TECHNICAL PAPER

Groundwater Development

Basic Concepts for Expanding CRS Water Programs

Vincent W. Uhl, Jaclyn A. Baron, William W. Davis,
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July 2009

WATER AND SANITATION | PROGRAM QUALITY

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Graphic design by Ephra Graham.

Cover photo by Andrew McConnell for CRS.

Published in 2009. Download this publication and related material at www.crsprogramquality.org.

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INTRODUCTION

Because of the growing importance of water in the health, agricultural, and environmental sectors, the development of groundwater sources is becoming increasingly central to the success of integrated rural development programs. CRS experience with and capacity to undertake groundwater development tends to be restricted by a shortage of technical staff. Where successful groundwater development programs have been implemented, the transfer of technical knowledge and best practices to other countries occasionally has been limited by an inadequate understanding of the potential benefits of groundwater within senior CRS staff at the regional and country levels.

The purpose of this technical paper is to inform CRS staff of the potential for groundwater development in country programs. It is not a planning or design guideline, but rather a general technical overview of a critical component of water development.

This paper explains basic groundwater and well drilling concepts and shows how they can be employed to strengthen and expand CRS water development programs. The target audience is the CRS Program Managers, Country Representatives and Regional Advisors who have responsibilities for programs and projects involving water.

To enhance a greater awareness and understanding of groundwater development, this technical paper has the following objectives:

- To highlight the uses of groundwater in development projects
- To show how groundwater can improve public health, expand food production, and support livelihoods
- To illustrate the principles of groundwater occurence
- To outline the basic technologies in groundwater projects

This technical paper is laid out in the following manner:

Part I: Groundwater Basics

1.1 Highlights the basics of groundwater hydrology

1.2 Outlines the fragility of groundwater as a renewable resource

1.3 Identifies advantages of using groundwater over surface water

1.4 Lists the many uses of groundwater

1.5 Describes groundwater quality and how it is determined

Part II: Wells and Boreholes

2.1 Outlines the siting of dug wells and boreholes

2.2 Describes the construction of wells

2.3 Outlines the variety of pumps, power sources, and engines

Part III: Groundwater Programming

3.1 Presents key considerations for groundwater programming

Appendices

PART I: GROUNDWATER BASICS

1.1 Groundwater: The Basics

Fresh groundwater occurs in a myriad of geologic forms. These range from vast regional aquifer systems such as the Nubian Aquifer (North Africa) and the Ogallala Aquifer (West Texas, Oklahoma, Kansas and Nebraska) which extend over millions of square miles, to localized river basin systems, and tiny freshwater lenses that occur between the surface and the seawater beneath islands in the Pacific Ocean. Groundwater is a principal source of supply for many villages, towns and cities serving domestic, commercial, institutional, industrial and agricultural users. The irrigation of crops worldwide uses more groundwater (70% or greater) than all other applications combined.

Groundwater development projects take advantage of water as it moves through an aquifer.

Groundwater occurs in unconsolidated and consolidated bedrock geologic formations. In unconsolidated formations which are made up of porous media (gravels, sands, silts and clays), the groundwater is stored and travels in the pore spaces between the particles. In bedrock formations, the water is stored and travels in joints, fissures and fractures in the rock, referred to as secondary porosity. As a rule, groundwater travels very slowly through its geologic matrix, often on the order of a few inches or feet per day. The rumored presence of "underground rivers" is no more than a myth in most types of geologic settings. However, limestone "karst" formations can have systems of major solution openings that comprise caverns and tunnels filled with water.

Water table aquifers are unconfined systems. In these aquifers, the top of the aquifer is the water table where the water is at atmospheric pressure. Wells installed in unconfined aquifers will show water levels that are often referred to as the water table, also known as the top of the zone of saturation. The water table rises in response to precipitation (recharge events) and falls/declines during dry periods. Depending on the aquifer formation and topographic location, the water table can fluctuate seasonally from a few inches to tens of feet or more under natural conditions.

Aquifers also occur in semi-confined and confined conditions. In confined (artesian) systems, the permeable aquifer is sandwiched between two relatively impermeable layers (clay or bedrock) called the upper and lower confining units. The water in the aquifer is at greater than atmospheric pressure and a surface analogous to the water table can be visualized above the actual aquifer representing the hydraulic head, which is called the piezometric surface. Wells installed in a confined or artesian aquifer will show water levels that are higher than the actual aquifer elevation and equivalent to the piezometric surface. In some cases a flowing artesian well results when the pressure head within an artesian aquifer is such that the piezometric surface is higher than the ground surface.

Groundwater development projects take advantage of water as it moves through an aquifer. Water that is removed by humans at one place in the aquifer may be replaced by rain that falls in another region. An aquifer is "charged" as groundwater is replenished, which serves as a kind of natural pipeline from one area to another. This phenomenon buffers against droughts. Some aquifers are so large that any water taken out has little effect on the remaining water. Most aquifers are not this large, however, and it is possible for an aquifer to become depleted through overpumping and other forms of water extraction. Depletion depends on the balance between how much water is taken out and how much is replaced. Overexploitation of aquifers is sometimes called "mining water."

1.2 Groundwater as a Renewable Resource

Groundwater development in CRS projects normally serves the needs of small rural communities for domestic water, local livelihoods and emergency purposes. It is essential, therefore, that such projects provide groundwater of sufficient quantity and quality to serve the identified needs. In its simplest and most immediate form this means that the installation of wells for a project must yield the desired quantity and quality of water (with or without treatment) on a sustainable basis.

For larger-scale projects, there is also the critical question of the sustainability of the aquifer itself for all of the stakeholders who draw their water supply from the aquifer. More recently, there has been increased concern and emphasis on the role of groundwater in sustaining the environment and preserving the dry weather base flows of streams and wetlands as habitats for ecological users.

The basic criterion for a safe and sustainable groundwater project is that the water being abstracted does not exceed the aquifer recharge. This comparison is usually made on an annual basis and takes into account the quantity of recharge during years of normal precipitation. During years of drought, the water supply may rely to some extent on the amount of water in storage that will decrease over time, until the aquifer is replenished again in years of normal or above-normal precipitation. If, over an extended period of time, the amount of water being pumped out is greater than the quantity of recharge, then the water level of the aquifer will decline and wells will eventually go dry. This unsound condition of aquifer depletion, aptly called "mining of groundwater," has been a growing problem in many parts of the world.

The growing use of groundwater and the resultant increased demand on limited groundwater supplies have led to more complex problems of sharing and allocation of stressed groundwater systems. Integrated water resource management or integrated river basin management (IWRM/IRBM) approaches consist of looking at the groundwater and surface water resources of watersheds or river basins as a whole in an attempt to balance the limits of the renewable resource against the needs of the competing users.

As with any natural resource, groundwater has to be developed with caution and managed with care, with respect for its vulnerability and awareness of its limitations. However, properly utilized in the right applications, CRS Country and Regional Managers should recognize groundwater as a powerful resource that can create many opportunities for local and regional development.

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1.3 Advantages of Groundwater

Groundwater often has advantages of quality, accessibility, and reliability over surface water.

Groundwater is usually free of microbiological pollutants. As water percolates from the surface into aquifers, soil and rocks filter out living organisms, which can be a major cause of disease. Water can also be safely and indefinitely stored in aquifers while maintaining a high level of quality. The quality of surface water can vary seasonally and require different disinfection processes to adapt to changing water conditions. Surface water requires closer monitoring and more extensive disinfection than groundwater.

Because of its protected condition, groundwater is less likely to be contaminated than surface water and has a lower potential for transmitting disease.

Because of its protected condition, groundwater is less likely to be contaminated than surface water and has a lower potential for transmitting disease. Even in areas that have ample yearly surface waters, developing groundwater sources may be a better choice to ensure the provision of safe water.

Aquifers are natural storage systems for water and, if an aquifer is large enough, may be able to provide water through dry seasons and droughts—times when surface water sources are unreliable or even absent. However, aquifers vary in size, in how much water they can store, and in how quickly the water is replenished. If too much water is drawn from an aquifer too quickly, the aquifer could become depleted. Pump testing of individual wells is necessary to determine long-term sustainable well yields.

Aquifers that underlie communities are convenient sources of water. People need travel only short distances to wells located in towns and villages, instead of having to walk to distant surface water sources. When water is easily available, more of it will be used. The increased use of water for drinking, cooking, bathing, washing clothes, and household cleaning improves hygiene and health. Sometimes areas outside of villages are not secure and women and children may face danger from criminals when fetching water from distant sources. Developing groundwater sources within villages helps to avoid these threats.

In many cases, groundwater-based water systems are less expensive to install and operate than surface water systems, mostly because surface water usually requires extensive treatment. Installation of wells and pumps generally requires a few days to a few weeks, including training local people to operate, maintain and repair the system. If the groundwater system promotes economic growth by increasing crop yield through irrigation, for example, a stepwise installation can be implemented with farmers building onto the original system over time as their incomes increase. In this way a start-up project can be expanded with the profits it generates.

1.4 Uses of Groundwater

Groundwater is used for a wide range of applications, including provision of potable drinking water for village, town, and urban supply; institutional supplies; agricultural supply for multiple uses; small-scale industrial use; and emergency water supply provision for refugees. Globally, many major cities, towns, villages, and remote communities rely on groundwater as their primary source of water supply.

Globally, many major cities, towns, villages, and remote communities rely on groundwater as their primary source of water supply.

Groundwater is often the only source available to locales that are distant from surface water sources. A well yield of a few gallons per minute (less than 0.2 liters per second (lps)) is often sufficient for a small village hand-pump application. For towns and cities, individual well yields in the tens and hundreds of gallons per minute (1 to 10's of lps) are desirable.

The framework of the CRS Water Sector specifies four categories of water use.

- **Water for domestic uses to improve health.** Promoting health is a primary goal of water development projects, and this goal should be a major driving factor in all water supply projects. It is well accepted that the domestic water use of water contributes to the improved health of households and communities.
- **Water for productive uses to strengthen livelihoods.** The productive uses of water in agriculture, small industries, and local construction contributes to strengthening the livelihoods of program beneficiaries.

- **Water for environmental protection to sustain natural resources.** Development programs should contribute to the sustainable use of water resources in the watershed.
- **Water for emergencies and disasters to protect lives and livelihoods.** Programs should contribute to the stabilization and restoration of the health and livelihoods of communities that are unable to cope with natural or man-made disasters affecting them.

Examples illustrating the above categories of water use follow.

Potable Supply for Villages

Groundwater can be a primary water source for communities. In many places, groundwater is the only alternative when surface water is not available and is often the best option even when surface water is available. The advantages of groundwater include:

a. Groundwater can often be developed in close proximity to or within a village/town setting.

b. The quality of groundwater is often superior to surface water, and treatment requirements are generally simpler and less expensive.

c. System installation costs are generally lower for groundwater well systems.

d. Installation timeframes are markedly shorter for groundwater well systems.

e. Operation & Maintenance (O&M) requirements are simpler and less costly for groundwater well systems as compared to sources derived from surface water.

Dennis Warner for CRS

A handpump used to supply groundwater to a village in Madagascar.

Institutional Supply for Schools, Hospitals, Universities, and Fire Protection

Institutions such as hospitals and schools that have wells on the premises are self-reliant and need not depend on water vendors, surface water, or other possibly unreliable sources. A well that can provide a constant supply of water helps to ensure continuity of institutional operations. In the absence of a nearby water source, schools often use students to carry water, which can take a great deal of time and energy. If a nearby well can supply a school with water, the burden of carrying water will be greatly reduced, there will be less chance for the water to get contaminated, and students will have more free time for their studies.

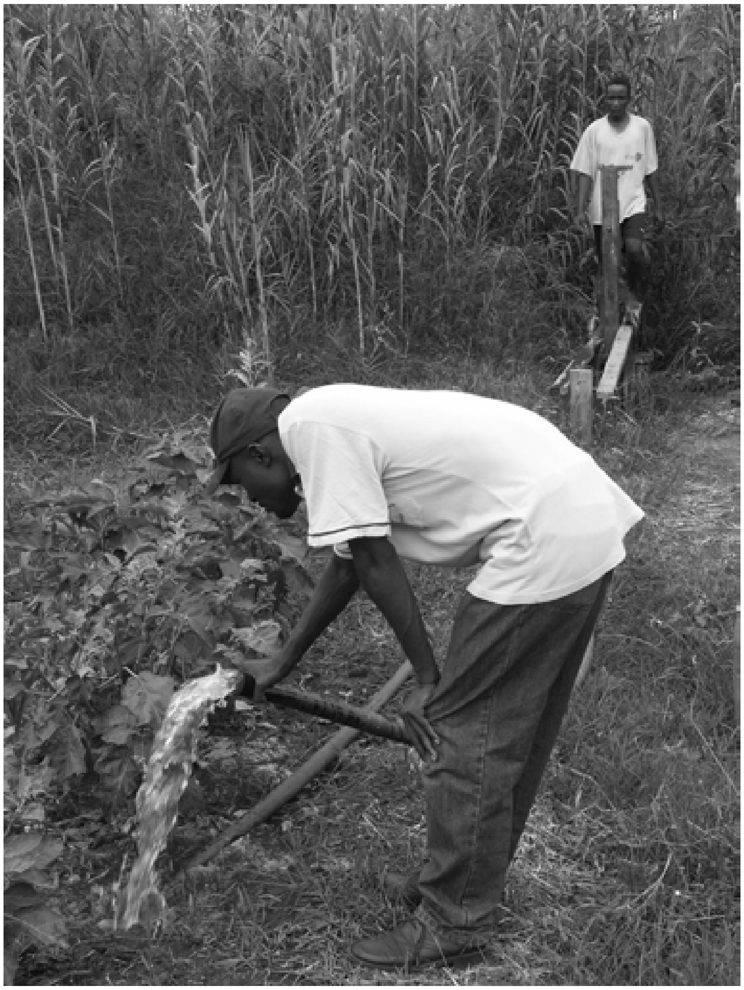
Institutions use their water supplies for several purposes, including drinking, cooking, landscaping and small garden irrigation, housekeeping, small-scale industry, and firefighting. Employees of the institution may use the well water for household use as a fringe benefit of employment.


Peter Kaizer for CRS

A handpump used to supply groundwater to a school in Burkina Faso.

Agricultural Supply for Irrigation/Farming

Farmers have been practicing irrigation for over eight thousand years, and since the advent of well-drilling technology groundwater has become an important source of irrigation water supplies. Wells can provide water for small-scale irrigation for private landholders as well as community farming. Irrigation also can help to extend growing seasons, protect against drought, and increase crop yields.



Sean Sprague for CRS

A treadle pump used to supply groundwater to a garden in Zambia.

Small-Scale Industrial Use

Village-level industries, such as brick making, textile production, dairy farming, and food processing, all require water. Groundwater development can provide a reliable supply of water for entrepreneurs, which can help to ensure a constant pace of production and provide for income generation.

Dennis Warner for CRS

A handpump used to supply groundwater for brickmaking activities.

Emergency Water Supply Development for Refugees/Displaced People

In emergency situations resources are usually scarce and time for implementing relief programs is limited. Trucking water to remote camps at the onset of a crisis is common, but it is also time-consuming and expensive. Because groundwater systems can be built in a short time and are able to deliver clean water on-site, they are often the preferred method for water supply.

1.5 Groundwater Quality

Physical, chemical, and microbiological parameters are used to measure groundwater quality. Physical parameters describe the color, temperature, and amount of solids that are suspended in the water. Chemical pollutants may originate from natural deposits in the soil or from industrial discharges, and different parameters exist for each pollutant source.

David Snyder for CRS

Groundwater supply systems provide high quality water in a relatively short amount of time for those people in desperate need of water

Microbiological pollutants mostly come from human and animal waste, although a few are naturally occurring. Bacteria in drinking water is a major cause of disease and keeping a water system free of bacteria is an important step in protecting community health. This section gives an overview of groundwater quality issues. Further information is available from the CRS Water Quality Manual, which provides greater detail on the scientific background of contaminants, disinfection techniques, testing kits, and water source protection.

Physical-Chemical Contaminants

There is a wide range of physical-chemical contaminants found in groundwater, most of which are harmless to human health, although a few pose serious hazards. Physical contaminants are judged by the appearance, taste, and odor they impart to the water. For drinking water, these characteristics should be acceptable to the consumers. Water that is colored or cloudy due to particulate matter and dissolved solids may not be harmful to health but may raise questions about the acceptability of the water to the users. Taste and odor issues can be caused by

Taste and odor issues can be caused by inorganic and organic chemical contaminants, biological sources or processes, corrosion, or as a result of water treatment.

inorganic and organic chemical contaminants, biological sources or processes, corrosion, or as a result of water treatment. In addition, taste and odor may indicate some form of pollution. Cloudy water also presents problems for chlorine disinfection. Bacteria thrive on suspended particles, which can interfere with and reduce the effectiveness of the chlorine disinfection process. Cloudiness can be removed with a variety of filtering processes.

Total dissolved solids (TDS) is the overall measure of the inorganic salts (calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) dissolved in the groundwater. The concentration of TDS determines whether the water may be considered fresh, brackish, or saline. A TDS level of less than 600 mg/liter, for example, is usually acceptable for drinking, while levels exceeding 1,000 mg/liter tend to cause drinking water to be too saline for normal consumption. High levels of TDS may also cause excessive scaling in water pipes, heaters, boilers, and household appliances.

The TDS concentration depends on climate, the host rock, and the residence (contact) time of the groundwater in the geologic matrix. TDS concentrations tend to be higher in arid/desert areas than in tropical areas that receive abundant rainfall. In coastal areas, groundwater salinity can increase with depth within a relatively short vertical distance and wells must be carefully installed to depths no greater than the extent of the freshwater layer. Saltwater intrusion/upwelling, as a result of excessive pumping of groundwater from a fresh water aquifer underlain by salt water, is a widespread problem that has occurred along many coastal areas.

Chemicals in groundwater usually come from underground mineral deposits, although industrial runoff can also be a source in more developed areas. Some chemicals, especially arsenic, fluoride, and nitrites, when present in high concentrations, can be harmful to humans. Arsenic concentrations in excess of World Health Organization (WHO) guidelines and national standards have been found at many locations globally. Arsenic can cause cancer, hyperkeratosis, and peripheral vascular disease. Fluorides are common in volcanic areas such as the rift valley of east and southern Africa and elsewhere. Fluorides can cause mottling of teeth and at elevated concentrations can cause skeletosis. Nitrates can be caused by the leaching of fertilizers into shallow groundwater and from septic systems draining to shallow groundwater, particularly in town and urban settings where septic systems are very dense. Nitrates can cause methemoglobinemia or "blue baby syndrome" in infants, in which the hemoglobin in the blood is unable to transport adequate amounts of oxygen throughout the body.

Standards for drinking water quality are set by national governments although individual organizations may establish their own internal guidelines. WHO publishes recommended limits for chemical concentrations based on health concerns. A sample of WHO guidelines for some common contaminants is found in Table 1.

Table 1

Common Groundwater Contaminants

Contaminant	Limit of human acceptability (taste/smell)	WHO guideline value	Major acceptability or health effects
Total Dissolved Solids (TDS)	1000 mg/L	N/A	Bad taste/smell
Fluoride	N/A	<1.5 mg/L	Dental and skeletal fluorosis
Nitrates	N/A	<50 mg/L	Methemoglobinemia (blue baby syndrome)
Arsenic	N/A	<0.01 mg/L	Skin, bladder and lung cancer
Fecal (E.coli) bacteria	N/A	0 mg/L	Gatrointestinal distress, intestinal infections

Source: Adapted from WHO (2006), Guidelines for Drinking-Water Quality, Vol. 1, 3rd ed.

Microbiological Contaminants

Many types of bacteria, viruses, protozoa, worms, and other organisms that live in water are known to cause disease in humans. Because a few of these organisms can multiply in the body and make a person ill, and a contaminated water source has the potential to infect great numbers of people, microbiological water quality is of paramount concern.

Organisms that make people sick are called pathogens. Because most waterborne pathogens come from human and animal feces, it is important to keep feces out of water supplies. The bacterium E. coli is found in human and animal feces and is used as an indicator for fecal contamination. Water that is contaminated with E. coli is probably also contaminated with other, more harmful, pathogens, thus the presence of E. coli is an indicator organism of pathogens. Field tests for E. coli measure the number of bacteria per volume of water. WHO water quality guidelines recommend that drinking water contain no E. coli or other fecal coliforms.

It should be noted that bacterial contamination of wells from human and animal wastes causes the most significant impacts on human health. Examples include a variety of intestinal infections including dysentery, cholera, typhoid, and hepatitis.

Drinking water wells need to be constructed with a sanitary protective seal of cement grout between the drilled borehole and well casing. This seal prevents surface contaminants, especially bacteria, from migrating (seeping) down the well between the casing and the borehole into the groundwater.

It is also important that drinking water wells be sited at safe distances from subsurface wastewater disposal systems (septic systems) and other land uses that can impact groundwater quality. Sources of pollution include workshops, fuel storage and dispensing facilities, garbage dumps and landfills, agricultural products and chemical storage areas, and areas of industry and manufacturing.

Principal water quality parameters, such as total coliform and fecal coliform bacteria, nitrates, and total dissolved solids, should be monitored on a routine basis. Quarterly or semi-annual monitoring is recommended for fecal coliform bacteria, while for total dissolved solids and nitrates, less frequent monitoring (i.e., annual or biannual) is usually sufficient. If fecal bacteria are found to be present in a water source, then corrective action should be implemented. This could take the form of (a) disinfecting the well with a chlorine solution and then retesting, (b) repairing the wellhead where water might be seeping/infiltrating into the well between the casing and the borehole, or (c) treating the water in the home or at the wellhead.

PART II: WELLS AND BOREHOLES

2.1 Selection of Well Sites

Several factors influence the selection process for the siting of wells. The availability of groundwater aquifers within or near a community is a factor, but just as important are community politics and factors influencing sustainability. The best site for a well is one that does not disrupt the social norms of a community and at the same time provides reasonable access and safe and sufficient quantities of water for the inhabitants.

Community Needs

Cultural norms are often difficult for outsiders to understand; therefore community members should be involved at all stages of well planning to ensure that the community will accept the new facility. Wells should be located on public grounds as close as possible to the users. Wells built on private property may cause problems of access and ownership between landowners and users. Wells built too far from the population or in dangerous parts of town could expose people to dangers when they fetch water. Because women and girls carry most of the water, the well should be in a place accessible to them and where they feel secure. The best way to determine this is to have the women participate in the selection of the well site.

Quantity of Water Needed

Public health in communities is greatly affected by both access to water sources and usage of water in households. WHO defines basic access to water to be at least 20 liters of water per person per day within one kilometer of the dwelling. It also recognizes that increasing the amount of available water can improve hygiene practices and reduce public health risks in communities. WHO does not set a daily minimum quantity of water per person, but uses a sliding scale that relates the level of service of household water use to public health risk, as shown in Table 2. Development agencies and communities are advised to recognize this relationship and work to improve public health by increasing the quantity of available water.

Table 2

Service Level and Quantity of Water Collected

Service level	Distance/time	Likely volumes of water collected	Public health risk from poor hygiene	Intervention priority and actions
No access	More than 1 km/ more than 30-min round trip	Very low—5 liter per person per day	***Very High*** Hygiene practice compromised Basic consumption may be compromised	***Very High*** Provision of basic service Hygiene education
Basic access	Within 1 km/ within 30-min round trip	Average—20 liter per person per day	***High*** Hygiene may be compromised Laundry may occur off plot	***High*** Hygiene education Provision of improved levels of service
Intermediate access	Water provided on-plot through at least one tap (yard level)	Average—50 liter per person per day	***Low*** Hygiene should not be compromised Laundry likely to occur on plot	***Low*** Hygiene promotion will yield health gains Encourage optimal access
Optimal access	Supply of water through multiple taps within the house	Average 100–200 liters per person per day	***Very Low*** Hygiene should not be compromised Laundry will occur on plot	***Very Low*** Hygiene promotion will yield health gains

Source: Howard & Bartram (2003) as cited in WHO (2006), Guidelines for Drinking-Water Quality, Vol. 1, 3rd.

In emergency situations, The Sphere Project guidelines recommend that each person receive an average of 15 liters of water per day (4 gallons per day) to be used for drinking, cooking, and personal hygiene. The Sphere guidelines are written for humanitarian emergencies, however, and should be taken as the minimum amount of water necessary to sustain critical health and survival needs. As noted above, greater quantities of water are required for development. CRS development projects that have a drinking water component usually provide a minimum of 20 liters/capita/

day but plan for larger quantities when possible. Depending on climate and individual physiology, The Sphere Project breaks down basic water needs as shown in Table 3.

Table 3
Simplified Table of Basic Survival Water Needs

Water needs	Amount of water	Influencing factors
Survival needs (drinking water and food)	2.5–3 liters per day	Climate and individual physiology
Basic hygiene practices	2–6 liters per day	Social and cultural norms
Basic cooking needs	3–6 liters per day	Food type, social and cultural norms
Total basic water needs	**7.5–15 liters per day**	

Source: Adapted from The Sphere Project. Humanitarian Charter and Minimum Guidelines in Disaster Response. Sphere Project, Geneva, 2004.

Well Yields

The amount of water available from a well depends on properties of the aquifer and construction of the well. Pumps are discussed in detail in Section 8.0. It is important to note that the maximum pumping rate for a hand pump is 3.5 cubic meters of water per hour (925 gallons per hour).

Geology

Exploring for groundwater requires skill and experience. An in-depth guide on how to explore for groundwater is beyond the scope of this document; however, observing several basic features of the landscape can help. Existing wells are a good indicator of the presence of groundwater. Groundwater is also usually found near surface water or in low-lying areas such as valleys. Some types of vegetation can also indicate the presence of groundwater. Local knowledge and scientific expertise can both be used to determine the most likely places to dig or drill.

Finding groundwater requires skill and experience.

A variety of technologies are available to assist in finding groundwater:

- Satellite imagery
- Aerial photography
- Field surveys of existing wells and springs

- Ground and down-hole geophysics
- Aquifer recharge and water balance calculations
- Water level measurements and preparation of groundwater flow maps
- Installation of test and observation wells
- Aquifer pumping tests
- Specific capacity tests on individual wells

The decision to use one or more groundwater exploration technologies will be influenced by the needs of the community, costs, and characteristics of each location.

Well Upgrades

If a community is already using wells, one solution to increasing water quantities as well as quality is to simply upgrade existing wells. Upgrades may include digging the well deeper, lining the well, disinfecting it, and covering it with an apron, collar and lid and installing a pump.

Data Collection

It is important to collect data on well locations, types of soil material excavated, depth to the bottom of the well, depth to the static level of water in the well, and well yield. This data can be used for planning future groundwater projects and evaluating the impact of current projects.

Pollution

It is imperative that wells are located uphill from sources of groundwater contamination such as latrines, septic systems, dumps, fuel stations, and oil storage tanks. Wells should be at least 30 meters (100 ft) from latrines and septic systems, and as far as possible from fuel and chemical storage and dispensing areas.

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2.2 Well Construction and Protection

Humans have long known the value of developing groundwater sources—hand-dug wells date from prehistoric times and are frequently mentioned in the Bible. Over 1,500 years ago well-digging technology advanced when the Chinese developed hand-powered drilling machines. Drilling rigs similar to those used by the ancient Chinese are in use today.

Hand-Dug Wells

Hand-dug wells can be constructed with local expertise and materials in both unconsolidated (sand and gravel) and bedrock aquifer systems. They are a good option in areas with relatively shallow water tables. Construction is more labor-intensive and therefore more time-consuming than drilling a borehole. Large diameter wells, termed "dug wells", are usually dug by hand using shovels and other tools. Workers stand in the bottom of the well and dig while other workers at the surface haul the loosened soil up and out of the well. Hand-dug wells typically range from one to three meters (3 to 10 feet) in diameter and usually extend to depths of less than 30 meters (100 feet) deep, although some are known to be 80 meters (260 feet) deep.

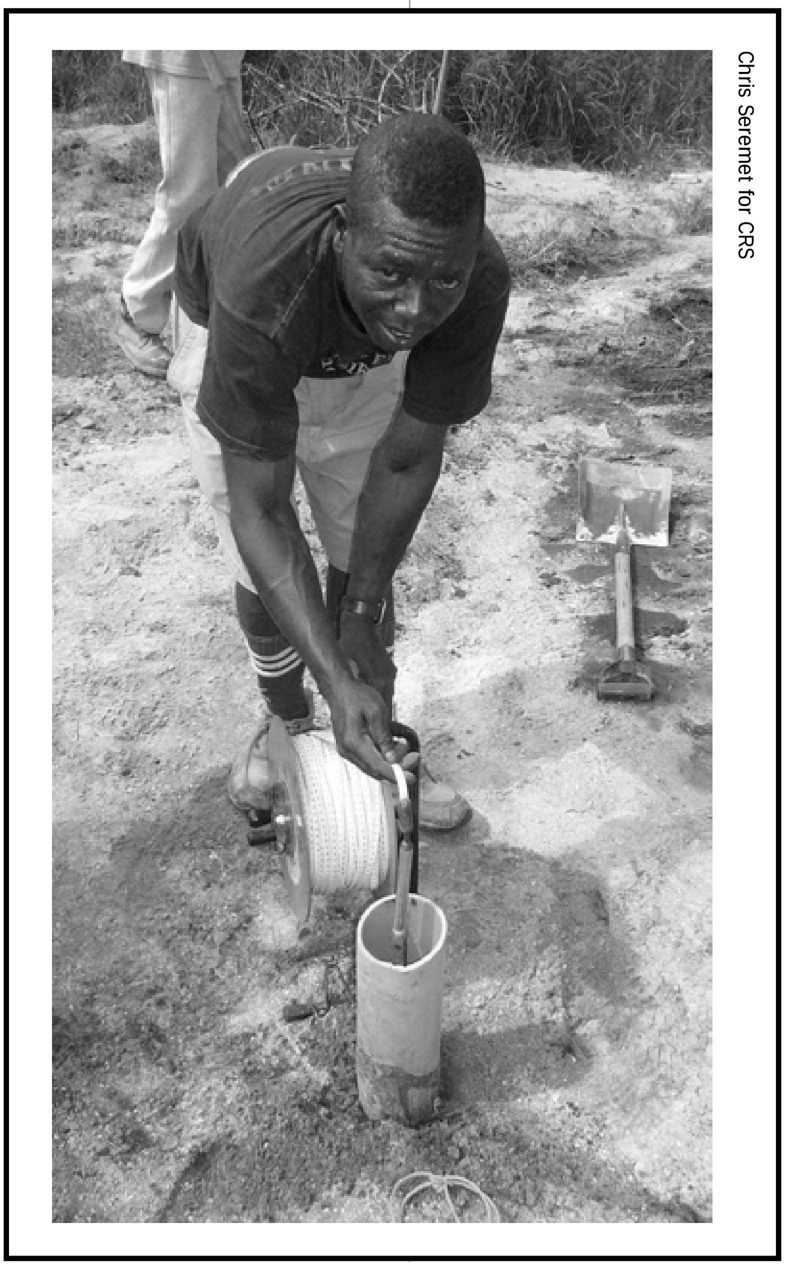
A man digging a well in sandy soil in Namibia.

Hand-dug wells in soft soils must be lined to prevent the walls from collapsing. Lining material can be reinforced concrete rings, stones or brick. No lining is needed in stable soils or bedrock. Digging may be difficult or impossible in rocky areas. It is also difficult to dig deeply into an aquifer by hand because once the aquifer is reached, the well starts to fill with water. Typical hand-dug wells usually reach only the upper part of an aquifer. Fluctuations in the water table during the dry season usually cause these wells to become dry. To remedy this problem, wells can be dug deeper in the dry season, or the inflowing water can be continually pumped during the time of construction. Care must be taken if engine-driven pumps are used to dewater the well. The engine exhaust must be prevented from entering the well and causing low-oxygen conditions when workers are deepening the well. Serious injury or even death may occur if this is not observed.

Drilled Wells

Drilled wells, also called boreholes, can be completed in unconsolidated sand and gravel aquifer systems and in bedrock aquifer systems. More information on aquifers can be found in Appendix C. Factors to take into consideration for a drilled well construction project include proper well siting, sanitary well construction, and well completion that is protective of the wellhead.

Boreholes, or tube wells, are typically 150 to 300 millimeters (6 to 12 inches) in diameter and are constructed either with hand augers or engine-powered drilling rigs. Boreholes can be constructed more quickly and can go deeper than hand-dug wells, which enables them to reach deep aquifers. For hand pump installations, the practical maximum depth to the static water level is 150 meters (500 feet) as pumping by hand is very difficult at this depth. The depth to the bottom of the borehole however, can be much deeper. Boreholes are lined with a casing (PVC or steel pipe) to prevent collapsing, as well as to prevent surface water from entering the well. A well screen is installed at the level of the water-bearing materials to allow groundwater to enter the borehole.



r in a small-diameter bored well in Sudan.

Well Protection

Wells are easy routes for surface pollution to enter into groundwater and care must be taken to ensure this does not happen. All wells used for providing water for consumption should be covered and equipped with a pump. Open wells should only be used for watering gardens and animal and industrial uses. A cover on the well prevents dirt, drainage water, or other forms of pollution from entering and serves as a base for installing a pump.

It is equally important that the well casing be properly sealed (cemented) to prevent surface contamination from entering the annulus between the well borehole and well casing. This is often overlooked in the well construction process as the casing annulus can serve as a major pathway for harmful bacteria to enter the well water.

Dennis Warner for CRS

A bored well installed with a handpump, concrete apron, and concrete spillway in Sudan.

Many hand dug wells are vulnerable to contamination because they are constructed without a cover and a pump . People commonly lower buckets or other containers by rope into open wells to draw water. This method greatly increases the chance of well contamination because buckets and ropes usually come into contact with the ground during handling and storage. Boreholes are typically fitted with a pumping system that can be powered by a variety of methods—hand, diesel, gas, electricity, wind, or solar. These same types of pumping systems can be installed in a properly designed and constructed hand-dug well.

Chris Seremet for CRS

A rope and bucket system used to retrieve unsanitary groundwater from an uncovered hand dug well in Senegal.

Protective measures for boreholes are generally the same as with dug wells. The well should be sited away from sources of groundwater contamination and the wellhead and platform should be constructed to prevent surface contamination from entering the well and to provide a well-drained and hygienic area for the community to collect water.

Wells should be disinfected with chlorine after construction and on a regular basis thereafter.

Community education is very important to prevent contamination of the well by ensuring that the well and pumping system are properly maintained, the apron is kept clean, and wastewater is properly drained.

Additional information for constructing, operating, and maintaining hand-dug wells and boreholes can be found in the CRS Water Supply and Sanitation Technical Reference Library DVD.

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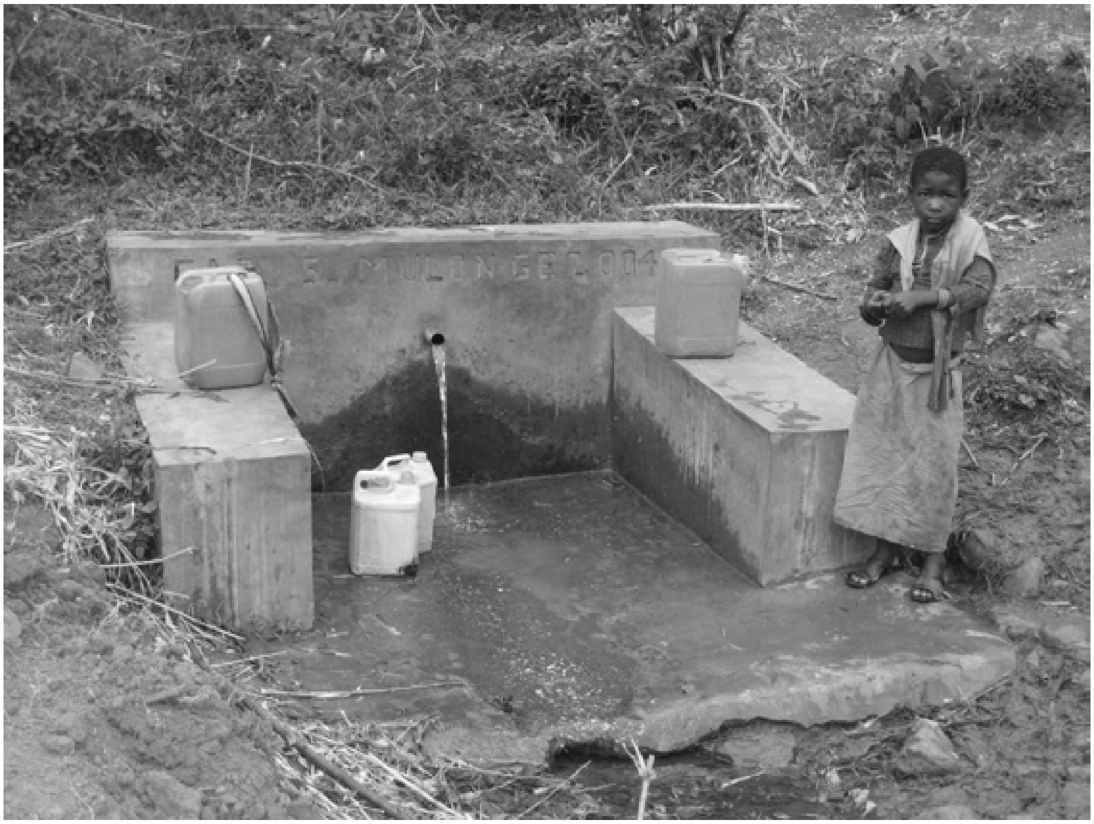
Springs

Springs represent an outcrop of the groundwater table, where groundwater expresses itself at the surface. Springs are generally more prevalent in hilly and mountainous terrains, and where rainfall is relatively plentiful. However, there are many documented springs in arid landscapes, for example, at desert oases. In mountainous areas, springs often can be developed as gravity systems, thus avoiding the need for pumping equipment. Springs also can appear when an overlaying layer of consolidated material (rock) creates significant pressure that forces the groundwater to the surface where it forms an artesian well. The rate at which water flows from a spring depends on the amount of water in the aquifer and the amount of pressure being applied by the weight of the consolidated material. This flow may vary seasonally.

Springs represent an outcrop of the groundwater table, where groundwater expresses itself at the surface.

Springs need only minor development to become good water sources. Because water flows freely from a spring, pumping mechanisms are usually not needed. The prospects for sustainability are usually better if pumping systems, which generally require skilled maintenance, can be avoided.

The biggest threat to spring water quality is from contamination by humans and animals. Contaminants, especially feces, can wash into the spring and introduce disease-causing organisms in the water. In order to prevent contamination, springs can be protected by building an enclosure, termed a "spring box," around the spring that is fitted with an outlet pipe. The area surrounding the spring should be fenced to keep humans and animals from contaminating or damaging it. A drainage ditch to protect the spring from rainwater runoff should be dug around the spring outside the fence. The area where the community draws water should have a clean apron and proper drainage for wastewater.



Dennis Warner for CRS

A protected spring water source in Eastern Congo.

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Borehole Drilling Techniques

Several different drilling techniques can be used to install boreholes. The best technique for any specific situation is determined by soil type.

Percussion drilling was one of the earliest drilling techniques developed. A drill bit is attached to a cable or shaft, which is raised by a winch and allowed to fall into the borehole. This process is repeated and the bit slowly chisels its way into the ground. The bit must be withdrawn periodically in order that loose soil and rock chips can be removed from the hole with a bailer (bucket). This process is also called cable-tool drilling.

Andrew McConnell for CRS

A rotary drilling rig using mud slurry to prevent the well from collapsing in Ethiopia.

Auger or rotary drilling uses a drill bit that turns as it plunges downward through the soil. Soil and chips of rock are brought to the surface by the drill bit and shaft.

Rotary percussion drilling uses an auger that also moves up and down in a chiseling motion. This is a powerful technique used to drill through rock and other hard materials.

Air, water, or a mud slurry are sometimes added to the drill shaft to cool and lubricate the drill bit, to help the bit break up soil, and to carry the soil to the surface. The slurry can be added through a hollow drill shaft and pumped out the hole, or sent down the hole and pumped back out the shaft. This process is called jetting, sludging, or flushing.

Just as different styles of drilling are appropriate for different soil types, different drill bits can be used on the same drill for different types of soil. Experienced drill operators will know which drilling method and drill bit to use in different soil and rock materials.

Drilling techniques suitable for use in various geologic conditions are identified in Table 4. The resource inputs and performance outputs of different well construction technologies are summarized in Table 5.

Table 4

Summary of the Appropriateness of Well Construction Technologies

	Hand digging	Hand drilling	Cable-tool rig	Air flush rotary	Multipurpose rotary
Cost (1000 US dollars)	1	1–5	20–100	100–150	200–500
Operating costs	Very low	Low	Low	Medium	Very high
Training needs for operation	Very low	Low	Low	Medium	Very high
Repair skills	Very low	Low	Low-medium	Medium	Very high
Back up support	Very low	Low	Low-medium	Medium	Very high
Meters dug per day	0.1-2	1-15	1-15	20-100	20-100
Small diameter wells in unconsolidated formations	Impossible	Fast	Fast	Impossible	Very fast
Larger diameter wells in unconsolidated formations	Slow	Slow	Fast	Impossible	Very fast
In semi-consolidated formations	Slow	Impossible	Fast	Impossible	Very fast
In consolidated formations	Very slow	Impossible	Slow	Impossible	Very fast

Source: Adapted from Wurzel, P. (2001). Drilling Boreholes for Handpumps. Working Papers on Water Supply and Environmental Sanitation / Vol. 2. St. Gallen, Switzerland: SKAT.

Table 5

Drilling Method Selection for Different Soil Types

Soil type		Hand digging	Hand-auger drilling	Percussion drilling	Jetting/ Sludging	Rotary Percussion drilling	Rotary drilling with flush
Gravel	Unconsolidated formations	OK	No	*OK?*	*No*	OK?	No
Sand		OK	OK	OK?	OK	OK?	OK
Silt		OK	OK	OK?	OK	OK?	OK
Clay		OK	OK	OK-slow	OK	OK-slow	OK
Sand w/rocks		OK	No	OK?	No	OK?	No
Shale	Soft to medium consolidated formations	No	No	OK	No	OK-slow	OK
Sandstone		No	No	OK	No	OK	OK
Limestone	Medium to hard consolidated formations	No	No	OK-slow	No	OK	OK-slow
Igneous		No	No	OK-slow	No	OK	No
Metamorphic		No	No	OK- v. slow	No	OK	No
Rock with fractures		No	No	No	No	OK	OK
Above water table		OK	OK	OK	?	OK	OK
Below water table		No	?	OK	OK	OK	OK
Note: OK—OK to drill; OK?—possible borehole collapse; ?—possible problems; No—not possible to drill							

Source: Adapted from Elson, R.J., & Shaw, R.J. (1995). Technical Brief No. 43: Simple Drilling Methods. Waterlines: Journal of Appropriate Technologies for Water Supply and Sanitation, 13 (3), 15-18.

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Wurzel, P. (2001). *Drilling Boreholes for Handpumps*. Working Papers on Water Supply and Environmental Sanitation / Vol. 2. St. Gallen, Switzerland: SKAT.

Power Sources for Drills

Well-drilling rigs can be powered by physical labor or by machines. Deep wells, especially those over 100 meters (330 feet), are always drilled with machine-driven rigs. Hand drilling may use human or animal power and usually requires more time than machine drilling. Machine-drilled wells, however, require costly drilling equipment and energy sources (diesel or gasoline) and may not be the best option in villages with relatively shallow groundwater tables and plentiful supplies of labor. Engine-powered drilling rigs can cost from $100,000 to over $1,000,000, depending on the capacity of the equipment. Hand- or animal-powered equipment costs a fraction of this total and often can be locally manufactured.

One major benefit of using local labor to drill a well is the need to generate significant participation of the community at all phases of the project. This involvement helps the community develop a sense of ownership toward the resulting facility. Once established, this sense of ownership provides a base for long-term maintenance and sustainability of the well.

One major benefit of using local labor to drill a well is the need to generate significant participation of the community at all phases of the project.

Borehole Development

Once a borehole is drilled and water is found, several steps must be taken to develop the well. These include a determination that the amount of groundwater is sufficient for the needs of the community and that adequate measures have been taken to prevent the collapse of the borehole and to improve the water flow from the aquifer.

Determining the proper depth. Once water is found, the flow rate should be measured and, if insufficient, the well should be deepened until the desired flow rate is achieved. The well then should be drilled up to an additional 10 meters (33 feet) to account for seasonal variances in the water table. Drilling time costs money and drilling wells unnecessarily deep can be wasteful.

Measuring water flow. It is important that water from an aquifer flows into a borehole at a rate that is sufficient to serve the community's water needs. A pumping test is conducted to measure this rate. The flow rate is determined by pumping the water at a high rate until the groundwater table stops declining and remains stable. The flow rate is calculated by dividing the volume of water pumped by the pumping time.

Developing the borehole. Water should be overpumped from the borehole for 2 to 24 hours. This procedure creates a rapid flow through the aquifer and into the borehole that removes soil and sediment from the region immediately surrounding the pump intake. Sometimes gravel is added to the bottom of the hole to aid the flow of water and to help filter it. A pipe or tube, called a casing, typically 8 to 12 inches in diameter, is inserted in the borehole to keep it from collapsing. The bottom section of the pipe has a screen, which is perforated with holes or slots, to allow water to enter the well.

SOURCES

WaterAid. "Hand dug wells." Retrieved from http://www.wateraid.org.uk/site/in_depth/technology_notes/297.asp

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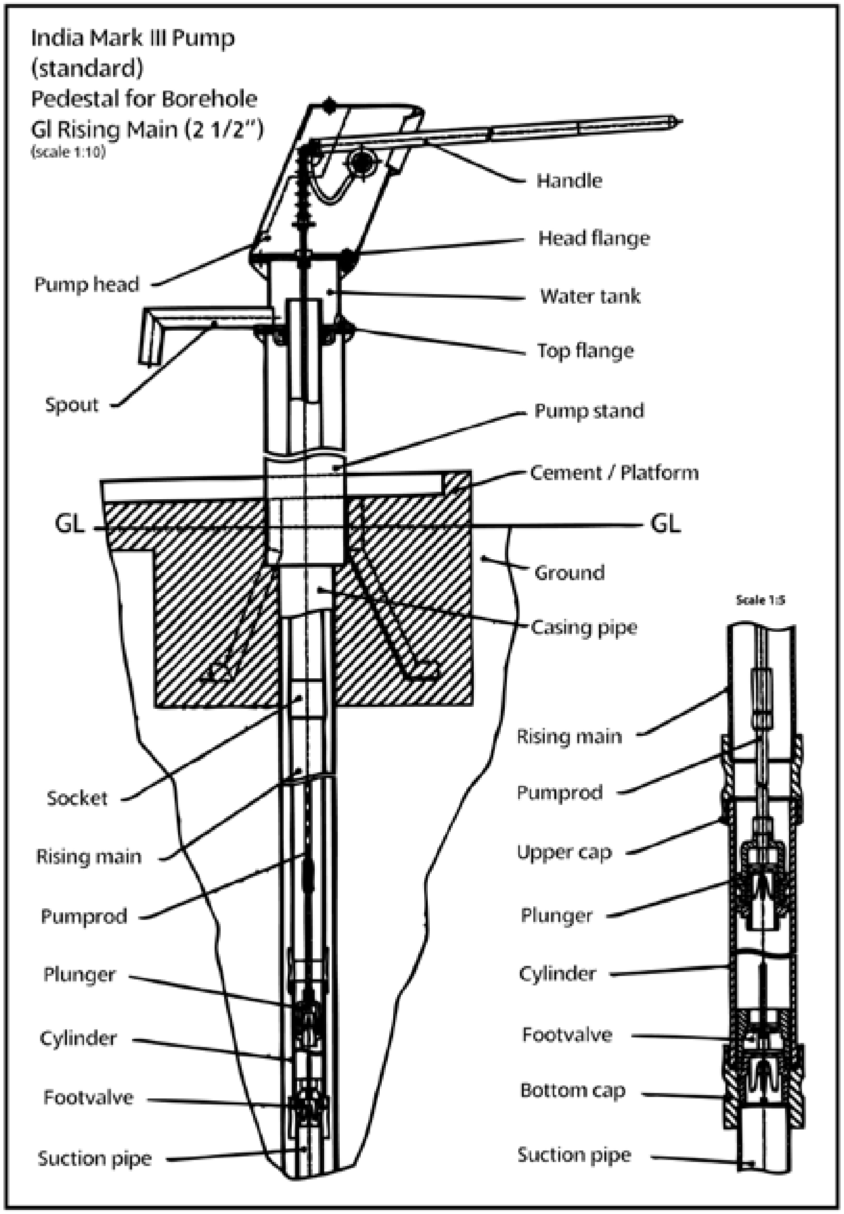
Elson, R. J., & Shaw, R. J. (1995). "Technical Brief No. 43: Simple Drilling Methods." *Waterlines: Journal of Appropriate Technologies for Water Supply and Sanitation, 13* (3), *15–18.*

2.3 Pumps and Power Systems

Traditionally, a container, such as an animal skin bag or bucket, is tied to a rope and lifted by hand or windlass to extract water from a well. Because it requires an uncovered well, the bucket and rope system makes the well vulnerable to contamination. This method is also inefficient and time consuming, especially with deep wells. Pumps, which are mechanical devices for lifting water, can supply greater quantities of water than traditional bucket systems and enable wells to be sealed off from outside contamination.

All pumping systems have two main components—the pump and the power supply. The pump is what physically lifts the water, while the power supply provides energy to operate the pump. Pumps move water either by creating suction in a pipe that draws water up the well or by lifting the water through force applied to the pipe at the bottom of the well. Because of the limitations of atmospheric pressure, suction pumps can operate to maximum depths of only 6 to 8 meters (20–25 ft). Beyond this depth, lift pumps must be used. A schematic drawing of a lift pump with a cylinder and piston manually powered by hand, called the India Mark III handpump, is shown in Figure 1.

Figure 1: India Mark III Pump



Dennis Warner for CRS

An India Mark III handpump used in a village in Madagascar.

The power supply to create the suction or to physically lift the water can be provided manually by humans or animals, or it can be converted from electricity, solar energy, gravity (falling water), wind, or the heat of combustion of hydrocarbons. Hand-operated pumps are the most common manual pumps and can function to well depths of up to 50 meters (165 feet). Electric- or diesel-powered pumps are the most common pumps used for deep wells.

Several types of pumps and power systems typically used in CRS water projects are discussed next.

VLOM Pump Concept

There are numerous manufacturers and models of pumps and power systems used to operate pumps and, often, several different systems may be equally appropriate for any one situation.

For sustainability purposes, however, it is important to select one system and use that system exclusively in the same geographical region. Standardization of pumps ensures that spare parts will be available and easy to find in the region. It also ensures that more people in the region will be familiar with that system and able to repair it. This arrangement pools resources among villages to solve problems. When different pumping systems are installed in different villages, repairmen and parts are of little value outside of their own village.

The main problem with hand pumps is sustainability. If local people are not trained to repair a pump, they must continually depend on the agency that installed it or a government institution to repair it when required. In this case local people may abandon the well and revert to older, less safe water sources.

Before the 1980s, hand pumps were generally light-weight, low quality, and imported from developed countries. Since they were designed for single family use, they often broke down under the heavy community demands in developing countries. When this occurred, rural people had difficulty finding spare parts and repair technicians to fix the pump.

In the 1980s the United Nations (UN) put enormous effort into groundwater development. The United Nations Development Programme (UNDP) and World Bank determined that large and complicated pumping systems could not be maintained with limited village-level resources, so they promoted the design of a new style of pump called the VLOM pump—the village-level operation and maintenance (VLOM) pump.

The criteria for VLOM pump designs are (Arlosoroff 1987):

- They should be able to be easily maintained by a village caretaker with few tools
- They should be manufactured in the country where they are used
- Spare parts should be readily available

...select one [pumping]system and use that system exclusively in the same geographical region.

- They should be durable
- They should be inexpensive to build and maintain

The India Mark III is a popular type of VLOM hand pump. With piping and essential spare parts this pump costs about $450 to $500.

Types of Pumps

There are two classifications of pumps. They are positive displacement pumps and variable displacement, or kinetic, pumps. Positive displacement pumps discharge a fixed volume of water for each stroke or revolution. Variable displacement pumps discharge less water as the pumping head, or the distance between the water surface in the well and the vertical height to the discharge point, increases. CRS water projects typically incorporate *positive displacement pumps*. This type of pump is discussed in more detail below.

The two most common types of positive displacement pumps are *reciprocating action pumps* and *rotary action pumps*.

Reciprocating action pumps use pistons, plungers, diaphragms, or bellows to lift the water from inside the well to the surface.

Many engine-driven and hand-operated pumps work on a piston-and-cylinder design. The cylinder is suspended from the top of the well, stationary, and has a one-way foot valve near the bottom. The piston has a one-way check valve at the bottom and moves up and down inside the cylinder. The check valve is open when the piston moves downward, which lets water pass up through the valve to the area above the piston. When the piston is raised, the valve closes and the piston lifts the water. At the same time as the piston is lifted, the foot valve at the bottom of the cylinder opens and water flows into the cylinder below the piston. This water flows through the piston valve when the piston is pushed downward again and the process repeats. This type of reciprocating action pump is used in aquifers where the depth to groundwater is greater than 7 meters (23 feet). The *India Mark III, Afridev,* and *Volanta* pumps are three styles of reciprocating action hand pumps that use a piston to lift water.


Dennis Warner for CRS

An Afridev handpump in use in Sudan.

Another type of reciprocating action pump is the *suction pump.* The cylinder and piston in suction pumps are in the head of the pump, above ground level. An advantage of these pumps is that they are easy to fix because the working parts are above ground. A major disadvantage is that if the cylinder needs to be primed, or filled, with water, contamination may be introduced into the well. These kinds of pumps are typically used for taking water out of large-diameter wells for gardening or livestock watering uses.

Dennis Warner for CRS

An Volanta handpump installed in Niger.

Suction pumps can only create suction large enough to pull water to a height of about 7 meters because of the limitations of atmospheric pressure. The atmosphere exerts pressure on the surface of water in a well and at the top of an aquifer. When a pipe is inserted into the water and suction is applied at the top of the pipe, the atmosphere pushes down on the water surface and between the atmospheric pressure pushing and the suction pulling, the water rises through the pipe. At about 7 meters, the push of the atmosphere is no longer sufficient to help raise the water. Thus the water level in the pipe cannot go higher than about 7 meters.

For wells deeper than 7 meters, the piston and cylinder must be located in the bottom of the well. These pumps push water up the casing from the bottom rather than sucking it up from the top, and thus the atmosphere and suction are not limiting factors.

Another type of reciprocating pump is the diaphragm pump. The Vergnet pump is a commonly used model. These pumps operate by the alternate

Chris Seremet for CRS

A locally-manufactured suction pump in Niger.

expansion and contraction of a reinforced rubber bladder positioned within a large cylinder at the bottom of the well. The expansion and contraction of the bladder is controlled by hydraulic pressure as applied by the user's foot or hand. The *Vergnet foot pump* schematic is shown in Figures 2-2b.

Figure 2: Vergnet Hydropump Schematic

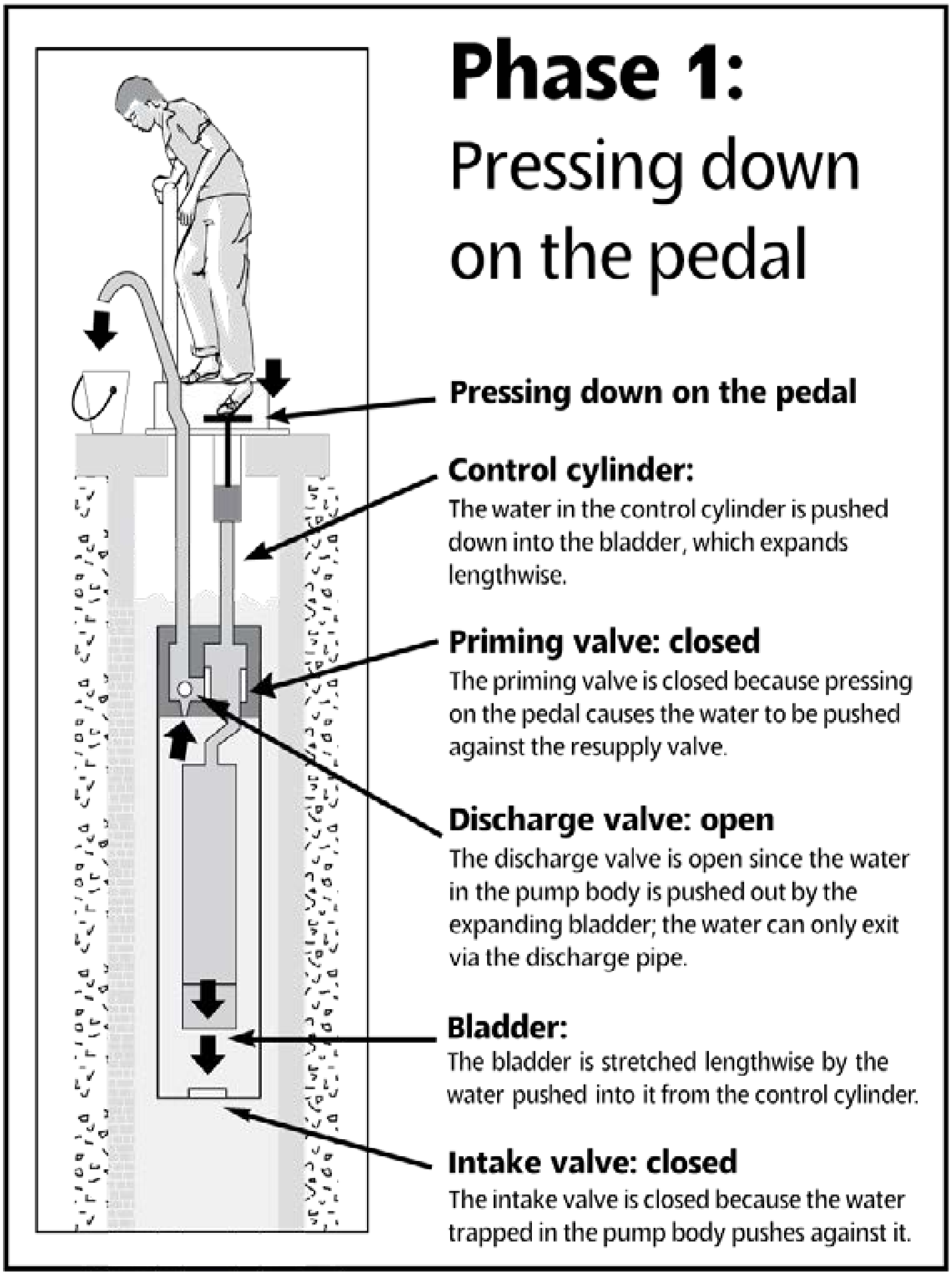
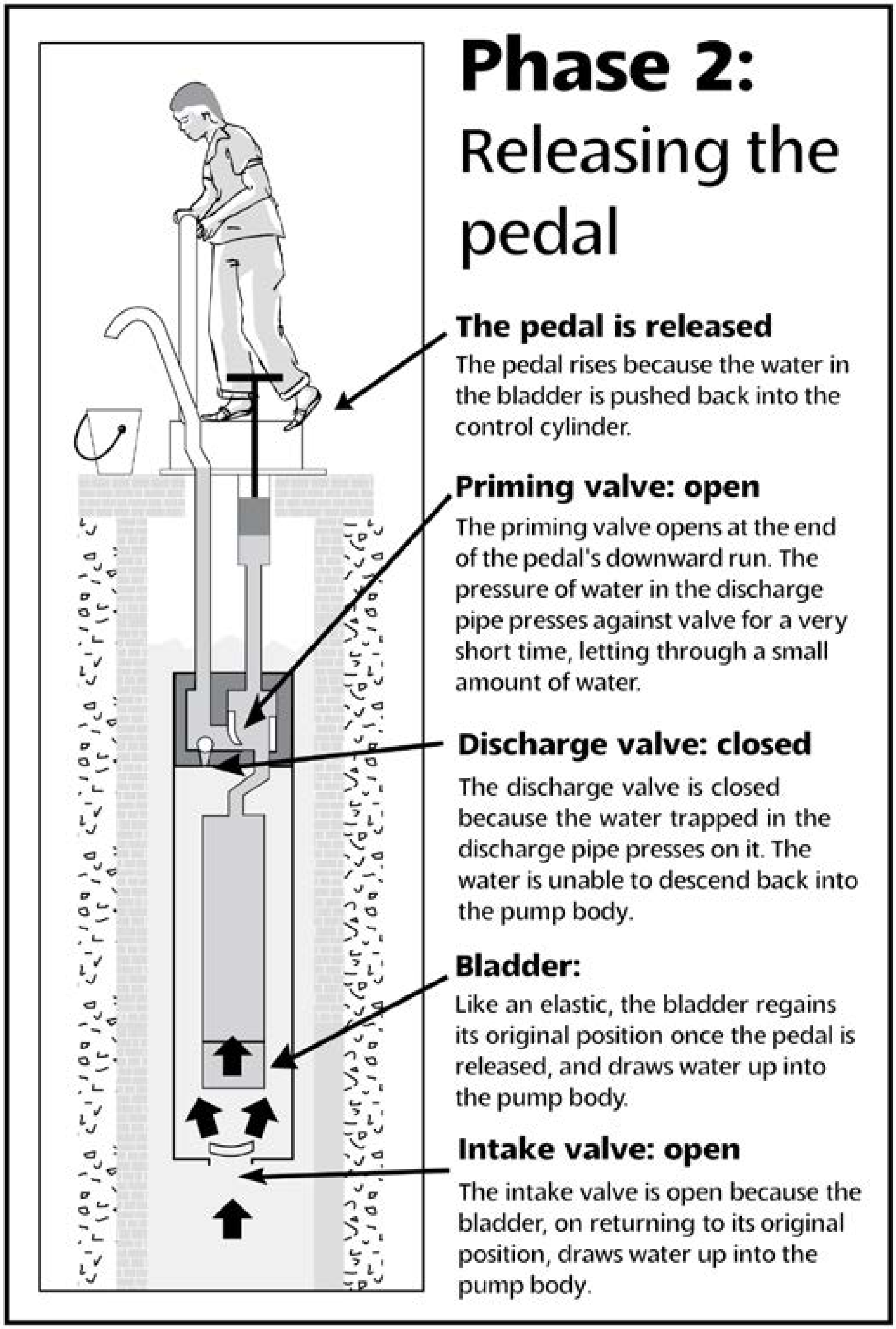


Figure 2b: Vergnet Hydropump Schematic



Rotary action pumps use impellers/vanes, screws, lobes, or progressing cavities to lift the water. As the device turns, it propels water up the casing and to the surface. Wells deeper that 100 meters (330 feet) are usually operated by engine-driven rotary action pumps.

Helical pumps are a type of rotary pump and operate like long screws. As the screw turns, water becomes trapped in cavities between the screw and the casing and is lifted to the surface. The Mono pump is a type of helical rotary action pump.

Types of Power Systems

Hand pumps

Hand pumps are inexpensive, easy to install, simple to operate and ideally can be maintained at low cost by local technicians. There are two basic types of hand pumps—*lift pumps* and *suction pumps*. *Lift pumps* are ideal for households and villages where the groundwater is found at considerable depths, generally 7 to 40 meters. *Suction pumps* are suitable for wells where the groundwater is close to the surface, usually a maximum depth of 7 meters. Different hand pumps are designed to lift water from different depths, so it is important to choose the pump design that corresponds to the depth of the well. A list of common pump types and their operating characteristics is shown in Table 8 on page 48.

Direct-action pumps have a handle attached directly to the piston—no leverage is used and the operator is essentially grasping the piston and moving it up and down. Because no lever is used, these pumps are best suited for shallow wells where a small amount of effort is sufficient to lift the water short distances. These pumps have very simple designs and are inexpensive.

Intermediate- and high-lift reciprocating pumps use levers or other mechanisms as a mechanical advantage to help the user operate the pump by hand. The lever is the pump handle. Because considerable effort is required to lift water from greater depths, the lever eases the burden on the pump operator. The India Mark III and the Afridev pumps use lever handles. Flywheels mounted vertically or horizontally on the pump can be used instead of levers. The pump operator turns the flywheel and this action is mechanically converted into an up-and down motion that drives the pump. The Volanta pump uses a flywheel to operate the pump.

TABLE 6

COMPARISON OF PUMPS

Pump type	Rope and bucket	Suction	Positive displacement	Helical	Turbine/ centrifugal	Diaphragm	Submersible centrifugal (“submersible electric”)	Hydram
Energy Source(s)	Hand, Animal	Hand	Hand, Wind, Animal	Engine, generator, power lines, solar	Engine w/drive shaft	Hand, generator, power lines, solar	Generator, power lines, solar	(Water)
Capacity Range (l/min)	7	15	15 to 30	100	120 to 360	15 to 60	40 to 240+	15
Targeted people per source	150–200	150	300 (up to 2,000 for windmills)	1,000–5,000	500–5,000	300–2,000	1,000-5,000 (fewer for solar)	---
Maximum well depth (m)	20—80	7	50 (up to 100 for windmills)	300	300	30–70	300 (less for solar)	Not used with wells
Required well diameter (cm)	Large, 100+	16	16	16	16	16	16	Not used with wells
Relative Total Cost	Low to medium	Medium	Medium (high for windmills)	High	High	High pump; high fuel	Medium pump; high fuel	Low to medium
Operation and Maintenance	Very simple	Simple, mechanism is above ground	Simple, needs occasional maintenance; not an issue for VLOM pumps	Both power source and pump require skilled maintenance	Both power source and pump require skilled maintenance	Both power source and pump require skilled maintenance, not energy efficient	Both power source and pump require skilled maintenance	Simple
Advantages	Very simple design, very low maintenance costs	Local manufacture is possible, easy to install and maintain; low capital costs; no fuel cost	Local manufacture is possible, easy to install and maintain; low capital costs; no fuel cost	High pumping capacity	High pumping capacity	High pumping capacity	High pumping capacity	Simple design; no energy costs
Disadvantages	High risk of contamination, can run dry	Well depth limited to 7m; low flow rates; priming can contaminate well	Energy inputs; inefficient; low flow rates	Energy costs; difficult to remove from hole for maintenance; parts may not be available	Energy costs; difficult to repair if bearings fail, parts may not be available	Energy costs; parts may not be available	Difficult to repair; high energy costs	Needs constant flow of water; cannot be used in a well

Adapted from:

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Animals can be attached to a horizontal wheel and, by walking in a circle, they can drive the pump.

Foot-Powered Pumps

The most common form of foot pump is the *treadle pump*, which is also a type of suction pump operated by alternatively stepping on first one lever than on the other. The *Vergnet diaphragm pump* uses a single foot-powered pedal to create pressure in the well, forcing water to the surface (Fig. 2-2b).

Sean Sprague for CRS

A treadle pump is used by a small boy in India.

Chris Seremet for CRS

A Vergnet footpump being operated by a woman in Mali.

Wind Power

Windmills have been used globally for many centuries. If wind is a reliable resource, these types of pumping systems may be well suited for water supply. The pumping system that is attached to a windmill is similar to a hand pump. Water can be lifted 100 meters at capacities greater than conventional hand pumps. Because wind may not be constant, water is typically pumped to a storage tank where it is retained until needed.

Animal Power

Animal-powered pumps work on the same principles as hand pumps, except that animals are used to work the pump. The most common pumping devices use animals to turn a large wheel attached to the pump, which drives the pumping mechanism. Throughout history, animals have been used to operate bucket systems to lift water. These expose wells to contamination, however, and are not recommended. Animals can do more work than humans and can thus pump more water in a day's work. Animals require feeding and care, and they may be needed for other activities such as plowing at certain times throughout the year.

Diesel Power

Diesel engines can be used to power pumps, typically rotary or helical pumps, submerged at the bottom of wells. Such pumps are driven by a drive belt or shaft connected to an engine on the surface. The drive belt or shaft from the engine is used to turn either the impeller or the screw of the pump.

Chris Seremet for CRS

A screw pump operated by drive belts turned by a diesel engine in Tanzania.

Electric Power

Electric power can be used to drive motors that move pumps. These pumps are typically located at the bottom of wells and are called submersible pumps. The motor is located inside a waterproof casing, and it drives the impeller of a turbine pump.

Electricity can be supplied by the electric grid via power lines, if available, as well as by diesel- or gas-powered generators or solar panels. Low-capacity submersible electrical pumps generally supply up to 10 liters per minute (<3 gallons per minute) and cost a few hundred dollars, while higher capacity pumps can lift a hundred or more liters per minute (30 gallons per minute) and cost several thousand dollars.

Diesel- or gasoline-powered electrical generators cost from hundreds to thousands of dollars depending on how much energy they produce. A major drawback of these systems is in their operating costs. Availability and cost of fuel may fluctuate, and any community relying on generator-powered pumps should have both present and future financial resources to operate them. Repairs can be very costly should they be required.

Solar panels avoid the problem of fuel costs, but they are expensive to purchase and complicated to maintain. Solar panels cost in the range of $5,000 to $6,000 per horsepower of energy delivered. Solar power is costly because each unit of horsepower requires additional solar panels. Electricity can be stored in batteries to ensure that the pump will operate at night and on cloudy days. Batteries and a water storage tank may be needed if the water flow from the borehole is low. During the day, the solar panels run the pump and charge the batteries, while the batteries run the pump at night. At night, the pump fills the storage tanks, which supplement pumped water during the day when water use is high.

Solar panels can be connected to electrical pumps to provide groundwater for small domestic village supplies of only a few liters per minute as well as large multi-acre irrigation projects supplying hundreds of liters per minute. Solar applications are most cost effective in areas that are not connected to a power grid and would otherwise be obliged to rely on diesel-driven pumping equipment. As noted above, solar-pumping systems cost in the range of $5,000 to $6,000 per horsepower. A one horsepower solar pump can deliver 30 to 40 liters per minute (10

Chris Seremet for CRS

Solar panels supplying power to an electric submersible pump in Mali.

gallons per minute) during the part of the day when the sun is high. Over an 8-hour sunny period, this would be equivalent to approximately 15,000 liters of water (4,000 gallons) per day.

The advantages and disadvantages of differing energy sources for powering pumps are listed in Table 7. The range of costs associated with various pumping systems is illustrated in Table 8.

TABLE 7

COMPARISON OF ENERGY SOURCES

Source	Advantages	Disadvantages
Human	• Readily available resource	• Limited pumping capacity • Opportunity cost of work
Animal	• More powerful than humans • Lower wages than humans • Dung may be used for cooking fuel	• Animals require feeding • Animals may be needed for other activities
Wind	• No fuel purchase requirements • Unattended operation • Low maintenance • Long life • Can be manufactured locally	• Water storage required for periods when wind is low • High capital costs • Difficult installation
Diesel- or gasoline-powered generator	• Quick and easy to install • Low capital costs • Widely used • Can be portable	• Fuel supplies may be erratic and costly • High maintenance costs • Short life expectancy • Noise and air pollution
Public power lines	• Uses existing infrastructure • Maintenance is responsibility of power company • Usually cheaper to connect to lines and purchase electricity than purchase diesel generators and fuel	• Maintenance is responsibility of power company • Electricity supply may not be reliable • Voltage fluctuations can damage pump motor
Solar	• Unattended operation • Low maintenance • Easy installation • Long life	• High capital costs • Battery back-up and Water storage required for cloudy periods or night use • Repairs require skilled technicians • Delivers less power than diesel generator

References: ITDG. "Solar (Photovoltaic) Water Pumping." Retrieved June 21, 2005 from the World Wide Web <http://www.itdg.org/docs/technical_information_service/solar_pv_waterpumps.pdf>

TABLE 8

PUMPING COSTS

Pump type	Targeted people per source	Investment cost (USD)	Investment cost per capita (USD)	Yearly maintenance cost (USD)	Running cost (USD per cubic meter of water pumped)
Hand-dug well*	150–200	900–1,500	5–10	15	0.06
Dug well with hand pump	200	2,400–3,000	12–15	45	0.11
Hand-drilled borehole with hand pump	300	3,600–4,500	12–15	45	
Machine-drilled borehole with hand pump	300	1,000–1,500	20	50–120	0.14
Borehole with windmill and pump	500–2,000	35,000–85,000	18–170	1,600	0.10
Borehole with electric pump	1,000–5,000	40,000–85,000	8–85	4,000	0.11
Borehole with diesel pump	500–5,000	40,000–85,000	8–170	5,000	0.22
Borehole with solar pump	500–2,000	35,000–85,000	18–170	1,600	0.10

* Water from open wells is highly susceptible to contamination and is usually not safe for drinking. The data given here only to enable a comparison with other abstraction methods, not as an endorsement of open wells.

Note: Costs are in 2001 dollars; diesel and electricity costs are most likely much higher now. Costs in Africa are considerably higher than costs in Asia, with significant variation between regions within each continent. The figures here are best used as a comparison, not as true costs that can be applied universally.

Adapted from:

- Wurzel, P. (2001). Drilling Boreholes for Handpumps. Working Papers on Water Supply and Environmental Sanitation / Vol. 2. St. Gallen, Switzerland: SKAT.
- WaterAid. “Handpumps.” Retrieved June 20, 2005 from the World Wide Web: http://www.wateraid.org.uk/site/in_depth/technology_notes/299.asp
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PART III: GROUNDWATER PROGRAMMING

3.1 Programming for Groundwater Development

An adequate and safe water supply is a critical ingredient for successful development. Initiatives to create new water supplies or to improve existing water infrastructure should be an integral part of any comprehensive rural development effort.

Debbie DeVoe for CRS

A protected water source improves people's health and livelihood.

At the village level, new water supplies can fulfill basic drinking and cooking needs, enhance healthy diets with produce from home and school gardens, and allow the expansion of small-scale cottage industries that can create livelihoods and greatly improve the quality of life. In some circumstances, major improvements can be accomplished by first testing the drinking water supply and then modifying the existing system to keep the water clean and safe. As discussed in the previous sections of this paper, utilizing groundwater for water supply has advantages that can often make it an excellent substitute, alternative, or supplement to surface water.

Some examples of groundwater programs that can make major contributions to development projects are outlined below.

Groundwater Project Planning

Experience has shown that well construction requires planning and stakeholder participation. Successful groundwater development programs for domestic as well as agricultural purposes generally contain the following elements:

1. Evaluation of the social-cultural effects of well installation and placement
2. Evaluation of the sustainability of groundwater use in a region
3. Groundwater exploration using geophysical and remote sensing exploration techniques to optimize the siting of wells and to maximize well yields
4. Consultations with local experts on well siting
5. Meetings with local stakeholders for input on the best and worst locations for the well
6. Establishment of a water committee
7. Selection and training of well-maintenance teams
8. Choosing appropriate pumping system
9. Determination of a baseline of disease incidence
10. Determination of the current availability of water
11. Well installation and construction
12. Testing of the well for yield and water quality
13. Monitoring and evaluation of water quality, water use, disease rates, and stakeholder satisfaction
14. Establishment of well-maintenance teams
15. Training for equipment operation and maintenance
16. Establishment of private sector to supply spare parts

Borehole Drilling Program Considerations

The installation of boreholes requires the use of drilling equipment. There are two approaches to utilizing this equipment in a drilling program. The first approach involves the purchase of new or used equipment if the project will be managed and operated by the development agency or implementing partner. The second approach involves subcontracting local drilling contractors for the drilling and well-development work. These two approaches are discussed below.

Purchasing Drilling Equipment

The following factors are crucial when the purchase of drilling equipment is being considered:

- The selection of appropriate drilling equipment for the anticipated geologic conditions and hydrogeologic environments is critical.
- Costs can be up to $1,000,000 inclusive of spare parts and drill bits for a single drilling rig that can operate in bedrock environments.
- Consideration should be given to the purchase of used drilling equipment. A used rig in good condition can be serviced in the USA, Europe, or in-country, and shipped to a project location with an ample supply of spare parts at a much lower cost than a new rig.
- Maintenance is crucial, and a trained mechanic and drilling supervisor need to be part of the project team.
- Project budgets need to include capital costs as well as recurrent costs, including well construction supplies (casing, cement, fuel), spare parts for the equipment, and crew and office expenses.
- Annual and long-term operation and maintenance costs should be factored into the project budget.
- A backlog of work is required for the drilling equipment to make a project economically feasible and to maintain donor interest.

Subcontracting a Local Drilling Company

Similarly, when local drilling contractors are being considered, the

Initiatives that focus on the proper operation, maintenance, and repair of existing wells are not capital intensive and can help ensure the continued operation and sustainability of entire systems.

following steps should be observed:

- The availability and competence of local drilling contractors need to be evaluated by an expert in the drilling field.
- References from past projects should be contacted.
- The contractor's estimate/bid should be evaluated on the basis of similar work performed for other clients.
- Contract documents for the proposed work need to include detailed drilling specifications prepared by an expert.
- Contract requirements should include a mechanism for ensuring the quality of the work. For example, the client should require a bond and retain a portion of the monthly payments until work is complete.
- The drilling and well-construction work should be supervised and documented in detail by a qualified hydrogeologist.

Well Repair and Maintenance Programs

Often one or more community wells may be out of service for months or years at a time. Initiatives that focus on the proper operation, maintenance, and repair of existing wells are not capital intensive and can help ensure the continued operation and sustainability of entire systems. Project sustainability, therefore, will require the organization of a village water committee, operational staff, and technical training. Continued performance monitoring and investment in good operational and maintenance procedures are absolutely essential for long-term project success.

Water Quality Testing and Public Health Programs

Poor water quality is a major cause of disease in the rural areas of the developing world. Effects of waterborne disease include debilitating illness, loss of economic productivity, poor quality of life, and sometimes death. Comprehensive rural development projects should ensure that people are drinking water that will not make them sick. To this end, there are many ways that CRS programs can improve the public health impact of existing groundwater sources of existing village water supplies. Some examples are:

- Monitoring and testing programs to identify contaminants that most directly impact community health. Water quality testing should be conducted before the water source is developed and, if the source is suitable, at regular intervals thereafter. At a minimum, monitoring and testing should be carried out on an annual basis, although it may be done more frequently if very large populations are served by the source.
- Mitigation programs, coupled with water quality testing programs, to improve groundwater source quality. Such programs should improve existing water supply sources and involve wellhead protection measures to eliminate or mitigate human-induced contamination of wells and springs.
- Hygiene education programs focused on water source protection, home water treatment and storage, and other issues relevant to improving water quality. Programs for the promotion of hygiene awareness and improved household water practices are essential for the achievement of the health benefits of groundwater development.

Small-Scale Irrigation Development Programs

Both hand-dug and shallow-drilled wells can provide water for small-scale irrigation projects. Projects that irrigate one or more acres can result in significant increases in agricultural productivity affecting income, livelihoods, and nutrition. In addition, people living with HIV and AIDS may be particularly benefited by having wells located within the community and adjacent to home gardens. Hand-dug well programs for watering home gardens can be organized at both the household and community levels by using local workers and materials.

Watershed Protection Programs

Environmental protection is important for maintaining the quantity and quality of water in an aquifer. Forests slow runoff from rain, which allows water to infiltrate the ground and recharge aquifers. Forestry projects and reforestation programs, therefore, not only provide income

Environmental protection is important for maintaining the quantity and quality of water in an aquifer.

from timber sales but also help to conserve water. Selective harvesting of trees serves to protect aquifers when some trees remain to anchor the soil and retain rainwater. Clearcutting of trees exposes the ground to the direct effects of rainfall and results in erosion, high rates of surface water flow, and very slow aquifer recharge. Programs focused on reforestation, aquifer recharge, and best practices for agriculture management within a watershed can complement water supply programs.

APPENDICES

Appendix A

Glossary of Technical Terms

Aquifer

An underground geologic formation capable of storing water.

Artificial gravel pack

Gravel and sand added to the bottom of a well to improve water flow into the well.

Auger

A drill, normally manually operated.

Bacteria

Single-celled micro-organisms.

Borehole

A narrow well constructed with a drill rig.

Cable-tooling

Technique used to drill a borehole that involves lifting and dropping a chisel-type drill bit into the borehole to pulverize rock.

Centrifugal pump

A pump that uses a spinning fan, or rotor, inside a casing to propel water through a pipe. Also called a turbine pump.

Charging aquifer

The process in which surface water or rain soaks into the earth and is stored there.

Coliform

A form of bacteria commonly found in unsanitary water.

Developing a borehole

Rapidly pumping water from a well in order to remove loose soil and to create a natural pack of sand and gravel at the bottom of the well.

Diaphragm pump

A pump that uses a rubber bellows to move water.

Disinfection

A process in which living organisms are killed, making the water safe to drink.

Fecal coliform

A collection of bacteria commonly found in human and animal feces.

Flushing

Adding air, water, or mud to a borehole to aid in its construction.

Groundwater

Water that is found beneath the earth's surface.

Helical pump

A pump that uses a rotating rubber stator inside a casing to lift water.

Immunocompromised

The state of having a weakened immune system.

Jetting

Adding water under pressure to a borehole to aid in its construction.

Mining water

Overuse and depletion of aquifers; nonsustainable exploitation of water resources.

Pathogen

Any organism that can cause disease in humans.

Pumping test

Rapidly pumping all the water from a borehole or well over a known period of time in order to determine the well yield.

Positive displacement pump

A pump in which a piston and cylinder are located at the bottom of the well.

Reservoir capacity

Property of a well that enables it to store water; the amount of water that a well can store.

Rotary percussion

Technique used to drill a borehole that involves both a rotary action and a reciprocating percussive action on the drill bit.

Sludging

Adding mud to a borehole to aid in the drilling process.

Sphere Guidelines

Recommendations for provision of minimum levels of basic health-related services in disaster response.

Submersible electric pump

A centrifugal pump powered by electricity used for pumping water from a well or other body of water.

Suction pump

A hand pump with the piston in the head of the pump that uses suction to draw water from depths of less than 7 meters.

Surface water

Water that is found above ground. Most commonly found as rivers, lakes, and streams.

Tube well

A small diameter well constructed with a drilling rig.

Turbidity

Cloudiness of water caused by suspended and dissolved solids and salts.

Turbine pump

A pump that uses a spinning fan inside a casing to propel water through a pipe; also called a centrifugal pump.

Well flow rate

See "well yield"

Well yield

The maximum rate at which water can be withdrawn from a well. It is the rate at which water flows from the aquifer into the well.

Appendix B

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Appendix C

Groundwater Fundamentals

Sources of Groundwater

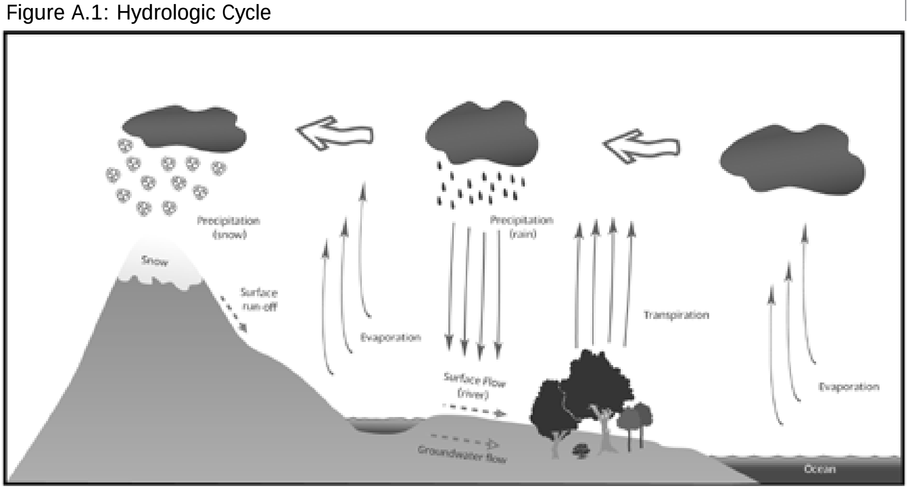
Studies of the world's water balance have shown that about two-thirds of the world's freshwater is stored as groundwater. Excluding the ice caps and glaciers, freshwater stored as groundwater comprises nearly all of the utilizable freshwater resource. It has been estimated that of the total freshwater resources, groundwater accounts for 94%; lakes, reservoirs, and river channels for 4%; and soil moisture for 2%[1].

Fresh groundwater occurs in a myriad of configurations. These range from vast regional aquifer systems such as the Nubian Aquifer (North Africa) and the Ogallala Aquifer (West Texas, Oklahoma, Kansas, and Nebraska), which extend over millions of square miles, to localized river basin systems, and tiny freshwater lenses that occur between the surface and the seawater beneath islands in the Pacific Ocean. Groundwater is a principal source of water for many villages, towns, and cities serving domestic, commercial, institutional, industrial, and agricultural users. The irrigation of crops worldwide uses more groundwater (70% or greater) than all other applications combined.

An overview of the main components of the hydrological cycle, including evaporation from the oceans and surface water bodies, surface runoff, groundwater flow, and evapotranspiration from plants is shown in Figure A.1.

A quote from McGuiness[2] captures the essence of how groundwater is distinct from surface water by virtue of its residence in underground geologic formations.

Figure A.1: Hydrologic Cycle



1 U.S. Geological Survey Water Supply Paper 2220, 1983. Basic Groundwater Hydrology by Ralph C. Heath.
2 Johnson Division, UOP, Inc. 1975. Ground Water and Wells, a Reference Book for the Water-Well Industry, p. 47.

> They [underground geologic formations] accept the water, they filter it to remove sediment and disease-causing bacteria, they store it in quantities vastly exceeding those which could be held in all natural and artificial surface-water bodies put together, they even out its temperature and chemical quality, they transport it from areas of replenishment to areas of need, and they slow down its natural discharge to the surface so that it makes up the dry-weather flow of streams.

The word aquifer is used loosely in many different connotations but the following definition conveys the fundamental meaning of the word in terms of function:

Aquifer: *A water-bearing formation which can yield water of sufficient quantity and quality to serve its intended purpose.*

The hydrogeologic characteristics of a groundwater formation, which will determine whether it may be classified as an aquifer, are based on the geologic properties of the solid matrix and the hydraulic properties of the water within it. However unique each formation is, the behavior of groundwater is governed by a set of established scientific principles. Within the aquifer, groundwater is both stored and transmitted. Darcy's Law, the basic equation describing the movement of groundwater under natural conditions, was derived by a French hydraulic engineer named Henry Darcy based on the results of a seminal laboratory experiment he conducted in 1856[3].

The concepts and analytical equations describing the dynamic behavior of groundwater being withdrawn in different types of aquifers were mainly developed by a group of scientists from the 1930s through the 1960s. Their work yielded what is considered to be the classical approach to assessing the feasibility of developing groundwater resources by understanding the response of these resources under pumping conditions.

Terms Related to Groundwater Storage

Porosity: *The porosity of a water-bearing formation is that part of its volume that consists of openings or pores – the proportion of its volume that is not occupied by solid material [normally expressed as a percentage of the*

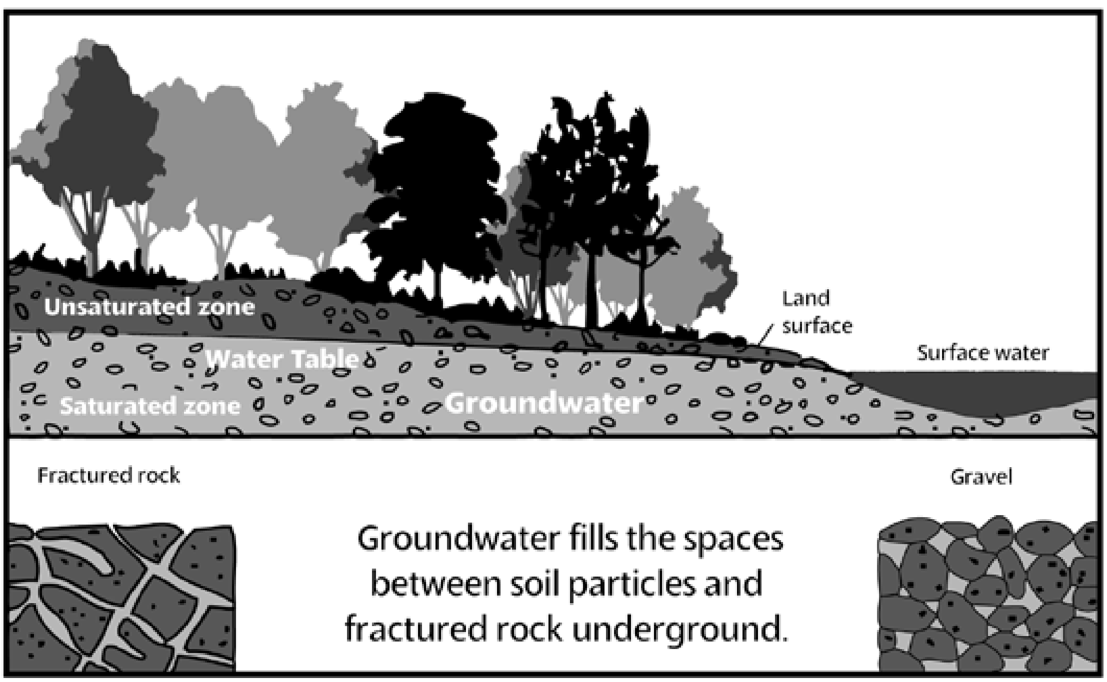
3 Freeze, R. Allan and Cherry, John, 1979. Groundwater, Prentice Hall, p. 15 and Walton, William C., 1970. Groundwater Resource Evaluation. McGraw-Hill Book Company, p. 6.

bulk volume of the material].

Specific Yield: *The quantity of water that a unit volume of the formation will give up (yield) when drained by gravity [expressed as a percent].*

Groundwater occurs in unconsolidated and consolidated bedrock geologic formations. In unconsolidated formations that are made up of porous media (gravels, sands, silts, and clays), the groundwater is stored and travels in the pore spaces between the particles. This is shown graphically in Figure A.2. In bedrock formations, the water is stored and travels in joints, fissures, and fractures in the rock, referred to as secondary porosity. As a rule, groundwater travels very slowly through its geologic matrix, often on the order of a few inches or feet per day. The rumored presence of "underground rivers" is no more than a myth in most types of geologic settings. However, limestone "karst" formations can have systems of major solution openings that comprise caverns and tunnels filled with water.

Figure A.2: Groundwater



Source: Image compliments of US Geological Survey, adapted by the Groundwater Foundation.

Not all of the groundwater in the primary or secondary porosity of a geologic formation can be extracted. The specific yield is but a fraction of the total porosity; the remaining water is retained by molecular forces acting in the formation. The difference between total porosity and specific yield in common geologic formations is shown in Table A.1.

TABLE A.1

TYPICAL RANGES OF POROSITY, SPECIFIC YIELD, AND HYDRAULIC CONDUCTIVITY IN TYPES OF GEOLOGIC FORMATIONS

Pump type	Porosity (%)	Specific Yield (%)	Hydraulic Conductivity (gpd/ft^2)
Clay, Silt	45–55	1–10	0.001–2
Sand	35–40	10–30	100–3,000
Gravel	30–40	15–30	1,000–15,000
Sand & Gravel	20–35	15–25	200–5,000
Sandstone	10–20	5–15	0.1–50
Shale	1–10	0.5–5	0.00001–0.1
Limestone	1–10	0.5–5	

Source: Walton, William, C., 1970. *Groundwater Resource Evaluation.* McGraw-Hill Book Company. Pp. 33-36.

Terms Related to Groundwater Movement

Hydraulic Gradient [I]: *The slope of the water table or piezometric surface under which groundwater movement takes place [often expressed as foot per foot or meter per meter].*

Hydraulic Conductivity [K]: *The quantity of water that will flow through a unit cross-sectional area of a porous material such as an aquifer per unit time under a unit hydraulic gradient [often expressed as gallons per day per square foot (gpd/ft2), ft/day, or m/day].*

Permeability [K]: *Hydraulic conductivity is also known as permeability, which refers to the capacity of a porous medium for transmitting water.*

Aquifer Storage Coefficient [S]: *The volume of water released from storage, or taken into storage, per unit of surface area of the aquifer per unit change in head [dimensionless]. The aquifer storage coefficient is also known as the specific yield of an aquifer.*

NOTE: The terms permeability and hydraulic conductivity are often used interchangeably, as a measure of how much water may be transmitted through an aquifer. The aquifer transmissivity, which takes into account the aquifer's thickness, is the measure of how much water may be delivered to, and thus extracted from, a pumping well.

Aquifer Transmissivity [T]: *The quantity of water that will flow through a unit width of a vertical section of an aquifer whose height is the thickness of the aquifer per unit time under a unit hydraulic gradient. [In other words, the aquifer transmissivity is the hydraulic conductivity times the aquifer thickness and is often expressed as gallons per day per foot (gpd/ft), ft2/day, or m2/day].*

Aquitard: *A water-bearing formation that does not yield appreciable quantities of water, but through which leakage is possible.*

The quantity of water flow in an aquifer is defined by the above properties in the relationship known as Darcy's Law, Q = K I A, where the flow (Q) in gallons per day (gpd) is equal to the hydraulic conductivity (K) in gpd/ft2, times the hydraulic gradient (I) in ft per ft, times the cross-sectional area (A) in ft2.

Unconsolidated formations comprised of fine-grained particles such as clays and silts are described as relatively impermeable and show very low hydraulic conductivity (permeability). These formations are generally not suitable as aquifers and may serve as aquitards instead. As unconsolidated formations contain a higher percentage of coarser-grained materials like sands and gravels, they become increasingly permeable and show higher hydraulic conductivity. Given equivalent aquifer thicknesses, the more permeable coarser-grained aquifers will exhibit higher transmissivity, and wells completed in these formations will have higher yields often in the range of hundreds to thousands of gallons per minute (gpm).

Bedrock units can be quite variable in their water-bearing properties with well yields ranging over 2 to 3 orders of magnitude for a similar rock type—such as granite. The magnitude of well yield in a given setting is dependent on the degree and interconnection of fractures in the bedrock as well as seasonal recharge.

Types of Aquifers

The geologic profile may be consistent or comprised of a number of materials of varying permeabilities that may make up one, none, or several aquifer units. When permeable and impermeable units alternate, distinct aquifer units occur, separated by aquitards.

Water table aquifers are unconfined systems. In these aquifers, the top of the aquifer is the water table where the water is at atmospheric pressure. Wells installed in unconfined aquifers will show water levels that are often referred to as the water table, also known as the top of the zone of saturation. The water table rises in response to precipitation (recharge events) and falls/declines during dry periods. Depending on the aquifer formation and topographic location, the water table can fluctuate seasonally from a few inches to tens of feet or more under natural conditions.

Aquifers also occur in semi-confined and confined conditions. In confined (artesian) systems, the permeable aquifer is sandwiched between two relatively impermeable layers (clay or bedrock) called the upper and lower confining units. The water in the aquifer is at greater than atmospheric pressure and a surface analogous to the water table can be visualized above the actual aquifer, representing the hydraulic head, which is called the piezometric surface. Wells installed in a confined or artesian aquifer show water levels that rise higher than the actual aquifer elevation until they are equivalent to the piezometric surface. In some cases a flowing artesian well results when the pressure head within an artesian aquifer is such that the piezometric surface is higher than the ground surface. Unconfined and confined aquifers and the effect of pressure on the piezometric surface are shown graphically in Figure A.3.

Under truly confined conditions, the aquifer is hydraulically isolated by the confining layers from upper and lower aquifer units. Often, aquifers are only semi-confined or what is known as leaky artesian. This effect is important because during pumping from the semi-confined aquifer, water from the shallower unit will "leak" and serve to recharge the deeper aquifer system.

Terms Related to Pumping Wells

Well Yield [Q]: *The volume of water per unit time discharged from a well, either by pumping or free flow [often expressed in gallons per minute or liters per second (gpm or lps)].*

Static Water Level: *The level at which water stands in a well when no water is pumped from the well. It is generally expressed as the distance in feet (or m) from the ground surface or a measuring point near the ground surface to the water level in a well.*

Piezometric Surface: *The level to which water will rise in a well due to the pressure on the aquifer. In a confined aquifer under pressure, the piezometric surface will be above the top of the aquifer.*

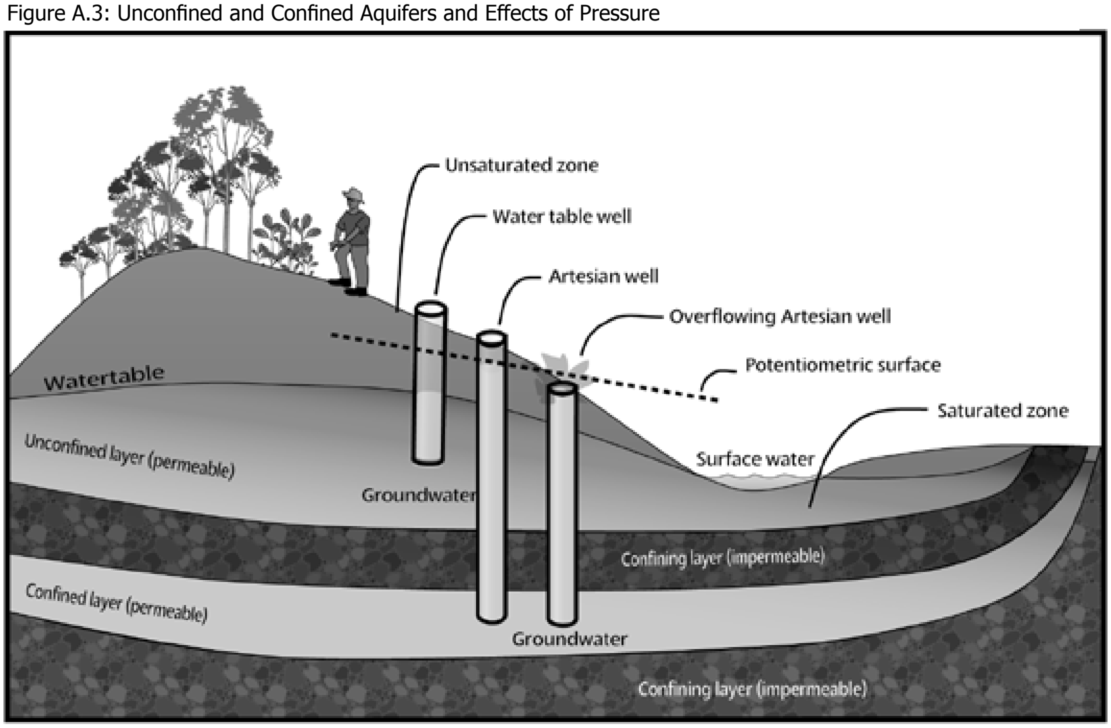
Drawdown [s]*: The extent of lowering of the water level when pumping is in progress. It is the difference in feet (or m) between the static water level and the pumping level.*

Specific Capacity [Q/s]: *The well yield per unit drawdown, [usually expressed as gallons per minute per foot of drawdown (gpm/ft)]. For instance, if the pumping rate is 160 gpm and the drawdown is found to be 20 ft, the specific capacity of the well is 8 gpm per foot of drawdown at the time the measurements are taken.*

Radius of Influence [r]*: The distance from the center of the well to the limit of the cone of depression (of the water level) that forms around a pumping well.*

Well Depths can range from a few tens of feet (shallow hand dug wells) to over a thousand feet (300 meters). In bedrock aquifer systems, well depths are often in the hundreds of feet but wells reaching depths of a thousand feet or more are not uncommon. Bedrock production wells

Figure A.3: Unconfined and Confined Aquifers and Effects of Pressure



are drilled to a few thousand feet in arid regions such as within the Nubian Aquifer in Northern Africa and certain areas in Australia. Deep production wells are also common in the unconsolidated sediments of the Atlantic Coastal Plain in the eastern USA. Well depths are often dictated by the depth and thickness of the targeted underlying aquifer units and the amount of saturated aquifer thickness required to derive the desired well yield. The well depth, static and pumping water levels, specific capacity, and aquifer characteristics are the constraining factors in determining the amount of yield that may be obtained from a well.

Well Yields are constrained by the hydraulics of the underlying aquifer system. In unconsolidated sand and gravel aquifer systems, well yields may range from hundreds to thousands of gallons per minute (gpm) (tens to hundreds of liters per second (lps)). Well yields may also vary considerably within specific types of bedrock aquifer systems. In granite, for example, well yields can range from less than 0.1 gpm to more than 500 gpm (less than 0.01 to 30 lps), depending on the degree and intensity of fracturing, fracture interconnection, and seasonal recharge. Limestone aquifer systems can demonstrate well yields as low as 1 gpm (0.06 lps) and as high as thousands of gpm (100s of lps), depending on the degree of fracturing and solution openings. Careful siting of wells is very important, particularly in a bedrock aquifer system, as well yields may be maximized by optimal placement within zones of relatively intensive fracturing or along structural features.

The cone of depression of large pumping centers can interfere with nearby users within their radius of influence. The presence of large capacity irrigation or urban water supply wells can impact the water levels in nearby wells by a few feet to several tens of feet depending on the magnitude of pumping and distance.

Groundwater as a Supply Source—Study Techniques

Groundwater supply projects may begin with groundwater exploration in totally unknown areas or consist of the addition or rehabilitation of wells in well-studied and long-utilized groundwater systems. There are many techniques available for the careful exploration, study, and development of a groundwater resource, including:

- Evaluation of remote sensing platforms (satellite imagery)
- Aerial photography analysis

- Field surveys of existing wells and springs
- Ground and down-hole geophysics
- Aquifer recharge and water balance calculations
- Water level measurements and preparation of groundwater flow maps
- Installation of test and observation wells
- Aquifer pumping tests
- Specific capacity tests on individual wells

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GROUNDWATER DEVELOPMENT

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