# *A GUIDE TO DESIGNING WATER WELLS*

*Khaled A. Rashed[1] and A. M. Abduljawad[2]*
*[1]Associate Professor, Department of Civil Engineering, University of Tripoli, Tripoli, Libya. Email: k65rashed@yahoo.co.uk*
*[2]Assistant Professor, Department of Civil Engineering, University of Tripoli, Tripoli, Libya. Email: jmjwad@gmail.com*

## ABSTRACT

Libya depends almost totally on groundwater resources for its water needs. In the past, groundwater was easily extracted through traditional manually dug large wells since water tables were very near to the ground surface. However, starting from the early sixties, groundwater abstraction rates accelerated rapidly and the use of submersible pumps became necessary to cope with the falling water tables. Despite the scarcity of water resources, water consumption is on the rise as a result of improving standards of living. Authorized and unauthorized water well drillings have been widespread especially in the Jefara, Greeen mountain, and the northern part of Hamada basins. Most of these drillings were carried out without proper well design and without professional well drilling, which, in turn, led to environmental and economical problems. The main aim of this paper was to prepare a step by step guide which can be used in designing water wells. To achieve this goal, an extensive literature review has been conducted covering the main types of aquifers and their characteristics and water well structures. Water well design criteria and steps, for different types of formations, have been prepared, including well casing, well screen and artificial gravel pack.

**Keywords:** Well design criteria, well casing, well screen, artificial gravel pack

## 1 INTRODUCTION

Libya, with a population of about six million people, relies on groundwater resources to cover urban, industrial and agriculture water needs. According to Rashed (2010), about 95% of water supply came from groundwater. There are six main groundwater basins in the country. Three of them are renewable basins (Jefara basin, Green Mountain basin and Hamada basin), whereas, the other three basins are non-renewable basins (Murzuq basin, Kufra basin and Sarir basin). Each basin contains two or more aquifer systems (Salem, 1998). In the past, groundwater was easily extracted through large diameter wells since water tables were very near to the ground surface. However, starting from the early sixties, groundwater abstraction rates accelerated rapidly and the use of submersible pumps became necessary to cope with the falling water tables. Despite the scarcity of water resources, water consumption is on the rise as a result of improving economic conditions, urbanization and improving standards of living. Water well drillings are widespread in the country because agriculture sector plays an important role in the Libyan economy. The sector consumes about 80% of groundwater withdrawals (Alghariani, 2007). Authorized and unauthorized water well drillings have been widespread especially in the Jefara, Green mountain basins and the northern part of Hamada basin, where most of the population live. Most of these drillings were carried out without proper well design and without professional well drilling, which in turn, led to environmental and economical problems. The aim of the study is to prepare a guide, which can be used in designing water wells. To achieve this aim, the following objectives were identified: (1) Reviewing main types of aquifers and their characteristics; (2) Reviewing water well structures, and (3) Preparing water well design procedures for different formations.

# 2 AQUIFERS

An aquifer is a groundwater reservoir composed of geologic formations that are saturated with water and sufficiently permeable to yield water in a usable quantity to wells and springs. Sand and gravel deposits, sandstone, limestone, and fractured, crystalline rocks are examples of geological formations that form aquifers. Aquifers provide two important functions: (1) Transmit groundwater from areas of recharge to areas of discharge, and (2) Provide a storage medium for useable quantities of groundwater. Most aquifers are of large areal extent and may be visualized as underground storage reservoirs. Aquifers may be classed as unconfined or confined, depending on the presence or absence of a water table, while a leaky aquifer represents a combination of the two types.

## 2.1 Unconfined aquifers

An unconfined aquifer is one in which groundwater surface is directly exposed to the atmosphere. Its upper boundary is the water table, which rises and falls according to changes in the volume of water in storage within the aquifer.

## 2.2 Confined aquifers

A confined aquifer, also known as artesian aquifer, occurs where groundwater is confined under pressure greater than atmospheric by overlying relatively impermeable strata. In a well penetrating a confined aquifer, the water level will rise to a surface called the piezometric surface. Rises and falls of water levels in result primarily from changes in pressure rather than changes in storage volumes.

## 2.3 Characteristics of aquifers

The following are the major characteristics of aquifers (Todd and Mays, 2005):

### 2.3.1 Porosity

Porosity is the percentage of rock or soil that is void of material. The larger the pore space, the higher the porosity and the larger the water holding capacity. In sediments, porosity depends on grain size, shape of the grains, degree of sorting and degree of cementation. In rocks, porosity depends on the extent, spacing and pattern of cracks and fractures.

### 2.3.2 Storage coefficient

This coefficient belongs to confined aquifers, and is defined as the volume of water released from a unit area of an aquifer due to a unit decrease in the piezometric surface. The coefficient is a dimensionless quantity involving a volume of water per volume of aquifer. In most confined aquifers, storage coefficient values fall in the range between 0.005% and 0.5%. Releasing water from a confined aquifer is due to compression of aquifer material and expansion of water.

### 2.3.3 Specific yield

This coefficient belongs to unconfined aquifers, and defined as the volume of water released from a unit area of an aquifer due to a unit decrease in the water table. The coefficient is a dimensionless quantity involving a volume of water per volume of aquifer. The specific yields of unconfined aquifers are much higher than the storage coefficient of confined aquifers. The usual value falls in the range between 1% and 30%. All the water stored in a water bearing stratum cannot be drained out by gravity or by pumping, because a portion of the water is rigidly held in the voids of the aquifer by molecular and surface tension forces (specific retention). The later is defined as the difference between porosity and the specific yield.

### 2.3.4 Hydraulic conductivity

A medium has a unit hydraulic conductivity if it will transmit in unit time a unit volume of groundwater through a cross-section of unit area, under a unit hydraulic gradient. Hydraulic conductivity values depend on a variety of physical factors, including porosity, particle size and distribution, shape of particles, and arrangement of particles. Aquifers with large pores such as coarse gravels are said to have a high hydraulic conductivity, and those with very small microscopic pores such as clay, have a low hydraulic conductivity. Hydraulic conductivity in saturated zones can be estimated using a variety of techniques, including calculation from formulas, laboratory methods, tracer tests, and pumping tests of wells.

# 3 WATER WELLS

Water well is a hole, shaft, or excavation used for the purpose of extracting ground water from the subsurface. Water may flow to the surface naturally after excavation of the hole or shaft, but more commonly, water must be pumped out of the well.

## 3.1 Water well components

Proper water well construction, incorporating the right well components, can assure that the well will provide clean and safe water during the expected well life. The main components of water well, as illustrated in Fig. 1, are described in the following sections (Danert, K. et al., 2010):

### 3.1.1 Borehole

The borehole should be about 50 mm wider all around than the well casing. The borehole needs to be clear of obstructions all the way down, and should be deep enough to reach the lowest expected water level.

### 3.1.2 Sanitary seal

If only native soils are allowed to fill in around the casing, a path of contaminated water can form on the outside of the casing and into the well. To keep this from happening, a sanitary seal is used.

### 3.1.3 Well casing

Steel or plastic tubing or pipe installed in the borehole during or after drilling to support the sides of the well and prevent caving.

### 3.1.4 Well screen

Well screens are filtering devices used to prevent excess sediment from entering the well. Attached to the bottom of the well casing, the screens allow water to move through the well while keeping out most sand and gravel. The most common screens are slotted or perforated pipe.

### 3.1.5 Gravel pack

A gravel pack is typically placed in the annular space (the space between the well casing and the wall of the drilled hole) outside the screen casing but within the drilled borehole. The gravel pack consists of sand or gravel that has been designed with grain size finer than the screen slot size. The gravel pack acts as a filter to prevent sediment from entering the well, and also to manage the velocity of the water passing through the aquifer and into the well. High speed water velocity, due to excessive pumping or improperly sized gravel pack, may result in erosion of the aquifer as sediment is pulled into the well.

### 3.1.6 Pump and pipes

The pump is located either above ground or submersed to draw water to the surface by a pipe. The types and size of the pump selected for a particular situation depend on the required capacity, location, operating conditions, and total head (pressure) for the system. After the needed characteristics of the pump have been determined, the pump is carefully selected using the recommendations of the manufacturer's representative or an engineer.

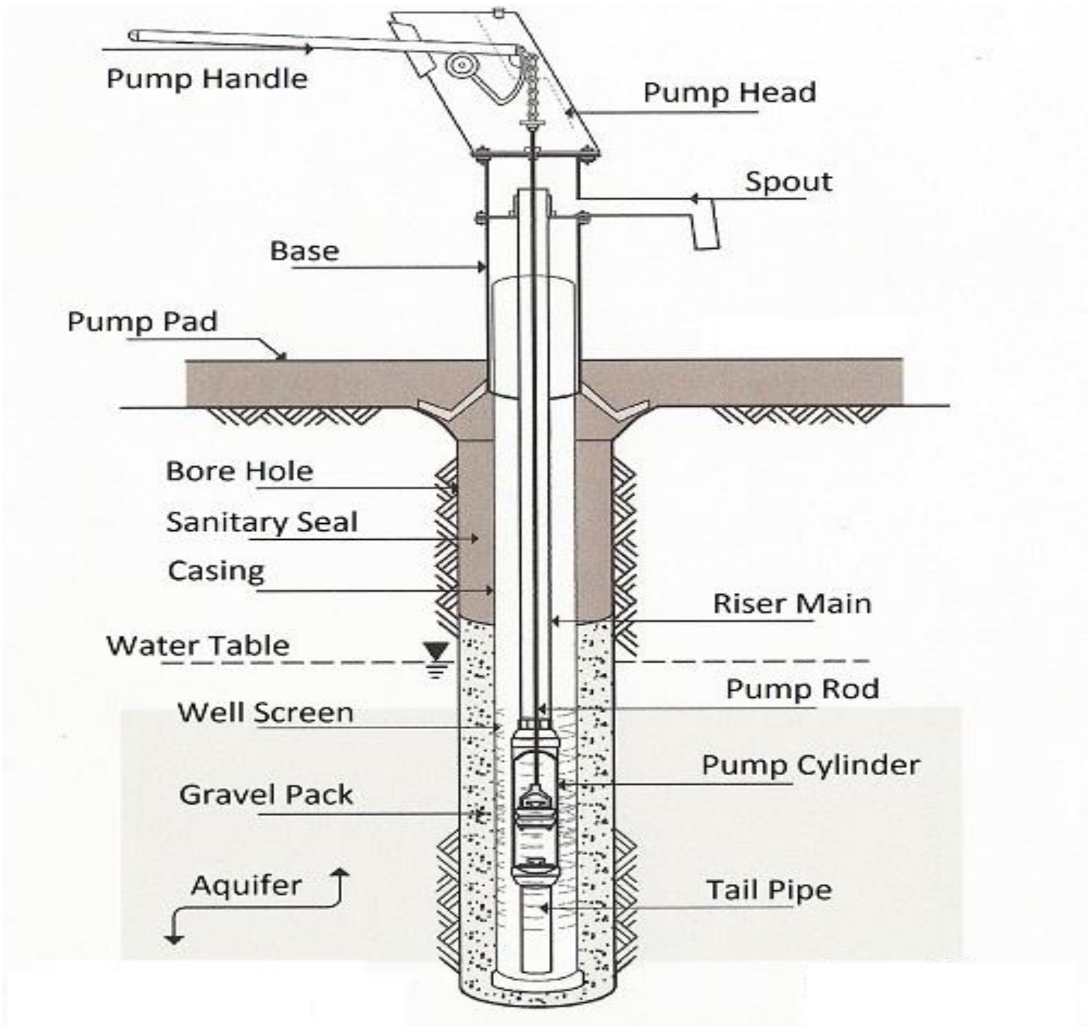


**Figure 1. Components of a typical water well**

## 3.2 Water well sitting

Before excavation, information about the geology, water table depth, seasonal fluctuations, recharge area and rate must be found. This work is typically done by a hydrogeologist, or a groundwater surveyor using a variety of tools including electro-seismic surveying, any available information from nearby wells, geologic maps sometimes geophysical imaging. The location of a well is mainly determined by the well's purpose, for drinking and irrigation water-production wells, groundwater quality and long-term groundwater supply are the most important considerations. The hydrogeological assessment to determine whether and where to locate a well should always be done by a knowledgeable driller or professional consultant. Danert et al. (2010), listed nine important factors which need to be considered when locating a well:

1- Sufficient yield for the intended purpose.
2- Sufficient renewable water resources for the intended purpose.
3- Appropriate water quality for the intended purpose.
4- Avoidance of potential sources of contamination.
5- Avoidance of interference with other groundwater sources and uses.
6- Avoidance of interference with natural groundwater discharge.
7- Engagement with local community.
8- Proximity to the point of use.
9- Access by construction team.

# 4 WATER WELL DESIGN

Once the well location has been determined, a preliminary well design is completed. For many large production wells, a test hole will be drilled before well drilling to obtain more detailed information about the depth of water-producing zones, confining beds, well production capabilities, water levels, and groundwater quality. The final design is subject to site-specific observations made in the test hole or during the well drilling. To produce a combination of longevity, performance and cost effectiveness a proper design reduces the risk of well failure, and thereby provides greater assurance that the well will satisfy the intended purposes (Driscoll, 1986). The main aims of water well design are:

1- The highest specific capacity consistent with aquifer capacity
2- Good quality water with proper protection from contamination
3- A well that has a long life (more than 25 years)
4- Water that remains sand free
5- Reasonable capital and operational costs

In designing water wells, it must be considered that the structure is permanent and the design cannot be easily modified after installation, so the estimation of parameters used in calculations needs to be conservative. In many instances, it is not possible to complete the well design until the well itself is drilled; this is especially true in fissured, consolidated strata or in unconsolidated granular materials which are often heterogeneous, but consolidated, granular aquifers tend to be more uniform and are therefore easier to predict. This means less judgment is required during drilling.

## 4.1 Water well design criteria

The design criteria that are going to be discussed in the following sections are based on Rafferty, 2001, Driscoll, 1986; Williams, 1981; and Walker, 1974.

### 4.1.1 Design steps

The following steps should be followed so as to design a water well:

1- Determine the yield required.
2- Identify formation with potential to support this yield.
3- Identify drilling method.
4- Identify aquifer type.
5- Determine depth of borehole.
6- Determine minimum well diameter.
7- Determine maximum discharge versus drawdown.
8- Determine dimensions of pump chamber.
9- Determine screen and filter characteristics.
10- Determine pump characteristics including stages and pumping rate.

### 4.1.2 Data collection

In order to locate the intake parts, to design the well casing, and to determine the size of the pump which in turn controls the diameter and length of upper well casing, the following data need to be collected for a well design:

1- Aquifer location (depth to water bearing strata and thickness)
2- Aquifer nature (confined or unconfined, consolidated or unconsolidated)
3- Aquifer parameters (hydraulic conductivity and storage coefficient)
4- Water balance conditions in the aquifer (steady state or unsteady state flow conditions)
5- Water quality

### 4.1.3 Wells in granular unconsolidated aquifers

These aquifers are usually heterogeneous, so the aquifer hydraulic conductivity and specific capacity cannot be accurately determined before drilling. Therefore, one of the following procedures can be used; (1) Initial investigation/exploratory drilling can provide an indication of likely lithologies, estimation of hydraulic conductivity and aquifer thickness; (2) Actual well design may have to be made after the well has been drilled using lithological descriptions and samples, estimates of hydraulic conductivity and specific capacity from lithology, casing and screen materials available on site.

Decisions need to be made about the depth to be drilled and whether the site should be abandon if anticipated specific capacity is very poor, so preparatory work is required to develop simple design rules to be applied at site to allow supervisory staff to judge which lithologies to screen; how much screen is required; when holes should be abandoned.

### 4.1.4 Wells in fissured hard rock aquifers

The aim is to tap the zones of high hydraulic conductivity, so site selection can be crucial; use maps, satellite imagery, aerial photos, geophysics to identify lineaments, faults, fracture systems, where fracture density likely to be high. During drilling take litholgical and driller's logs and identify where productive sections are located.

## 4.2 Well casing parameters

### 4.2.1 Well casing length

The length of the well casing is controlled by the requirements of the pump. The pump usually needs to remain submerged, with the minimum submergence recommended by the manufacturer. The pump operating level is determined from the minimum anticipated pumping water level and the anticipated drawdown at the well. A safety margin should be added to make allowance for the variation in aquifer transmissivity due to aquifer heterogeneity, well deterioration, well energy losses, and future contingencies for well interference or variations in static water level. So the minimum length of the well casing is given by equation (1).

$$L = H + s_w + x + y + z \qquad (1)$$

$L$ Length of well casing (m).
$H$ Distance between lowest static water level and ground level (m).
$s_w$ Maximum expected drawdown in the well (m).
$x$ Minimum submergence of pump recommended by manufacturer (m).
$y$ length of the casing above the ground level (m).
$z$ Factor of safety (usually 25% of L).

### 4.2.2 Well casing diameter

The size of pump required to deliver the required yield from the well will determine a lower limit for the casing size. The diameter must be large enough for the pump to be a comfortable fit, making allowances for non-verticality of the borehole. A diameter 100 mm larger than the nominal pump diameter is often recommended. Manufacturers of pumps will recommend a minimum casing diameter. Table 1 shows recommended well casing diameters for various pumping rates.

Table 1. Recommended well casing diameters for various pumping rate (after Driscoll, 1986)

| Well discharge ($m^3$/d) | Nominal size of pump bowls (mm) | Optimum size of well casing (mm) | Smallest size of well casing (mm) |
|---|---|---|---|
| Less than 545 | 102 | 152 | 127 |
| 409 - 954 | 127 | 203 | 152 |
| 818 - 1910 | 152 | 254 | 203 |
| 1640 - 3820 | 203 | 305 | 254 |
| 2730 - 5450 | 254 | 356 | 305 |
| 4360 - 9810 | 305 | 406 | 356 |
| 6540 - 16400 | 356 | 508 | 406 |
| 10900 - 20700 | 406 | 610 | 508 |
| 16400 - 32700 | 508 | 762 | 610 |

### 4.2.3 Well casing material and thickness

Selection of well casing material is based on water quality, drilling procedures, purpose of the well, well depth and diameter, local regulations and cost. The types of casing used in water wells construction are steel, stainless steel, plastic, fibreglass and concrete. Steel is used most commonly, but plastic type is becoming more popular, especially in areas where groundwater is highly corrosive. Casing must have the column, collapse and tensile strengths required for a specific borehole. The casing thickness is based mainly on the strength of the material (Driscoll, 1986). Suggested well casing thickness is presented in table 2.

Table 2. Suggested thickness of well casing (after Driscoll, 1986)

| Depth of well (m) | Diameter of well casing (mm) | | | | |
|---|---|---|---|---|---|
| | 150 | 200 | 250 | 300 | 350 |
| 0-10 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 10-20 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 20-30 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 30-40 | 1.59 | 1.59 | 1.59 | 1.98 | 1.98 |
| 40-50 | 1.59 | 1.59 | 1.98 | 1.98 | 2.78 |
| 50-60 | 1.59 | 1.98 | 1.98 | 2.78 | 2.78 |
| 60-70 | 1.98 | 1.98 | 1.98 | 2.78 | 2.78 |
| 70-80 | 1.98 | 1.98 | 1.98 | 2.78 | 3.75 |
| 80-90 | 1.98 | 1.98 | 2.78 | 2.78 | 3.75 |
| 90-100 | 1.98 | 2.78 | 2.78 | 3.75 | 3.75 |
| 100-110 | 1.98 | 2.78 | 3.75 | 3.75 | 3.75 |
| 110-120 | 1.98 | 2.78 | 3.75 | 3.75 | 4.76 |
| Above 120 | 2.78 | 3.75 | 3.75 | 4.76 | 4.76 |

## 4.3 Well screen parameters

Well screen is used to give the formation support (prevent well collapse), and to prevent entry of fine aquifer material into the well through regulating water flow. Well screen is generally installed in the zones with high hydraulic conductivity. Unproductive sections are not usually screened as blank casing is cheaper than screen. Unconsolidated formations with grain size less than the design formation must be cased out to protect the pump from pumping sand and to prevent erosion of the aquifer material which puts stress on the casing. The designs of well screen parameters, which are going to be discussed in the following sections, are based on Rafferty, 2001, Driscoll, 1986; Williams, 1981; and Walker, 1974.

### 4.3.1 Well screen length

The optimum length of well screen for a specific well is based on aquifer thickness, available drawdown, stratification within the aquifer, and aquifer type. Criteria for determining the screen length for different aquifer configurations are described in the following sections:

**1- Homogeneous unconfined aquifers**

Selection of screen length is a compromise: higher specific capacity is obtained by using the largest screen possible, and the largest available drawdown results from using the shortest screen possible. However, it is uneconomical to pump a well in such aquifer to a drawdown that exceeds two-thirds of the thickness of the aquifer. Theoretical considerations and experience have shown that screening of the bottom one-third to one-half of shallow aquifers may provide the optimum design. In some cases, particularly in thick and deep aquifers, as much as 80% of the aquifer may be screened to obtain higher specific capacity. The well screen is positioned in the lower portion of the aquifer because the upper part is dewatered during pumping.

**2- Heterogeneous unconfined aquifers**

The basic principles of well design for homogenous case also apply here. The only variation is that the screen or screen sections are positioned in the most permeable layers of the lower portions of the aquifer so that maximum drawdown is available. If possible, the total screen length should be approximately one-third of the aquifer thickness.

**3- Homogeneous confined aquifers**

If the pumping water level is above the top of the aquifer, 80 to 90 % of the aquifer thickness should be screened. If the water level is drawn down below the top of the aquifer it will behave like an unconfined aquifer. These screen lengths generally result in specific capacities of about 90 to 95 % of that would be obtained if the entire aquifer were screened. Best results are obtained by centring the screen section in the aquifer.

**4- Heterogeneous confined aquifers**

In heterogeneous or stratified confined aquifers, the most permeable zones need to be screened. Screen 80 to 90% of the most permeable layers.

### 4.3.2 Well screen diameter

To prevent excessive head losses due to friction in the well, the up velocity should be restricted to 1.5 m/s. Since the velocity in the well is given by equation (2), the minimum well screen diameter ($D_{min}$) can be determined by equation (3).

$$v = \frac{Q}{A} \tag{2}$$

$$D_{\min} = 2\sqrt{\frac{Q}{1.5\pi}} \tag{3}$$

$v$ Up velocity (m/s)
$Q$ Well discharge ($m^3$/s)
$A$ Cross sectional area of flow ($m^2$)

The optimum well screen diameter is affected by factors such as; (1) Up flow loss; (2) Approach velocity; (3) Screen velocity; and (4) Entrance velocity. The following procedure explains the screen diameter design steps:

1- Design on up flow losses: select a screen size that reduces these to a value of few percent of the overall pumping head.

2- If resulting values of approach velocity, screen velocity and entrance velocity are not within the acceptable ranges, consider increasing screen diameter.

3- If cost of increasing diameter is significant and no significant reduction in up flow losses occur, the use of a larger well diameter would be advised if well deterioration, encrustation or screen corrosion are recognised problems in existing wells in the region.

**1- Up flow losses**

It is head loss due to friction in the well. It can be estimated using Bakiewicz et, al. (1985) method, which assumes that the flow in the well increases linearly from zero at the bottom of the screen to (Q) at the top, the total up flow head loss is given by equation (4).

$$h = 3.428 Q^2 n^2 L_s D_s^{\left(\frac{-16}{3}\right)} \tag{4}$$

$h$ Up flow loss (m).
$Q$ Well discharge ($m^3$/s).
$n$ Manning’s roughness coefficient (dimensionless).
$L_s$ Screen length (m).
$D_s$ Screen diameter (m).

**2- Approach velocity**

It has been argued that movement of fine material from the aquifer to the gravel pack or well is controlled by the approach velocity of the water to the well at the edge of the borehole, equation (5).

$$v_a = \frac{Q}{L_s \pi D_d} \tag{5}$$

$v_a$ Approach velocity (m/s).
$D_d$ Drilled diameter (m).
$Q$ Well discharge ($m^3$/s).
$L_s$ Screen length (m).

The approach velocity represents the flux not the actual velocity. The actual velocity equals to the flux divided by porosity. To prevent the entry of fine material, the approach velocity should be within the following range, equation (6).

$$v_a < \frac{\sqrt{K}}{15} \tag{6}$$

$v_a$ Approach velocity (m/s).
$K$ Hydraulic conductivity (m/s).

**3- Screen velocity**

It is the velocity of water flowing through screen opening, equation (7). To avoid turbulence in the gravel pack it has been suggested that the Reynolds number should be < 4, equation (7).

$$v_s = \frac{Q}{L_s \pi D_s} \tag{7}$$

$$R_e = \frac{\rho v_s d_{50}}{\mu} \tag{8}$$

$v_s$ Screen velocity (m/s).
$R_e$ Reynolds number (dimensionless).
$d_{50}$ Median gravel pack grain size (m).
$\mu$ Absolute viscosity of water (N.s/$m^2$).
$\rho$ Density of water (kg/$m^3$).
$D_s$ Screen diameter (m).

**4- Entrance velocity**

It is the velocity with which the groundwater enters the well through the well screen and is given by equation (9).

$$v_e = \frac{Q}{L_s \pi D_s OAR} \tag{9}$$

$v_e$ Entrance velocity (m/s).
$OAR$ Open area ratio within the screen (dimensionless).
$Q$ Well discharge ($m^3$/s).
$L_s$ Screen length (m).
$D_s$ Screen diameter (m).

Large entrance velocities may cause problems such as; large energy losses, increased corrosion and encrustation potential, and movement of fine material towards the screen, either blocking gaps or passing into the well. To avoid these problems, the entrance velocity should be less than 0.03 m/s.

### 4.3.3 Well screen slots

The main two forms of screen slots are (1) Horizontal slots, which are less likely to be blocked, so they may be used with relatively large openings (figure 2.a), and (2) Vertical slots, which are most likely to be blocked by fine materials, so they are only used with small openings (figure 2.b).


(a) (b)

**Figure 2. (a) Horizontal and (b) Vertical well screen slots**

## 4.4 Gravel pack

The design of artificial gravel pack, which is going to be discussed in the following sections, are based on Rafferty, 2001, Driscoll, 1986; Williams, 1981; and Walker, 1974. Gravel pack is made of natural material, which should be clean and well rounded to increase permeability. Gravel packed well is one containing an artificially placed gravel screen or envelope surrounding the well screen with a maximum grain size of around 1.0 cm, while the thickness should be in the range of 8 to 15 cm. The gravel pack is intended to fulfil functions such as; (1) Stabilizing the aquifer, (2) Minimising sand pumping, (3) Permitting use of a large screen slot with a maximum open area, and (4) Providing an annular zone of high permeability, which increases the effective radius and yield of the well. Artificial gravel pack is needed when the following conditions are met, equations (10 and 11).

$$u = \frac{D_{60}}{D_{10}} < 3 \qquad (10)$$

$$D_{10} < 0.25\text{mm} \qquad (11)$$

$u$ Uniformity coefficient.
$D_{60}$ Grain diameter (mm) corresponding to 60% passing by weight.
$D_{10}$ Grain diameter (mm) corresponding to 10% passing by weight.

### 4.4.1 Grain size analysis

A grain size analysis is conducted to determine the distribution of grain sizes in unconsolidated sediment. A sample of the sediment is passed through a series of increasingly finer sieves and the sediment retained in each sieve is weighed. The results can be plotted to give a grain size distribution. The (D) number represents the percentage of the sediment that will pass through a given size sieve. For example; if $D_{40}$ = 0.3 mm then only 40% of the sediment sample will pass through a sieve with opening of diameter 0.3 mm. A large uniformity coefficient (u) represents ill-sorted sediment (which means there is a large variation in grain size). Grain size analysis can be used to give; (1) Rough estimates of hydraulic conductivity, (2) Idea about gravel pack design, and (3) Selection of well screen slot size.

### 4.4.2 Selection of gravel grading

The aim is to identify the material which will act as an efficient filter whilst maintaining a high hydraulic conductivity value. The basic rule given by Terzaghi (1943), equation (12).

$$\frac{D_{15}^{f}}{D_{85}^{a}} < 4 < \frac{D_{15}^{f}}{D_{15}^{a}} \tag{12}$$

*f* Stands for filter.
*a* Stands for aquifer.

To construct a grain size distribution curve (a) and a grading curve (b) for gravel pack follow these steps:
1- Calculate cumulative mass passing from given mass retained.
2- Calculate % passing.
3- Draw graph (a) for aquifer between grain size (mm) in logarithmic scale in x-axis and % passing in normal scale in y-axis.
4- Check the gravel pack conditions, equations (10 and 11).
5- If the result is that gravel pack is needed, then construct grading curve (b) for filter. By multiplying each value for curve (a) by a factor (4-10) says (5) and constructs a new curve (b).
6- Use slot size (≈ $D_{85}$) of retained in filter or ($D_{15}$) of passing in filter.
7- Check Terzaghi rule, equation (12).

## 4.5 Installation of gravel pack

Installation of gravel pack must be accomplished so as to minimise the segregation of different size grains as well as the problem of bridging. All gravel pack must be treated with a bactericide (usually chlorine) before installation.

### 4.5.1 In shallow and medium wells

In shallow to medium depth wells, the gravel is poured with water using tremie pipes. They are connectable pipes used to transfer gravel pack material from the surface to the bottom of the well. Then the tremie pipes are withdrawn slowly as the gravel pack settles.

### 4.5.2 In deep wells

In deep wells the gravel is poured directly from the surface. Reverse circulation of drilling fluid is used to prevent separation and bridging (bridging means that particles tend to lock together causing placement problem).

## 4.6 Well completion

### 4.6.1 Grouting

Wells are sealed with cement in the annular space surrounding the upper well casing to prevent the entrance of contaminants. It is important that the grout is introduced to the bottom of the space to be grouted to ensure a proper seal. Grout is usually put in place via tremie pipes.

### 4.6.2 Head works

This includes the construction of the well head works, the pump house and the water distribution system. Head works provide support for the pump and security for the installation.

### 4.6.3 Development

A new well is developed to increase its specific capacity; prevent sanding; obtain maximum economic well life. Development procedures are varied and include pumping; surging; hydraulic jetting; chemicals; surging with air; and backwashing with air. The widely used technique is pumping method.

## 5 CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

Being an arid zone country, Libya depends heavily on groundwater resources. Water well drillings are widespread especially in the renewable basins. Most of these drillings were carried out without proper well design, which in turns lead to environmental and economical problems. The aim of the study is preparing water well design guide for different formations. This aim has been achieved through reviewing main types of aquifers and water well structure. Finally, design criteria and steps for water wells have been prepared, with special focus on; (1) Water well casing, including length, diameter, location and thickness; (2) Water well screen, including length, diameter, location and slots; and (3) Artificial gravel pack, including grain size analysis, gravel pack grading and thickness.

### 5.2 Recommendations

It is suggested to adopt this guide officially by water authorities in Libya and should be made available in Arabic to all entities and individuals. Further, it is suggested to investigate the use of economic well design, which has not been covered in this study. Furthermore, this work could be used as a basis for establishing a national code dealing with water well design.

## REFERENCES

[1]. Alghariani, S. (2007) Reducing agriculture demand in Libya through improving water use efficiency and crop water productivity. *Proceedings of the WRM 2007*, Honolulu, Hawaii

[2]. Danert, K. et al. (2010) Code of practice for cost-effective boreholes. *Rural water supply network*. Switzerland

[3]. Driscoll, F. (1986) *Groundwater and wells*. Johnson Division. USA

[4]. Rafferty, K. (2001) Specification of water wells. *American Society of Heating, Refrigerating and Air-Conditioning Engineering*. Vol. 107

[5]. Rashed, K. (2010) Challenges facing urban water sector in Libya. *Proceedings of BHS International Hydrology Symposium*, Newcastle Upon Tyne, UK

[6]. Salem, O. (1998) National water policy review and management of water scarcity in Libya. *Proceedings of the 2nd expert consultation on national water policy in the Near East*, FAO

[7]. Todd, D. and Mays, L. (2005) *Groundwater Hydrology*. John Wiley & Sons. Canada

[8]. Walker, W. (1974) Tube wells, open wells and optimum groundwater resource development. *Groundwater*. Vol. 12, No. 1

[9]. Williams, E. (1981) Fundamental concepts of well design. *Groundwater*. Vol. 19, No. 5