These methods of water prospecting are at too large a scale and are too costly for small rural water projects.

Water prospecting for rural water projects in developing countries consists mainly of simple techniques used to increase the chances of constructing a successful well. In sedimentary formations, less expensive methods are generally most viable. Simple water prospecting in sedimentary material basically is an attempt to discover a location where relatively permeable material will be encountered and the hydraulic head of the water will be relatively high.

When attempting to find aquifers of shallow to moderate depth in basement complex formations, the goal is often to find areas of saprolite (weathered bedrock). It is in concentrated zones of saprolite where groundwater is best exploited (Carruthers and Smith, 1992: 203). Vegetation and topography can give some indication as to areas of saprolite. In some areas it becomes economical to employ more complex methods of water prospecting such as electrical resistivity methods (EM) (Carruthers and Smith, 1992).

Prospecting for deep aquifers becomes much more complex and expensive. In both sedimentary and basement complex formations, far more complex and expensive methods must be used. Accuracy is decreased and uncertainty is increased as it becomes necessary to prospect deeper into the earth.

If a water well constructor or a water engineer knows that groundwater is plentiful in an area, there is little need for water prospecting, and other concerns (social, economic) should be used to determine the location of the well. If aquifers are known to be sporadic or are unknown in an area, some amount of prospecting is worthwhile prior to determining the well location. In most cases, there will be little geological data and few aerial photographs available for rural areas in developing countries. If there is such data available it can be very useful in locating aquifers. Geological information can help to pinpoint aquifers, while aerial photographs can help in interpreting topological features (old riverbeds, hills and valleys, etc.) that may help determine optimal sites (Lifewater, 1998b). If these are unavailable, other methods will need to suffice. An examination of the topography of a region from ground level will help locate surface features. Certain types of vegetation, such as papyrus, date palm, certain species of ficus and crops like bananas, yams, and sugar cane can be an indication of shallow ground water (Blankwaardt, 1984: 22). Knowledge from local villagers about springs, streams, and existing wells can be very valuable information. Usually the best source of well siting information is talking to people who have dug local water wells and personal inspection of water wells in the area (Lifewater, 1998).

Bored wells also allow for a much greater opportunity for local people to help determine where a well should be sited. Local knowledge of groundwater gained from existing wells or springs becomes far less relevant when exploiting deeper aquifers. The use of local knowledge is of vital importance to the sustainability of projects both in a physical and social sense (Narayan, 1995: 57). In these efforts it is very important

to include women as they tend to have a much better knowledge of local groundwater sources than men (van Wijk-Sijbema, 1985: 51)

Through gathering the available information, a prospector can increase the chances of choosing a successful well site. Water prospecting relates to well construction techniques, and specifically bored wells, in that simple inexpensive methods only work for shallow groundwater sources. Those methods which can be carried out with very simple technology are only relevant for bored and drilled wells of shallow to moderate depth. If deeper sources of water must be sought out, water prospecting becomes much more expensive and much less reliable. In rural areas of the developing world this type of expense is unaffordable. If it is available, the exploitation of shallower aquifers is preferable. Bored wells allow for the exploitation of shallow aquifers, which have too slow a flow rate to create a small diameter well. Water prospecting becomes much cheaper and more accurate when bored wells are considered as an option.

Chapter 7: Social Aspects of Bored Water Well Supply

Perhaps the most comprehensive work describing the social dimensions of rural water supply in developing countries is “Drawers of Water: Domestic Water Use in East Africa” (White et al., 1972). White argues that water supply has more than simply economic and hydrogeologic dimensions. Since the time of White’s writing the practice of water projects has changed somewhat, but still, a lack of understanding of local customs and beliefs causes problems in multitudes of water projects. It is very important in projects which are attempting to improve or introduce water supply systems that social considerations are accounted for. In choosing the design and the method of construction of a water well there are a variety of related social concerns.

The Social Situation

The social dimensions of water supply are complex and diverse between cultures. In rural areas, people generally must collect and carry water to their homes. Water wells most often supply a number of families. The following is only a brief look at some of the insights put forth in academic literature.

In Africa, as in much of the developing world, water collection is most often divided through gender. Women are the primary managers of domestic water supply (Narayan, 1995: 10; King, 1994: 7-8). In most societies, men avoid the work of water collection. It is often considered demeaning for a man to be involved with such activity. This means that women are the primary decision makers as to how and where water is obtained. In urban areas, the need to purchase water has begun to

break down some of these gender barriers as it has been traditionally a man's job to pay for such amenities. In rural areas, water is seldom purchased, but rather collected from lakes, ponds, rivers, streams, wells, or springs. Quite often these sources of water are contaminated and distant. This results in the spread of disease and a great deal of time and energy spent on water collection. The goal of most water projects is to supply areas with safe and accessible water supplies. This is often a new well. The role of local people and specifically the role of women has been poorly addressed in many programs. As women are the primary choice makers when it comes to choosing a water source, it is important that they are actively included in decision making regarding the new source.

A common problem among many water well projects has been the lack of attention paid to social dimensions of water supply. It is necessary to have an understanding of local social concerns. It is important to consider local input as to water well location. It is also important to understand how and why people choose one water source over another. It has been demonstrated that it is of utmost importance that those individuals who are actually involved in water collection (mostly women, sometimes children) are a part of the decision making process (Evans and Appleton, 1993: 17-18; Okuni and Rockhold, 1996: 24; Mangin, 1991: 305). Without care for these aspects of a project, the result may be that the new system is not used. More recently a demand driven supply of new wells has been encouraged in development literature as well as in practice. Wells are only supplied in areas where aid agencies or governments have been contacted by local people. The local people are then expected to contribute a reasonable amount of the cost of the project, thus

ensuring that there is local interest and local people will use and care for a new water source.

The need for well site maintenance is often left out of project design. Well site maintenance includes cleaning of the site, as well as maintenance of a pumping system. Sites must be properly designed so that a sanitary condition can be maintained. A good design requires a socially acceptable wellsite which maintains a sanitary condition as well as satisfies the needs of the people (washing troughs, bathing areas, etc.) Another concern is that the well and all its equipment be an appropriate technology. Appropriate technologies must be used so that the local community has both the ability and the means to maintain the system.

Effects of Well Choice

The choice of well design and construction technique affects and is affected by social aspects of the situation in a number of ways. Most directly, the local employment capacity of a project is affected by the choice of well construction technique. This can affect the level of local participation which can be attained by a project, and thus can affect project sustainability. A second social consideration in choosing water well design is local acceptance of the new water source. There are factors beyond the actual functioning of the well, such as appearance and location, which may affect whether the new well is used and maintained by local people. These local perceptions are of great importance to the success of a water project. Lastly is the question of appropriate technology. Different well designs have technologic aspects which may or may not suit the rural situations in developing countries.

Participation

In recent years it has been argued in much development literature that community (or beneficiary) participation in a project leads to improved sustainability of that project (IRC, 1988: 51; Wood and Dinna, 1996: 39; Narayan, 1995; Mabuba, 1994: 12-14). While many aspects of community participation (health education, cost sharing) are relevant to a water well project regardless of well design, other aspects are relevant to the choice of well design (well location, well construction, and village level maintenance of the system).

Modern boring equipment does not offer significantly greater opportunity for community participation during construction than other modern construction methods (punching, drilling). The materials it makes use of, although often produced within the country, are too complex to be made by local groups. There may be greater potential for locals to help in providing the sand for a sandpack for a bored well rather than for a drilled well. This is because the quality (uniformity of grain size) does not need to be as exact due to the much larger annulus of the bored well. There is also a much larger amount of sand required for a bored well than a drilled well. Generally though, boring with modern equipment would need to be done by a crew that is familiar with the machinery.

There may be much more opportunity for community participation when traditional boring methods are employed. These methods generally make use of animal power, but these machines could make use of human power with very simple modifications. The process would allow local individuals an opportunity to contribute to the well construction process. With alternating crews, the work would be hard, but

by no means unreasonable. The use of the power of people in this fashion would work well for the boring operation. It would remove the need for training and caring for animals (as discussed in chapter three). The local involvement may result in a feeling of ownership of the new well which is a large factor in promoting sustainability of such a system.

In addition to the actual construction of a well, there are other opportunities for local participation which are relevant to the well type which is used (hand dug, hand drilled, bored, drilled, etc.). A major aspect of community participation and consultation is deciding where to locate a well. By considering the use of a bored well as a potential construction technique, a much larger physical area may be considered for potential well sites. This may allow more flexibility for local social concerns. This is further discussed later in this chapter when discussing well siting. Bored wells also offer a much greater opportunity for the use of VLOM (Village level operated and maintained) pumping systems than drilled wells do. This is also discussed later when discussing issues of appropriate water pumping methodologies.

Choice of Use

There is often more than one source available to a household for water supply. It is important in a water project that the proposed users of the new source of water actually utilize the new source. Users of such sources tend to base their decisions on a number of factors. White (1972) suggests that in East Africa these decisions are based mostly on four factors: the perception of the quality of water, the technical means available to draw upon the source, the expected returns and costs (including distance

to the source), and the interaction with others who may use the source (White et al, 1972: 227)

A very important factor in the decision of a water collector for a family is the quality of the source that they are drawing upon. As it is the users who are making the decision which water source they make use of it is *their* perception of the water which is of importance. Sometimes local people's perceptions can be altered through education programs explaining aspects of water and health. Often though, water quality is determined by other factors such as oily appearance, turbidity, mineral taste, odor, and color (White, 1972: 239,239; IRC 1988: 51; van Wijk-Sijbesma, 1985: 14,43). There may be strong implications from this in considering well construction. If a community has traditionally used a hand dug well as their primary source of water, they most likely have grown accustomed to the characteristics of the water. Water from deeper aquifers, which would be exploited through the use of a drilled well, most often will have different characteristics (mineral content, taste, odor, etc.). This may result in local people rejecting the new source in favor of that which is familiar. In addition to the different preference characteristics, a change in water chemistry (change of aquifers exploited) may initially cause people to get slightly ill (until their body adjusts to the difference in water characteristics). This may again result in the non-use of the new source. In the same situation, another alternative would be to use a bored well to produce a safe reliable water source from the same aquifer previously exploited by the dug well. The greater depth and improved construction of the bored well would result in a safe reliable source of water, while maintaining the non-health related qualities of the traditional water source. The

similar characteristics of the bored well water and dug well water may lead to greater local acceptance by the community of the new water source than would occur if a deeper drilled well were constructed.

Another issue regarding water quality as perceived by the users is the source of the water itself. If people in an area are familiar with hand dug wells, they generally feel comfortable with them. They can observe the water entering the well from the ground simply from looking in from above. The well is very visible and easily understood. The same can be said for a bored well. A completed bored well appears almost exactly the same as a hand dug well. The water can be seen entering the hole in the same manner. The two technologies are visibly, very similar. The construction of a bored well is also easily understood. Although local people may not understand the mechanics of the machine boring the hole, they can easily observe material being drawn from the hole and piled off to the side. The simplicity of the boring process may not be as alarming as the complexity of a drilling operation. In discussing the requirements of appropriate technology Wanchai suggests that technology should “be simple enough to understand” (1987: 212). In my experience of both drilling and boring water wells in North America, I have found that observers have great difficulty understanding the processes involved in rotary drilling a well, but quickly grasp the boring process. In North America people are quite comfortable and trusting of water wells and don’t really question the process or supply if a professional has assured them that it is safe. This may not be the case in rural areas of developing countries. The more complex and enigmatic a process is, the greater the potential that it will be mis-trusted. This argument is difficult to quantify and rests on basic principles rather

than extensive evidence. The following examples though, perhaps best demonstrate how this can occur in a real world circumstance.

On a project in the Ogaden desert in Ethiopia, a Gus Pech Super George boring machine was used to bore over 60 successful wells. As the wells were bored, the crew regularly allowed local residents (who would commonly watch) to look into the hole before it was capped with a pump. Hand dug wells were common in many of the areas and people seemed comfortable using the new wells. The same project also made use of a Dando rotary-percussion combination (drilling) rig. The Dando rig was used in areas that were not hydrogeologically suitable for the boring rig. At one site where the Dando rig was drilling a deep well (over 100m.) the local chief inquired as to where all the drillstem of the rig were going. Drillstem is added every 7m or so as the rig drills to deeper depths. Once the chief understood how deep the well was, he stated that they would not be able to drink the water. When asked why, he stated that the water was so far down that it must be the devil's water and that it would not be safe to drink. Water that was more familiar to the local people (the shallower groundwater) was acceptable, but deeper water was not as easy to accept as a safe source.

A second example can be seen in the following passage:

...for years the Thai authorities have invested hundreds of millions of baht in an attempt to provide villages in the northeast with "clean" deep-well water. To their surprise, the villagers never use this water for drinking as they regard it unhealthy, even to the extent of being poisonous. They would rather drink

“milky” water from shallow wells that they are used to, even though they have to walk kilometers to fetch the water (Wanchai, 1987: 211).

Pumping Systems

Another strong factor influencing what source an individual chooses to use for water supply is the available means to draw water from the source. To ensure that the local people make use of a new well it is of utmost importance that the withdrawal system be effective and reliable. To prevent contamination of a public well in a rural development situation, it is necessary that the top of the well be sealed and a pump installed.

In rural development situations there is often a large concern regarding pump reliability and maintenance. This concern has arisen due to the realization that many water well projects have resulted in failure because pumps have broken down and have not been repaired (IRC, 1988: 63). The use of appropriate pump technology along with the setting up of a proper maintenance system has been touted as the solution to such problems. The simplest pumping mechanism is perhaps a bucket and rope system, unfortunately this leads to contamination of the water supply. A much more contamination resistant system that still maintains simplicity is a handpump.

Handpumps are generally seen as the most appropriate method to remove water from a well in rural situations. Fossil fuel pumps and electric pumps are more powerful, but are very complex and difficult to fix. Ease of repair and simplicity of design are the most attractive aspects of handpumps. If local people can care for their pumping system, there is a greater chance that it will remain working (IRC, 1988: 64-65). A great deal of work has been done on designing handpumps for use in

developing countries. The Indian Mark series and the Afradev pumps are currently very popular designs used in development projects.

The use of handpumps though, is limited by well depth. Raising water takes energy. The greater the distance that water must be lifted, the larger the amount of energy required. When using handpumps this is an important factor. The amount of energy required to lift water cannot be more than that which the individuals operating the pump can supply. In the developing world, it is most often women and children who collect water. Often they are somewhat malnourished, ill, tired, or otherwise incapacitated. This leads to a practical depth limit to the use of hand pumps.

Although different pump designs have different attributes, the common maximum depth limit given in pump literature is about 45 m (Reynolds, 1987: 20; Rondinelli, 1991: 426; Wood, 1993: 31; Kennedy and Rogers, 1985: 56). It is also important that these pumps be at a depth that is serviceable. Advances in technology have allowed for certain pumps (AFRADEV) to be serviced by local people up to a depth of about 40m (IRC, 1988: 66). Up to a depth of about 7m suction handpumps can be used. These are extremely simple pumps in which all of the working parts are at ground level. More complex pumps with mechanical parts (piston or screw) within the well are required to lift water from greater depths. At depths greater than 45 meters it is generally necessary to employ more complex pumping systems (diesel, electric, wind powered, etc.).

Effectively, the complexity of pumping systems increase as the depth from which they must pump water increases. As simplicity is desirable, other things being equal, it is preferable to lift water from a shallow aquifer than from a deep one. In

chapter three it was noted that there are (many) areas where a bored well or a drilled well would supply a similar quantity of water per day; the bored well being of shallow to moderate depth and making use of its reservoir capability to exploit a slow aquifer, the drilled well being deeper and having a greater flow rate. In a situation where an electric or diesel pump was being installed in the well, this depth difference would be of little concern (only a small price difference). In a rural area in the developing world though, this depth difference could be very significant. It could be the difference in being able to install a hand pump or being forced to install a diesel pump. Currently, in most development projects where this situation exists, bored wells are not being considered. Drilled wells are being constructed and diesel pumps are being installed. The benefits of handpumps are well documented; and bored wells provide greater opportunity to make use of them.

Safety Net

Referring to hand dug wells, the International Water and Sanitation Center of the IRC, suggests that another benefit of a large diameter well is its accessibility (1988: 72). If a pump is broken beyond repair, the well is large enough to accommodate a bucket and rope system alongside of the broken pump. An access panel, which should remain locked and sealed, could be built into the well cap. If the pump fails and cannot be repaired by local people, whomever is in charge of the well site could unlock the access hatch, thus allowing for water removal by bucket. This is not a perfect solution and may even result in temporary well contamination, but it will allow the people to access the water they require to live. Once the pump has been repaired, the well can be treated and the access hatch closed. This is a far better

alternative than a water shortage. The access hatch could also be used to remove any sediment that has entered the well (Walude, 1996: 108). The large size of a bored well can also allow for multiple pumps to be installed. This would greatly lower the chance of a well being out of service. If one pump breaks down, the other would suffice until repairs were made.

Improved Sand Resistance

Proper well design and development are of extreme importance regarding the performance of water well pumps (IRC, 1988: 71,85). A major factor in the breakdown of pumps is sand and silt entering a well. This leads to wear of seals and valves, abrasion of cylinder walls, and the clogging of the well itself (IRC, 1988: 71). As stated in chapter three, bored wells can be constructed and developed in a much superior manner than hand dug wells. This superior construction results in wells that are much more resistant to the entry of sand and silt. Pumps last longer and perform better under such conditions. As maintenance is both expensive and difficult in rural areas of developing countries, bored wells are far superior to hand dug wells regarding pumping issues.

Pumps in bored wells also tend to face fewer sand problems than pumps in drilled wells. This is due to two factors. The large diameter of bored wells result in a low vertical velocity of water movement. This low velocity of movement has less tendency to 'stir up' sediment than the rapid water movement occurring in a small diameter well. The second factor is the settling time that the water has before being pumped. In a drilled well the water is being pumped directly out of the formation and

into the pump. In a bored well the water seeps into the well, any sediment settles out, and the water is later pumped out.

It is important that water wells and pumping systems be reliable and easy to maintain. If a source is not reliable and the pumping system cannot be maintained locally, a project will run into sustainability difficulties. Bored wells offer greater opportunity for reliability, and for the use of appropriate pump technologies.

Well Siting

The location of the well is one of its most significant attributes. As stated above, the returns and costs of a particular water source also affect people's decisions as to where they obtain their water. In rural development situations, the returns are the gains of having water, while the cost is generally the time taken and effort extended in getting that water. Women prefer water sources which are reliable and from which water collection requires the least amount of time and energy (van Wijk-Sijbesma, 1985: 13). If a well is too far away, it will not be used (IRC, 1988: 51). Distance is the most significant factor contributing to increased cost and is a direct result of well location.

The last major factor that influences where individuals draw their water from is the potential for interaction with others. The actual preference for this differs from society to society; some users show a preference for company at a water source, while others prefer privacy (White, 1972: 240-243). Some prefer to avoid contact with certain groups of people. Both the costs involved with obtaining water (distance, time, and effort) and the potential for interactions are influenced by one main factor, that being the location of the well.

Well location has a multitude of social dimensions in most communities and is something which local people should be involved in designating (another opportunity for participation) (IRC, 1988: 59). One of the difficulties with siting a well though, is that social concerns must be considered within hydrogeologic possibilities. As discussed in chapter four, there are many physical areas where bored wells will function while other well types will not. The greater range of physical opportunities afforded through the consideration of bored wells may then allow for a well to be placed where it is socially and economically most viable (see Figure 7.1). This greater flexibility with regards to well siting greatly increases the opportunity for local decision making regarding well location to prevail. This allowance for local decision making is of extreme importance for sustainability of a project (Evans and Appleton, 1993: 8). Through considering bored wells as an option, a project may become more sensitive to community needs and concerns.

Figure 7.1 : Potential Well Location

Through the inclusion of bored wells as an option, a much larger range of well site locations is available. Social and economic considerations regarding well location are easier to fulfill with this increased range.

Chapter Conclusion

Bored wells offer a number of solutions to common social problems of water development programs. Most importantly, bored wells increase the physical range of siting of wells, and therefore well siting can be more responsive to local needs. This should improve local participation in the project and should improve usage of the new well. There may be further opportunity for local participation in a project if traditional boring methods are used. The next significant improvement offered through the use of bored wells is the potential for handpump usage. Bored wells can make use of handpumps in areas where deeper drilled wells must employ more complex pumps. Bored wells are more resistant to sedimentation, the result of which is fewer pump breakdowns and longer pump life. If pump failure does result, a bucket and rope can be used in a bored well until pump repairs can be performed. Lastly, bored wells are much more similar in design, water characteristics, and appearance to traditional hand dug wells than are drilled wells. I suggest this may improve local acceptance of the well and the water from it. These 'social' aspects of bored wells may result in improved project success. This may make bored wells the better option over drilled wells in areas where either would function hydrogeologically. These benefits may even result in using bored wells in areas where shallow to mid-depth drilled wells could be used.

Chapter 8: Examples from the Real World

The previous chapters have focused on the potential usage of bored wells. Examples given (such as geologic figures) have been simplified to demonstrate particular principles. This chapter attempts to apply previously discussed information to actual examples of bored wells in use. The chapter has three separate sections. The first section discusses a typical case in which bored wells were constructed successfully in an area after attempts were made to construct a drilled well. The second section is a brief description of a water supply project in western Ethiopia in which bored wells were constructed. Lastly, is a discussion of a water project in which hand dug wells were installed, but faced problems which would have been overcome if bored water wells were constructed instead.

Bored Well in Alberta

The first site to be examined is located in Alberta at the legal land location SE1/4 Section 7 Township 51 range 25 West of the Fourth Meridian. It is Southwest of Edmonton Alberta near the North Saskatchewan river. The site is an excellent example of a location where small diameter wells are ineffective, but large diameter bored wells are effective. In 1996 four test wells were drilled to a depth of approximately 400 feet (125m) throughout an area of approximately 15 acres (Sheoppe, 1997). In June of 1997 two more test wells with a depth of 90 feet (28m) were drilled (Alberta Environmental Protection, 1997). All six wells yielded insufficient quantities of water to produce an acceptable well. One of the 90-foot wells was producing approximately 1 U.S.gallon/minute (4 liters/minute) from a coal

and sandstone aquifer located at a depth of 38 ft to 48 feet (11.7m to 14.8m) below ground level. It was decided that a well of 600mm diameter would be bored in an attempt to exploit this slow flowing aquifer. A bored well with a depth of 65 feet (20m) was completed. When tested, the bored well showed a flow rate of approximately 3 U.S.gallons/minute (12 litres/minute), significantly higher than the small diameter test well. The water level in the well rose to a height of 24 feet (7.5m) from the surface, thus presenting a water storage of approximately 820 gallons (3280 litres). The flow of water and the storage met the requirements of the owner and the project was finished successfully.

The significance of the above project is that success was found in an area after the drilled well option failed. In most development projects, the area would have been designated as unsuitable for a water well. A layer of shale above the water bearing strata, added to the difficulty of adequate aquifer penetration, would have made constructing a hand dug very difficult. Drilled wells would be inappropriate due to their small diameter. In this case the bored well is the only functional option.

Rural Water Supply Projects in Sierra Leone

Since the mid-1970s a number of government sponsored water schemes have attempted to provide villages in Sierra Leone with improved water well systems. From 1989 to 1991, Osman Mohammed Bah of the University of Sierra Leone (1991) carried out an extensive study of two of these schemes. Under investigation were the Northern Integrated Agricultural Development Project (NIADP) and the Magbosi Integrated Agricultural Development Project (Magbosi IADP). The report discovers

major shortcomings of the projects. The following is a brief look at the findings of Bah, as they relate to this thesis.

The areas involved with the study are all located near central Sierra Leone. The projects consisted of hand digging wells in rural villages and equipping them with a bucket and pulley pumping system. The geology of the area consists mainly of unconsolidated sediment overlying bedrock. There are also significant saprolite (weathered basement) formations. Bah's description of the depth of the overburden (unconsolidated sediment) uses very general terms (i.e. deep to moderately deep), but what is apparent is that in most areas basement complex rock is not encountered until well after the water table. This suggests that significant aquifer penetration and well storage is possible to attain. Many of the formations encountered when digging had propensity to cave-in, thus making hand digging difficult (Bah, 1991: 24). The area has very polarized weather patterns, with a rainy season of between five to seven months.

Wells were hand dug by government or agency paid water well diggers. Construction of these wells was done throughout the year. Wells were an average of about 10m (Bah, 1991: 47) in depth and were lined using cement cribbing.

The results of the study found that over sixty percent of the wells were not in use at the time surveys were conducted (Bah, 1991: 45). It was found that most of the wells would go dry during the dry season (Bah, 1991: 150). Wells dug during the rainy season had a much greater chance of being dry than those dug in the dry season. The study concluded that deepening these wells would be very expensive and encouraged the promotion of different well construction techniques. It was found that

a number of the traditional wells which existed outside of the program were more reliable because they had been deepened numerous times throughout different dry periods. A difficulty remains though with deepening or digging wells during the final months of the dry season (the optimum time to dig wells) as labour is in demand for agriculture (preparing for the coming growing season) (Bah, 1991: 47).

The projects examined by Bah demonstrate the difficulties involved with hand dug well projects. Failure rates are generally high and the optimum period for well digging is limited to two or three months. Aquifer penetration is the problem, as adequate groundwater resources exist, but the water table tends to fluctuate due to the polarized weather patterns.

This situation appears to be an optimal one for the use of either machine bored wells or wells bored using animal powered boring rigs. Drilled wells tend to be ineffective because in many areas the flow transmissivity of the aquifers is not substantial enough for a small diameter well. Deeper aquifers are rare, as below the unconsolidated sediment is crystalline basement complex rock. The depth of most hand dug wells is less than 15m. Bored wells of maximum depths of 20 m would be very reliable sources of water, even during a drought period. Bored wells would make use of the same casing as hand dug wells. Costs would be kept low if animal powered machinery were used to construct wells. They are quite capable of boring the material described in Bah's report. Bah's report also mentions that there are local blacksmiths in the areas (Bah, 1991: 35). This suggests that repairs of animal powered machinery could take place locally. Because boring machines can bore below the water table, wells could be successfully constructed year round. Because additional depth of wells

adds little cost or time to constructing wells, they could be located in areas where they best serve the population rather than in those areas where groundwater is shallowest (as was attempted in the IADP projects). Due to the much greater rate of well construction, there would be far fewer crews of water well constructors needed if boring machines (modern or animal powered) were employed. It is difficult to determine whether costs would be higher or lower if animal powered rigs were employed. Bucket boring requires smaller crews, shorter time periods on each well (by a factor of at least 1/10), and smaller diameter casing. It also requires care for an animal, maintenance of the equipment, and more rings of cribbing (due to increased depth). When a greater success rate of wells is factored into the equation, it is likely that animal powered boring would be cheaper than hand digging of wells.

Bucket boring appears to be a far better option in the Sierra Leone development projects. There is little evidence that hand digging methods hold any benefits over bucket boring. The wells produced by the IADP projects are almost valueless as they tend to dry up when most needed. This would not be the case for bucket bored wells. Most likely, the most cost-effective method of supplying the rural villages of Sierra Leone is a combination of hand drilled wells, and bucket bored wells.

Ogaden Water Project

In the late 1980s (approximately 1985-1988) World University Services of Canada (WUSC), in association with the United Nations High Commission for Refugees and the Ethiopian government, carried out an integrated development program in the Ogaden desert region of Ethiopia. Included in the project was the

provision of water supply to rural areas. Thin layers of unconsolidated sediment (up to 10m) overlaying limestone of great depth characterize the Ogaden region. Groundwater is difficult to find and can be quite saline in some areas. The project employed both modern bucket boring methods as well as modern rotary drilling techniques.

Following the end of WUSC's involvement in the project, the organization went through significant changes, including two moves of their head office in Canada. Ethiopia saw the overthrow of its government and the end of a revolution. Records of the project are few, and are difficult to find. My information stems from three sources. The first of these sources are records that I obtained from WUSC. There is little on the water supply project other than documents dealing with the entire integrated development project (WUSC, 1985-88). Secondly, I have the personal experience of my father, who was the manager of the water compound in Kebri Dahar and the Boring supervisor throughout almost the entire duration of WUSC's involvement in the project (Summers, 1998). I also have access to his daily logs (which includes well logs of the boring operation) (Summers, 1985-87).

The project was very typical of large scale integrated projects of the day. Directives came from the top. Often, even the decisions on sites for water wells came from either WUSC's head offices in Dira Dowa (hundreds of kms away) (WUSC, 1985-1988) or from government officials who made decisions on political rather than social or geological grounds. Geologic information that was presented prior to the beginning of well boring was quite inaccurate. Many wells were completed in

limestone that had to be either ground up using the regular bucket (Plate 8.1) or cut away using a coring bucket.

Regardless of the inappropriate design of the project, over a period of 18 months of boring (with many interruptions due to government interference and lack of supplies such as diesel) more than 60 successful wells were completed (Summers, 1985-87). Boring was difficult and slow as limestone often had to be cored using a coring bucket. Successful well completion was in the range of about sixty percent (Summers, 1985-87). The reason for failure in most cases was the lack of groundwater. Much of this may be related to the inappropriate siting methods that were discussed earlier. Those deciding the sites of new wells disregarded information supplied by local people and information which could be ascertained through traditional wells which existed there (Summers, 1998).

Many wells had flow rates below 20 liters per minute and required the large diameter for successful completion. Some wells produced far greater than 20 liters per minute. In areas where aquifers were not available at an accessible depth for the boring rig, the drilling rig was utilized. Many of these holes did not produce sufficient water either. Test holes of up to 500m were drilled. The deeper drilled wells were far more expensive to produce and required the use of diesel pumps to lift water (WUSC, 1985-88; Summers, 1998). Hand dug wells in the region were most often unreliable during the dry season and therefore hand digging was not an option. In most cases hand drilled wells would have been unable to penetrate the limestone and would suffer the same difficulties as hand dug wells.

Plate 8.1: Limestone bored from well using regular bucket.

Although the project was not as successful as hoped in supplying water to rural areas, it fared far better than most water projects in the region. There is also ample evidence that the project could have fared far better had it been more responsive to local conditions and was less influenced by government policies. The project was also extremely expensive for the results it obtained. The geology of the area though is very inhospitable for water supply. In addition, the project was halted after less than two full years of operation. This was mostly due to WUSC's own domestic difficulties. The project was to be handed over to the government, but indications are that nothing was done with the equipment after outside agencies left.

I present this project here because it is very rare in that boring technology was employed. There was reasonable success in producing safe, reliable wells for local people. It is unlikely that the same number of wells could have been completed with another method. Also important is that this is a very challenging region in which to obtain groundwater. It demonstrates that bored wells can function in environments which are far different than that which they are optional in.

Chapter Conclusion

The three examples given above are presented simply to demonstrate some of the information given throughout the thesis. The first example demonstrates the physical 'niche', which bored wells can be effective in. The second example demonstrates a project where the use of bored wells would have severely improved results. Example three is an example of bored wells being used in an environment which is not so perfectly matched with boring technology. Another project in Algeria

supposedly has shown very good success, but there is little documentation available as government changes have made access difficult (Collins, 1997).

Chapter 9: Conclusion

Water well construction techniques used in development programs have been too focused on making use of hand dug wells and drilled wells without considering other alternatives. Through considering alternative methods of well construction, projects can be more flexible in accommodating the physical and social needs of an area. Hand dug wells are not likely the most 'appropriate' technology for use in these projects. Deep drilled wells are not the only alternative to hand dug wells. There are a number of alternatives including bucket boring of wells. Bucket boring has many advantages relevant to rural water projects.

Boring and Hand Digging of Wells

Boring methods have many advantages over hand digging of wells. Bored wells achieve greater aquifer penetration which makes them far more reliable than hand dug wells. This becomes very significant in areas with polarized weather patterns (defined rainy and dry seasons), and in areas where droughts may occur. Bored wells are far more resistant to the entry of sediment. This is because casing can be installed more precisely, because the hole can be bottomed in clay or consolidated sediment, and because the well can be developed more effectively. Bored wells also have much larger storage capabilities than hand dug wells due to their greater depths.

Hand dug wells have remained popular because there are few capital costs involved in purchasing equipment for such operations. The actual cost of well construction is not significantly less than for a bored well though, because the well still must be cased and there is a great deal of labour involved. Greater failure rates

also increase the cost of hand dug wells. Animal powered machines offer an alternative to hand digging which maintains the benefits of bucket boring without greatly increasing the complexity or cost of the operation.

Boring and Drilling of Wells

Modern bucket boring equipment is far less complex than modern drilling equipment. Fewer and less complex breakdowns make bucket boring more appropriate for the developing world. Bucket boring also requires less supporting equipment when constructing a well. Bucket boring can exploit aquifers of low transmissivity which small diameter wells cannot. This aspect of bored wells mean that wells can be shallower than if drilling methods are used. Shallower wells mean that simpler pumping systems can be employed. The ability to tap low flowing aquifers also greatly increases potential well sites. This increase in potential well sites allows well siting to be far more responsive to non-physical aspects of well siting. This includes social and logistical concerns. Another favorable aspect of large diameter wells when compared to small diameter wells is the increased protection pumps gain from sediment. This occurs because the large diameter prevents rapid movement of water. Water prospecting for shallow aquifers is far cheaper and more accurate than for deep aquifers. This means that it is cheaper and easier to prospect for successful bored well construction than it is for drilled well construction.

In some areas bored wells may be more acceptable by local people. This may occur because the water which the bored well is exploiting would be more similar to local hand dug wells in non-health related characteristics. Also, bored wells are similar in design to hand dug wells and the boring process is less enigmatic than the

drilling process. Animal powered boring machines allow for an even less complex method of construction. Repairs and parts could easily be done locally. Animal powered boring rigs would be far more appropriate for rural areas than modern drilling rigs.

Appropriate Choice

The advantages that bucket boring may offer are significant. Each method of well construction has particular advantages that it holds over other methods. It is necessary prior to commencement of well construction to determine which method is likely to be most appropriate. Generally the solution sought after by development agencies is the least-cost alternative which will function effectively. This means the creation of a sediment resistant well which will serve the needs of the community, which will be accepted and used by the community, and which will do so at as low a cost as possible. Included in that is consideration for the maintenance needs and costs of the well and pumping equipment. There are choices that must be made. Each area will have specific needs, but there are also some general tendencies among projects which can act as a guideline to work from.

If available, the exploitation of aquifers of shallow to moderate depth has been shown to be more appropriate to most rural development situations. Currently the most economical method of exploiting these aquifers is through the use of hand drilled wells (Blankwaardt, 1984). Hand drilled wells, however, are only effective in aquifers with production rates of about 15 litres per minute (850 litres per hour) or greater (Blankwaardt, 1984: 33-36). Large diameter wells can make use of aquifers with flow rates of less than 5 litres per minute (300 litres per hour). It is impossible to state,

without further research, what level of cost animal powered bored wells would result in, but I would suggest that animal powered boring rigs would have a low cost rivaling the costs of hand drilled wells. Animal powered boring rigs could also be used to bore small diameter holes which could be used as test holes or even wells where successful.

If aquifers of shallow to moderate depth are suspected in an area, the cheapest method of exploitation would either be through a hand drilled or animal bored well. If the geology does not permit for the use of either of those types of wells, then shallow to moderate depth machine bored, machine drilled, or machine punched wells are generally the next most appropriate option. If adequate groundwater is not available at shallow or moderate depths, the final groundwater solution would be a deep drilled or punched well. Hand dug wells are not included in this list because hand drilled wells or animal bored wells are a much more effective method of exploiting groundwater and they can be done for the same or less cost as hand dug wells. Effectively, hand dug wells are not the most appropriate technology because they are known to be unreliable and generate pump difficulties. They are not 'technically efficient' as required by the WHO for a technology to be considered appropriate (1994: 14). In certain areas hand dug wells work reasonably well, but if sustainability is the goal of water projects, other construction methods will serve better.

Further Work

As this has only been a preliminary examination of the potential for bored well usage in developing countries, it can only state that there appears to be strong potential for bored well use. The benefits of including boring technology as an option alongside other technologies appear to be substantial. Further work must be done though. An

examination into the costs involved in using each of these technologies would be useful. This would be area specific, but it would help to give some insight into the expenses involved. The most useful method for this to be carried out may be by including boring technology as an option in water supply projects. Costs would then be explored and decisions could be based upon them.

There is also great potential for further research into the use of animal traction in water well construction. The technology appears to have application in development projects and perhaps even in private industry. The individuals who worked on these machines in the past are now elderly and may not be around for a great deal of time. There is a vast amount of knowledge that may be quite relevant to developing world applications among these people. The technology appears to meet many of the guidelines of 'appropriate' technology. Most importantly, its cost is rather low. Further work needs to be done in discovering how animals from different parts of the world could be utilized for such work. Nothing found in this thesis suggests any reason as to why this technology would not be feasible in the developing world.

Final analysis

There appears to be ample reasons for considering the use of bucket boring in development projects. There does not appear to be any reason for development agencies or companies to not consider the use of bored wells when designing a project. The technology has its benefits as well as its shortcomings. Those who make decisions regarding what well construction techniques are employed in water supply projects should make the effort to learn about bucket boring. Those

who write about different methods of construction should begin to include bucket boring as an option. Included as an option, it may well result in development projects being more respondent to particular physical and social environments.

Appendix A: Glossary

ALLUVIAL DEPOSITS - The general name for all sediments, including clay, (ALLUVIUM) silt, sand, gravel or similar unconsolidated material deposited in a sorted or semi-sorted condition by a stream or other body of running water, in a stream bed, floodplain, delta or at the base of a mountain slope as a fan.

ALLUVIAL FANS - A fan shaped deposit of sediment deposited by a stream where it emerges from a steep mountain slope or from an upland onto a less steeply sloping terrain.

ANIMAL TRACTION - The use of animals to provide power for simple tools and machines. Most often used in the agriculture field.

ANNULAR SPACE ("annulus") - The space between the well casing and the borehole walls.

APPROPRIATE TECHNOLOGY - A technology tailored to fit, and proven effective in, the psychological and biophysical context prevailing in a particular location and period.

AQUIFER - An aquifer is a formation, group of formations or part of a formation containing enough saturated permeable material to produce significant amounts of water to wells and springs (see also confined aquifers or artesian aquifers and unconfined aquifers).

AQUIFER PENETRATION - The depth with which a well attains below the top of an aquifer.

AQUIFER DEPLETION - Aquifer depletion occurs when groundwater is withdrawn from an aquifer at a rate greater than it can be replenished.

AQUIFER VULNERABILITY - A measure of how vulnerable an aquifer is to contamination.

AQUITARD - Geological formations or strata that have the ability to store water but can only transmit water in very small quantities (e.g. silt, siltstone).

ARTESIAN AQUIFER - See confined aquifer.

ARTESIAN WELL - A well obtaining its water from an artesian or confined aquifer in which the water level in the well rises above the top of the aquifer. The water level in a flowing artesian well rises above the land surface.

BEDROCK - Rock underlying soil and other unconsolidated material.

BORED WELL - A well created using boring or auger methods.

BORER - The operator of a bucket boring rig.

CAISSONING - Installing cement cribbing in a well as digging or boring is occurring. The string of cribbing sinks in the well as material is removed below it. New joints of cribbing are added to the string from above.

CONE OF DEPRESSION - Cone of depression (or "influence") is the draw-down of the water table or potentiometric surface that happens when a well is pumped. The drawdown cones of two wells close together may overlap so that if the wells are pumped simultaneously they will compete with each other for available groundwater (well interference).

CONFINED AQUIFER - Confined is synonymous with artesian. A confined aquifer or an artesian aquifer is an aquifer bounded both below and above by beds of considerably lower permeability than that existing in the aquifer itself.

CONFINING BED - A bed of impermeable material stratigraphically adjacent to one or more aquifers. Confining bed is now used to replace terms such as "aquiclude", "aquitard", and "aquifuge".

CONTAMINANT - Solute which through human action intrudes into the hydrologic.

CONTAMINATION - Impairment of natural water quality by chemical or bacterial pollution as a result of human activities. The degree of contamination allowed before an actual hazard to public health is created will depend upon the intended end use, or uses of the water.

CRETACEOUS - The most recent geologic period in the Mesozoic Era.

CRIBBING - Well casing material that is made of cement or wood.

DEEP WELL - A well of depth greater than 50 meters.

DISCHARGE AREA - The zone in which groundwater leaves the ground either as a spring or into a water body.

DOWN THE HOLE HAMMER - A tool used to penetrate hard rock when drilling a well. Powered by compressed air, it functions similar to a jackhammer. Also known as a downhole hammer.

DRAWDOWN - The variation in the water level in a well prior to commencement of pumping compared to the water level in the well while pumping. In flowing wells drawdown can be expressed as the lowering of the pressure level due to the discharge of well water.

DRIFT (GLACIAL) - Glacial drift includes all rock material in transport by glacier ice, the deposits made by glacier ice and all materials mainly of glacial origin deposited in the sea or in glacial melt water bodies including materials rafted in by ice bergs or transported indirectly in the water itself. Glacial drift therefore includes till, rock fragments and stratified drift.

DRILL STEM - Pipe connected together to obtain depth for drilling operations. Also known as drill string.

DRILLED WELL - A well that is constructed with a drilling rig. Also known as rotary drilling.

DRILLER - The operator of a drilling rig.

DUG WELL - A well that is dug by hand or excavated by backhoe. Dug wells are usually shallow.

EVAPOTRANSPIRATION - A combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants.

FLOODPLAIN - The flat land adjacent to a river, formed by deposition of fluvial materials.

FLUVIAL DEPOSITS - Deposits related to a river or stream.

FRACTURE - A break or crack in the bedrock.

GEOMORPHOLOGY - Geomorphology is the science dealing with the origin and evolution of land forms.

GLACIAL DRIFT - See Drift (Glacial)

GLACIO-FLUVIAL DEPOSITS - Deposits related to the joint action of glaciers and meltwater streams.

GNEISS - A hard, coarse-grained, foliated (banded), metamorphic rock (altered by great temperature and/or pressure) of quartz, feldspar and mica; often has low water.

GROUNDWATER - Water that occurs in the subsurface below the water table.

GROUNDWATER MINING - Permanent depletion of groundwater reserves.

GROUNDWATER TABLE - That surface below which rock, gravel, sand or other material is saturated. It is the surface of a body of unconfined groundwater at which the pressure is atmospheric.

HARDNESS - When hard water is used with soap it will form an insoluble residue and hard water will form a scale in utensils in which the water has been allowed to evaporate. Hardness is mainly caused by calcium and magnesium ions. Hardness is generally expressed in mg/L calcium carbonate (Ca CO_3).

HETEROGENEOUS DEPOSIT - Non uniform structure and composition throughout the deposit.

HOMOGENEOUS DEPOSIT - Structure or composition of the deposit is uniform.

HYDRAULIC CONDUCTIVITY - Hydraulic conductivity is a measure of the ability of a fluid to flow through a porous medium determined by the size and shape of the pore spaces in the medium and their degree of interconnection and also by the viscosity of the fluid.

Hydraulic conductivity can be expressed as the volume of fluid that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

HYDRAULIC GRADIENT - The change in hydraulic head (pressure) per unit distance in a given direction. It is the driving force of fluid flow in a porous medium.

HYDRAULIC HEAD - The level to which water rises in a well with reference to a datum such as sea level.

HYDROGEOLOGY - Study of groundwater in its geological context.

HYDROLOGICAL CYCLE - The continuous circulation of moisture and water on earth. The amount of water never changes but its state and position in the cycle does change.

IGNEOUS ROCKS - Rocks that solidified from molten or partly molten materials, that is from a magma or lava.

IMPERMEABLE - Impervious to flow of fluids.

INCRUSTATION - Mineral matter deposited by water. One of the major causes of well failure is the chemical and biological incrustation of well screen through precipitation of calcium and magnesium carbonates or sulfates. The precipitation of iron and manganese compounds and slime producing iron bacteria will also plug well screens.

INFILTRATION RATE - The rate at which water permeates the pores or interstices of the ground.

INTAKE - Area of a well where casing is perforated or screen is installed to allow for water entry.

ISOTROPIC - Exhibiting properties with the same values in all directions.

LACUSTRINE DEPOSITS - Sediments laid down in a lake. Includes gravelly deposits at the margin and clay in deeper water. Sediments commonly show seasonal banding or varve clays.

LARGE DIAMETER WELL - A well with a diameter greater than 600mm. Includes hand dug wells and most bored wells.

LITHOLOGY - All the physical properties, the visible characteristics of mineral composition, structure, grain size etc. which give individuality to a rock.

MARINE DEPOSITS - Mostly silt and clay materials deposited under a marine environment.

MESOZOIC - Geologic era preceding the Cenozoic Era. The Mesozoic Era was a time when the rocks of the Triassic, Jurassic and Cretaceous Systems were deposited.

METAMORPHIC ROCKS - Any rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment, generally at depth in the Earth's crust.

MODERATE DEPTH WELL - A well of depth between 7 meters and 50 meters.

OBSERVATION WELL - A well constructed for the objective of undertaking observations such as water levels, pressure readings and groundwater quality.

OUTWASH DEPOSITS - Stratified drift deposited by meltwater streams flowing away from melting ice.

OVERBURDEN - The layer of fragmental and unconsolidated material including loose soil, silt, sand and gravel overlying bedrock, which has been either transported from elsewhere or formed in place (saprolite).

PALAEOZOIC - Geological era preceding the Mesozoic Era. The Palaeozoic is a major division of geologic time and it includes in descending order the Permian, Carboniferous, Devonian, Silurian, Ordovician and the Cambrian.

PERCHED WATER TABLE - A separate continuous body of groundwater lying (perched) above the main water table. Clay beds located within a sedimentary sequence, if of limited aerial extent, may have a shallow perched groundwater body overlying them.

PERMEABILITY - The property of a porous rock, sediment or soil for transmitting a fluid, it is a test of the relative ease of fluid flow in a porous medium.

PERMEABLE - The property of a porous medium to allow the easy passage of a fluid through it.

PIEZOMETRIC SURFACE - The water level surface that can be defined from the mapping of water level elevations in wells tapping into a confined aquifer.

PLEISTOCENE - The period following the Pliocene during which an ice sheet covered the greater part of North America. Named by Lyell in 1839.

POROSITY - The ratio of the volume of voids to the total volume of a rock or unconsolidated material. It is a measure of the amount of empty 'space' in a material.

POTABLE WATER - Water fit for human consumption.

POTENTIAL WELL YIELD - An estimate of well yield generally above the existing yield rate or test rate, but considered possible on the basis of available information, data and present well performance.

PUMPING LEVEL - The level at which water stands in a well when pumping is in progress.

PUMPING TEST - A test conducted by pumping a well to determine aquifer or well characteristics.

PUNCHED WELL - A well constructed using a punching or cable tool rig.

PUNCHER - The operator of a punching rig (also known as a cable tool rig).

QUATERNARY - The period of geologic time that follows the Tertiary. The Quaternary includes the Pleistocene and Recent Periods and is part of the Cenozoic Era.

RECHARGE AREA - An area where water infiltrates into the ground and joins the zone of saturation. In the recharge area, there is a downward component of hydraulic head.

SALINE GROUNDWATERS - Groundwater consisting of or containing salt.

SALT WATER INTRUSION - Movement of salty or brackish groundwater into wells and into aquifers previously occupied by fresh or less mineralized groundwater either through upcoming or seawater encroachment.

SANDSTONE - A sedimentary rock composed of mostly sand sized particles.

SANITARY SURFACE SEALS - A grouted annular space around the well casing which usually extends from the land surface to several meters deep. The sanitary well seal functions to prevent any contaminated surface and near surface water from seeping down the side of the well to the aquifer.

SAPROLITE - Bedrock which has been weathered through chemical processes. Are often the best source of aquifers in basement complex rock. Found almost exclusively in the tropics.

SATURATED ZONE - The zone below and including the water table in which all pore spaces or fissures are totally filled with water. Also referred to as the phreatic zone.

SEDIMENTARY ROCKS - Rocks formed from consolidation of loose sediments such as clay, silt, sand, and gravel.

SHALE - A fine-grained sedimentary rock, formed by the consolidation of clay, silt, or mud. It is characterized by finely laminated structure and is sufficiently indurated so that it will not fall apart on wetting.

SHALLOW WELL - A well of depth less than 7 meters.

SMALL DIAMETER WELLS - Wells with a diameter of less than 200 mm.

SPECIFIC CAPACITY - A measure of the number of gallons per minute pumped per foot of drawdown in a well at any point in time. Knowing the specific capacity of a well, the operator can estimate the drawdown that will be produced at different pumping rates. For example, the specific capacity of a well that delivers 20 gpm with 40 ft of drawdown would be 0.5 gpm/ft. At 30 gpm the drawdown would be $30/.5 = 60$ ft.

STATIC WATER LEVEL - The level of water in a well that is not being influenced by groundwater withdrawals. The distance to water in a well is measured with respect to some datum, usually the top of the well casing or ground level.

STORATIVITY - The volume of water released from storage per unit surface area of aquifer per unit decline in hydraulic head (dimensionless).

STRATA - Layers of deposited rock, soil etc which are distinguishable from each other.

SURFICIAL DEPOSITS - Deposits overlying bedrock and consisting of soil, silt, sand, gravel and other unconsolidated materials.

SUSTAINED YIELD - Rate at which groundwater can be withdrawn from an aquifer without long term depletion of the supply.

TERTIARY - Geologic period of the Cenozoic Era and that period prior to the Quaternary.

TILL - Till consists of a generally unconsolidated, unsorted, unstratified heterogeneous mixture of clay, silt, sand, gravel and boulders of different sizes and shapes. Till is deposited directly by and underneath glacial ice without subsequent reworking by meltwater.

TOPOGRAPHY - The configuration of a surface including its relief and the position of its natural features.

TOTAL DISSOLVED SOLIDS (TDS) - Concentration of total dissolved solids (TDS) in groundwater expressed in milligrams per litre (mg/L), is found by evaporating a measured volume of filtered sample to dryness and weighing this dry solid residue.

TRANSMISSIVITY - Rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity values can be expressed as square metres per day (m^2/day), or as square metres per second (m^2/s).

TRANSPIRATION - The process by which water absorbed by plants, usually through the roots, is evaporated into the atmosphere from the plant surface.

UNCONFINED AQUIFER - An aquifer whose upper boundary is defined by the water table (water is at atmospheric pressure). Water usually saturates only part of the geologic unit and there is no upper confining layer. Also called a "water table aquifer".

UNCONSOLIDATED DEPOSITS - Deposits overlying bedrock and consisting of soil, silt, sand, gravel and other material which have either been formed in place or have been transported in from elsewhere.

UNSATURATED ZONE - The zone above the water table in which soil pores or fissures are less than totally saturated. It is also called the vadose zone or the zone of aeration.

VLOM PUMP - (Village Level Operated and Maintained) A pump which is designed to be maintained at a village level, with simple tools and few resources.

WATER BALANCE (HYDROLOGIC BUDGET) - A record of the outflow from, inflow to, and storage in a hydrologic unit like an aquifer, drainage basin etc.

WATER TABLE - The top of the zone in which all pore spaces or fissures are totally filled with water.

WATERSHED - A catchment area for water that is bounded by the height of land and drains to a point on a stream or body of water, a watershed can be wholly contained within another watershed.

WELL CONSTRUCTOR - An individual (or individuals) who construct a well using any method.

WELL DEVELOPMENT - This operation helps make water enter the well more easily and can make the difference between a satisfactory and an unsatisfactory well. Different techniques for well development can be used, the aim is to remove the smaller sized particles from the aquifer surrounding the well screen and to provide a coarser filter zone around the

screen. The smaller sized particles are drawn into the well screen and can then be removed by bailing or pumping.

WELL POINTS - Also referred to as sand points, gravel points, are used in shallow permeable unconfined (usually) aquifers generally less than 30 feet deep. Well points consist of a short length of screened pipe with a sharp point on the bottom end. As the pipe is driven into the ground, additional lengths of pipe are added to the top end. Sand points are also available with a check valve at the lower end to enable the pipe to be washed down in sand and fine gravel aquifers. Water can be pumped down the pipe and it passes out the check valve at the bottom and washes the sand up the hole to the ground surface.

WELL SCREEN - A cylindrical filter used to prevent sediment from entering a water well. There are several types of well screens, which can be ordered in various slot widths, selected on the basis of the grain size of the aquifer material where the well screen is to be located. In very fine grained aquifers, a zone of fine gravel or coarse sand may be required to act as a filter between the screen and the aquifer.

WELL SEALS - Cover for the top of the well.

WELL YIELD - The volume of water which can be constantly discharged from a well without interruption in litres per minute (L/min), litres per second (L/s), or cubic metres per day (m³/day).

WELLHEAD PROTECTION - Protection of the recharge (or capture zone) area of a pumping well.

ZONE OF SATURATION - See saturated zone.

Bibliography

- Afrodisis, S. (1980). The Hydrology of the Island of Cyprus. Hydrology in Commonwealth Africa, Lobatse, Botswana, Commonwealth Geological Liaison Office.
- Alberta Environmental Protection, (!997). Water Well logs.
- Bah, O. M. (1991). Evaluation of Rural Water Supply Projects in Sierra Leone. Ottawa, The International Development Research Center (IDRC).
- Barr, R., et al. (year unknown). Large Diameter Bores.
- Bennison, E. W. (1947). GroundWater: Its Development, Uses and Conservation. St. Paul, Minnesota, Edward E. Johnson Inc.
- Blankwaardt, B. (1984). Hand Drilled Wells. Dar es Salaam, Tanzania, Rwegarulila Water Resources Institute.
- Bowen, R. (1986). Groundwater. New York., Elsevier Applied Science.
- Brush, R. E. (1979). Wells Construction: Hand Dug and Hand Drilled. Washington, D.C., Peace Corps.
- Carr, J. R. (1969). "Boring Equipment is One More Tool For Water Well Contractor." UOP Johnson Drillers Journal Sept-Oct: 1-3.
- Carruthers, R. M., and Smith, I.F. (1992). The Use of Ground Electrical Survey Methods for Siting Water-Supply Boreholes in Shallow Crystalline Basement Terrains. Hydrogeology of Crystalline Basement Aquifers in Africa. E. P. Wright, and Burgess, W.G. London, Geological Society Special Publications. 66: 203-220.
- Chachadi, A. G., and Venkataramana, D. (1991). Methodology for Estimation of Aquifer Transmissivity Using Specific Capacity of Large-Diameter Well. Ninth Annual Convention and National Seminar of Association of Hydrologists of India. P. Koteswaram. Junagadh, India, Gujarat Agricultural University, Jenagadh Campus. 9: 29-30.
- Clark, L. (1988). The Field Guide to Water wells and boreholes. New York, Halsted Press.
- Collins, C. (1997). Personal Communication with President of Gus Pech Mfg. co.

- DHV Consulting, (1978). Tanzania Shinyanga Region: Shallow and Medium Depth Wells, Final Report Part 1. Amersfoort, The Netherlands, DHV Consulting Engineers.
- DHV Consulting, (1979). Shallow Wells. Amersfoort, The Netherlands, DHV Consulting Engineers.
- Davies, J., et. al. (1980). Groundwater Research in Botswana: Past, Present, and Future. Hydrology in Commonwealth Africa, Lobatse, Botswana, Commonwealth Geological Liaison Office.
- Driscoll, F. G. (1986). Groundwater and Wells. St Paul, Minnesota, Johnson Division.
- Eberle, M., and Persons, J. (1978). Appropriate Well Drilling technologies: A Manual for Developing Countries. Washington, D.C., Agency for International Development.
- Edward. E. Johnson Inc. (1966). Ground Water and Wells: A Reference for the Water-Well Industry. St. Paul, Minnesota, Edward E. Johnson Inc.
- Evans, P., and Appleton, Brian. (1993). Community Management Today: The Role of Communities in the Management of Improved Water Supply Systems. The Hague, IRC International Water and Sanitation Centre.
- Fair, D. (1995). "Water and sanitation in sub-Saharan Africa." Africa Insight 25(1): 48-54.
- Faisen, W. C. (1998). National Drillers Buyers Guide. Bonifay, Florida, W.C. Faison & Associates. 19.
- Fitzgibbon, J. (1998). Personal Communication.
- Freeze, R. A., and Cherry, J.A. (1979) Groundwater, Englewood Cliffs, Prentice-Hall
- Funk, G., McClenaghan, William A., and Holland, Cyril (1982). Water Wells and Ground Water Supplies in Ontario. Ottawa, Ontario Ministry of the Environment.
- Gibson, U., and Singer, R. (1969). Small Wells Manual: A Manual of Location, Design, Construction, Use and Maintenance. Washington, D.C., Agency for International Development.
- Gibson, U. P., and Singer, R.D. (1971). Water Well Manual. Berkley, California, Premier Press.

Guillemin, F., Henry, Pascale., Uwechue, Ndidi., and Monjour, Loic. (1991). "Faecal Contamination of Rural Water Supply in the Sahelian Area." Water Research 25(8): 923-927.

Gus-Pech Video. (year unknown). Gus Pech Super George Bucket Drill.

Gus-Pech (unknown). "Earth Drilling Equipment" (pamphlet).

Hamill, L., and Bell, F.G. (1986) Groundwater Resource Development, London, Butterworth.

Heederik, J. P., et. al. (1984). "Water Resources Assessment Study in Kiambu District , Kenya." Challenges in African Hydrology and Water Resources 144.

Herbert, R., Barker, John A., Sakthivadivel, R., and Rushton, K.R. (1990). "Numerical Analysis of Large Diameter Wells With a Seepage Face: Discussion and Reply." Journal of Hydrology 113(1-4): 371-375.

Herbert, R., et. al. (1981). "Determination of Aquifer Perimeters from Large Diameter Pumping Tests." Ground Water 19(4): 593-599.

Howe, C. (1993). "Inefficiencies in Water Project Design and Operation in the Third World: An Economic Perspective." Water Resources Research 29(7): 1889-1894.

Iowa State University (1993). Good Wells For Safe Water. Ames, Iowa, Iowa State University: University Extension.

IRC (1988). Issues and Concepts in Rural Water Supply Programmes. The Hague, International Water and Sanitation Center.

Kaplinsky, R. (1990). The Economics of Small: Appropriate technology in a changing world. London, Appropriate Technology International.

Kennedy, W. K., and Rogers T.A. (1985). Human and Animal-Powered Water-Lifting Devices. London, Intermediate Technology Publications.

Ker, A. (1995). Farming Systems in the African Savanna: A Continent in Crisis. <http://idrc.ca/books/focus/793/chap10.html>, IDRC.

Key, R. (1992). An Introduction to the Crystalline Basement of Africa. Hydrology of the Crystalline Basement Aquifers in Africa. Wright, E. and Burgess, W. London, Geological Society Special Publication No. 66.

King, R. S., and Dinye, Romanus. (1994). Women, children, water/sanitation development. Water, Sanitation, Environment and Development. J Pickford. et. al. London, Intermediate Technology Publications: 7-8.

- Kinley, D. (1990). "Zimbabwe Pioneers Low-Cost Technologies." Source 2(3): 14-17.
- Kjellerup, B., and Ockelford, Jeremy (1993). "Handpump Standardization in Cambodia." Waterlines 12(1): 23-25.
- Kolm, K.E. et al. (1989) Water Well Design and Construction, Amsterdam, Elsevier.
- Larson, D. (1979). "Manitobans Find an Answer to Shallow Wells." Johnson Drillers Journal July-August: 5-7.
- Lifewater International. (1998a) Well Construction tutorial: Finding Underground Water, <http://lifewater.ca/tutorial.htm>
- Lifewater International. (1998b) Well Construction tutorial: well Siting, <http://lifewater.ca/tutorial.htm>
- Lloyd (1990). "Groundwater Resources Development in the Eastern Sahara." Journal of Hydrology 1990(119): 71-87.
- Mabuba, P. B. (1994). Strategies for effective community involvement. Water, Sanitation, Environment and Development. J Pickford. et. al. London, Intermediate Technology Publications: 12-14.
- Mangin, J.M. (1991). "Rural Water Supply in Southern Ethiopia: Failures and Alternatives." Canadian Journal of Development Studies 12(2): 297-312.
- Mcperson, H. J. (1988). Personal Communication.
- Meijerink, A. a. V. W., W. (1997). Contribution to the groundwater hydrology of the Amboseli ecosystem, Kenya. Groundwater/Surface Water Ecotones: Biological and Hydrological Interaction and Management Options. L Gilbert. et. al. Cambridge, Cambridge University Press.
- Narayan, D. (1995). The Contribution of People's Participation: Evidence from 121 Rural Water Supply Projects. Washington, D.C., The World Bank.
- Okun, D. A. (1982). Water Supply Around the World: Appropriate Technology. Water Supply and Sanitation in Developing Countries. E. J. Schiller, and Droste, Ronald L. Ann Arbor, Michigan, Ann Arbor Science.
- Okuni, P. A., and Rockhold, John P. (1996). An approach for community-based sustainability. Sustainability of Water and Sanitation Systems. J. Pickford, et al. London, Intermediate Technology Publications: 23-25.
- Reynolds, J. (1987). "Testing Handpumps for Community Water Supply." Waterlines 6(1): 20-23.

- Robson, E. (1991). "From Provider to Promoter: Gambia's Rocky Transition." Source 3(2): 10-13.
- Rondinelli, D., A. (1991). "Decentralizing water supply services in developing countries: factors affecting the success of community management." Public Administration and Development. 11: 415-430.
- Roscoe Moss Company, (1990). Handbook of Ground Water Development. New York, John Wiley & Sons Inc.
- Schreurs, R. L. (1990). Well Development is Critical. Developing World Water. J. Pickford. London, Grosvenor Press International: 40-41.
- Schumacher (1973). Small is Beautiful. London, Blond & Briggs.
- Selby (1985). Earth's Changing Surface. Oxford, Clarendon Press.
- Shazly, E. et. al. (1985). "Groundwater potential of the St. Katherine Monastery Environs, Sinai, Egypt." Egyptian Journal of Geology 29(1-2): 89-100.
- Shoepp, R. (1997). Personal Communication.
- Sparks, E. (1997). Personal Communication.
- Summers, J. (1985-87). Personal Logs.
- Summers, J. (1998). Personal Communication.
- Swanson, G. J. (1997). "What It's Like to Drill in Garbage." Water Well Journal 3: 62-65.
- Tolman, C. F. (1937). Ground Water. New York, McGraw-Hill Book Company.
- UNICEF. (1998). "State of the World's Children".
- United Nations. (1988). Ground Water in North and West Africa. New York, United Nations.
- United Nations. (1988). Ground Water in South and East Africa. New York, United Nations.
- United Nations. (1973). Ground Water in Africa. New York, U.N. Publications.
- van Wijk-Sijbesma, C. (1985). Participation of Women in Water Supply and Sanitation: roles and realities. The Hague, International Centre for Community Water Supply and Sanitation.

- Wagner E.G. and Lanoix, J.N. (1959). Water Supply for Rural Areas and Small Communities. Geneva, World Health Organization.
- Walsh, R., Hulme, M., and Campbell, M. (1988). "Recent Rainfall Changes and Their Impact on Hydrology and Water Supply in the Semi-Arid Zone of the Sudan." The Geographical Journal 154(2): 181-198.
- Walton, W. C. (1991). Principles of Groundwater Engineering. Chelsea, Michigan, Lewis Publishers.
- Walude, M. (1996). Sustainability of Kabarole shallow wells. Sustainability of Water and Sanitation Systems. J. Pickford, et al. London, Intermediate Technology Publications: 108-109.
- Wanchai, G. (1986). Social Aspects of water supply and sanitation. World Water '86: Water technology for the developing world, London, Thomas Telford Limited.
- Warner, D. B. (1985). Emergency Water Supply and Sanitation Assistance to the Ethiopian Drought and Famine. Washington, DC, Water and Sanitation for Health Project.
- Water Well Journal, (1996). "Buyers Guide." Water Well Journal L(1). White, G., Bradley, D. and White, U. (1972). Drawers of Water: Domestic Water use in East Africa. Chicago, The University of Chicago Press.
- Watt, S. B., and Wood, W.E. (1979). Hand Dug Wells and Their Construction. London, Intermediate Technology Publications.
- Willoughby, K., W. (1990). Technology Choice: A Critique of the Appropriate Technology Movement. San Francisco, Westview Press.
- Wood, M. (1993). "A Handpump for Africa: the Afridev Experience." Waterlines 11(4): 29-31.
- Wood, M., and Dinna, Negash. (1996). Buying into rural water systems. Sustainability of Water and Sanitation Systems. J. Pickford, et al. London, Intermediate Technology Publications: 39-41.
- World Health Organization, (1994). Financial management of water supply and sanitation: A Handbook. Geneva, World Health Organization.
- Wright, E. P. (1985). Water Resources for Humans, Livestock and Irrigation. Geohydrology of Drought Prone Areas in Africa, Lobatse, Botswana, CSC Publication.
- WUSC, (1985-1988). Miscellaneous Papers from Archive Box 1212.

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