OPTIMUM DESIGN AND CONSTRUCTION OF WATER WELLS (CASE STUDY)

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ABSTRACT

Groundwater is the largest source of fresh water accessible on earth. Effective methods and tools are now available for hydrogeological research and exploitation, and therefore for more understanding of groundwater. Water wells are the hydraulic structures used for supplying water from the groundwater storage. The proper design and construction of water wells is highly required in order to maximize the benefits from water wells.

This paper deals with the optimum design and construction techniques of water wells in two locations. The first location is in eastern Sudan where wells are tapping a non-confined aquifer of limited depth. The second location is western Sudan where wells are tapping a deep confined aquifer. These optimum design and construction techniques will lead to reliable and sustainable water supply consistent with needs and capabilities of the aquifer, suitable water quality that is free of sediments and contaminants, long expected life, less operating and maintenance costs, and ease of monitoring well performance.

INTRODUCTION

Groundwater is an important component in the water cycle or the *hydrologic cycle*, involving the continuous recycling of water above, on, and below the surface of the earth. The importance of groundwater grows with time as a source of irrigation requirements, industrial requirements, human consumption and other domestic uses in dry as well as in humid regions. Water wells are hydraulic structures designed and mainly used for withdrawal of water from the water-bearing formations. The economic feasibility of using groundwater has led to rapid growth in its use. Water wells are increasingly used for both public and private exploitation, and may be particularly valuable for augmenting surface water supplied during short period of peak demand. Water systems based on wells can be brought into operation much more rapidly and efficiently than systems based on water treatment units, which may take a number of years to complete. Moreover, ground water development can be phased with demand avoiding costly excess capacity in early stages of development.

For all these reasons, the widespread expansion of groundwater resources development is economically justified (Naggar, 2002).

GROUNDWATER IN SUDAN

Sudan is a large country area wise. Although it occupies about 60% of the River Nile Basin Area, the Nile and its tributaries covers only 4% of country's area. As a result, groundwater is the vital and the major source of water in large parts of Sudan far from the Nile, especially for pastoralists and agriculturalists spreading over hundreds of thousands of square kilometers of the arid and semi-arid areas of Sudan.

Due to the importance of groundwater in Sudan, proper design and construction of wells is very essential. Successful design of wells generally provide an efficient well with a long service life, use techniques in drilling and well construction that take maximum advantage of the hydrogeologic conditions, and apply the principles of hydraulics in a practical way to the analysis of wells and aquifer performance.

CONFINED AND UNCONFINED AQUIFERS

An aquifer is a geologic formation that is water bearing or saturated with water and is capable of yielding sufficient quantity of water for economical exploitation (Sharma & Chawla, 1977). If the aquifer is confined between two almost impervious beds and slopes gradually downwards towards its terminal boundary it is named as confined, artesian or potentiometric aquifer (Kashef, 1987). And, if the aquifer is exposed to the atmosphere or possesses a free surface, it is named as unconfined aquifer. The terms "water-table", "phreatic", "ordinary", or "gravitational" are also used to denote unconfined aquifers. The hydraulic head at any level within a water-table aquifer is equal to the depth from the water-table to the point under consideration (see Fig. 1).

DESIGN ASPECTS OF WATER WELLS

Water wells are hydraulic structures used to draw water from the underground storage. Wells are also used for disposal of industrial or sewage wastes, artificial recharge, relieving pressures under hydraulic structures, and draining out agricultural lands.

Well design is the process of specifying the physical materials and dimensions for a well (Driscoll, 1986). Though conflicting design criteria have been enunciated from time to time by those working in the field of well design, a stage has now been reached when it is possible to design an optimum well for almost all the aquifer conditions met with in nature (Garge,1987). A good design of a well should aim at efficient utilization of aquifer, long useful life, suitable initial cost, and low maintenance and operation costs.

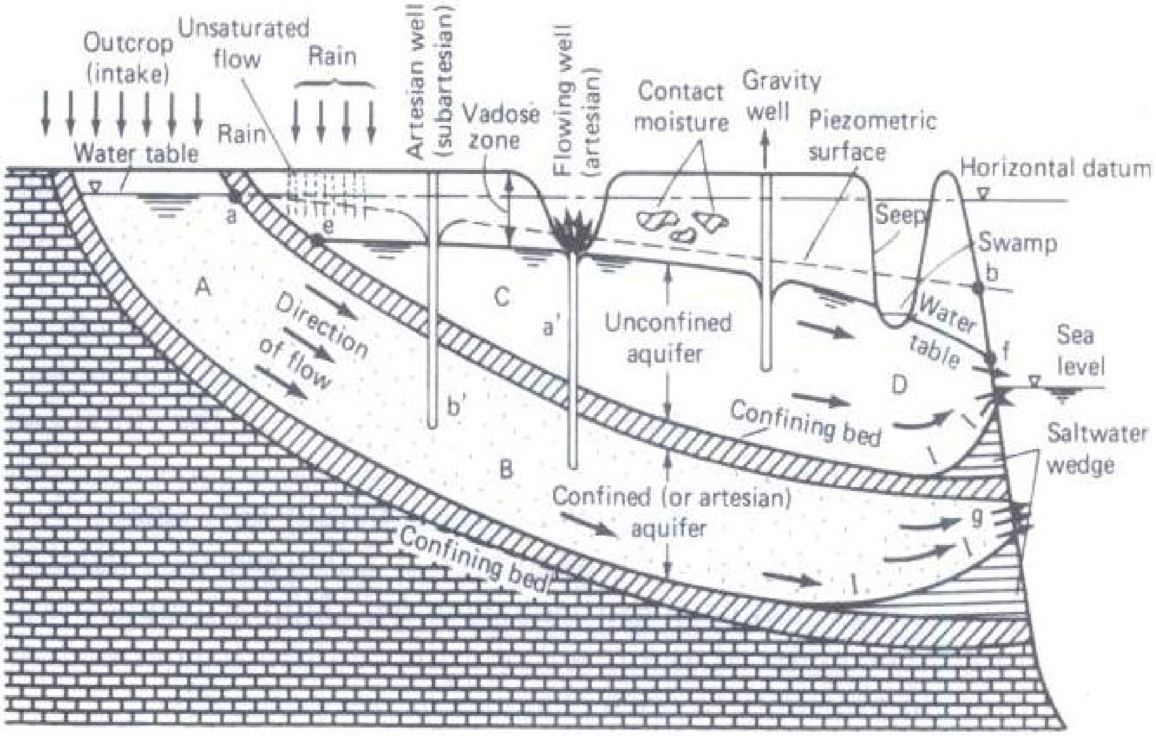

Fig. (1): Groundwater Occurrence (Kashef, 1987)

The most important hydrogeologic information required for the design of efficient high capacity wells includes:

- Stratigraphic information concerning the aquifer and overlying sediments.
- Transmisivity of the aquifer.
- Storage coefficient for the aquifer.
- Current and long term water balance conditions in the aquifer.
- Grain-size analyses of unconsolidated aquifer materials and identification of rock or mineral types if necessary.
- Water quality of the groundwater.

The main components of a well to be designed are: the well casing and the intake portion. The design details of these components are determined after a test well is bored. The procedure of design involves the following steps:

i- Mechanical analysis of samples collected from various depths and preparation of a bore log.
ii- Selection the type of well whether naturally or artificially packed.
iii- Determination of depth of casing pipe, diameter, and thickness.
iv- Selection of strata to be screened and fixing the length of the screen.
v- Determination of size of gravel for shrouding.
vi- Design of well screen-optimum diameter, length and material of screen.
vii- Selection of pumping set.

Well Casing: the pipe used to support the hole during drilling (*in cable tool method*) or installed afterwards to complete the well assembly. The diameter of the casing pipe depends on the size of the hole and must be large enough to house the pump and to allow the water upwards velocity within a certain limit.

Well Depth: Well depth depends on the soil and rock samples taken during the drilling of a test bore hole. More accurate information about the bore log can be obtained using gamma ray log in the test hole.

Screen: well screen is that part of well through which water moves from the aquifer into the well. The success of well mainly depend on the performance of the screen. The screen is either a manufactured with a specified size of openings or mechanically slotted or perforated pipe using cutting too or drill. The main idea behind the design of screens is to allow maximum amount of water in and maximum amount of sediments out.

DESIGN OF WELLS IN CONFINED AQUIFERS

Bara basin in North Kordofan State (Sudan) is chosen to be our case study. The basin is one of the main sources of water supply to Alobied town, capital of North Kordofan State. It is a good example where we can find confined and unconfined aquifers. The basin represents a large tectonic depression with an area of about 6000 km^2, filled with sediments of Umm Ruwaba Series. The basin is bounded in the north, west and south by magmatic and metamorphic rocks of basement complex, as well as the older sediments of Nawa Nubian formations, and in the east, open towards the White Nile (Mayer & Dulic', 1986). Two types of aquifers can be distinguished in the basin: shallow aquifers, which can be dry locally or from time to time, and deep confined aquifer. The first shallow aquifer exists from the depth of 50 m to 60 m. It consists of fine sand partly saturated with groundwater. The second deep aquifer exists at different depths and composed of gravely sand or sandy gravel material with some clayey intervals. A cross section of the aquifer is shown in Figure (2).

Data on hydrological parameters are not very reliable. The value of transmisivity estimated at 35 locations has a wide range from 0.24 m^2/d to 209.6 m^2/d (Hunting, 1975), with a median value of 12.6 m^2/d and upper quartile of 21.8 m^2/d. However, the average values of transmisivity coefficient determined by Geotehnika (1985) for Umm Ushara is 280 m^2/d, and for Umm Dabbus is 4.2 m^2/d. For illustration of the design procedure, an optimum design will be carried for Umm Ushara location.

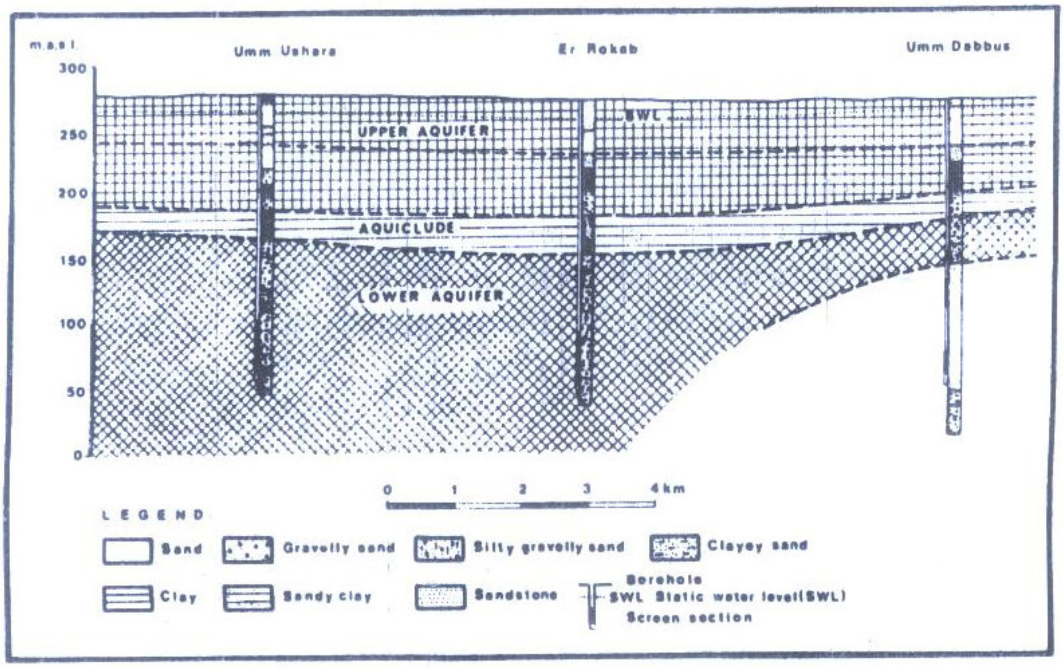

Fig. (2): Hydrologeological Cross Sections at Umm Ushara, Er Rokab, and Umm Dabbus (Mayer & Dulic', 1986)

1. Design Procedure

Step (1): Screen length: As per Geotehnika Report (1991), the beginning aquifer is more clayey, up to the depth of approximately of 210 m then sand component becomes more abundant. The screen is, therefore, proposed to be placed from depth of 215 to 295, i.e. length of screen is 80 m. This length agrees with Driscol (1986) recommendations for optimum design of screen length i.e. 80% to 90% of the most permeable layer should be screened.

Step (2): Depth of well: based on the location of the screen and leaving a depth of 5 m at the bottom of the screen, the total depth of well will be 300 m.

Step (3): Selection of type of well whether naturally or artificially packed: The gravel packing is justified when the diameter of the aquifer material d_{10} is less than 0.25 mm and C_u is less than 3. Also gravel should be provided if d_{50} of the aquifer material is less than 0.75 mm and C_u is less than 3.
Using the typical grain size distribution curve, and for the finest aquifer sample given by Geotehnika (1991):
$d_{10} = 0.10$ mm, $d_{30} = 0.34$ mm, $d_{40} = 0.39$ mm, $d_{50} = 0.45$ mm, $d_{60} = 0.55$mm, $d_{70} = 0.83$ mm.
Uniformity Coefficient = $C_u = d_{60} / d_{10} = 0.55/0.10 = 5.5$
Although $C_u > 4$, gravel pack should be provided because $d_{10} < 0.25$ mm, and $d_{50} < 0.75$ mm.

Step (4): Gravel pack size: for non uniform formations, it is recommended to multiply the 70% size (i.e. 70% detained or *30% finer*) of the sediment by a factor between 4 and 10 and $C_u < 2.0$ (Driscoll, 1986). Taking 7 as the multiplier,

(D_{30} of Gravel Pack)= (d_{30} of Aquifer Material) × 7 = 2.38 mm, this is the point of the 30% finer of the gravel. Using this point a smooth curve is drawn on the typical grain size distribution curve such that the uniformity coefficient is equal to 2 or less. As a result the gravel pack size ranges from 2 mm to 5 mm.

Step (5): Gravel pack thickness: most investigators advise gravel pack thickness between 7.5 cm and 23 cm, hence a thickness of 15 cm is adequate.

***Step (6)*:** Slot size: the slot size of the screen should be such that it retains at least 90% of the gravel pack material. The slot size should, therefore, be 2 mm.

Step (7): Screen diameter: as per the recommendations of U.S.B.R. for a discharge of 1200 l/min., minimum screen diameter is 20 cm. Hence, a diameter of 22.22 cm (commercial diameter of 8.75 inch) is selected, with open area 20%.

Step (8): Well casing: the optimum well casing diameter for a discharge of 20 l/s (1728 m^3/d) recommended by U.S.B.R. is 20 to 25 cm and by Driscol (1986) is 12" (305 mm). Since the well casing significantly affect the cost of structure (Naggar,2003), take the optimum well casing diameter between 20 to 25cm i.e. same diameter of screen, 22.22 cm (commercial diameter of 8.75 inch). Length of casing pipe is 215 m.

DESIGN OF WELLS IN UNCONFINED AQUIFERS

An important example, studied here, is the aquifer of *Khor Arbaat* in the Red Sea State, East of Sudan. The *Khor* is located some 40 k m Northwest of Port Sudan between longitudes 36° and 37° 15'E and latitudes 19° and 20° N. It drains a catchment area of about 4375 km^2 lying on the Pre-Cambrian basement complex of the Red Sea Hills (Mosalami, 2003). The *Khor* is considered as the main source of water supply to Port Sudan, the main port of Sudan and the largest city in the Red Sea State. The well field supplying the town is bounded by an upper gate (about 30 m wide) and a lower gate (about 450 m wide). The portion of the *Khor* between the two gates is of 12 km length and about 1 km average width. The average transmisivity of the aquifer obtained from pumping and recovery test is 3.4×10^{-4} m^2/s, storage coefficient is 0.015 and the permeability range is 1.01×10^{-5} m/s to 2.9 $\times10^{-3}$ m/s. The annual renewed volume of water in *Khor Arbaat* well field is 13.5 million cubic metres (Hussein, 1986). The thickness of the alluvial sediments in the area varies from place to another, with an average of 20 metres, and the average depth of water table is 10 m, with seasonal fluctuations of 1.5 to 2.5 m.
Figure (3) shows a cross along the lower gate of the *Khor*.

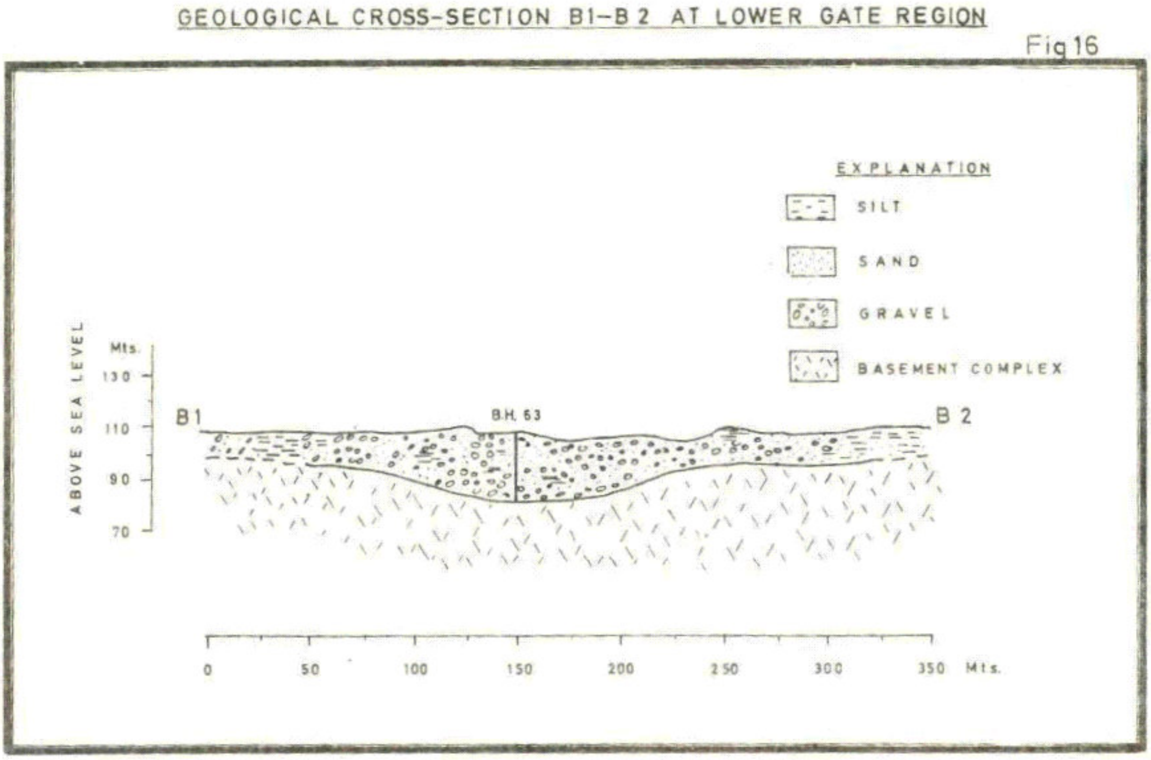

Fig. (3): Geological cross-section at lower gate of Khor Arbaat

As mentioned before, Arbaat well field is one of the main sources of water for Port Sudan. An optimum well design for a discharge of 10 lit/s will be carried herein and for the average hydrological conditions of the Khor.

1. Well Design Procedure

***Step (1)*:** Screen length: for homogeneous and non homogeneous aquifers, optimum screening is recommended to be for the bottom 0.33 to 0.50 of an aquifer less than 150 ft thick. Hence, a 6 m length (= 0.48 aquifer thickness) placed 0.5 m above the bottom of the aquifer is adequate.

***Step (2)*:** Depth of well: based on the location of the well, average depth of well will be 20 m.

***Step (3)*:** Selection of type of well whether naturally or artificially packed: The gravel packing is justified when the diameter of the aquifer material d_{10} is less than 0.25 mm and C_u is less than 3. Also gravel should be provided if d_{50} of the aquifer material is less than 0.75 mm and C_u is less than 3.

Using the typical grain size distribution curve, and drawing the curve for the finest aquifer sample given by Hussein (1975):

$d_{10} = 0.2$ mm, $d_{30} = 0.40$ mm, $d_{40} = 0.55$ mm, $d_{50} = 0.90$ mm, $d_{60} = 1.60$ mm, $d_{70} = 2.50$ mm.

Uniformity Coefficient = $C_u = d_{60}/d_{10} = 1.6/0.2 = 8$.

Although $d_{10} < 0.25$ mm for one sample, $C_u > 4$ and $d_{50} < 0.75$ mm for all samples. Hence, the aquifer is naturally packed and no gravel pack is needed.

***Step (4)*:** Slot size: the slot size of the screen should be such that it retains at least 90% of the aquifer material (i.e. *10% finer*)
The slot size should, therefore, be 2 mm.

Step (5): Screen diameter: as per the recommendations of U.S.B.R. for a discharge of 600 lit/min., minimum and recommended screen diameter is 15 cm. However, according to Driscol (1986), the nominal size of the pump bowel is 5", which is very close 6". Hence, screen diameter of 8"(203 mm) with open area of 20% is selected.

Step (6): Well casing: the optimum well casing diameter recommended by U.S.B.R. for a discharge of 10 l/s (864 m^3/d) is 15 to 25 cm and by Driscol (1986) is 8" to 10". Take the optimum well casing diameter as 8" (203 mm). Length of casing pipe is 13.5 m

CONSTRUCTION OF WELLS

Optimum construction of wells involves the following:

- Choosing an experienced well contractor to construct the well.
- Choosing the well site: should be accessible for all operations i.e. cleaning, testing, monitoring, maintenance and repair. The ground surrounding the well should slope away from the well. It should be as far as possible from sources of potential contaminations such as sewage tanks, sewage wells, fuel stations...etc.
- Drilling the bore-hole.
- Installing well casing, screen, gravel packing,
- Development of well,
- Disinfection of well,

1. Methods of Drilling

There are two main drilling methods:

- *Cable tool or Percussion Method:* operate by repeatedly lifting and dropping a heavy drilling bit the resulting loose material or small fragments of crashed rocks mixed with water is removed using a bailer or sand pumps. This method can be used in hard as well as loose formations. The rate of drilling depends upon the type of formation, depth and diameter of the hole, type of the drilling equipment, and experience of the contractor.
- *Rotary:* wells are constructed using a drill bit on the end of a rotating drill stem. The cutting of rock or unconsolidated formation is accomplished by the rotating bits of different sizes an shapes. The cuttings are removed by continuous circulation of a drilling fluid as the bit penetrates the formation material. The daily progress may range between 10 to 15 m in rock formation and 100 to 150 in unconsolidated formations.

Both methods can be used for our cases. But the Rotary method is preferred for its faster rate, and because of the difficulties that may be faced when drilling in loose formations using the Cable tool Method.

2. Drilling Fluids (moods)

It is used to support the walls of the bore and prevent caving. Considerations which govern the selection of type of mud are: ease of removal, penetrations into the pores, reaction with clay and formation to be penetrated, and formation of precipitates. A drilling mud contains water, colloidal solids, non colloidal solids, and dissolved chemicals. The colloidal solids such as bentonite are the major constituents. This widely used in well drilling and it is recommended to be used.

INSTALLATION OF WELL ASSEMBLY

Methods for installing well assembly, depends upon the design and method of drilling and problems faced during drilling. The pull back method can be used for rotary drilled wells. The casing pipe is lowered after the completion of drilling, and the screen is lowered inside the casing before pulling it back. In case it is not practical to use the pull back method, the screen may be lowered directly into the well. The casing may be used in the position at which it is to be set permanently for use as housing pipe either before carrying drilling or after completing drilling up to full depth (Sharma & Chawla).

PLACEMENT OF GRAVEL PACK

Poorly placed gravel may result in bridging or segregation of resulting in the movement of sand. Excessive movement of sand may lead to failure of well. Gravel should be placed into the well annular space between the side of the casing and the well with a conductor pipe. Although this method is slow but it is better than shoveling or baskets method. Gravel pack should be cleaned before placing, or it can be placed against circulating fluid to enable removing of all fine materials trapped in the gravel pack.

WELL DEVELOPMENT

The development of well means removing finer material from around the screen for increasing the permeability of the surrounding aquifer material resulting in an increase of effective radius and consequent well yield. The methods generally used in well development are:

- *Overpumping* is the simplest and the most inexpensive method, but it is not suitable for high capacity wells (more water is needed). The method can not break bridging of fine particles, due to non reversal of flow.

- *Backwashing* is simple and inexpensive, and can give satisfactory results. It is not suitable where there is danger of subsidence due to excessive removal of fine material from the overlying formations. The method requires large amounts of water for the alternate washing and cleaning. The method caused vigorous vibration of the aquifer and should not be used where there are weak sandy clay layers.
- *Surging* is an effective method of development, created by a quick up and down movement of a plunger. This rapid motion breaks the bridging of fine materials and draws them into the well.
- Compressed air method is rapid and effective. It can be employed in most situations and is widely used. The method does not require special equipment and there is a little chance of over development.
- *High velocity jetting* is the most effective method of development in case of large open screen area. Every part of the screen can be covered using this method.

WELL DISINFECTION

New wells should be disinfected. The concentration is calculated on the volume of water in the well. The concentration must be at least 200 mg of chlorine per every litre of water present in the well. This concentration must remain for at least 12 hours to ensure the destruction of all bacteria. Chlorination is done after installing the pumping equipment and before the well put into production.

RESULTS AND DISCUSSION

The results obtained for optimum design are shown in Table (1).

Table (1) Design and Construction Parameters

	Bara Basin Well	**Khor Arbaat Well**
Discharge (lit/s)	20	10
Depth (m)	300	20
Casing Pipe length (m)	215	13.5
Casing Pipe Diameter (mm)	222	203
Screen Length (m)	80	6
Screen Diameter (mm)	222	203
Slot Opening (mm)	2	2
Screen Open Area (%)	20	20
Gravel Pack Size (mm)	2 to 5	-
Gravel Pack Thickness (cm)	15	-
Method of Drilling	Rotary	Rotary
Method of Installation	Pull-Back	Pull-Back

CONCLUSION AND RECOMMENDATIONS

- Optimum design and construction is proposed herein for two locations in Sudan, and for two types of aquifers-confined and unconfined.
- The obtained design is carried based on my experience (as a chief engineer and project director at the two locations), manuals on groundwater and wells, text books, and technical reports.
- It is recommended here to do a study of the groundwater production cost in order to have a more refined design procedure.

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