

CHAPTER FIVE

GROUNDWATER WELLS DESIGN

5.1 Objectives

To produce a combination of longevity, performance and cost effectiveness. Proper design reduces the risk of well failure, and thereby provides greater assurance that the well will satisfy the intended purposes. The main aims are:

- ✓ To obtain the design yield with minimum drawdown consistent with aquifer capability and economic optimization of the well;
- ✓ Good quality water with proper protection from contamination;
- ✓ Water that remains solid-free;
- ✓ A well with a long life (more than 25 years);
- ✓ Reasonable capital and operational costs.

The main points in designing a well are:

- ✓ Choice of well location;
- ✓ Selection of appropriate drilling method;
- ✓ Selection of appropriate construction materials, including pump specification;
- ✓ Proper dimensional factors of borehole and well structure;
- ✓ Geological and geophysical logging, water quality sampling and test-pumping can be carried out in a satisfactory way;
- ✓ The well pumping rate should satisfy the demand for water;
- ✓ The inflow sections of the well should be designed opposite those permeable geological formations;
- ✓ Well design should be such that pollutants from land surface or other sources can not enter the well;
- ✓ Materials used in the well should be resistant to corrosion and possess sufficient strength to prevent collapse
- ✓ Well design should be based on low installation and running costs while not affecting well performance.

5.2 Introduction

In the field of groundwater hydrology, major attention has been devoted to the development and application of aquifer hydraulics, but unfortunately, much less consideration is given to the well structure itself. Although substantial effort may be expended on aquifer testing and computations to quantify the groundwater withdrawal, successful operation of the system may not be achieved if the well is not properly designed. In many instances, the project hydrogeologist or contractor has only a cursory knowledge of screen entrance velocity criteria, and artificial gravel filters are often designed solely on the basis of other previously installed wells in the area. This lack of attention to proper design can result in inefficient well, requiring frequent cleaning and redevelopment, that is ultimately of limited usefulness to the owner.

Water well is a hole or shaft, usually vertical, excavated in the earth for bringing groundwater to the surface. Occasionally wells serve other purposes, such as for subsurface exploration and observation, artificial recharge, and disposal of wastewaters. Many methods exist for constructing wells; selection of a particular method depends on the purpose of the well, the quantity of water required, depth to

groundwater, geologic conditions, and economic factors. Attention to proper design will ensure efficient and long-lived wells.

5.3 Steps of Designing a Well

The following steps should be followed so as to design a 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 vs. drawdown;
 - ✓ If $Q > \text{yield}$, then reduce diameter of the well.
 - ✓ If $Q < \text{yield}$, then drill another well (discuss the matter financially!!!)
8. Determine dimensions of pump chamber;
9. Determine screen and filter characteristics (see if you need filter at all!!!)
10. Determine pump characteristics including stages and pumping rate

5.4 Information Required for Well Design

Information required before design can be completed includes:

Aquifer location

- depth to water bearing strata, and
- thickness of strata (aquifer thickness).

Aquifer nature:

- consolidated or unconsolidated material,
- hard or friable rock,
- confined or unconfined,
- leaky or with delayed yield, etc.

Aquifer parameters:

- hydraulic conductivity,
- transmissivity,
- storativity,
- grain size,

Location of aquifer boundaries;

Aquifer recharge characteristics;

Nature of formations above aquifer;

The need for this type of data is:

1. to establish where the intake parts of the well should be located;
2. to design the type of well casing required to ensure that the borehole remains stable and does not collapse;

3. to allow computation of likely drawdown in the well, and so determine the location of the pump intake. This in turn controls the diameters and length of upper well casing.

5.5 Well Structure

The main elements to well structure are the housing and the well screen at the intake zone where the water enters the well. The components (**see Figure 5.1**) that need to be specified in a properly designed well include:

1. **Upper Well Casing and Pump Housing** (prevents hole collapse, keeping the borehole and conduit open.)

- ✓ Length;
- ✓ Diameter;
- ✓ Materials;
- ✓ Thickness.

2. **Well Screen** “where required” (enables water, but not aquifer material, to enter the well which enables development and/or rehabilitation of the well, and structurally supports the well in loose formation materials)

- ✓ Location in well;
- ✓ Length;
- ✓ Diameter;
- ✓ Slot types;
- ✓ Open area (slot dimensions);
- ✓ Materials;
- ✓ Thickness;

3. **Filter or Gravel Pack** “where required” (enables good flow to the well, without pumping fine-grained materials)

- ✓ Material;
- ✓ Grading;

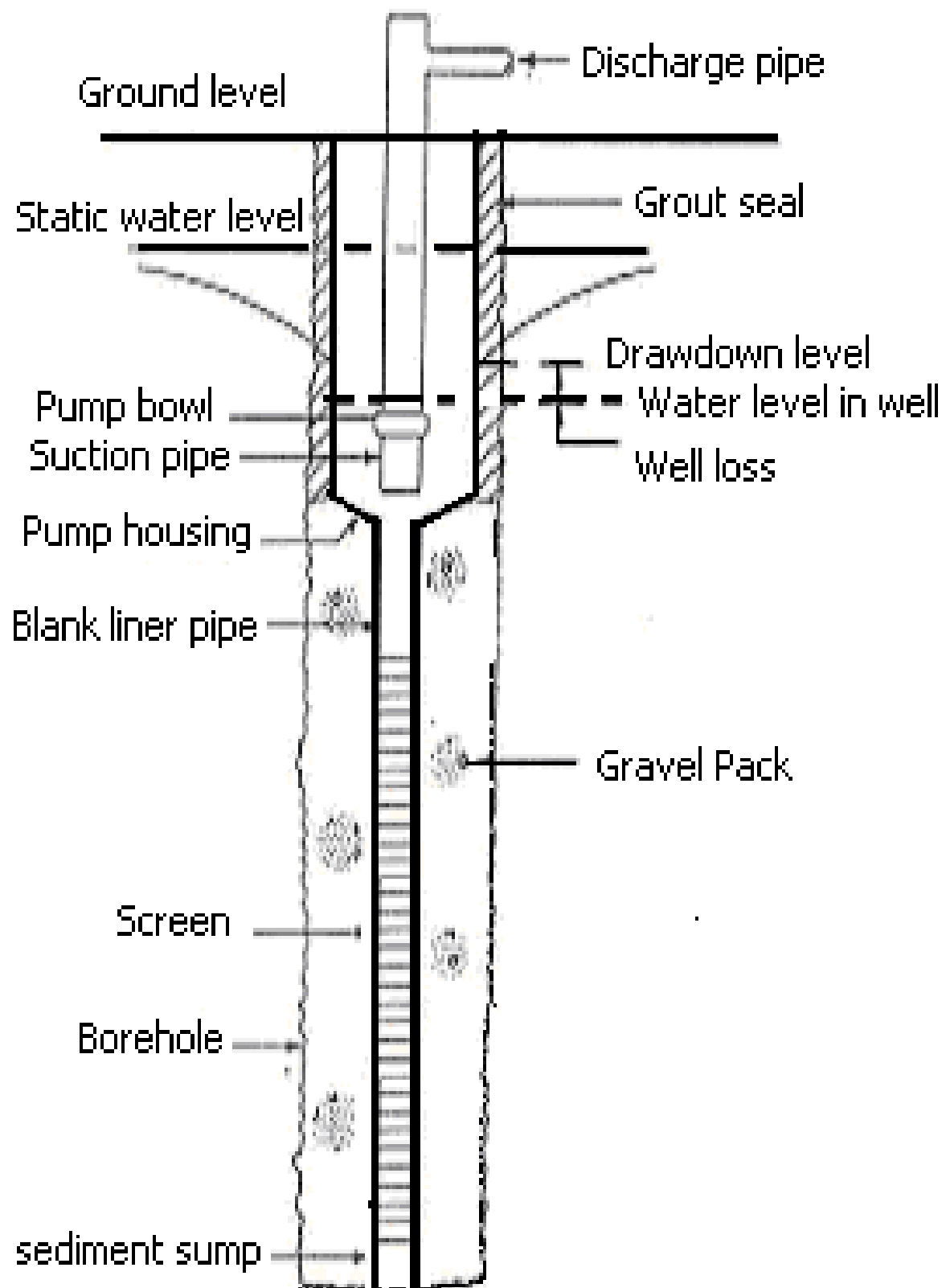


Figure 5.1 Components of a typical well

5.6 Upper Well Casing and Pump Housing

5.6.1 Length of Casing

The length of the upper 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 “operating” water level in the well can be calculated as the distance below ground level of the static piezometric level “static water level” (**H**) less the anticipated drawdown at the well (**s_w**) less a safety margin(**SF**).

The anticipated well drawdown (**s_w**) is usually calculated for steady state conditions, as a function of the well design discharge and the aquifer transmissivity (or the product of the screen length and the aquifer permeability).

The Safety margin (**SF**) should include allowance for:

- ✓ The variation in aquifer transmissivity due to aquifer heterogeneity;
- ✓ Well deterioration;
- ✓ Well energy losses (arising from flow through the screen and gravel pack);
- ✓ Future contingencies for well interference, seasonal or over-year decline in static water levels etc.;

So, the length of the upper casing becomes;

$$L = H + S_w + SF + PR \quad (5.1)$$

Where,

L	length of the upper casing	(m)
H	depth to static water level	(m bgl)
S_w	anticipated drawdown	(m)
SF	Safety margin (safety factor)	
PR	Pump requirements that includes:	
	✓ Pump submergence to the impeller inlet; plus	
	✓ Length of pump below this point; plus	
	✓ Manufacturer's recommended clearance below this point;	

The consequences of making inadequate provision for lower pumping water levels than anticipate by having too short an upper casing is serious in that a reduced discharge must be accepted or the well must be re-drilled.

Sometimes the upper well casing is extended to the aquifer top, but the cost of this exercise is often prohibitive.

5.6.2 Diameter

The diameter of upper well casing required is that needed to accommodate the pump, with some margin for clearance around the unit.

Manufacturers of pump will recommend a “minimum” casing (see **Table 5.1**). 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. In general, the vertical velocity within the well casing needs to be less than 1.5-2 m/sec to minimize well losses.

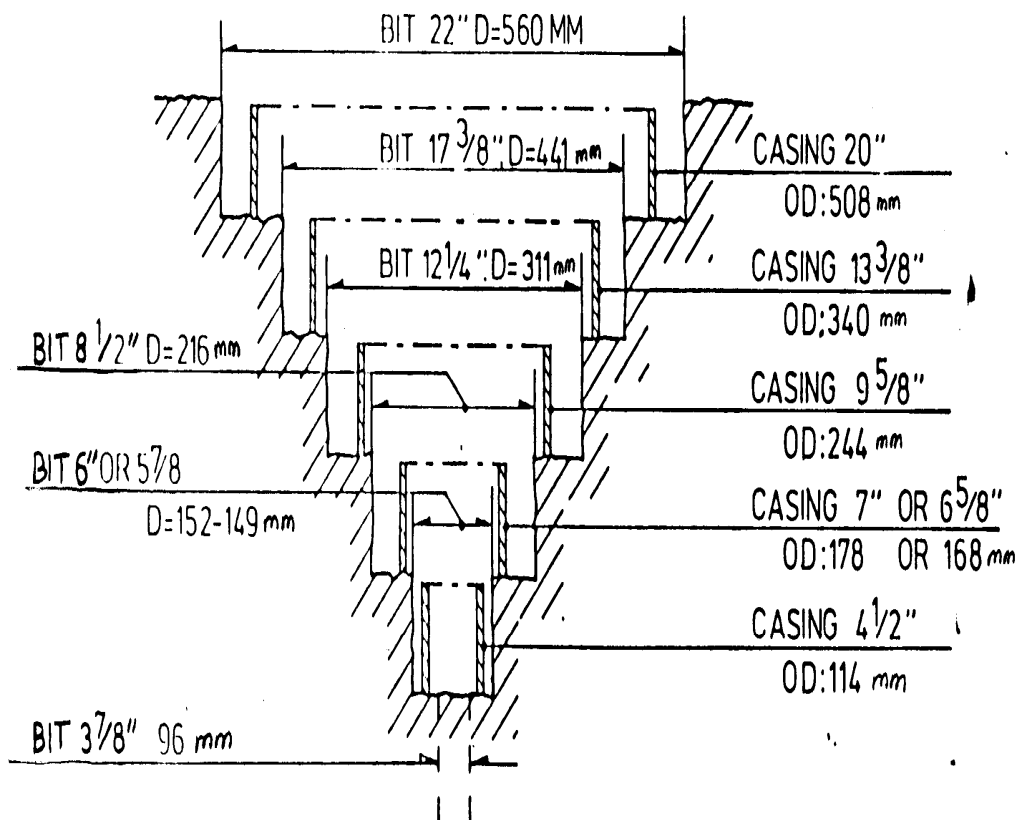
Table 5.1 Recommended well Diameters for various pumping rate* (after Driscoll, 1989)

Anticipated Well Yield m ³ /day	Nominal Size of Pump Bowls		Optimum Size of Well Casing		Smallest Size of Well Casing	
	in	mm	in	mm	in	mm
Less than 545	4	102	6 ID	152 ID	5 ID	127 ID
409 - 954	5	127	8 ID	203 ID	6 ID	152 ID
818 - 1,910	6	152	10 ID	254 ID	8 ID	203 ID
1,640 - 3,820	8	203	12 ID	305 ID	10 ID	245 ID
2,730 - 5,450	10	254	14 OD	356 OD	12 ID	305 ID
4,360 - 9,810	12	305	16 OD	406 OD	14 OD	356 OD
6,540 - 16,400	14	356	20 OD	508 OD	16 OD	406 OD
10,900 - 20,700	16	406	24 OD	610 OD	20 OD	508 OD
16,400 - 32,700	18	508	30 OD	762 OD	24 OD	610 OD

One should recognize that:

- For specific pump information, the well-design engineer should contact a pump supplier, providing the anticipated yield, the head conditions, and the required pump.
- The size of the well casing is based on the outer diameter of the bowls for vertical turbine pumps, and on the diameter of either the pump bowls or the motor for submersible pumps.

Moreover, the casing diameter is also based on the size of the bit used in drilling the borehole. **Figure 5.2** shows the relationship between hole and casing diameter.

**Figure 5.2** Hole and casing diameter

5.7 Well Screen and Lower Well Casing

Lower well casing and screen is used:

- ✓ To give the formation support (prevent well collapse)
- ✓ To prevent entry of the fine aquifer material into the well
- ✓ To reduce loss of drilling fluids
- ✓ To facilitate installation or removal of other casing
- ✓ To aid in placing a sanitary seal
- ✓ To serve as a reservoir for a gravel pack

For well screen design it is necessary to consider the following points:

- ✓ Minimum entrance velocity
- ✓ Maximum open area of screen
- ✓ Correct design of slot to fit aquifer or gravel pack material
- ✓ Periodic maintenance
- ✓ Selection of screen material for corrosion resistance

5.7.1 Screen Length and Location

The optimum length of well screen for a specific well is based on aquifer thickness, available drawdown, stratification within the aquifer, and if the aquifer is unconfined or confined. Criteria for determining the screen length for homogeneous and heterogeneous, confined and water-table aquifer wells are described in the following sections.

The basic design principle is to screen the whole aquifer as a first assumption. This approach is inefficient in:

- Very thick aquifers – use existing developments to have some guidelines (either local “rules of thumb” indicating a certain length of screen per unit discharge or data to use in equations to calculate optimum screen length for a specified discharge)
- Shallow unconfined aquifers – upper well casing is likely to occupy much of the aquifer thickness. The relative dimensions of the upper and lower parts of the well will be dependent upon the relative importance of well efficiency and maximum yield.

Partial penetration of the well-screen will be less efficient (see **Figure 5.3**). Costs of additional screen must be balanced against the benefits of reduced drawdown.

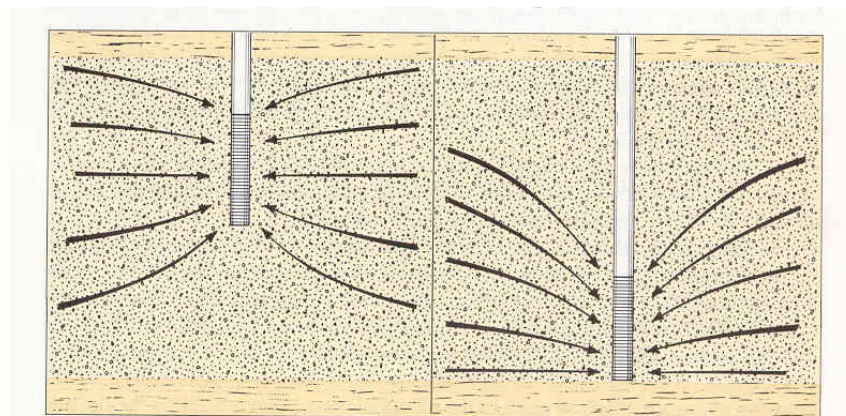


Figure 5.3 partial penetrations when the intake portion of the well is less than the full thickness of the aquifer. This causes distortion of the flow lines and greater head losses.

Field identification of screenable aquifer will largely be made on the basis of the lithological log. Clays and unproductive sections are usually screened as blank casing is cheaper than screen. Unconsolidated formations with grain size less than the “design” formation must be cased out (see **Figure 5.4**). This:

- Protects the material from being eroded thereby placing the casing under stress.
- Protects the pump from the ill effects of pumping sand.

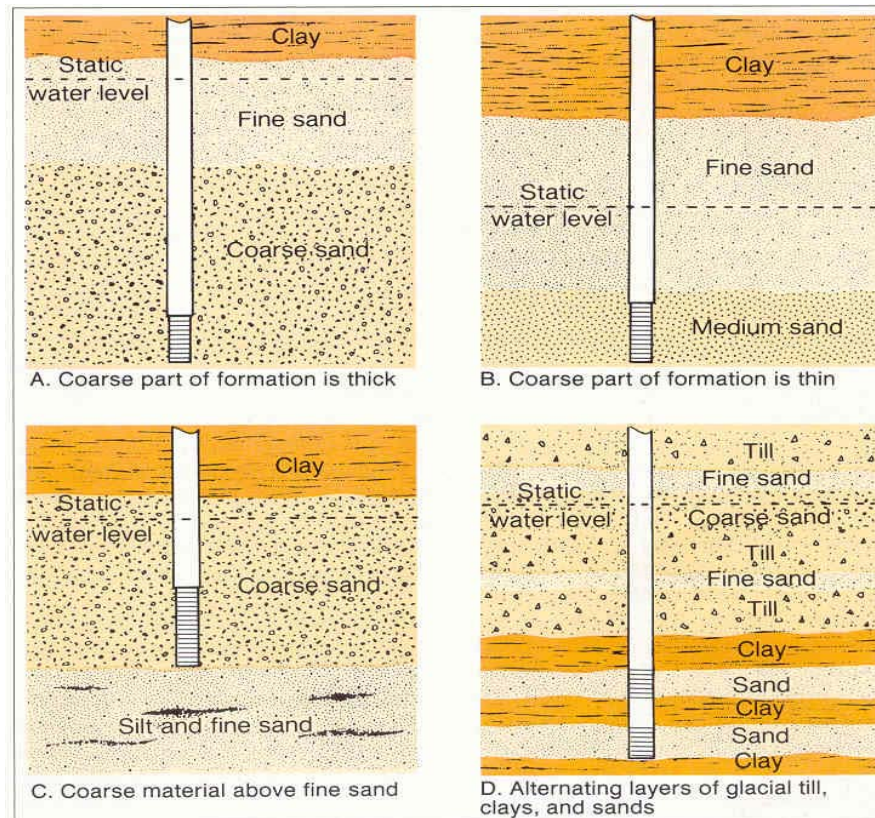


Figure 5.4 Suggested positioning of well screens in various stratified water-bearing formations

Homogeneous Confined (Artesian) Aquifer

The maximum drawdown in wells in confined aquifers needs to be limited to the top of the aquifer. Provided the pumping level will not induce drawdown below the top of the aquifer (the aquifer does not become unconfined), **70 to 80 percent** of the thickness of the water-bearing unit can be screened.

The general rules for screen length in confined aquifers are as follows:

- If the aquifer thickness is less than 8 m, screen 70% of the aquifer.
- If the aquifer thickness is (8 - 16) m, screen 75% of the aquifer.
- If the aquifer thickness is greater than 16 m, screen 80% of the aquifer.

In many applications, fully screening a thick, generally uniform aquifer would be prohibitively expensive or would result in rates of entrance velocity through the well screen that were too slow. Therefore, for best results, the screen section needs to be centered or divided into sections of equal length and interspersed with sections of blank pipe to minimize convergence of flow lines that approach the well bore, and improve well performance (**Figure 5.5**).

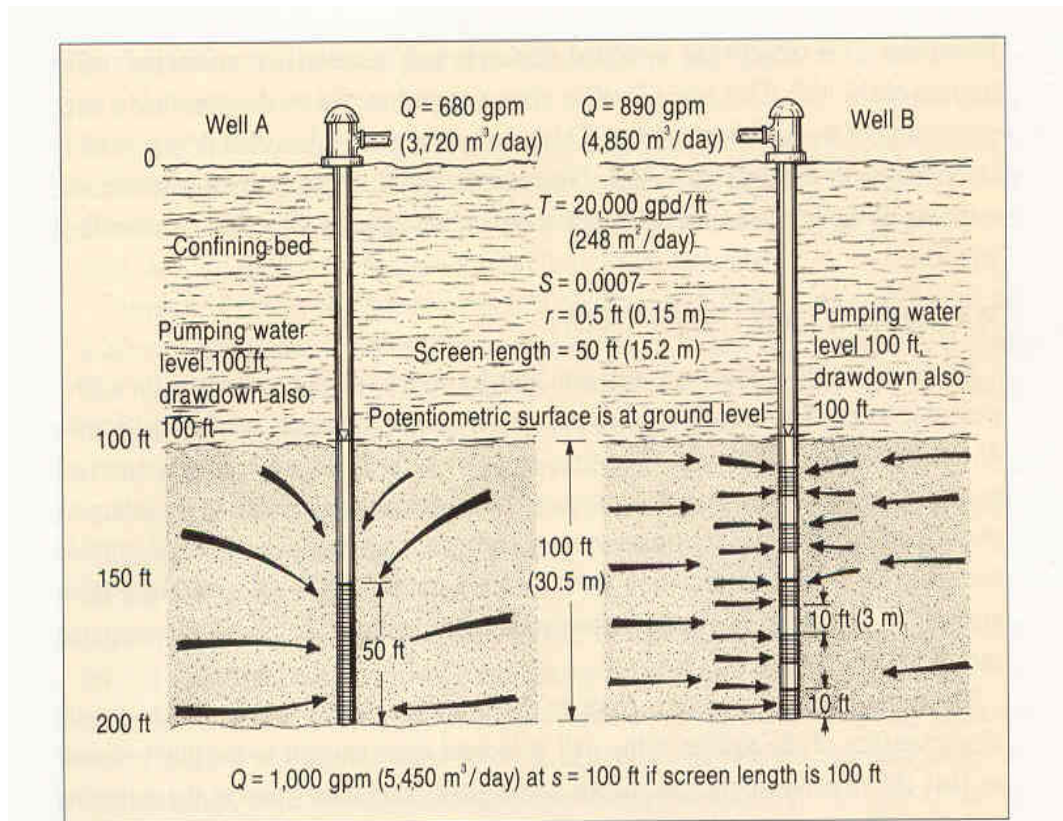


Figure 5.5 Flow line convergence to a screened interval is minimized and well performance can be improved by using sections of well screen in a thick aquifer to reduce the effect of partial penetration. Total screen length is the same in both wells.

Heterogeneous Confined (Artesian) Aquifer

In heterogeneous or stratified confined aquifers, the most permeable zones need to be screened; these zones can be determined by one or several of the following methods:

- Permeability tests (falling head and constant head tests)
- Sieve analysis and comparison of grain-size curves.
 - ✓ If the slopes of the grain-size curves are about the same, the relative permeability of two or more samples can be estimated by the square of the effective size of each sample. For example, sand that has an effective grain size of 0.2 mm will have about 4 times the hydraulic conductivity of sand that has an effective grain size of 0.1 mm.
 - ✓ If two samples have the same effective size, the curve that has the steepest slope usually has the largest hydraulic conductivity.
- Well-bore velocity surveys, if feasible, to start well production prior to completion or to install an extended section of perforated casing or screen in the borehole;
- Interpretation of borehole geophysical logs;

In heterogeneous or stratified aquifers, (80-90) % of the most permeable layers needs to be screened.

Homogeneous Unconfined (Water-Table) Aquifer

- Screening the bottom one-third of the saturated zone in a homogeneous unconfined aquifer normally provides the optimum design.
- In some wells, screening the bottom one-half of the saturated layers may be more desirable for obtaining a larger specific capacity (if well efficiency is more desirable than the maximum yield).
- In water-table wells, larger specific capacity is obtained by using as long screen as possible; therefore, convergence of flow lines and the entrance velocity through the well screen are minimized. However, there is more available drawdown when a shorter screen is used.

5.7.2 Well Screen Diameter

A rule of thumb is that the upflow velocity limit of **1.5 m/s** will produce a well with reasonable upflow losses.

Screen Diameter Design Procedures

- Design on upflow losses – select a screen size that reduces these to a value of a few percent of the overall pumping head (or the economic optimum size);
- Screen sizes usually standard, in increments of about 1 in. for small sizes and 2 in. above 6 in. diameter.
- If the cost of increasing diameter is significant, and no significant reduction in upflow losses accrues, use of large diameter would only be advised if the following are recognized problems in the area:
 - well deterioration
 - encrustation
 - screen corrosion
- The screen diameter is selected to fulfill the essential principle: the total area of the screen openings needs to be provided so the entrance velocity will not exceed the design standard. Diameter can be varied after length and size of the screen openings have been selected. Frequently, the length of the screen and the slot size are fixed by the natural characteristics of the formation; thus screen diameter is the main variable.
- Laboratory tests and experience indicate that if the screen entrance velocity is maintained at about 0.03 m/sec:
 - Frictional losses in screen openings will be negligible.
 - The rate of incrustation will be minimized.
 - The rate of corrosion will be minimized.
- The entrance velocity is equal to the expected or desired yield divided by the total area of openings in the screen. If the entrance velocity is greater than 0.03 m/sec. the screen diameter needs to be increased to provide sufficient open area so the entrance velocity is about 0.03 m/sec. The pump needs to be set above the top of the screen for these designs.

5.8 Slot Types and Open Area

Well screens are manufactured from a variety of materials and range from crude hand-made contrivance (**Figure 5.6**) to highly efficient and long life models made on machines costing hundreds of thousands of dollars (**Figure 5.7**). The value of a screen depends on how effectively it contributes to the success of a well. Important screen criteria and functions are discussed before as:

1. Criteria
 - Larger percentage of open area
 - Nonclogging slots
 - Resistant to corrosion
 - Sufficient column and collapse strength
2. Functions
 - Easily developed
 - Minimal incrusting tendency
 - Low head loss through the screen
 - Control sand pumping in all types of aquifers

Maximizing each of these criteria in constructing screens is not always possible depending on the actual screen design. For example, the open area of slotted casing cannot exceed (11-12) % or the column strength will be insufficient to support the overlying casing during screen installation. However, open areas of 30 to 50 percent are common for continuous-slot screens with no loss of column strength. In high corrosive waters, the use of plastic is desirable, but its relatively low strength makes its use impractical for deep wells.

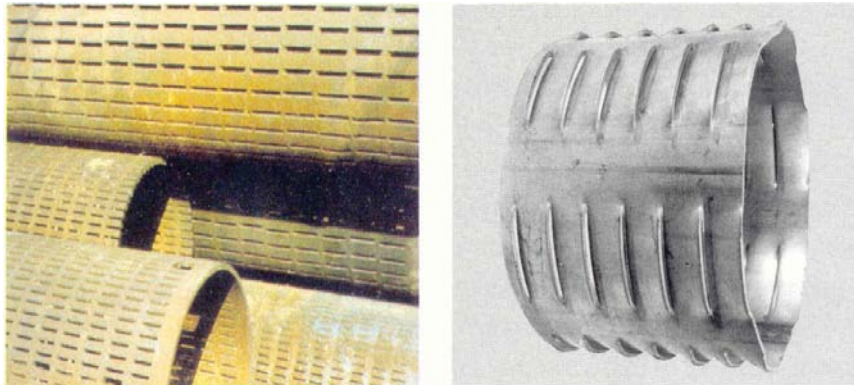


Figure 5.6 Some screen openings are produced by hand cutting and by punching holes or louvers in casing.

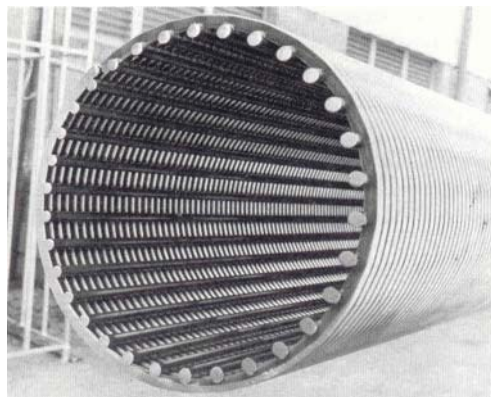


Figure 5.7 Continuous-slot screens are widely used for water wells. They are constructed by winding cold-rolled, triangular-shaped wire around a circular array of longitudinal rods.

- Slot openings should be continuous around the circumference of the screen, permitting maximum accessibility to the aquifer so that efficient development is possible.
- Slot openings should be spaced to provide maximum open area consistent with strength requirements to take advantage of the aquifer hydraulic conductivity.
- Individual slot openings should be V- shaped and widen inward to reduce clogging of the slots and sized to control sand pumping (see **Figure 5.8**)

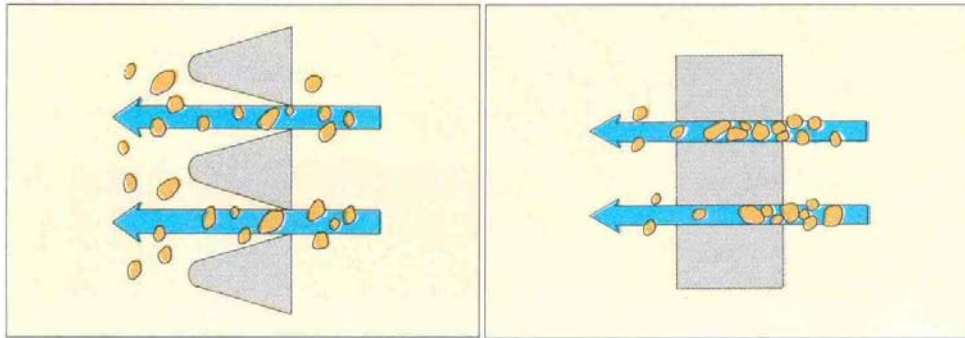


Figure 5.8 V-shaped slot openings reduce clogging where straight cut, punched or gauze-type openings can be clogged by elongate or slightly oversize particles

5.8.1 Screen Slot Types

There are mainly four types of well screen (see **Figure 5.9**), they are:

- ✓ Continuous slot screen
- ✓ Bridge slot screen
- ✓ Louvered screen
- ✓ Slotted pipe

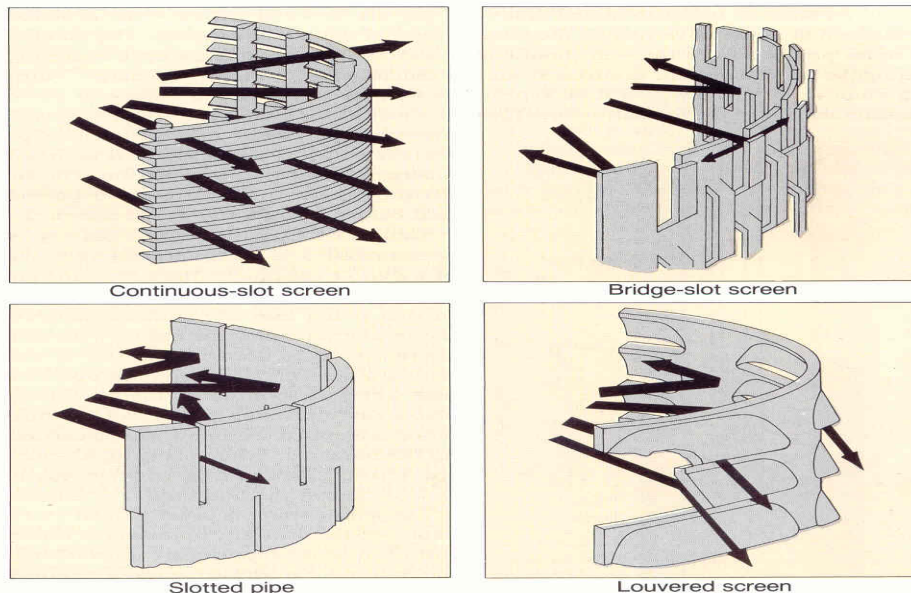


Figure 5.9 Configuration of the slot openings

5.8.2 Screen Slot Size

For naturally developed wells, well-screen slot openings need to be selected from sieve analysis for representative samples from the water-bearing formation. For a homogeneous formation that consists of fine, uniform sand, the size of the screen opening (slot size) is selected as the size that will pass (50-60) % of the sand (Johnson Division, 1975) i.e. (40-50) % retained. (see **Figure 5.10**)

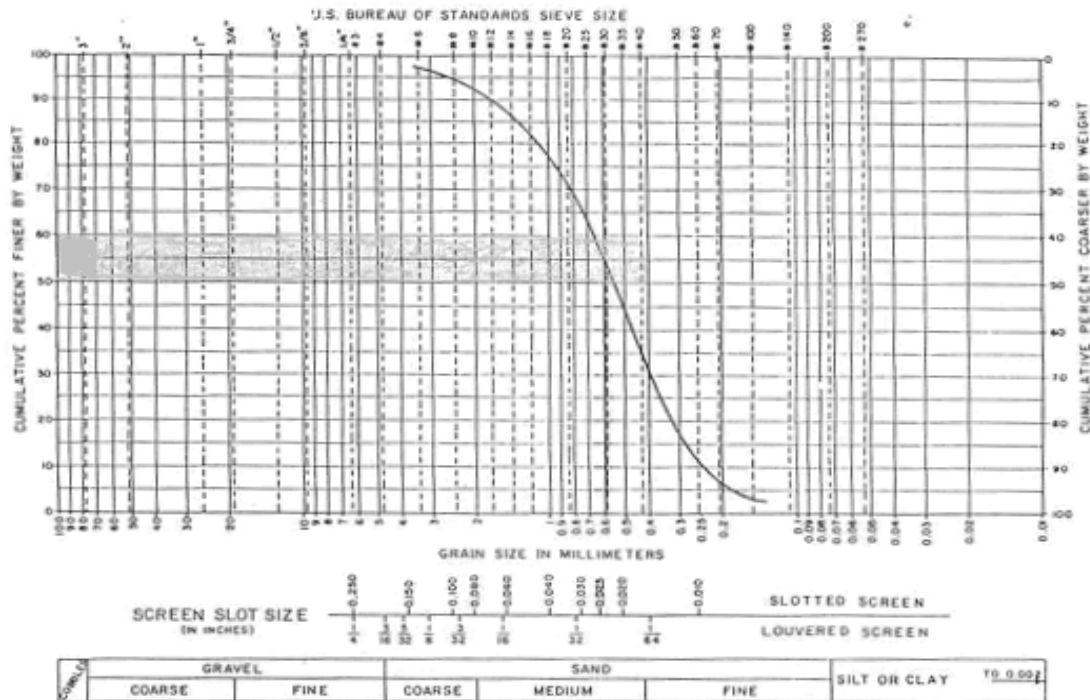


Figure 5.10 Selection of screen slot size for uniform sand

- The 60-percent passing value needs to be used where the ground water is not particularly corrosive, and there is minimal doubt as to the reliability of the sample.
- The 50-percent passing value is used if the water is corrosive or if there is doubt as to the reliability of the sample; the 50-percent passing value is the more conservative design.

In general, a larger slot-size selection enables the development of a thicker zone surrounding the screen, therefore, increasing the specific capacity. In addition, if the water is encrusting, a larger slot size will result in a longer service life. However, the use of a larger slot size may necessitate longer development times to produce a sand-free condition.

A more conservative selection of slot size (for instance, a 50% passing value) is selected if there is uncertainty as to the reliability of the sample; if the aquifer is overlain or underlain by fine-grained, loose materials; or if development time is expensive.

In general, the same sieve-analysis techniques can be used for heterogeneous or stratified aquifers, except as follows:

- If a firm layer overlies the aquifer being evaluated, a slot size that corresponds to a 70% passing value is used.
- If a loose layer overlies the aquifer being evaluated, a slot size that corresponds to a 50% passing value is used.

- If multiple screens are used and if fine-grained material overlies coarse material (**Figure 5.11**):

Extend at least 0.9 m (3ft) of screen that has a slot size designed for the fine material into the coarse section.

The slot size in the coarse material should not be more than double the slot size for the overlying finer material. Doubling of the slot size should be done over screen increments of 2 ft (0.6m) or more.

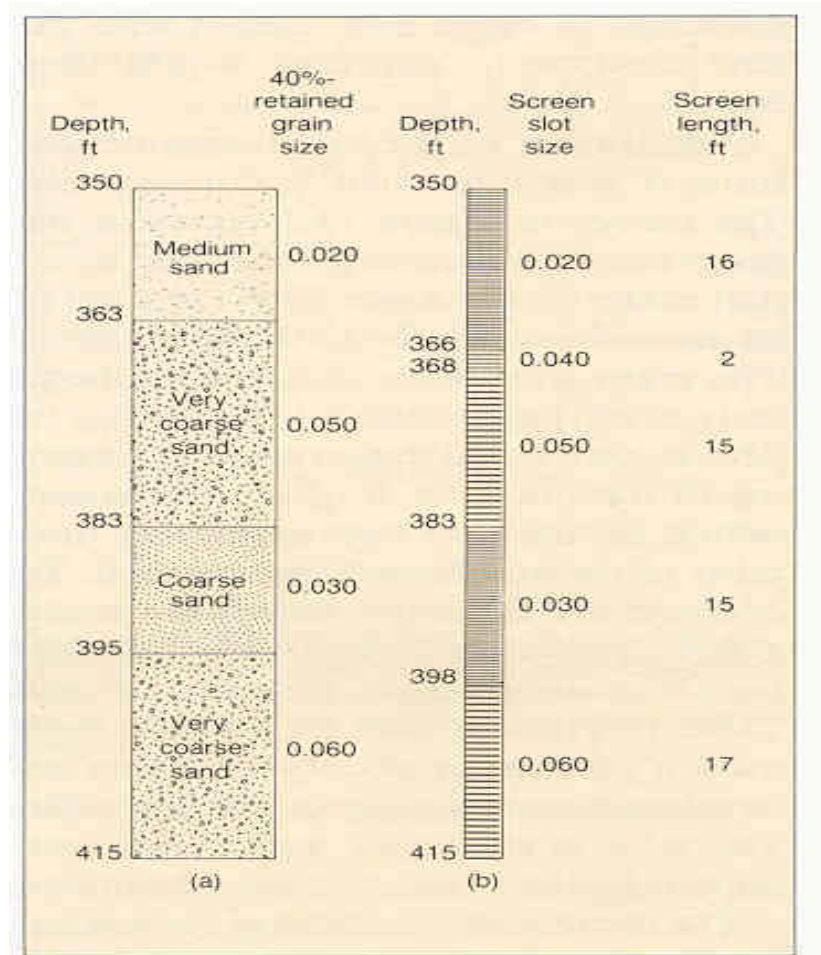


Figure 5.11 (a) Stratigraphic section that will be screened with slot sizes corresponding to various layers. (b) Sketch of screen showing the slot sizes selected on the previous rules (a and b)

5.9 Gravel and Filter Packs

5.9.1 Basic Requirements of Gravel Pack

For formations of fine sands and silts the aquifer must be stabilized. It is not usually practicable to have very small slot sizes, and so an artificial gravel pack is selected which forms the correct size of pore opening, and stabilizes the sand in formation. The use of a pack in a fine formation enables the screen opening to be considerably larger than if the screen were placed in the formation by itself. There is a consequent reduction in head loss. If the grading in the aquifer is small, several gradings in the aquifer is very small, several gradings of gravel pack may be required to retain the formation, and provide practical screen opening sizes.

The gravel pack adjoining the screen consists of larger sized particles than the surrounding formation, and hence larger voids are formed at and close to the screen allowing water entry nearly free from head loss.

Necessary conditions for a gravel pack are:

- ✓ Sand-free operation after development,
- ✓ Highest permeability with stability (low resistance),
- ✓ Low entrance velocities,
- ✓ Efficient service life, i.e. resistant to chemical attack.

5.9.2 Definitions

The following terms are used:

Standard grain size: A particular grain size characteristics of the aquifer (see Module One)

D_x: The sizes of particles such that x percent is smaller, i.e. (100 – x) percent is retained.

Uniformity coefficient: Ratio of the D₆₀ size to D₁₀ size of the material (low coefficient indicates uniform material).

Pack-Aquifer ration (P-A ratio): The ratio of the D₅₀ size of the gravel pack to the D₅₀ size of the aquifer

5.9.3 Natural Gravel Packs

These are produced by the development of the formation itself. Development techniques are used to draw the finer fraction of the unconsolidated aquifer through the screen leaving behind a stable envelope of coarser and therefore more permeable material.

Suitable aquifers are coarse grained and ill sorted, generally with a **uniformity coefficient greater than 3**.

Slot size recommended for the screen is between D₁₀ and D₆₀ (often D₄₀). Choice of slot size is then dependent upon the reliability of the sample and nature of aquifer (e.g. thin and overlain by fine material, formation is well sorted). Not recommended if slot size is less than **0.5 mm. (see Figure 5.12)**



Figure 5.12 Natural development removes most particles near the well screen that are smaller than the slot openings, thereby increasing porosity and hydraulic conductivity in a zone surrounding the screen.

5.9.4 Artificial Gravel Pack

Also known as gravel filter pack (see **Figure 5.13**), graded envelope, the gravel pack is intended to fulfill the following functions:

- ✓ To support the aquifer formations and prevent collapse into the casing;
- ✓ To laterally restrain the casing, effectively strengthening the casing;
- ✓ To prevent the movement of fine aquifer material into the well.

The normal approach is to use a filter pack when:

- ✓ The uniformity coefficient < 3 ;
- ✓ The aquifer is fine, with D_{10} of the formation < 0.25 mm.

5.9.5 Gravel Pack Materials

Gravel Pack should be (see **Table 5.2**):

- ✓ Clean.
- ✓ Have well-rounded grains.
- ✓ Free from water soluble compounds such as carbonates (siliceous sands and gravels)
- ✓ Be well graded to insure its function as designed.

Table 5.2 Desirable filter pack characteristics and derived advantages

Characteristic	Advantage
Clean	Little loss of material during development Less development time
Well-rounded grains	Higher hydraulic conductivity and porosity Reduced drawdown Higher yield More effective development
(90-95)% quartz grains	No loss of volume caused by dissolution of minerals
Uniformity coefficient of 2.5 or less	Less separation during installation Lower head loss through filter pack

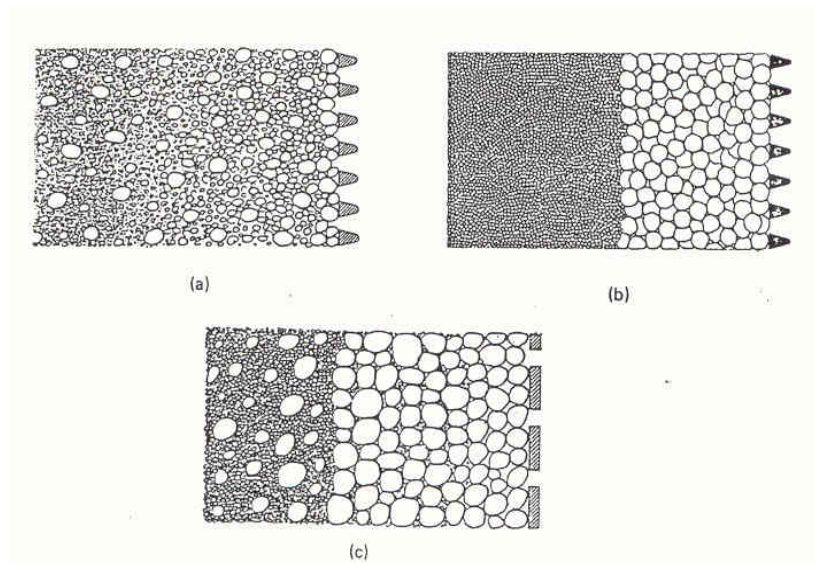


Figure 5.13 The basic differences between the arrangement of the sand and gravel in natural and artificial gravel packed wells. **(a)** The principle of the natural or 'developed' well with each zone correctly graded to the next so that the whole pack is stabilized. **(b)** An artificial gravel packed well in which the correct size relationship is established between the size and thickness of the gravel pack material and the screen slot width. Such a well can be effectively developed and will be efficient and stable. **(c)** Undesirable result of using gravel that is too coarse. The aquifer sand is not stabilized and will eventually migrate into the well. This unstable condition will persist regardless of how thick the gravel pack may be, thus causing a continued threat of sand pumping.

5.9.6 Thickness of Gravel Pack

In theory, a pack thickness of 2 or 3 grains is all that is required to retain formation particles. In practice around 10 cm is used to ensure an envelope around the well. Upper limit of thickness of the gravel pack is 20 cm; otherwise, final well development becomes too difficult and cost of drilling escalates. Packs with a thickness of less than 5 cm are simply formation stabilizers, acting to support the formation, but not effective as a filter.

5.9.7 Selection of Gravel Grading

The aim is to identify the material which will stop significant quantities of material moving into the well while minimizing energy losses. Artificial gravel packs are used where the aquifer material is fine, well-sorted or laminated and heterogeneous. They allow the use of larger slot sizes than would otherwise be possible.

Several methods of determining the gravel pack grain sizes have been suggested. All based initially on a sieve analysis of the aquifer.

The basic rule is (after Terzaghi, 1943):

$$\frac{D_{15 \text{ filter}}}{D_{85 \text{ aquifer}}} < 4 < \frac{D_{15 \text{ filter}}}{D_{15 \text{ aquifer}}} \quad (5.2)$$

A common consensus is that a gravel pack will normally perform well if the uniformity coefficient is similar to that of the aquifer, i.e. the grain size distribution curves of the filter pack and the aquifer material are similar (see **Figure 5.14**). The grain size of the aquifer material should be multiplied by a

constant of approximately (4-7) with average **(5)** to create an envelope defining the filter grading. (see **Figure 5.15**)

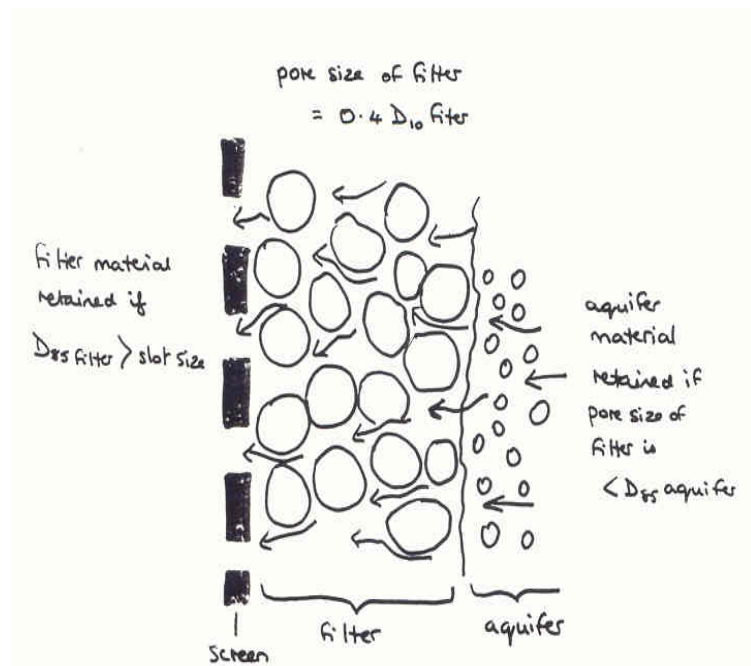


Figure 5.14 Illustration of Terzaghi rule

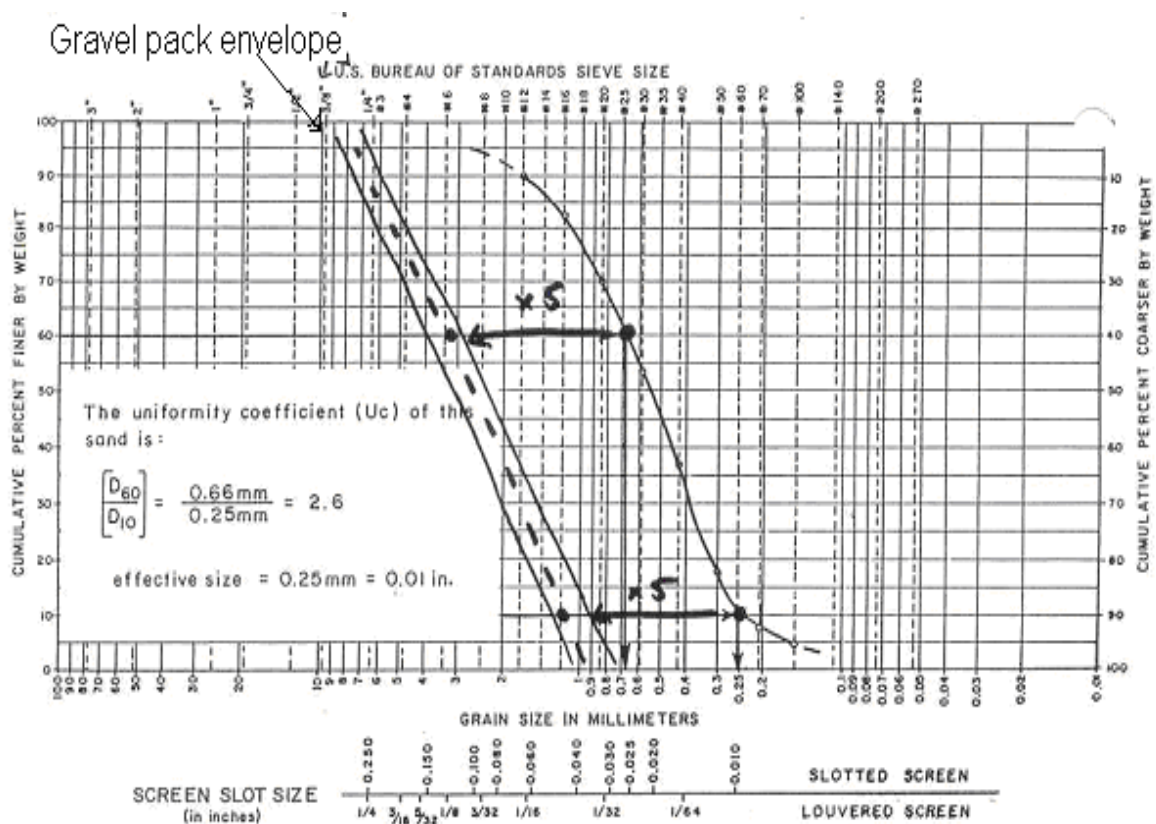


Figure 9.15 Selection of gravel grading

Example 5.1: Well Siting and Well Design

From the details shown on **Figure 5.16** and the data presented in **Table 5.3**,

- Determine the areas most suitable for good yielding wells for potable supply.
- Suggest a location for a well which is likely to support a minimum of 20 l/s for the drinking water of the town indicated. Using data from nearby wells.
- Then for the selected well, suggest likely lithology and depth to bedrock and estimate values of rest water level, surface elevation and specific capacity.
- From information found in (c), estimate the long-term drawdown if pumping at 20 l/s. Suggest an appropriate drilling method for this well. Assume that no gravel pack is required, sketch a well design, giving drilled diameter, casing diameter, appropriate pumping size, and screen length.

Table 5.3

Borehole number	Rest water level elevation (m)	Surface elevation (m)	Depth to bedrock (m)	Lithology (m)	Schedule details	Specific Capacity (l/s/m)
1	608.7	609.2	11.1	0-11.1 : Silty sands	8" well, with screen and gravel pack from 8-11 m. Yield 8 l/s	3.2
2	608.8	609.5	11.3	0-11.3 : Sands with silts and clay	Unused	-
3	607.9	609.0	11.0	0-6.8 : Silty sands 6.8-11.0 : Clay and silt	Unused	-
4	-	611.6	13.9	0-13.9 : Well cemented sand and silt	Dry	-
5	-	611.7	13.5	0-13.5 : Well cemented gravel and silt	Dry	-
6	603.9	607.0	9.8	0-9.8 : Gravels and sands	10" slotted pipe 4-9.8 m Contaminated	-
7	603.8	606.9	10.4	0-10.4 : Sandy gravel	10" slotted pipe 4-10.4 m Contaminated	-
8	603.7	607.0	10.8	0-10.8 : Gravels and sands	10" slotted pipe 4-10.8 m Contaminated	6.8
9	603.7	607.0	9.6	0-9.6 : Sands with silts	10" slotted pipe 4-9.6 m Contaminated	-
10	605.2	607.8	10.6	0 - 10.6 : Sands and silts	8" slotted pipe gravel packed, 8.8-10 m. Yield 9.5 l/s	2.4
11	607.8	609.1	11.1	0-11.1 : Sandy silt	Abandoned	-
12	607.1	608.6	11.1	0-11.1 : Sand and gravel	10" slotted pipe gravel 6-10 m. Yield 18 l/s	6.4
13	606.3	608.1	11.1	0-11.1 : Sand and gravel	6" screen, unused, screen damaged	-
14	606.2	608.1	11.0	0-11.0 : Sandy silt and clay	8" slotted pipe 5-10 m. pulling fine material	2.1
15	608.3	609.1	10.4	0-10.4 : Silty sand and clay	Abandoned	-
16	609.9	609.5	11.2	0-11.2 : Gravel with sand and silt	5" slotted pipe 6-10 m. Yield 4 l/s for factory supply	5.8
17	605.5	608.9	11.9	0-11.9 : Sands with silt and clay	8" slotted pipe gravel packed, unused	1.9
18	606.0	609.0	11.8	0-8.6 : Silt and sand 8.6 - 11.8 : Sand and silt	Abandoned	-
19	602.2	606.5	10.5	0-10.5 : Silty sand	Old dug well, partially collapsed, contaminated	-
20	605.1	607.7	11.2	0-11.2 : Sand and gravel	8" slotted pipe 5-11 m. Previous 9.5 l/s yield. Contaminated	5.3

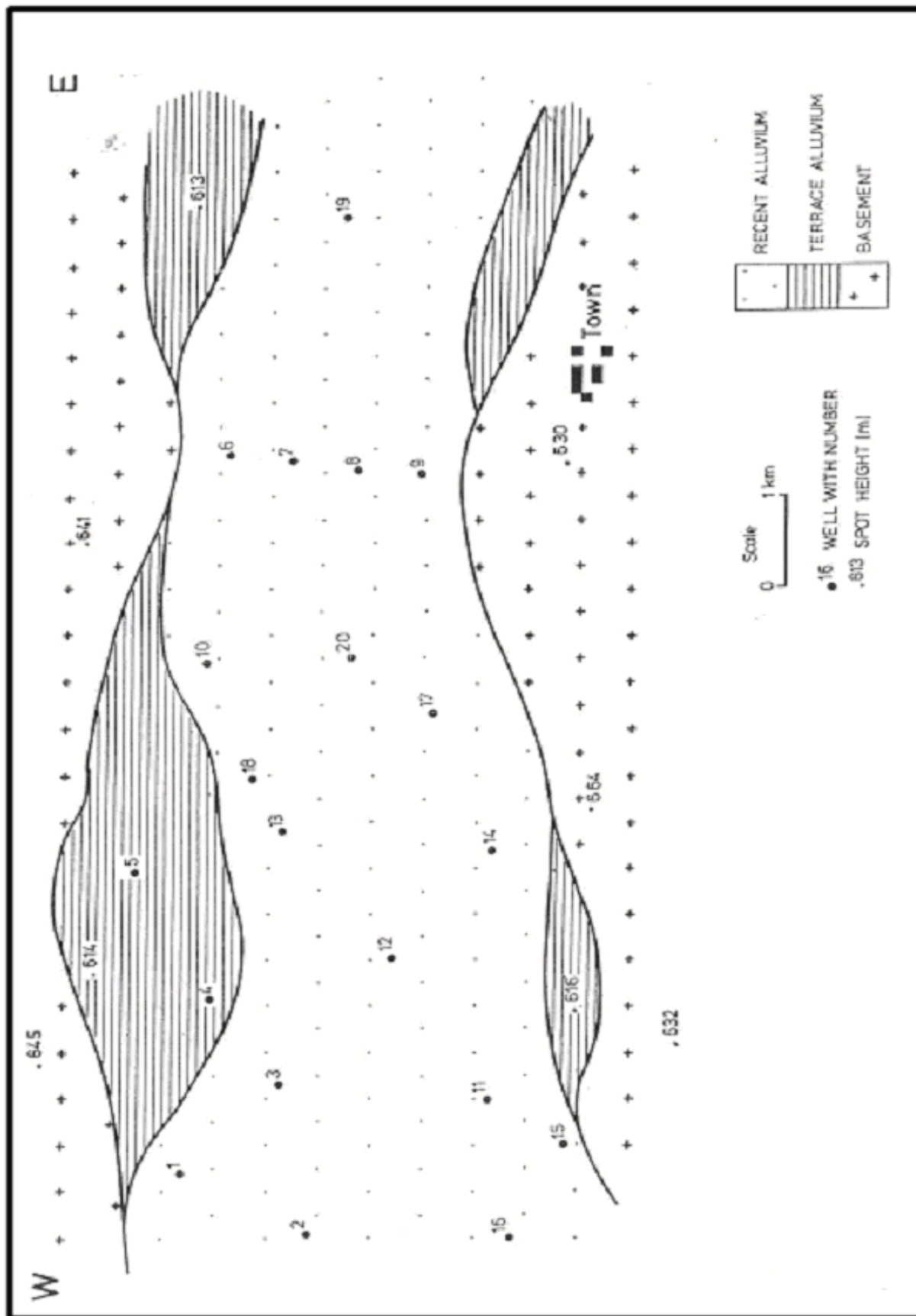
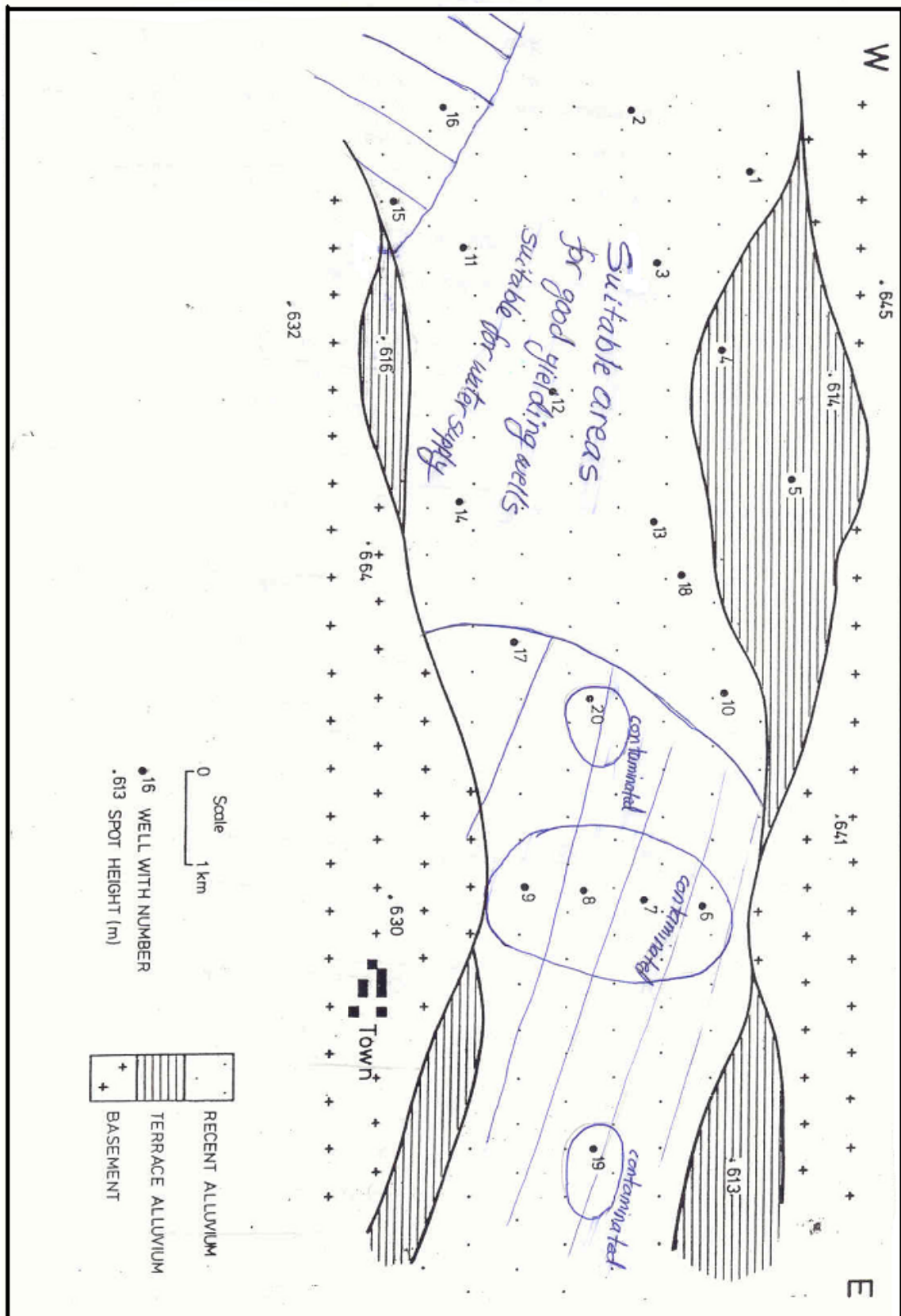


Figure 5.16

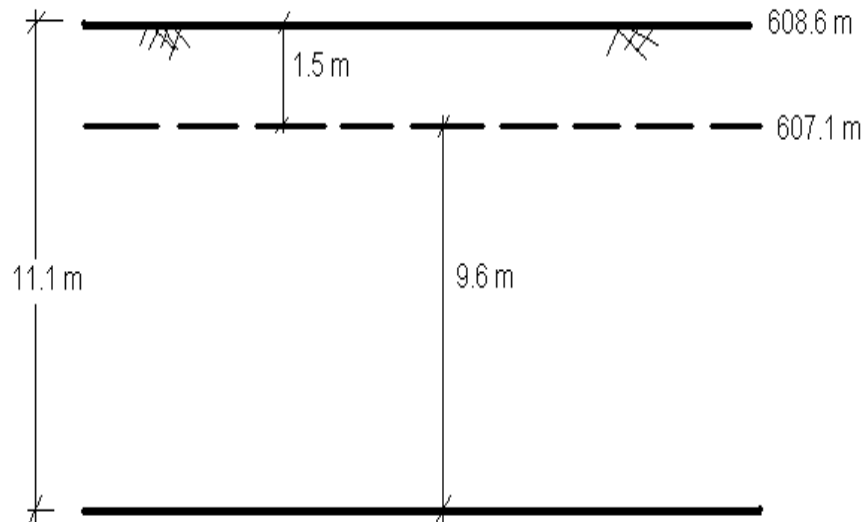
Answer 5.1

- a. The most suitable are for good yielding wells for potable supply is shown in the following figure,



b. The best site is well # 12 because:

- Saturated thickness = 9.6 m.
- Specific capacity = $6.4 \text{ l/s/m} = 553 \text{ m}^2/\text{day}$
- The value of specific capacity is high, so $Q \geq 20 \text{ l/s}$ is easily achieved



c. For the selected well,

- Lithology 0 - 11.1 sand and gravel
- Depth to bedrock 11.1 m
- Depth to rest water level 1.5 m
- Surface elevation 608.6 m
- Specific capacity $6.4 \text{ l/s/m} \approx 553 \text{ m}^2/\text{day}$

d. For the selected well,

- Long-term drawdown $s_w = 1.22 \frac{Q}{T} \Rightarrow T = 1.22 \frac{Q}{s_w} = 1.22 \times \text{specific capacity}$

$$T = 1.22 \times 553 = 675 \text{ m}^2/\text{day}$$

$$\Rightarrow s_w = 1.22 \frac{Q}{T} = \frac{1.22 \times (20 \times 10^{-3} \times 60 \times 60 \times 24)}{675} = 3.12 \text{ m.}$$

- Appropriate drilling method for this well is power augering, because:

1. The depth is limited only 11.1 m.
2. lithology is loose (sand and gravel)

➤ **Well Design:**

(Screen diameter)

$$Q = V \times A \Rightarrow A = \frac{Q}{V} = \frac{20 \times 10^{-3} \text{ m}^3 / \text{sec}}{1.5 \text{ m} / \text{sec}}$$

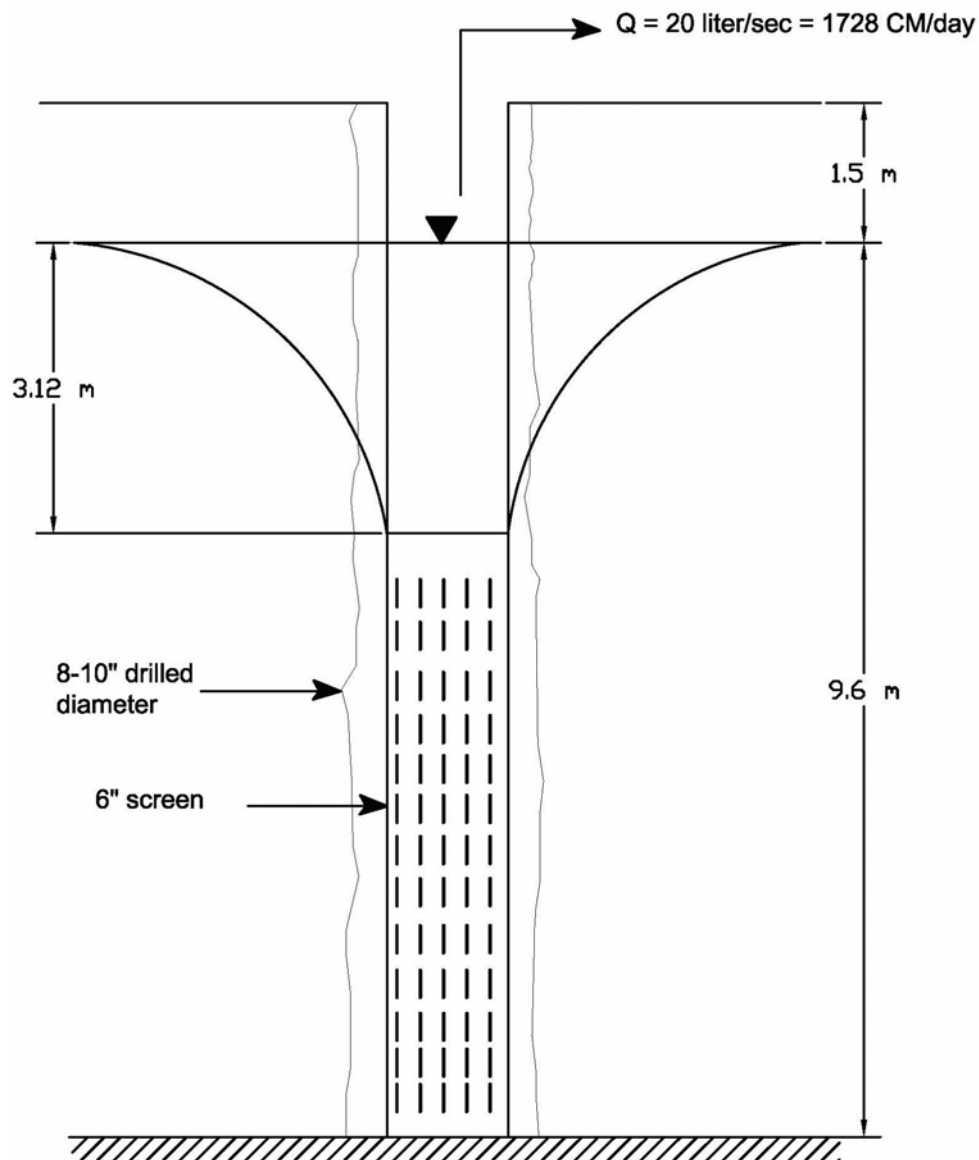
$$\Rightarrow A = 0.0133 \text{ m}^2$$

$$\text{but, } A = \frac{\pi d^2}{4} \Rightarrow d^2 = \frac{4 \times A}{\pi} \Rightarrow d = \sqrt{\frac{4A}{\pi}}$$

$$\Rightarrow d = 0.13 \text{ m}$$

Use 6" screen diameter

(Pump size) - Use 4" diameter



Example 5.2: Gravel Pack Design

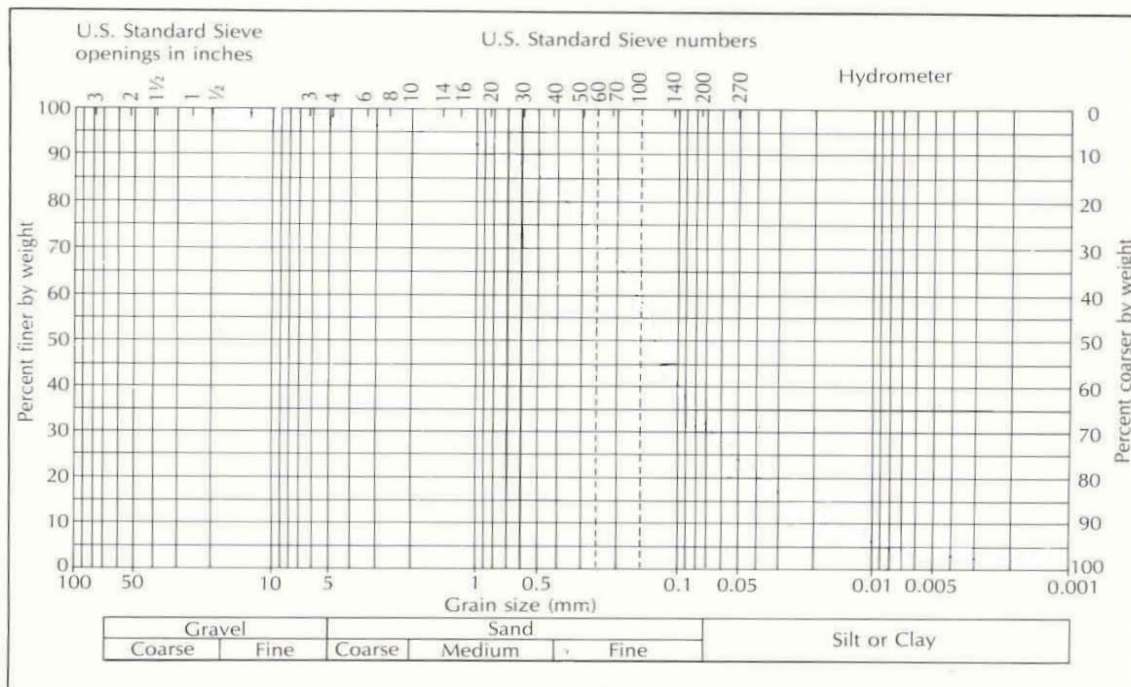
The following table gives the results of a sieve analysis of formation samples taken during drilling of a borehole for water well.

Sieve size	Mass retained (kg)
2	0
1	0.24
0.5	0.50
0.25	0.78
0.125	0.30
0.063	0.05
Mass passing through 0.063	0

- Describe the main functions of an artificial gravel pack.
- Construct a grain size distribution curve (Use the attached paper).
- Confirm that an artificial gravel pack is required.
- Construct a grading curve for the gravel pack (Use the same attached paper).
- Suggest a suitable screen slot size.
- What are the main problems that can occur when installing gravel and suggest how they can be kept to a minimum?

Hint

Uniformity coefficient = D_{60} / D_{10}



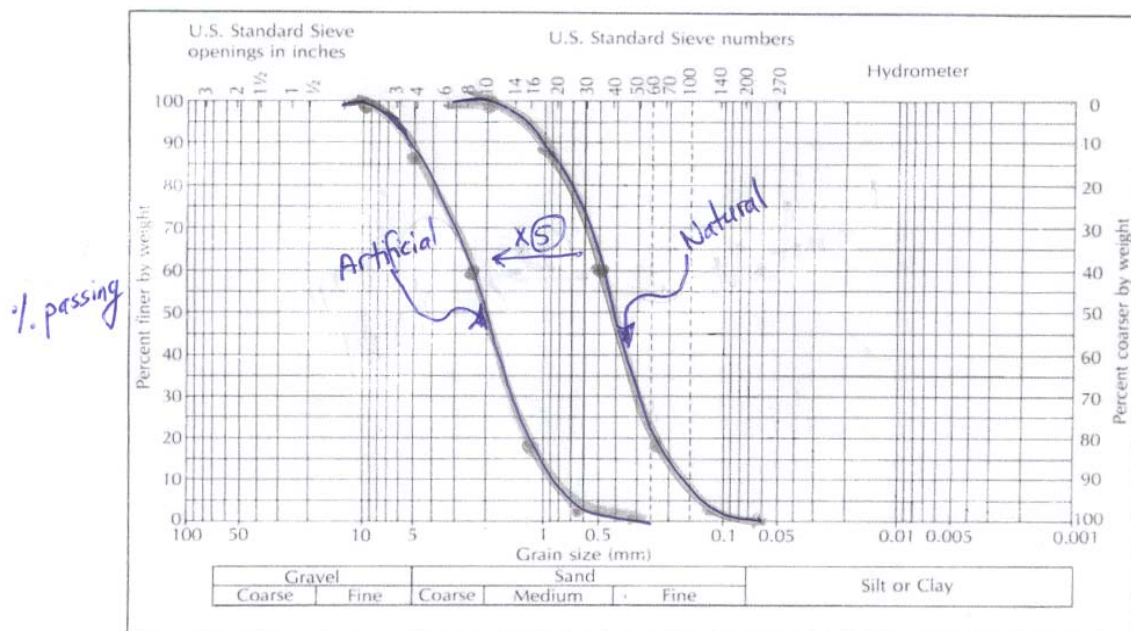
Grain-size distribution curve of a silty fine to medium sand.

Answer 5.2

Sieve size (mm) (Natural)	Mass retained (kg)	Cumulative mass passing (Kg)	% Passing	Artificial grain size (mm) = natural x 5
2	0	1.87	100	10
1	0.24	1.63	87	5
0.5	0.50	1.13	60	2.5
0.25	0.78	0.35	19	1.25
0.125	0.30	0.05	3	0.625
0.063	0.05	0	0	0.315
Mass passing through 0.063	0	0	0	These values are the sizes for gravel pack
	Sum = 1.87 kg			

a. 1. Prevention of fines in well, 2. increase effective hydraulic radius, 3. support formation and prevent collapse leading to damage, 4. laterally restrain and effectively strengthening casing.

b. the grain size distribution curve is shown below:



Grain-size distribution curve of a silty fine to medium sand.

c. the artificial gravel pack is required, because:

- ✓ Uniformity Coefficient = $D_{60} / D_{10} = 0.5 / 0.172 = 2.91 < 3$.
- ✓ $D_{10} = 0.172 \text{ mm} < 0.25 \text{ mm}$

d. See the graph above.

e. Size of screen slot is 85% retained, i.e. 15% pass the gravel pack = **1.3 mm**

f. Problems and solutions are:

- ✓ **Problems:** segregation and bridging
- ✓ **Solutions:** installation using treimie pipe or reverse circulation

Example 5.3: Gravel Pack Design

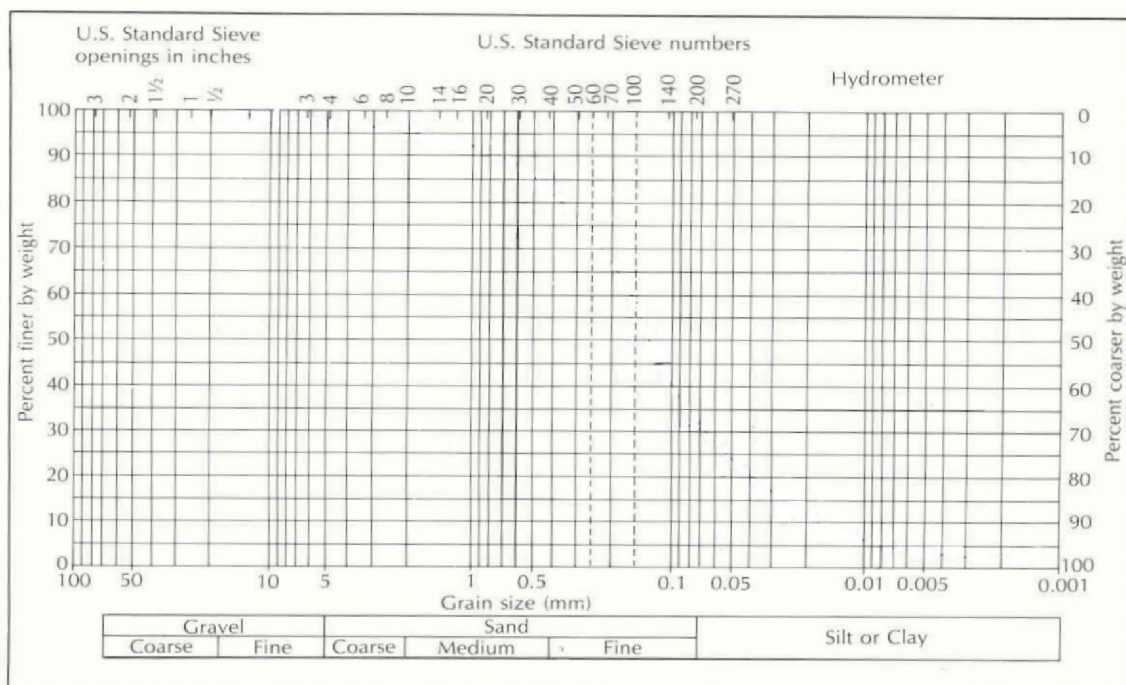
The following table gives the results of a sieve analysis of formation samples taken during drilling of a borehole for water well.

Sieve size	Mass retained (kg)
2	0
1	0.24
0.5	0.50
0.25	0.78
0.125	0.30
0.063	0.05
Mass passing through 0.063	0

- Describe the main functions of an artificial gravel pack
- Construct a grain size distribution curve (Use the attached paper)
- Confirm that an artificial gravel pack is required.
- Construct a grading curve for the gravel pack (Use the same attached paper)
- Suggest a suitable screen slot size
- What are the main problems that can occur when installing a gravel and suggest how they can be kept to a minimum.

Hint

Uniformity coefficient = D_{60} / D_{10}



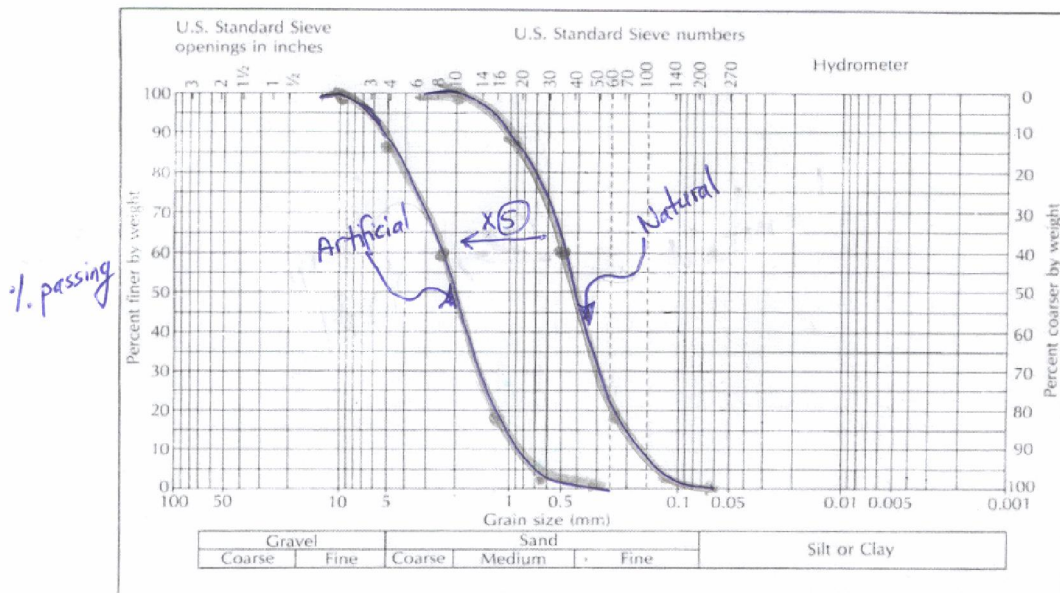
Grain-size distribution curve of a silty fine to medium sand.

Answer for Example 5.3

Sieve size (mm) (Natural)	Mass retained (kg)	Cumulative mass passing (Kg)	% Passing	Artificial grain size (mm) = natural x 5
2	0	1.87	100	10
1	0.24	1.63	87	5
0.5	0.50	1.13	60	2.5
0.25	0.78	0.35	19	1.25
0.125	0.30	0.05	3	0.625
0.063	0.05	0	0	0.315
Mass passing through 0.063	0	0	0	These values are the sizes for gravel pack
	Sum = 1.87 kg			

a. 1. Prevention of fines in well, 2. increase effective hydraulic radius, 3. support formation and prevent collapse leading to damage, 4. laterally restrain and effectively strengthening casing.

b. the grain size distribution curve is shown below:



Example 5.4: Design of a tube well

Design a tube well assembly to match the strata chart shown in Figure 5.17. The grain-size distribution curve of the aquifer lying between 40 m and 85 m is given in Figure 5.18. The anticipated drawdown is 5 m. The seasonal fluctuation of the water table is 1 m. The hydraulic conductivity is 0.0003216 m/sec and the expected discharge of the well is 0.05 m³/sec.

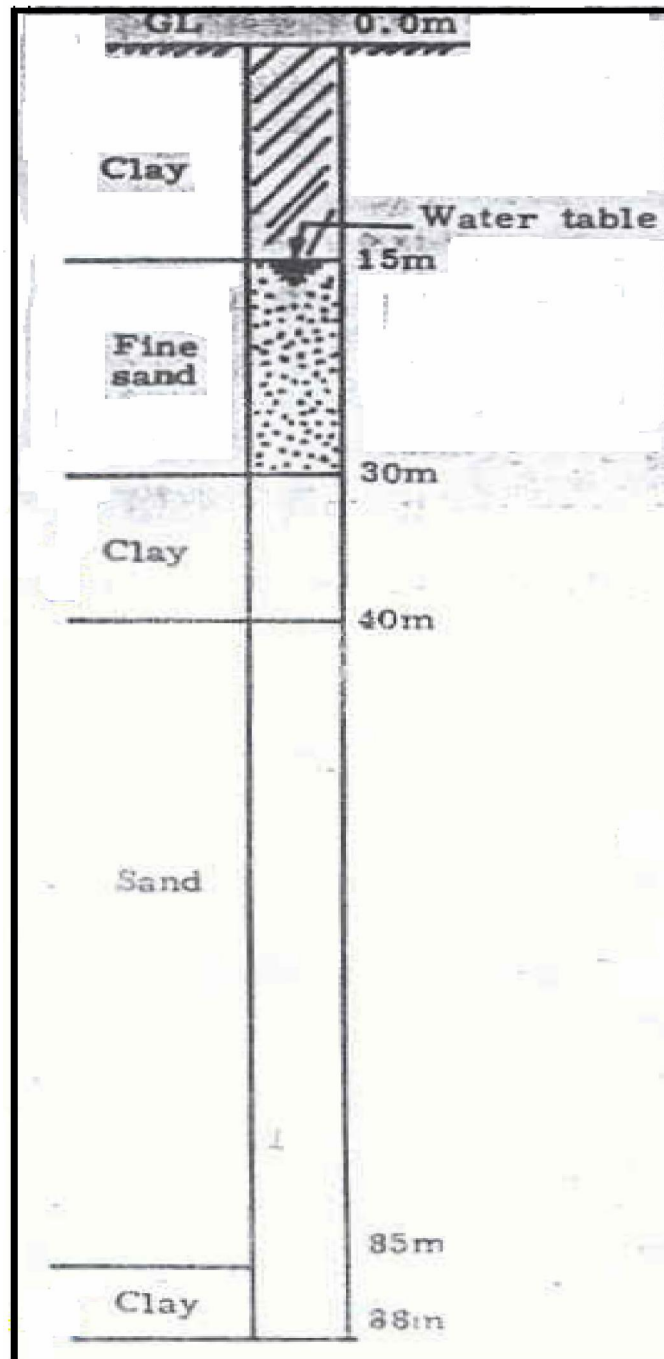


Figure 5.17 Well log

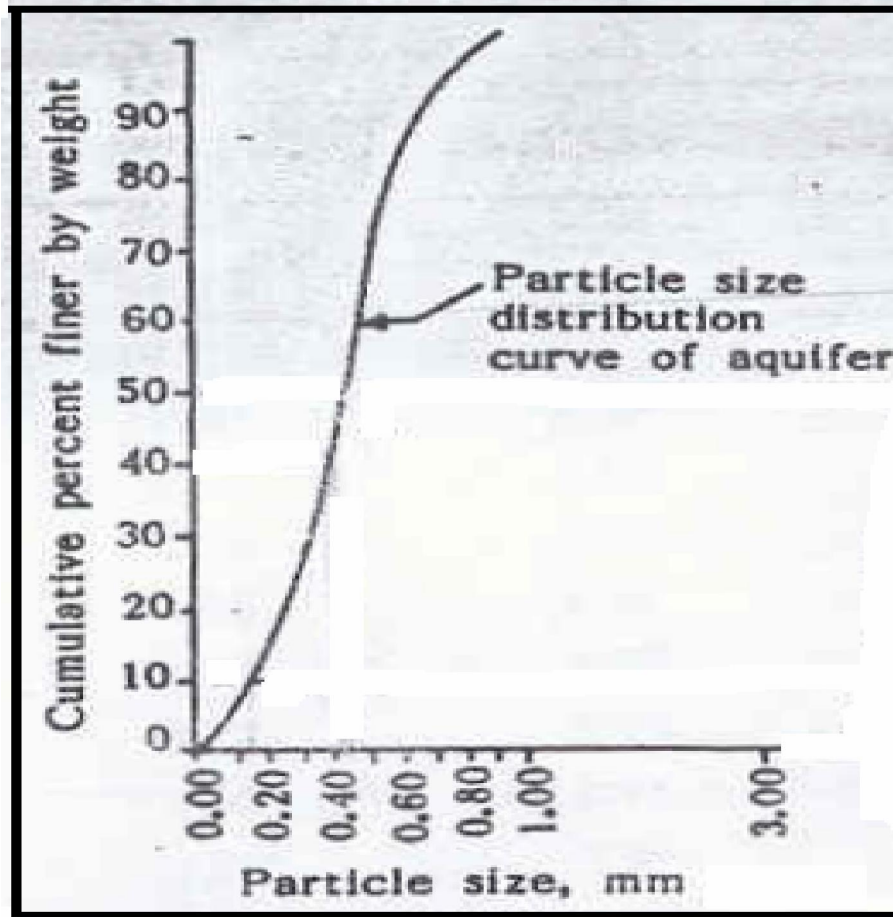


Figure 5.18 grain-size distribution curve of the aquifer

You may use the following tables in the design.

Table 5.4 Diameter and thickness of housing pipes of the tube wells for different sizes of turbines/submersible pumps

Discharge (l/min)	Nominal diameter of pump (cm)	Diameter of housing pipe (cm)	Thickness of housing pipe (mm)
475	12.5	15.0 – 20.0	1.5 – 3.5
1150	15.0	20.0 – 25.0	1.5 – 3.5
2275	20.0	25.0 – 30.0	2.0 – 3.5
4550	30.0	35.0	2.0 – 5.0
7500	35.0	40.0	2.0 – 6.0
11500	40.0	45.0	2.0 – 6.0

Table 5.5 Suggested Thickness of well casing pipe, mm

Depth of well m	Diameter of well casing, cm				
	15	20	25	30	35
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

Table 5.6 Recommended Diameter of casing pipe and well screen

Discharge (l/min)	Casing pipe / screen diameter, cm	
	Minimum	Recommended
475	10	10
475 – 1125	15	15
1125 – 3000	20	25
3000 – 5250	25	30
5250 – 9500	30	35
9500 - 13300	35	40

Hint: Minimum length of screen $= h = \frac{Q_o}{A_o V_o}$,

Where,

- Q_o maximum expected discharge (m³/min),
 A_o effective open area per meter length of the well screen (m²),
 V_o entrance velocity at the screen (m/min)

Answer for Example 5.4

1. Design of Housing Pipe

- ü Diameter: The diameter should be large enough to accommodate the pump, with adequate clearance for installation. For a given discharge 3000 l/min (0.05 m³/sec), the nominal diameter of the pump is 30 cm and the recommended diameter of housing pipe is 35 cm. (see Table 5.4).
- ü Thickness of housing pipe: Referring to table 5.4, the thickness of the housing pipe may be taken as 3 mm.
- ü Depth: Depth of housing pipe = Static water level below ground level + drawdown + seasonal fluctuation + allowance for submergence of pump

Assume the allowance for submergence to be 5.5 m.

Assume the clearance between pump and bottom of housing pipe to be 0.5m.

So, the depth of housing pipe = 15 + 5 + 1 + 5.5 + 0.5 = 27 m.

2. Design of Well Casing Pipe

- ü Diameter: Assuming a flow velocity of 1.5 m/sec, for a discharge of 0.05 m³/sec (3000 l/min), the cross-sectional area of the casing pipe,

$$Q = V \times A \Rightarrow A = \frac{Q}{V} = \frac{0.05 \text{ m}^3/\text{sec}}{1.5 \text{ m/sec}}$$

$$\Rightarrow A = 0.0333 \text{ m}^2$$

$$\text{but, } A = \frac{\pi \times d^2}{4} \Rightarrow d^2 = \frac{4 \times A}{\pi} \Rightarrow d = \sqrt{\frac{4 \times A}{\pi}}$$

$$\Rightarrow d = 0.206 \text{ m} = 20.6 \text{ cm}$$

However, referring to table 5.6, the minimum diameter of casing pipe for a discharge of 3000 l/min is 20 cm, which is lower than the calculated value. Hence, a plain pipe of 25-cm diameter is selected

- ü Thickness: Referring to table 5.5 for a 25-cm diameter, 87 m deep well, the thickness of a pipe is 2.78 mm.

3. Design of Gravel Pack

The grain size distribution curve of the aquifer material is given in Figure 5.5. The grain sizes d_{10} , d_{50} and d_{60} are 0.13, 0.32, and 0.36 mm, respectively.

The uniformity coefficient is $d_{60}/d_{10} = 0.36/0.13 = 2.8 < 3$ and $d_{10} = 0.13 < 0.25$ mm. it is apparent that the aquifer cannot be developed naturally, and artificial gravel packing has to be provided.

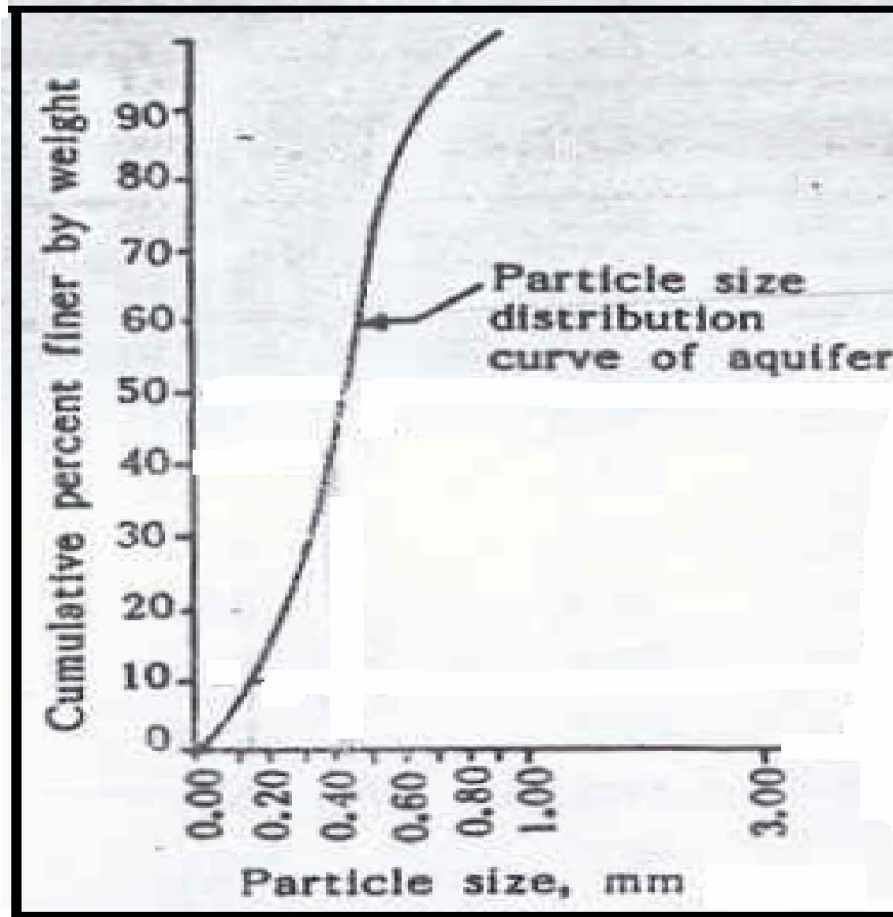


Figure 5.18 grain-size distribution curve of the aquifer

You may use the following tables in the design.

Table 5.4 Diameter and thickness of housing pipes of the tube wells for different sizes of turbines/submersible pumps

Discharge (l/min)	Nominal diameter of pump (cm)	Diameter of housing pipe (cm)	Thickness of housing pipe (mm)
475	12.5	15.0 – 20.0	1.5 – 3.5
1150	15.0	20.0 – 25.0	1.5 – 3.5
2275	20.0	25.0 – 30.0	2.0 – 3.5
4550	30.0	35.0	2.0 – 5.0
7500	35.0	40.0	2.0 – 6.0
11500	40.0	45.0	2.0 – 6.0

- ü Diameter of well screen: The diameter of the well screen is usually kept the same as that of the casing pipe. Hence, it may be kept as 25 cm.
- ü Screen length: The effective area per meter length of the well screen is given by

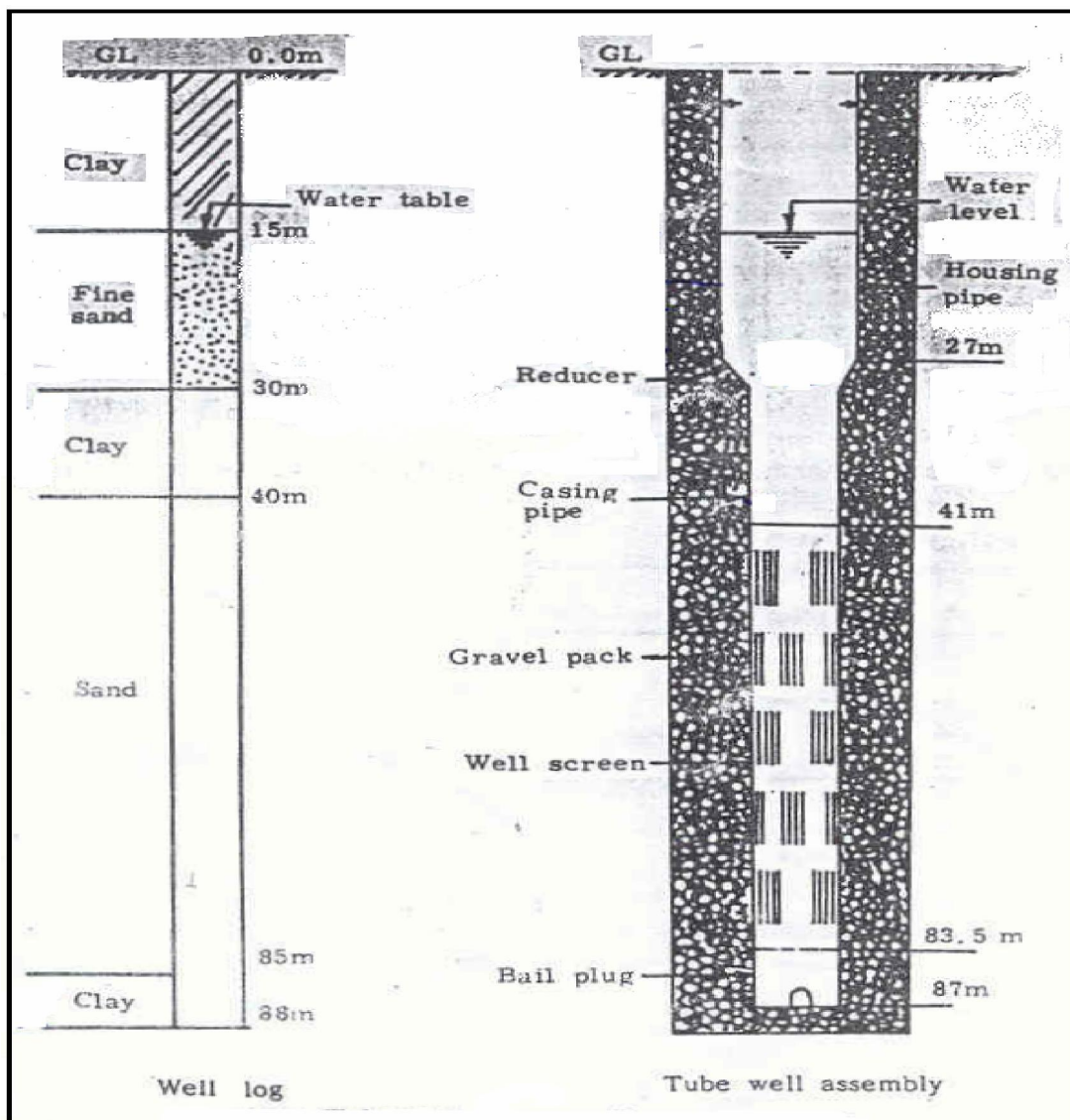
$$A_o = \pi d \times \% \text{ of open area} = \pi \times 0.25 \times 0.1 = 0.078 \text{ m}^2$$

V_o assume to be 1.8 m/min

$$Q_o = 3000 \text{ l/min} = 3 \text{ m}^3/\text{min}$$

$$\text{Then, } h = 3 / (0.078 \times 1.8) = 26.45 \text{ m, say } 27 \text{ m.}$$

The aquifer thickness is 45 m. Therefore, it is desirable to provide about 40 m length of screen, which is more than 27 m and about 90 percent of the aquifer depth. The screen may be provided in the central portion of the aquifer, leaving equal depths untapped at both ends. The design details are illustrated in the following figure.



Tube well pipe assembly to suit well log

ECONOMIC DESIGN OF WELLS



1. Introduction

The cost of water from a well depends upon **the capital invested** and **the annual recurring costs**. A large part of the recurring element derives from the cost of pumping. Capital costs and pumping costs are interdependent to the degree that the design of the well affects the drawdown and thus the pumping cost. For example, a short screen section will produce a larger drawdown than a long screen for a given discharge. Thus saving in capital is offset by increased pumping costs. Similarly a screen of small diameter produces large entry and upflow losses and again increased recurring costs. For each chosen design parameter there is an optimum solution for least cost. This session is concerned with the determination of such least cost solutions.

1. Introduction

The principle of the analysis is to produce an equation representing the total cost in terms of a single design parameter and to apply a discount cash flow procedure to calculate the present value. Differentiation of the present value expression with respect to the chosen parameter leads to the determination of the optimum value of that parameter for minimum cost.



2. Principles of Economic Well Design

In designing wells, the objective is **to produce water for the least cost**. In economic analysis, a distinction is normally made between **economic and financial cost concepts** and the general principles outlined in this session are valid for either approach. The cost of drilling and operating a well comprises the capital investment plus annual recurring costs. A conventional discounting procedure can be applied to these costs and a present value obtained. It is this present value which must be minimized to obtain the optimum well design.



2. Principles of Economic Well Design

Capital and recurring costs of wells are closely interdependent because in a deep aquifer any changes in well screen length, in diameter, or in discharge may affect the drawdown in a well and thus the total head through which the water must be pumped. For example, large diameter well screen and liner may substantially reduce pipe losses. Thus, an increase in capital cost will reduce pumping head and hence pumping costs. Somewhere there is an optimum.



2. Principles of Economic Well Design

The costs of a well can be presented as a functions of the various parameters involved, (see **Figure 2.1**):

$$\text{Capital cost} \quad C = F_1(D, W, \phi, s_w)$$

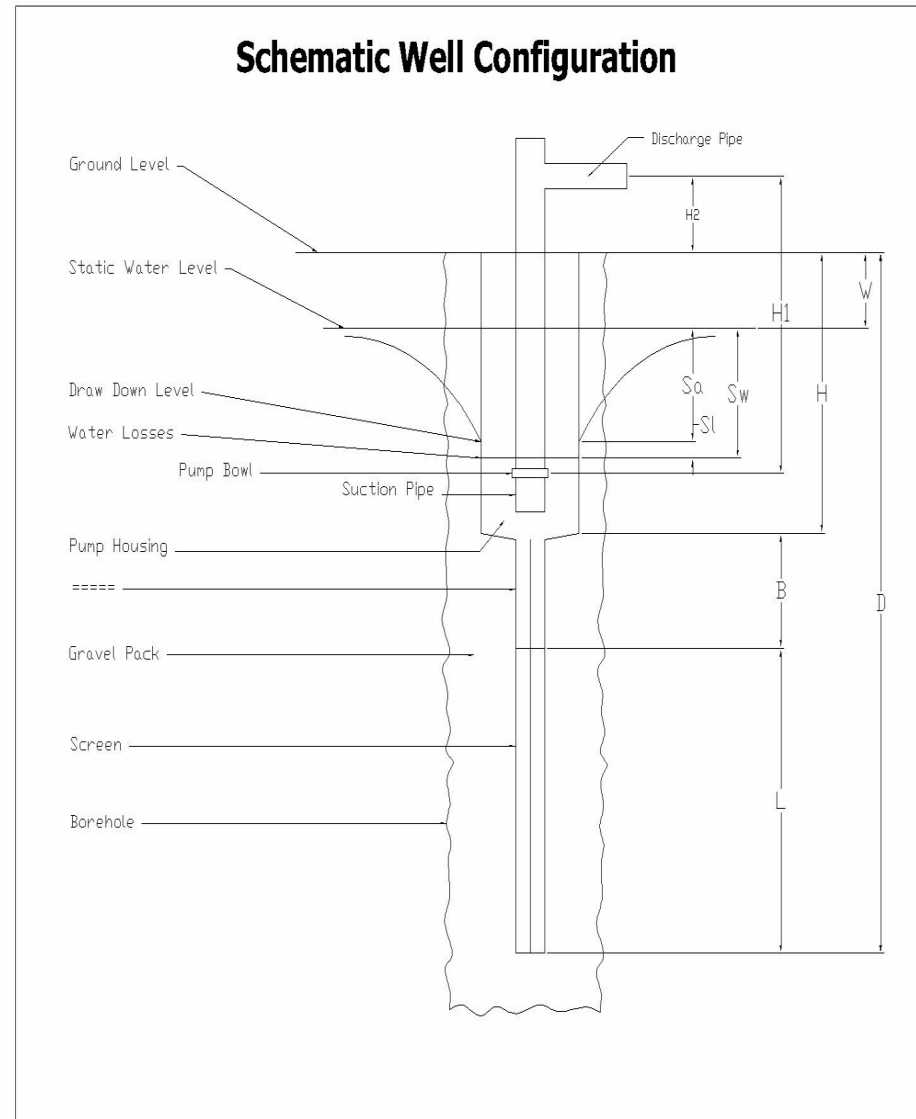
$$\text{Recurring cost} \quad c = F_2(H_2, Q, s_w, m, t)$$

where,

- D** total depth of well
- W** depth of water table or piezometric surface below ground level
- Φ** non-specific diameter
- s_w** drawdown of water level in the well
- H_2** distance between ground level and discharge pipe
- Q** discharge
- m** maintenance cost
- t** hours pumped per year

2. Principles of Economic Well Design

Figure 2.1 Schematic well configuration



2. Principles of Economic Well Design

If $c_1, c_2, \dots, c_n$ represent recurring costs in the years 1 to n , then:

$$\text{Present value } PV = C + c_1 f_1 + c_2 f_2 + \dots + c_n f_n$$

$$f_n = \frac{1}{\left(1 + \frac{r}{100}\right)^n}$$

where,

n is the life of the well in years,
 f_n is the discount factor as shown,
 r is the interest rate percent per annum. Usually values for f are taken from standard tables.

2. Principles of Economic Well Design

By partially differentiating the PV with respect to any of the variables and equating to zero, the optimum value of each variable can be determined for minimum cost.

Thus, **$d \text{ PV} / d L = 0$** would give the optimum screen length for a fixed discharge, diameter, interest rate, and time of pumping. By examining the various partial differentials in turn the well design can be optimized.



3. Inter-relationships Between The Variables

Solutions to the equations depend upon the relationships between **Q**, **s_w**, **d** (diameter of flow conduit “pipe or casing”) and **L** (length of screen). These relationships are entirely empirical and have been derived from a large number of well tests.

For a uniform aquifer, which is deep compared with all likely screen length. The drawdown in the well (**s_w**) is the same as the drawdown in the aquifer (**s_a**), for wells of zero well losses, and at equilibrium:

$$s_w = \frac{AQ}{KL}$$

3. Inter-relationships Between The Variables

To account for the well loss (s_l), the relationship derived by Rorabaugh (1953) gives:

$$s_w = BQ + CQ^n$$

or

$$S_w = S_a + S_l$$

in these equations, **A**, **B**, and **C** are constants and **K** is the hydraulic conductivity of the aquifer. Well losses are presented by the term **CQⁿ** and can be broken down further into screen entrance losses and pipe losses in the well.

For most practical cases of wells correctly designed, entrance losses should be negligible and may be disregarded.

3. Inter-relationships Between The Variables

The manner in which costs relate to the variable parameters is not easy to obtain.

For example, while it is fairly easy to abstract well costs from a contractor's tender, it is more difficult to determine just how these costs might change if the diameter of the well was increased; heavier equipment might be required than that assumed in pricing an existing tender.

Similarly, to obtain a complete matrix of pump price variations with different discharges, pump settings, and total delivery heads is more than many manufacturers are willing to provide.

4. Calculation Of The Present Value (PV)

To calculate PV, one should follow the following procedures:

1. It is necessary to reduce the number of variables in the capital cost.

$$s_w = \frac{1.25Q}{KL}$$

The dimensional relationships used in the simplification may be derived from **Figure 2.1** and are for a particular case:

$$H_1 = W + H_2 + 1.25s_w$$

$$H = H_1 - H_2 + 3.6$$

$$D = H + B + L$$

4. Calculation Of The Present Value (PV)

These allow for:

- ✓ the mean drawdown throughout the well's life to be 25% greater than the initial value,
 - ✓ a pump housing length **H** to induce an extra **3.6 m (12 ft)** below the pump bowl, **3 m (10 ft)** for the length of suction pipe and **0.61 m (2 ft)** for the end clearance.
2. The capital cost must be derived from the collected and estimated data.
 3. The recurring costs “running costs” must be derived from the collected and estimated data.

4. Calculation Of The Present Value (PV)

4. Note, when the running cost is the same every year, it can be discounted to present value by using a single factor which is dependent on the life of the project and the discount rate adopted. **For example**, if a life of 20 years is used and an interest rate of 10%, then the **discount factor** is **$f = 8.5136$** , and the present value of the total cost is **$PV = C + 8.5136c$** . since,

$$\text{Running cost} = c_1 f_1 + c_2 f_2 + \dots + c_n f_n$$

$$\text{but in this case } c_1 = c_2 = \dots = c_n$$

$$\text{so, running cost} = c(f_1 + f_2 + \dots + f_n) = c f$$

$$f_n = \frac{1}{\left(1 + \frac{r}{100}\right)^n}$$

And, $f_1 = 1/1.1^1 = 0.909$, $f_2 = 1/1.1^2 = 0.826$, $f_3 = 1/1.1^3 = 0.751$,
 $f_4 = 0.683$, ... , $f_{20} = 1/1.1^{20} = 0.147$.

So, **discount factor (f)** = $f_1 + f_2 + \dots + f_{20} = 8.5136$

4. Calculation Of The Present Value (PV)

5. Now, the total cost can be determined, which is the sum of capital costs and running costs.

Present value $PV = C + c_1 f_1 + c_2 f_2 + \dots + c_n f_n$

5. Optimum Screen Length

For minimum present value, the partial differential of present value with respect to screen length must equal to zero (see **Figure 4.1**):

$$dPV/dL = 0$$

The method outlined above only gives the optimum for minimum overall cost, but it is interesting to examine the nature of that minimum and to test the sensitivity of the result to changes in the assumptions.



6. Optimum Discharge

By a similar process to that illustrated previously, the optimum discharge can be determined from the present value equation. But because the least cost in terms of Q occurs when the well is not pumped at all, it is necessary to consider the problem in terms of least cost of water per unit of discharge. Thus dividing the present value by the well capacity, as shown below:

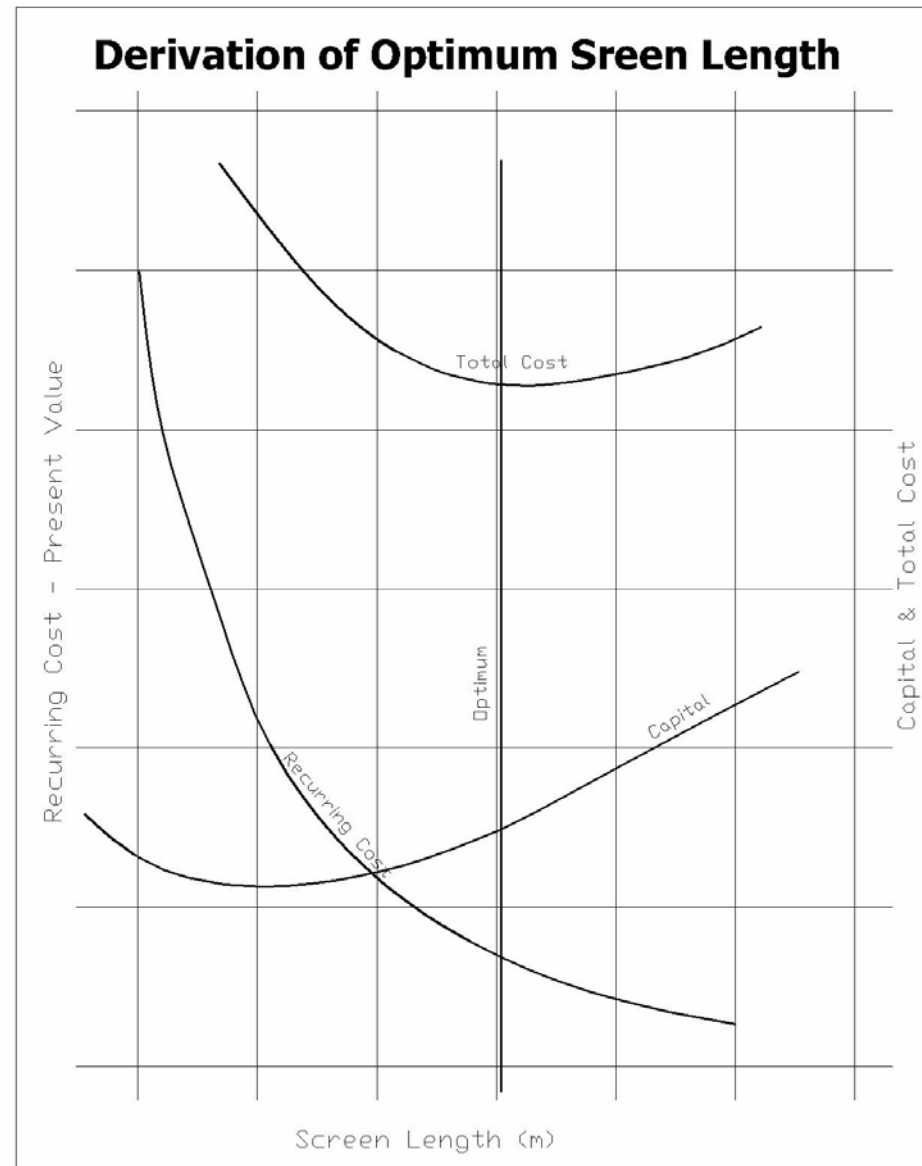
$$V = \frac{PV}{Q}$$

then ,

$$\frac{dV}{dQ} = 0$$

4. Calculation Of The Present Value (PV)

Figure 4.1 Derivation of optimum screen length



Example 5.5: Economic Design of Well

The following information relates to a well in an extensive aquifer:

AQUIFER: Unconfined

Maximum depth to static water	10 m
Hydraulic conductivity	40 m/day

PUMP:

Discharge	3000 m ³ /day
Recommended submergence (from operating water level in well to clearance below lowest part of pump)	2.5 m
Discharge delivery head (above ground level)	1.0 m

WELL DRAWDOWN:

Drawdown given by	$S = \frac{1.3Q}{KL}$
Factor of safety against deterioration in specific capacity	25%
Screen upflow losses (in metre-day units)	$2.0 \times 10^{-15} Q^2 L r_w^{-16/3} m$

COSTS:

Drilling and other related length costs	\$240/day
Upper well casing	\$130/day
Screen: 200 mm diameter	\$200/day
150 mm diameter	\$165/day
Fixed costs	\$20000
Pumping costs (Q in m ³ d ⁻¹ and H in m)	\$0.16QH/year
Discount factor	8.0

Determine the screen diameter and length which gives the minimum cost well.

Note: You may assume that there are no geological constraints on screen length or position. Screen is supplied in lengths which are multiples of a meter.

Answer for **Example 5.5**

For 200 mm diameter screen

CAPITAL COST

Fixed Capital cost = 20,000

Variable Capital Cost

$$\begin{aligned} \text{Drilling and other related costs} &= 240 [10 \text{ 'depth to static level' } + 2.5 \text{ 'recommended submergence' } + \text{total } s_w + L \text{ 'screen length'}] \\ &= 240 [12.5 + \text{total } s_w + L] \end{aligned}$$

$$\text{Upper well casing} = 130 [12.5 + \text{total } s_w]$$

$$\text{Screen} = 200 L$$

$$\text{Total variable capital costs (C)} = 4,625 + 370 \text{ total } s_w + 440 L$$

$$\begin{aligned} \text{but, Total drawdown} &= 1.25 \times [\text{drawdown of aquifer "s}_w\text{" } + \text{screen upflow losses}] \\ &= 1.25 \times \left[\frac{1.3Q}{KL} + 2.0 \times 10^{-15} Q^2 L r_w^{-16/3} \right] \\ &= 1.25 \times \left[\frac{1.3 \times 3000}{40 \times L} + 2.0 \times 10^{-15} 3000^2 L \times 0.1^{-16/3} \right] \\ &= 1.25 \times \left[\frac{97.5}{L} + 3.878 \times 10^{-3} L \right] \\ &= \frac{121.88}{L} + 4.848 \times 10^{-3} L \end{aligned}$$

$$\begin{aligned} \text{So, total variable capital costs} &= 4,625 + 370 \left[\frac{121.88}{L} + 4.848 \times 10^{-3} L \right] + 440 L \\ &= 4,625 + 441.8 L + \frac{45,095.6}{L} \end{aligned}$$

$$\text{TOTAL CAPITAL COST} = 24,625 + 441.8 L + \frac{45,095.6}{L}$$

OPERATING COSTS

$$c = 0.16QH, \text{ where } H = 10 + 1 + 2.5 + 1.25 \text{ total } s_w = [13.5 + 1.25 \text{ total } s_w]$$

$$c = 0.16 \times 3000 \times [13.5 + 1.25 \times (\frac{121.88}{L} + 4.848 \times 10^{-3} L)]$$

$$= 6,480 + \frac{73,128}{L} + 2.9 L$$

$$PV = cf = [6,480 + \frac{73,128}{L} + 2.9 L] \times 8 = 51,840 + \frac{585,024}{L} + 23.2 L$$

$$\text{Total PV} = [24,625 + 441.8 L + \frac{45,095.6}{L}] + [51,840 + \frac{585,024}{L} + 23.2 L]$$

$$= 76,465 + 465 L + \frac{630,119.6}{L}$$

$$\frac{dPV}{dL} = 465 - \frac{630,119.6}{L^2}$$

$$\text{For minimum cost } \frac{dPV}{dL} = 0$$

$$L^2 = \frac{630,119.6}{465} = 1355.1$$

$$L = 36.8 \text{ m}$$

$$\begin{aligned} \text{Cost} &= 76,465 + 465 \times 36.8 + \frac{630,119.6}{36.8} \\ &= \text{US \$ } 110,700 \end{aligned}$$

For 150 mm diameter screen

CAPITAL COST

Fixed Capital cost = 20,000

Variable Capital Cost

$$\text{Drilling and other related costs} = 240 [12.5 + \text{total } s_w + L]$$

$$\text{Upper well casing} = 130 [12.5 + \text{total } s_w]$$

$$\text{Screen} = 165 L$$

$$\text{Total variable capital costs (C)} = 4,625 + 370 \text{ total } s_w + 405 L$$

$$\text{but, Total drawdown} = 1.25 \times [\text{drawdown of aquifer "s}_w\text{" + screen upflow losses}]$$

$$= 1.25 \times \left[\frac{1.3Q}{KL} + 2.0 \times 10^{-15} Q^2 L r_w^{-16/3} \right]$$

$$= 1.25 \times \left[\frac{1.3 \times 3000}{40 \times L} + 2.0 \times 10^{-15} 3000^2 L \times 0.075^{-16/3} \right]$$

$$= 1.25 \times \left[\frac{97.5}{L} + 1.799 \times 10^{-2} L \right]$$

$$= \frac{121.88}{L} + 2.248 \times 10^{-2} L$$

$$\text{So, total variable capital costs} = 4,625 + 370 \left[\frac{121.88}{L} + 2.248 \times 10^{-2} L \right] + 405 L$$

$$= 4,625 + 413.32 L + \frac{45,095.6}{L}$$

$$\text{TOTAL CAPITAL COST} = 24,625 + 413.32 L + \frac{45,095.6}{L}$$

OPERATING COSTS

$$c = 0.16 \times 3000 \times \left[13.5 + 1.25 \times \left(\frac{121.88}{L} + 2.248 \times 10^{-2} L \right) \right] = 6,480 + \frac{73,128}{L} + 16.86 L$$

$$\text{PV} = \text{cf} = \left[6,480 + \frac{73,128}{L} + 16.86 L \right] \times 8 = 51,840 + \frac{585,024}{L} + 134.88 L$$

$$\begin{aligned}
 \text{Total PV} &= [24,625 + 413.32 L + \frac{45,095.6}{L}] + [51,840 + \frac{585,024}{L} + 134.88 L] \\
 &= 76,465 + 548.2 L + \frac{630,119.6}{L}
 \end{aligned}$$

$$\frac{dPV}{dL} = 548.2 - \frac{630,119.6}{L^2}$$

$$\text{For minimum cost } \frac{dPV}{dL} = 0$$

$$L^2 = \frac{630,119.6}{548.2} = 1,149.43$$

$$L = 33.9 \text{ m}$$

$$\begin{aligned}
 \text{Cost} &= 76,465 + 548.2 \times 33.9 + \frac{630,119.6}{33.9} \\
 &= \text{US\$ } 113,637
 \end{aligned}$$

So, the cheapest option is to use 37 m of 200 mm screen

Example 5.6: Economic Design of Well

You have been asked to produce a least cost design for a new well penetrating a confined aquifer. Given the following cost information and design data, determine the optimal single string well design.

AQUIFER DATA

Top of aquifer	25 m/bgl
Base of aquifer	80 m/bgl
Average Piezometric Surface	10 m/bgl
Yearly Fluctuation	+/- 1.0 m
Long term yearly av. Fluctuation	+/- 4.0 m
Long term drawdown	6.0 m
Average Hydraulic Conductivity	20 m/day

WELL MATERIAL COST

Pump Chamber Casing	\$ 50/m
Well Screen	\$ 80/m
Drilling	\$ 35/m
Reducer	\$ 175
Bail Foot	\$ 60
Gravel Pack	\$ 20/m
Pump Installation	\$ 2500

OPERATING COSTS

$$c = 1.58 \times 10^{-4} \times Q \cdot H \cdot t$$

where, Q = discharge m³/day

H = water lift (m)

t = time in days

DESIGN CONSIDERATION

Well Life	20 years
Pump Replacement	every 8 years
Well Deterioration	1%/ year
(i.e. an increase in the drawdown in the well of 1% each year)	
Pump sitting	1 m
Well losses	0.1 s _w
Safety against deterioration	3 m

EQUATIONS

Drawdown given by	$S_w = \frac{1.3Q}{KL}$
Present Value	$NPV(A) = \frac{A[(1+r)^n - 1]}{r(1+r)^{n-1}}$

Where, A: annuity, r: interest rate, n: number of years.

HINT

Formulate all the equations in terms of Q and L, then find the least cost and the optimal screen length when Q was 10, 20, and 30 l/s

Answer for Example 5.6

ü CAPITAL COST

(i) Pump chamber casing (PC)

Pump chamber length= 10 (average piezometric surface) + 4 (long term fluctuation) + 1 (yearly fluctuation) + 6 (long term drawdown) + 1 (pump sitting) + 3 (safety) + s_w (drawdown) + 20% s_w (1% an increase in the drawdown for each year) + 10% s_w (10% of the drawdown for the well losses).

$$PCL = 10 + 4 + 1 + 6 + 1 + 3 + s_w + 0.2s_w + 0.1s_w$$

$$PCL = 25 + 1.3 s_w$$

$$\text{But, } S_w = \frac{1.22Q}{KL}$$

$$\text{Then P.C.L} = 25 + \frac{1.59Q}{20L_s} = 25 + \frac{0.0793Q}{20L_s}$$

Assume that the peak discharge is 10 l/sec = 864 m³/day.

$$\text{Then, P.C.L} = 25 + \frac{68.5}{L_s}$$

$$\text{But, cost of P.C} = \$ 50/\text{m} = 50 \left[25 + \frac{68.5}{L_s} \right] = 1250 + 3425/L_s$$

So,

	L_s (m)	Cost of the pump chamber length (\$)
ü	10	1592.5
ü	20	1421.25
ü	30	1346.17
ü	40	1335.6
ü	50	1318.5

(ii) Well screen (L_s) = cost of well screen = 80 L_s

(iii) Drilling length = L_s + PCL + length of reducer + Length of bail foot

$$= L_s + 25 + \frac{68.5}{L_s} + 1 + 2$$

$$= 28 + L_s + \frac{68.5}{L_s}$$

$$\text{Cost of drilling} = 25 \left[28 + L_s + \frac{68.5}{L_s} \right]$$

$$= 980 + 35 L_s + 2397.5 / L_s$$

(iv) Cost of Bail foot = \$ 60

(v) Cost of Reducer = \$ 175

(vi) Gravel Pack

The pack will cover the length of the screen + extra length for operating + length of reducer + length of bail foot.

$$\begin{aligned}\text{Length of gravel pack} &= L_s + (4 \text{ extra}) + 1 + 2 \\ &= L_s + 7\end{aligned}$$

$$\text{Cost of gravel Pack} = 20 [L_s + 7] = 20 L_s + 140$$

So, the Capital Costs = cost of pump chamber length + cost of well screen length + cost of drilling + cost of bail foot + cost of reducer + cost of gravel pack

$$= 1250 + 3425/L_s + 80 L_s + 980 + 35 L_s + 2397.5 / L_s + 60 + 175 + 20 L_s + 140$$

$$\text{Capital cost} = 2605 + 135 L_s + 5822.5/L_s$$

L_s (m)	Capital Costs (\$)
ü 10	4537.25
ü 20	5596.13
ü 30	6849.1
ü 40	8150.5
ü 50	9471.5

ü RUNNING COST

$$R_c = 1.58 \times 10^{-4} \times Q.H.t$$

$$Q = 864 \text{ m}^3/\text{day}$$

t = here we assume that the operating is 24 hours/day, so t = 365 day

$$\begin{aligned}H &= \text{water lift} = \text{Distance above the ground level we want to lift the water to it} + \\ &\quad \text{water table below ground level} + \text{drawdown} + \text{well losses} (0.1 s_w) \\ &= 1 + 10 + s_w + 0.1 s_w = H\end{aligned}$$

but we know that the drawdown is fluctuated along the life of the well so we take the average of that = $(0.1+0.2)s_w/2 = 0.105 s_w$

$$\text{Finally, } H = 11 + 1.1 s_w + 0.105 s_w = 11 + 1.205 s_w$$

$$\text{But, } s_w = \frac{1.22Q}{KL} = 1.22 \times 864 / 20L_s = 52.704 / L_s$$

$$\text{Then, } H = 11 + 63.51/L_s$$

$$\text{So, } R_c = 1.58 \times 10^{-4} \times 864 \times [11 + 63.51/L_s] \times 365$$

$$R_c = 548 + 3164.5/L_s$$

So, we need to calculate the Net Present Value (NPV) of Running cost (Rc)

$$NPV(A) = \frac{A[(1+r)^n - 1]}{r(1+r)^{n-1}} = [548 + 3164.5/L_s] \times \frac{1.1^{20} - 1}{(0.1)(1.1)^{19}}$$

$$NPV_1 = [5132 + 29635/L_s]$$

Then, for installation after 8 years $NPV_2 = 2500 \times \frac{1}{(1+0.1)^8} = 1166$

For installation after 8 years $NPV_3 = 2500 \times \frac{1}{(1+0.1)^{16}} = 544$

Running Costs = $NPV_1 + NPV_2 + NPV_3 = 6842 + 29635/L_s$

ü TOTAL COST

L_s (m)	Running costs (\$)	Capital Costs (\$)	Total Costs (\$)
ü 10	9806	4537	14343
ü 20	8324	5596	13920
ü 30	7830	6849	14679
ü 40	7583	8150	15733
ü 50	7435	9472	16907

So, Design $L_s = 20$ m , with total cost = US \$ 13920

Example 5.7: Economic Design of Well

The following information relates to a well in an extensive alluvial aquifer:

AQUIFER: Unconfined

Maximum depth to static water	5 m
Hydraulic conductivity	50 m/day

PUMP:

Recommended submergence (from operating water level in well to clearance below lowest part of pump)	2.5 m
Discharge delivery head (above ground level)	1.0 m

WELL DRAWDOWN:

Drawdown given by	$S = \frac{1.3Q}{KL}$
Factor of safety against deterioration in specific capacity	25%

COSTS:

Drilling and other related length costs	\$ 300/m
Upper well casing	\$ 120/m
Screen	\$ 200/m
Fixed costs	\$ 15,000
Pumping costs	\$ 0.14QH/ year

Where, Q: the pump discharged (m³/day).

H: the total pumping head (m).

Discount factor	8.0
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- I. Obtain an expression for the total cost of the well in terms of Q and L
- II. Determine the optimum screen length for a discharge of 2000 m³/day
- III. Calculate the discharge that will provide the cheapest water for a screen length of 15 m

Answer for **Example 5.7**

(i)

$$s_w = 1.25 \times \frac{1.3Q}{50L} = 0.0325 \frac{Q}{L}$$

$$\begin{aligned} \text{Capital costs} &= \left(5 + 2.5 + 0.0325 \frac{Q}{L} \right) (300 + 120) + L(300 + 200) \\ &= 3150 + 13.65 \frac{Q}{L} + 500L \end{aligned}$$

$$\begin{aligned} \text{Operating costs} &= 0.14 \times Q \times \left(1 + 5 + 0.0325 \frac{Q}{L} \right) \times 8 \\ &= 6.72Q + 0.0364 \frac{Q^2}{L} \end{aligned}$$

$$\text{Total Cost} = 3150 + 13.65 \frac{Q}{L} + 500L + 6.72Q + 0.0364 \frac{Q^2}{L}$$

(ii)

$$\frac{\partial C}{\partial L} = -\frac{13.65Q}{L^2} + 500 - \frac{0.0364Q^2}{L^2}$$

For minimum C

$$\frac{13.65Q + 0.0364Q^2}{500} = L^2$$

For a discharge of $2000 \text{ m}^3 / \text{day}$

$$L = 18.6 \text{ m}$$

(iii)

$$\frac{C}{Q} = \frac{3150}{Q} + \frac{13.65}{L} + 500 \frac{L}{Q} + 6.72 + 0.0364 \frac{Q}{L}$$

For cheapest water

$$\frac{\partial(C/Q)}{\partial Q} = -\frac{3150}{Q^2} - \frac{500L}{Q^2} + \frac{0.0364}{L} = 0$$

So,

$$Q^2 = \frac{(500L + 3150)L}{0.0364}$$

when $L = 15 \text{ m}$

$$Q = 2095 \text{ m}^3 / \text{day}$$

Example 5.8: Economic Design of Well

Determine the optimum screen length for a well to pump 2000 m³/day to be constructed in an extensive alluvial aquifer using the following information:

AQUIFER PARAMETERS AND DRAWDOWN CONSIDARATIONS

Hydraulic conductivity	45 m/day
Drawdown in the well is given by	$S_w = \frac{1.25Q}{KL}$
Drawdown safety factor	25%

UNIT CONSTRUCTION COSTS

Drilling and other related length costs	\$ 200/m
Upper well casing	\$ 40/m
Well Screen (0.15 m diameter)	\$ 100/m

OPERATING COSTS

Annual Pumping Costs	\$ 0.1QH/ year
Where, Q: the pump discharged (m ³ /day).	
H: the total pumping head (m).	

Discount factor	7.0
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You may assume that

- (i) Well and friction losses are small.
- (ii) There are effectively no geological constraints on screen length or position.

If a 0.1 m diameter well screen (costing \$ 70/m) of the same length were to be used, what would be the extra overall cost or saving?

Assume in this case that upscreen losses are given by

$$2.0 \times 10^{-15} Q^2 L r_w^{-16/3} m$$

Answer for 5.8

1. Optimum screen length

- Capital cost (C).

$$\text{Well screen cost} = 100 L$$

$$\begin{aligned}\text{Upper well casing cost} &= 40 \times 1.25 s_w \\ &= 50 s_w\end{aligned}$$

$$\begin{aligned}\text{Drilling cost} &= 200 \times \text{drilling depth (considering the drawdown safety factor)} \\ &= 200 \times [1.25 s_w + L] \\ &= 250 s_w + 200 L\end{aligned}$$

$$\text{So, } C = 100 L + 50 s_w + 250 s_w + 200 L$$

$$C = 300 s_w + 300 L$$

- Operating cost (c).

$$\begin{aligned}c &= 0.1 Q H \\ &= 0.1 \times 200 \times 1.25 s_w\end{aligned}$$

$$c = 250 s_w$$

$$\text{But } f = 7. \text{ So, } c f = 250 s_w \times 7 = 1750 s_w$$

- Total cost (PV)

$$\begin{aligned}\text{Total cost (PV)} &= C + c f \\ &= 300 s_w + 300 L + 1750 s_w \\ &= 2050 s_w + 300 L\end{aligned}$$

$$\text{But, } s_w = \frac{1.25Q}{KL} = \frac{1.25 \times 2000}{45L} = \frac{2000}{36L}$$

$$\begin{aligned}\text{Total cost} &= 2050 \times \frac{2000}{36L} + 300 L \\ \text{PV} &= 113888.9/L + 300 L\end{aligned}$$

$$\begin{aligned}\text{Now, } dPV/dL &= 0 \\ -113888.9 / L^2 + 300 &= 0\end{aligned}$$

Solving the equation,

$$L = 19.5 \text{ m}$$

2. The overall cost or saving

Because there are losses in the upper screen, extra drawdown occurs.

$$\begin{aligned}\text{Extra drawdown due to the upper screen losses} &= 2 \times 10^{-15} Q^2 L r_w^{-\frac{16}{3}} \\ &= 2 \times 10^{-15} \times (2000)^2 \times 19.5 \times (0.05)^{-16/3} \\ &= 1.335 \text{ m}\end{aligned}$$

This should go into the drawdown term:

$$\text{Total cost (PV)} = 2050 s_w + 300 L$$

$$\text{New drawdown cost} = 2050 (s_w + 1.335)$$

$$\text{Thus the increase in cost} = 2050 \times 1.335 = \text{US \$ } 2777.75$$

$$\text{Saving from the screen cost} = (100 - 70) \times 19.5 = \text{US \$ } 585$$

$$\text{Hence, overall extra cost} = \text{US\$ } 2192.75$$