Table 1.2-2: Criteria for Selection of Gravel Pack Material

Uniformity Coefficient (U_c) of Aquifer	Gravel Pack Criteria	Screen Slot Size
<2.5	(a) U_c between 1 and 2.5 with the 50% size not greater than 6 times the 50% size of the aquifer (b) If (a) is not available, U_c between 2.5 and 5 with 50% size not greater than 9 times the 50% size of the aquifer	≤10% passing size of the gravel pack
2.5–5	(a) U_c between 1 and 2.5 with the 50% size not greater than 9 times the 50% size of the formation (b) If (a) is not available, U_c between 2.5 and 5 with 50% size not greater than 12 times the 50% size of the aquifer	≤10% passing size of the gravel pack
>5	(a) Multiply the 30% passing size of the aquifer by 6 and 9 and locate the points on the grain-size distribution graph on the same horizontal line (b) Through these points draw two parallel lines representing materials with $U_c \leq 2.5$ (c) Select gravel pack material that falls between the two lines	≤10% passing size of the gravel pack

1.3 Well Development

Following completion, a new well is developed to increase its specific capacity, prevent sanding, and obtain maximum economic well life. These results are accomplished by removing the finer material from the natural formations surrounding the perforated sections of the casing. Where a well has been gravel-packed, much of the same purpose has been accomplished, although development is still beneficial. The importance of developing wells cannot be underestimated; all too often development is not carried out adequately to produce full potential yields.

Development procedures are varied and include pumping, surging, use of compressed air, hydraulic jetting, addition chemicals, hydraulic fracturing, and use of explosives.

a. Pumping

This procedure involves pumping a well in a series of steps from low discharge to one exceeding the design capacity[1]. To be most effective the intake area of the pump should extend to near the center of the screened section. At each step the well is pumped until the water clears, after which the power is shut off and water in the pump column surges back into the well. The step is repeated until only clear water appears. The discharge rate is then increased and the procedure repeated until the final rate is the maximum capacity of the pump or well. This irregular and noncontiguous pumping agitates the fine material surrounding the well so that it can be carried into the well and pumped out. The coarser fraction entering the well is removed by a bailer or sand pump from the bottom. This development method by pumping is recommended as finishing procedure after any of the development techniques described subsequently.

b. Surging

Another method for developing a well is by the up-and-down motion of a surge block attached to the bottom of a drill stem. Such blocks are particularly applicable with a cable tool rig. Solid, vented, and spring-loaded surge blocks, often constructed by well-drilling contractors, are employed[2]. The cylindrical block is 2 to 5 cm smaller than the well screen and fitted with belting, rubber, or leather that will not damage the screen. As the block is moved up and down in the screen, a surging action is imparted to the water. The downstroke causes backwash to break up any bridging which may occur, while the upstroke pulls dislodged sand grains into the well.

Initially, surging should begin with a slow stroke at the bottom of the screen and progress to the top pf the screen. This should then be repeated with increasingly faster strokes. The procedure is completed when material accumulating in the bottom of the well becomes negligible. For wells in rock aquifers, surging can be accomplished in the casing above open holes.

c. Surging with Air

To develop wells by compressed air, an air compressor is connected to an air pipe into the well. Around the air pipe a discharge pipe is fitted, as shown in Figure 1.3-1. Both pipes should be capable of being shifted vertically by clamps. Initially, the pipes extend to near the bottom of the screened section; for efficient operation, the water depth in the discharge pipe should exceed two-thirds the length of the pipe. To begin the development, the air pipe is closed and the air pressure is allowed to build up to 0.7 to 1.0×10^6 Pa, whereupon it is released suddenly into the well by means of a quick-opening valve. The inrush of air creates a powerful surge within the well, first increasing then decreasing the pressure as water is forced up the discharge pipe. The process loosens the fine material surrounding the perforations; the material may then be brought into the well by continuous air injection creating an airlift pump. The operation is repeated at intervals along the screened section until sand accretion becomes negligible.

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1 In the field this technique is sometimes referred to as "rawhiding" a well. If a high discharge occurs initially, "bridging" (wedging sand grains around individual perforations formed by the sudden pull on the sand toward the well) can prevent fine material from being removed and reduce the effectiveness of the development process.

2 Surging can be accomplished with a flap-valve bailer, if a close fit exists within the well screen.

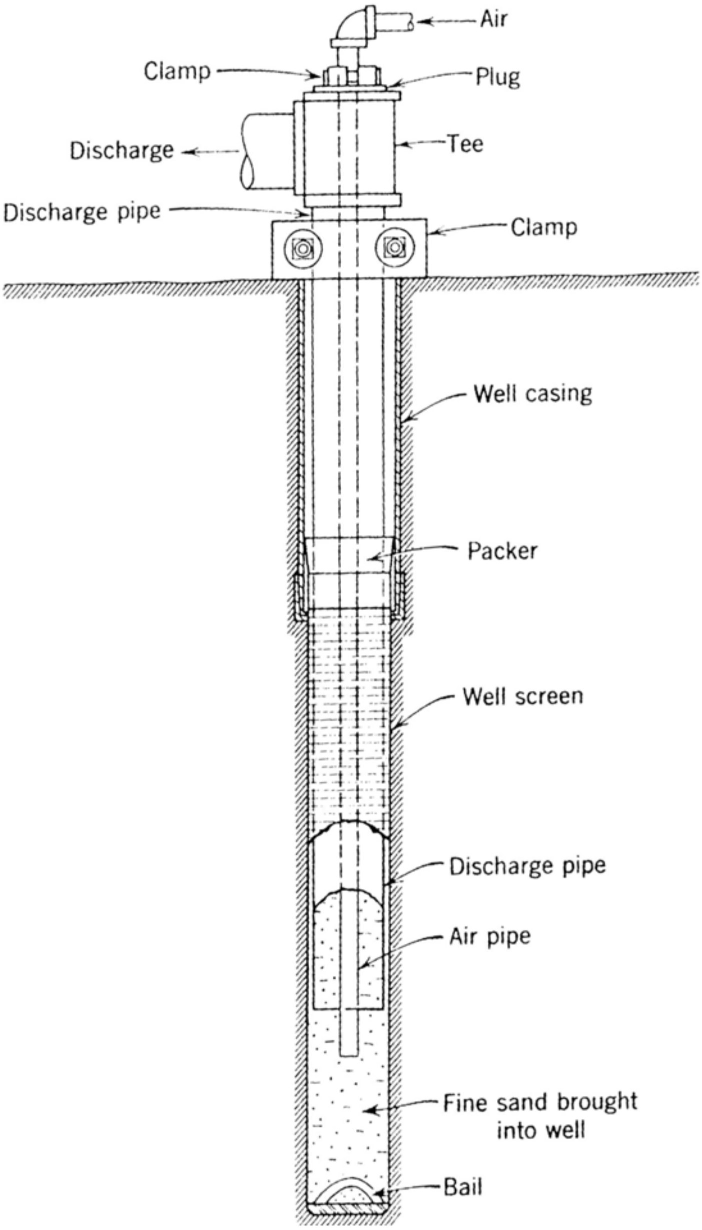

Figure 1.3-1: Installation for Well Development with Compressed Air

d. Backwashing with Air

In the backwashing method the top of the well is fitted with an airtight cover. Discharge and air pipes are installed similar to the previous method, together with a separate short air pipe and three-way valve, as shown in Figure 1.3-2. Compressed air is released through the long air pipe, forcing air and water out of the well through the discharge pipe. After the water clears, the air supply is shut off and water is allowed to return to its static level. The three-way valve is then turned to admit air into the top of the well through the short air pipe. This backwashes the water from the well through the discharge pipe and at the same time agitates the sand grains surrounding the well. Air is forced into the well until it begins escaping from the discharge pipe, after which the three-way valve is turned and the air supply is again directed down the long air pipe to pump the well. Backwashing is repeated until the well is fully developed.

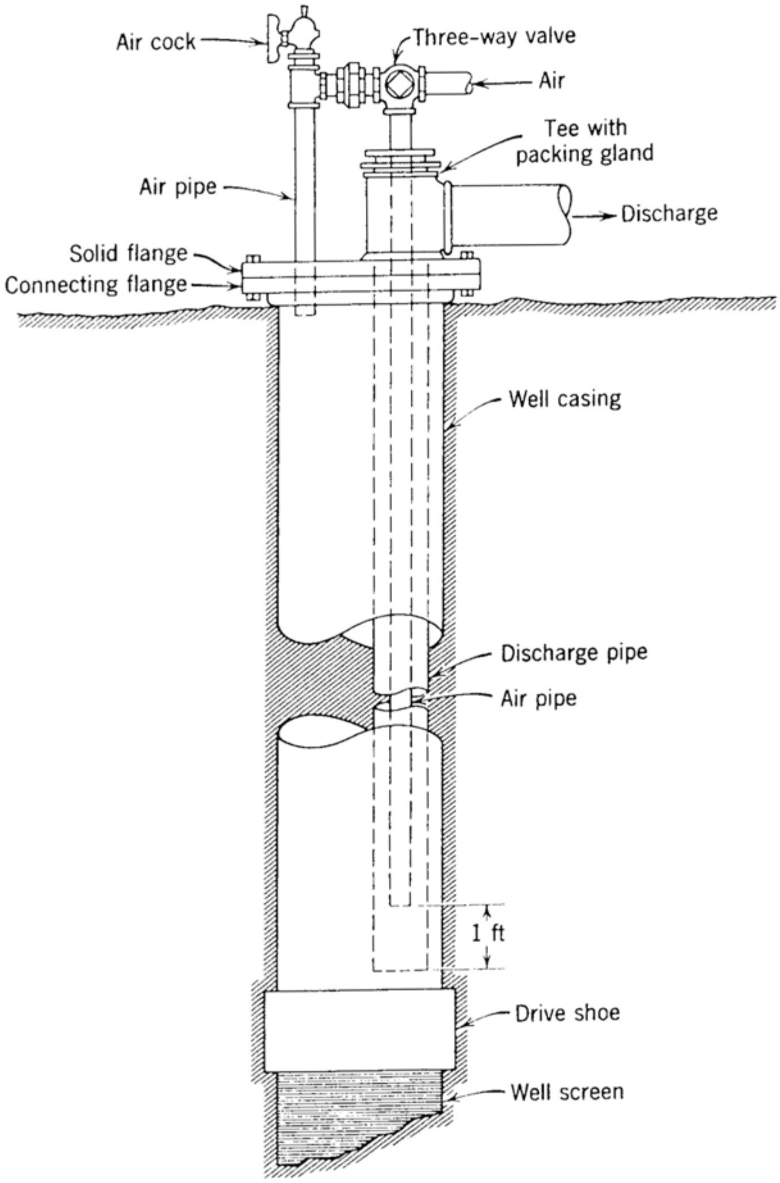

Figure 1.3-2: Installation for Well Development Backwashing with Air

e. Hydraulic Jetting

Jetting with a high-velocity stream of water is an effective development technique in open rock holes and in wells containing screens with large percentage opening (see Figure 1.3-3). The jet nozzle, mounted horizontally, is attached to a string of pipe, which is connected through a swivel and hose to a high-pressure, high-capacity pump. The jet head is slowly rotated and to successively highly levels. Fine-grained material from unconsolidated aquifers is carried into the well by the turbulent flow; in addition, the method is particularly effective in developing gravel-packed wells.

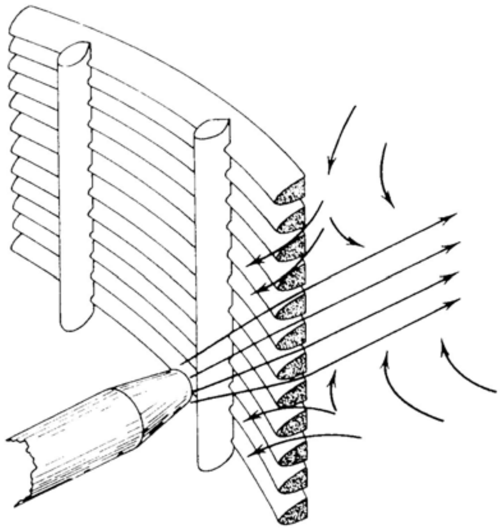

Figure 1.3-3: High-velocity Hydraulic Jetting through a Continuous Slot wire-wound Well Screen for Well Development

f. Chemicals

Open-hole wells in limestone or dolomite formations can be developed by adding hydrochloric acid to water in the well. The solvent action removes fine particles and tends to widen fractures leading into the well bore. Normally this procedure would be followed by one of the previously described development methods. Hydrofluoric acid can be similarly employed for rocks containing silicates.

For most development methods adding one of the polyphosphates[1] to water in the well will aid the development process. These compounds act as deflocculants and dispersants of clays and other fine-grained materials, thereby enabling the mud cake on the wall of a hole and the clay fractions in an aquifer to be more readily removed by the development.

Blocks of solid carbon dioxide (dry ice) are sometimes added to a well after acidizing and surging with compressed air to complete well development. The accumulation of gaseous carbon dioxide released by sublimation builds up a pressure within the well; upon release this causes a burst of muddy water from the well

g. Hydraulic Fracturing

Hydraulic fracturing, a technique borrowed from the petroleum industry, is occasionally employed to enhance the yield of open-hole rock wells. Inflatable packers on a pipe extending to ground surface isolate a section of aquifer. After filling the pipe and isolated section with water, pump pressure is applied to fracture the rock. Sand is sometimes pumped into the section to force the grains into the rock fractures so as to maintain the openings.

[1] Common household phosphate-based detergents can be serve as substitute; excessive foaming when the well is pumped may result.

h. Explosives

Detonation of explosives in rock wells often increases yields by enlarging the hole, increasing rock fractures, and removing fine-grained deposits on the face of the well bore.

1.4 Protection of Wells

a. Sanitary Protection

Wherever groundwater pumped from a well is intended for human consumption, proper sanitary precautions must be taken to protect the water quality. Pollution sources may exist either above or below ground surface. Precautions apply equally to springs; Figure 1.4-1 shows, for example, a typical method for protecting a spring water supply.

Surface pollution can enter wells either through the annular space outside of the casing or through the top of the well itself. To close avenues of access for undesirable water outside of the casing, the annular space should be filled with cement grout. Entry through the top of the well can be avoided by providing a watertight cover to seal the top of the casing. Some pumps are available with closed metal bases that provide the necessary closure. For pumps having an open-type base, or where the pump is not places directly over the well, a seal is required for the annular opening between the discharge pipe and casing[1]. Seals may be made of metal or lead packing; asphaltic and mastic compounds are also satisfactory. Covers around the well should be made of concrete, should be elevated above the adjacent land level, and should slope away from the well (see Figure 1.4-2).

Whenever a new well is completed or an old well repaired, contamination from equipment, well materials, or surface water may be introduced into the well. Following disinfection, the well should be pumped to waste until all traces of chlorine are removed. As a final check on the portability of the water, a sample should be collected and sent to a laboratory for bacteriological examination.

b. Abandonment of Wells

Whenever a well is abandoned, for whatever reason, it should be sealed by filling it with clay, concrete, or earth. Not only is surface contamination then unable to enter the well, but sealing serves other useful purposes; prevents accidents, avoids possible movement of inferior water from one aquifer to another, and conserves water in flowing wells.

[1] It is desirable to provide a small opening in or below the pump base to allow for periodic water level measurements.

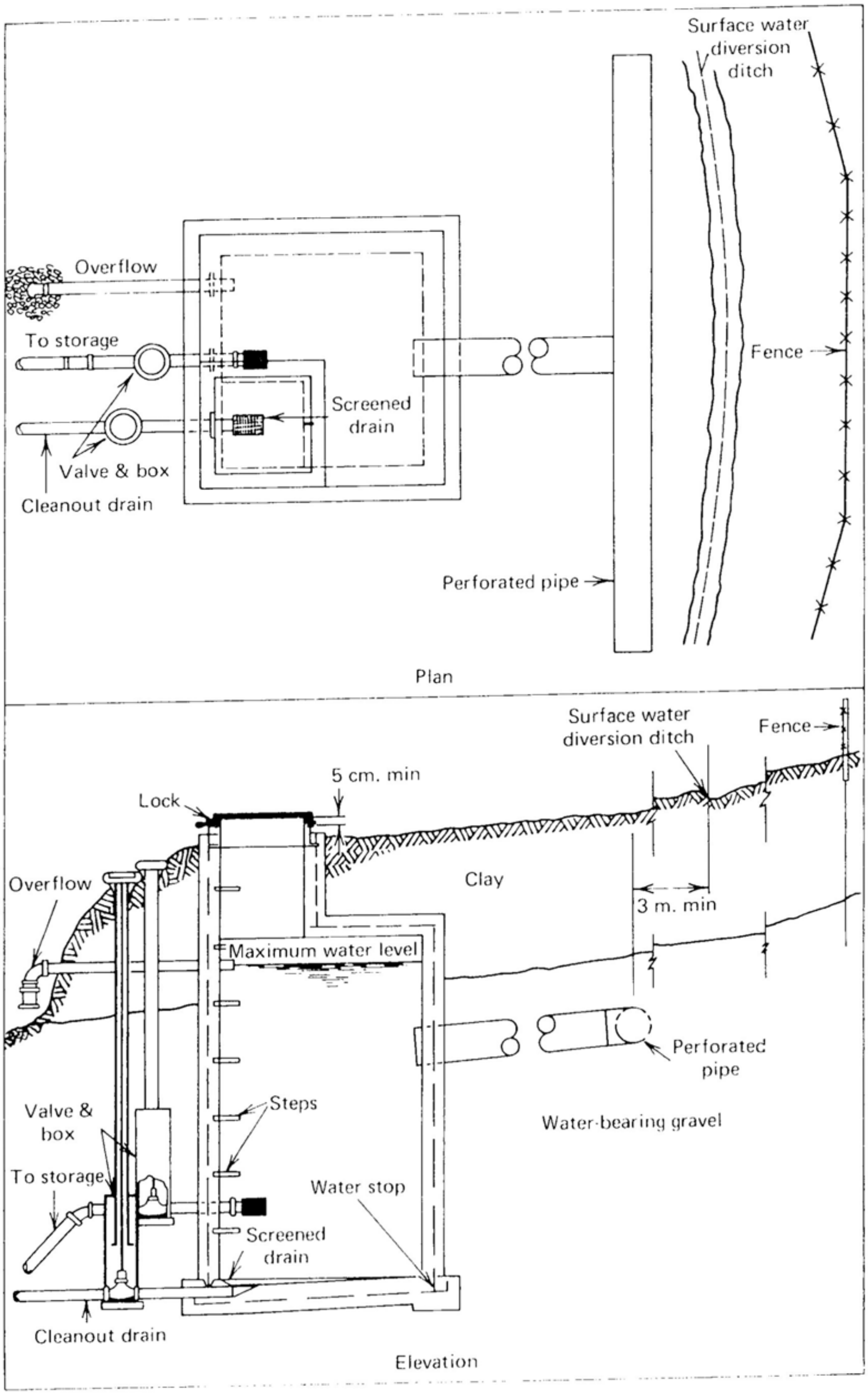

Figure 1.4-1: Plan and Elevation Views of a Developed Spring Showing a Typical Method for Providing Sanitary

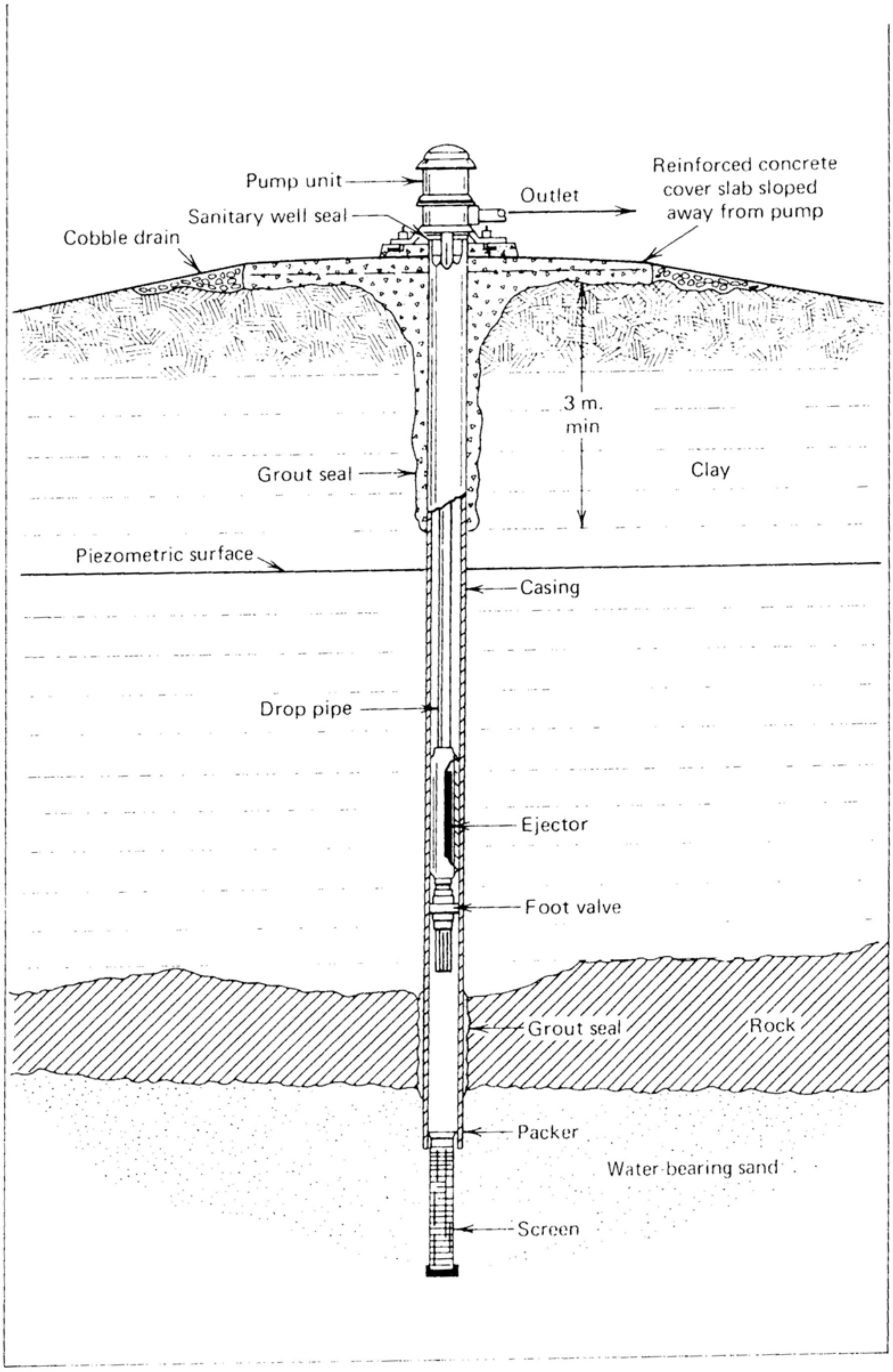

Figure 1.4-2: A Drilled Well Showing Grout Seal, Concrete slab, and Well Seal for Sanitary Protection

1.5 Well Rehabilitation

A new well, properly drilled, cased, and developed, will give years of satisfactory service with little attention. Many wells fail, however; that is, they yield decreasing quantities of water with time[1]. Table 1.5-1 lists well rehabilitation methods and their applications to various types of aquifers.

One case of failure is depletion of the groundwater supply. Not a fault of the well, this trouble can sometimes be remedied by decreasing pumping drafts, resetting the pump, or deepening the well. A second of well trouble results from faulty well construction. Such item as poor casing connections, improper perforations or screens, incomplete placement of gravel packs, and poorly seated wells are typical of difficulties encountered. Depending on the particular situation as determined form a television or photographic survey of the well, it may be possible to repair the well, but sudden failure involving entrance of sand or collapse of a casing often require replacement of the entire well.

The third and most prevalent cause of well failure results from corrosion or incrustation of well screens. Corrosion may result from direct chemical action of the groundwater or from electrolytic action caused by the presence of two different metals in the well. The effects of corrosion can be minimized by selecting nonmetallic well screens or ones of corrosion-resistant metal (such as nickel copper, or stainless steel), and by providing cathodic protection[2]. If the damage is located it may be possible to insert a liner inside the screen to prevent excessive sand pumping.

Incrustation is caused by precipitation on or near well screens of materials carried in solution by groundwater. The sudden pressure drop associated with water entering a well under heavy pumping can release carbon dioxide and cause precipitation of calcium carbonate. Another cause of incrustation stems from the presence of oxygen in a well; this can change soluble ferrous iron to insoluble ferric hydroxide. Screens can be cleaned by shooting a string of vibratory explosives in the well or by adding hydrochloric acid (HCl) or sulfamic acid (H_2NSO_3H) to the well, followed by agitation and surging. Where slime-forming organisms block screens, particularly in recharge wells, treatment with chlorine gas or hypochlorite solutions can remedy the problem. For improving yields of rock wells, acidizing or shooting with explosive is generally effective.

[1] Frequently the pump rather than well is at fault; hence, it should be checked before beginning any extensive well repair.

[2] One method of providing cathodic protection for a well is to introduce a metal low on the electrochemical scale that will be corroded instead of the well casing. Rods of magnesium suspended in the well water serve this purpose.

Table 1.5-1: Rehabilitation Methods and Their Applications to Various Types of Aquifer

Method	Unconsolidated Aquifers	Consolidated Sandstone	Consolidated Limestone
Muriatic acid[a] followed by chlorine	Removes iron, sulfur, and carbonate deposits	Not usually effective	Sometimes beneficial; best results obtained by pressure acidizing
Polyphosphate followed by chlorine	Removes fine silt, clay, colloids, disseminated shale, and soft iron deposits	Not usually effective	Not usually effective
Dynamiting	Not recommended	Effective for all types of well-screen deposits	Effective when very large charges are used
Compressed air	Removes plugging deposits of silt and fine sand in areas adjacent to screens	Not used	Not used
Dry ice	Same as compressed air	Used only rarely, to remove cuttings from the face of a new production well	Not usually effective
Surging	Same as compressed air	Rarely used	Rarely used
Chlorine[b]	Removes iron and slime-forming bacteria	Removes iron and slime-forming bacteria	Removes iron and slime-forming bacteria
Caustic soda	Removes oil scum left by oil-lubricating pumps	Removes oil scum left by oil-lubricating pumps	Removes oil scum left by oil-lubricating pumps

[a]Not to be used with concrete screens.
[b]Usually used in a concentration of 500 mg/l.

2 GEOPHYSICAL LOGGING

2.1 Summary of Logging Application

Geophysical logging involves lowering sensing devices in a borehole and recording a physical parameter that may be interpreted in terms of formation characteristics; groundwater quantity, quality, and movement; or physical structure of the borehole. A wide variety of logging technique is available. Table 2.2-1 lists the types of information that can be obtained from various logging techniques.

Geophysical logs furnish continuous records of subsurface conditions that can be correlated form one well to another. They serve as valuable supplements to geologic logs. Data from geophysical logs can be digitized, and stored. Graphic displays of log data permit rapid visual interpretations and comparisons in the field so decisions regarding completion and testing of wells can be made immediately.

The application of geophysical logging to groundwater hydrology lags far behind its comparable use in petroleum exploration. It is doubtful if more than a few percent of the new water wells drilled each year are logged by geophysical equipment. The primary reason for this is cost. Most water wells are shallow, small-diameter holes for domestic water supply; logging costs would be relatively large and usually unnecessary. But for deeper and more expensive wells, such as for municipal, irrigation, or injection purposes, logging can be economically justified in terms of improved well construction and performance. Another deterrent to geophysical logging is the lack of experience among drillers, engineers, and geologists in the interpretation of logs. As logging techniques become more sophisticated, the data they produce become more complex. The interpretation of many logs is more of an art than a science; log responses are governed by numerous environmental factors, making quantitative analysis difficult. In general, best results are obtained with experience and with supplemental hydrogeologic information.

Figure 2.2-1 is schematic diagram showing several of the logs and their typical relative responses in various unconsolidated and consolidated geologic formations.

2.2 Resistivity logging

Within an uncased well, current and potential electrodes can be lowered to measure electric resistivities of the surrounding media and to obtain a trace of their variation with depth. The result is a resistivity (or electric) log. Such a log is affected by fluid within a well, by well diameter, by the character of surrounding strata, and by groundwater.

Table 2.2-1: Summary of Logging Application to Groundwater Hydrology

Required Information	Possible Logging Techniques
Lithology and stratigraphic correlation of aquifers and associated rocks	Resistivity, sonic, or caliper logs made in open holes; radiation logs made in open or cased holes
Total porosity or bulk density	Calibrated sonic logs in open holes; calibrated neutron or gamma-gamma logs in open or cased holes
Effective porosity or true resistivity	Calibrated long-normal resistivity logs
Clay or shale content	Natural gamma logs
Permeability	Under some conditions long-normal resistivity logs
Secondary permeability—fractures, solution openings	Caliper, sonic, or television logs
Specific yield of unconfined aquifers	Calibrated neutron logs
Grain size	Possible relation to formation factor derived from resistivity logs
Location of water level or saturated zones	Resistivity, temperature, or fluid conductivity logs; neutron or gamma-gamma logs in open or cased holes
Moisture content	Calibrated neutron logs
Infiltration	Time-interval neutron logs
Dispersion, dilution, and movement of waste	Fluid conductivity or temperature logs; natural gamma logs for some radioactive wastes
Source and movement of water in a well	Fluid velocity or temperature logs
Chemical and physical characteristics of water, including salinity, temperature, density and viscosity	Calibrated fluid conductivity or temperature logs; resistivity logs
Construction of existing wells, diameter and position of casing, perforations, screens	Gamma-gamma, caliper, casing, or television logs
Guide to screen setting	All logs providing data on the lithology, water-bearing characteristics, and correlation and thickness of aquifers
Cementing	Caliper, temperature, or gamma-gamma logs; acoustic logs for cement bond
Casing corrosion	Under some conditions caliper, casing, or television logs
Casing leaks and/or plugged screen	Fluid velocity logs

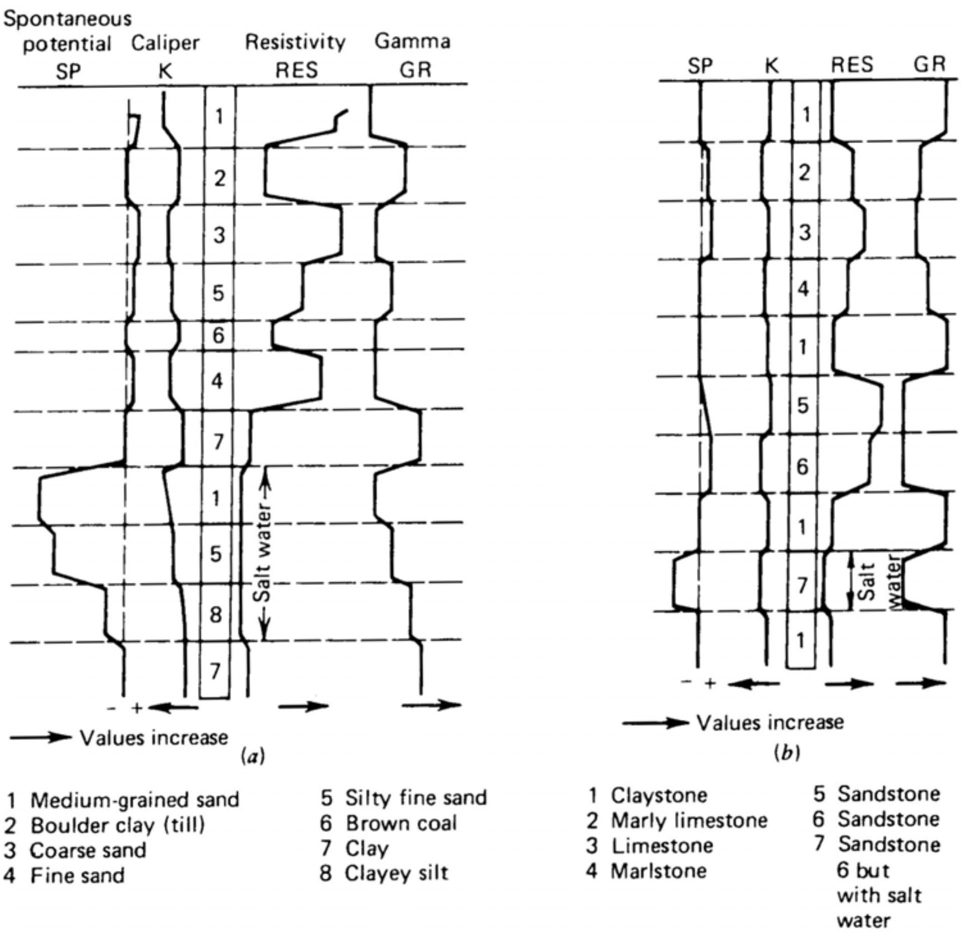

Figure 2.2-1: Schematic Diagram of Various Geophysical Logs Showing their Relative Responses in (a) unconsolidated rocks and (b) consolidated rocks

Of several possible methods for measuring underground resistivities, the multielectrode method is most commonly employed, because it minimized effects of the drilling fluid and well diameter and also makes possible a direct comparison of several recorded resistivity curves. Four electrodes, two for emitting current and two for potential measurement, constitute the system. Recorded curves are termed normal or lateral, depending on the electrode arrangement, as shown in Figure 2.2-1. In the normal arrangement the effective spacing is considered to be the distance AM (Figure 2.2-2(a)) and the recorded curve is designated AM. Sometimes a long normal curve (AM') is recorded based on the same electrode arrangement as the normal but with a large AM distance (Figure 2.2-2(b)). The spacing for lateral (AO) curves is taken as the distance AO, measured between A and a point midway between the electrodes M and N (Figure 2.2-2(c)). Boundaries of formations having different resistivities are located most readily with a short electrode spacing, whereas information on fluids in thick permeable formations can be obtained best with long spacings.

An electrode log of a well usually consists of vertical traverses that record the short and long normals, the lateral, and the spontaneous potential curves (see following section). An illustration of an electric log is given in Figure 2.2-4. Accurate interpretation of resistivity log is difficult, requires careful analysis, and is best done by specialists.

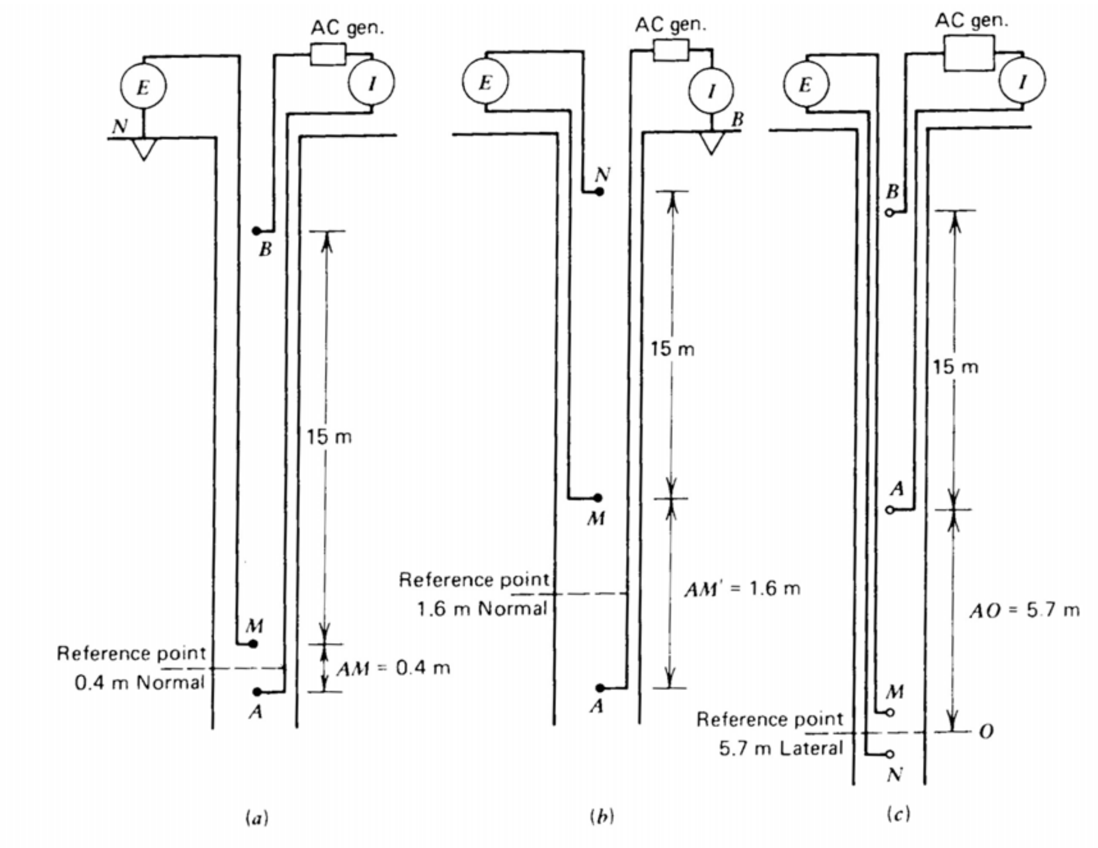

Figure 2.2-2: Typical Electrode Arrangements and Standardized Distances for Resistivity Logs (1). (a) Short Normal, (b) Long Normal, (c) Lateral

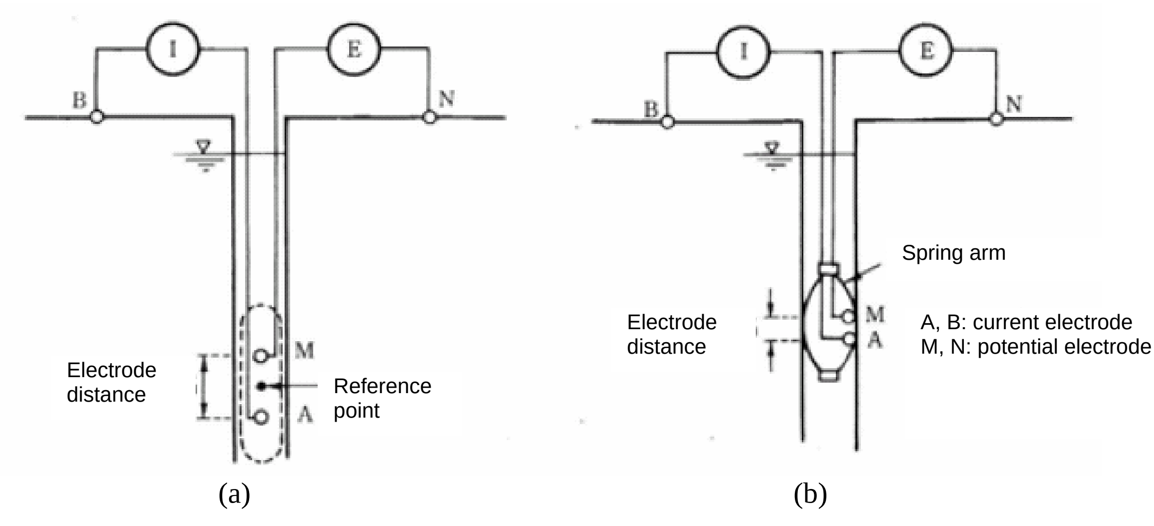

Figure 2.2-3: Typical Electrode Arrangements and Standardized Distances for Resistivity Logs (2). (a) Normal, (b) Micro

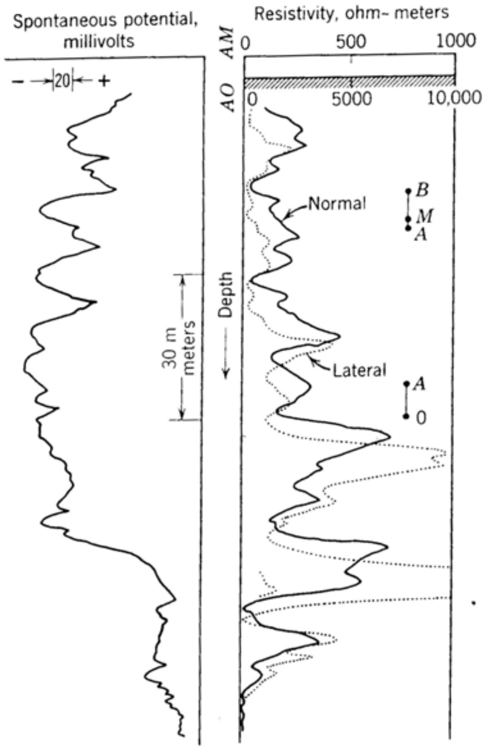

Figure 2.2-4: Spontaneous Potential and Resistivity Logs of a Well

Resistivity curves indicate the lithology of rock strata penetrated by the well and enable fresh and salt waters to be distinguished in the surrounding material. In old wells exact locations of casings can be determined. Resistivity logs may be used to determine specific resistivities of strata, or they may indicate qualitatively changes of importance. Resistivity of unconsolidated aquifer is controlled primarily by porosity, packing, water resistivity, degree of saturation, and temperature. Although specific resistivity values cannot be stated for different aquifers, on a relative basis shale, clay, and saltwater sand give low values, freshwater sand moderate to high values, and cemented sandstone and nonporous limestone high value. Casings and metallic objects will indicate very low resistivities. Correlation of rock samples, taken from wells during drilling, with resistivity curves furnishes a sound basis for interpretation of curves measured in nearby wells without available samples.

Resistivity logs can also aid in identifying wells that intersect both fresh and saline zones. Circulation within such a well under nonpumping conditions depends on the relative hydrostatic heads, water densities, aquifer locations and thickness, and the physical structure and condition of the well. Various hydrologic conditions for pumping and nonpumping wells are shown diagrammatically in Figure 2.2-5 together with corresponding resistivity curves. Resistivity logs are also employed for locating aquifers, determining bed sequences, correlating aquifers, and estimating changes in groundwater quality.

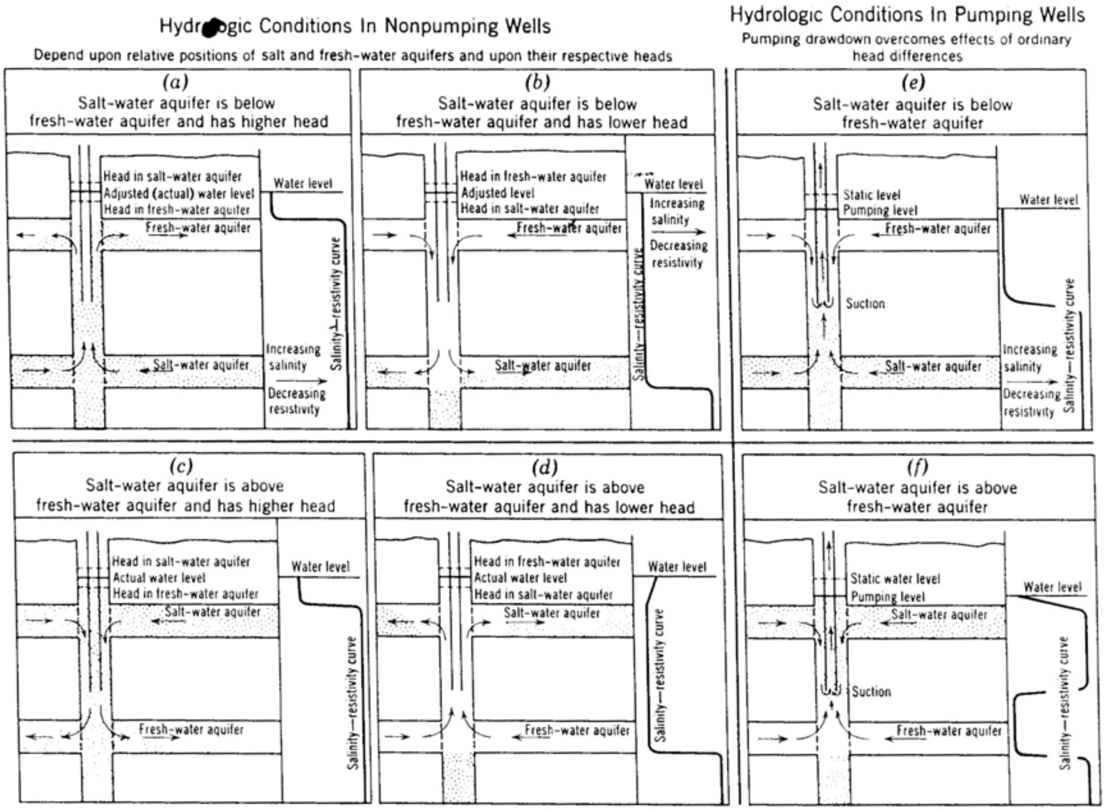

Figure 2.2-5: Hydrologic Conditions and Resistivity Curves for Wells Penetrating Two Aquifer of Different Salinities

2.3 Spontaneous Potential Logging

The spontaneous potential method measures natural electrical potentials found within the earth.[1] Measurements, usually in millivolts, are obtained from a recording potentiometer connected to two like electrode. One electrode is lowered in an uncased well and the other is connected to the ground surface, as illustrated by electrodes M and N in Figure 2.2-2(a). The potentials are primarily produced by electrochemical cells formed by the electrical conductivity differences of drilling mud and groundwater where boundaries of permeable zones intersect a borehole. In some instances electrokinetic effects of fluids moving through permeable formations are also responsible for spontaneous potentials. Therefore, potential logs indicate permeable zones but not in absolute terms; they can also aid in determining casing lengths and in estimating total dissolved solids in groundwater. Where no sharp contrasts occur in permeable zones, as often happens in shallow alluvial formations, potential logs lack relief and contribute little. In urban and industrial areas, spurious earth currents may occur, such as from electric railroads, which interfere with potential logging.

Potential values range from zero to several hundred millivolts. By convention potential logs are read in terms of positive and negative deflections from an arbitrary baseline, usually associated with an impermeable formation of considerable thickness. The sign of the potential depends on the ratio of salinity (or resistivity) of the drilling mud to the formation water.

1 Potentials are also referred to as self-potential or simply SP.

Spontaneous potentials resulting from electrochemical potentials can be expressed by

$$SP = -(64.3 + 0.239T)\log\frac{\rho_f}{\rho_w}$$

where ρ_f is the drilling fluid resistivity in ohm-m, ρ_w is the groundwater resistivity in ohm-m, and T is the boreholes temperature in ℃. Therefore, for measured SP, ρ_f and T values, the resistivity and hence salinity of groundwater can be determined. It should be noted, however, that the formula applied only where the groundwater is very saline. NaCl is the predominant salt, and the drilling mud contains no unusual additives.

In practice, potential and resistivity logs are usually recorded together as shown Figure 2.2-4. The two logs often indicate the same subsurface conditions and thereby supplement each other; however, occasionally the two types of logs will furnish information not available directly from either alone.

3 PUMPING TEST

3.1 Method of pumping test

The most reliable method for estimating aquifer hydraulic conductivity is by pumping test of wells. Based on observation of water levels near pumping wells, an integrated K value over a sizable aquifer section can be obtained. Then, too, because the aquifer is not distributed, the reliability of such determinations is superior to laboratory methods.

3.2 Theis method of solution and Cooper-Jacob method of solution

a. Unsteady Radial Flow in a Confined Aquifer

When a well penetrating an extensive confined aquifer is pumped at a constant rate, the influence of the discharge extends outward with time. The rate of decline of head times the storage coefficient summed over the area of influence equals the discharge. Because the water must come from a reduction of storage within the aquifer, the head will continue to decline as long as the aquifer is effectively infinite; therefore, unsteady, or transient, flow exists. The rate of decline, however, decreases continuously as the area of influence expands.

The applicable differential equation in plane polar coordinate is

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad \text{(Eq. 3-1)}$$

where h is head, r is radial distance from the pumped well, S is storage coefficient, T is transmissivity, and t is the time since beginning of pumping. Theis obtained a solution for Eq. 3-1 based on the analogy between groundwater flow and heat conduction. By assuming that the well is replaced by a mathematical sink of constant strength and imposing the boundary conditions h=h0 for t=0, and h→h0 as r→∞ for t $\geq$ 0, the solution

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}du}{u} \qquad \text{(Eq. 3-2)}$$

is obtained, where s is drawdown, Q is the constant well discharge, and

$$u = \frac{r^2 S}{4Tt} \qquad \text{(Eq. 3-3)}$$

Eq. 3-2 is known as the nonequilibrium, or Theis, equation.

The integral is function of the lower limit u and is known as an exponential integral. It can be expanded as a convergent series so that Eq. 3-2becomes

$$s = \frac{Q}{4\pi T}\left[-0.5772 - \ln u + u - \frac{u^2}{2\bullet 2!} + \frac{u^3}{3\bullet 3!} - \frac{u^4}{4\bullet 4!} + \cdots\right] \qquad \text{(Eq. 3-4)}$$

The nonequilibrium equation permits determination of the formation consists S and T by means of pumping tests of wells. The equation is widely applied in practice and is preferred over the equilibrium equation because:

- a value for S can be determined,
- only on e observation well is required,
- a shorter period of pumping is generally necessary,
- no assumption of steady-state flow conditions is required.

The assumption inherent Eq. 3-2 should be emphasized because they are often overlooked in applying the nonequilibrium equation and thereby can lead to erroneous results. The assumptions include:

- The aquifer is homogeneous, isotropic, of uniform thickness, and of infinite areal extent.
- Before pumping, the piezometric surface is horizontal.
- The well is pumped at a constant discharge rate.
- The pumped well penetrates the entire aquifer, and flow is everywhere horizontal within the aquifer to the well.
- The well distribution is infinitesimal so that storage within the well can be neglected.
- Water removed from storage is discharged instantaneously with decline of head.

Seldom, if ever, are these assumptions strictly satisfied, but recognition of them can create an awareness of the approximations involved for employing the nonequilibrium equation under field conditions. Average values of S and T can be obtained in the vicinity of a pumped well by measuring in one or more observation wells the change in drawdown with time under the influence of a constant pumping rate. Because of the mathematical difficulties encountered in applying Eq. 3-2 or its equivalent Eq. 3-4, several investigators have developing simpler approximate solutions that can be readily applied for field purposes. Two methods by Theis, and Cooper and Jacob, are described in the following sections with the necessary tables and/or graphs. An illustrative example accompanies each method.

b. Theis Method of Solution

Eq. 3-2 may be simplified to

$$s = \left(\frac{Q}{4\pi T}\right)W(u) \qquad \text{(Eq. 3-5)}$$

where W(u), termed the well function, is a convenient symbolic form of the exponential integral. Rewriting Eq. 3-3 as

$$\frac{r^2}{t} = \left(\frac{4T}{S}\right)u \qquad \text{(Eq. 3-6)}$$

it can be seen the relation between W(u) and u must be similar to that between s and r^2/t because the terms in parentheses in the two equations are constants. Given this similarity Theis suggested an approximate solution for S and T based on a graphic method of superposition.

A plot on logarithmic paper W(u) versus u, known as a type curve, is prepared. Table 3.2-1 gives values of W(u) for a wide range of u. Values of drawdowns are plotted against values of r^2/t on logarithmic paper of the same size as for the type curve. The observed time-drawdown data are superimposed on the type curve, keeping the coordinate axes of the two curves parallel, and adjusted until a position is found by trial whereby most of the plotted points of the observed data fall on a segment of the type curve. Any convenient point is selected, and the coordinates of this matched point are recorded. With values of W(u), u, s, and r^2/t thus determined, S and T can be obtained from Eq. 3-5 and Eq. 3-6.

In areas where several wells exist near a well being test-pumped, simultaneous reading of s in the wells enable distance-drawdown data to be fitted to a type curve in a manner identical to that for time-drawdown data.

Table 3.2-1: Values of W(u) for Values of u

u	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
$\times 1$	0.219	0.049	0.013	0.0038	0.0011	0.00036	0.00012	0.000038	0.000012
$\times 10^{-1}$	1.82	1.22	0.91	0.70	0.56	0.45	0.37	0.31	0.26
$\times 10^{-2}$	4.04	3.35	2.96	2.68	2.47	2.30	2.15	2.03	1.92
$\times 10^{-3}$	6.33	5.64	5.23	4.95	4.73	4.54	4.39	4.26	4.14
$\times 10^{-4}$	8.63	7.94	7.53	7.25	7.02	6.84	6.69	6.55	6.44
$\times 10^{-5}$	10.94	10.24	9.84	9.55	9.33	9.14	8.99	8.86	8.74
$\times 10^{-6}$	13.24	12.55	12.14	11.85	11.63	11.45	11.29	11.16	11.04
$\times 10^{-7}$	15.54	14.85	14.44	14.15	13.93	13.75	13.60	13.46	13.34
$\times 10^{-8}$	17.84	17.15	16.74	16.46	16.23	16.05	15.90	15.76	15.65
$\times 10^{-9}$	20.15	19.45	19.05	18.76	18.54	18.35	18.20	18.07	17.95
$\times 10^{-10}$	22.45	21.76	21.35	21.06	20.84	20.66	20.50	20.37	20.25
$\times 10^{-11}$	24.75	24.06	23.65	23.36	23.14	22.96	22.81	22.67	22.55
$\times 10^{-12}$	27.05	26.36	25.96	25.67	25.44	25.26	25.11	24.97	24.86
$\times 10^{-13}$	29.36	28.66	28.26	27.97	27.75	27.56	27.41	27.28	27.16
$\times 10^{-14}$	31.66	30.97	30.56	30.27	30.05	29.87	29.71	29.58	29.46
$\times 10^{-15}$	33.96	33.27	32.86	32.58	32.35	32.17	32.02	31.88	31.76

c. Example of Theis Method

A well penetrating a confined aquifer is pumped at a uniform rate of 2,500m^3/day. Drawdowns during the pumping period are measured in an observation well 60m away; observations of t and s are listed in Table 3.2-2. Values of r^2/t in m^2/min are computed and appear in the right column of Table 3.2-2. Values of s and r2/t are plotted on logarithmic paper. Values of W(u) and u from Table 3.2-1 are plotted on another sheet of logarithmic paper and a curve is drawn through the points. The two sheets are superposed and shifted with coordinate axes parallel until the observational points coincide with the curve, as shown in Figure 3.2-1. A convenient match points is selected with W(u)=1.00 and u=1×10^{-2}, so that s=0.18m and $r^2/t=150m^2/min=216{,}000m^2/day$.

Thus, from Eq. 3-5,

$$T = \frac{Q}{4\pi s} W(u) = \frac{2500(1.00)}{4\pi(0.18)} = 1110 m^2 / day$$

and from Eq. 3-6,

$$S = \frac{4Tu}{r^2/t} = \frac{4(1110)(1\times 10^{-2})}{216000} = 0.000206$$

Table 3.2-2: Pumping Test Data

	(r = 60 m)	
t, min	s, m	r^2/t, m²/min
0	0	∞
1.0	0.20	3600
1.5	0.27	2400
2.0	0.30	1800
2.5	0.34	1440
3.0	0.37	1200
4	0.41	900
5	0.45	720
6	0.48	600
8	0.53	450
10	0.57	360
12	0.60	300
14	0.63	257
18	0.67	200
24	0.72	150
30	0.76	120
40	0.81	90
50	0.85	72
60	0.90	60
80	0.93	45
100	0.96	36
120	1.00	30
150	1.04	24
180	1.07	20
210	1.10	17
240	1.12	15

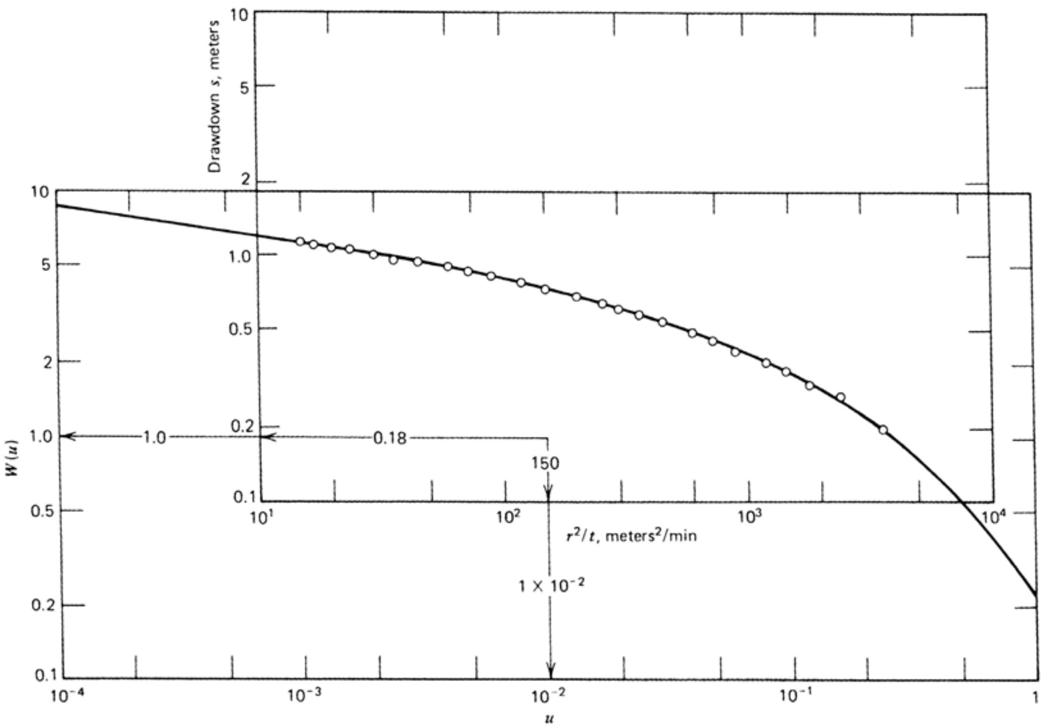

Figure 3.2-1: Theis Method of Superposition for Solution of the Nonequilibrium Equation

d. Cooper-Jacob Method of Solution

It was noted by Cooper and Jacob that for small values of r and large Values of t, u is small, so that series terms in Eq. 3-4 become negligible after the first two terms. As a result, the drawdown can be expressed by the asymptote

$$s = \frac{Q}{4\pi T}\left(-0.5772 - \ln\frac{r^2 S}{4Tt}\right) \quad \text{(Eq. 3-7)}$$

Rewriting and changing to decimal logarithms, this reduces to

$$s = \frac{2.30Q}{4\pi T}\log\frac{2.25Tt}{r^2 S} \quad \text{(Eq. 3-8)}$$

Therefore, a plot of drawdown s versus the logarithm of t forms a straight line. Projecting this line to s=0, where t=t_0 (see Figure 3.2-2).

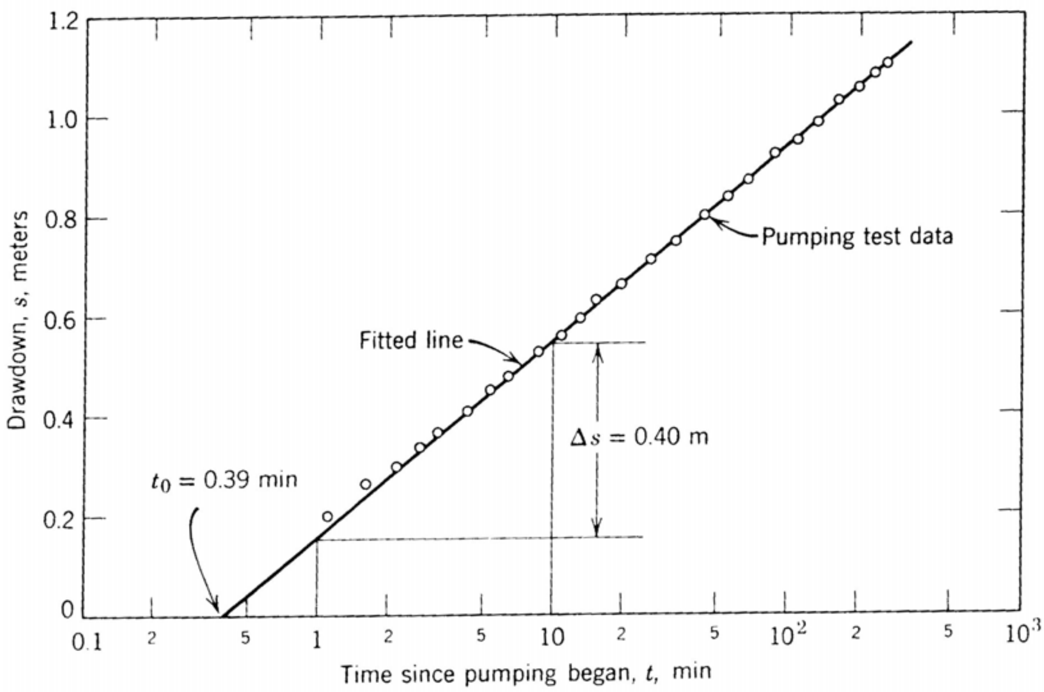

Figure 3.2-2: Cooper-Jacob Method for Solution of the Nonequilibrium Equation

$$0 = \frac{2.30Q}{4\pi T}\log\frac{2.25Tt_0}{r^2 S} \quad \text{(Eq. 3-9)}$$

and it follows that

$$\frac{2.25Tt_0}{r^2 S} = 1 \quad \text{(Eq. 3-10)}$$

resulting in

$$S = \frac{2.25Tt_0}{r^2} \quad \text{(Eq. 3-11)}$$

A value for T can be obtained by noting that if $t/t_0=10$, then $\log t/t_0=1$; therefore, replacing s by Δs, where Δs is the drawdown difference per log cycle of t, Eq. 3-8 becomes

$$T = \frac{2.30Q}{4\pi\Delta s} \qquad \text{(Eq. 3-12)}$$

Thus, the procedure is first to solve for T with Eq. 3-12 and then to solve for S with Eq. 3-11. The straight-line approximation for this method should be restricted to small values of u (u<0.01) to avoid large errors.

e. Example of Cooper-Jacob Method

From the pumping test data of Table 3.2-2, s and t are plotted on semilogarithmic paper, as shown in Figure 3.2-2. A straight line is fitted through the points, and Δs=0.40m and t_0=0.39min=2.70×10-4day are read. Thus,

$$T = \frac{2.30(2500)}{4\pi(0.40)} = 1090\, m^2/day$$

and

$$S = \frac{2.25T_0}{r^2} = \frac{2.25(1090)(2.70\times10^{-4})}{(60)^2} = 0.000184$$

f. Recovery Test

At the end of a pumping test, when the pump is stopped, the water level in pumping and observation wells will begin to rise. This is referred to as the recovery of groundwater levels, while measurements of drawdown below the original static water level (prior to pumping) during the recovery period are known as residual drawdowns. A schematic diagram of change in water level with time during and after pumping is shown in Figure 3.2-3.

It is good practices to measure residual drawdowns because analysis of the data enable transmissivity to be calculated, thereby providing an independent check on pumping test results. Also, costs are nominal in relation to the conduct of a pumping test.[1] Furthermore the rate of recharge Q to the well during recovery is assumed constant and equal to the mean pumping rate, whereas pumping rates often vary and are difficult to control accurately in the field.

If a well is pumped for a known period of time and then shut down, the drawdown thereafter will be identically the same as if the discharge had been continued and hypothetical recharge well with the same flow were superposed on the discharging well at the instant the discharge is shut down. From this principal Theis showed that the residual drawdown s' can be given as

$$s' = \frac{Q}{4\pi T}\left[W(u) - W(u')\right] \qquad \text{(Eq. 3-13)}$$

where

$$u = \frac{r^2 S}{4Tt} \quad and \quad u' = \frac{r^2 S}{4Tt'} \qquad \text{(Eq. 3-14)}$$

1 In addition, it should be noted that measurement of the recovery within a pumped well will provide an estimate of transmissivity even without an observation well.

and t and t' are defined in Figure 3.2-3. For r small and t' large, the well functions can be approximated by the first two terms of Eq. 3-4 so that Eq. 3-13 can be written as

$$s' = \frac{2.30Q}{4\pi T} \log \frac{t}{t'} \qquad \text{(Eq. 3-15)}$$

Thus s plot of residual drawdown s' versus the logarithm of t/t' forms a straight line. The slope of the line equal 2.30Q/4 π T so that for Δ s', the residual drawdown per log cycle of t/t', the transmissivity becomes

$$T = \frac{2.30Q}{4\pi\Delta s'} \qquad \text{(Eq. 3-16)}$$

No comparable value of S can be determined by this recovery test method.

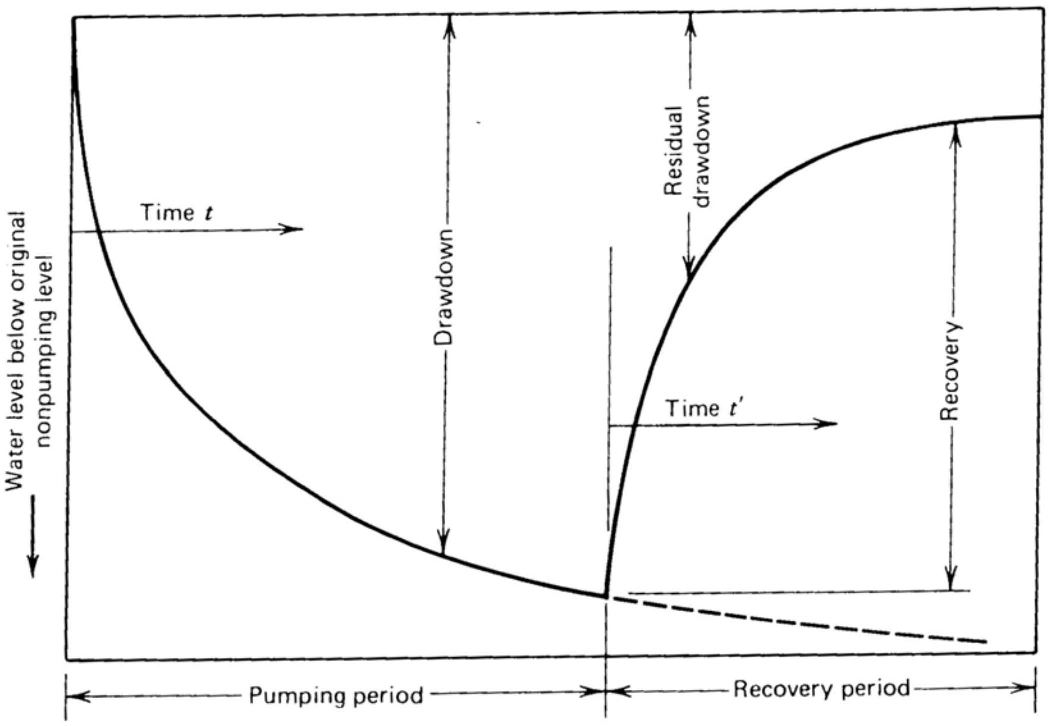

Figure 3.2-3: Drawdown and Recovery Curves in an Observation Well near a Pumping Well

g. Example of Recovery Test

A well pumping at a uniform rate of 2,500m^3/day was shut down after 240 min; thereafter, measurements of s' and t' tabulated in Table 3.2-3 were made in an observation well. Values of t/t' are computed, as shown in Table 3.2-3, and then plotted versus s' on semilogarithmic paper (see Figure 3.2-4). A straight line is fitted through the points and Δ s'=0.40m is determined; then

$$T = \frac{2.30Q}{4\pi s'} = \frac{2.30(2500)}{4\pi(0.40)} = 1140\, m^2/day$$