SCS
NATIONAL
ENGINEERING
HANDBOOK

SECTION 18

GROUND WATER

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

Section 18, Ground Water, SCS National Engineering Handbook, was prepared by the following Service personnel (listed in alphabetical order): G. M. Brune, Fort Worth, Texas; E. F. Dosch, deceased, Washington, D. C.; R. F. Fonner, Upper Darby, Pennsylvania; A. F. Geiger, Washington, D. C.; D. H. Griswold, Portland, Oregon; F. K. Heller, Durham, New Hampshire; O. J. Henbest, Fort Worth, Texas; D. H. Hixson, Hyattsville, Maryland; J. N. Holeman, Hyattsville, Maryland; J. L. Holland, Portland, Oregon; and O. J. Scherer, Lincoln, Nebraska.

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NATIONAL ENGINEERING HANDBOOK

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GROUND WATER

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INTRODUCTION

Purpose and Scope

The purpose of this section of the National Engineering Handbook is to present information on ground water as it relates to Soil Conservation Service programs. This material was compiled to help SCS personnel plan and conduct ground-water studies under established SCS standards and policies.

Investigations are made (1) to determine the availability and suitability of ground water for beneficial use and (2) to provide ground-water information needed to plan, design and construct works of improvement. SCS does not make ground-water surveys or studies for the sole purpose of collecting basic data.

In many areas basic ground-water data have been collected and compiled by other Federal, State, and private agencies. This information may be available in published documents or in unpublished field reports. When these data are either insufficient in detail or outdated, the SCS must conduct further investigations.

Because problems associated with ground water are complex, a flexible pattern of investigational procedures is needed. Each ground-water situation will have some identifiable characteristics which will help to determine the best procedures to use. The ability of the investigator to recognize these characteristics and select the most applicable procedures will largely determine the adequacy of the investigations.

Ground-Water Uses

At present, about one-fifth of all water used in the world is obtained from ground-water sources. The demand is steadily increasing. In the United States irrigation makes the greatest single demand, using about 70 percent of all extracted ground water. About 11 percent is used by industry, 13 percent for public water supplies, and 6 percent for rural water needs other than irrigation. In the 17 western States, 91 percent of the ground water used is for crop production.

Ground-Water Rights

State laws regarding the use of ground water must be followed. There are three principal sets of rules or "doctrines" upon which these laws are based. These are:

1. *Absolute ownership*, or the *common-law* rule, which states that the owner of the land is the absolute owner of all underground waters under his property. He may develop and use his ground water as he pleases without regard to the effect upon the ground-water supplies of adjacent landowners. However, in many States where this rule is followed, it is subject to some qualifications. This doctrine does not recognize flowing ground water or the effect that its misuse may have on other landowners using the same source.

2. *Ownership with reasonable use* is similar to the common-law ownership but limits the owner to a reasonable use with regard to the needs of other owners of lands overlying a common ground-water source. Export of ground water outside of the basin or area is prohibited when owners within the basin or area are in need of these waters. New Hampshire was the first to adopt this rule in 1862. Since then it has been adopted by California, Nebraska, Oklahoma, and Hawaii.

3. The *appropriation doctrine* follows the rule that, where ground-water limits or boundaries can be reasonably established, the subsurface waters are public waters and subject to appropriation. Priority rights are issued from a designated State agency after an examination of the intent of use. The appropriation system places emphasis upon beneficial use and conservation, security of investment, and responsibility for administrative guidance. Statutes based on this doctrine are best known in New Mexico, Oregon, Washington, Kansas, Nevada, Utah, and Arizona. In parts of New York and New Jersey modified versions of this rule apply.

Administration

Most States regulate the development and administration of ground-water resources in the public interest.

The more common State regulations are: (1) All persons drilling wells for others must be licensed; (2) drilling permits, logs, and any work performed on wells must be reported to the State on prescribed forms; (3) wells furnishing domestic or municipal water must be properly constructed and finished to prevent contamination; (4) flowing wells must be suitably capped and regulated to avoid waste; (5) abandoned wells must be sealed; (6) air-conditioning and cooling waters must be returned to the ground through recharge wells; and (7) disposal of any contaminants, such as brines or industrial wastes, which affect the quality of public water supplies can be restricted.

Administration of these regulations is usually the responsibility of a designated State agency. Administration and control of ground water in overdraft areas pose many complex technical problems.

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CHAPTER 1. GROUND-WATER HYDROLOGY

The Hydrologic Cycle

Water exists in the atmosphere, on the earth's surface (the hydrosphere), and under the earth's surface (the lithosphere). A continual interchange produces a closed system that is known as the hydrologic cycle. Ground water is an integral part of this system.

The Hydraulic Properties of Materials

Water in the lithosphere is in the form of free water, water vapor or ice, or is chemically combined. Subsurface, uncombined water must occupy space within the soil or rocks which is not occupied by solid mineral matter. These spaces are called *interstices*. Interstitial space may be occupied by air or other gases or by water or other liquids.

A rock or soil is said to be porous or to have *porosity* if it contains interstices or voids. Porosity can be quantitatively expressed as the ratio of the total volume of voids to the total volume of the rock or soil. It is usually given as a percentage. Primary porosity comes into existence as a result of the processes by which the rock or soil was formed. Secondary porosity is produced by fracture, solution or recrystallization. Ground water occurs in both primary and secondary voids.

Voids can be divided into three classes with respect to their size and interaction with water. These are *capillary, supercapillary* and *subcapillary* interstices.

Ground water will rise in a capillary interstice by surface tension to a given height above the water table. The amount of rise is dependent upon the size, shape, and composition of the walls of the void. The upper limit of capillary size is in the neighborhood of 3 millimeters.

An interstice larger than the upper size limit of a capillary is said to be supercapillary. Water in a supercapillary interstice will not rise appreciably above the elevation of the water table.

A subcapillary interstice is so small that water in it is held by adhesion to the sides of the interstice. The adhesive forces exceed the cohesive forces of the water. Movement is impossible except by external forces which greatly exceed those normally found in the zone of ground water.

A rock or soil which has communicating voids of capillary or supercapillary size is said to be *permeable*. The permeability of a material is its capacity to transmit fluids under pressure.

While a material must have porosity in order to be permeable, there is no direct relationship between total porosity and permeability. This is illustrated in Table 1-1.

Table 1-1. Comparison of Typical Porosities and Coefficients of Permeability for Common Materials (From various sources)

Material	Porosity %	Coefficient of Permeability $ft^3/ft^2/day$
Poorly-graded gravels	30-40	More than 3000
Poorly-graded sands	30-40	300 to 3000
Well-graded sands	20-35	15 to 300
Fine sands	30-35	15 to 150
Silty sands	30-40	.3 to 6
Silts	40-50	.03 to 1
Clays	45-60	Less than .003

A water-bearing formation contains gravity ground water. Formations that contain enough water to be used as a source of supply are called *aquifers*. An aquifer may be an entire formation, a group of formations or part of a formation. It may be either consolidated or unconsolidated.

An *aquiclude* is porous and may contain ground water but will not transmit it fast enough to be of consequence as a water supply. What is considered to be an aquifer in one area may be considered to be an aquiclude in another area because of differences in demand and availability of alternate supplies.

An *aquifuge* is a formation containing no communicating voids.

The Occurrence of Ground Water

The lithosphere can be divided into two general zones. The *zone of rock fracture*, which includes the regolith, is the zone where rocks are under stresses less than those required to close voids by internal deformation. The *zone of rock flowage* is below the zone of rock fracture where all rocks are under stresses exceeding their elastic limits. In this zone voids are absent or insignificant and water exists only as *internal* water. There is an intermediate zone where strong rocks are fractured and weak rocks flow. See Figure 1-1.

In the zone of rock fracture subsurface water exists in two broad zones--the *zone of saturation* and the *zone of aeration.*

Zone of Saturation

In the zone of saturation all communicating voids are filled with water under hydrostatic pressure. Water is the zone of saturation is *ground water* or *phreatic water.*

Zone of Aeration

In the zone of aeration, voids in permeable materials are empty, partially filled, or filled with water either moving downward under the force of gravity or being held by capillary action.

The zone of aeration is divided into three sub-zones. These are the *capillary fringe,* the *zone of soil water,* and an *intermediate zone.*

Capillary Fringe.--Immediately overlying the zone of saturation and continuous with the water in the zone of saturation is the capillary fringe. It is held above the water table by capillarity acting against gravity. All interstices of capillary size may be filled with water but no hydrostatic head will be exhibited. Since the height to which water is held by capillarity is inversely proportional to the diameter of the interstitial space, the thickness of the capillary fringe will vary with the texture of the rock or soil, all other things being equal. If the material has only supercapillary openings, the capillary fringe will be practically absent. If the openings are all subcapillary the material is impermeable. Most materials have some capillary interstices, however. Some typical values for the height of capillary rise in common materials are presented in Table 1-2.

Table 1-2. Typical Values of Capillary Rise

Soil Type	Height of Capillary Rise, inches
Coarse sand	1/2 to 2
Sand	5 to 14
Fine sand	14 to 28
Silt	28 to 60
Clay	80 to 160 or more

At equilibrium, any water reaching the capillary fringe from above by gravity flow will cause the immediate discharge of an equivalent amount of water to the zone of saturation. In effect, this raises the elevation of the water table.

Zone of Soil Water.--The soil-water zone extends from the surface to slightly below the depth of root penetration. Water in this zone is available for transpiration by plants or for direct evaporation. The soil-water zone is not saturated except temporarily when excess water is applied. Water is held by surface tension and is moved by capillary action. If excess water is available it drains through the soil under the influence of gravity.

Water which has penetrated to a depth from which it cannot be returned to the root zone by capillary action is lost to the zone of soil water.

The thickness of the zone varies greatly with different types of soil and vegetation.

Water in this zone is commonly called *soil water.*

Intermediate Zone.--The zone of soil water and the capillary fringe may or may not be separated by an intermediate zone. The intermediate zone is the residual part of the zone of aeration. It does not exist where the capillary fringe or the water table approaches the surface and may be several hundred feet thick in deep water table areas.

Water in the intermediate zone cannot be brought back to the soil-water zone by capillary action, but it has not yet reached the capillary fringe. It is held in place by surface tension or is moving downward under the force of gravity.

The amount of stationary or *pellicular* water in the intermediate zone is dependent upon the nature of the soil or rock and is equivalent to the *field capacity* of the same materials in the soil-water zone and to the *specific retention* of an aquifer. Water in excess of this amount, if and when it becomes available from the soil zone, moves downward under the force of gravity to the capillary fringe where it displaces fringe water into the zone of saturation.

The Water Table

The upper surface of a zone of saturation is called a *water table* except where that surface is formed by an impermeable body.

The shape and slope of the water table varies, depending upon the location of areas of recharge and discharge and upon variations in permeability. In most localities it reflects the topography in a general way but with less relief.

Fluctuations in the elevation of the water table reflect changes in the volume of water in storage.

Water-bearing formations which exhibit an unconfined water table are called *phreatic aquifers.*

Ground water is said to be *perched* if it is separated from the main water table by unsaturated materials. The upper surface of this perched zone of saturation is a *perched water table.* Water may be perched either temporarily or permanently. It is underlain by a negative confining bed which stops or retards the downward movement of water under the force of gravity.

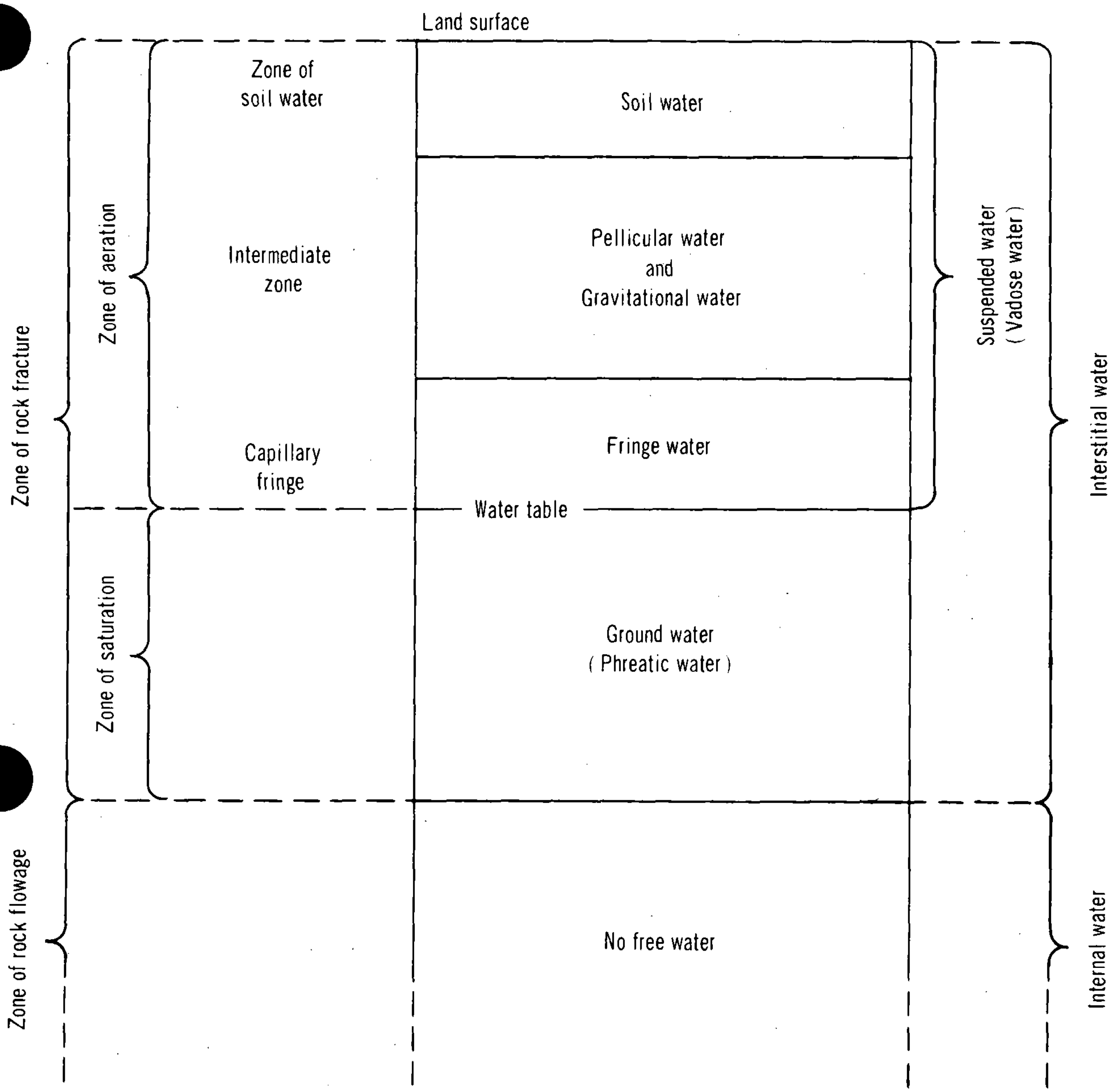


FIGURE 1-1. -- Divisions of subsurface water

The Piezometric Surface

Where the upper surface of the zone of saturation lies in a less permeable stratum and the water level in a well penetrating into the zone of saturation will rise above the upper surface of the zone of saturation, artesian conditions exist and the ground water is said to have a *piezometric surface*. This is an imaginary surface that coincides everywhere with the static pressure head elevation of the ground water. The aquifer is known as a *confined* or *artesian* aquifer. The confining layer need not be impermeable for artesian conditions to exist but must be less permeable than the aquifer.

Recharge to an artesian aquifer occurs where the water table is higher than the piezometric surface, or where the permeable formation rises above the piezometric surface and the aquifer becomes a phreatic aquifer.

Recharge may occur where the confining bed is permeable and the water table is higher than the piezometric surface. The aquifer in this case is subartesian. The same aquifer may be subartesian in one area, phreatic in another area, and artesian in still another area.

Changes in the elevation of the piezometric surface indicate changes in pressure rather than changes in the volume of water in storage.

The above ground-water relationships are illustrated in Figure 1-2.

Aquifer Characteristics

An aquifer has been defined as a formation, group of formations or part of a formation that will yield significant quantities of water.

Many major aquifers are composed of unconsolidated materials, chiefly sands and gravels. Less important aquifers are found in heterogeneous alluvial deposits, loess, and till.

Indurated sedimentary rocks yield most of their water through joints and fractures and through passages opened by weathering or solution. Some less thoroughly cemented sandstones yield water from original porosity.

Extrusive igneous rocks yield water from shrinkage cracks, joints, flow breccias and lava tubes. Basalt flows may be the source of very large amounts of ground water.

Intrusive igneous rocks and metamorphic rocks are generally unproductive but may yield small supplies for domestic use from fractures and weathered zones.

Ground Water Movement

Darcy's Law

In 1856, Henri Darcy, in France, observed that the volume of flow through a porous medium when flow is laminar is directly proportional to the head loss and inversely proportional to the length of the flow path. This is now known as Darcy's Law. It can be expressed mathematically as:

$$v = \frac{k \Delta h}{\ell} = kI \qquad (1\text{-}1)$$

where v = volume of water per unit cross-sectional area of a column of permeable material, expressed as a velocity (eg., ft./day)

Δh = difference in pressure head at the ends of the column (ft.)

ℓ = length of flow path (ft.)

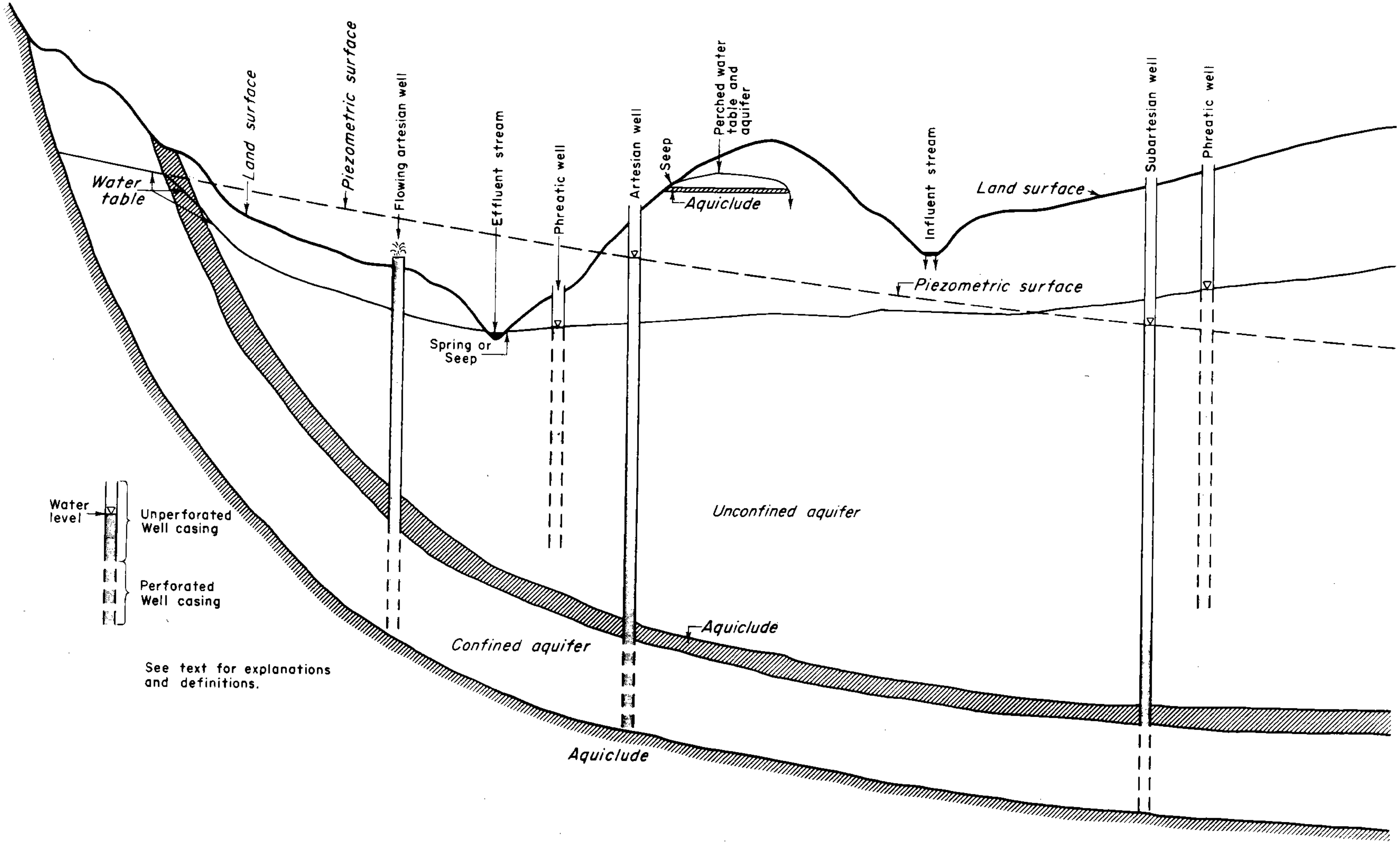


Figure 1 – 2. Ground-water Relationships

k = coefficient of permeability - a constant dependent upon the character of the material (ft.^{3}/ft.^{2}/day)

$I = \frac{\Delta h}{\ell}$ = hydraulic gradient (dimensionless)

These relationships are illustrated in Figure 1-3. In the equation, v represents the rate of motion of a solid column of water the size of the test section.

The actual rate of movement of the water, as measured with dye tracers for instance, is the velocity v in equation 1-1 divided by porosity:

$$V = \frac{v}{p} = \frac{kI}{p} \qquad (1\text{-}2)$$

V = actual rate of movement (ft./day)

p = effective porosity (dimensionless decimal)

and v, k, and I are as defined in equation 1-1.

It naturally follows that:

$$k = \frac{pV}{I} \qquad (1\text{-}3)$$

This is a useful concept in estimating field permeabilities with the use of dye tracers.

Coefficients of Permeability and Transmissibility

The *coefficient of permeability* k of a given material is the volume of water that will flow through a unit cross-sectional area in unit time, under unit hydraulic gradient and at a standard temperature. SCS commonly expresses the coefficient of permeability in cubic feet of water

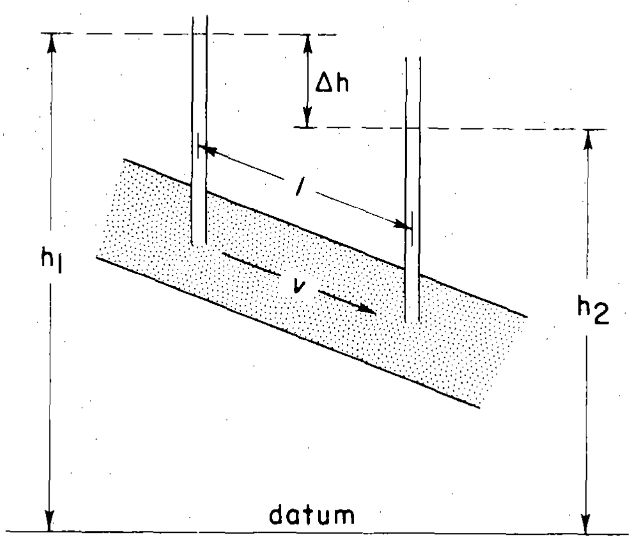


FIGURE 1-3. - Factors involved in Darcy's Law

per day through a cross-sectional area of the aquifer one foot square under a hydraulic gradient of one foot per foot at a temperature of 20° C. This is:

$$k = \frac{\text{ft.}^3 \text{ at } 20° \text{ C}}{(1 \text{ day})\ (1 \text{ ft.}^2)\ (1 \text{ ft./ft.})}$$

The U.S. Geological Survey commonly expresses the coefficient of permeability in Meinzer's units. This is in gallons per day at 60° F. with the other terms remaining the same or:

$$Pm = \frac{\text{gal. at } 60°\text{F}}{(1 \text{ day})\ (1 \text{ ft.}^2)\ (1 \text{ ft./ft.})}$$

The viscosity of water is a function of temperature. For this reason permeabilities are adjusted to a standard temperature. The temperature range of most aquifers, however, is small and it is common practice in water development field procedures to ignore the temperature correction and compute field coefficients of permeability at the prevailing temperature.

The *coefficient of transmissibility* T is the rate of flow of water through a vertical strip of unit width which extends the entire saturated thickness of the aquifer under unit hydraulic gradient and at the prevailing water temperature. This is expressed as:

$$T = \frac{\text{ft.}^3}{(1 \text{ day})\ (1 \text{ foot})\ (\text{thickness-m ft.})\ (1 \text{ ft./ft.})}$$

$$\text{or} \quad T = \frac{\text{gal.}}{(1 \text{ day})\ (1 \text{ foot})\ (\text{thickness-m ft.})\ (1 \text{ ft./ft.})}$$

In a uniform aquifer the coefficient of transmissibility is equal to the field coefficient of permeability times the saturated thickness.

Figure 1-4 illustrates the relationships of permeability and transmissibility.

A useful form of Darcy's law is given by the formula:

$$Q = k\ I\ A = T\ I\ L \qquad (1\text{-}4)$$

where Q = discharge (ft.^3/day)

k = coefficient of permeability ($\text{ft.}^3/\text{ft.}^2$/day)

I = hydraulic gradient (ft./ft.)

A = cross-sectional area through which discharge occurs (ft.^2)

T = coefficient of transmissibility (ft.^3/ft./day)

L = width of section through which discharge occurs (ft.)

Coefficients of transmissibility determined in the field can be converted to coefficients of permeability by dividing by the thickness of the

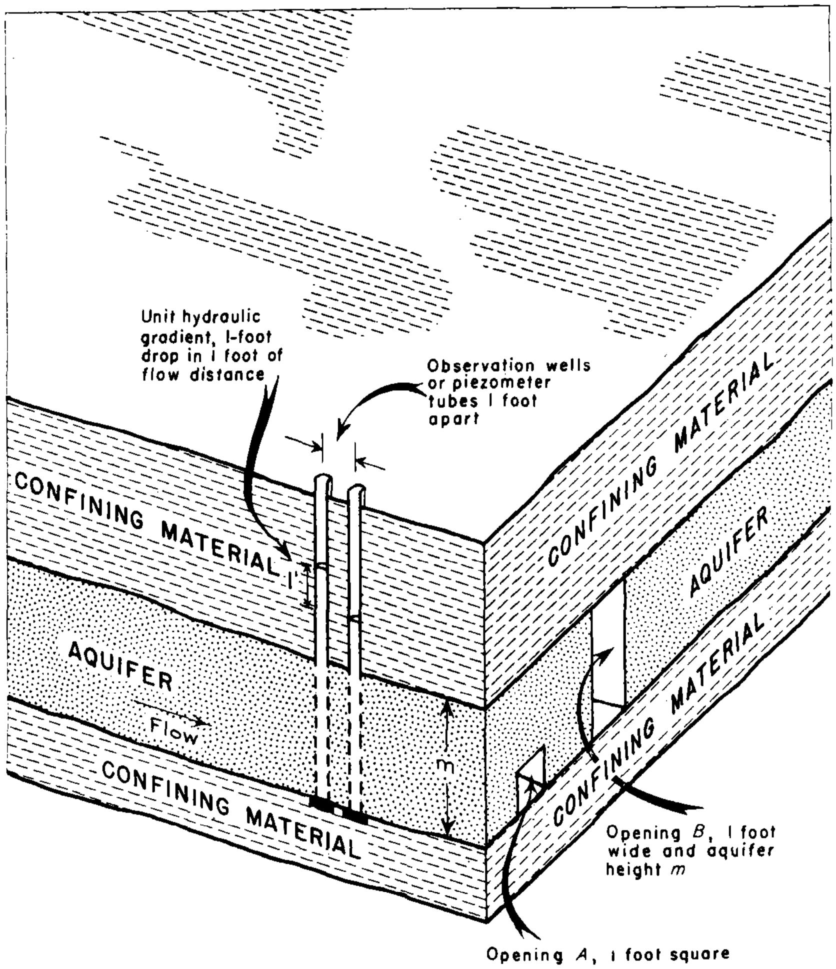


Figure 1-4. Coefficients of Permeability and Transmissibility

(From Theory of Aquifer Tests by J. G. Ferris et al, 1962, U. S. Geol. Surv. Water Supply Paper 1536-E)

aquifer. This represents the overall average permeability of the aquifer tested.

Methods of determining k and T by pump tests are discussed in the section on Well Hydraulics.

Flow Lines and Equipotential Lines

A *streamline* or *flow line* is the mean path of flow of an individual particle of water as it moves through an aquifer in the direction of decreasing head.

Equipotential lines in an aquifer represent contours of equal head. They intersect flow lines at right angles. Ground-water contours in an unconfined aquifer and *isopiestic* (equal pressure) lines in a confined aquifer are equipotential lines.

A *flow net* is a graphical representation of a flow pattern and is composed of families of flow lines and equipotential lines. The actual flow pattern contains an infinite number of flow lines and equipotential lines. The graphical representation is constructed using only a few of these lines, selected so that the quantity of flow is equal between adjacent pairs of flow lines and the drop in head is equal between adjacent pairs of equipotential lines.

When constructing a flow net the flow lines are drawn orthagonal to the equipotential lines resulting in a pattern of rectangles (or squares) with the ratio of the mean dimensions of each rectangle equal.

A flow net can represent a vertical plane through an aquifer (BFGC in Figure 1-5) or any plane parallel to the flow (AEFB in Figure 1-5).

In three dimensions, each equipotential line becomes a plane. Under ideal conditions (an isotropic aquifer) this plane is vertical. The upper edge of the plane is a line on the upper surface of the aquifer and the lower edge is a line on the bottom of the aquifer. Piezometers set at any point on this plane will have the same water level. An equipotential plane is represented by plane ABCD in Figure 1-5. Figure 1-5 represents a prism taken from an ideal aquifer where the equipotential lines are straight and equally spaced and the flow lines are equally spaced. The discharge from the small squares on the face of the prism are all equal, as are their areas. Under field conditions, the discharges, by definition, would be equal but the areas would probably vary.

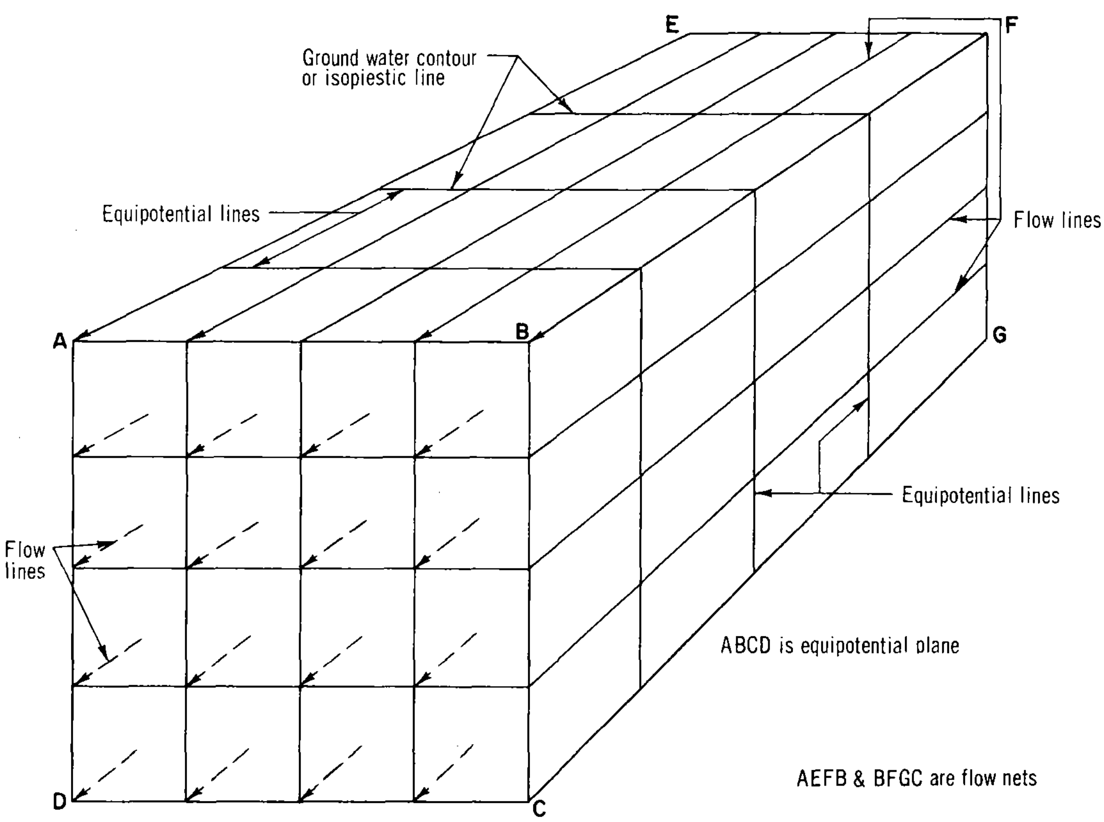


Figure 1-5. Flow Nets

Since flow cannot cross an impermeable boundary, flow lines adjacent to a boundary must parallel the boundary. In an unconfined aquifer, the water table is also a bounding surface. Flow lines adjacent to the water table must parallel the surface of the water table, and since ground water contours are in reality equipotential lines, flow lines must be perpendicular to the contours. The relative spacing of the flow lines will be dependent upon the water table gradient and the permeability and thickness of the aquifer.

Coefficient of Storage

The *coefficient of storage* of an aquifer is the volume of water it releases or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. This is illustrated in Figure 1-6.

In an unconfined aquifer the coefficient of storage is equivalent to the *specific yield.* It is the volume of water, in cubic feet, that a cubic foot of the aquifer will yield to gravity drainage. It will range from about 0.05 to 0.30.

The storage coefficient of a confined aquifer equals the volume of water in cubic feet released from a vertical column one foot square extending through the aquifer when the piezometric surface declines one foot. This volume is attributable to the compressibility of the aquifer material and of the water. The storage coefficients of artesian aquifers usually range from 0.00001 to 0.001.

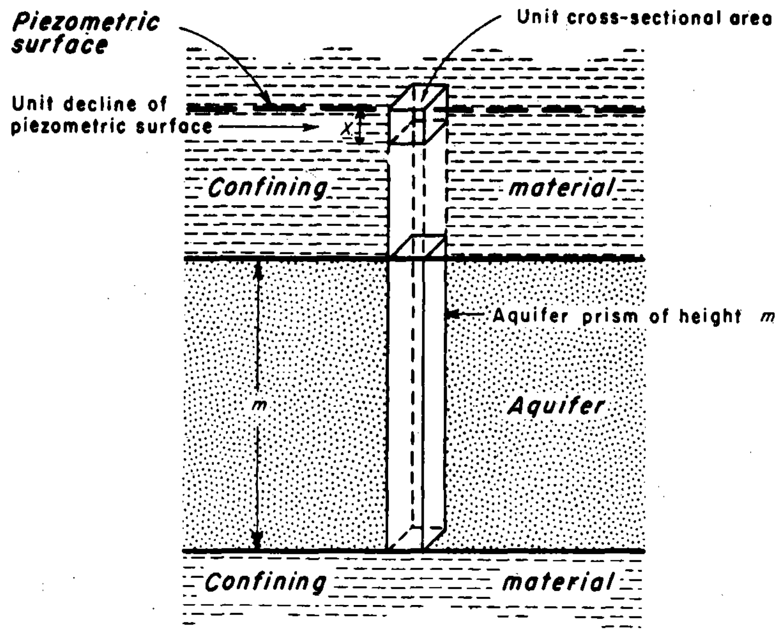
An unconfined aquifer will yield 50 to 30,000 times more water per foot decline in head than will a confined aquifer, other things being equal. From this it can be seen that decline in the piezometric surface over large areas is required to produce significant amounts of water from a confined aquifer.

Hydraulics of Wells

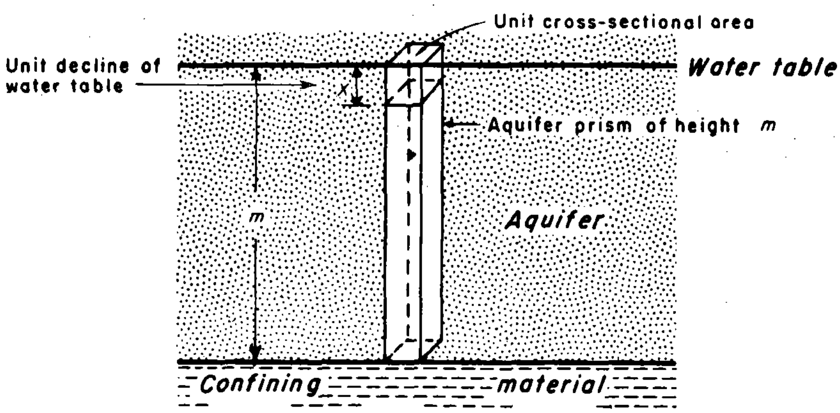
A ground-water reservoir tends toward a state of equilibrium with natural discharge balancing natural recharge. The installation of a discharging well disturbs this balance and a new equilibrium state is reached by the propagation of a *cone of depression.* As the cone of depression extends outward and deepens, natural recharge is increased, or natural and well discharge are decreased, until equilibrium is again established. The extent of the cone of depression is called the *area of influence.*

Equilibrium Conditions

In an ideal, homogeneous, isotropic aquifer of finite thickness and infinite extent, a completely penetrating discharging well can be considered as being surrounded by a series of concentric cylinders. At equilibrium the discharge through the wall of each of these cylinders is equal to the discharge from the well. At successively greater distances from the well the side areas of the cylinders increase at an increasing rate since the area of a cylinder equals $2\pi rh$.



A. ARTESIAN AQUIFER



B. WATER-TABLE AQUIFER

Figure 1-6. Coefficient of Storage

(From Theory of Aquifer Tests by J. G. Ferris et al, 1962, U. S. Geol. Surv. Water Supply Paper 1536-E)

Since, according to Darcy's law

$$Q = kIA \qquad (1\text{-}4)$$

and therefore,

$$k = \frac{Q}{I\ A}$$

the permeability of the aquifer can be determined if the hydraulic gradient of the ground water is known at a distance r from a well discharging a known volume of water. At this distance the area of the cylinder through which flow occurs is $2\Pi rm$ for a confined aquifer where m is the thickness of the aquifer. For an unconfined aquifer the area of the cylinder is $2\Pi r\,(m-s)$ where m is saturated thickness before pumping and s is drawdown.

Since the hydraulic gradient cannot be measured at a *point*, a mathematical treatment of Darcy's equation was developed that substitutes the drawdown in two observation wells for the hydraulic gradient. This is known as the *Thiem* formula:

$$k = \frac{Q \log_e \frac{r_2}{r_1}}{2\Pi m \; (s_1 - s_2)} \tag{1-5}$$

where k = coefficient of permeability ($ft.^3/ft.^2/day$)

Q = discharge from pumped well ($ft.^3/day$)

r_1 and r_2 = distances from pumped well to two observation wells (ft.)

s_1 and s_2 = drawdown in the observation wells (ft.)

m = saturated aquifer thickness before pumping (ft.)

The formula can be used to compute permeabilities under equilibrium conditions. However, it assumes the following:

1. The aquifer is isotropic, of infinite areal extent and rests on a horizontal impermeable bed;
2. the discharging well penetrates the entire saturated thickness of the aquifer;
3. the observation wells are placed in line with the discharging well;
4. pumping has continued at a constant rate for sufficient time for the drawdown cone to have reached a steady state;
5. flow to the well is radial;
6. the non-pumped water table was horizontal.

The Thiem equation applies to confined aquifers and unconfined aquifers if the difference in drawdown between the two observation wells is small compared to the saturated thickness. Figure 1-7 illustrates the various relationships in the Thiem equation.

The severe limitations placed on the equilibrium formula can sometimes be overcome by appropriate adjustments. These adjustments and their

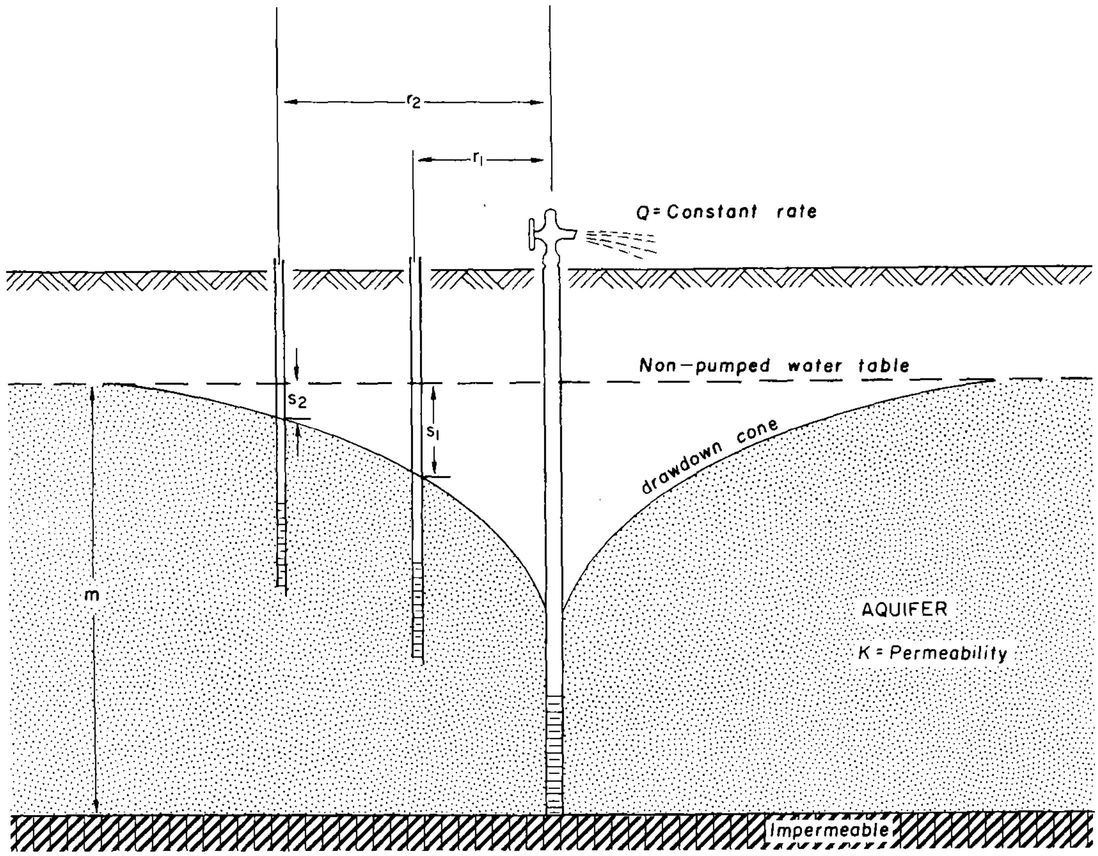


Figure 1-7. Aquifer Pump Test

validity and limitations are discussed by Wenzel (1942), Ferris et al (1962), and Bentall (1963).

In practice, one procedure for using the Thiem equation is to measure the drawdown in the observation wells at a time when equilibrium of the cone of depression has been established by pumping at a constant rate. These measurements are plotted on semilog coordinate paper, the drawdown s on the arithmetic scale and distance r on the logarithmic scale. When two or more observation wells are used all values of r and s at a given time t should fall on a straight line on the semilog plotting if equilibrium has been attained. Convenient values of r_1 and r_2 and s_1 and s_2 can then be picked from the curve and the Thiem equation solved for k. An example of these procedures is given in chapter 3.

Non-equilibrium Conditions

In the case where equilibrium of the drawdown cone is not established, a non-equilibrium equation can be applied to determine the aquifer constants. This equation, developed by C. V. Theis in 1935, is based on the assumption that hydraulic conditions in an aquifer and thermal conditions in a thermal system are analagous in mathematical theory. The following aquifer conditions are assumed in the application of the equation:

1. The aquifer is homogeneous and isotropic;

2. the aquifer has infinite areal extent

3. the discharging well penetrates the entire thickness of the aquifer;

4. the coefficient of transmissibility is constant at all times and all places;

5. the well has an infinitesimally (reasonably) small diameter;

6. the water removed from storage is discharged instantaneously with decline in head.

The final equation for the drawdown of the water level in the vicinity of a discharging well as developed by Theis is:

$$s = \frac{114.6\ Q}{T} \int_u^\infty \frac{e^{-u}}{u}\, du \qquad (1\text{-}6)$$

where s = drawdown at a point r distance from a pumping well (ft.)

Q = discharge from the well (gallons per minute 1/)

T = coefficient of transmissibility (gal./day/ft.)

$u = \dfrac{1.87\ r^2 S}{Tt}$

r = distance from pump well to point where drawdown s is determined (ft.)

S = coefficient of storage (dimensionless)

t = time that pump well has been discharging (days).

The expression:

$$\int_u^\infty \frac{e^{-u}}{u}\, du$$

is an exponential integral and cannot be integrated directly. The notation for this integral is $W(u)$, which is read "well function of u," and its value is given by the series:

$$W(u) = -0.577216 - \log_e u + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} - \frac{u^4}{4\cdot 4!} \cdots \qquad (1\text{-}7)$$

1/ Gallons is used here instead of cubic feet because most literature concerning pumps and pump tests is in terms of gallons. Appropriate conversion factors can be used after computations have been completed.

Equation (1-6) can then be written:

$$s = \frac{114.6\ Q}{T}\ W(u) \tag{1-8}$$

Selected values of *W(u)* for given values of *u* between 10^{-15} and 9.5 are given in Table 1-3.

Table 1-3. Selected Values of *u* and *W(u)*

u	*W(u)*	*u*	*W(u)*
9.5	0.0000072	0.01	4.04
6.0	0.00036	0.005	4.73
4.0	0.0038	10^{-3}	6.33
3.0	0.013	10^{-4}	8.63
2.0	0.049	10^{-5}	10.94
1.5	0.10	10^{-6}	13.24
1.0	0.22	10^{-7}	15.54
0.75	0.34	10^{-8}	17.84
0.5	0.56	10^{-9}	20.15
0.4	0.70	10^{-10}	22.45
0.3	0.91	10^{-11}	24.75
0.2	1.22	10^{-12}	27.05
0.1	1.82	10^{-13}	29.36
0.075	2.09	10^{-14}	31.66
0.05	2.47	10^{-15}	33.96
0.025	3.14		

If the coefficient of transmissibility and coefficient of storage are known, the drawdown on the cone of depression at any time and any distance from the well can be determined after the well starts discharging. This is done by substituting the known values of *S* and *T* and the desired values of *t* and *r* in the equation:

$$u = \frac{1.87\ r^2\ S}{Tt} \tag{1-9}$$

and the equation solved to determine *u*. The value of *W(u)* for *u* is obtained from Table 1-3 and equation (1-8) is then solved for the drawdown *s*.

The non-equilibrium equation can also be solved for transmissibility T and storage coefficient S if several values of drawdown s at times t are known for one distance r from the pumpwell or several values of s and r are known for one value of t. The solution requires the graphical determination of $W(u)$, u, s, and either r^2/t or the reciprocal of time ($1/t$).

A type curve of $W(u)$ versus u for the values shown in Table 1-3 is plotted on log-log coordinate paper, Figure 1-8 is an example. (See Ferris et al, 1962, pp. 94-98 and other related references). Data from the observation wells are then plotted on log-log tracing paper at the same scale as the type curve. Values of s are plotted against r^2/t (or $1/t$ if only one observation well is used and r therefore is constant).

The curve of the observed data is superimposed on the type curve and with the axes of the curves kept parallel the superimposed sheet is shifted until a section of the two curves matches. The values of $W(u)$, u, s, and r^2/t of an arbitrary common point on the matched section of the curves are recorded and the equation:

$$T = \frac{114.6\ Q}{s} W(u) \qquad (1\text{-}10)$$

is solved for T. The equation:

$$u = \frac{1.87\ r^2\ S}{Tt} \qquad (1\text{-}9)$$

can then be solved for S.

There are many modifications, simplifications and alterations that can be applied to the non-equilibrium equations. Conditions such as impermeable boundaries, recharge boundaries, leaky aquifers, partial penetration of the aquifer by discharging wells and other conditions encountered in the field require adjustments and modifications of the basic equations. These adjustments and modifications, as well as alternate methods of hydraulic analysis of aquifers, are discussed in some of the publications listed under references at the end of this chapter. An example of a pump-out test is given in chapter 3.

Quality of Ground Water

All ground waters carry salts in solution. The primary source of these salts is the solution of minerals. Relative quality of water depends upon not only the total amounts of dissolved solids but also the kinds of salts and the use to which the water will be put. The principal constituents of natural waters are calcium, magnesium, sodium, potassium, and ferric and ferrous iron as cations, and carbonate, bicarbonate, sulphate, chloride, fluoride, and nitrate as anions. Usual minor constituents are aluminum, manganese, silica, boron, and selenium. Traces of any of the known elements may be present and considerable concentrations may exist in local areas.

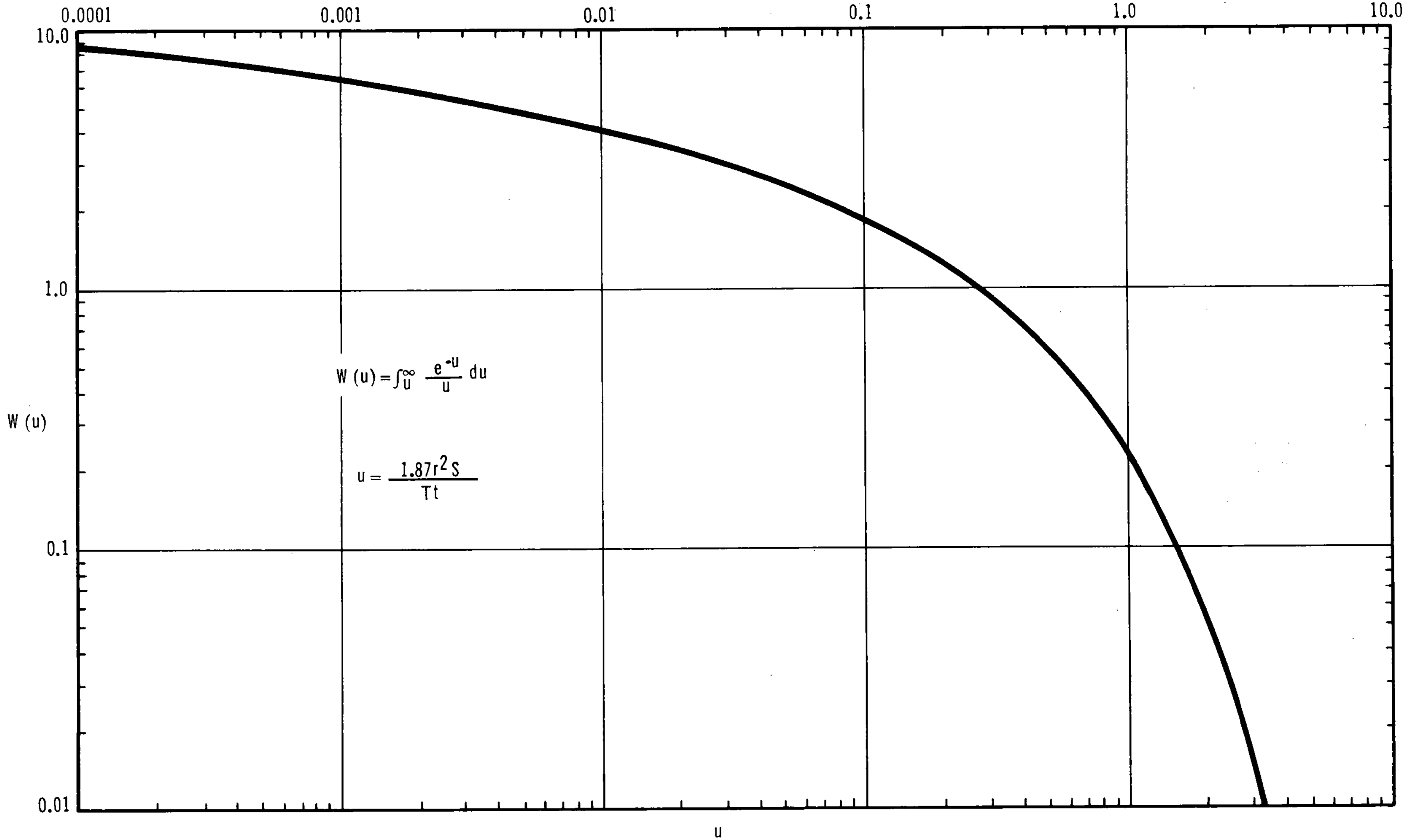


FIGURE 1-8 Relation Between u and W(u)

The U.S. Public Health Service has set standards for drinking water which have been adopted by most States. The chemical substances listed in Table 1-4 (from U.S. Department of Health, Education, and Welfare, 1962) should not be present in excess of the concentrations shown if an alternate suitable water supply is available.

Table 1-4. Drinking Water Standards

Chemical Substance	Concentration mg/l
Alkyl Benzene Sulfonate(ABS)	0.5
Arsenic(As)	0.01
Chloride(Cl)	250.
Copper(Cu)	1.
Carbon Chloroform Extract(CCE)	0.2
Cyanide(CN)	0.01
Fluoride(F)	1/
Iron(Fe)	0.3
Manganese(Mn)	0.05
Nitrate(NO_3)	45.
Phenols	0.001
Sulfate(SO_4)	250.
Zinc(Zn)	5.

1/ Depends on the average annual maximum daily temperature and varies from 1.7 mg/l at 50.0°-53.7°F to 0.8 mg/l at 79.3°-90.5°F.

If the concentration of any of the substances exceeds that shown in Table 1-5 the water supply is unsuitable for human consumption.

There are also established standards for turbidity, color, taste, odor, and bacterial content.

Table 1-5. Water Unsuitable for Human Consumption

Chemical Substance	Concentration mg/l
Arsenic(As)	0.05
Barium(Ba)	1.0
Cadmium(Cd)	0.01
Chromium(Hexavalent)(Cr^{+6})	0.05
Cyanide(CN)	0.2
Fluoride(F)	1/
Lead(Pb)	0.05
Selenium(Se)	0.01
Silver(Ag)	0.05

1/ Depends on the average annual maximum daily temperature and varies from 2.4 mg/l at 50.0°-53.7°F to 1.4 mg/l at 79.3°-90.5°F.

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SECTION 18

GROUND WATER

CHAPTER 2. GROUND-WATER GEOLOGY

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SECTION 18

GROUND WATER

CHAPTER 2. GROUND-WATER GEOLOGY

Materials of the Earth's Crust

The earth's crust consists of rock of various kinds; accumulations of rock debris; and soils formed by water, wind, and glacial action. Materials vary from single elements to varied mixtures of minerals that form many kinds of rocks. Understanding of the order and manner in which materials occur or were deposited and their characteristics is fundamental to proper water development.

Unconsolidated Materials

Unconsolidated materials consist of soil and recent deposits of rock-slide debris, talus, fans, mud flows, alluvium, lake sediments, loess, dune sand and glacial drift. They are important to the planning and development of water resources wherever they are involved in site conditions.

Rock-slide debris.--Rock-slide debris is generally very porous and highly permeable. It is difficult to develop as a source of ground water but is usually excellent for ground water recharge developments.

Mudflows.--Mudflow deposits may have low permeability and are of little value for water developments.

Talus and fans.--Talus deposits and fans in stream valleys may be good sources of ground water depending on their size and topographic position. The discussion of alluvium following also applies to these deposits.

Alluvium.--Alluvium is stream-deposited detritus.

Alluvium varies in thickness, texture, degree of sorting, stratification, porosity, and permeability. Its thickness is usually proportional to the size of the drainage area. The coarse-textured materials are usually deposited in headwater areas, but may also occur at or near the base of the deposit.

Understanding of the principles of valley alluvial deposition as related to glacial influences is important in the interpretation and evaluation of site conditions for ground-water development.

During the Pleistocene, degradation in the stream systems occurred when sea level was lowered by increasing accumulation of ice in the continental glaciers. Conversely, aggradation occurred in the stream systems with the ablation of the glaciers.

This degradation and aggradation that accompanied each glacial advance and retreat represents one cycle of sedimentation. Seven such cycles have been recognized in non-glaciated as well as glaciated areas.

Deep channel and terrace deposits at Natchez, Mississippi, Figure 2-1, indicate that sea level may have been as much as 300 feet lower during the peak of glacial ice accumulation than it is now.

In glaciated areas some preglacial and interglacial channels have been blocked and filled by succeeding glaciers. In many instances the present drainage system differs from the antecedent. Many of these antecedent or ancient drainage systems have been discovered by drilling ground-water test wells. They constitute a very important reservoir for the accumulation and storage of ground water. Ground water in the channel deposits of these drainage systems meets the needs of agricultural, municipal, and industrial water developments. These shallow aquifers are readily replenished by local precipitation, and the quality of the water is generally suitable for agricultural uses.

Permeability and specific yield of alluvial deposits vary considerably with the texture. Textural information can be obtained from the logs of test wells and the mechanical analyses of the water-bearing materials. This information is important for the proper design and development of wells.

Yields of large wells versus thicknesses of saturated sediments were plotted to aid in estimating potential yields. Variabilities in yields are affected by differences in static water level, well characteristics and degree of sorting of aquifer materials; however, these factors were disregarded. These plots (Figures 2-2 and 2-3) indicate a requirement of about 25 feet of saturated sands and gravels and about 90 feet of saturated very fine sand to yield 500 gpm. Figure 2-4 is plotted to show the reported yields of wells in gpm, the yield (gpm) per foot of drawdown, and the theoretical maximum potential yield of the well at 100 percent drawdown.

Natural replenishment to alluvial water-bearing materials is influenced by intensity and duration of precipitation, intake rates of soil and subsoil, runoff from the drainage basin, and in some areas, by ground water underflow from nearby drainage basins. Ground-water replenishment is also influenced by land slope, plant cover, land use, and available storage capacity. Frozen ground is an effective barrier against infiltration.

The chemical quality of the water is influenced by local geology, land use, climate and disposal of domestic, municipal, and industrial wastes.

Lake sediments.--Lacustrine deposits consist of clays, silts, sands, gravels, marl, tufa, peat and evaporites. Sands and gravels occur as deltaic and shoreline or beach deposits, whereas silts and clays may be lakewide in occurrence. Limonite along with manganese oxide may occur as nodular and concretionary deposits of irregular distribution. Peat is common along the margins and sapropel (black muds rich in

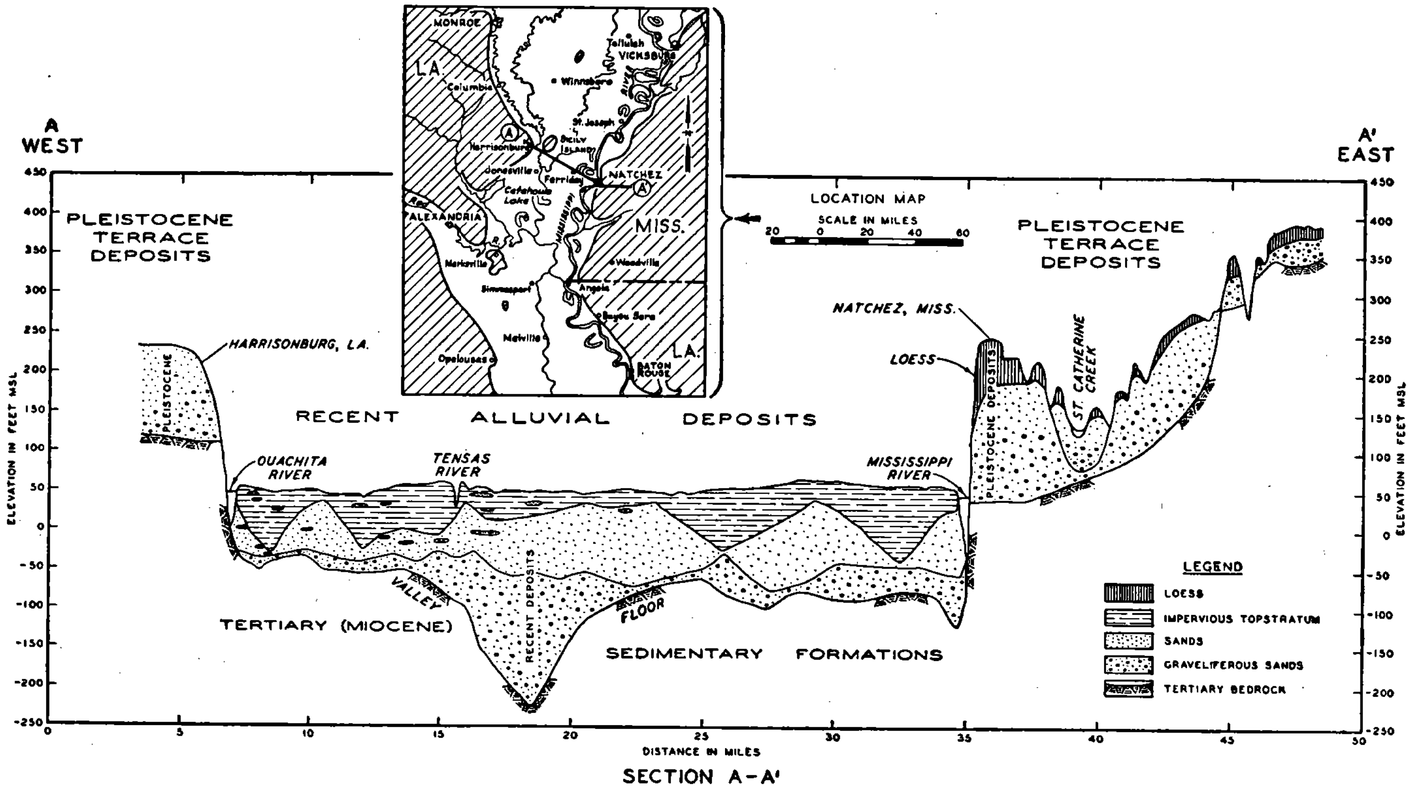

FIGURE 2-1. Geological section near Natchez, Mississippi

(From Applied Sedimentation, Edited by P. D. Trask, New York: John Wiley and Sons, 1950. Used by permission of John Wiley and Sons.)

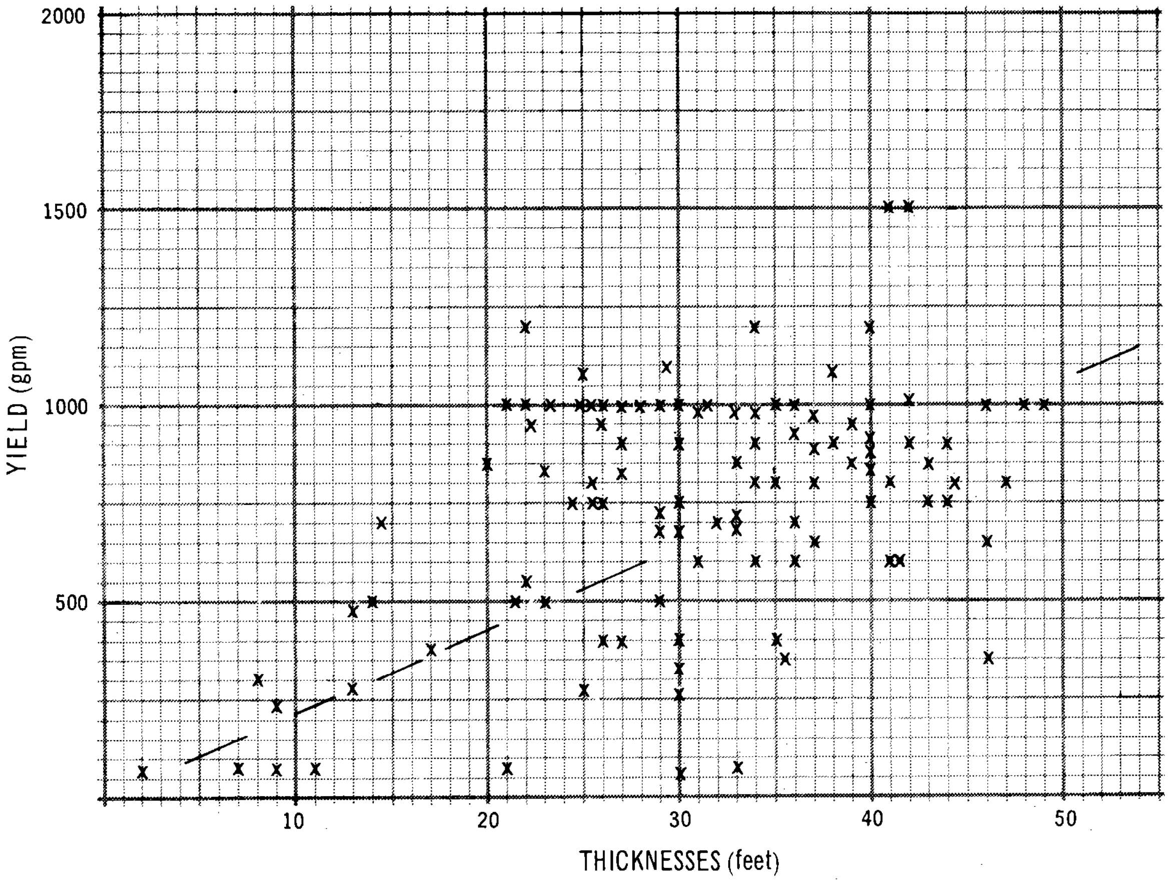

FIGURE 2-2 Yields of Saturated Sands and Gravels in Irrigation Wells

(Compiled from Lugn and Wenzel, 1938)

organic matter) is deposited in the central parts of lakes. Marl and tufa are precipitated in the greatest temperature change zone.

Evaporites are common in lake deposits of arid regions. Some lake deposits have a predominance of carbonates.

Deltas and beaches are ground water catchment areas. They are also good areas in which to develop ground water providing they are deep enough to be classified as aquifers. Water quality is usually good because of rapid intake from precipitation.

Water developments from the central portions of lake plains are less favorable because of low permeabilities of silts and clays and accumulations of dissolved solids.

Loess.--Loess is an eolian or windblown deposit that consists mainly of silts that are generally loose and noncohesive, and may contain clay and sand. The clay content of some loessial soils is affected by soil development and associated chemical changes. The clay particles in the A soil horizon may be transported by percolating water into the B horizon.

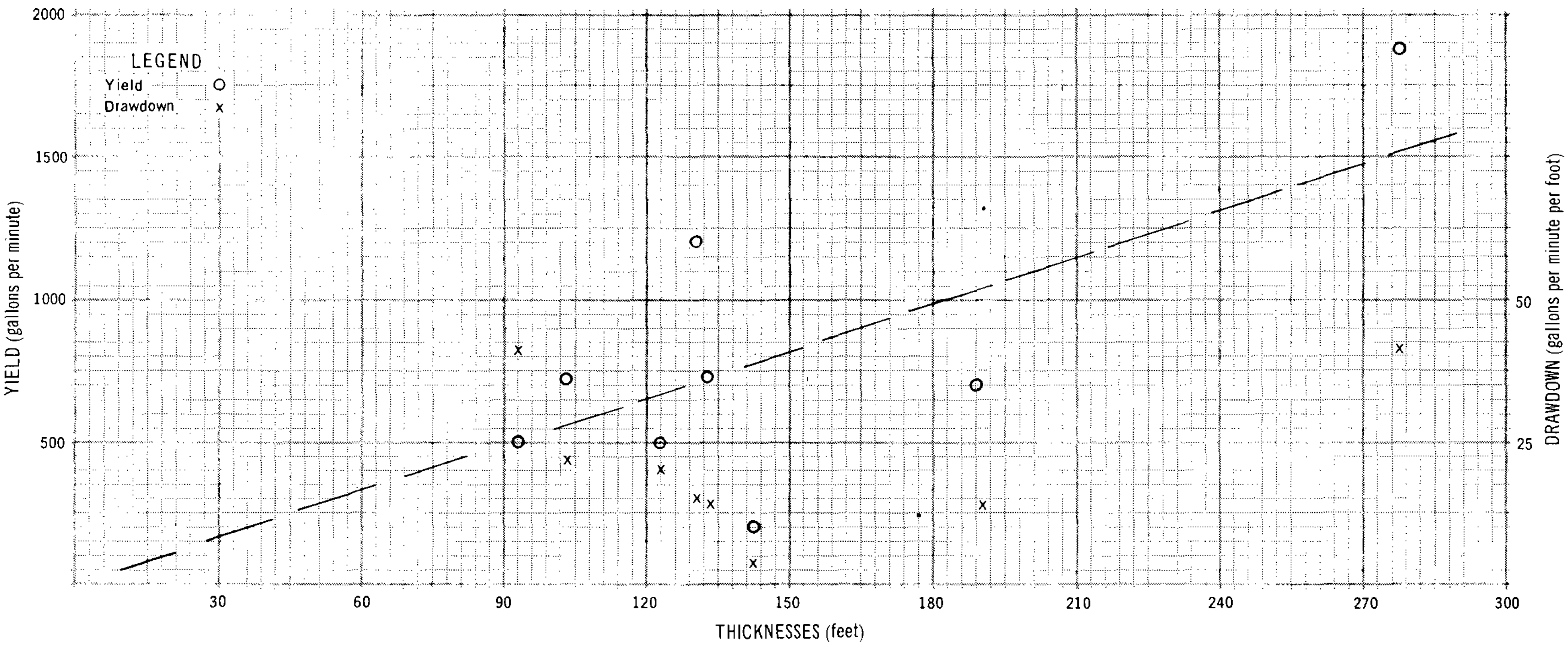

FIGURE 2–3 Yields of Saturated Very–fine Sands in Wells

(Compiled from Cady and Scherer, 1946)

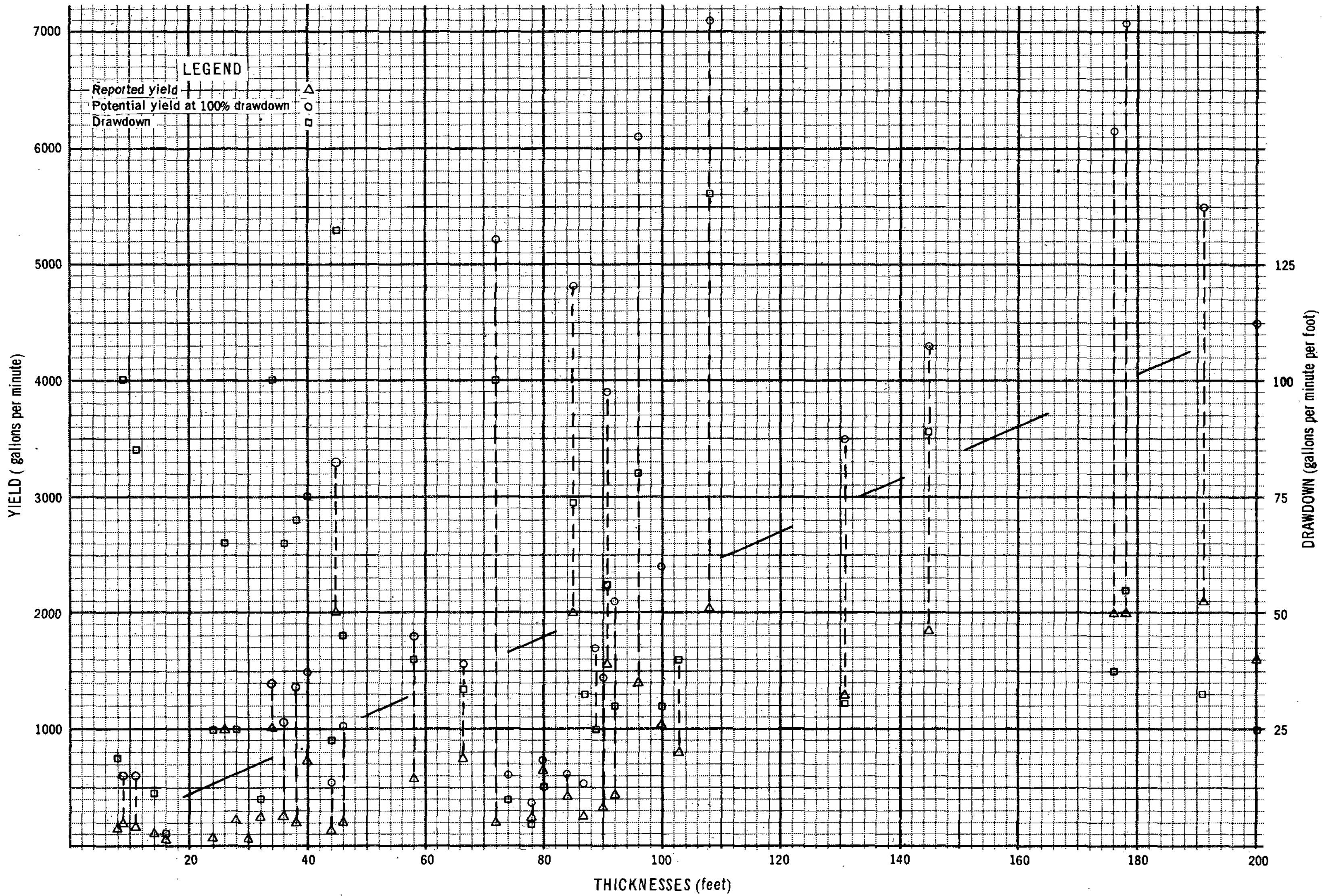

FIGURE 2–4 Yields and Potential Yields of Saturated Sands and Gravels in Irrigation Wells

(Compiled from William and Lohman, 1949)

Loess occurs in intermontane valleys, in hilltops, throughout great lengths of tablelands and uplands, in terraces of stream systems, and floodplains and stream beds of some drainage systems. It may contain buried soils and tends to mantle antecedent topography.

Porosity, permeability and specific yield of loess will vary with different grade sizes of particles and degree of sorting. The coefficient of permeability of loess is so low, 1 to 4 Meinzer units (Lugn and Wenzel, 1938), that it is not considered an aquifer. However, thick saturated sections of loess can sometimes be developed for water supplies through the use of large diameter wells. The storage capacity of the well is used to offset the low permeability of the loess.

Dune sand.--Wherever materials contain sand that is available for transport by the wind, local dunes may develop. Eolian sands may be found in any geologic time period. Some consist of gypsum, oölites, and shell fragments. The St. Peter, Tensleep, and Navajo sandstones are examples of wind-worked sands.

Where sand dunes migrate into a water environment, particles may be rearranged from the complex dune cross-bedding to an aqueous stratification.

Eolian sands that occur in relatively shallow, topographically high accumulations, act as good intake areas for ground-water recharge to underlying formations but may themselves be above the main zone of saturation.

Glacial deposits.--Glacial deposits consist of glacial drift as ground, terminal, lateral, and recessional moraines and outwash deposits from the melting of glacial ice. Unstratified drift consists of a heterogeneous mixture of clay, sand, gravel, cobbles, and boulders. The glacial drift of mountainous areas and the New England States is predominantly an unstratified mass of boulders whereas that of the northern Great Plains contains considerable clay derived from glacial gouging of Cretaceous shales. Some glacial drift in the northern Great Plains contain inclusions of stratified silts, sands and gravels of various cross-sectional dimensions with the bedding planes tilted from the horizontal. These suggest an origin of stratified deposits in the margin of the main mass of glacial ice. Some of these sand and gravel inclusions are large enough to be reservoirs for ground water.

The Nebraska glacial till has been reported as "almost impervious to water," (Shimek, 1910). Kansan and younger glacial deposits furnish water to many small wells in the north central United States. Permeability of the tills is very low so that dug wells are usually considered most satisfactory methods of water development. Large diameter dug wells serve the purpose of reservoir storage.

Kames, eskers, and outwash sands and gravels are usually very porous and highly permeable. Where they are low enough topographically to be within the main zone of saturation, they are excellent sources of ground water for domestic and livestock use. High iron content of some of these waters, however, may stain plumbing fixtures and is objectionable for some domestic uses.

Rocks

The consolidated materials of the earth's crust are classified into three major groups: (1) Igneous rocks, formed by cooling from the molten state; (2) sedimentary rocks, formed by lithification of unconsolidated material, chemical and organic action, or evaporation; and (3) metamorphic rocks, formed from pre-existing rocks by stress and increased temperature.

Igneous rocks.--Molten rock may be extruded on to the surface as lava flows, blown out by volcanic eruptions, or intruded into the earth's crust at various depths below the surface.

Pyroclastic rocks and some lava flows contain openings due to fragmentation, gas bubbles, or contraction during cooling. Locally these openings may be connected so that ground water can move through them. Most igneous rocks, however, are dense and lack voids. They are not considered potential sources for ground water unless openings have developed by fracturing, jointing or faulting. Where joint systems are well developed, as in some dense lava flows, large amounts of ground water may be available. Jointed and fractured granitic masses may also yield some ground water.

The Columbia River basin in Washington, Oregon, and Idaho drains about 50,000 square miles of lava. The lava occurs in individual flows that vary in thickness from about 5 to 150 feet. The total maximum thickness is about 5,000 feet and the total number of individual flows about 100. Tunnels may be formed by molten lava flowing out from beneath a solidified crust. The base of some flows contain local rubble that is permeable and the tops of some are columnar and blocky from fracturing caused by cooling. Columnar structure contributes to permeability. Diastrophism subsequent to these Late Tertiary flows has produced folds and possibly additional ruptures in some areas. Faulting transverse to the dip of bedrock has produced barriers to horizontal flow of water in some localities. The rock varies from dense massive columnar-jointed rock to vesicular and fractured masses on weathered surfaces of individual flows. Precipitation and runoff from the mountainous areas filter into surface fractures and migrate to lower strata along faults and major fractures. Most highly productive wells are located in structural troughs, some are artesian.

Sedimentary rocks.--Sedimentary rocks are the products of chemical, organic and mechanical processes. See Table 2-1. The materials of mechanical origin--shale, sandstones, and conglomerates--are the consolidated products of erosion that have been removed from one environment, transported, and deposited in another and converted to rock by the addition of accumulating load. Shales are the consolidated products of muds, and sandstones and conglomerates the products of coarse clastics.

Consolidation is the process of changing loose, highly porous earth materials to more dense, less porous materials by means of compression

Table 2-1 Genetics of Sediments

- SEDIMENTATION
  - Weathering influenced by: climate, parent material (primary and secondary rocks), topography, time, organisms
    - Exfoliation
    - Granular Disintegration--differential expansion and contraction
    - Frost action
    - Soil development
    - Root wedging
      - Physical--disintegration
      - Chemical--decomposition
  - Erosion influenced by: plant cover, topography, land use
    - Fragmentation or Clastation-- (Breaking or shattering in situ)
    - Ablation (Separation and removal)
      - Mechanical (Corrasion)
        - Denudation--base leveling by water
        - Deflation--base leveling by wind--fluted yardangs, ventifacts
        - Abrasion--wear on the cutting particles
        - Quarrying--undercutting
      - Chemical (Corrosion)
        - OXIDATION--addition of oxygen--changes the color and volume of a rock. Reduction of SO_4 and CO_3 reduces volume.
        - CARBONATION--most commonly affects silicate rocks to form Ca, Na, Mg, and K Carbonates--source of CO_2 is atmosphere and plants.
        - HYDRATION--addition of water of crystallization. Change of feldspars to clay. Chemical action of ground water.
        - KAOLINIZATION--
          $2KAl\ Si_3\ O_8$(orthoclase) + $2H_2O$ + CO_2 = $H_4Al_2Si_2O_9$ (Kaolin-clay) + $4SiO_2$ + K_2CO_3
          Leaching of silica and potash reduces volume 54%.
        - LATERIZATION--in moist tropics the change of feldspar is more complete--to Hydrargillite $Al_2O_3 \cdot 3H_2O$ or bauxite. Silica is soluble only in water of excess OH - ions. pH changes with dry and wet seasons. Silica probably dissolves in the dry season and leaches in the early part of the moist season. May form precipitate of agate or chalcedony.
  - Transportation
    - Wind
    - Water
    - Ice -- glaciers
    - Gravity -- slides are manifestation of the effect of gravity and failure of foundation
    - Animals
  - Sorting
    - Changes in channel grade
    - Uniform discharge
    - Riffling
    - Winnowing
  - Deposition influenced by loss of energy, place, time
    - Reduction in channel grade
    - Reduction in turbulence
    - Spreading of water
    - Loss of stream grade
    - Settling in relatively quiet water
    - Loss of velocity
    - Eolian transport from arid to humid and aqueous environment
    - Chemical precipitation
    - Evaporites, supersaturation, Caliche Formation
  - Diagenesis
    - Compression to stone
    - Cementation to stone

from accumulating overburden. Porosities vary from about 15 to 65 percent for clay materials to as low as 8 percent for consolidated shales. Density also increases as the result of desiccation.

Physical and chemical changes under increasing load eventually lithify earth materials to rock, for example, clay to shale. The degree of consolidation may be a measure of the load that has been applied to produce a given kind of rock.

Consolidation is also produced by chemical bonding of materials and by fusion under high temperatures and pressure into rock. The clastic sedimentary rocks are the lithified sediments that were transported by water, ice, wind, and gravity. They are usually classified on the basis of texture, mineral composition, structure and additional pertinent characteristics, such as cementation and color.

When muds, silts, or clays are indurated they are termed respectively mudstone, siltstone and claystone when massive, and shale when laminated or fissile. The cleavage of shale tends to parallel the bedding. Secondary cleavage not parallel to the bedding is produced by pressure of overlying sediments and plastic flow. The lamination and fissility of shale is usually best displayed after weathering.

Weller (1959) stated that, "Mud and shale are compacted in several stages that involve: (1) squeezing out of interstitial water until the sedimentary grains come in contact with each other; (2) rearrangement of grains and development of closer packing; (3) soft clay minerals are forced into the interstices between the more resistant minerals; and (4) the latter are deformed until all porosity is eliminated."

Shales have very low porosity and are generally considered nonwater-bearing. Shale has been known to yield a very limited amount of water at some localities, but quality is generally poor.

Weathering and fracturing of shales produce secondary voids. These are initiated and produced by crustal disturbances that develop cracks and fissures. Shales may also heave and rebound from release of load to produce fractures. Freezing, thawing, root action, and chemical changes tend to increase the size and extent of fractures.

Well sites in weathered shale must be selected carefully. Conditions of infiltration, storage, and seepage must be recognized locally. A large diameter well is usually the best method of obtaining water from weathered and fractured shale. Sites that are topographically high will usually be dry.

When clastic material of sand size is lithified it becomes sandstone. Sand may be composed of any mineral assemblage. The mineral content, therefore, is important to its description.

Poorly sorted or well-cemented sandstones have low porosity and low permeability, and are considered only fair to poor as ground-water reservoirs. Poorly sorted sandstones that are highly fractured may be good aquifers; therefore, a recognition of the degree and extent of fracturing is important in evaluating the rock for water development. Well-sorted, poorly cemented, clean quartz sandstones are probably the most dependable reservoir rock for ground water.

Sandstones famous for the dependability of water supplies are found in the Dresbach, Jordan, St. Peter, Dakota, Mesaverde, Brandywine, Ripley, Wilcox, and Ogallala formations.

The quality of water in sands and sandstones is influenced by structural geology, geomorphology, stratigraphy, sedimentation, porosity, permeability, infiltration and circulation of ground water. Where circulation is restricted or connate water is present, quality is poor to unsatisfactory.

Along a coastline, ground-water quality is influenced by its relation to sea level. A fresh water - salt water interface is kept in balance by ground-water recharge and ground-water movement seaward. Withdrawal of ground water in excess of recharge lowers the water table. When the water table is lowered, salt-water intrusion of the fresh-water aquifer occurs. Research on controlling salt-water intrusion is continuing.

Chemically precipitated sedimentary rocks that are important water-hearing formations in some areas are: limestones, dolomites, chalk, and gypsum. Paleozoic limestones and dolomites of the northeastern United States yield water to springs and wells. Cretaceous limestones in the southern United States furnish water for many municipalities.

The porosity of limestones is influenced by granularity, matrix, cement, skeletal remains, reefs, fractures, dolomitization, and solution. Solution cavities in the rock follow fractures, joints, and bedding planes and may be well developed within depths of 200 to 300 feet below the land surface. See Figure 2-5. Brackish water trapped in structural basins may be flushed after uplifting and faulting. Circulation of ground water is influenced by fractures, faults, and structural geology to considerable depths.

As in sandstones, circulation of water in limestones and dolomites is important to water quality.

Development of water supplies from wells in limestones depend upon fractures and solution cavities that are adequate to store and yield large volumes of water within economic pumping lifts.

Coal and lignite are genetically associated with sedimentary rocks. They are associated with valley flat deposits and some coal strata are in contact with sand. Many coal beds have partially burned and formed clinker beds that are extremely porous. Coals will fracture under stresses of crustal movements produced by earthquakes. Locally they are aquifers, but the water is generally of poor quality.

Metamorphic rocks.--The texture and mineral composition of rocks change when they are subjected to high temperatures and pressures. Under metamorphic processes, the rocks are compressed to maximum density and may exhibit foliation or banding as in slate, phyllite, schist and gneiss. They are usually so dense that they lack interstices and are incapable of absorbing water. They may, however, become fractured and faulted during and after metamorphism. The fractures may create a system of connecting ruptures that will absorb and transmit water. Zones of fracture may be suitable for ground-water development.

Different mineral constituents of metamorphic and igneous rocks will weather at different rates. Examination to determine the mineral constituents of rocks may indicate weathered zones favorable for the development of ground-water supplies.

Stratigraphy

Stratigraphy is a branch of geology that pertains to the study, identification, classification, and correlation of the layered rocks of the earth's crust. It is concerned with the origin, composition, occurrence, distribution, characteristics, sequence, and ages of the various strata. Environments of deposition are indicated by fossils, lithology, and other characteristics that reflect the influence of land masses and structure. Table 2-2 shows the relationship between sedimentary deposition and tectonic framework.

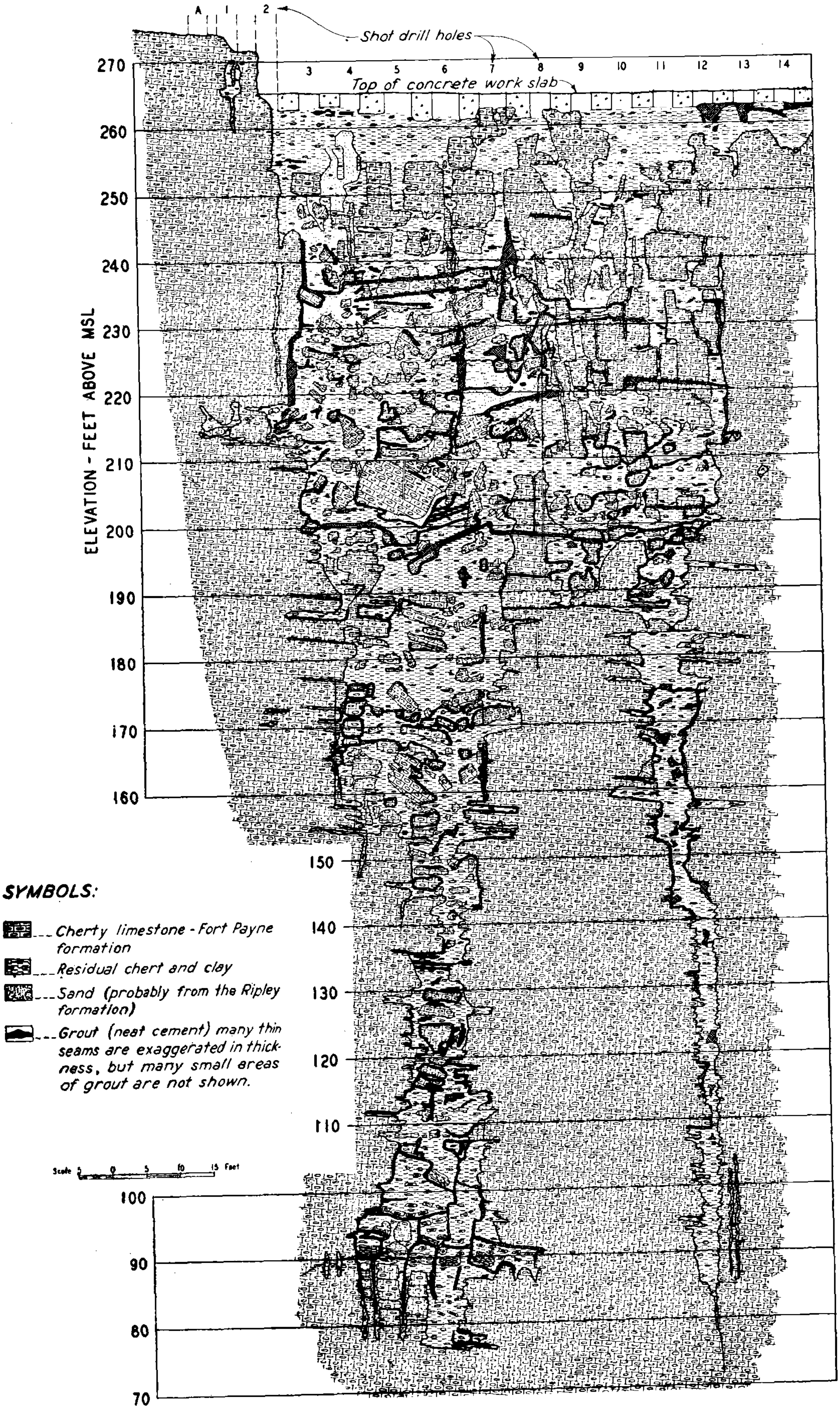

FIGURE 2–5 Deep Solution Zone

(From U. S. Tenn. Valley Authority Tech. Rpt. No. 22, 1949)

Table 2-2. Summary of Lithologic Associations

(from *Tectonic Control of Lithologic Associations*, by E. C. Dapples, W. C. Krumbein, and L. L. Sloss, Am. Assoc. Petroleum Geologists, Bull. Vol. 32, No. 10, 1948. Used by Permission of Am. Assoc. Petroleum Geologists)

Observed Sedimentary Associations			*Inferred Tectonic Framework*	
Clastics		*Non-Clastics*		
Sandstones	*Shales*	*Limestones, et Cetera*	*Depositional Area*	*Source Area*
Pure quartz Quartz-glauconite Quartz-iron oxide Quartz-muscovite	Chiefly claystones; any colors; calcareous, glauconitic, carbonaceous; quartz common in silt	Normal marine Fragmental Foraminiferal Secondary chert and dolomite Random reef distribution	Stable shelf	Stable to mildly epeirogenic
Quartz-potash feldspar "Blanket" arkose Quartz-muscovite (subgraywacke)	Chiefly siltstones; any colors; micaceous; carbonaceous; feldspar may be common in silt	Nodular, with uneven bedding Dense, argillaceous	Mildly unstable shelf	
Subgraywacke	Chiefly siltstones; any colors; micaceous, calcareous, siliceous, carbonaceous; variety of minerals in silt	Thickened shelf types Evaporites (primary dolomites, sulphates, chlorides) Marginal reefs	Intra-cratonic basin	Stable to strongly epeirogenic
"Wedge" arkose	Red, chocolate; silty; micaceous	Nodular limestones Special evaporite sequences		Strongly positive
Graywacke	Chiefly siltstones; any colors; chloritic, siliceous, micaceous, carbonaceous, pyritic; large variety of minerals	Thick, dense, dark siliceous	Geosyncline	Strongly orogenic

Chemical composition, density, compaction, and consolidation of materials reflect the origin and the diagenetic stage of development of a sedimentary rock. The younger sedimentary materials rest on older materials except where crustal disturbances have modified the normal stratigraphic sequence, or where materials have accumulated in crevices and caves.

Determining the capacity of strata to hold, yield, and transmit water is the object of subsurface investigations for water developments. A knowledge of stratigraphy is valuable in evaluating the kinds of rocks that occur in the foundations of water-development projects. Abrupt vertical changes in composition of strata are caused by rapid transgressions and regressions of the seas in marine and associated environments and cycles of cut and fill (Figure 2-6). Abrupt horizontal changes in composition of strata are influenced by orogenic activity, subsidence, changes in source materials, and changes in oceanic currents. In Figure 2-7 the thickening of clastic rocks toward the southeast indicate that deformation took place southeast of the area in Middle and Upper Ordovician time. In continental deposits abrupt horizontal changes in texture and composition are influenced by shifting channels, changes in discharge of the transporting agent, changes in turbulence, changes in gradient, and changes in source materials.

A vast amount of data on stratigraphy has been compiled in numerous reports published by States, the Federal Government, and geological societies. These data can be used in the development of ground-water resources.

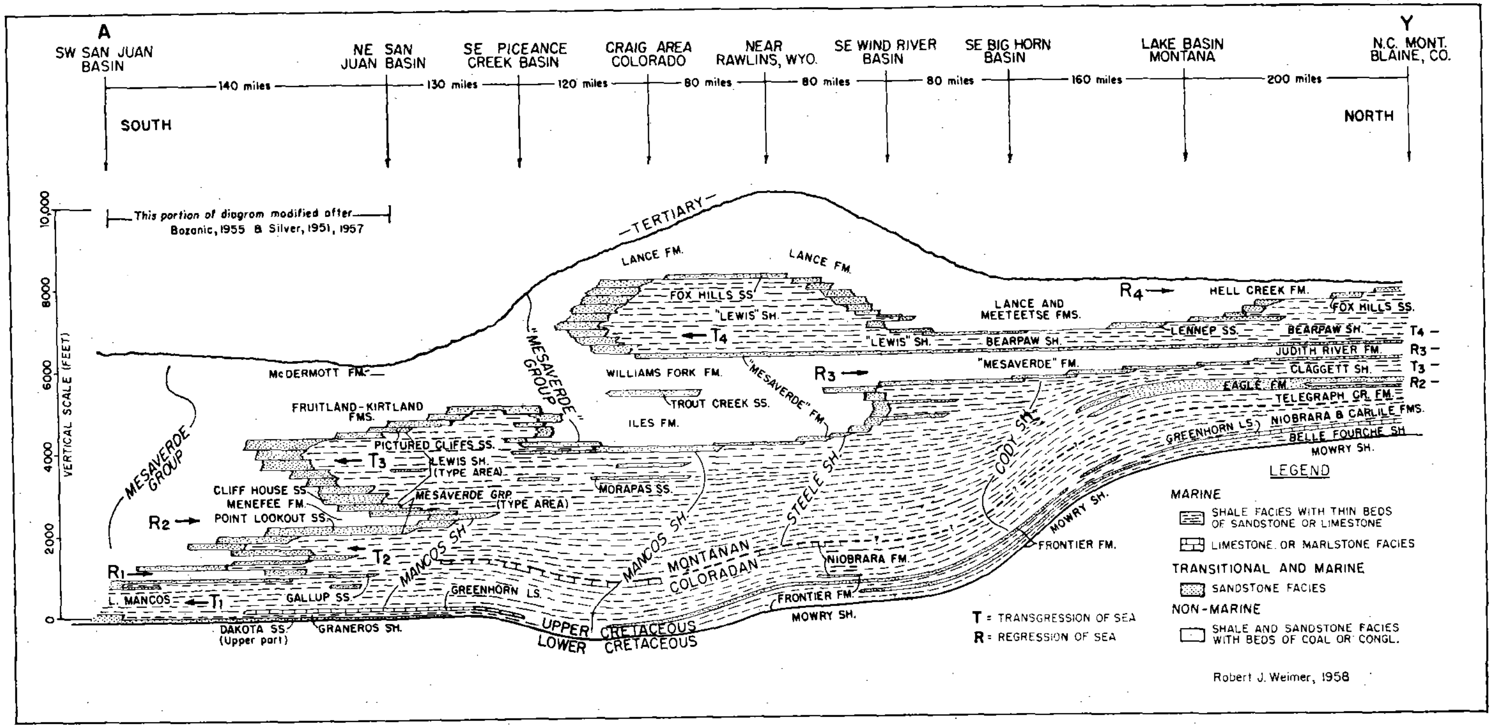

FIGURE 2–6. Stratigraphic diagram of Western U. S.

From Upper Cretaceous Stratigraphy, Rocky Mountain Area, by R. S. Weinier. Am. Assoc. Petroleum Geologists Bull. Vol. 44, No.1, 1960. Used by permission of Am. Assoc. Petroleum Geologists.)

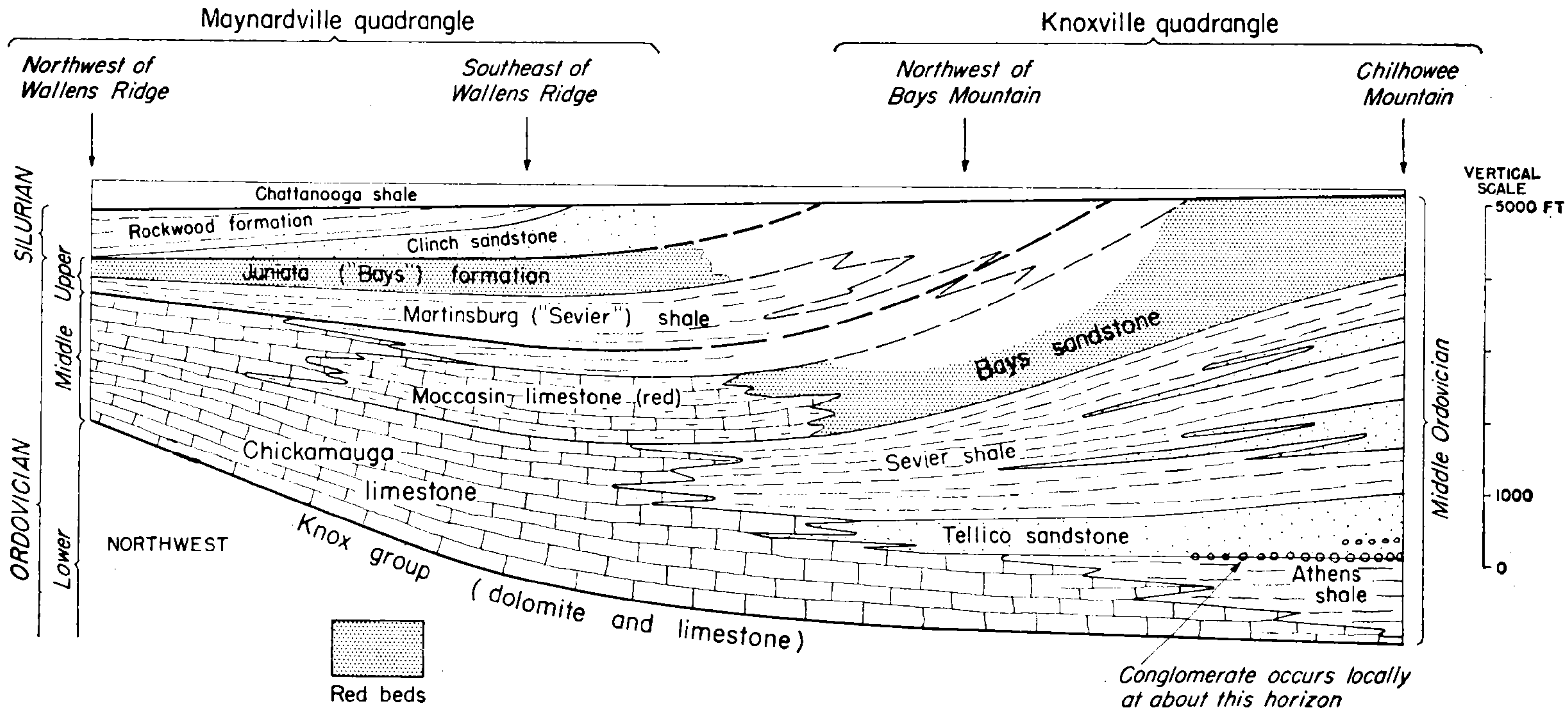

FIGURE 2–7. Stratigraphic diagram of Tennessee

(From Tectonic Framework of Southeastern United States, by P. B. King. Am. Assoc. Petroleum Geologists Bull. Vol. 34, No. 4, 1950. Used by permission of Am. Assoc. Petroleum Geologists.)

Stratigraphic Traps

Stratigraphic traps limit the continuity of a reservoir rock and terminate circulation. Fluid or gas once occupying the reservoir voids cannot escape. Varieties of stratigraphic traps such as pinch-out, overlap, and change in facies are illustrated in Figure 2-8 and 2-9.

In Figure 2-8 the Dakota, Jordan, St. Peter and Dresbach sandstones are good aquifers; the glacial drift yields water in most places but not everywhere in adequate amounts; the Sioux quartzite yields small supplies; and the basal complex yields virtually none. Geologic interpretation is required to predict the results of drilling at the points indicated by the arrows.

Pinch-outs may result from certain conditions of sedimentation, erosion, truncation, and overlap. In alluvial deposits they may be in the form of splays, deltas, tributary fans, and cut and filled channels and meander loops in valleys. Those of marine sediments may be in the form of offshore bars, deltas, and other shoreline features. Figure 2-9 is a diagrammatic section of the Atlantic Coastal Plain showing pinch-outs and change in facies.

Change in facies is a lateral change in the composition or grain size of the deposited material. It may be due to a change in the source of the deposited material, distance from the source of the material, tectonic activity or combinations of these.

Perhaps the most important of the stratigraphic traps that pertain to development of ground-water resources are those associated with channel deposits. Channels with trapped water may be associated with any geologic age formation, as shown in Figure 2-10.

Structure

Structure refers to the arrangement and relative position of rock masses. A description of rock, features such as folds, faults, bedding, joints, flow banding, parting, cleavage, brecciation, pillowy bodies, and blocky or ropey features are used to describe structure. Some structural features such as stratification, jointing and blocky development are exhibited by unconsolidated materials and are a part of the structure of those bodies of material.

Structure may influence the occurrence and availability of ground water. When a permeable stratum is confined between impermeable strata, water available to the permeable materials is dependent upon intake along structurally high areas. When a permeable stratum is faulted so that the displacement terminates the permeable materials against impermeable, and the fault plane or fault zone is impermeable, the supply of water may be cut off to the side away from the recharge area. Wells on one side of the fault might yield artesian water in large quantities whereas wells across the fault may be unsatisfactory.

Major Features

Folds.--Folds may be defined as warps, flexures, or bends in strata. They may be very gentle and simple patterns, or very complex. They

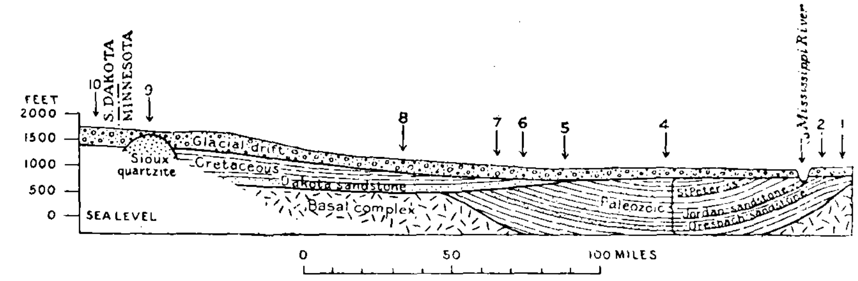

FIGURE 2–8 Stratigraphic traps

(From The Occurrence of Ground Water in the United States, by O. E. Meinzer. U. S. Geol. Surv. Water–Supply Paper 489, 1923.)

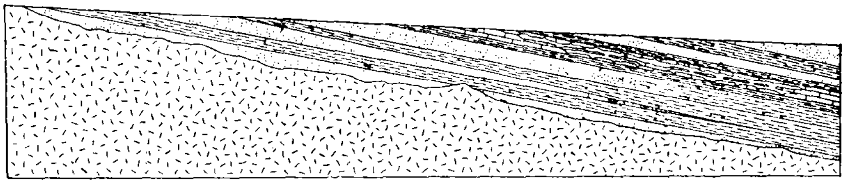

FIGURE 2–9. Stratigraphic traps

(From The Occurrence of Ground Water in the United States, by O. E. Meinzer. U. S. Geol. Surv. Water–Supply Paper 489, 1923.)

may be symmetrical, unsymmetrical, squeezed, overturned, or recumbent. Interpretation, as illustrated in Figure 2-11, is necessary in selecting well sites and calculating depths to aquifers. In Figure 2-11 the Bearpaw shale, Claggett formation, and Colorado shale yield little or no water; the Lance and Judith River formations and Eagle sandstone are good aquifers. Forecasting the presence and depth to the aquifers at any point in these ten townships requires geologic interpretation.

Synclines, as illustrated in Figure 2-8, are the most productive folds for storage and replenishment of ground water. Recharge to basin aquifers is usually revealed by water-table contour maps or cross sections. Quality of water varies with the geology of each basin.

Faults.--These are breaks in the rocks of the earth's crust along which movement and displacement can be identified. They can sometimes be identified on areal photos. They may be normal, reverse, thrust, upfaulted block (horst), downfaulted block (graben), horizontal, or variations thereof. Faults that occur during deposition are contemporaneous faults. Huge downfaulted blocks are commonly called rift valleys. Fault displacements may vary from a few inches to many miles. The Lewis and Clark Thrust has a displacement of about 25 miles (Hume, 1957).

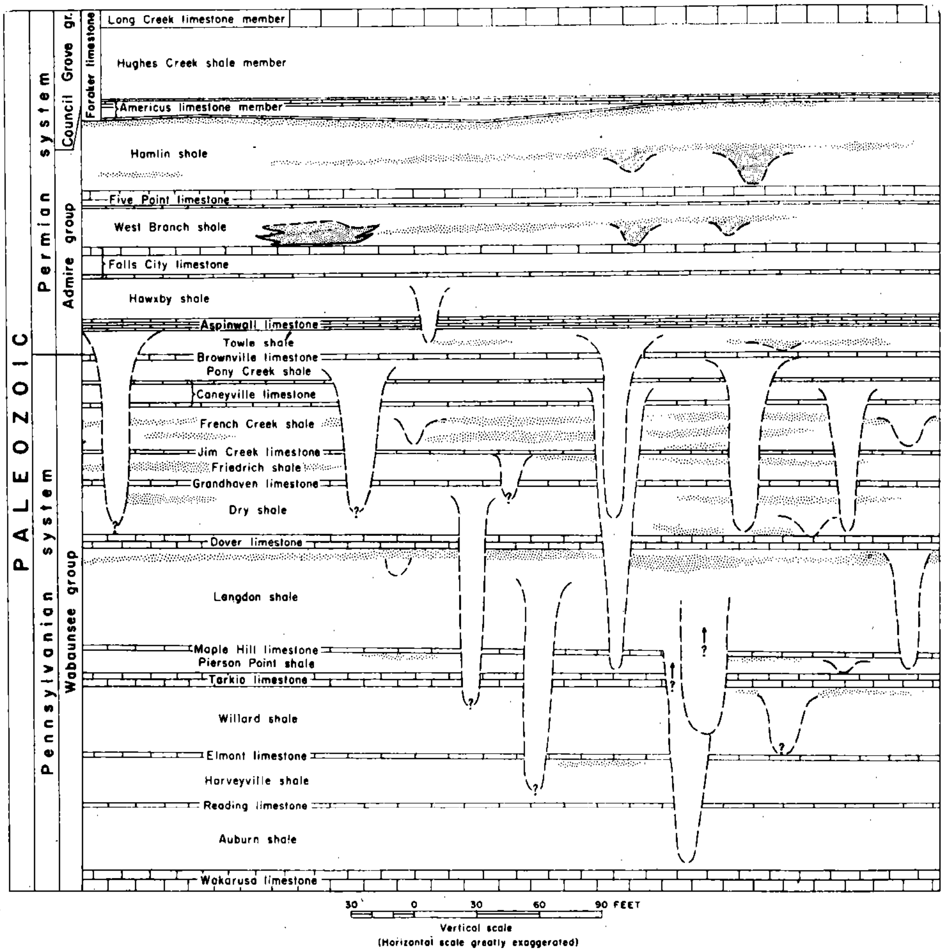

FIGURE 2–10. Buried channels

(From Sandstones in Channels in Upper Pennsylvanian and Lower Permian of Kansas, by M. R. Mudge. Am. Assoc. Petroleum Geologists Bull. Vol. 40, No. 4, 1956. Used by permission of Am. Assoc. Petroleum Geologists.)

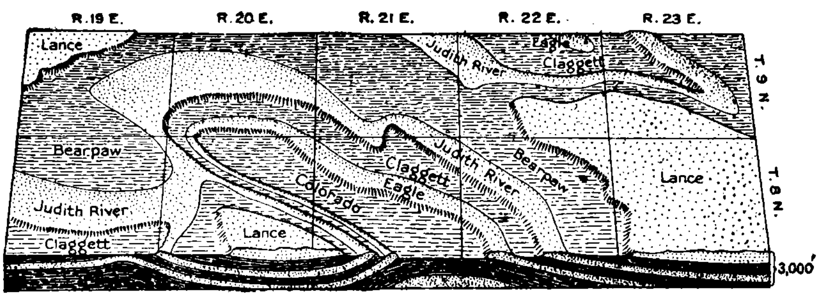

FIGURE 2–11. Stereogram of central Montana

(From The Occurrence of Ground Water in the United States, by O. E. Meinzer. U. S. Geol. Surv. Water–Supply Paper 489, 1923.)

Unconformities.--Unconformities are surfaces that indicate periods of non-deposition or erosion.

Evidences of unconformities are: discordant strata, basal conglomerate, basal black shale, fossil desert varnish, lag gravel, edgewise conglomerate, residual chert, concentration of glauconite, phosphatic pellets and nodules, manganese and iron concretions, clastic zones in nonclastic rocks, abrupt changes in heavy-mineral assemblages, sharp differences in lithology or fossil assemblages and buried soils. Unconformities may influence the migration of water in aquifers, as illustrated in Figure 2-8, 2-9, and 2-10. They also identify the boundaries of some formations and aid in correlation.

Minor Features

Cleavage.--Cleavage is the tendency of rocks to split or break apart under stress along definite smooth, parallel, closely spaced planes. The openings transmit water but are not considered important ground-water sources. Cleavage is a secondary phenomenon that influences weathering and rock disintegration.

Fractures.--Fractures are cracks or breaks in rock. They are openings along which the walls of the voids are distinctly separated. Joints, faults, and fissures are varieties of fractures.

Fractures are good sources of ground water in some geologic formations. Locally they may yield enough for irrigation well developments. Even fractured quartzites and argillites may be important sources of ground water. Open fractures in limestone lead to the development of solution channels.

Joints.--Fractures in rock along which there has been little or no transverse movement are called joints. They may be caused by expansion and contraction resulting from changes in moisture content or temperature, or as a result of stress. A joint set consists of a group of breaks that are parallel or nearly so. A joint system is a group of two or more intersecting sets or any group of joints with a characteristic pattern such as radiating or concentric.

Joints are passageways for the movement of water. They are usually inadequate as reservoirs for other than minor quantities of ground water unless well developed. Figure 2-12 illustrates how a well obtains water by cutting joints. They may, however, contribute to ground-water recharge and where there are well-developed joint systems, as in some basalts, large supplies of water may be available.

Solution openings.--Solution openings may be formed from the solution of carbonates by ground-water circulation along fractures, joints and bedding planes. Some cavities become enlarged to form extensive caverns and caves. In limestone areas ground-water gradients are usually low. Limestone voids will usually not be saturated at elevations above the elevation of permanently flowing streams. Consequently, wells will have to be drilled to depths greater than the elevation of these streams.

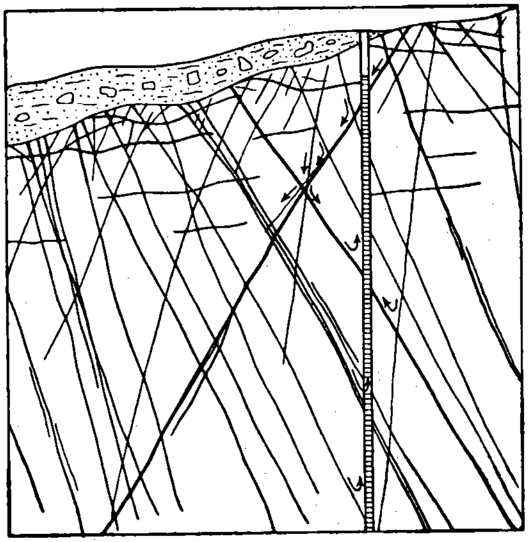

FIGURE 2-12. **Joint system**

(From The Occurrence of Ground Water in the United States, by O. E. Meinzer. U. S. Geol. Surv. Water-Supply Paper 489, 1923.)

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NATIONAL ENGINEERING HANDBOOK

SECTION 18

GROUND WATER

CHAPTER 3. INVESTIGATION METHODS AND EQUIPMENT

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NATIONAL ENGINEERING HANDBOOK

SECTION 18

GROUND WATER

CHAPTER 3. INVESTIGATION METHODS AND EQUIPMENT

Introduction

Field geology includes observing, measuring, recording, describing, and interpreting earth features according to established principles of rock origin and geologic structure. This information, together with ground-water data shown on maps and structure sections, will enable appraisal of ground-water resources. A geologic map is essential in ground-water investigation.

Published Geologic Maps and Reports

Geologic investigations have been conducted in most areas of the United States, and as a result published maps and reports thereon are usually obtainable. The principal source is the Geological Survey, U.S. Department of Interior. Other sources include state geological surveys, bureaus of mines, universities, and colleges. Bulletins and special publications of technical societies such as American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, American Water Well Association, Association of Engineering Geologists, Geological Society of America, and others are additional sources. Several state geological societies publish guide books, maps, and road logs for annual meetings. Table 3-1 is a directory of U.S. Geological Survey Water Resource Division offices. Table 3-2 lists the state geological survey offices.

The Tectonic Map (1962) and Geologic Map (1974), of the United States, published by the U.S. Geological Survey, are helpful in studying regional structure and stratigraphy. Both maps are on a scale of 1:2,500,000, about 40 inches per mile. State geologic bedrock and surficial geology maps, at intermediate scales are also helpful. These are generally on a scale of 1:250,000, about 4 inches per mile, or smaller. Photographic enlargement of small or intermediate scale maps will often show relationships that may not have been noted. Piezometric or ground-water favorability maps may be used with the geologic maps to select areas favorable for ground-water development.

State Geological Map Indexes - This includes maps and a reference list for each state. All maps outlined on the state indexes are at a scale of 1:250,000 or larger. Geologic maps that are indexed includes those published by the U.S. Geological Survey, State Geological Surveys, professional societies, universities and commerical organizations. USGS open-file maps and reports are also referenced. During 1975, computerized assisted methods were initiated by the Geological Survey in order to

Table 3-1, U.S. GEOLOGICAL SURVEY, WATER RESOURCES DIVISION DISTRICT OFFICES

(Each address below should be preceded by "U.S. Geological Survey, WRD")

ALABAMA
P.O. Box V
University, Alabama 35486

ALASKA
Skyline Bldg., 218 "E" Street
Anchorage, Alaska 99501

ARIZONA
Federal Bldg. 301 W. Congress
Tucson, Arizona 85701

ARKANSAS
Rm. 2301 Federal Office Bldg.
700 W. Capitol Avenue
Little Rock, Arkansas 72201

CALIFORNIA
855 Oak Grove Avenue
Menlo Park, California 94025

COLORADO
Bldg. 53, Stop 415, Box 25046
Denver Federal Center
Lakewood, Colorado 80225

CONNECTICUT
Rm. 235, Post Office Bldg.
135 High Street
Hartford, Connecticut 06101

DELAWARE
(See Maryland District Office)

FLORIDA
Suite F-240, 325 John Knox Rd.
Tallahassee, Florida 32303

GEORGIA
6481 Peachtree Industrial Blvd.
Suite B
Doraville, Georgia 30360

HAWAII
1833 Kalakaua Ave., 5th Fl.
Honolulu, Hawaii 96815

IDAHO
Rm. 365, Federal Bldg. Box 036
550 W. Fort Street
Boise, Idaho 83724

ILLINOIS
P.O. Box 1026, 605 N. Neil St.
Champaign, Illinois 61820

INDIANA
1819 N. Meridian St.
Indianapolis, Indiana 46202

IOWA
P.O. Box 1230
Rm. 269 Federal Bldg.
Iowa City, Iowa 52240

KANSAS
1950 Avenue "A", Campus West
University of Kansas
Lawrence, Kansas 66045

KENTUCKY
Rm. 572 Federal Bldg.
600 Federal Place
Louisville, Kentucky 40202

LOUISIANA
P.O. Box 66492
Baton Rouge, Louisiana 70806

MAINE
(See Massachusetts District Office)

MARYLAND
8600 LaSalle Road
Towson, Maryland 21204

MASSACHUSETTS (also ME, NH, RI & VT)
150 Causeway St. Suite 1001
Boston, Massachusetts 02114

MICHIGAN
2400 Science Parkway
Red Cedar Research Park
Okemos, Michigan 48864

MINNESOTA
1033 Post Office Bldg.
St. Paul, Minnesota 55101

MISSISSIPPI
430 Bounds Streets
Jackson, Mississippi 39206

MISSOURI
1400 Independence Rd.
Rolla, Missouri 65401

MONTANA
P.O. Box 1696
421 Federal Bldg.
316 N. Park
Helena, Montana 59601

NEBRASKA
Rm. 406, Federal Bldg.
U.S. Courthouse
Lincoln, Nebraska 68508

NEVADA
Rm. 229, Federal Bldg.
705 N. Plaza Street
Carson City, Nevada 89701

NEW HAMPSHIRE
(See Massachusetts District Office)

NEW JERSEY
P.O. Box 1238
Rm. 420, Federal Bldg.
402 E. State Street
Trenton, New Jersey 08607

NEW MEXICO
P.O. Box 4369 Geology Bldg. 2nd Fl.
University of New Mexico Campus
Albuquerque, New Mexico 87106

NEW YORK
P.O. Box 1350
343 U.S. P.O. and Courthouse
Albany, New York 12201

NORTH CAROLINA
P.O. Box 2857
Century Station, P.O. Bldg.
Rm. 436
Raleigh, North Carolina 27602

NORTH DAKOTA
P.O. Box 778
Rm. 332, New Federal Bldg.
3rd St. and Rosser Avenue
Bismarck, North Dakota 58501

Table 3-1 (Continued)

OHIO
975 W. Third Avenue
Columbus, Ohio 43212

OKLAHOMA
Rm. 621, 201 N.W. 3rd
Oklahoma City, Oklahoma 73102

OREGON
P.O. Box 3202
830 N.E. Holladay St.
Portland, OR 97208

PENNSYLVANIA
P.O. Box 1107
4th Fl. Federal Bldg.
Harrisburg, Pennsylvania 17108

PUERTO RICO
Bldg. 652, P.O. Box 34168
Ft. Buchanan, Puerto Rico 00934

RHODE ISLAND
(See Massachusetts District Office)

SOUTH CAROLINA
2001 Assembly St., Suite 200
Columbia, South Carolina 29201

SOUTH DAKOTA
P.O. Box 1412 Rm. 231, Fed. Bldg.
Huron, South Dakota 57350

TENNESSEE
A-143 Fed. Bldg. U.S. Courthouse
Nashville, Tennessee 37203

TEXAS
649 Federal Bldg. 300 E. 8th St.
Austin, Texas 78701

UTAH
8022 Federal Bldg.
125 South State Street
Salt Lake City, Utah 84138

VERMONT
(See Massachusetts)

VIRGINIA
200 W. Grace St. Rm. 304
Richmond, Virginia 23220

WASHINGTON
1201 Pacific Ave., Suite 600
Tacoma, Washington 98402

WEST VIRGINIA
500 Quarrier St. E
Rm. 3303, Fed. Bldg. and U.S. Courthouse
Charleston, West Virginia 25301

WISCONSIN
Rm. 200, 1815 University Ave.
Madison, Wisconsin 53706

WYOMING
P.O. Box 2087
Cheyenne, Wyoming 82001

Table 3-2. STATE GEOLOGICAL SURVEY OFFICES

ALABAMA
Geological Survey of Alabama
P.O. Drawer 0
University, AL 35486

ALASKA
Division of Geological and
Geophysical Surveys
3001 Porcupine Drive
Anchorage, AK 99501

ARIZONA
Arizona Bureau of Mines
University of Arizona
Tucson, AZ 85721

ARKANSAS
Arkansas Geological Commission
Vardelle Parham Geologic Center
3815 W. Roosevelt Road
Little Rock, AR 72204

CALIFORNIA
Division of Mines & Geology
Department of Conservation
Resources Building, Rm. 1341
1416 Ninth Street
Sacramento, CA 95814

COLORADO
Colorado Geological Survey
1313 Sherman Street, Rm. 715
Denver, CO 80203

CONNECTICUT
Connecticut Geological and
Natural History Survey
State Office Building, Rm. 561
165 Capitol Avenue
Hartford, CT 06115

DELAWARE
Delaware Geological Survey
University of Delaware
101 Penny Hall
Newark, DE 19711

FLORIDA
Bureau of Geology
Department of Natural Resources
903 West Tennessee Street
Tallahassee, FL 32304

GEORGIA
Geologic & Water Resources Division
Department of Natural Resources
19 Hunter Street, SW
Atlanta, GA 30334

HAWAII
Division of Water & Land Development
Department of Land & Natural Resources
P.O. Box 373
Honolulu, HI 96809

IDAHO
Idaho Bureau of Mines & Geology
Moscow, ID 83843

ILLINOIS
Illinois State Geological Survey
121 Natural Resources Building
Urbana, IL 61801

INDIANA
Indiana Geological Survey
Department of Natural Resources
611 N. Walnut Grove
Bloomington, IN 47401

IOWA
Iowa Geological Survey
Geological Survey Building
123 North Capitol
Iowa City, IA 52242

KANSAS
Kansas Geological Survey
1930 Aveune "A", Campus West
University of Kansas
Lawrence, KS 66044

KENTUCKY
Kentucky Geological Survey
University of Kentucky
307 Mineral Industries Building
120 Graham Avenue
Lexington, KY 40506

LOUISIANA
Louisiana Geological Survey
Box G, University Station
Baton Rouge, LA 70803

MAINE
Maine Geological Survey
State Office Building, Rm. 211
Augusta, ME 04330

MARYLAND
Maryland Geological Survey
Merryman Hall, Johns Hopkins
University
Baltimore, MD 21218

MASSACHUSETTS
Division of Waterways
Department of Environmental
Quality Engineering
100 Nashua Street, Rm. 532
Boston, MA 02114

MICHIGAN
Geological Survey Division
Department of Natural Resources
Stevens T. Mason Bldg., Box 30028
Lansing, MI 48909

MINNESOTA
Minnesota Geological Survey
University of Minnesota
1633 Eustis Street
St. Paul, MN 55108

MISSISSIPPI
Mississippi Geological, Economic
and Topographical Survey
2525 N. West Street
P.O. Box 4915
Jackson, MS 39216

MISSOURI
Missouri Geological Survey
Division of Geology & Land Surveys
P.O. Box 250
Rolla, MO 65401

Table 3-2 (Continued)

<u>MONTANA</u>
Montana Bureau of Mines & Geology
Montana College of Mineral
  Science and Technology
Butte, MT 59701

<u>NEBRASKA</u>
Conservation & Survey Division
University of Nebraska
Lincoln, NB 68508

<u>NEVADA</u>
Nevada Bureau of Mines & Geology
University of Nevada
Reno, NV 89507

<u>NEW HAMPSHIRE</u>
Office of State Geologist
James Hall, University of
  New Hampshire
Durham, NH 03824

<u>NEW JERSEY</u>
New Jersey Bureau of Geology
  and Topography
P.O. Box 2809
Trenton, NJ 08625

<u>NEW MEXICO</u>
New Mexico Bureau of Mines
  and Mineral Resources
New Mexico Tech
Socorro, NM 87801

<u>NEW YORK</u>
New York State Geological Survey
New York State Education Building,
  Rm. 973
Albany, NY 12224

<u>NORTH CAROLINA</u>
Department of Natural and
  Economic Resources
Office of Earth Resources
P.O. Box 27687
Raleigh, NC 27611

<u>NORTH DAKOTA</u>
North Dakota Geological Survey
University Station
Grand Forks, ND 58201

<u>OHIO</u>
Division of Geological Survey
Ohio Department of Natural Resources
Fountain Square, Building 6
Columbus, OH 43224

<u>OKLAHOMA</u>
Oklahoma Geological Survey
University of Oklahoma
830 Van Vleet Oval, Rm. 163
Norman, OK 73069

<u>OREGON</u>
Department of Geology and
  Mineral Industries
1069 State Office Building
Portland, OR 97201

<u>PENNSYLVANIA</u>
Bureau of Topographic and
  Geologic Survey
Department of Environmental Resources
P.O. Box 2357
Harrisburg, PA 17120

<u>RHODE ISLAND</u>
Graduate School of Oceanography
University of Rhode Island
Kingston, RI 02881

<u>SOUTH CAROLINA</u>
Division of Geology
State Development Board
Harbison Forest Road
Columbia, SC 29210

<u>SOUTH DAKOTA</u>
South Dakota Geological Survey
Science Center, University of
  South Dakota
Vermillion, SD 57069

<u>TENNESSEE</u>
Division of Geology
Department of Conservation
G-5 State Office Building
Nashville, TN 37219

<u>TEXAS</u>
Bureau of Economic Geology
University of Texas at Austin
University Station, Box X

<u>UTAH</u>
Utah Geological & Mineral Survey
606 Black Hawk Way
Salt Lake City, UT 84108

<u>VERMONT</u>
Office of State Geologist
Agency of Environmental Conservation
5 Court Street
Montpelier, VT 05602

<u>VIRGINIA</u>
Division of Mineral Resources
Natural Resources Building
P.O. Box 3667
Charlottsville, VA 22903

<u>WASHINGTON</u>
Geology & Earth Resources Division
Department of Natural Resources
Olympia, WA 98504

<u>WEST VIRGINIA</u>
West Virginia Geological and
  Economic Survey
P.O. Box 879
Morgantown, WV 26505

<u>WISCONSIN</u>
Wisconsin Geological & Natural
  History Survey
University of Wisconsin
1815 University Avenue
Madison, WI 53706

<u>WYOMING</u>
Geological Survey of Wyoming
P.O. Box 3008
University Station
Laramie, WY 82071

improve the geologic map indexes and to update them more frequently. Twenty-two states are now indexed by the new format (May 1978), with all states scheduled to be completed by 1979.

State Water Resources Investigations - These folders summarize the status of ground-water, surface-water, and quality of water investigations for each state. They are updated frequently. Selected references include reports which concern ground-water quantity and quality. Ground-water maps show pertinent data such as areal extent of principal aquifers, ground-water availability, depths of wells, and range in well yields. Areas which have water resource investigations in progress are outlined on a state map and referenced.

State Geologic and Water-Supply Reports and Maps - This is a catalog that lists USGS reports and maps that relate to geology, mineral, and water resources for individual states. The list is categorized by type of report or map.

Topographic Maps

Much information helpful in studying geology may be interpreted from topography. A topographic map is an excellent base for geologic mapping. The Topographic Division of the USGS is the principal source and will supply state topographic map indexes free on request. Field units of SCS Cartographic Division maintain files and can usually furnish 7-1/2 and 15-minute topographic quadrangles.

Aerial Photos

Contact prints are excellent bases for mapping geology. Aerial photos can be of invaluable assistance, both in office study and during field work (Legget, 1962). They show relations of physiographic features, evidence of earth movements, sand and gravel deposits, structural features and conditions meriting further investigation. Study of photos in the field with a stereoscope often reveals information not otherwise discernible.

Scales

The choice of scale depends on the scope of investigation, complexity of geology, and availability of aerial photos or base maps. Geology for most ground-water studies is best shown at scales between 1:20,000 (3.17" = 1 mile) and 1:62,500 (1" = 1 mile approximately).

Geologic Maps and Mapping

Surface Exposures

Surface geology, as may reasonably be inferred, is based on the study of outcrops. The classification of materials, measurement of bed, joint and fracture attitudes, tracing of beds, and outlining of formation boundaries are accomplished through study of surface exposures.

Outcrops of sedimentary, metamorphic, and igneous rocks permit inferences regarding stratigraphy and structure based on knowledge of the local geologic section. Alluvium, glacial drift, lacustrine and loessial deposits and products of volcanism are, because of their depositional environments, irregular in thickness and extent and do not permit inference of materials and conditions at depth. Surface observations in outcrop areas of the latter must be supplemented by subsurface investigations.

Geologic maps show classification, correlation, and distribution of surface materials, locations of faults, and axes of structural features. Accompanying cross sections show an interpretation of subsurface conditions. The maps and sections are based on information obtained at each exposure studied regarding location, elevation, rock classification, and attitude. Field Notes, page 3-8, should be referred to before and after studying these distinguishing characteristics.

Location. - The method of locating exposures or features observed will depend on the base map used, its scale, requirements of the survey, and amount of vegetative cover. Three methods--location by inspection, by compass and paced traverse, or by plane table survey--may be used. If mapping is to be done on aerial photo contact prints, enlarged prints, or topographic maps published after about 1900, points may be located by inspection with a high degree of accuracy. On planimetric maps, sufficient detail may be shown to use inspection, but on these and other plan maps location of points by compass and pacing probably will be desirable. Plane table surveys of topography and geology are often needed for detailed studies. They should be made separately. For geologic surveys the geologist should select points to show geologic information.

Elevation. - Position of outcrop or feature above or below mean sea level, or an assumed datum, should be noted. Vertical relationships are important in most geologic investigations, and especially those for ground water, as a basis for developing cross sections and interpreting structure. Elevations may be determined by inspection of topographic maps or by altimeter traverse, plane table, or differential leveling.

Classification. - Note properties of the rock as observed at the outcrop. Standardization of rock classification is desirable as a means of promoting uniform description. After the primary genetic classification of rocks as igneous, sedimentary, or metamorphic, the almost universally used method is to "name rocks on the basis of visible features not on the basis of inference" (Travis, 1955). Correct identification is important because nature of the material indicated geologic history and potential behavior or influence on the problem.

Standard practice in Service classification is to describe or classify rocks by features that may be seen with a good hand lens (10X). The three charts, Classification of Igneous, Sedimentary, and Metamorphic Rocks, contained in Travis (1955), will enable the naming of rocks as precisely as warranted by examination methods. All gradations of composition and texture are possible, and to some extent charts are an artificial systematization. Descriptions should be brief but give sufficient information for purposes of the investigation.

In making Service geologic investigations for ground water it is often possible to develop a suitable map by making detailed additions to a published map. Accurate classification will help to correlate new work with the known columnar section and permit utilization of recognized stratigraphic relations or the describing of a new formation as may be required.

Attitude. - Strike and dip together define the attitude of beds or planar features such as joints, foliation, fractures, and faults. The strike is the bearing, angle from north, of a horizontal line in the bedding plane, or other plane. The dip is the angle of inclination of the plane below the horizontal measured at right angles to the strike. It is necessary to include the direction of dip because the dip could be in either of two directions and still be at right angles to the strike. Written as: strike N37° W, dip 52° NE. If azimuth is used, the zero reference point is north.

The principal means of mapping geologic structure is by measuring and plotting locations, elevations and representative attitudes of beds and other planar features. In some instances more than one interpretation may be made if attitudes alone are used. Where strata are steeply dipping or considerably broken, the possibility of their having been overturned needs to be investigated.

Several primary features developed during deposition of sediments or eruption of lavas are among the most reliable indicators of top or bottom of bed. These include fossil evidence, ripple marks, cross bedding, graded bedding, local unconformities, channeling, mud cracks, rain imprints, animal tracks, contemporaneous deformation, pillow structure, and vesicular tops of lavas. The development of drag folds may sometimes be used but their evidence is not always conclusive (Billings, 1954).

Field Notes. - It is essential that notes show information on items discussed in foregoing paragraphs (Location, Elevation, Classification, Attitude) adequately and without ambiguity. Opinions vary as to how much should be recorded. Some geologists use only the briefest descriptions while others write at length. Experience has shown it is better practice not to rely upon memory. As an outline, notes should first contain observed facts, then inferences, and finally any theories to be investigated further. Inferences and theories should be identified as such with a question mark in parentheses. As the examination progresses, the geologist will be able to adjust the detail to fit the purpose of the survey. Observations and notes should aim at one visit to an outcrop although return to some points for further study may become necessary as ideas develop. Because field notes usually are the record of observations at various points along a traverse, together with some observations enroute, the use of place designations--A.T.P. for At This Point and S.L.O. for Since Last Observation--will be found helpful in properly separating entries (Willis, 1923). The geologist must be observant and alert for indications that either confirm or contradict previous findings.

Use of Aerial Photos

Interpretation of geology from aerial photographs is an application of geomorphology. Aerial photos are versatile and valuable tools for those who map geology, survey soils or locate ground water (Howe, et al, 1956). Photo geologic interpretation has done much to bring civil engineering and geology together. It permits interpretation of stratigraphy and structure from land forms and furnishes clues regarding engineering properties of soils.

Geologic interpretation of aerial photos is based upon observed relations of rock outcrops and physiographic features, knowledge of area stratigraphy, and inferences that may be drawn therefrom. Interpretation may be accomplished by viewing photo prints with a pocket stereoscope, a mirror and prism stereoscope, or with one of several of photogrammetric instruments that, in addition to viewing, permit measuring horizontal, vertical and slope distances, and plotting of interpreted information (Ray, 1956). Criteria of interpretation are the same regardless of equipment used. Through photogrammetry, measurements enabling the calculation of dip and thickness of formations, the positioning of contacts, and drawing of geologic cross sections may be accomplished. It should be emphasized, however, that photo interpretation is most useful as a supplement to field mapping and results need frequent field checks.

Photo geologic interpretation is a two-step process; the first step consists of observation, identification, and measurement of features; the second involves use of inductive and deductive reasoning to analyze significance of the features. A thorough knowledge of land forms is essential. Features are identified by their relative photographic tone, color, texture, pattern, shape, and size. These recognition elements are more meaningful if they can be used in combination. Similarly, an association of physiographic features may permit identification where one might not be distinctive. The use of an additional set of photos at a scale of about 1:62,500, or study of a photo index mosaic is often advantageous because a larger area can be viewed.

Linear features less than a mile in length that may indicate joints or small faults and can be mapped by stereoscopic study of photos are called fracture traces. Lineaments are features perhaps many miles in length that may indicate major faults and can best be studies on aerial mosaics (Lattman, 1958). Lineaments may often be most readily discerned by viewing with line of sight at a low angle to the mosaic (Colwell, 1960).

Through recognition of land forms, information on lithology and structure may be interpreted. The amount of information obtainable depends primarily on types of rock exposed, climate and stage of the erosion cycle. Areas of gently folded sedimentary rocks of contrasting hardness will yield the most information, areas of igneous rock next, and metamorphic rock areas the least (Ray, 1960). Sedimentary terrains have marked differential erosion characteristics that stand out on aerial photographs while intrusive rocks are relatively homogeneous over wide areas. A criss-cross joint pattern of short lineations is distinctive in many areas and most intrusive igneous rocks have strong development of irregularly and widely spaced joints (Ray, 1960). Extrusive rocks are marked be characteristic land forms such as volcanic cones and lava flows. The processes of metamorphism tend to destroy the erosional differences and land form characteristics of the original sedimentary or igneous rocks and, as a consequence, aerial photographs of metamorphic terrains may reveal little information. In such areas the prominent regional cross joints commonly are widely spaced and streams flow along them. Fault lineation characteristics may be rectilinear depressions (Ray, 1960).

Although climate, vegetation and stage of erosion cycle introduce variables, the following list of photo images and commonly associated rock types summarized from Liang and Belcher (1958), Ray (1960), and Amenta will prove helpful in determining lithology of most terrains.

Photo-image	Photo-interpretation
Terrain Features	
1. Flat to gently rolling	a. Flat-lying or nearly flat-lying sedimentary rocks underlying coastal plains, plateaus, mesas
	b. Peneplain on homogeneous, igneous or metamorphic rocks
2. Gently rolling to moderately rolling; smoothly rounded	a. Shale exposed in humid climate
	b. Old igneous or metamorphic rock with deep saprolitic soil
3. Gently rolling to moderately rolling; hilltops are flat or rounded with accordant elevations	a. Dissected horizontal sedimentary rocks in humid climate
	b. Dissected peneplain on homogeneous, igneous or metamorphic rocks
4. Moderately rolling to hilly with variations in relief	a. Igneous or metamorphic terrains; variations in relief caused by non-homogeneous rock or structure
5. Low to high relief with parallel ridges and valleys	a. Folded and faulted sedimentary rocks
Drainage Pattern[1/]	
1. Dendritic	a. Horizontal or gently dipping sedimentary rocks
	b. Homogeneous rocks with lack of structural control
2. Subdendritic	a. Homogeneous rock at surface underlain by non-homogeneous rock

1/ Usually pattern may be most effectively studied by tracing drainage lines on a separate sheet.

Photo-image	Photo-interpretation
3. Trellis	a. Steeply dipping sedimentary rocks; less commonly the result of faulting
4. Angulate	a. Strongly jointed or faulted igneous or metamorphic rocks
5. Annular or ring-like	a. Sedimentary rocks in structural domes or basins b. Ring dikes in regions of igneous activity
6. Deranged	a. Recent glacial deposits; landslides
Drainage Texture	
1. Fine	a. Shale[2/], siltstone, impervious rock; loess is an exception probably because of fine grain size.
2. Coarse	a. Sandstone, conglomerate, pervious rocks
3. Absent	a. Well-drained materials--gravel terrace, sand dunes, river flood plains, terrace alluvium
4. Karst	a. Limestone, dolomite; possibly gypsum or halite
Photographic Tone	
1. Light	a. Sandstone, siltstone, weathered shale, limestone, dolomite, chalk, gypsum, acid igneous rocks
2. Dark	a. Red sandstone, graywacke, shale, gray limestone and dolomite, basic igneous rocks
Outcrop Features	
1. Massive	a. Conglomerate, limestone, dolomite, gypsum, chalk, quartzite, igneous plutons
2. Bedded	a. Sandstone, siltstone, shale, limestone, precipitates, tuff, series of successive lava flows

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2/ Rock types underlined show photo-image more often than those not underlined.

Photo-image	Photo-interpretation
3. Banded	a. Sandstone, siltstone, limestone, dolomite, <u>metamorphic rocks</u>
4. Foliated (dominant lineation direction)	a. <u>Schist</u>, <u>slate</u>
5. Other linear features (may or may not be outlined by vegetation)	a. Faults, joints b. Igneous dikes c. Glacial grooving
Other Features	
1. Lobate pattern of vegetation in vicinity of volcanic cone	a. Areas of flow rock
2. Similar curvature of streams in areas of gently dipping sedimentary rocks	a. Indicates position of structural axis b. Convexity indicates direction of structural plunge
3. Modified dendritic drainage and scoop-shaped valley heads	a. Dissected loess
4. Gully shape	Near surface materials are:
a. Long, smoothly rounded	a. Clays
b. "U" shaped	b. Silts
c. "V" shaped	c. Sands and gravels
5. Mottled soils of drift plain	a. Light-toned areas generally slightly higher and better drained than darker areas in which clay materials and humus have accumulated. Linear pattern of light-toned areas may represent minor recessional moraines.
6. Sharpness of tonal boundary between dark and light soils	Soil properties
a. Distinct	a. Coarse grained, well drained
b. Fuzzy, irregular	b. Fine textured, poorly drained
7. Rounded topography, intricate drainage channels and heavy vegetation	a. Probable deep soils
8. Sharp, steep, resistant ridges and rock controlled channels	a. Area of shallow soils

Photo-image	Photo-interpretation
9. Scarp with hummocky topography below and local lobate outlines, undrained depressions	a. Landslide
10. Sinuous ridge, smoothly rounded surface, short steep gullies, very poor vegetative cover, dull gray tones	a. Serpentine outcrop area.

In Service geologic and ground water investigations aerial photo geologic interpretation is useful in locating faults, outlining and studying geologic structure, supplementing and corroborating information obtained in the field.

Color aerial photographs are effective in showing geology in areas where color contrast is strong. They cost more than black and white pictures for limited areas but reportedly can be obtained at more competitive figures for larger areas. Their use will aid preparation of geologic maps where colors outline complex features (Colwell, 1960).

Infrared imagery in 3 to 5 micron and 8 to 14 micron wave lengths obtained by aerial reconnaissance has proven useful for distinguishing thermal emission contrasts related to various geologic features. If a temperature differential exists, it can be read. Infrared investigations of parts of the Island of Hawaii; the Steamboat Springs hot springs area, Nevada; the Salton Sea geothermal area, California; and Yellowstone National Park, Wyoming, have shown thermal anomalies that helped to delineate faults, contacts between rock types and locate springs both hot and cold, steam vents and mud pots.

Comparison of infrared imagery with conventional photography of part of the Shenandoah Valley, Virginia, by S. J. Gawarecki, discloses that many old drainage channels, sinkholes, and emerging subterranean streams not readily visible on conventional aerial photographs are clearly visible on infrared imagery. Based on these results, infrared imagery may be particularly effective in engineering geology and ground water studies (Nolan, 1963 and 1964).

Ground-Water Observations

The sources and occurrence of ground water have been discussed in Chapter 1, Ground-Water Hydrology. The influence on ground water of stratigraphic and structural features has been described in Chapter 2, Ground-Water Geology. This chapter contains information concerning methods and equipment for investigating ground water availability. Measurements of water levels, flows of springs and streams, and production of wells in an area all may be used to relate hydrology to geology and permit estimates of ground water occurrence, movement and availability. Field observations of ground water are the basis for ground water maps just as descriptions of surface exposures are for geologic maps.

Howe, et al(1956), prepared a ground water prediction map for Tippecanoe County, Indiana, based on geologic, soils, and drainage maps made principally from stereoscopic study of photographs supplemented by ground water observations. Examination of well records confirmed their analysis.

Elevation of Water-Surface. - Information regarding position of the water surface is essential to preparation of ground water maps. Elevations are used to draw contour maps of the water table or piezometric surface for confined aquifers from which may be determined the direction of water movement, hydraulic gradient, relative aquifer permeabilities, and the position of ground water divides.

Under normal conditions the elevation of the water surface fluctuates seasonally. It rises as a result of recharge by precipitation and streamflow and falls because of natural discharge and pumping from wells. This change may be enough to influence accuracy of the survey. It is important to note the date and hour that measurements are made to permit correlating observations with annual water level fluctuations recorded in most areas by the U.S. Geological Survey.

Sufficient observations of water surface elevation should be made at streams, lakes, reservoirs, springs and in wells to meet needs of the survey. Land surface elevations may be determined as described on page 3-7.

Water Table Measurement.--Method of measurement from a surface reference point to the water surface will need to be adapted to site conditions. Consideration needs to be given to geology and the possibility that the water surface observed may be perched. Efforts should be made to obtain information on the main water table.

There are several satisfactory methods of measuring depth to water in wells, including the chalked tape, tape and float, tape and inverted cup-shaped weight, electrical sounding devices, and air lines installed in wells. The chalked tape method has been found to be the simplest and most satisfactory for rapid and accurate measurement in most wells. A steel tape is used with a small lead weight attached. The lower few feet are covered with carpenter's chalk, then wetted and drawn through the fingers to spread the chalk in a even film. The tape is lowered into the well until the weight is a few inches beneath the water surface. A reading is made at the surface and the tape quickly withdrawn and read at the water mark. Depth to the water level is obtained by subtraction. The tape should be held only momentarily at the surface measuring point because water tends to rise on the tape by capillarity in the chalk film. In place of chalk a paste called "National Water Finder," manufactured by the Metal Hose and Tubing Co., Dover, New Jersey, may be used. The paste is spread on the tape or probe and the part that dips into the water will turn red.

If chalk or paste on tape are to be used in a pumping well or one in which there is splash, tape must be inserted in a 1/2" to 3/4" pipe extending from ground surface deeper than the lowest water level to be measured.

There are several types of electrical sounders but in all the circuit is closed by contact with the water. Electric sounders are advantageous for deep wells and wells in which there is splash.

Many wells are equipped with a pressure gage and an air line of known length. The air line is usually a copper tube one-eighth to one-quarter inch in diameter but may be one-fourth inch galvanized pipe, with surface end connected to a pressure gage with an air inlet valve just below the gage. See Figure 3-1. The lower end of tube or pipe is open. The pipe must be airtight and it should extend 20 feet or more below the lowest pumping level (Wood, 1950). Depth to the lower end of the air line must be accurately known. Air pressure can be furnished by an ordinary tire pump. The gage indicates pressure necessary to counter-balance depth of water outside the air line. (This is maximum pressure that can be attained). Practically all gages are now calibrated in feet, so that direct reading of water level above end of air line can be made. Depth to water level is depth to lower end of air line less gage reading in feet. If gage reads in pounds per square inch, multiply reading by 2.31.

Water levels of flowing wells may be calculated by measuring the pressure developed when the well is closed, or for low heads by connecting a short length of hose to the well and elevating the end until flow stops.

Piezometers.--Ground water piezometers are accurate, reliable and inexpensive tools for determining hydrostatic pressure at particular depths or in selected layers of soil or rock. A piezometer consists of standard one-fourth or three-eighths inch iron pipe driven vertically into the ground to a definite elevation or stratum. The pipe is driven so that no leakage occurs and ground water can enter only at the bottom. Construction details of observation wells and piezometers and differences in design and conditions measured are shown in Figure 3-2.

Because ground water moves from points of high hydrostatic pressure to points of lower pressure, it is possible by measuring pressure at a number of points to determine the movement of water. Results may be plotted in both plan and section and contours or equipotential lines drawn on the pressure surface indicated by the piezometer readings. Flow lines drawn perpendicular to the equipotential lines show direction of flow, hydraulic gradient, and areas of concentrated flow.

Piezometers, as well as being a principal tool in drainage investigations, are useful in planning development of confined ground water, in analyzing effect of engineering structures on local ground water conditions, determining need for and location of relief wells, and in measuring pore pressure in the foundation of structures.

Effective positioning of piezometers horizontally and vertically requires knowledge of underlying aquifers, preferably based on carefully logged borings. Piezometers may also be located in a grid pattern with a number of pipes of different length at each location depending upon depths

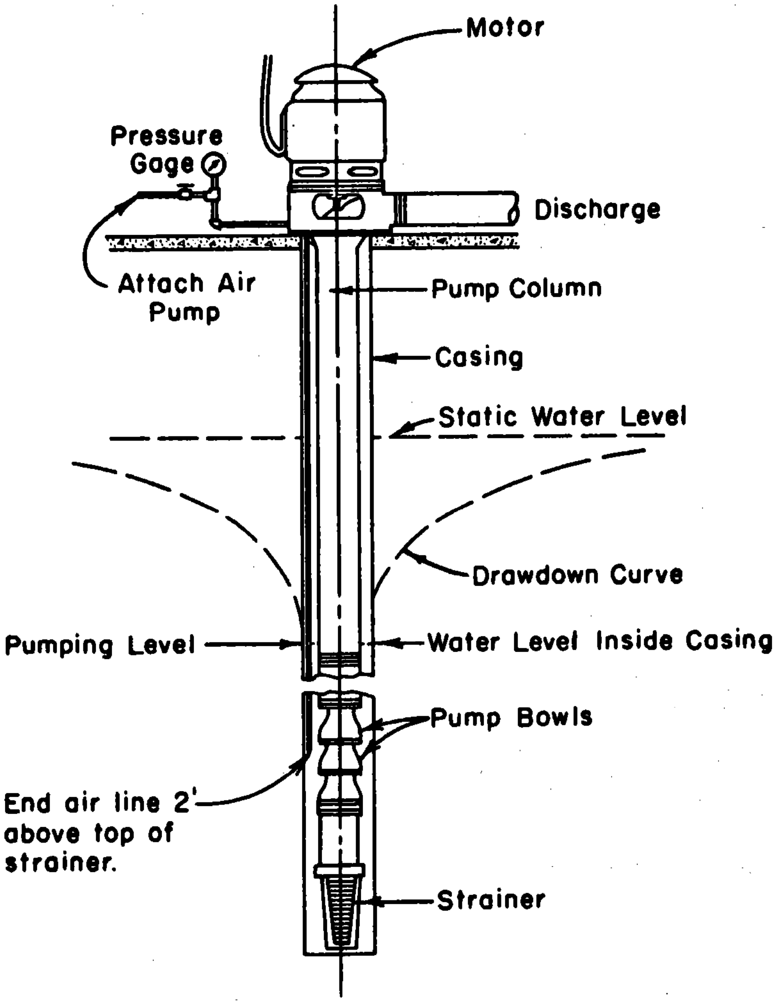
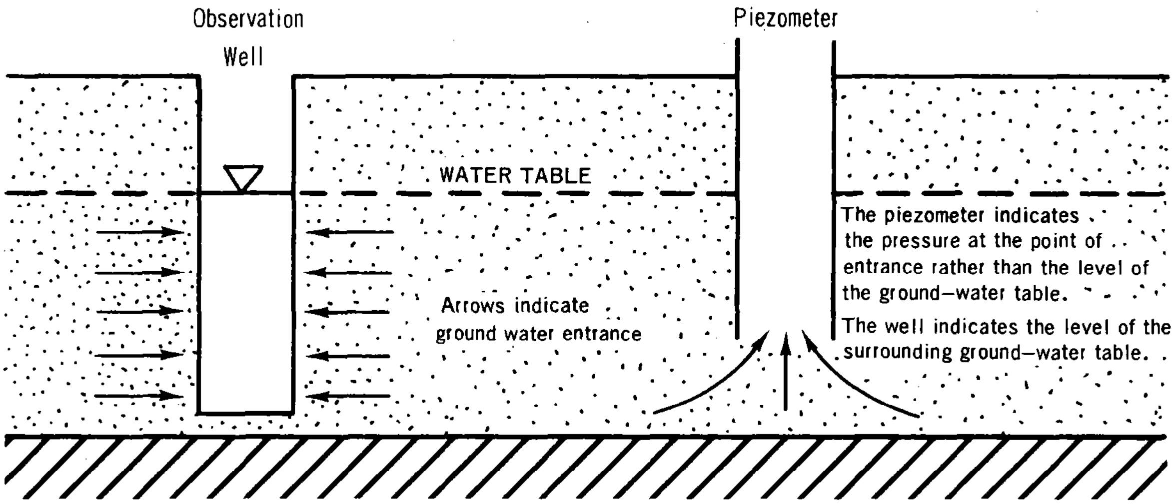
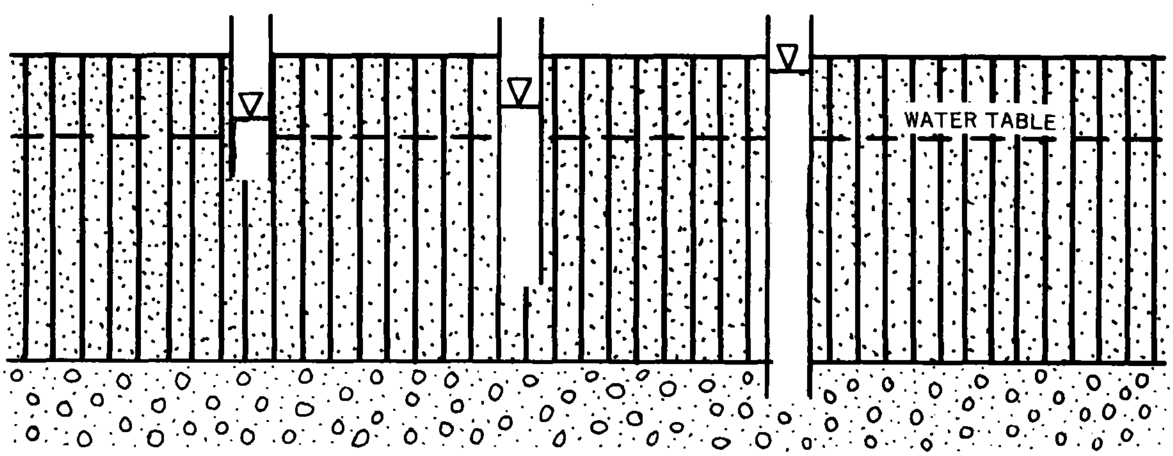


Figure 3-1. Air Line for Measuring Depth to Water Level

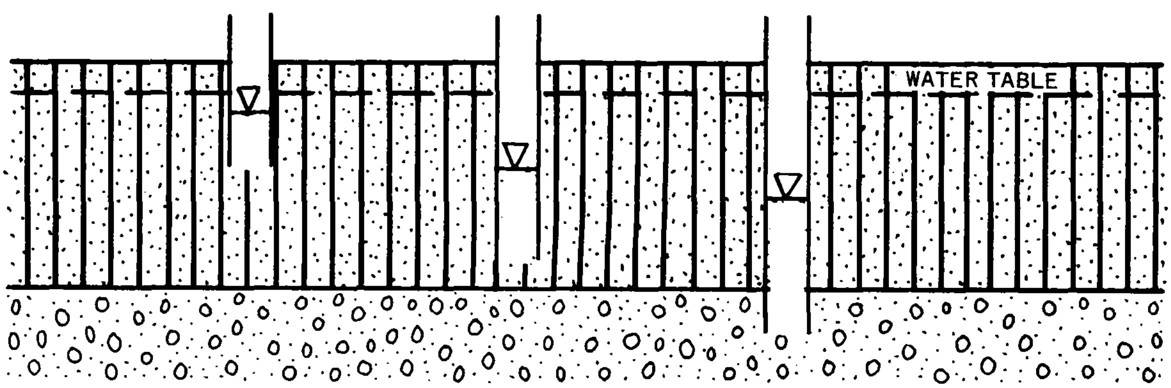
(From Wood, 1950)



A – Construction of observation wells and piezometers



B – Piezometers indicate water under artesian pressure in sand and gravel zone is leaking into overlying material.



C – Piezometers indicate a perched water table draining slowly into underlying sand and gravel.

FIGURE 3–2. Observation Wells and Piezometers to aquifers. Piezometer locations should be referenced horizontally and vertically.

In unconsolidated materials piezometers are driven or a hole is augured part way and the pipe driven the last few feet. In rock, the hole is drilled and pipe or casing 3 inches or 4 inches in diameter is used. The hole is drilled nearly to the intended depth, pipe is cemented in place and the hole then drilled to final depth using a smaller bit.

Instructions for installing, flushing, testing, and reading piezometers are contained in Chapter 2, Section 16, National Engineering Handbook. Additional information on piezometers can be obtained from Donnan and Bradshaw (1952) and The Yearbook of Agriculture (1955).

Discharge of Springs and Streams. - Information concerning the flow of springs and streams is important because these flows, in effect, summarize ground water conditions and may tell much about geology. In consolidated rocks, the location and alignment of springs is related to the location of faults or other structures influencing water accumulation, and the flows give information on aquifers. Springs in either bedrock or alluvium may be caused by bodies of perched ground water, water under artesian pressure, or outcrop of the main water table. Gains or losses in base flow of streams mark effluent or influent reaches resulting from ground water discharge or recharge.

Estimates of flows are sufficiently accurate for preliminary surveys, but measurements are needed for detailed ground water investigations. The U.S. Geological Survey measures the flow of most streams and many springs and publishes discharge records in water supply papers.

In estimating small flows, it is helpful to visualize the time required for that flow to fill a one, five, or fifty gallon container. Flows of more than 100 gpm may be most satisfactorily estimated by measuring the average velocity of an object floating on the stream and estimating or measuring the average cross sectional area of flow.

Measurements of a few gallons per minute can be made rapidly and accurately by collecting the flow and timing the filling of known volume containers. Flows of over 100 gallons per minute may best be measured with sharp-crested weir or Parshall flume as described in McGuiness (1963) and Donnan and Bradshaw (1952).

Production of Wells. - Well records are of value in showing the amount of ground water that has been obtained and providing information with which to estimate possibilities for additional production. See Chapter 2, Figures 2, 3, and 4 for yields and potential yields of irrigation wells from saturated thicknesses of sands and gravels, and from very fine sands. The volume of water pumped with resultant drawdown indicates the capacity of aquifers at specific locations.

Data on production may be obtained from owners, lessees, drillers, pump agencies, well testing firms, power or gas companies, state engineer records, and U.S. Geological Survey records. The information obtainable is, in most instances, definitely worth the time and effort required to collect it.

If wells are in operation, their production may be estimated using nomographs for flow from pipes. See Figure 3-3.

Pipe orifices are commonly used to measure discharges ranging from 50 to 2,000 gallons per minute (see Chapter 9, Section 15, National Engineering Handbook).

Subsurface Information

The amount of subsurface information available is a major factor in preparation of accurate geologic and ground water maps. Advantage should be taken of all opportunities to obtain subsurface information. The great value of reliable subsurface data and the considerable cost of obtaining it first hand justify diligent search for and acquisition of exploration records.

Common sources of subsurface information are well logs, auger holes, test pits, geophysical probes and test holes. In some areas gravel pits, quarries, strip mines and underground mine workings may afford opportunities to examine and measure stratigraphic sections. Logs of oil tests and seismograph shot holes may often be obtained from state departments of geology and mineral resources and sometimes from the oil companies.

Well Logs. - Complete water well logs show materials penetrated, depth and thickness of principal aquifers, static water level, yield, pumping water level, pump setting, casing, and perforation record. See Figure 3-4. Such logs provide data on stratigraphy, water table, nature and capacity of aquifers needed to interpret and evaluate ground water occurrence. Some logs may contain incomplete information and sources suggested above will need to be canvassed. The passage of state ground water codes with provisions that require licensing and bonding of drillers, and filing of well logs generally has improved the quality and availability of records. Many states maintain files of water well logs from which copies may be obtained by request to the state engineer or designated ground water authority.

Hand Auger Holes. - Exploration by hand auger is limited in usefulness by gravel or rock fragments. Augers are used in prospecting for shallow water and constructing observation wells in relatively fine-grained alluvium.

Test Pits. - Pits are commonly used to explore earth materials, uncover bedrock for identification, measurement of attitude, and location of formation contacts. Pits have a definite advantage in permitting examination and sampling of materials in place but the walls require support in wet soils.

Geophysical Surveys. - Precise measurement of relative physical properties of soils and rock often help to more closely delineate stratigraphy and structure where general geologic features are known. The properties measured by geophysical methods include electrical resistivity, elasticity or rate of transmission of sound or shock waves, density or gravitational field and magnetic field. It is not possible to determine the presence of ground water directly by geophysical surveys. Depending upon soluble solids contained, the first property, electrical resistivity, is influenced by water. Elasticity is also influenced by water but to a greater extent by consolidation. Density measurements may reflect presence or absence of voids and thus, indirectly, the possibilities of water. Anomalies, or variations from general trend, in the magnetic field indicate structures that favor in some instances but in others hinder accumulation of ground water.

If the ground water contains sufficient dissolved solids to serve as a conductor, depth to the water table may be calculated from observed reduction in electrical resistance measured with resistivity equipment. Resistivities are usually high for dense impervious rocks and low for porous rocks containing water (Legget, 1962). The resistivity method is especially effective in measuring depth to fresh water-salt water interfaces because of the much lower resistance of salt water (Taylor, 1960).

The water table may be indicated by velocity of shock or sound transmission of about 5,000 feet per second measured with a refraction seismograph. However, other materials not saturated, such as coarse and compact soils, sandstone and cemented soils, may show approximately the same velocity. It is most effective in porous soils where water surface is well defined. Inaccuracies have been noted in fine-grained, slowly permeable soils because capillary forces act to raise the zone of saturation and wetness several feet above the water table. The seismic method is effective in materials that increase in density with depth.

Differences in density of materials in the earth's crust indicate geologic structure which may influence ground water accumulation. An area with low gravity value adjacent to a gravity high might be a body of alluvium along a mountain front. Information on aquifer boundaries could be deduced under special conditions but it is unlikely that inferences regarding presence of ground water would be warranted.

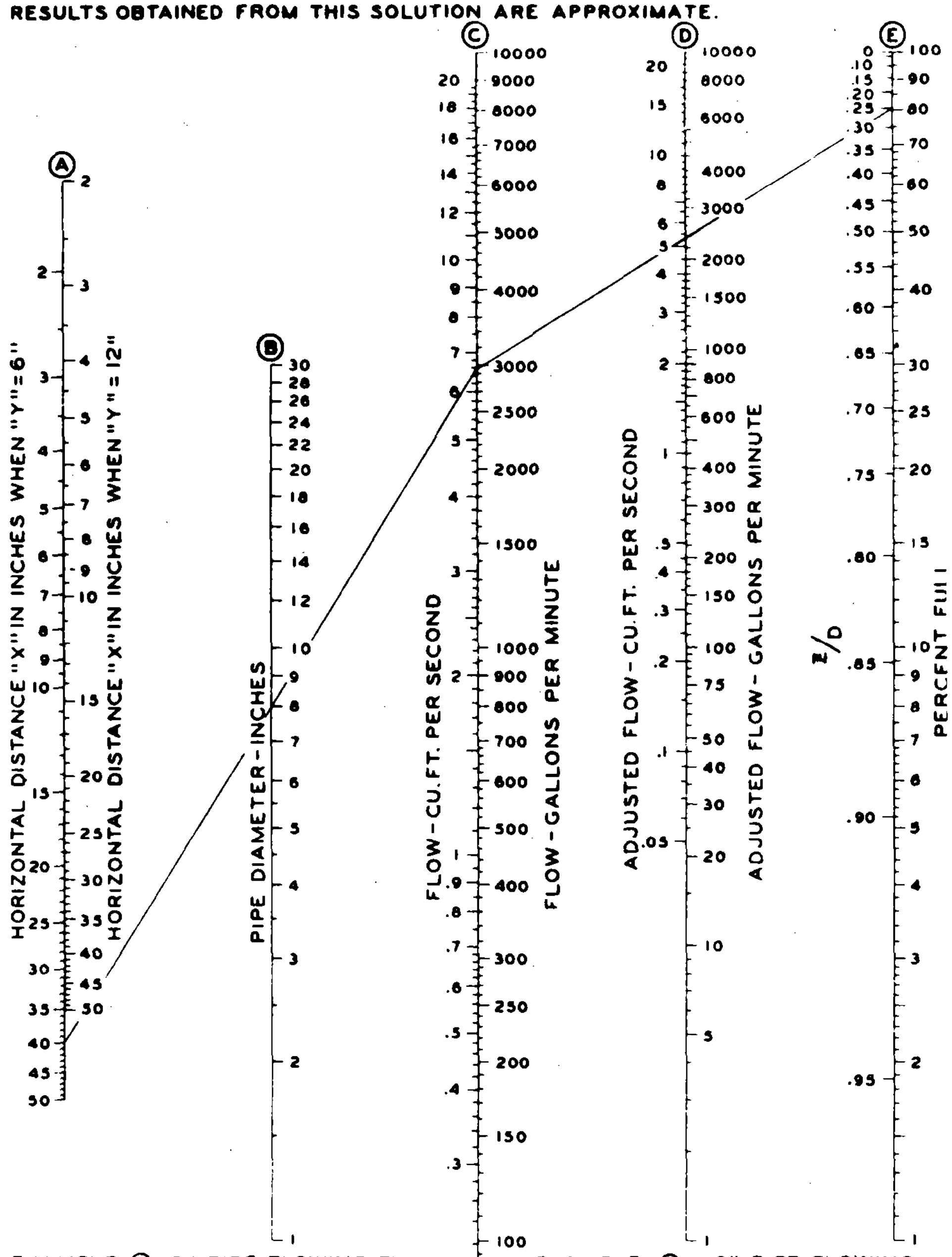
Magnetic anomalies result from uplift or intrusion of large bodies of igneous rock, emplacement of dikes or sills and extrusion of basalt. In general, magnetic highs resulting from igneous intrusion correspond to structural highs in overlying sedimentary rocks and are not favorable for accumulation of ground water. Conversely, magnetic lows may indicate synclinal structure and favorable conditions. Dikes and sills tend to form barriers to water movement in sedimentary rocks. Basalt flows, where below the water table, may contain ground water in joints or porous interflow zones. Magnetic surveys are rapid and effective in locating anomalies. Additional geologic and ground water information must be obtained to relate survey findings to ground water occurrence.

The resistivity and seismic methods are useful in supplementing subsurface information available from well logs and test drilling. The

WHEN PIPE IS FULL & Y=6", Q=1.157D²X (GPM)
WHEN PIPE IS FULL & Y=12", Q=0.818D²X (GPM)

WHEN PIPE IS PARTLY FULL, ASSUME PIPE FULL, COMPUTE Z/D AND OBTAIN ADJUSTED Q FROM SCALE (D)

USE EITHER FOLDING RULE OR TEMPLATE WITH "Y" = TO 6" OR 12".
FOR SLIGHTLY INCLINED PIPES, MEASURE "X" PARALLEL TO PIPE & "Y" VERTICALLY.
RESULTS OBTAINED FROM THIS SOLUTION ARE APPROXIMATE.



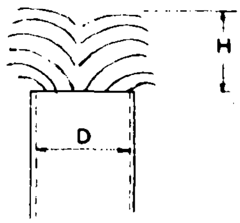
EXAMPLE (1): 8" PIPE FLOWING FULL, "X" = 40", "Y" = 6" START IN SCALE (A) AT 40" WHERE "Y" = 6" CONTINUE THRU 8" IN SCALE (B) TO 6.58 C.F.S. OR 2962 GAL. PER MIN. IN SCALE (C).

EXAMPLE (2): 8" PIPE FLOWING PARTLY FULL. "X" = 40". "Y" = 6" AND Z=2". ASSUME PIPE IS FULL AND PROCEED AS IN EXAMPLE (1). Z/D=0.25. CONNECT LINE FROM 2962 G.P.M. IN SCALE (C) TO Z/D=0.25 IN SCALE (E) AND OBTAIN ADJUSTED FLOW = 2382 G.P.M. IN SCALE (D).

Figure 3–3. Estimated Flows from Pipes

Figure 3–3. (Continued)

B. Estimated Flow from Vertical Pipe



THE APPROXIMATE FLOW FROM VERTICAL PIPES OR CASINGS CAN BE DETERMINED BY MEASURING THE MAXIMUM HEIGHT (H) IN INCHES TO WHICH THE WATER JET RISES ABOVE THE PIPE, AND INSIDE DIAMETER OF THE PIPE (D) IN INCHES.

THE FLOW IN GALLONS PER MINUTE IS GIVEN IN THE FOLLOWING TABLE FOR DIFFERENT SIZES OF STANDARD PIPE AND FOR DIFFERENT HEIGHTS OF THE WATER JETS.

Height (H) inches	Nominal Diameter (D) of Standard Pipe-inches				
	2	3	4	5	6
2	28	59	97	138	193
2.5	32	71	117	176	248
3	34	76	131	195	271
3.5	38	86	147	224	327
4	40	91	159	239	330
5	45	103	180	277	398
6	50	113	199	307	448
7	55	126	221	341	497
8	58	131	233	363	526
9	63	144	253	390	568
10	66	148	263	408	595
12	74	168	295	457	668
14	81	183	320	493	723
16	86	196	344	530	775
18	90	204	360	557	808
20	98	221	387	599	870

SCS______

WELL RECORD
Soil Conservation Service

Well No.______ (State or USGS)

Date:________________, 19__ Record by____________________________

Source of Data____

1. LOCATION: State________ County__________ Area_____ SCD________________

Nearest Town________________ ____¼ ____¼ Sec._____ T_____N/S R_____E/W

2. OWNER:______________________________ Address____________________________

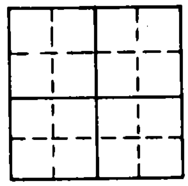
Tenant______________________________ Address____________________________

Driller______________________________ Address____________________________

3. TOPOGRAPHY ________________________________

4. ELEVATION __________ft. (ground surface or reference point)

5. TYPE: Dug; drilled; driven; jetted ______________, 19__



6. DEPTH: ________________ Date____________, 19__ Locate well in section.
reported; measured

7. CASING: Kind________ Size________ Length________ Perforated _____ft. to _____ft.
________ ________ ________ _____ _____

8. WATERBEARING STRATA

From ______ to ______ Material (sand, gravel, sandstone, limestone, basalt) ________________ Formation____________
______ ______ ________________ ____________
______ ______ ________________ ____________

9. WATER LEVEL:________ft. Reported / Measured ______________, 19__ Above______ / Below______ (ground surface (or ref. point)

10. PUMP: Type__________ Capacity______________ Power________________________

Bowl Setting __________ (depth) Discharge pipe __________ (dia.) Pump column________________ (dia.)

11. YIELD: Flow__________ (gpm) Pump____________ (gpm) (measured (reported (estimated Type of test - Bailer________ Pump________

Drawdown ________ft. after ________ hours pumping __________ (gpm)

12. USE: ______________________________ (Dom; stock; irrig.; other) Adequacy, permanence ________________

13. QUALITY: ____ (Taste; odor; color; analysis) Temp.________ °F

14. REMARKS: ____
(Gravel pack data; perforation size; screen opening and dimensions; source
____
of data; etc.)

15. RECORD LOG OF WELL ON REVERSE SIDE

Figure 3-4. Well Record Sample Form

Figure 3-4. (Continued)

LOG OF WELL

Kind of Rock or Other Material (Give color and tell whether hard or soft)	Depth in Feet From - To	Thickness in feet	Remarks (Especially information as to water found)

equipment, its uses, capabilities, and limitations are described in Chapter 2, Section 8, National Engineering Handbook.

Test Drilling. - If logs are not available or wells have not been drilled in an area, test holes at carefully selected locations will be needed to determine stratigraphy and obtain ground water information. Such test drilling should be planned to complete geologic cross sections, provide a basis for interpreting geophysical probes or aid in delineating complex structures.

Conclusions regarding apparently favorable well locations in unproven areas should be confirmed by test drilling of one or more holes. Borings 4 inches to 6 inches in diameter may be used to check stratigraphy, determine depth to water and thickness of aquifer, and obtain samples of the aquifer and the water.

Alluvial aquifers often are lenticular bodies of sand or sand and gravel in former stream channels. Several test holes drilled along a line perpendicular to the estimated direction of former flow probably will be needed to locate the thickest permeable section.

In rock, test holes are of value in verifying stratigraphy and determining whether or not conditions of jointing, fracturing or development of solution passages are favorable in advance of sinking the larger hole.

Test drilling provides a means of obtaining information and samples needed to design and construct a well of maximum efficiency. An estimate of probable water obtainable, on which to decide diameter of final well, may be based on timed bailing of test hole or calculated from thickness and permeability of aquifers as determined from test hole log and mechanical analysis of samples. Preliminary estimates of the permeability of aquifers may be obtained from grain-size distribution using "Effective Size-Permeability Curve," Plate 1 in Scherer (1959).

Test pumping to determine well characteristics, optimum pumping rate, pump setting and power required is usually performed after development of the final well is completed. Pumping tests are further discussed on page 3-33.

If salt water encroachment needs to be guarded against, the depth to fresh water-salt water interface should be determined by test drilling. This depth is needed to calculate depth at which well should bottom. Wells should not be drilled too deep if there is a possibility that salt water may lie beneath the fresh ground water. This is likely in coastal areas, on islands, and in arid areas where evaporite deposits occur in the geologic section. Beneath coastal areas, movement of fresh ground water toward the sea usually prevents landward intrusion of the slightly denser salt water.

Equilibrium is established between these fluids of different densities when, for each foot of fresh water above sea level, there are about 40 feet of fresh water lying below sea level. The fresh water-salt water interface thus slopes downward away from the ocean and the water table rises. This is known as the Ghyben-Herzberg relation between fresh and saline waters. It was originated by two independent investigators on the European coast about 50 years ago (Taylor, 1960 and Todd 1959).

As general guides in planning, wells in proximity of the coast should not pump from below sea level; interior basin wells should bottom above the expected elevation of fresh water-salt water interface, taking into consideration the anticipated drawdown. (Interface will rise as much as 40 feet for each foot of drawdown). Such wells should be designed and developed for minimum drawdown and located so that drawdown is distributed as widely as possible.

Logging.--An accurate and comprehensive record of materials penetrated and hydrologic conditions encountered in test drilling must be maintained. The purpose of test drilling is to obtain all possible subsurface information. Logging is the recording of that information. In addition to the record of materials, it is important to observe and note the depth at which water is reached, the depth to the static water level, and any changes in static level during drilling. Such changes indicate flow up or down the hole as a result of confined or unconfined water. Samples of all materials and water should be obtained for analysis.

Instructions for logging test holes contained in Chapter 4, Section 8, National Engineering Handbook, are entirely appropriate for ground water investigations and should be followed as closely as possible. Several other kinds of logs are helpful in obtaining additional information and can sometimes be employed to advantage.

The drilling-time log is an accurate record of the time required to drill each foot. Hardness of material being drilled controls drilling time and is basis for distinguishing different formations (Kirby, 1954).

Electric logging has become accepted practice for most oil wells on completion of drilling. Since 1945, its use as a supplement to sample logs has been increasing in water well construction. Electric logging usually includes measuring the self potential, spontaneous potential or "SP" of the earth and resistivity of formations penetrated.

Radioactive logging, using gamma and neutron rays, has been widely used in the petroleum industry and has been applied successfully to water wells to locate porous zones, estimate porosity, and make local correlations.

A temperature log, using a recording resistance thermometer, may show ground water circulation or some geologic feature if temperature varies from the normal 1° C. rise for each 100 feet of depth.

Caliper logging, using a device with four spring loaded arms connected to a recording electric resistor, developed by the Illinois Geological Survey, shows the average diameter of hole and is useful in locating caved portions and casing in old wells.

Other devices to obtain subsurface information include well current meters for tracing flows, fluid samplers to sample at particular depths to determine quality and check electric logs, photographs, and TV cameras for viewing well interiors.

Aquifer Sample Requirements.--In unconsolidated deposits, the grain size distribution, depth and saturated thickness of aquifers govern well design. Determination of size, number, and distribution of casing perforations; advisability of installing a well screen, or need for constructing a gravel envelope should be based on sieve analyses of aquifer samples and study of the test hole log. In rock aquifers, core samples show bedding, jointing, fracturing and cementation. They provide a basis for recommending aquifer improvement by shooting or acidizing.

Undisturbed samples of unconsolidated aquifers should be obtained for permeability tests if necessary. Such samples will be obtained during a detailed ground water investigation. Compact sand can often be sampled with a double tube soil core barrel sampler (Denison type), and medium to loose sand with a stationary piston sampler (Osterberg type). Samples of material from two feet above the aquifer to two feet below it should be taken. In many instances, undisturbed samples cannot be obtained and permeability must be determined by pumping tests.

If perforation, screen, or gravel envelope design must be based on disturbed samples, care must be taken they are not contaminated. If drilling is done with cable tools, casing should be driven to the depth at which sampling is to begin. After each hole advance is completed during the sampling, the casing should be driven to the bottom of the hole. If a hydraulic rotary drill is used, samples should be taken with a double tube soil core sampler or stationary piston sampler, as outlined in the preceding paragraph.

Geologic Sections

Structure and stratigraphy may be shown to best advantage by sections drawn approximately at right angles to the longitudinal axes of major folds or the trend of faults. Where necessary to show plunging folds or transverse faults, sections should also be drawn parallel to the longitudinal axes of the folds, and at right angles to the cross faults.

Because one bed or formation seldom outcrops throughout the area mapped, observations are necessarily made on the several formations exposed. Development of information concerning the columnar section, or normal sequence of formations and their thicknesses, is thus necessary for interpretation of features and the drawing of geologic sections. Unless an unconformity, indicating an erosional interval is present, the vertical interval between two beds may be considered relatively uniform throughout a limited area. Variations in thickness occur, however, in larger areas, necessitating surface measurement of beds and reference to well logs, and test hole logs for actual thicknesses wherever possible. The accuracy of a geologic cross section depends on the spacing and number of measured thicknesses it contains.

Geologic sections are plotted along a profile of the land surface. They show the kind and distribution of rocks and direction and amount of dip observed at outcrops on, or projected along strike to the line of section. All subsurface information is shown in relative position. Lines indicating the boundaries between beds or formations are drawn as indicated by formation changes on the logs and according to dip of surface exposures.

Scale. - Geologic sections drawn to natural scale--1 horizontal = 1 vertical--show relationships without distortion and are best for interpretation of geologic and ground water conditions. If accentuation of features is desirable, the vertical scale should usually not be more than 5 times as great as the horizontal scale.

Chart for Figuring Apparent Angle of Dip. - The strike of beds may not lie at right angles to the line of a geologic section even though the section is perpendicular to the major structural axis or fault trend. If this is the case, the apparent dip of the intersection of such a bed with the plane of the section must be calculated or determined graphically. The apparent dip of such a bed is always less than the true or observed dip and becomes increasingly less as the strike deviates from a right angle with the section line. A convenient method of determining apparent dip of beds is by use of the protractor devised by Smith (1925) and shown with explanation in Figure 3-5.

Permeability Investigations

Investigations of permeability are made to estimate the amount of water that may be obtained from a given aquifer, to estimate the safe yield of ground water reservoirs, and the time required to recharge such reservoirs after pumping has stopped. Several methods have been developed by a number of investigators during the past century. All are based on Darcy's law that velocity, when laminar or nonturbulent flow exists, is proportional to the hydraulic gradient and the coefficient of permeability.

Relationship of the various methods for determining permeability is shown in Figure 3-6.

Laboratory methods are direct and indirect. The latter are based on analyses of samples for grain size and porosity developed by Hazen, Slichter, Terzaghi, Hulbert and Feben, and Fair and Hatch. Calculation of permeability on the basis of Hazen's effective or D_{10} size using Slichter's porosity of material and temperature of fluid tables, holds for filter sands and fine, clean, well-sorted sand (National Resources Committee, 1939). This method should not be used indiscriminately but for the materials mentioned, yields satisfactory preliminary results.

Direct methods consist of measuring flow of water through undisturbed samples using permeameters of various designs and is discussed by Wenzel (1942). Laboratory permeability tests may reach a high degree of accuracy for a particular sample but determinations must be made on a sufficient number to adequately represent the aquifer. This would amount to a considerable number for a thick and extensive alluvial aquifer. In gravelly sand and gravel the taking of undisturbed samples is difficult and may require freezing of the materials.

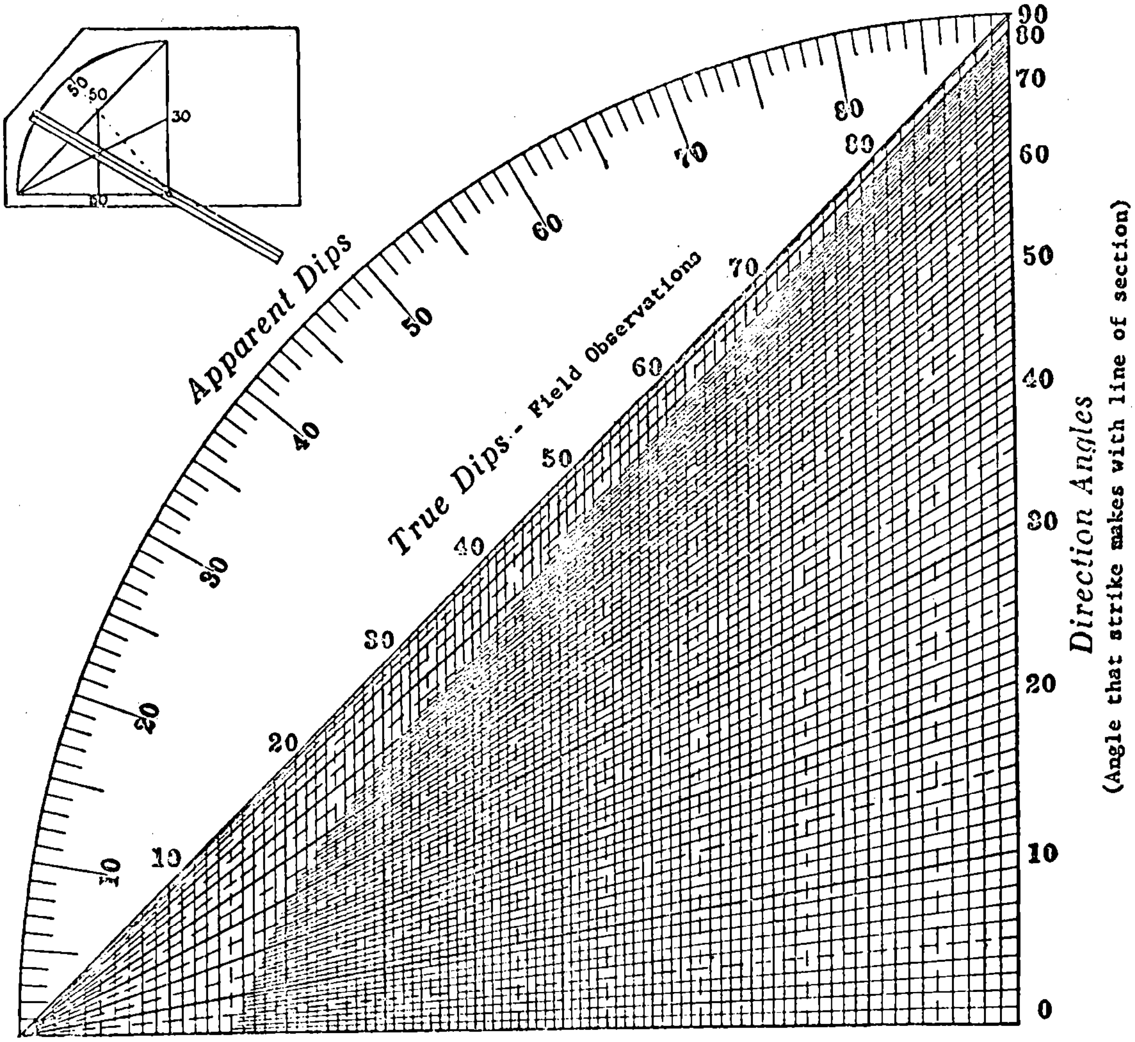


Figure 3–5. Protractor for Correction of Dip

(From An Apparent–Dip Protractor, by W. S. Tangier Smith, Econ. Geology, Vol. 20, 1925. Used by permission of Economic Geology.)

Figure 3–5. (Continued)

PROTRACTOR FOR CORRECTION OF DIP

In this protractor, degrees of true dip (field observations) are represented by the vertical lines (Fig. 3-5) marked along the chord connecting the two ends of the arc; degrees of apparent dip are represented on the arc; and the angle between the strike of the inclined bed or surface and the direction in which the dip component is measured (line of section) is shown by the converging lines marked on the right of the diagram.

To illustrate the use of this protractor, assume that a layer is dipping 30° from the horizontal and that we want to find its inclination measured in a direction 60° from its strike. Find the point of intersection of the inclined line marked 60° at the right of the diagram and the vertical line marked 30° for true dip. Through this intersection point and the vertex of the protractor (center of the arc at lower right corner) lay a straightedge, which will then intersect the arc at approximately 26°35', which is the dip component or apparent dip required.

To find the true dip, reverse this procedure. Place the straightedge on the center of the arc and on the angle for apparent dip as shown on the arc. Assume that this apparent dip is 15° and that the angle of inclination is in a direction at 25° to the strike. Note on which vertical line the straightedge cuts the diagonal for 25°. Here it is approximately on the 32° vertical, thus indicating a true dip of about 32°.

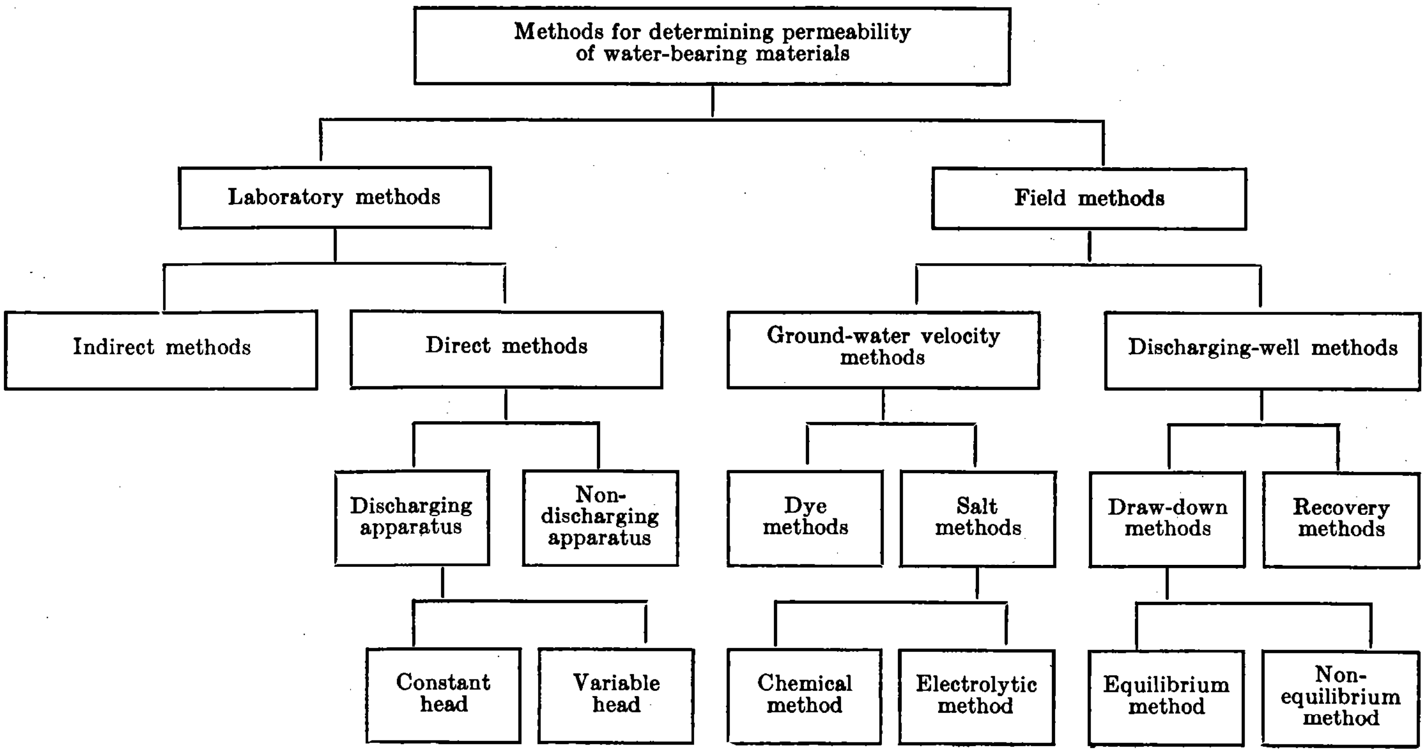


Figure 3–6. Methods for Determining Permeability of Water–Bearing Materials

(From Wenzel, 1942)

Field methods include measurement of velocity by tracing dyes or salt solutions and observation of water levels in wells during and after drawdown. Timing the movement of colored or salted water between wells is subject to limitations and difficulties but has given satisfactory results in very uniform materials. It has given very erroneous results in interbedded coarse and fine-grained materials. The latter is not adapted to use where ground water movement is slow because the heavier salt solution tends to sink. There is additional discussion of tracers in Chapter 4.

The most satisfactory basis for aquifer permeability estimates is by pumping tests with wells. Estimates thus obtained represent average characteristics of materials throughout a considerable area. Discharging well methods have a definite advantage over laboratory methods because the materials remain in place. The formulas for calculating aquifer characteristics from well tests are based on assumption of some more or less ideal conditions. The absence of some conditions will prevent indiscriminate use of many formulas but consistent results may be obtained by selection of a formula in close accord with geologic characteristics of the aquifer (Ferris, et al, 1962).

Discharging well methods present opportunities to obtain test data during both drawdown and recovery of water levels. It is recognized that a recovery test is the reverse of a drawdown test. As the name implies, it involves shutting off a pumping well and observing water levels in nearby observation wells or the pumped well. Slichter and Muskat each developed formulas for calculating permeability from recovery data using the equilibrium method. Neither of these takes into consideration the length of time the well discharged prior to being shut off. The Theis formula for determining permeability from recovery data uses the non-equilibrium method (Wenzel, 1942). The term "recovery" as used in the Theis formula means the difference between the water level in a well at any time after pumping is stopped and the water level that would have resulted if pumping has continued until that time.

An advantage of a recovery analysis of a pumped well is that it provides an easy check on pumping test results; also, it implies a constant discharge Q, which often is difficult to control accurately in the field.

Drawdown test data are used to determine aquifer characteristics by the equilibrium (Thiem) method and the non-equilibrium (Theis) method (see Chapter 1).

Important differences in requirements and results of the two methods are--the equilibrium method requires two or more observation wells while the non-equilibrium method requires one or more observation wells. The non-equilibrium equation includes time as a factor and enables the computation of future pumping levels when the flow of ground water due to pumping does not approach an equilibrium condition.

Laboratory Tests

Two types of permeameters are used to measure permeability in the laboratory, the constant head and variable head types. In the constant head type, the quantity of water flowing through a sample of known area and length in a given time can be measured. This type is applicable to relatively permeable materials. The variable head type of permeameter is adapted to relatively impermeable materials. In it, the quantity of water percolating through the sample is measured indirectly by observation of the rate of fall of water level in the standpipe above the specimen. All quantities are measured and the permeability is readily found by formulas in Wenzel (1942).

Aquifer Tests

Aquifer pump tests are made to determine the transmissibility and, when using the non-equilibrium procedure, the coefficient of storage of an aquifer.

Equipment. - Preliminary to the actual test is the installation of the testing equipment. Observation wells must be installed and ready to use. Equipment such as pumps, water-level measuring devices, timing watches, and well discharge measuring devices must be assembled and on the site. It is advisable to make a brief "test run" a few days before the actual aquifer test is to be made to be sure all equipment is in good operating condition and the personnel involved are familiar with their duties.

Pumps.--The pump and power source to be used must be adequate to pump the required volume of water for a period of 24 to 72 hours. If the aquifer to be tested is artesian, a 24-hour test is usually long enough. If it is an unconfined aquifer, at least a 72-hour test is desirable. Pumping for a short period of a few days prior to the test is helpful in determining if the pump is adequate to provide the drawdown required and all equipment is in good operating condition,

Provisions must be made to conduct all discharge water away from the site during the test. Recharge of the pumped water to the aquifer during the test will invalidate the test results.

Observation wells.--The number of observation wells required to furnish adequate information depends on the geologic and hydrologic conditions present and the aquifer test method to be used.

For example, if boundary conditions are anticipated (recharge, impermeable or less permeable boundary) the observation wells should be located to indicate these conditions. In this case, one or more observation wells should be located between the discharging well and the suspected boundary, and an additional well or wells should be located where boundary interference will be minimum. With this arrangement the effect of the boundary will be indicated. See Bentall (1963), E. E. Johnson, Inc. (1966), and Todd (1959) for additional details.

If boundary conditions are not present and the aquifer is isotropic, the drawdown cone will be symmetrical. The observation wells can be located anywhere within the drawdown cone as long as the distance from the discharging well is known.

As stated previously, the minimum number of observation wells required for the Thiem equilibrium method is two, and the minimum number for the Theis non-equilibrium method is one. For limited water-level recovery calculations no observation wells are required, but at least one is desirable.

The observation wells should be screened and at least lightly developed so they will respond quickly to water level fluctuations. The mid-point of the screens of the observation wells should be at about the same elevation as the mid-point of the screen in the discharging well and, if possible, in a coarse-grained zone in the aquifer. The observation wells should be located accurately with respect to the pumping well. The elevation of a point at the top of each well from which water level measurements will be referenced should be known to 0.01 feet.

Water level measurements.--Exact timing during the test is necessary for an accurate test. The time the test starts and exact time of all measurements must be made. The time interval between readings is small when the drawdown is changing rapidly and greater as the drawdown changes more slowly.

Water level measurements must also be accurate and should be read to the nearest 0.01 foot. An electric sounder, wetted tape or "popper" are preferred over the airline method for measuring the water level in the observation wells. When using the electric sounder, the electrode should be immersed to give the same deflection on the milliammeter for each water-level reading. The "popper" method employs a steel tape and a weight. The bottom of the weight is cup shaped or hollow. When the weight strikes the water surface, it makes a "popping" noise. The popper and electric sounder do not have to be withdrawn from the well after every measurement, the chalked tape does. The airline method is not as accurate as the above-mentioned techniques but is adequate for use in the pumped well.

Discharge measurements.--It is essential that the yield of the test well be measured accurately during a pump test and that the yield be constant. Pipe orifices are commonly used to measure discharges within a range of 50 to 2000 gallons per minute. Parshall flumes or sharp-crested weirs are used to measure larger flows. These methods are discussed in the SCS National Engineering Handbook, Section 15, Irrigation, Chapter 9, Measurement of Irrigation Water.

A constant rate of discharge is required for pump tests. Governing the discharge by varying the pump motor speed is difficult. A gate valve installed in the discharge line is a very effective method. The valve is partially closed at the beginning of the test so it can be adjusted to maintain a constant yield from the well as drawdown increases during the test.

Discharging Well Method. - The information from pump tests should be tabulated as shown in Figure 3-7.

Project:

Location:

Discharge measured by: 1-foot Parshall Flume
Drawdown measured by: Electrocal sounder
Reference point: North side of casing collar

PUMP TEST NO. 1, PUMPING WELL

Date	Time	Depth to water(feet)	Drawdown s (feet)	Gage reading (feet)	Discharge (gpm)	Remarks
5-16	0840	60.99				
5-17	0830	61.01				
5-18	0845	61.00				
5-19	0820	60.98				
	0840	60.99 1/	0.0			Pump started
	0900	72.30	11.3	0.79	1210	
	1000	72.60	11.6	.79	1210	
	1100	72.80	11.8	.79	1210	Pump off 5-21 at 0730
	1155	72.80	11.8	.80	1210	
	1255	72.80	11.8	.80	1215	Avg Q = 1210 gpm
	1355	73.00	12.0	.80	1210	
	1455	73.20	12.2	.80	1210	
	1555	73.20	12.2	.80	1200	m = 50 ft.
	1655	73.20	12.2	.80	1210	
	1800	73.20	12.2	.80	1210	
	1856	73.30	12.3	.80	1210	
	1948	73.40	12.4	.80	1210	
	2057	73.40	12.4	.80	1200	
	2203	73.40	12.4	.80	1210	
	2300	73.60	12.6	.80	1210	
	2358	73.50	12.5	.80	1210	
5-20	0104	73.60	12.6	.80	1210	
	0204	73.60	12.6	.80	1210	
	0259	73.60	12.6	.80	1210	
	0400	73.80	12.8	.80	1210	
	0501	74.00	13.0	.80	1210	
	0602	73.90	12.9	.80	1210	
	0702	73.90	12.9	.80	1210	
	0759	73.80	12.8	.80	1210	
	0855	73.80	12.8	.80	1210	
	0955	73.80	12.8	.80	1210	
	1055	73.80	12.8	.80	1210	

Continued but not reproduced.

1/ Static water level.

Figure 3–7A. Pump Test Drawdown Data Sheet

Project: Drawdown measured by: Electric sounder
Reference point: North side of casing collar

Location:

PUMP TEST NO. 1, OBSERVATION WELL NO. 1, r = 100 feet

Date	Time	Depth to water(feet)	Drawdown s (feet)	t (minutes)	$\frac{r^2}{t}$	Remarks
5-16	0845	60.43				
5-17	0825	60.45				
5-18	0840	60.43				
5-19	0815	60.42				
	0841	60.42	0.00			Pump started at 0840
	0845	60.50	0.08	5	2,000	
	0850	60.64	0.22	10	1,000	Pump off 5-21 at 0730
	0855	60.74	0.32	15	670	
	0900	60.83	0.41	20	500	
	0905	60.90	0.48	25	400	
	0910	60.96	0.54	30	333	m = 50 ft.
	0920	61.06	0.64	40	250	
	0930	61.14	0.72	50	200	
	0940	61.20	0.78	60	170	
	0950	61.27	0.85	70	140	
	1000	61.32	0.90	80	125	
	1010	61.36	0.94	90	110	
	1020	61.40	0.98	100	100	
	1030	61.44	1.02	110	91	
	1040	61.47	1.05	120	83	
	1140	61.62	1.20	180	56	
	1240	61.73	1.31	240	42	
	1340	61.83	1.41	300	33	
	1440	61.90	1.48	360	28	
	1540	61.96	1.54	420	24	
	1640	62.01	1.59	480	21	
	1740	62.05	1.63	540	19	
	1840	62.09	1.67	600	17	
	1940	62.14	1.72	660	15	
	2040	62.17	1.75	720	14	
	2240	62.26	1.84	840	12	
5-20	0040	62.31	1.89	960	10	
	--	--	--	--	--	
5-20	1845	62.59	2.17	2,045	4.9	

Continued but not reproduced.

Figure 3-7B. Pump Test Drawdown Data Sheet

Project: | Drawdown measured by: Electric sounder
Reference point: East side of casing collar
Location:

PUMP TEST NO. 1, OBSERVATION WELL NO. 2, r = 200 feet

Date	Time	Depth to water(feet)	Drawdown s (feet)	t (minutes)	$\frac{r^2}{t}$	Remarks
5-16	0835	58.41				
5-17	0820	58.39				
5-18	0820	58.40				
5-19	0810	58.41				
	0838	58.41 1/				Pump started at 0840
	0847	58.41	0.00	7	5,720	
	0852	58.44	0.03	12	3,332	Pump off 5-21 at 0730
	0857	58.48	0.07	17	2,352	
	0902	58.52	0.11	22	1,820	
	0907	58.56	0.15	27	1,480	m = 50 ft.
	0912	58.59	0.18	32	1,252	
	0922	58.66	0.25	42	952	
	0932	58.72	0.31	52	768	
	0942	58.77	0.36	62	644	
	0952	58.81	0.40	72	556	
	1002	58.85	0.44	82	488	
	1012	58.89	0.48	92	436	
	1022	58.92	0.51	102	392	
	1032	58.95	0.54	112	357	
	1042	58.98	0.57	122	328	
	1142	59.12	0.71	182	220	
	1242	59.22	0.81	242	165	
	1342	59.30	0.89	302	132	
	1442	59.38	0.97	362	110	
	1542	59.44	1.03	422	94	
	1642	59.49	1.08	482	83	
	1742	59.53	1.12	542	72	
	1842	59.57	1.16	602	66	
	1942	59.61	1.20	662	60	
	2042	59.64	1.23	722	55	
	2242	59.73	1.32	842	44	
5-20	0042	59.77	1.36	962	40	
	--	--	--	--	--	
5-20	1845	60.01	1.65	2045	20	

Continued but not reproduced.

1/ Static water level.

Figure 3-7C. Pump Test Drawdown Data Sheet

Project:

Location:

Drawdown measured by: "Popper"
Reference point: East side of casing collar

PUMP TEST NO. 1, OBSERVATION WELL NO. 3, r = 400 feet

Date	Time	Depth to water(feet)	Drawdown s (feet)	t (minutes)	$\frac{r^2}{t}$	Remarks
5-16	0850	58.47				
5-17	0830	58.48				
5-18	0835	58.48				
5-19	0820	58.47				
	0838	58.47 1/				Pump on at 0840
	0855	58.47	0.00	15	10,720	Pump off 5-21 at 0730
	0900	58.47	.00	20	8,000	
	0905	58.47	.00	25	6,400	
	0910	58.47	.00	30	5,280	m = 50 ft.
	0915	58.48	.01	35	4,640	
	0920	58.49	.02	40	4,000	
	0930	58.50	.03	50	3,200	
	0940	58.52	.05	60	2,720	
	0950	58.54	.07	70	2,240	
	1000	58.55	.08	80	2,080	
	1010	58.57	.10	90	1,760	
	1020	58.59	.12	100	1,600	
	1030	58.61	.14	110	1,456	
	1040	58.62	.15	120	1,328	
	1050	58.64	.17	130	1,232	
	1150	58.73	.26	190	848	
	1250	58.81	.34	250	640	
	1350	58.87	.40	310	512	
	1450	58.93	.46	370	432	
	1550	58.98	.51	430	368	
	1650	59.02	.55	490	320	
	1750	59.06	.59	550	288	
	1850	59.10	.63	610	256	
	1950	59.12	.65	670	240	
	2050	59.15	.68	730	224	
	2250	59.22	.75	850	192	
5-20	0050	59.27	.80	970	160	
	--	--	--	--	--	
5-20	1845	59.54	1.07	2,045	78	

Continued but not reproduced.

1/ Static water level.

Figure 3–7D. Pump Test Drawdown Data Sheet

The basic hydraulic equations for determining aquifer characteristics have been given in Chapter 1. An example of the application of these equations for equilibrium and non-equilibrium conditions will be given using data from the U.S. Bureau of Reclamation (1964).

Equilibrium method.--The Thiem equilibrium equation is:

$$k = \frac{Q \log_e \left(\frac{r_2}{r_1}\right)}{2 \pi m (s_1 - s_2)}$$

or

$$P = \frac{527.7 \, Q \log_{10} \frac{r_2}{r_1}}{m (s_1 - s_2)}$$

These parameters are illustrated in Figure 3-8.

This information is obtained from pump test data sheets, Figure 3-7:

m = 50 feet
Q = 1210 gpm
r_1 = 100 feet
r_2 = 200 feet
r_3 = 400 feet
t = 2045 minutes
s_1 = 2.17 feet
s_2 = 1.65 feet
s_3 = 1.07 feet

Using data from observation wells 1 and 2:

$$P = \frac{(527.7)(1210)(\log_{10} \frac{200}{100})}{50 \, (2.17 - 1.65)}$$

= 7400 gallons per ft^2 per day

Using data from observation wells 1 and 3:

$$P = \frac{(527.7)(1210) \log \frac{400}{100}}{50 \, (2.17 - 1.07)}$$

= 7000 gallons per ft^2 per day

Using data from observation wells 2 and 3:

$$P = \frac{(527.7)(1210)(\log \frac{400}{200})}{50 \, (1.65 - 1.07)}$$

= 6750 gallons per ft^2 per day

Average P = 7050 gallons per ft^2 per day

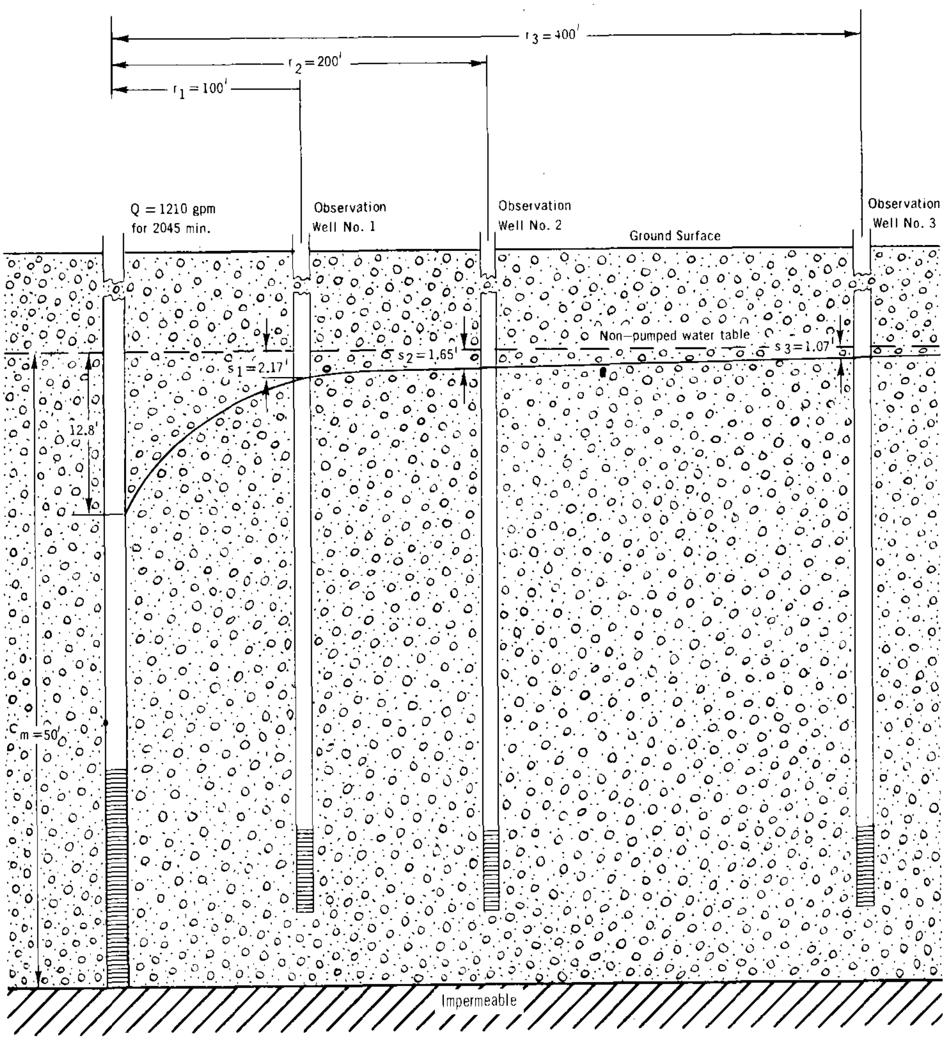


Figure 3-8. Drawdown Cone

Non-equilibrium method.--The Theis equation to determine aquifer characteristics under non-equilibrium conditions as discussed in Chapter 1 is:

$$s = \frac{114.6\ Q}{T} W(u)$$

where s = drawdown at a point r distant from a pumping well (ft.)
Q = discharge from the well (gallons per minute)
T = coefficient of transmissibility (gal./day/ft)
W(u) = exponential integral
u $= \frac{1.87\ r^2\ S}{Tt}$
r = distance from pump well to point where drawdown s is determined (ft.)
S = coefficient of storage (dimensionless)
t = time that pump well has been discharging (days).

If the coefficient of transmissibility and coefficient of storage are known, the drawdown on the cone of depression at any time and any distance from the well can be determined after the well starts discharging. This is done by substituting the known values of S and T and the desired values of t and r in the equation:

$$u = \frac{1.87\ r^2\ S}{Tt}$$

and the equation solved to determine u. The value of W(u) for u is read from Table 1-3 and the equation:

$$s = \frac{114.6\ Q}{T}\ W(u)$$

is then solved for the drawdown s.

The non-equilibrium equation can also be solved for transmissibility T and storage coefficient S if several values of drawdown s at times t are known for one distance r from the pumpwell or several values of s and r are known for one value of t. The solution requires the graphical determination of W(u), u, s, and either r^2/t or the reciprocal of time (1/t).

Figure 3-9 is a type curve of W(u) versus u and is plotted from the data in Table 1-3.

In Figure 3-10 test well data from Figure 3-7 is plotted at the same scale on logarithmic paper as the type curve. Note that this data curve is plotted as s versus t instead of 1/t. The logarithmic data curve, as plotted, is a mirror image of the curve that would be plotted as s versus 1/t. The calculation of the reciprocal values of time is not necessary. The type and data curves are matched face to face (a light table is useful). Keep the axes parallel, pick a common point on a matched section of the two curves and obtain values of W(u), u, s, and t for the common point.

Since the curve fitting process is a measure of displacement of the data curve with respect to the type curve, a simplified procedure can sometimes be used. Move the curves, keeping the axes parallel until a fit is found. If the data curve fits section II of the type curve select as a common point on the type curve W(u) and u equal one (1) and determine the value of s and t (or r^2/t) for this point on the plotted curve.

Data from the three observation wells is plotted in Figure 3-10 and matched to the type curve (Figure 3-9). Values for W(u), u, s, and t were obtained by picking a common point on the matched section of the fitted curves and for the common point at W(u) and u equal to one (1) when curves were fitted. As can be seen from the following calculations, both methods give approximately the same result. All values of time on the data curve are in minutes. To be consistent with the units in the equation, these time values must be divided by 1440 to convert to days.

Observation Well No. 1 $\quad r = 100$ feet

$W(u) = 1$	$W(u) = 2.4$
$u = 1$	$u = 5.5 \times 10^{-2}$
$t = 5.25/1440$	$t = 100/1440$
$s = 0.42$	$s = 0.98$

$$T = \frac{114.6\ Q}{s} W(u)$$

$$= \frac{(114.6)(1210)(1)}{0.42} \qquad = \frac{(114.6)(1210)(2.4)}{0.98}$$

$$= 330{,}000 \qquad = 340{,}000$$

$$S = \frac{uTt}{1.87\ r^2}$$

$$= \frac{(1)(33 \times 10^5)(\frac{5.25}{1440})}{(1.87)(100)^2} \qquad = \frac{(5.5 \times 10^{-2})(3.4 \times 10^5)(\frac{100}{1440})}{(1.87)(100)^2}$$

$$= .064 \qquad = .069$$

Observation Well No. 2 $\quad r = 200$ feet

$W(u) = 1$	$W(u) = 1.22$
$u = 1$	$u = 0.2$
$t = 20/1440$	$t = 100/1440$
$s = .40$	$s = .51$

$$T = \frac{114.6\ Q\ W(u)}{s}$$

$$= \frac{(114.6)(1210)(1)}{.40} \qquad = \frac{(114.6)(1210)(1.22)}{.51}$$

$$= 346{,}000 \qquad = 330{,}00$$

$$S = \frac{uTt}{1.87\ r^2}$$

$$= \frac{(1)(346{,}000)(\frac{20}{1440})}{(1.87)(200)^2} \qquad = \frac{(0.2)(330{,}000)(\frac{100}{1440})}{(1.87)(200)^2}$$

$$= .064 \qquad = .061$$

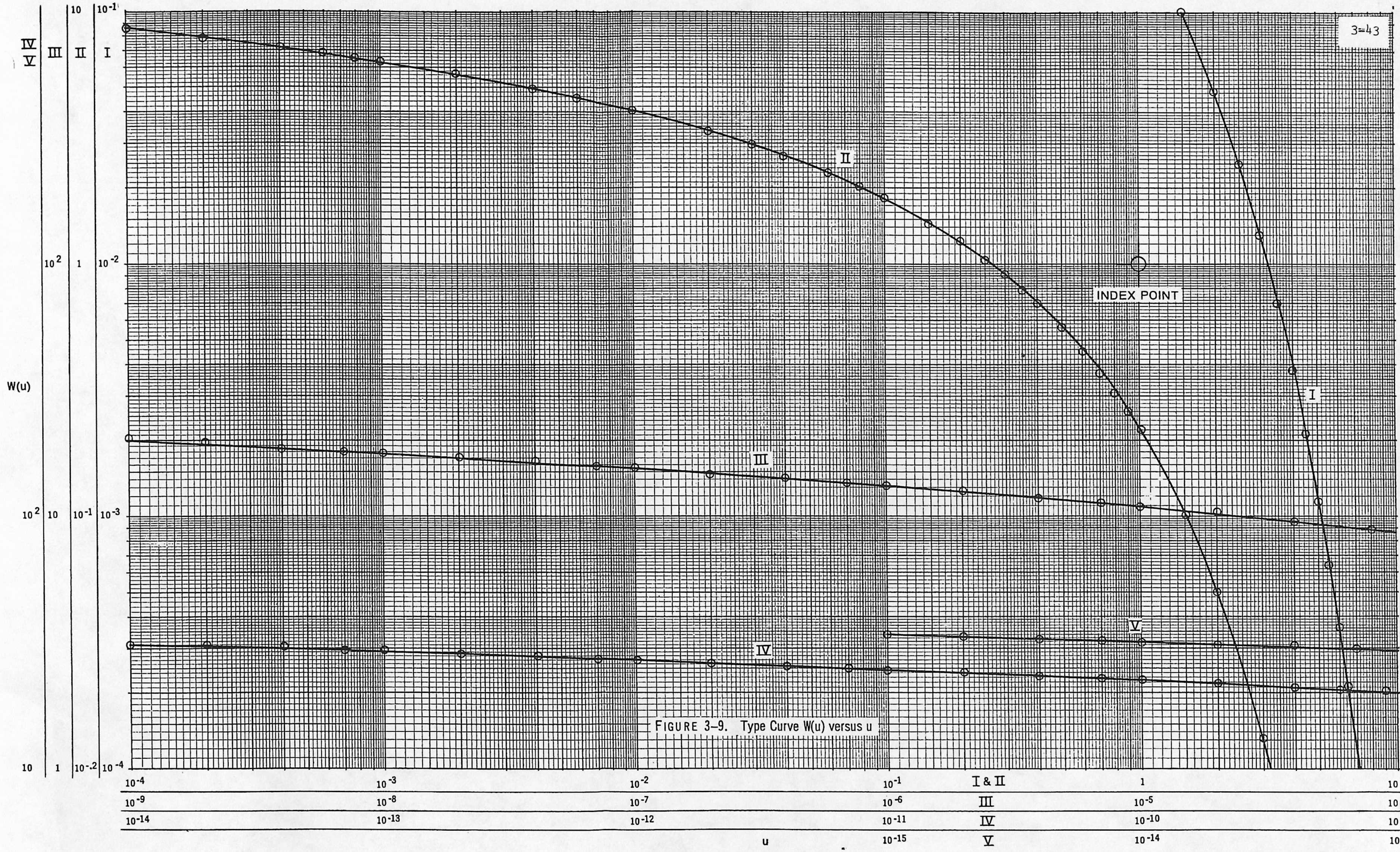


FIGURE 3–9. Type Curve W(u) versus u

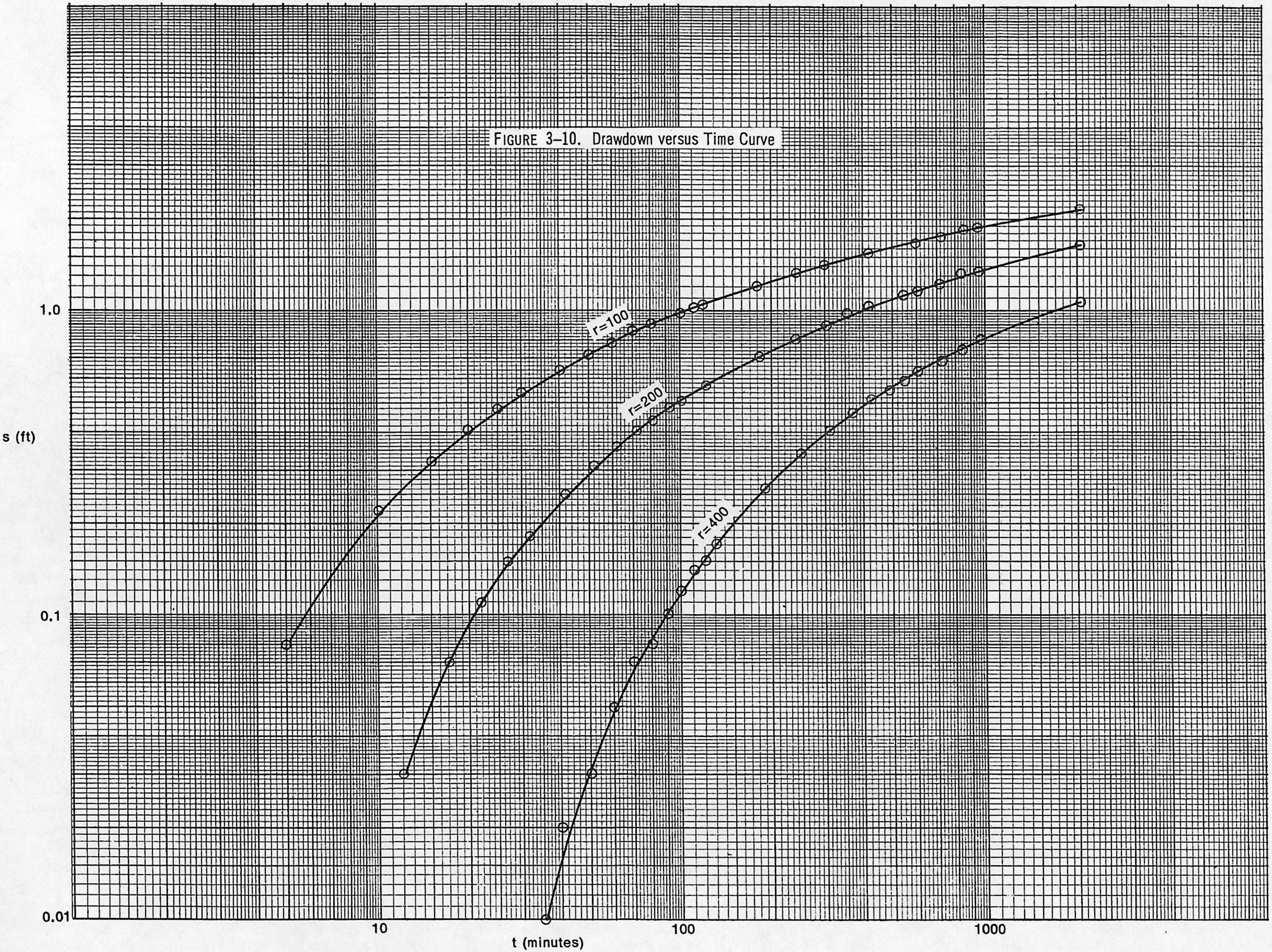


FIGURE 3-10. Drawdown versus Time Curve

Observation Well No. 3 $r = 400$ feet

$W(u) = 1$

$u = 1$

$t = 86/1440$

$s = .42$

$$T = \frac{144.6\ Q\ W(u)}{s}$$

$$= \frac{(114.6)(1210)(1)}{.42}$$

$$= 330,000$$

$$S = \frac{uTt}{1.87\ r^2}$$

$$= \frac{(1)(330,000)(86/1440)}{(1.87)(400)^2}$$

$$= .066$$

$W(u) = .22$

$u = 1$

$t = 86$

$s = .096$

$$= \frac{(114.6)(1210)(.22)}{.096}$$

$$= 320,000$$

$$= \frac{(1)(320,000)(86/1440)}{(1.87)(400^2)}$$

$$= .064$$

Average T = 335,000

Average S = .065

Average T = 300,000

Average S = .065

When plotting r^2/t versus s all points for the three observation wells fall on the same curve when plotted on logarithmic paper (Figure 3-11). This curve should also be plotted at the same scale as the type curve. Values of a common point on the type and plotted curve when fitted and the values of r^2/t and s when W(u) and u equal one (1) and the curves are fitted give essentially the same results for values of S and T. This is illustrated in the following example. In this example also the time in minutes is divided by 1440 to convert to days.

$W(u) = 1$	$W(u) = 1.22$
$u = 1$	$u = 0.2$
$r^2/t = 1950$	$r^2/t = 390$
$s = 0.4$	$s = 0.5$

$$T = \frac{114.6\ Q\ W(u)}{s} = \frac{(114.6)(1210)(1)}{0.4} = 346{,}000$$

$$T = \frac{114.6\ Q\ W(u)}{s} = \frac{(114.6)(1210)(1.22)}{0.5} = 339{,}000$$

$$S = \frac{uT}{1.87\ r^2/t} = \frac{(1)(346{,}000)}{(1.87)(1950)(1440)} = .066$$

$$S = \frac{uT}{1.87\ r^2/t} = \frac{(0.2)(339{,}000)}{(1.87)(390)(1440)} = .065$$

Modified non-equilibrium method.--There is, under certain conditions, a short-cut method for solving the Theis non-equilibrium equation. In the equation:

$$u = \frac{1.87\ r^2 S}{Tt}$$

the value of u decreases when time t increases. When u becomes less than about 0.01 the equation:

$$s = \frac{114.6\ Q}{T}\ W(u)$$

can be re-written as:

$$s = \frac{264}{T}\ Q\ \log_{10} \frac{0.3\ Tt}{r^2 S}$$

Solving this equation for transmissibility it becomes:

$$T = \frac{264\ Q\ \log_{10} t_2/t_1}{s_2 - s_1}$$

where T = transmissibility
Q = pumping rate (gpm)
s_1 = drawdown (ft) at time t_1 and
s_2 = drawdown (ft) at time t_2 in an observation well at r distance from the discharging well.

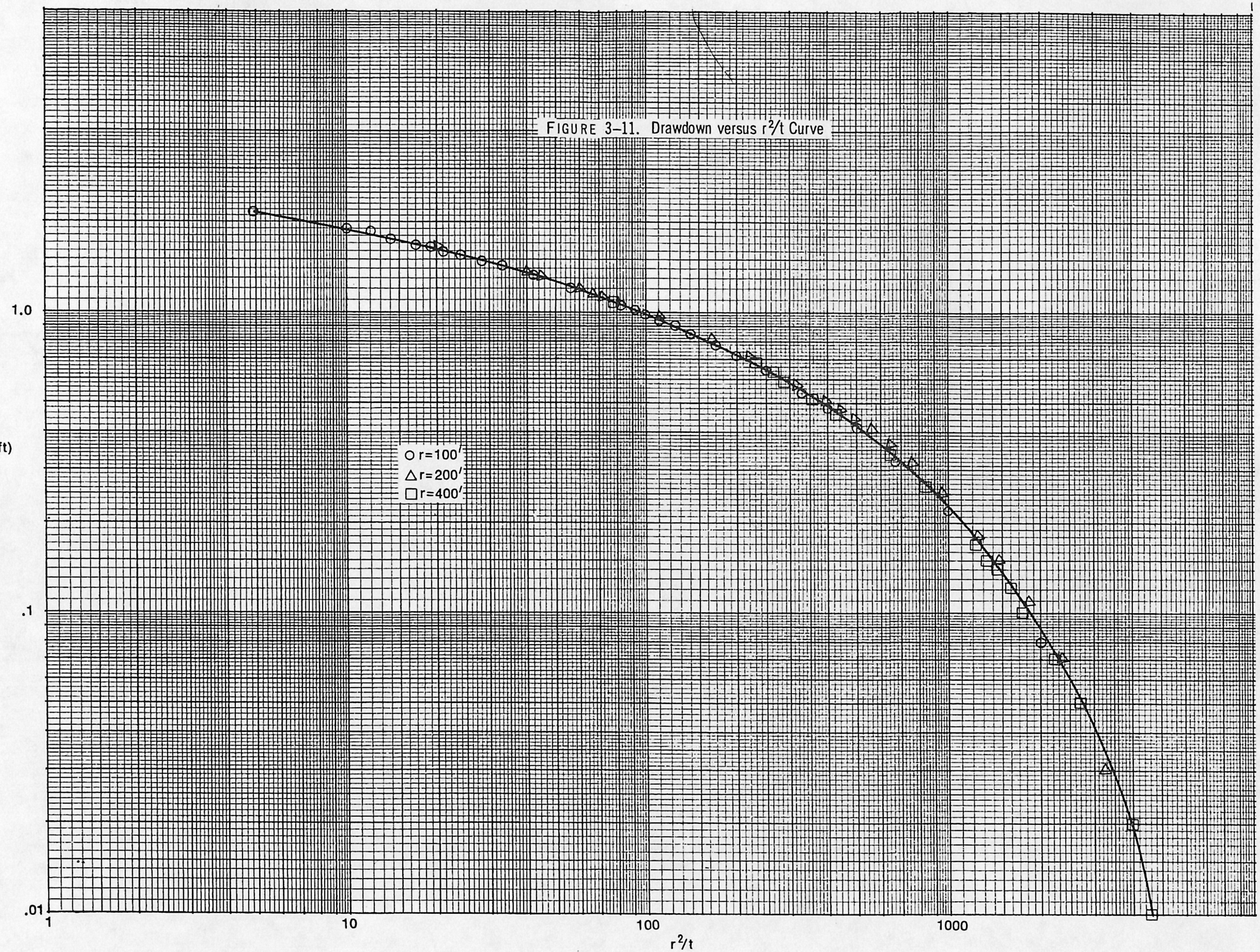


FIGURE 3-11. Drawdown versus r^2/t Curve

This equation can be solved graphically by plotting on semi-logarithmic paper values of t (logarithmic) and s (arithmetic). These points will fall on a straight line when u becomes less than about 0.01 as t becomes large. The equation is solved for T by selecting values of t_1, t_2, s_1, and s_2 from the straight line portion of the curve. If t_1 and t_2 are selected one log cycle apart the value of:

$$\log_{10} \frac{t_2}{t_1} = 1$$

and the equation becomes:

$$T = \frac{264\ Q}{\Delta s}$$

where Δs is $s_2 - s_1$ over one log cycle of time.

The equation:

$$s = \frac{264\ Q}{T} \log_{10} \frac{0.3\ Tt}{r^2 S}$$

when solved for the coefficient of storage becomes:

$$S = \frac{0.3\ Tt_0}{r^2}$$

If the straight line portion of the semi-logarithmic curve is extended to intersect the zero drawdown axis and t_0 is the time in days where this intersection occurs, the coefficient of storage S can be determined from the above equation.

Following are calculations of S and T using Δs and t_0 values from Figure 3-12:

For observation well no. 1 (r = 100 ft.)

$$\Delta s = 0.90$$

$$t_0 = 8/1440$$

$$T = \frac{(264)(1210)}{0.90} = 355{,}000$$

$$S = \frac{(0.3)(355{,}000)(8)}{(100)^2\ (1440)} = 0.059$$

For observation well no. 2 (r = 200 ft.)

$$\Delta s = 0.89$$

$$t_0 = 28/1440$$

$$T = \frac{(264)(1210)}{(.89)} = 359{,}000$$

$$S = \frac{(0.3)(359{,}000)(28)}{(200)^2\ (1440)} = 0.052$$

For observation well no. 3 (r = 400 ft.)

$$\Delta s = 0.88$$

$$t_0 = 115/1440$$

$$T = \frac{(264)(1210)}{0.88} = 363,000$$

$$S = \frac{(0.3)(363,000)(115)}{(400)^2\ (1440)} = 0.054$$

Average T = 359,000

Average S = 0.055

Water Level Recovery Method. - The water level recovery method is a useful check on the validity of the discharging well test results. Where no observation well is available limited calculations can be made of the Coefficient of Transmissibility of the aquifer but not the Coefficient of Storage.

If a recovery test is to be made after the pump-out test the exact time the pump is shut down is recorded. Water level recovery measurements are made and recorded in the same manner as in the pump-out test. These measurements are made at frequent intervals when recovery is rapid and less frequently as the rate of recovery decreases. See E. E. Johnson, Inc. (1966).

In the case where a recovery test is to be made without a pump-out test the static water level is measured and recorded before starting the pump. The pump is then started, the exact time recorded, and the discharge maintained at a uniform rate. Measurements of drawdown are continued until the drawdown increases only slightly (0.1 foot per hour or less) with time. The pump is then stopped and water level recovery measurements are made as before.

Figure 3-13 (from U.S. Bureau of Reclamation, 1964) is an example of a water level recovery test data sheet when no observation well was available.

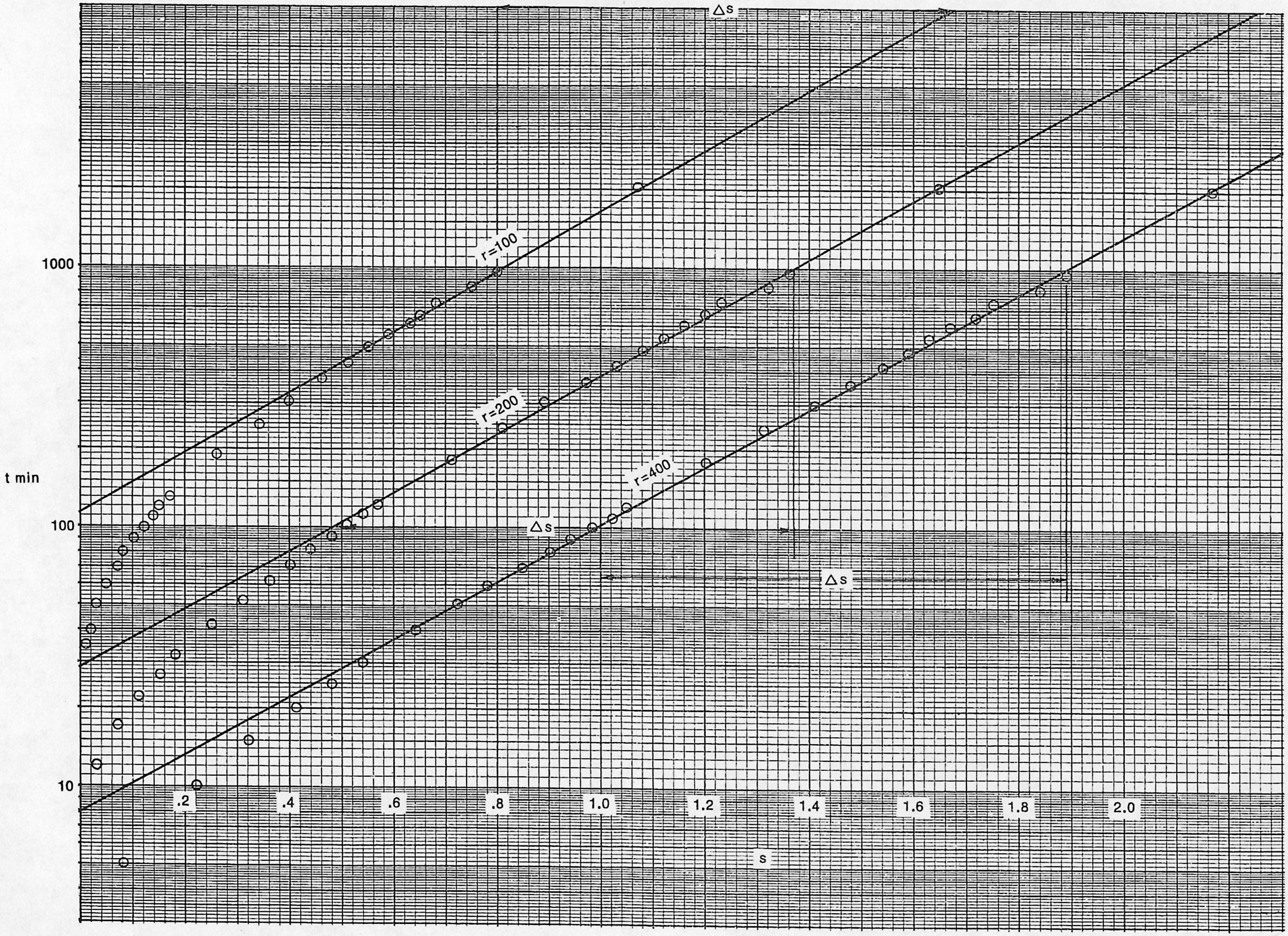
The Coefficient of Transmissibility can be determined using the straight line method by plotting residual drawdown versus log t/t^1. Residual drawdown is the difference in the water level before pumping began and at anytime after the pump has been stopped. Time t is time since pumping was started and t^1 is the time since the pump was stopped (recovery started). The time can be measured in any consistant units (minutes, hours, days) because t/t^1 is a ratio and is dimensionless.

The Coefficient of Transmissibility can be determined from the straight-line equation:

$$T = \frac{264\ Q}{\Delta s}$$

where Δs is residual drawdown over one log cycle of time (t/t^1).

FIGURE 3-12. Time Drawdown Curves



Project:
Feature:
Location:

Drawdown measured by: Electrical sounder
Discharge measured by: Totalizing meter
Reference point: Hole on north side of drive head

TEST OF TOWN WELL NO. 1

Date	Time	Time since pumping stopped (minutes) t[1]	Depth to water (feet)	Drawdown s (feet)	Time since pumping started (minutes) t	Ratio t/t[1]	Remarks
10-5	2100		30.05	0			Pump on 10-5
10-7	0515	0	41.50	11.45	1,920		at 2115 hrs
	0516	1	26.00	(4.05)	1,921	1,921	Pump off 10-7
	0517	2	29.90	(0.15)	1,922	961	at 0515 hrs
	0518	3	32.50	2.45	1,923	641	
	0519	4	32.50	2.45	1,924	481	Discharge into
	0520	5	32.44	2.39	1,925	385	reservoir
	0521	6	32.36	2.31	1,926	323	
	0522	7	32.30	2.25	1,927	275	Static water
	0523	8	32.25	2.20	1,928	241	level on 10-5
	0524	9	32.20	2.15	1,929	214	at 2115 hrs = 30.04 ft
	0525	10	32.16	2.11	1,930	193	Pumping level
	0530	15	32.00	1.95	1,935	129	on 10-7 at
	0535	20	31.88	1.83	1,940	97	0515 hrs =
	0540	25	31.80	1.75	1,945	78	41.50 ft
	0545	30	31.73	1.68	1,950	65	Meter reading
	0550	35	31.67	1.62	1,955	56	on 10-5 at
	0555	40	31.62	1.57	1,960	49	2110 hrs =
	0605	50	31.53	1.48	1,970	39	510 gal
	0615	60	31.45	1.40	1,980	33	Meter reading
	*	*	*	*	*	*	on 10-7 at
	0705	110	31.23	1.18	2,030	18	0515 hrs =
	0715	120	31.19	1.14	2,040	17	2,323,800 gal
	0815	180	31.04	0.99	2,100	12	Total discharge
	0915	240	30.93	0.88	2,160	9.0	= 2,323,290
	1015	300	30.85	0.80	2,220	7.4	gal
	*	*	*	*	*	*	Time of pumping
10-8	0215	1,440	30.38	0.33	3,360	2.3	= 1,920 min.
	0415	1,500	30.36	0.31	3,480	2.2	2,323,290/1920
	0615	1,680	30.35	0.30	3,600	2.1	= 1,210 gpm
	0815	1,800	30.34	0.29	3,720	2.1	
	1015	1,920	30.33	0.28	3,840	2.0	

Figure 3-13. Recovery Measurement Data Sheet

Figure 3-14 is the residual drawdown versus time (t/t^1) curve plotted from the data in Figure 3-13. From this curve and data sheet we obtain:

$$Q = 1210 \text{ gpm}$$
$$\Delta s = 0.93 \text{ feet}$$

T is obtained by solving the equation:

$$T = \frac{264\ Q}{\Delta s}$$

$$T = \frac{(264)(1210)}{0.93} = 343{,}000$$

Interpretation of Aquifer Test. - The results of the aquifer tests shown in the examples indicate it is essentially an isotropic aquifer of great extent.

Observation of the shape of the drawdown curves will indicate if boundary conditions are present in the aquifer. On the time drawdown curve, Figure 3-12, if as time increases the slope of the curve increases, showing greater drawdown, this would indicate an impermeable boundary at some distance from the well. If the slope of the drawdown curve decreases, showing less drawdown, this would indicate recharge to the aquifer is taking place; and if the slope of the line is flat, this would indicate recharge was equal to discharge.

Well interference, boundary conditions, leaky-roofed aquifers, image wells and the many variations and ramifications encountered in aquifer pump tests are discussed in the extensive literature. Some of these references are: E. E. Johnson, Inc. (1966), Wenzel (1942), Bental (1963), Lang (1961), Ferris, et al (1962), Todd (1959), Bruin and Hudson (1961), and Walton (1962).

When the transmissibility and coefficient of storage of an aquifer are known, the drawdown at any distance from the discharging well can be predicted for a constant discharge for any period of time with the non-equilibrium equation. An example of this procedure follows.

From the preceding example of an aquifer test we know:

$$T = 335{,}000 \text{ gallons per day per foot}$$

$$S = 0.065$$

What would be the drawdown 1,000 feet from the discharging well after it has been pumped at 1,000 gpm for 10 days? In this case,

$$r = 1{,}000 \text{ feet}$$

$$Q = 1{,}000 \text{ gallons per minute}$$

$$t = 10 \text{ days}$$

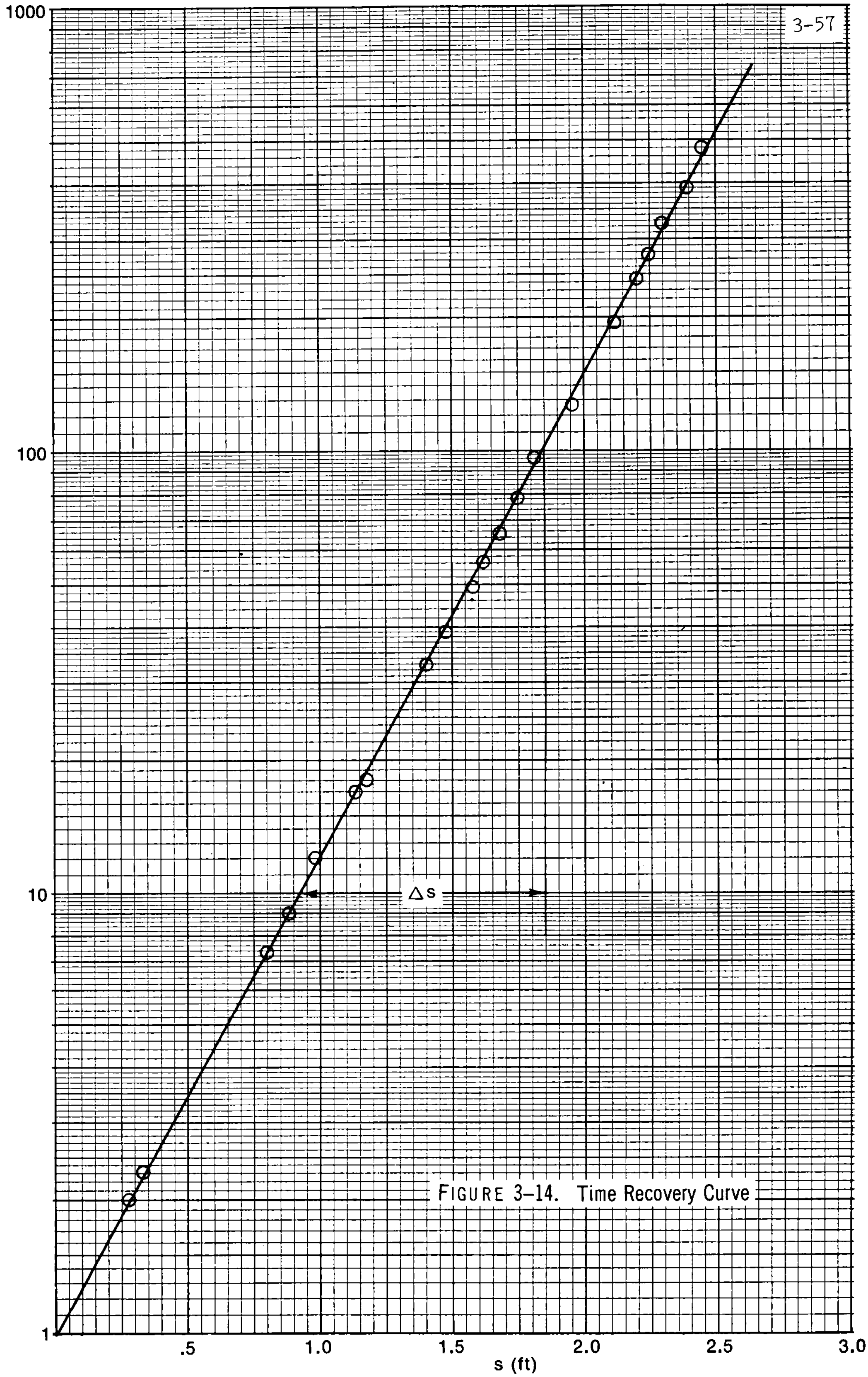


FIGURE 3-14. Time Recovery Curve

$$u = \frac{1.87\ r^2S}{Tt} = \frac{(1.87)(1000)^2(0.065)}{(335{,}000)(10)} = 3.5 \times 10^{-2}$$

From Table 1-3 the value of W(u) for $u = 3.5 \times 10^{-2}$ is interpolated:

$$W(u) = 2.87$$

The drawdown is calculated from the formula:

$$s = \frac{114.6\ Q}{T}\ W(u) = \frac{(114.6)(1000)(2.87)}{335{,}000} = 0.98 \text{ ft.}$$

The same procedure, r equaling the radius of the well, can be used to calculate the drawdown outside the well casing. What would be the drawdown outside a 14 inch (OD) well after it has been pumped at 1,000 gpm for 10 days? The following data is used:

T = 335,000 gallons per day per foot

S = 0.065

Q = 1,000 gallons per minute

t = 10 days

r = 7 inches = 0.583 feet

$$u = \frac{1.87\ r^2S}{Tt} = \frac{(1.87)(0.583)^2(0.065)}{(335{,}000)(10)} = 1.23 \times 10^{-8}$$

Interpolating from Table 1-3:

$$W(u) = 17.27$$

The drawdown outside the well casing is calculated from the formula:

$$s = \frac{114.6\ Q}{T}\ W(u) = \frac{(114.6)(1{,}000)(17.27)}{335{,}000} = 5.92 \text{ feet}$$

Since wells are not 100 percent efficient, the difference in drawdown inside and outside the casing depends on the efficiency of the well. A very good well will have an efficiency of 85 to 90 percent.

Whenever possible, wells should be spaced so their drawdown cone or radii of influence do not intersect. When aquifer characteristics and pumping requirements are known the above procedure can be used to locate wells to minimize interference between them. If drawdown cones intersect, drawdown is increased in the discharging wells for a given discharge. One of the factors in the cost of pumping water is height it has to be lifted, therefore, increasing the drawdown in a well increases the cost of pumping.

Individual Equipment

This list is presented as a check list to facilitate field work. Other equipment and references may be needed for special investigations.

Acid, dilute HCl, 2 oz., 1/10 normal

Altimeter

Benzidine, 2 oz.

Briefcase

Brunton compass with case

Camera, 35 mm. or 2" x 2".

Data Sheets (looseleaf) AGI 1 to 476, GEO-Times, 1956-64, American Geological Institute

Field drafting equipment such as protractor, lettering triangle, 30°-60° triangle, 10", French curve 6", engineer's scale, and scales with representative fractions of 1:20,000, 1:24,000, 1:31,680, and 1:62,500.

Handbooks of Minerals (Hurlbut, 1955, or Pough, 1960)

Hand lens, 10X

Knapsack or mussett bag

Light meter

Notebook

Pocket stereoscope

Snake bite kit

Thermometer, pocket, 30°-100°, or 0°-220° F.

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NATIONAL ENGINEERING HANDBOOK

SECTION 18

GROUND WATER

CHAPTER 4. GROUND-WATER INVESTIGATIONS

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SECTION 18

GROUND WATER

CHAPTER 4. GROUND-WATER INVESTIGATIONS

Introduction

Ground-water investigations are made by the Service to provide assistance to cooperators in Soil Conservation Districts and to provide data necessary for planning and design of works of improvement in the watershed programs. The purpose and scope of ground-water investigations are set forth in Engineering Memorandum 10, (Rev. 1) dated April 28, 1971.

Because many types of Service projects require ground-water investigation, minimum criteria and guidance are presented in this chapter.

General Requirements

Some uncertainty is inherent in new ground-water developments and water table control projects. To reduce the risk of failure and consequent financial loss, it is desirable that Service ground-water investigations be conducted by professional geologists.

The intensity of ground-water investigations depend on project purposes and scope, complexity of site conditions, and availability and accuracy of existing information and records. Recommendations must conform to State water and health laws.

Types of Investigations

There are three general types of ground-water investigations; namely, reconnaissance, preliminary, and detailed.

A reconnaissance investigation is required to establish project need and to determine project measures from a review of existing information and an examination of surface features at the site.

A preliminary investigation is made to determine characteristics of the subsurface material, ground-water conditions, approximate yields, quality, and their geologic relationship. This will establish geologic feasibility of the project, be a basis for estimating project costs, or determine the need and intensities for further studies.

A detailed investigation is made to document with factual data and sound geologic interpretations, the specific site materials and ground-water conditions at a site and to provide sufficient subsurface information for the design and construction of project measures.

Reconnaissance Investigations

The reconnaissance is made to acquaint the investigator with the nature and characteristics of surface features and conditions. From observation and examination, correlations with existing map information can be established. Tentative interpretations regarding subsurface materials and ground-water conditions can be formulated. Any material or condition appearing to adversely affect project function, design, or construction should be located and referenced for further investigation.

Prior to making a reconnaissance of the site, the investigator should assemble and study topographic, geologic, and soil maps and literature and reports regarding geology and ground water applying to the area. Data from a field reconnaissance should contain general descriptions and locations of the surface features and conditions, including the following items:

1. General geology of the project site.

2. Geologic conditions that influence ground-water movement and recharge.

3. Surface features resulting from ground-water movement, such as seeps, springs, and landslides.

4. General character of streams and valleys, including volumes of flow, streambanks and bed, steepness of valley grades and side slopes.

5. Ground-water development, yields, quality, and use.

Interpretation of subsurface conditions, materials, and yields may be required for project formulation. Interpretations must be general, are not considered factual data, and may have to be based on the projection of known data and conditions from areas of similar geologic and physical features.

A written report should describe the site, provide interpretations or assumptions of the subsurface conditions and any conclusions regarding project feasibility or need for additional studies. Copies of supporting maps, sketches, well logs, other data and published references should be attached. Reports prepared for non-Service use shall contain only factual descriptions, observations, and remarks.

Preliminary Investigation

The preliminary ground-water investigation consists of a review of the reconnaissance report, if available, and geologic literature of the area, a detailed surface study, and limited subsurface investigations at representative or critical locations. The nature and characteristics of subsurface materials, ground-water conditions, yields, quality, and other pertinent features are established from existing logs and records and may be verified by geophysical surveys.

Assembly of Information

When starting a preliminary ground-water investigation, all geologic, ground-water, and well drilling data pertinent to the area should be reviewed. The sources of this information have been outlined in Chapter 3.

In some parts of the country, work unit conservationists have well records on file for their county or work area. Much helpful information may be obtained in most parts of the country by contacting well drillers and well owners.

Map Study

A study of the maps outlined in Chapter 3 is needed in a preliminary ground-water investigation. For some states the Soil Conservation Service has guide materials, including appropriate maps, which can be used as a starting point.

Since the objectives of ground-water investigation vary widely, the geologist must use judgment in deciding which maps will be useful for a particular study. However, general guidelines may be given by a discussion of maps available.

Several national and sectional maps of the United States are useful for orientation and correlation with work being done in other states.

A new Geologic Map of the United States on a scale of 1:2,500,000 was published by the U.S. Geological Survey (USGS) in 1974, accompanied by an explanatory text (King and Beikman, USGS-Professional Paper 901). State Geologic Maps are published by a variety of organizations, chiefly the state geological agencies, some by the U.S. Geological Survey, and a few by professional societies or state universities.

The Tectonic Map of the United States was published by the American Association of Petroleum Geologists (AAPG) in 1944 on a scale of 1:2,500,000. Its most recent printing was by the USGS in 1962. The geologist would find it helpful in ground-water studies to have an enlargement of this map for the state or area in which he is working.

Other U.S. maps useful in ground-water studies are the Physiographic Map of the U.S. (Fenneman, 1946), and the Map of the United States Showing Ground-water Provinces (Meinzer, 1923). In 1963 a generalized map was published, showing Annual Runoff and Productive Aquifers in the conterminous United States (McGuinness, 1963). The National Atlas of the United States, published in 1970 contains many maps useful for general reference. Among these is the map showing Productive Aquifers and Withdrawals from Wells, reduced from a scale of 1:7,500,000 for inclusion in this handbook and other publications (See Figure 4-1).

Reports and maps by the various state geological surveys and the USGS Ground-water Branch provide basic data which can be used as a starting point for studies within a watershed area. In addition to their published data, unpublished reports and maps are kept on file at most state geological survey offices and at USGS Ground-water Branch District Offices.

Topographic maps on a scale of 1:62,500 to 1:24,000 are available in many areas and provide suitable base maps for a preliminary ground-water investigation. For a few areas geologic maps are available on topographic maps of these scales. Watershed or county maps may be used for base maps where good topographic maps are not available. Howe (1958) has used aerial photo interpretation in locating ground water in glacial drift areas. This method can provide valuable information on structure, stratigraphy and location, and extent of possible aquifers, but the interpretations need frequent field checks. Other maps which are helpful for interpretation are structural geology maps, particularly those with structural contours drawn on top of the aquifer and piezometric maps.

Enlargement.--Enlargement of large scale maps may be of assistance in preliminary studies on limited areas, such as a county or watershed. Topographic, geologic, piezometric or tectonic maps may be enlarged for the area being studied.

Projection of Tectonic Features.--Where it appears desirable, the tectonic features may be projected on to another map. This may be helpful where geologic structure affects the occurrence of ground water. In states where orientation to a particular area is needed, the tectonic map of the United States may be enlarged for the state. This is especially helpful in the western states, or other parts of the country, where geologic structure may have controlling influence on the occurrence of ground water.

Field Study

Field study must provide information which will enable the geologist to interpret subsurface conditions. There are several methods of obtaining the required information. Choice of the method will depend upon the nature of the problem and the geologic features being studied.

In areas where stratified sedimentary rocks are exposed, the details of local structure, as well as its position in respect to possible aquifers in the geologic section, must be determined. This is done by measuring and plotting the attitude (strike and dip), and elevation of the exposed strata on the map of the area. Aerial photo contact prints are very helpful and should be used wherever possible. Stereoscopic study of aerial photographs during the field examination will in some cases show geologic features, such as faults, which may not be noticed without their aid. See Figure 4-2. For field study of larger areas, USGS Quadrangle Sheets at scales of 1:62,500 to 1:24,000 and aerial photo mosaics or index sheets are useful base maps. If a number of wells have been drilled in an area and logs of these are available, the preparation of a structure contour map will aid in making accurate forecasts of depth. Structure contour maps are especially useful in cross-bedded or indefinitely bedded sedimentary strata.

Where subsurface structure is not clearly indicated by outcrops, interpretation of the logs of wells in the general area will furnish the best basis for predicting conditions beneath the site being studied and can be supplemented by use of refraction seismograph or electrical

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Figure 2. Ground-water reservoirs.

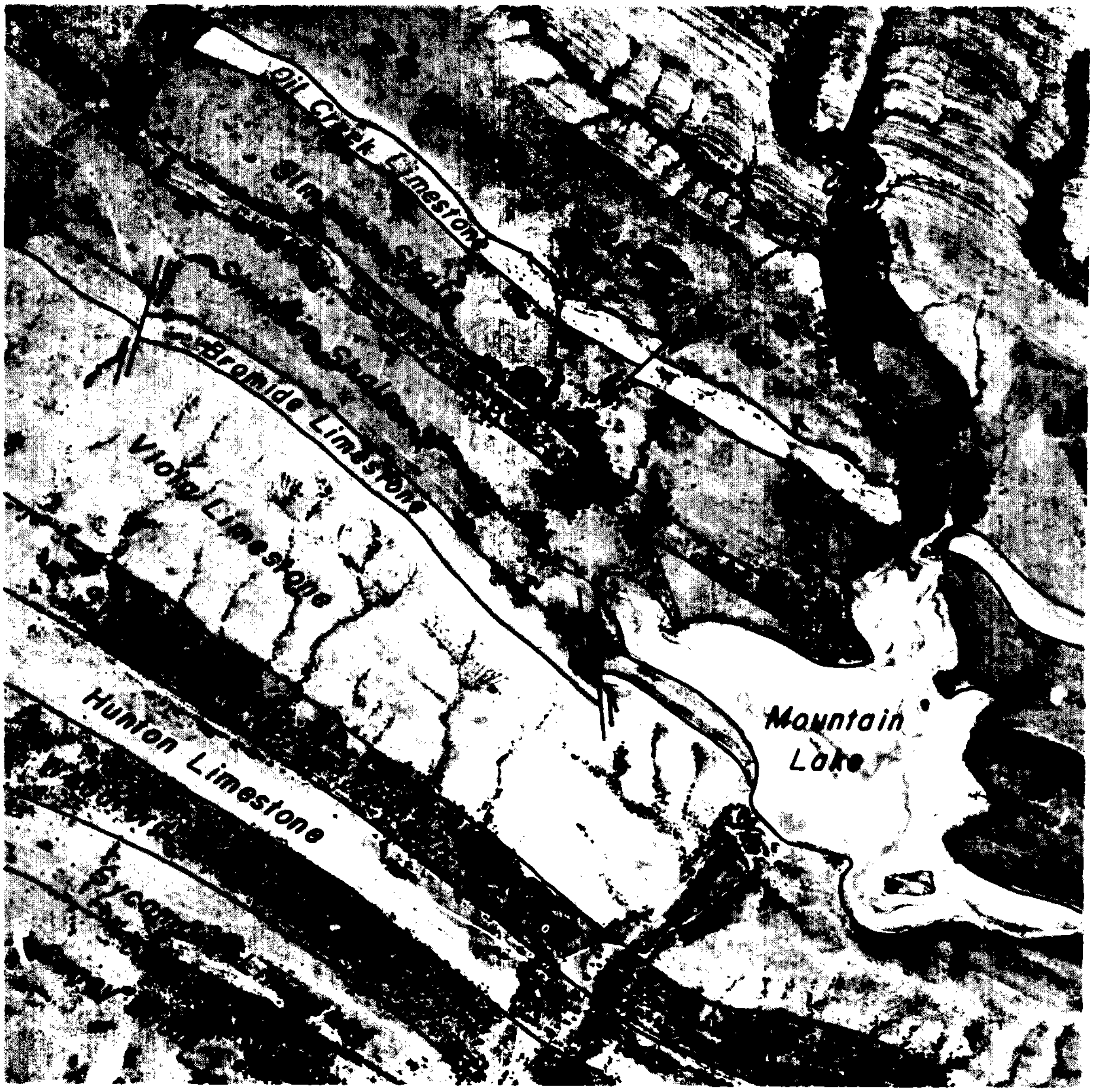

FIGURE 4-2 Aerial photograph used in geologic mapping

resistivity equipment. This would apply in the southeastern coastal plain, in areas covered by glacial drift, or in the filled basins of the west. From the logs and elevations of the respective wells, the conditions of deposition of the various sediments, their continuity, and probability of penetrating satisfactory aquifers at the new location may be estimated. Highly variable conditions of sedimentation have existed in some areas underlain by unconsolidated deposits, so that an accurate forecast of the depth and nature of water-bearing horizons is not always feasible. In these areas there is a considerable element of chance in the identification and development of ground-water supplies. In other areas, as in some parts of the southeastern coastal plain, successful development can be predicted over considerable areas.

Geologic features of importance to ground-water occurrence in areas underlain by crystalline or metamorphic rocks include (1) the depth of the weathered zone in the country rock, and (2) the existence of fractures, joints and fault zones within a few hundred feet of the surface. Field work will consist of a reconnaissance of the area to observe and plot the joint system or faults, and the occurrence and elevation of springs. Field study should be supplemented by stereoscopic study of aerial photographs and collection of well logs if available. In this connection, studies have shown that topography has a controlling influence on well yields as in the metamorphic rocks in the southeast (Herrick and LeGrand, 1949, and Mundorff, 1948). It has also been shown that flood plain deposits in metamorphic rock areas have a possibility for ground-water development (Mundorff, 1950).

In areas of extrusive igneous rocks, the thickness of flow or series of flows and the elevation of the water table should be observed in addition to the characteristics of jointing, the presence of faults, and springs. Again, much may be learned by studying the aerial photographs with a stereoscope and by obtaining well logs whenever possible.

<u>Mapping</u>

A geologic map on the best available base map should always be prepared of the watershed, county, or area in which a ground-water investigation is made. This geologic map should include:

1. Areal and surficial geology.

2. Structure of bedrock, stratification, schistosity, faults or fractures.

3. Surface ground-water features including springs, seeps, swamps and marshes.

4. Legend listing all formations shown on map. This includes a brief description of characteristics of aquifers, aquicludes and other pertinent information.

5. Locations of wells. Well record data will be included in reports.

In addition to a geologic map, it will be advisable in many cases to prepare specialized maps to illustrate ground-water problems. Structural contour maps or piezometric maps should be prepared when needed, based on field observations and well data.

<u>Geologic Sections</u>

In order to complete and interpret the information on a geologic map, one or more geologic sections and fence diagrams should be prepared. These geologic sections and fence diagrams for ground-water studies will usually be based upon logs of wells, test holes, geophysical studies, or other related information. It should be prepared on horizontal and vertical scales suitable to study the problem. If the vertical scale is exaggerated, the degree or percent of surface slopes, dip, and hydraulic gradients should be indicated on the drawing and in the report.

Report of Preliminary Investigation

A geologic report generally following the outline at the end of this chapter should be prepared for a preliminary ground-water investigation. The report should include a concise discussion of ground-water conditions, interpretations, conclusions, and recommendations for solving any problems. The preliminary report should also include recommendations for methods to be used in making a detailed ground-water investigation, where needed. Well records, log of borings, and other supporting data should be reviewed, interpreted and included where applicable with the preliminary investigation report. Geologic maps and sections should be included.

Detailed Investigations

Detailed investigations will include a review of the information covered by the preliminary investigations, the collection of additional data, the preparation of a complete report including logs, maps, geologic sections, fence diagrams and results of field tests and the collection and laboratory analysis of samples.

Location of wells, water levels, withdrawal areas, amounts of withdrawal, springs or other discharge areas, hydraulic gradients, and rate and direction of ground water movement should be determined. Seismic or electrical resistivity apparatus and tracers should be used if conditions are favorable and their use is economically justifiable. Drilling or the excavation of pits may be required to obtain more information, and to take samples of water and soil or rock materials. Field permeability tests, pumping tests, and pressure testing often are desirable. The installation of observation wells and piezometers may be advisable under some conditions.

Water quality should be determined to establish its potability for humans or livestock and its suitability for irrigation or other agricultural use. Information obtained on water quality should be made available to industries or municipalities. The risk of tapping salt water zones or the possibility of permitting salt water to enter and contaminate fresh water aquifers should be determined. An investigation may be required to determine the extent of salt water intrusion and the feasibility of constructing reservoirs or boring wells to develop a fresh water barrier or trough (Todd, 1959, p. 284) to block the intrusion of salt water.

Natural recharge areas should be determined and the feasibility of artificial recharge should be studied. If recharge is involved, determinations should be made as to who will be benefited, the value of the benefits, how much of the recharged water can be recovered, and the use that will be made of the recovered water. Where recharge or underground disposal of surface water is planned, it must be determined that pollution of the ground water will not result.

In brief, detailed ground water investigations consist of:

1. Drilling, sampling, logging, describing, and classifying all strata that will influence ground-water hydrology.

2. Pressure testing for in-place permeability and seepage through fractured rock and voids in soluble strata where control of seepage is important.

3. Ascertaining the influence of structural geology, faulting, folding, and fracturing on transmissibility of ground water.

4. Installing piezometers or observation wells in hydrologically significant strata.

Review of Preliminary Investigations

The reports of preliminary investigations may be on file in the work unit, the watershed office, or the state office. All available data and reports should be reviewed, not only to obtain technical data on geology and ground-water conditions, but to review the need and justification for further ground-water investigations. For example, a study in the past may have found a proposal not feasible, but due to changed conditions, a restudy may be justifiable. The thoroughness of the original investigations may be a determining factor in deciding whether a restudy is needed or whether the original report and decisions are still valid.

Assembly of Additional Data

A restudy including information made available since the last report of preliminary investigations should be made of all avaliable maps, well logs, geologic sections, electric well logs, and geophysical surveys showing the depth to and thickness and character of all geologic formations above the aquifer. The depth, thickness, and character of the aquifer or cavernous water-bearing formations will be defined or estimated if precise information is not available.

A stereoscopic study of recent aerial photography may furnish new and valuable information. The location of ground water sources by photo interpretation methods is becoming more widespread but frequent field checks are necessary. This topic is discussed by Fluhr and Leggett (1962), Mollard (1961), and Mollard and Patton (1960).

Tentative geologic cross sections should be prepared as a supplement to a report for a plan for detailed investigation. In addition, areal maps showing outcrops, structural geology, faulting, caverns, aquicludes, and other conditions affecting the storage or transmission of ground water should be prepared.

Subsurface Investigations

During the course of a detailed ground-water investigation, it may be necessary and desirable to obtain additional subsurface information. This may entail geophysical surveys, test drilling and sampling, installation of observation wells or piezometers, or use of dyes or other tracers to provide the necessary information.

Geophysical Surveys.--All useful information should be obtained from companies or agencies which have made seismic or electrical resistivity explorations in the area. Often this information is difficult to get because the oil companies or other agencies that compute and correlate the data may be reluctant to release it. If their computations and correlations do not show detail in the upper few hundred feet, they are of little use in investigations made by the Soil Conservation Service. If additional geophysical survey information will be helpful, seismic or various types of electrical resistivity equipment can be used. Some states own single-trace or multiple-trace portable seismographs, or suitable equipment may be available on a loan, lease or contract basis.

Test Drilling.--Detailed plans should be prepared showing locations and depths of wells desired to obtain sufficient information on the position, depth, gradient, and nature of the aquifer or underground cavernous or water storage area. Field permeability tests may be needed on the aquifer and overlying materials. Samples of water should be obtained to determine its quality.

Prior to the start of drilling, bulldozers or other appropriate equipment should prepare roadways, channel crossings, and remove trees or rocks to permit access of equipment to the sites. Positions may need to be excavated on hillsides or in channels for setting up drill rigs or other equipment. The necessary drilling and sampling equipment and procedures are discussed in Chapters 3 and 6 of this section, Chapters 3 and 4, Section 8, National Engineering Handbook, the Earth Manual (1963), and various SCS guides to geologic site investigations.

All drill holes and surface exposures studied should be logged in detail to supply information relating to storage, transmissibility, or chemical conditions affecting ground water. The logging should include location, elevation, and depth of the hole or exposure, Unified Soil Classification System classification of each horizon, stratification, density or consistency of materials, size range of the particles, cementation, chemical composition, and estimates of pore space and permeability. Most of these features will apply to both unconsolidated and consolidated materials, except that in consolidated materials the USCS classification should be replaced by the kind of rock and its characteristics regarding the storage and transmissibility of water.

Field tests such as pressure testing, pumping in, pumping out, well permeameter tests, and sieve analysis should be tabulated and summarized.

Observation wells and piezometers perform an important function in the study of ground water. They help define its movement, hydrostatic pressure, piezometric surface, unconfined water surface, seasonal fluctuations in surface elevations, and the effects of flooding, withdrawal, or water levels in nearby streams or bodies of water. Piezometers usually are small diameter pipes with the bottom open, and are installed at shallow or moderate depths by driving or jetting methods. See Chapter 3.

Observation wells may be of any size but often are 2- to 3-inch pipe with a screen attached at the bottom. They usually are installed by jetting or inserting in a hole bored by a rotary drill or continuous flight auger. The depths may vary from a few feet to hundreds of feet depending on the depth that information is needed. The water levels may be measured by tape or simple sounding equipment or by mechanical or electrical recording devices which obtain continuous records. The USGS is the agency assigned the responsibility for making extensive ground water studies, but it may install wells for cooperative study with the SCS.

Sampling.--When drilling is done during the detailed investigation, samples should be collected to:

1. Determine gradation, storage capacity, chemical composition, and permeability rates of unconsolidated materials and rock formations.

2. Assist in the correlation of horizons or rock formations.

3. Determine the nature and extent of faulting, jointing, and cavernous conditions.

4. Determine the possibility of surface subsidence or collapse of certain horizons.

5. Determine the nature of an aquifer, its storage potential, productive capacity, and transmissibility of ground water.

Disturbed samples may be desired from channels, dozer pits, or auger borings to determine grain size distribution or the potential for recharge.

Undisturbed samples of unconsolidated materials may be desired from certain horizons to determine permeability rates, storage potential, or stability. Field permeability tests, however, are generally more reliable than laboratory tests.

Cores of representative rock formations may be needed to determine faulting, jointing, permeability, composition, and solubility.

Samples should be listed both on the log sheets and the soil sample list.

For drilling and sampling in caving materials, either the hole may be cased or a hollow-stem continuous flight auger may be used. The latter will permit taking samples at any depth that can be drilled even in severely caving conditions.

Tracers.--To use tracers in ground-water investigations, the "upstream" or intake area must be accessible. If not, drill holes or test pits will need to be prepared. The discharge area also must be accessible or holes or pits will be needed at a measured distance in the down-gradient direction where water samples can be quickly observed or tested.

Techniques in the use of tracers have advanced remarkably in recent years. Colored dyes are adequate in most situations. Radioactive tracers, such as Tritium and Iodine 131, can be detected in minute amounts and are very effective. The ion of chlorine is used in electrical conductivity tests.

The following dyes are the most common ones used: Fluorescein "B", potassium permanganate, rhodamine "B", methylene blue, aniline red, aniline blue, and auramine yellow. Caution is advisable in using any kind of tracers, especially if large amounts are used and they find their way into drinking water for humans or animals or into water used for fish and wildlife. Poisonous or objectionable tracers should not be used.

The volume of water, its acidity or alkalinity, and the distance covered by the test will determine the amounts or kinds of dyes to use. Also, the coloring ability of the dye and the strength of other tracers will determine the amount to use. Fluorescein "B" is probably the most powerful of these dyes.

The ion of chlorine applied in a concentrated solution of sodium chloride or ammonium chloride is detected in a down-gradient well by titration with silver nitrate or by the change in electrical conductivity of the water.

Tests of the chlorine ion concentration of the natural water must be made less than 24 hours prior to the tracer test if the titration method is to be used. If the chlorine ion concentration is already high, this method will not give satisfactory results.

Injecting a fluid into an aquifer through a well will temporarily raise the water level adjacent to the well. This increases the hydraulic gradient and results in increased velocity of the fluid away from the well. For best results the salt solution should be introduced through an injection well and the travel time of the solution measured between two observation wells located down gradient.

A typical detection arrangement is shown in Figure 4-3.

Radioactive tracers are an effective method of determining direction and velocity of ground-water flow. The tracers used should not change the density of the water nor should they be affected by the chemical nature of the soils, minerals, or water. They should be easy to trace, reasonable in cost, have a short period of decay and be harmless to humans and other life. Permission for their use must be obtained from the Atomic Energy Commission. The Johnson Drillers Journal (1963) has an article concerning the use of radioactive tracers.

The velocity determined by any of these tracer methods tends to be the maximum velocity. This could result in computed permeabilities that

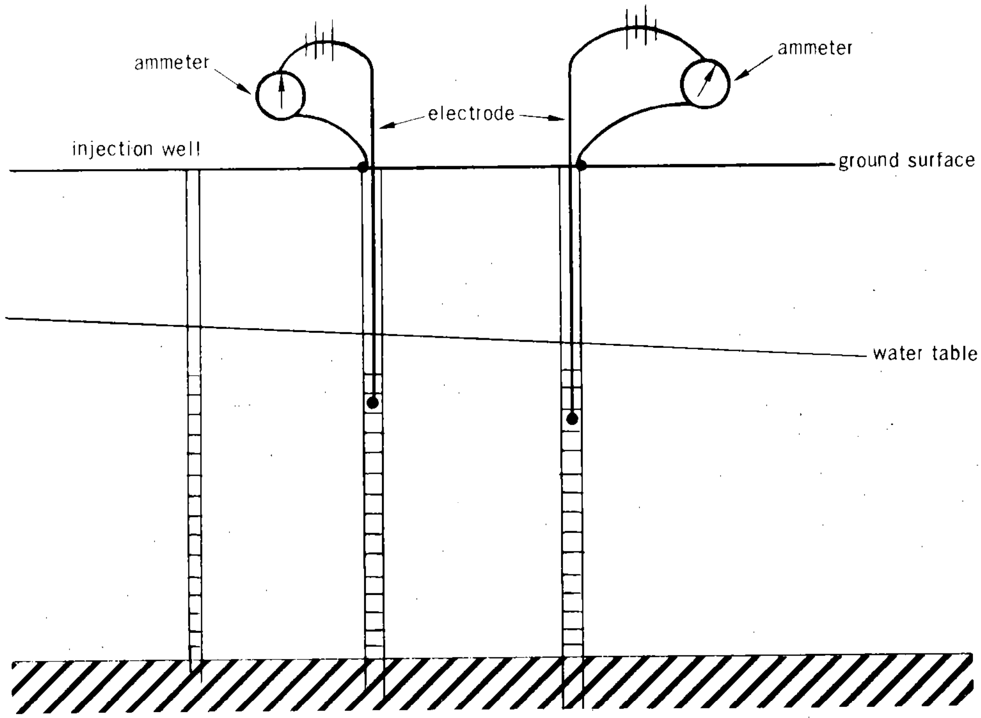

FIGURE 4-3. Typical salt detection arrangement

are generally greater than the average for the section of the aquifer tested.

If seepage from a body of water is a problem the dye may be enclosed in a paper bag, tied to a weight or long pole, and placed in the area where the origin of the seepage is suspected. Successive tests may be made with the same or different colors at other locations. The American Colloid Company has published some leaflets on the use of dyes as tracers. Denisov (1957) discusses dyes and electrical conductivity methods.

In many localities, the general public, through lack of understanding, strongly objects to the use of radioactive isotopes as tracers in ground-water investigations. Public relations must be considered when using any tracer.

Correlation and Interpretation

After reviewing the available information and completion of geophysical, drilling, and excavation investigations, detailed geologic sections and fence diagrams can be prepared and correlated. The data obtained should be complete enough to provide accurate correlation of geologic conditions and to supply the desired information on ground water. These sections will show stratigraphic sequence, geologic age, thickness, character, and composition of unconsolidated and consolidated strata. Correlation will be shown graphically and by notations indicating continuity, confining or impervious strata, barriers or aquicludes, water-bearing formations, cavernous or fractured rock conditions, and water levels.

Maps of the area should be prepared showing extent of the aquifer, barriers, faults, caverns, confining strata, isopiestic lines, recharge areas, withdrawal areas, springs or other natural discharge areas, geologic formations, geologic structures, structural contours, and any other features relating to ground-water supply, movement, gradient, or storage.

Figures 4-4, 4-5, and 4-6 are typical examples of cross-sections, fence diagrams and water table contour maps. The fence diagram is constructed in three-dimensional perspective from actual well logs to show geologic relationships.

Selection of sites for irrigation wells must be contingent upon the physiography of the drainage system in which ground water occurs with reference to channeling, topography of land to be irrigated, soils, depths to water, pumping lifts, water rights, and ground water recharge. Test holes in bedrock aquifers must be contingent upon structural geology, stratigraphy, chemical quality of water, permeability, pumping lifts, and ground water recharge.

The surface or shallow horizons will be correlated to determine whether recharge may be accomplished by natural or artificial means.

Design and construction of injection wells must be based upon data that identify aquifers, aquicludes, depths, intake rates, and need for chemical treatment of water. Untreated surface waters contaminate aquifers, and the kind of treatment, differences in temperature, and chemical reactions may have adverse effects on recharge.

Ground-water recharge via spreader systems, pits, and galleries will need to be designed from detailed subsurface investigations that pertain to infiltration and sealing by colloids, sediment, and precipitates. Scarification of surfaces and perhaps other techniques will be needed to maintain the highest possible infiltration rates.

Report of Detailed Investigation

A report will be prepared on the results of the detailed ground-water investigation. One section of the report will contain factual data on observations made and other information assembled during the investigation and the other section will contain interpretations, conclusions, and recommendations made from these factual data.

Factual Data.--A narrative report will be prepared describing the factual data obtained from published data or former investigations, and the findings during the detailed investigations, including geology, correlation charts of unconsolidated and consolidated materials and other facts relating to the problem being investigated. Since this part of the report relates to facts, it may be used for reference by cooperators, prospective bidders, and other interested personnel or

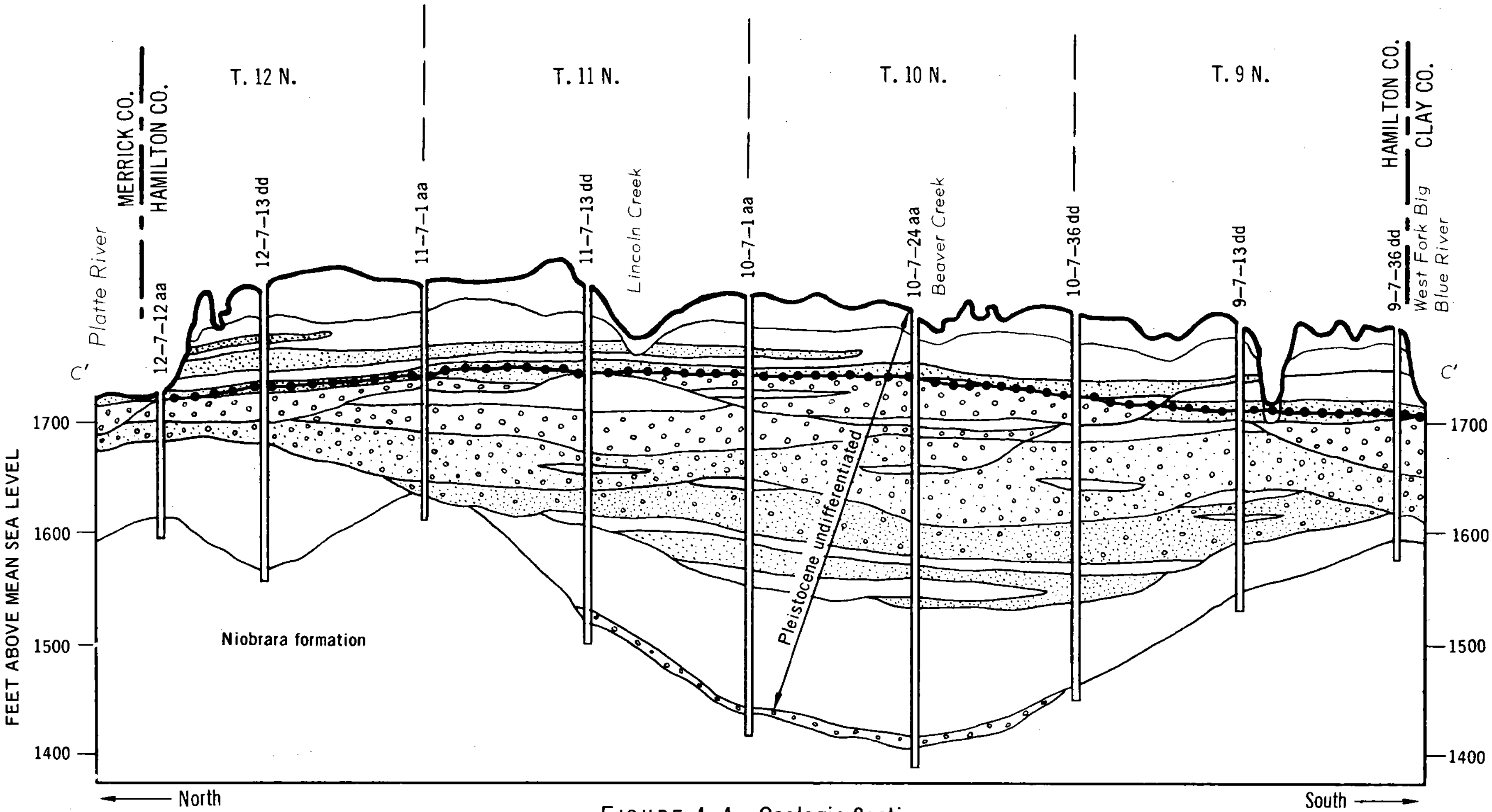

FIGURE 4-4 Geologic Section

(From Ground-Water Resources of Hamilton County, Nebraska by C. F. Keech, 1962, U. S. Geol. Surv. Water-Supply Paper 1539-N.)

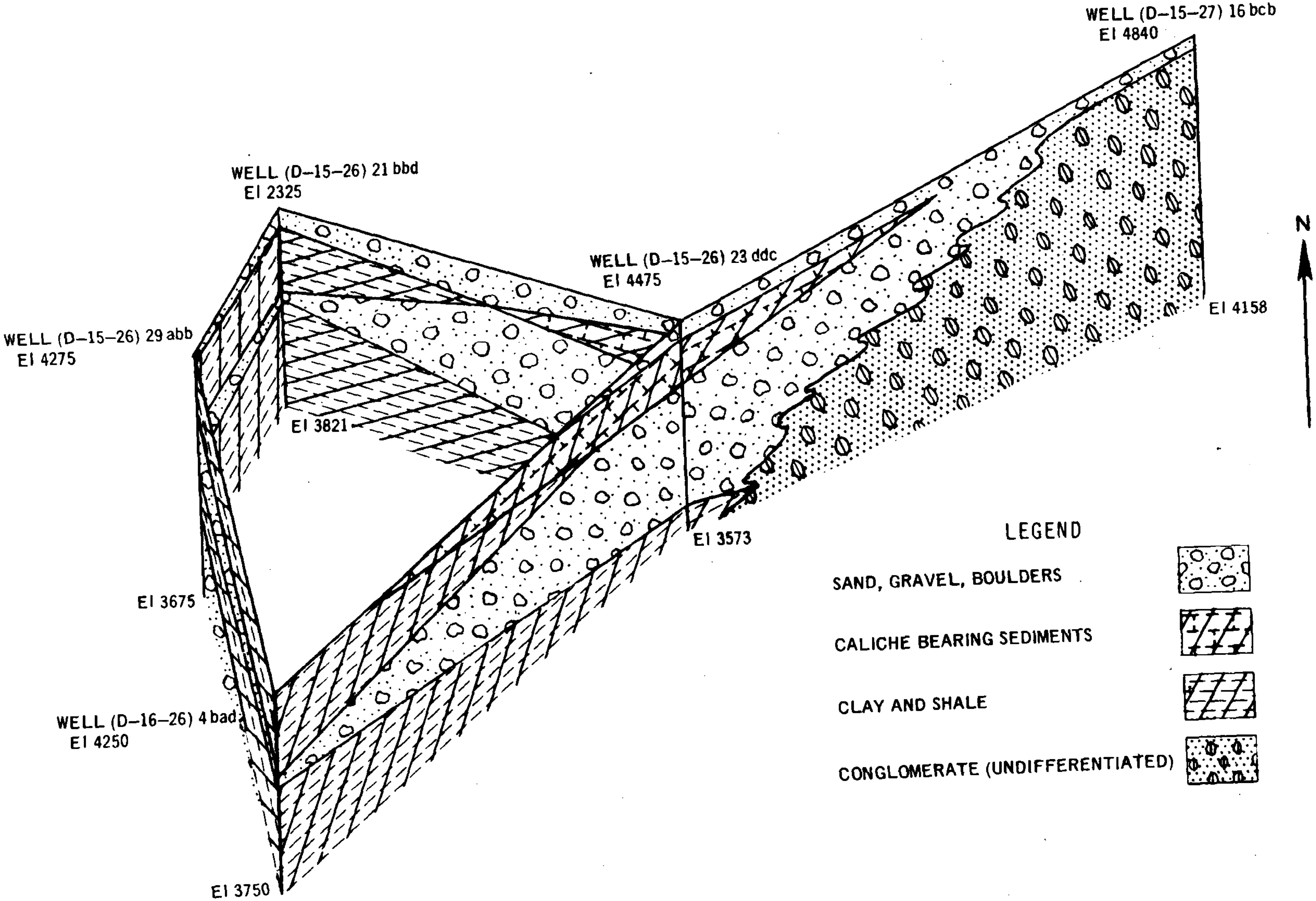

FIGURE 4–5. Fence Diagram

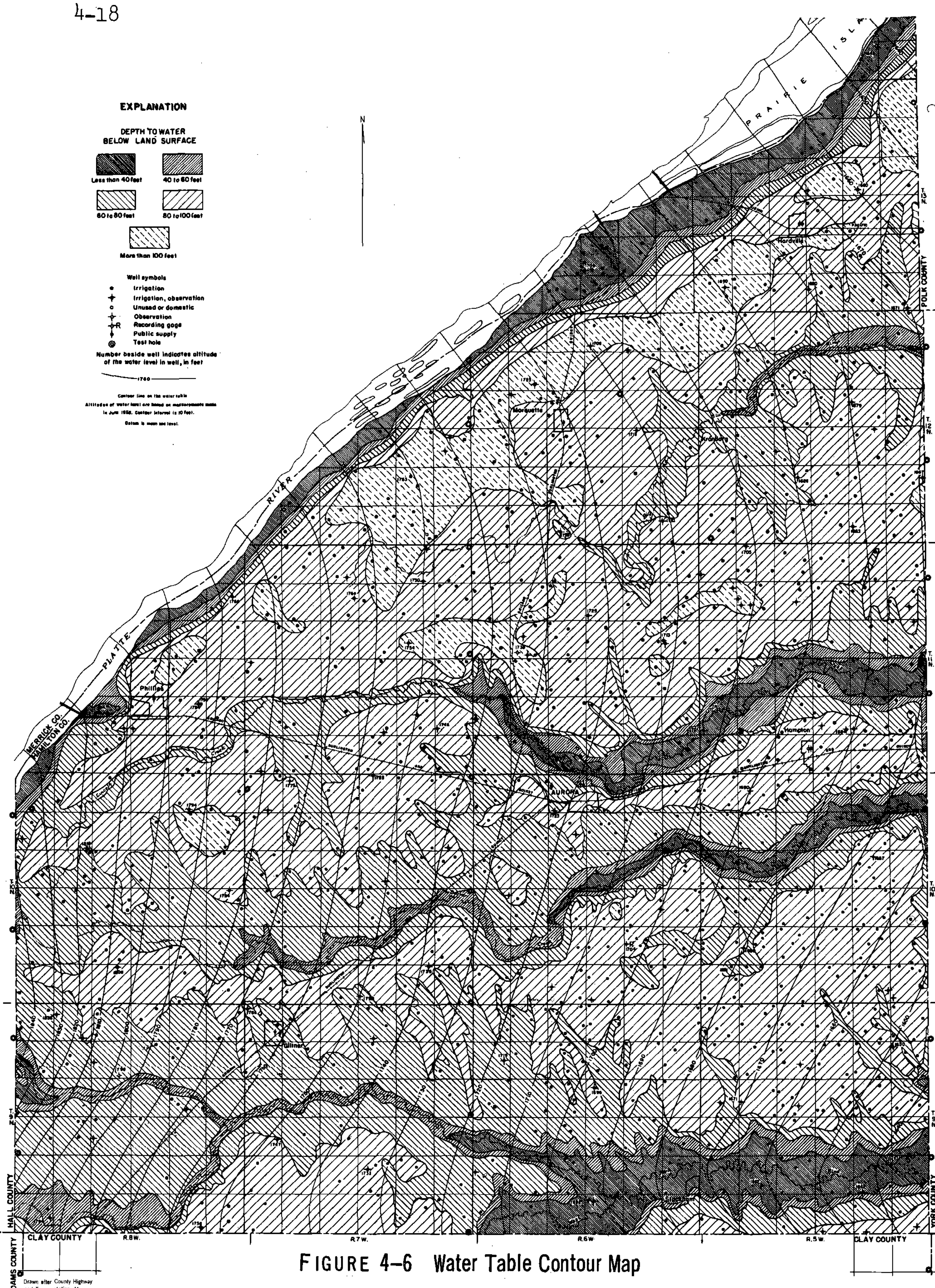

FIGURE 4-6 Water Table Contour Map

(From Ground-Water Resources of Hamilton County, Nebraska by C. F. Keech, 1962, U. S. Geol. Surv. Water-Supply Paper 1539-N.)

1 0 1 2 3 4 5 6 MILES

organizations. Included also may be columnar sections, and maps showing areal extent of important materials or rock formations, locations of test holes, pits, rock exposures, natural recharge areas, springs or withdrawal areas, and locations of logged wells or other published data used for correlation purposes.

Log sheets will be prepared, if applicable, describing materials, encountered or observed, their classification, hardness, density, estimated gradation, and permeability. Facts regarding geologic structure, dip, faults, jointing, caverns, and barriers to ground-water movement will be shown on cross sections and discussed in this report.

Data on water levels will be described or plotted. Whether water tables are static, perched, or under artesian pressure will be indicated and the dates of observations will be shown. Records of pumping or permeability tests will be reported. If fluctuating or high water tables have adverse effects on agricultural use of the land, the problem will be described including tables showing seasonal water tables, and the cause of the adverse condition.

Interpretation and Conclusions.--This supplement to the report will give the interpretations and conclusions based on factual data. Specific recommendations may be made, or procedures may be suggested as agreed upon after consultation with other geologists, engineers, attorneys, or water board officials.

Estimates on storage potential, transmissibility, and rate of water movement may be given as based on Darcy's law, Hazen's approximation (see Chapters 1 and 3), or field permeability tests (see Chapter 3). If tracers were used, the results of the findings will be reported.

The potability and chemical nature of the water, and the chemical composition of soils and rocks may be estimated. If tests were actually made, the results will be described under factual data, or if samples were submitted for testing, a statement should be made that the results will be reported by the laboratory or the laboratory report is attached.

The advisability and possibility of recharge may be discussed, if applicable, and estimates made on storage and recovery of ground water and its potential uses.

If a high-water table is a problem, data will be given or estimates will be made on fluctuation of water levels and their effect on agricultural, cultural, industrial, or other uses of the land.

If the problem is stability, estimates will be made on water level fluctuations and their effect on subsidence, landslides, slumping or creeping of soil, seepage, levees, channel banks, and unstable foundations for dams, building, highways, railroads, or other structures.

Opinions or data may be presented which will indicate whether the problem is the result of (1) natural conditions such as excessive erosion, valley filling, stream piracy and glaciation; or (2) conditions induced by natural causes or works of man such as channel aggradation, channel degradation, land movement, earth collapse, or formation of natural levees. Some of these conditions are excessive burning, deforestation or other change in vegetative cover; works of improvement for water control (dams, drainage, stream diversion, irrigation, canals, and facilities for stream navigation); water disposal--either underground or in surface streams; excessive use and disposal of herbicides, detergents, or other chemical products and pollutants; and abandoned mines.

Data should be obtained on the excessive withdrawal of water or oil and the resulting effect on land subsidence, or salt water intrusion.

Recommendations may be made regarding the use of well points or other dewatering devices, or the installation of barriers such as curtain grout to limit permanently the movement of ground water for the protection of works of improvement, or sheet piling for the temporary exclusion of water during construction.

Estimates may be required as to the effects that works of improvement in water management will have on water levels or water supply, and whether these effects are beneficial or damaging. Cost estimates may be required on the benefits or damages.

The report should generally follow the outline below.

Outline for Ground-water Investigation Report

The outline may be modified as necessary and only those items that are pertinent to the investigation and report should be used.

I Introduction
- A. Name of watershed or designation of area covered by the report
- B. Personnel making study and data
- C. Purpose of study
- D. Objectives
- E. Methods
- F. Sources of information

II Ground Water or Well Development
- A. Source
- B. Movement
- C. Reservoir
  1. geomorphology
  2. structure
  3. stratigraphy
- D. Aquifers
- E. Aquicludes
- F. Reservoir capacity
  1. total storage
  2. recharge rate
  3. safe yield

G. Well development
   1. well type and size
   2. elevation
   3. depth
   4. static water level
   5. pumping level
   6. production (gpm)
   7. specific capacity
   8. pump size
   9. power unit (type)
H. Cost data (indicate the estimated Federal and non-Federal costs for each item)
   1. drilling
   2. furnishing casing in place
   3. furnishing screen in place
   4. installing filter pack
   5. furnishing and installing pump
   6. furnishing and installing power unit
   7. development
   8. other costs
   9. total cost
   10. comparison with cost of surface water supply, where available

III Water Table Control
A. Drainage
   1. agricultural
   2. engineering
      (a) dewatering excavation; may be excavation for foundation, quarry, mine, etc.
      (b) engineering subdrainage

IV Ground-Water Recharge
A. Recharge
   1. location and extent
   2. natural
   3. artificial
B. Surface drainage
   1. influent seepage
   2. effluent seepage
C. Sub-surface movement
   1. interstices
   2. bedding planes, joints, fractures
   3. solution channels
D. Reservoir type
   1. monocline
   2. syncline
   3. sediment-filled valley or basin
   4. fault trap
   5. stratigraphic trap
   6. topographic control
E. Artificial recharge methods
   1. spreading

2. injecting
3. impounding

F. Reservoir capacity
1. total storage
2. recharge rate
3. safe yield

V Problems

A. Ground-water development
1. reservoir
2. pipeline
3. watercourse

B. Drainage

C. Artificial recharge

D. Engineering structures
1. effect on ground-water regime
2. effect on structural stability or functioning

VI Interpretations

VII Conclusions

VIII Recommendations

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NATIONAL ENGINEERING HANDBOOK

SECTION 18

GROUND WATER

CHAPTER 5. METHODS AND TECHNIQUES OF SPRING DEVELOPMENT

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NATIONAL ENGINEERING HANDBOOK

SECTION 18

GROUND WATER

CHAPTER 5. METHODS AND TECHNIQUES OF SPRING DEVELOPMENT

Introduction

"A *spring* is a place where, without the agency of man, water flows from a rock or soil upon the land or into a body of surface water." (Meinzer 1923 b, p. 48).

This chapter presents some of the methods and techniques for developing springs.

Classification of Springs

Springs are usually classified according to the geologic structure and forces bringing water to the surface (Schultz and Cleaves, 1955). The two categories of springs in which we are interested are gravity and artesian. Some typical examples of these will be discussed.

Magmatic springs usually yield highly mineralized hot water that is associated with deep-seated magmas. They will not be discussed in this chapter.

Gravity Springs. - Gravity springs are formed by the outcrop of water flowing under action of gravity. Some of the types of gravity springs are: depression springs, contact springs, and fracture and tubular springs. A representative occurrence of each type is shown, but inclusion of all combinations of conditions causing springs has not been attempted. (See Tolman, 1937).

Depression springs.--

1. Characteristic Features

   A. Location: Along outcrop of water table at edges or in bottom of alluvial valleys; basins; depressions in moraines; and valleys cut in massive permeable sandstone or volcanic ash. See Figure 5-1.
   B. Type of Opening: Irregular spaces between grains of the material.
   C. Yield: Depends upon height and gradient of the water table, permeability of the water-bearing material, and size and intake opportunity of the tributary area. Flow may range from less than one to several gallons per minute (gpm).
   D. Type of Flow: May be either perennial or intermittent, depending upon rise or fall of the water table. If the tributary area is small, the flow will depend on local precipitation.
   E. Quality of Water: Usually fair to excellent, but may be mineralized if the aquifer contains soluble substances.

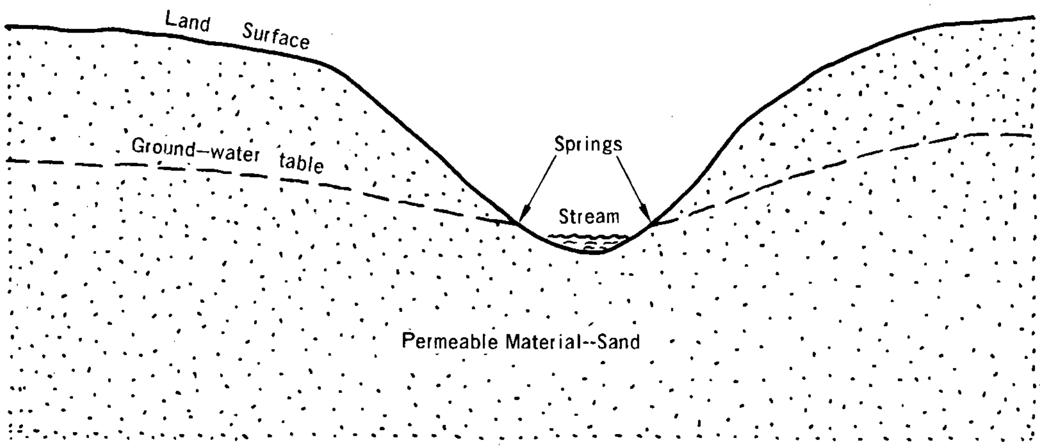


Figure 5-1. Depression Spring, Seepage or Filtration Type

F. Water Temperature: The temperature of the water will generally approximate the mean annual atmospheric temperature.

G. Features Produced: Usually none in valleys. In humid areas minor slumps, headcuts, or swamping may sometimes develop. In wind-swept arid and semi-arid basins the wetted areas and the vegetation growing around spring may cause deposition of material forming a mound.

2. Method of Development: Remove obstructions to flow, expose additional area of water-bearing material, collect flow. (See Figure 5-8 for details).

Contact springs.--

1. Characteristic Features

A. Location: May occur on hillsides or in valleys; in fact, wherever the outcrop of an impermeable layer occurs beneath a water-bearing permeable layer. See Figure 5-2.

B. Type of Opening: Openings in sand or gravel are irregular, intergranular spaces. Openings in rocks are joints, fractures, or open bedding planes. Openings may be tubular in limestone, gypsum, and basalt.

C. Yield: Volume of flow may range from less than one to several thousand gpm, depending upon the height and gradient of the water table, permeability fracturing or development of solution openings of the water-bearing material, the volume of aquifer tributary to the spring, and conditions of water intake.

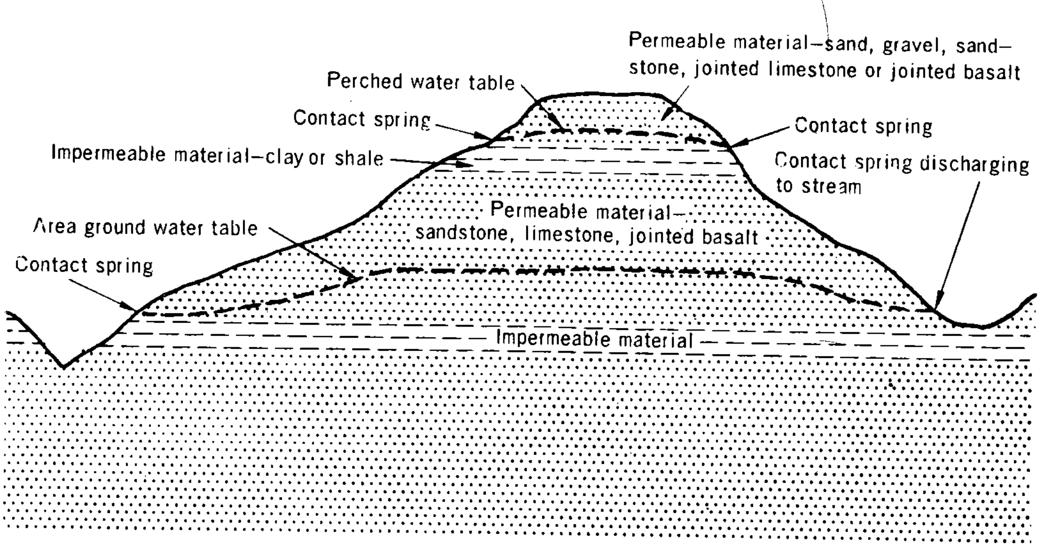


Figure 5-2. Typical Contact Springs

D. Type of Flow: Usually perennial for contact springs supplied by the area water table. If contact spring is supplied by a perched water table, the flow may be intermittent.
E. Quality of Water: Usually fair to excellent, but may be mineralized if water-bearing material is soluble.
F. Water Temperature: The temperature of the water will approximate the mean annual atmospheric temperature of the location with the same exceptions as noted under Fracture and Joint Springs.
G. Features Produced: Travertine ($CaCO_3$) may be deposited as described under Fracture and Joint Springs.

2. Method of Development: Remove obstructions to flow; expose additional area of water-bearing formation; collect flow. (See Figure 5-8 for details).

Fracture, joint and tubular springs.--

1. Characteristic Features

   A. Location: On hillsides or in valleys or wherever land surface is below the water table. See Figures 5-3, 5-4, and 5-5.
   B. Type of Opening: Fractures and open bedding planes in all rocks, sometimes tubular openings in limestone, gypsum, and lava.
   C. Type of Water-Bearing Material: Fractured or jointed rocks.
   D. Type of Flow: Usually perennial, may fluctuate with precipitation if tributary area is small.

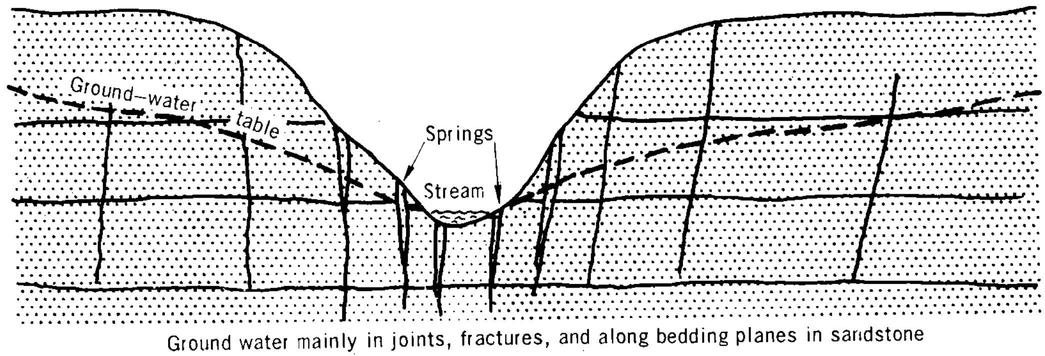


Figure 5-3. Spring in Jointed Sandstone

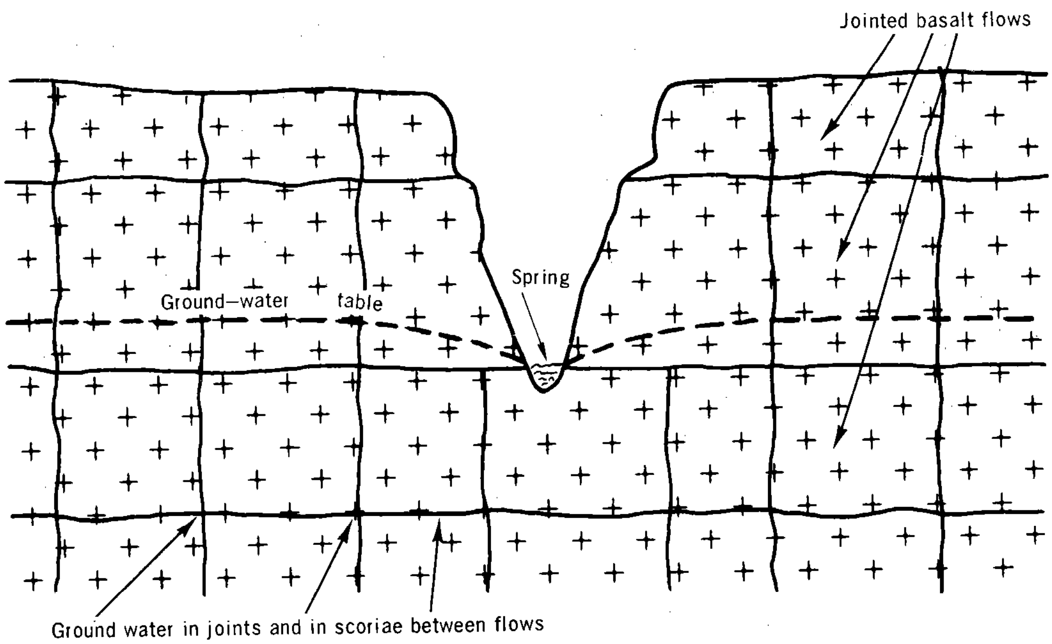


Figure 5-4. Spring in Jointed Basalt

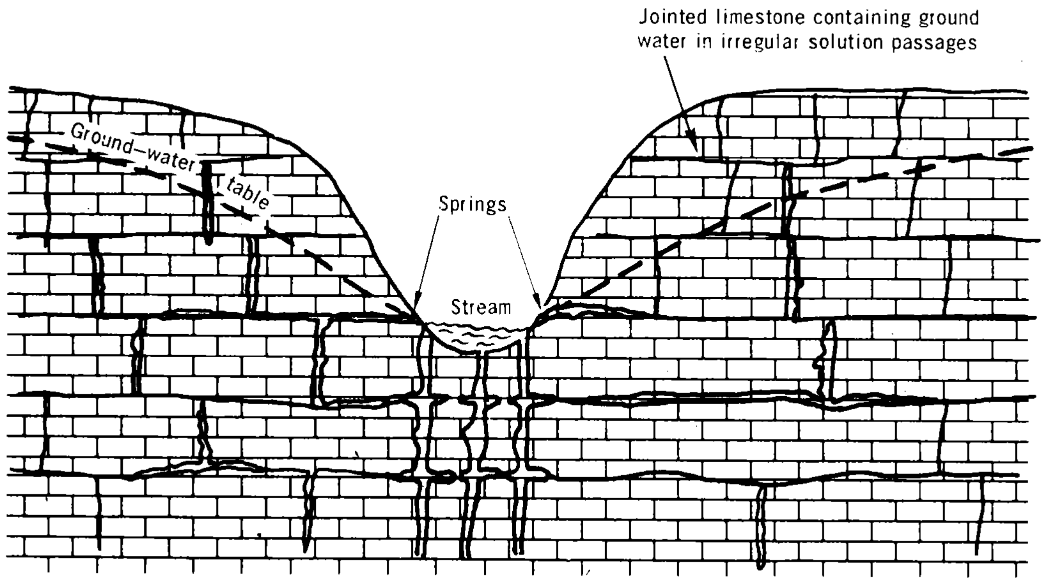


Figure 5-5. Spring in Jointed Limestone

E. Yield: Flow may range from less than one to hundreds of gpm depending upon the extent of fractures, solution passages, or joint system tributary to the opening.

F. Quality of Water: Usually good to excellent. May be hard (contain $CaCO_3$) if spring issues from or percolates through limestone.

G. Water Temperature: The temperature of the water will approximate the mean annual atmospheric temperature at location with exceptions as follows: If movement of water occurs through passages which are open to the circulation of air, cooling to as much as several degrees below mean annual temperature will occur; if water is not in contact with circulating air and the depth to the water table is several hundred feet, the water will be a few degrees (generally about 1° for each 100 ft. depth) warmer than the mean annual temperature. Buried igneous rock if still hot will raise the temperature of ground water producing hot springs.

H. Features Produced: If the water is warmer than the mean annual atmospheric temperature and has percolated through limestone on its way to point of discharge, Travertine ($CaCO_3$) may be deposited about the spring opening. Water from other materials usually produce no surface features.

2. Method of Development: Remove obstructions to flow; find other fractures which are seeping and clean them out; collect flows. (See Figure 5-8 for details).

Artesian Springs. - Artesian springs are formed where the piezometric surface is above the land surface and the water issues under artesian pressure. Two types of artesian springs are aquifer outcrop springs and fault springs.

Aquifer outcrop springs.--

1. Characteristic Features

   A. Location: May occur in any topographic position along outcrop of aquifer. See Figure 5-6.
   B. Type of Opening: Will depend upon nature of water-bearing material. If aquifer is sandstone, water may seep from spaces between grains, from fractures or from open bedding planes. If aquifer is limestone, water will issue from joints or tubular openings.
   C. Water-Bearing Material: May be sandstone, limestone, or jointed basalt.
   D. Type of Flow: Perennial, usually constant. Quickly affected by wells drawing from same aquifer. May be affected by long continued drouth.
   E. Yield: Flow may range from a few gpm to several thousand gpm.
   F. Quality of Water: Usually good to excellent. Water may be hard or mineralized (contain $CaCO_3$) if aquifer is limestone.
   G. Water Temperature: The temperature of the water will approximate the mean annual atmospheric temperature of the location unless the aquifer is deeply buried. If so, temperature will be a few degrees above the mean annual temperature (about 1° for each 100 feet aquifer lies beneath the surface).
   H. Features Produced: If water is from a limestone aquifer and is warmer than the mean annual temperature, travertine ($CaCO_3$) may be deposited.

2. Method of Development: Remove obstructions to flow; expose additional area of aquifer, or if from joints or fractures, find other openings that are seeping and clean them out. Lower outlet elevation and improve drainage. Collect flow. (See Figure 5-8 for details).

Fault springs.--

1. Characteristic Features

   A. Location: May occur at any location along a fault or related fractures. See Figure 5-7.
   B. Type of Opening: Will depend upon nature of material at land surface. If surface is alluvium, water will issue from spaces between grains. If surface is rock, water will issue from fractures.
   C. Type of Water-Bearing Material: May be any kind of rock. Surface material may not indicate what the aquifer consists of.
   D. Yield: Volume of flow may range from a few gpm to several thousand gpm.

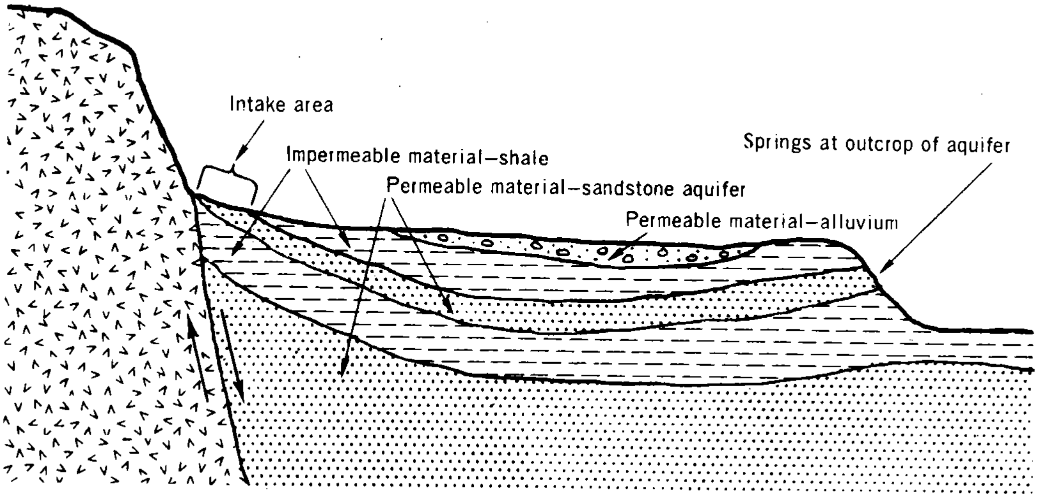


Figure 5–6. Artesian Spring at Outcrop of Aquifer

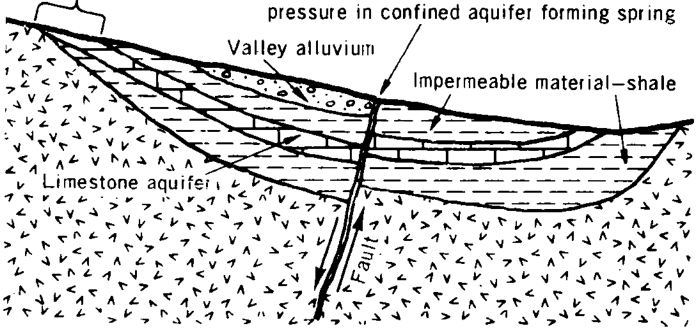


Figure 5–7. Artesian Spring Occurring along a Fault

E. Type of Flow: Perennial, constant, and only affected by long periods of drouth. Quickly affected by pumping from wells drawing upon the source aquifer.
F. Quality of Water: Usually good to excellent. Water may be hard or mineralized (contain $CaCO_3$) if aquifer is limestone.
G. Water Temperature: See Aquifer Outcrop Springs.
H. Features Produced: See Aquifer Outcrop Springs.

2. Method of Development: Remove obstructions to flow; search for other fractures that are seeping and clean them out; lower outlet elevation, improve drainage; collect flows. (See Figure 5-8 for details).

Development of Springs

The objective of a spring development is to make available for use ground water that is unused, under used or wasted. Where yield or potential yield greatly exceeds the needs, conservation of the supply may not be a critical consideration in the development. Conversely, where the yield or potential yield is low, proper development to assure full utilization of the available water is very important.

Methods. - Information should be obtained, preferably during a dry season, on the volume and reliability of present flow; the nature of the water-bearing material; and the hydrogeologic conditions which cause the spring, before proceeding with plans for development. One or more of the following described measures may be expected to improve spring flow.

Protection of springs from contamination is of prime concern in any development. The location of possible sources of contamination and direction of ground-water flow must always be considered in planning spring developments. Seepage from barns, feed lots, septic fields, and other sources that can enter the zone of saturation and gradually increase the bacterial count and chemical pollutants of spring water should be recognized. There is no easy way to ascertain when the water may become unsafe. A water analysis indicating safe water is no assurance that contamination from bacteria, insecticides, herbicides, detergents, and other chemicals cannot or will not occur in the near future.

If a spring is developed for domestic and livestock use, a spring box will usually be needed. If the supply of water greatly exceeds the needs, a pipe line can be connected to a sand point or filtering pipe laid or driven into the base of the aquifer or connected with a system of collection lines in the spring area. Where supplies are limited, float-type control valves can be installed to conserve water.

Developments of limited water supplies from low yielding springs should be planned and developed to maintain a full head of water in the reservoir area of the spring.

Excavations made during the installation of spring boxes, wing walls, collector lines and outlet works will dewater some of the spring area.

When the earth materials are replaced after construction is completed, the reservoir capacity of the spring area will not be impaired.

Where wing walls or spring boxes are used, an overflow pipe can be set below the top of the wing wall at the design storage profile of the reservoir. (See Figures 5-8 and 5-9). The overflow can be piped to a storage tank or outlet into permeable materials away from the spring keeping the area below the spring dry.

Where fractured rock is the reservoir for a spring, opportunities for control of storage in the spring area are less favorable. A collecting system at the outcrop of the spring and impermeable stratum would be less costly than a system of galleries along the bedding plane.

A storage tank is usually required--the size will depend on the use of the water and the yield and dependability of the spring.

Removal of obstructions.--Obstructions to flow may be deposits of travertine ($CaCO_3$) or fine-grained materials (sand, silt, or clay) brought to the outlet by spring flow, or they may be slope wash materials deposited on the outlet by surface waters. Vegetation growing in or about the outlet may obstruct flow and will certainly consume water which would otherwise issue as spring flow. Usually the removal of such materials or growth will add appreciably to the flow of springs.

If the spring water carries sediment to the opening, some means of desilting the water such as a filter or sump will be desirable. When a sump is used it should be located below the spring so that the sediment will not build up over the outlet between periodic cleanings. The sump should be designed to facilitate cleaning by sluicing if possible.

Ditches located so as to divert surface drainage away from the spring will prevent the clogging of outlets by slope wash material. If the collection of several small flows is planned, use covered galleries or drains to avoid cleaning and maintaining open ditches.

The flow of small springs can be reduced substantially by transpiration of phreatophytes. These phreatophytes can be eliminated by the use of chemicals or eradicated mechanically. Care must be exercised with either method. The chemicals used to eliminate the phreatophytes could contaminate the spring. Mechanical eradication may expose large areas of bare earth that could erode. The resulting sediment could impair the spring opening or downstream areas unless suitable vegetation is established.

Collection of flow.--At some locations, collecting the flow issuing at several openings, or seeping from an outcrop of water-bearing material, is the only means of development. Where water issues from fractures, the individual openings should be cleaned, and the water collected by means of a tile or perforated pipeline, or gravel-filled ditch "French Drain" graded to a central sump or spring box. In collecting water seeping from permeable material, the ditch or tunnel should expose the length and thickness of the water-bearing zones. The excavation must extend sufficiently below the water-bearing zones to afford drainage.

Drainage of additional area of the water-bearing formation.--The flow of springs of the depression and contact type may usually be increased by excavation located to drain additional portions of the aquifer. Such excavation may be either by ditches or tunnels, depending upon topography at the spring and the characteristics of the water-bearing and underlying materials.

If the spring occurs in gently sloping or nearly level terrain, a ditch along the outcrop of the water-bearing material will usually be the most economical method. The ditch should be dug so as to intercept the maximum area of the water-bearing zone.

A tunnel or infiltration gallery may be the most practical method of developing depression or contact springs in steep, hilly terrain. See Table 5-1 for tunnel locations in consolidated and unconsolidated material. Tunneling in unconsolidated and many consolidated deposits will require support of the roof and lining to prevent cave-ins. Miners or others experienced in and equipped for such work should be employed for extensive tunneling. The guiding principle in excavating tunnels for water development should be "follow the water."

Lowering outlet elevation.--This method is effective in improving the flow of springs which are supplied by an extensive system of channels in rock, or by a large volume of permeable water-bearing material as in some artesian springs. By lowering the outlet elevation, added head of water is made available to increase flow at the spring. If the volume of ground-water tributary to the outlet is great, the lowering of the outlet elevation may produce a substantial and long-lasting increase in flow. If the volume of water tributary to the spring is limited, the increase in flow may be expected to be of short duration. A study of the source of supply should precede lowering the outlet.

Explosives.--The use of explosives is not recommended because the shattering and dislocation of rock resulting from blasting may, by closure of a fracture or joint, cause the existing flow to cease or to issue at some other location.

Structures. - Various types of structures and methods may be used in the collection of ground water for spring developments including perforated or tile pipelines laid in gravel-filled ditches, drainage ditches back-filled with gravel or sand, infiltration galleries or tunnels. Selection of the method should be influenced by conditions of spring occurrence such as topography, nature of the water-bearing material, type of openings from which water issues, and volume of flow.

A spring box and pipeline are the most satisfactory means of delivering water to the point of use. The spring box or collecting basin should be located or designed so that water does not pond over the spring openings. Ponding over the spring openings will reduce spring discharge and may cause seeps to change their path of flow.

Table 5-1. Tunnel Location

Aquifer Material	Material Underlying the Aquifer	Location of Tunnel
Consolidated	Consolidated	In underlying material with top of tunnel exposing bottom of aquifer.
Unconsolidated	Unconsolidated	In aquifer at contact with underlying material.
Unconsolidated	Consolidated	In aquifer at contact with underlying material.

Sketches of a typical Spring Collection System and a Spring Box and Pipe Arrangement are shown in Figures 5-8 and 5-9. The collection system shown is suitable for development of a seepage or filtration type spring.

Collector.--The collector may consist of clay tile or perforated pipe laid in graded small gravel (1/4" or less diameter) or graded sand as shown in Figure 5-8. In Figure 5-8, the DETAIL OF COLLECTOR, SECTION A-A, would be a section of a "French Drain" if the clay tile was not installed in the gravel envelope.

In constructing a collector in permeable material, it is good practice to place an impervious barrier on the downhill side of the trench as shown. The barrier should extend down to impervious material to intercept the water and cause it to flow to the point of collection. Under some conditions sand points may be driven into saturated material to serve as collectors.

In plan, the head-wall or cut-off is usually constructed as a large V, with the apex downhill, and the wing walls extending into the hill to prevent water from escaping. If concrete is used, the wall should be at least 6" thick. Masonry, sheet piling, or clay may also be used for the head wall which should extend deep enough to prevent underflow.

Spring box.--A spring box may be constructed to advantage in the apex of the V-shaped head wall as shown in Figure 5-8. Use of a spring box provides a settling basin for sediment removal, and facilitates maintenance of the development. If a spring box is used with a collector system as shown, the upstream wall should have openings located so that all the water collected can enter the box. Satisfactory spring boxes may be constructed of concrete, sections of large diameter pipe, oil drums, etc. Wooden spring boxes deteriorate in a few years and are not satisfactory. For springs not requiring a collector system, the upstream wall of the box may sometimes be omitted. The spring box should have a tight-fitting cover and the entire development should be covered with earth to a depth which will prevent freezing.

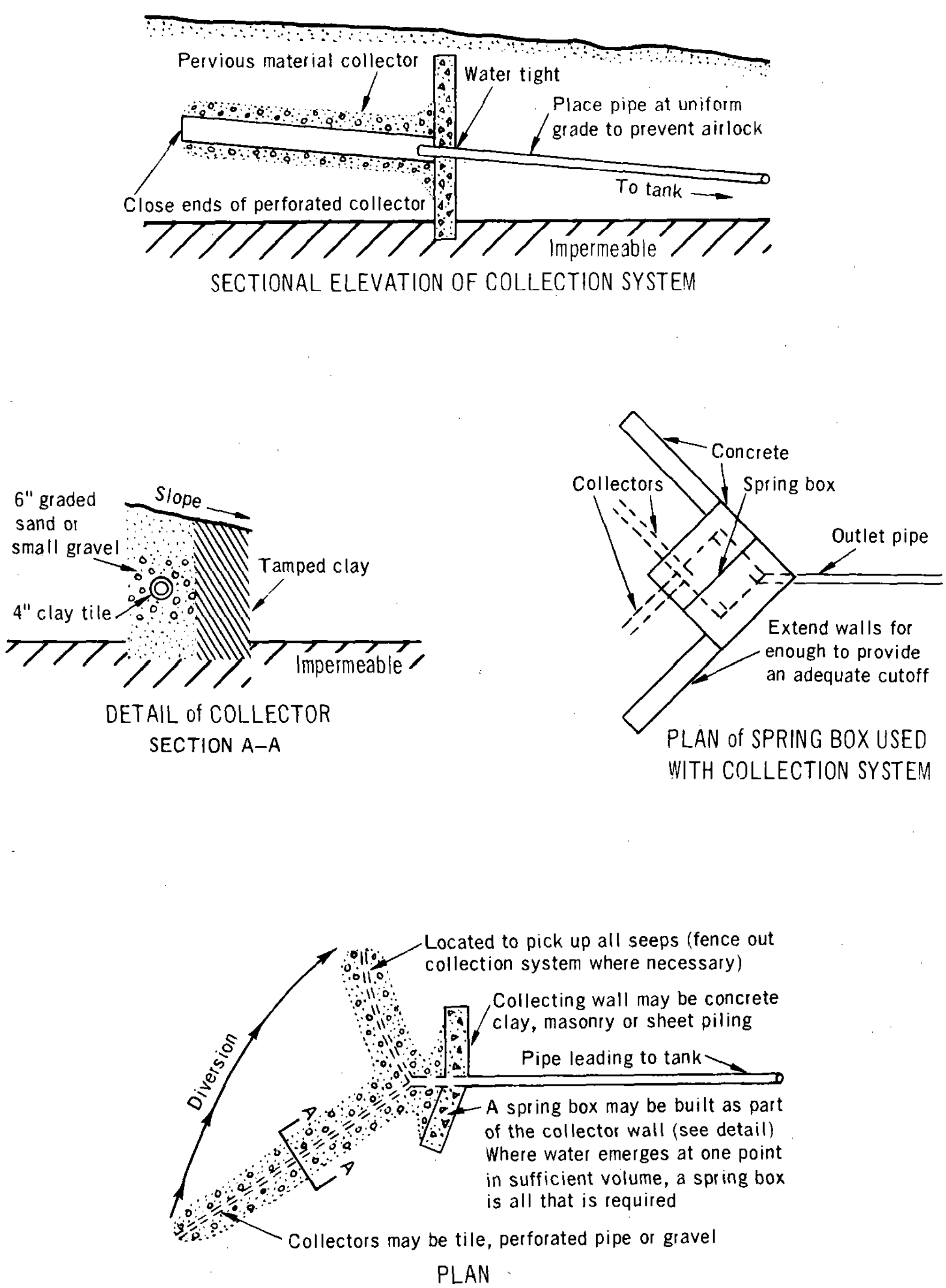


Figure 5–8. Spring Collection System

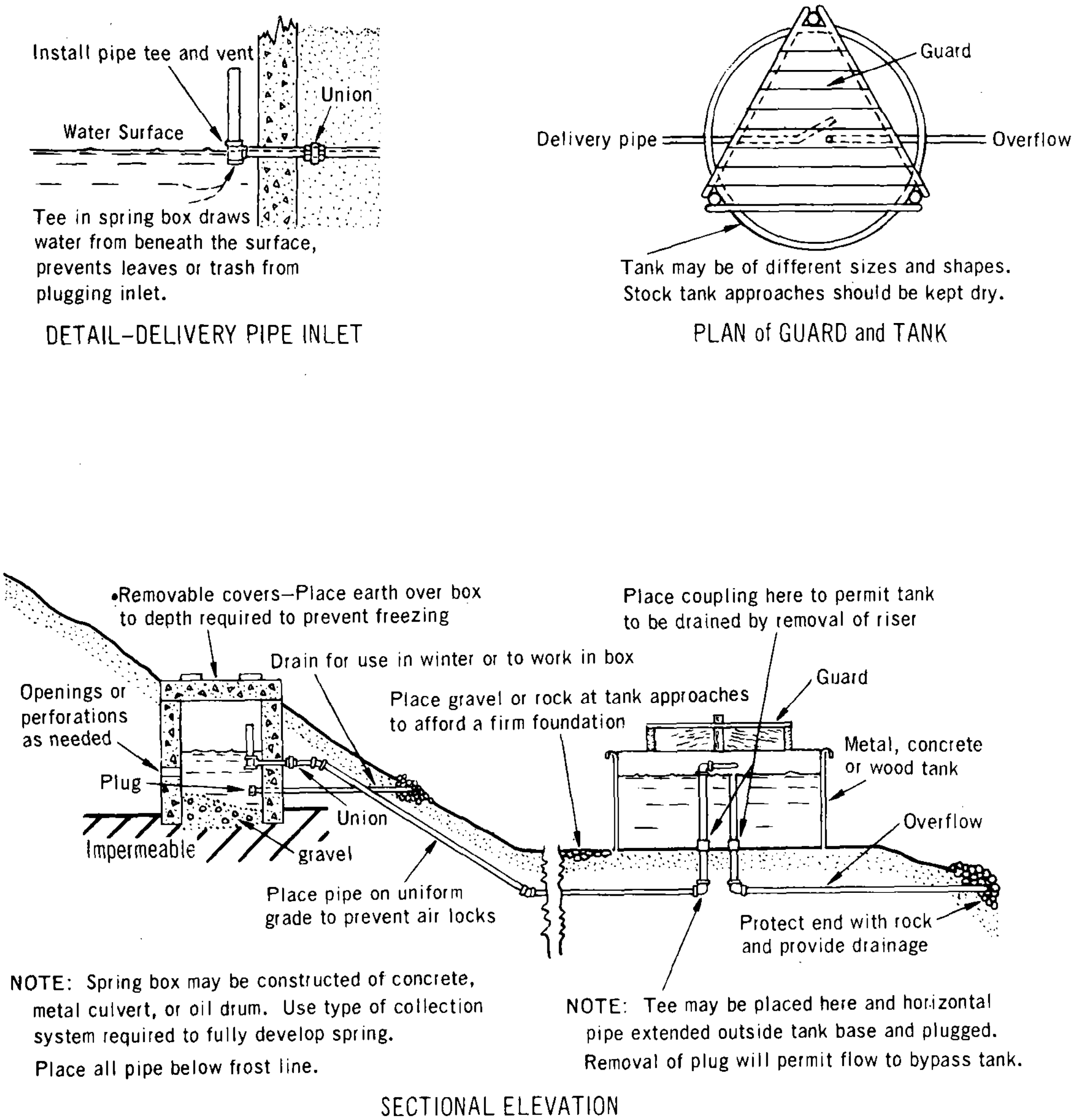


Figure 5–9. Spring Box and Pipe Arrangement

Delivery pipes.--An important part of the spring development is the arrangement of the delivery and overflow pipe layout (Figure 5-9). The pipes may be steel, copper or plastic. Experience indicates that a pipe having a diameter of not less than 1-1/4 inches should be used where the grade is over 1 percent. Where the grade is between 0.5 percent and 1.0 percent, a pipe having a 1-1/2 inch or larger diameter is recommended. Grades under 0.5 percent require a 2 inch diameter pipe as a minimum. Grades less than 0.2 percent are not recommended. When pipes smaller than recommended are used, there is a tendency for them to become clogged and they are difficult to clean. Cleaning may be facilitated by placing "T's" or "Y's" with plugs at selected points in the pipeline.

The pipe should be laid on a positive grade. High spots usually create air locks which may stop the flow. They also reduce the velocity of flow. Pipes should be laid below the frost line and covered to prevent freezing.

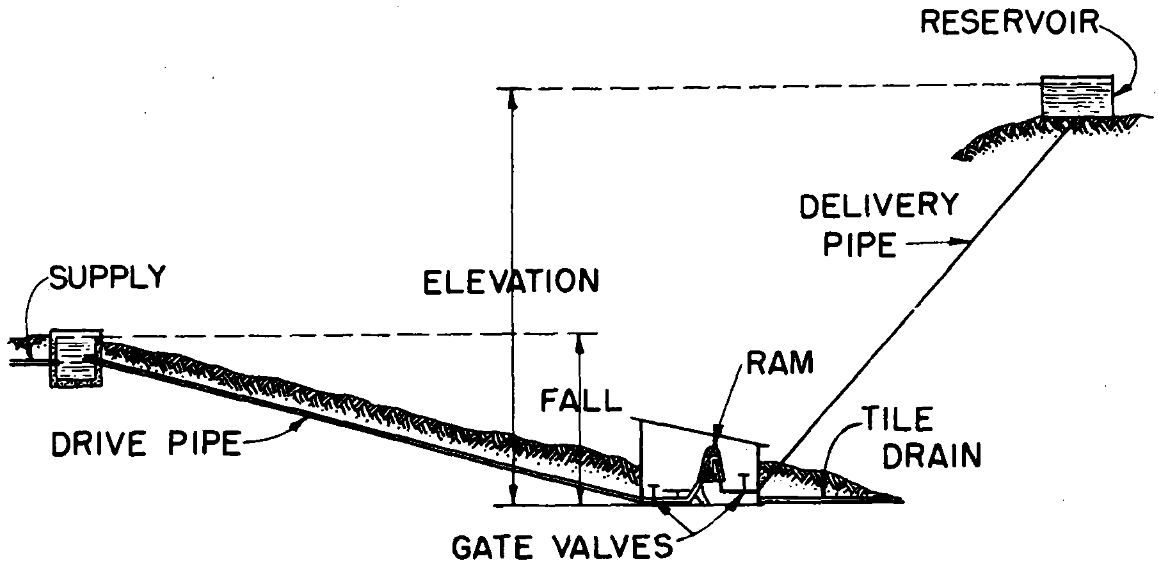
The pipe leaving the spring box should be placed at least 6" above the floor to provide a sediment trap. A water-tight connection must be made where the pipe leaves the spring box or goes through the cut-off wall. A union should be placed on the pipe outside of the wall to permit easy removal of pipe section. A tee and vent pipe should be installed on the pipe within the spring box to reduce plugging from leaves or trash.

The pipe connection with the water tank may be accomplished in a number of ways. The practice of bringing the pipe under the tank and vertically through the bottom is usually considered the most desirable where the tank is to be used during freezing weather. It has also been found beneficial to have the inlet and outlet pipes fairly close together, near the center of the tank. Even though the water freezes around the edge of the tank, it will tend to stay open at the center depending on the rate of inflow. In cold climates tanks should be designed to be watertight when the surface is frozen to a reasonable depth. Figure 5-9 illustrates a good method of bringing the delivery pipe into the tank and of bypassing the flow.

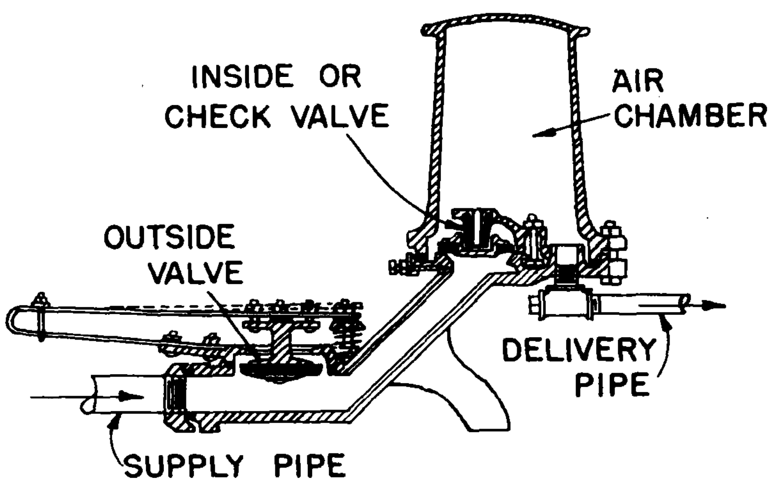
Hydraulic rams.--If it is necessary to deliver water from a spring development to a higher elevation than the outlet of the spring, a hydraulic ram can be used.

A hydraulic ram is an automatic pump operated by water power. It utilizes the power developed by the surge of a quantity of falling water to force a much lesser amount to an elevation above the source of supply. Figure 5-10 is a sketch of a typical ram installation and a diagrammatic sketch of a ram.

Briefly, this is how a hydraulic ram works: Water from the supply flows down the drive pipe to the ram, thus developing a certain power due to its weight and movement. It flows through the outside valve of the ram until it reaches a certain velocity, whereupon the valve closes. The column of water continues on through the inside valve into the air



SKETCH OF TYPICAL RAM INSTALLATION



DIAGRAMMATIC SKETCH OF RAM

Figure 5-10. Hydraulic Ram

chamber. When the pressure in the air chamber equalizes and overcomes the power in the column of water, a rebound takes place which closes the inside valve and opens the outside valve, allowing the water to start flowing again and the entire process is repeated. It is repeated from 25 to 100 times per minute, building up pressure in the air chamber, which in turn forces water through the delivery pipe to the place where it can be used.

The volume of water that a ram will pump is dependent on the fall between the source of supply and the ram, the height the water is to be raised from the ram to the outlet, and the quantity of water available.

When the water supply is limited, a ram must be selected which will operate with the minimum quantity of water available; where there is an abundant water supply the size is governed by the quantity of water needed per day.

Manufacturers build rams that will operate successfully on flows of 1-1/2 gpm or more when operating under a head of not less than 2.0 feet.

A formula for estimating the number of gallons of water delivered per hour to a given point is as follows:

$$D = \frac{V \times F \times 40}{E}$$

D = gallons per hour that the ram will deliver
V = gallons per minute of supply water available
F = fall in feet
E = vertical elevation in feet that water is to be raised.

Similar information can be obtained by referring to Table 5-2.

In order to ascertain the practicability of installing a ram under any particular set of conditions, the following information should be collected:

1. The number of gallons per minute which the spring, artesian well, or stream will deliver.
2. Number of gallons per 24-hour day desired from the ram.
3. Available fall in feet from the source of water to the ram.
4. Elevation to which water is to be raised above the ram.
5. Pipe line distance from ram to point of discharge.
6. Pipe line distance from the source of water to the ram.

Submission of this information to reputable ram manufacturers will enable a recommendation to be made regarding the installation. Due to the variations encountered in ram installations and the difference in standards embodied in the rams built by various manufacturers, no attempt is made to discuss the details of selection and installation.

Protection.--Springs frequently occur at locations which are susceptible to flooding. Protection should be afforded to the spring and its appurtenant structures to permit use without continual maintenance.

Table 5-2. Gallons of Water Lifted by Hydraulic Ram per Gallon Received from Source
(From Farmers' Bulletin No. 1978 Safe Water for the Farm)

Fall in Feet	Height Delivered (in feet)							
	12	18	24	30	36	48	60	72
2	0.1							
4	0.18	0.15	0.1					
6	0.33	0.2	0.17	0.13	0.1			
8	0.42	0.28	0.2	0.17	0.15	0.1		
10	0.54	0.36	0.27	0.22	0.18	0.14	0.1	
12	0.67	0.44	0.33	0.26	0.22	0.16	0.13	0.1

Diversions properly located will afford protection in many instances.

The spring itself may be developed so that flood flows passing over the top will not cause damage. A concrete retaining or wing wall properly constructed and located will prevent channel degradation and dewatering of the spring aquifer. A spring box with a steel or concrete lid placed below the top of the concrete wing wall and protected by a debris basin of rock and gravel may be adequate flood protection. The pipeline should be extended far enough down valley to place the watering tank above flood crests. This type of development is illustrated in Figure 5-11.

Dugouts.--Dugouts are excavations below the water table usually made with drag-line equipment. They need to extend into the zone of saturation deep enough to allow for an abnormally low water table during dry periods to make certain that the supply is permanent. They are generally located in valleys of stream systems, but may be developed wherever the water table is permanently close to the land surface. Dugouts are favored kinds of water developments because they are (1) easy to construct, (2) automatic water holes, (3) usually require very little attention, and (4) economical.

The unfavorable aspects of a dugout are (1) sanitation, (2) death traps where foundation materials are so soft that animals mire and get stuck in the mud, (3) not suitable for cold climate winter use because of ice, and (4) sedimentation. The sanitary hazards pertain to bacterial contamination and lack of drainage away from the water supply. Flood waters may do some flushing of bacteria, but they also introduce loose muds that contribute to miring and adding to the hazard of trapping animals.

In areas of shallow ground water, where dugouts are usually constructed, a shallow well would probably be a more satisfactory livestock watering facility. If electric service is available, a watering tank with a float switch to activate an electrically-operated pump would provide a

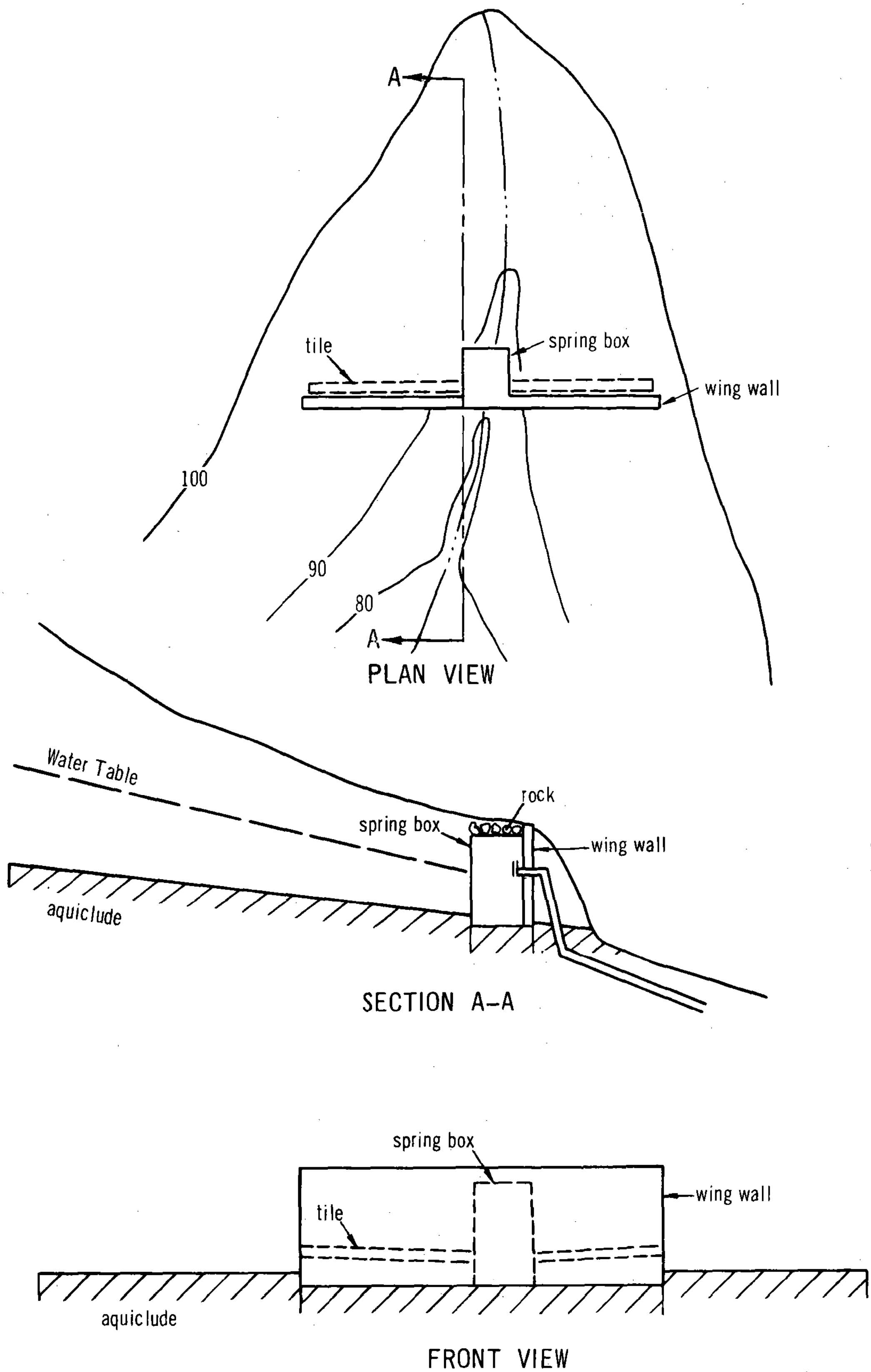


Figure 5-11. Spring Development in Stream Channel

more desirable and sanitary water supply. If electric power is not available at the site, a windmill would provide a source of power for a pump. In this case, the tank should have an overflow pipe that will dispose of excess water some distance away to prevent a mud hole from developing around the tank.

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NATIONAL ENGINEERING HANDBOOK

SECTION 18

GROUND WATER

CHAPTER 6. METHODS AND TECHNIQUES OF WELL DEVELOPMENT

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SECTION 18

GROUND WATER

CHAPTER 6. METHODS AND TECHNIQUES OF WELL DEVELOPMENT

Introduction

A well, as used herein, is a vertically drilled or dug hole in the ground constructed for the purpose of obtaining water from the material which it penetrates.

An efficient well is designed and constructed utilizing sound geological and engineering principles. Some of these principles such as methods of drilling and logging wells, screen and filter pack design, casing design, development of wells, and maintenance will be discussed in this chapter.

Methods of Drilling Wells

Wells may be drilled by one of five principal methods: rotary hydraulic, reverse hydraulic, percussion or cable tool, jetting, and boring. Each method has advantages over the other methods under certain conditions. Table 6-1 shows the various drilling methods and their application to subsurface conditions and water uses.

Rotary Hydraulic

The rotary hydraulic method of drilling wells is based upon the principle of flushing cuttings out of the well with the aid of water, thus the name hydraulic. A local clay, bentonite, or gel is usually mixed with the water to make a slurry or drilling mud. The consistency of the drilling mud is varied by adding either barite, clay, or water, depending on the mud weight needed to stabilize the hole and the character of the material being penetrated. This mud is pumped under pressure through a hollow drill stem to the bottom of the hole where it is discharged through openings in the bit. The bit is designed to cut materials from the bottom of the hole as the drill stem and bit are rotated. The drill cuttings are carried to the surface in the annular space between the drill stem and wall of the hole by the drilling mud.

The cuttings settle out of the mud in pits before the mud is recirculated. Mud pressure and consistency must be adequate to maintain circulation in the system and carry drill cuttings out of the hole while drilling.

The hydraulic rotary method is effective for drilling most rocks. With calyx shot, bort and diamond bits, the hardest rock may be drilled. Drilling is rapid in all except the hardest rocks. Difficulty is encountered in penetrating loose, hard boulders.

Table 6-1. Water Well Construction Methods 1/

Method	Materials for Which Best Suited	Water Table Depth for Which Best Suited	Usual Maximum Depth	Usual Diameter Range	Usual Casing Material	Customary Use	Yield 2/	Remarks
Dug Wells								
Hand	Clay, silt, sand, gravel	5 - 30 ft.	50 ft.	3- 8 ft.	Brikk, rock, timber	Dom., stock	3- 20 gpm.	Surface seal necessary; foundation problems.
Machine	" " " "	5 - 20 ft.	25 ft.	6-40 ft.	Wood or steel sheet piling	Munic. ind. irrig.	100-1500 gpm.	Foundation problems; development not possible.
Driven Wells								
Hand, air hammer	Silt, sand, gravel less than 2".	5 - 15 ft.	50 ft.	1¼-4 in.	Standard weight pipe	Dom., drain.	3- 40 gpm.	Limited to shallow W.T., no large gravel.
Jetted Wells								
Light, portable rig	Silt, sand, gravel less than 1".	5 - 15 ft.	50 ft.	1½-3 in.	Standard weight pipe	Dom., drain.	3- 30 gpm.	Limited to shallow W.T., no large gravel.
Drilled Wells								
Cable tools	Unconsolidated and consolidated medium hard and hard rock	Any depth	1500 ft. 3/	3-24 in.	Steel or wrought iron pipe	All uses	3-3000 gpm.	Effective for water exploration. Requires casing in loose materials. Mud-scow and hollow rod bits developed for drilling unconsolidated fine to medium sediments.
Hydraulic rotary	Silt, sand, gravel less than 1 inch; soft to hard consolidated rock.	Any depth	1500 ft. 3/	3-18 in.	Steel or wrought iron pipe	All uses	3-3000 gpm.	Fastest method for all except hardest rock. Casing usually not required during drilling. Effective for gravel envelope wells.
Reverse hydraulic rotary	Silt, sand, gravel, cobble	5 - 100 ft.	200 ft.	16-48 in.	Steel or wrought iron pipe	Irrig.; ind.; munic.	500-4000 gpm.	Effective for large diameter holes in unconsolidated and partially consolidated deposits. Requires large volume of water for drilling. Effective for gravel envelope wells.
Air rotary	Silt, sand, gravel less than 2", soft to hard consolidated rock.	Any depth	2000 ft. 3/	12-20 in.	Steel or wrought iron pipe	Irrig.; ind.; munic.	500-3000 gpm.	Now used in oil exploration. Very fast drilling. Combines rotary and percussion methods (air drilling) cuttings removed by air. Would be economical for deep water wells. 4/
Augering								
Hand auger	Clay, silt, sand, gravel less than 1".	5 - 30 ft.	35 ft.	2-8 in.	Sheet metal	Dom.; drain.	3- 50 gpm.	Most effective for penetrating and removing clay. Limited by gravel over 1". Casing required if material is loose.
Power auger	Clay, silt, sand, gravel less than 2"	5 - 50 ft.	75 ft.	6-36 in.	Steel or wrought iron, or concrete pipe	Dom.; irrig.; drain.	3- 100 gpm.	Limited by gravel over 2", otherwise same as for hand auger.

1/ References (3) (24) (29) (34) (35)
2/ Yield influenced primarily by geology and availability of ground water.
3/ Greater depths reached with heavier equipment.
4/ Jackson, Gordon, 1959, AN ANALYSIS OF AIR DRILLING, The Drilling Contractor, American Assn. of Oil Well Drilling Contractors, 211 North Ervay Building, Dallas 1,Texas,

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Reverse Hydraulic

The reverse hydraulic method is similar to the rotary hydraulic except the drilling fluid is circulated in reverse order. It is best suited for drilling large diameter wells, because reverse circulation maintains a high velocity in the water rising in the drill stem and efficiently removes cuttings. Water is used instead of drilling mud. The drill stem is larger and is connected with a suction pump instead of a pressure pump. Water and drill cuttings are removed from the drill stem by the suction pump and "jet eductor" (see Figure 6-1), and discharged into pits. To avoid caving, it is important to keep the hole full of water.

Cable Tool

The cable tool, percussion, or standard method of drilling is based upon the principle of applying sufficient energy to pulverize the soil or rock by percussion. The energy applied is varied by controlling the length of the stroke and the weight of the drill stem and bit. Bits vary in diameter from a few inches up to two feet depending on the desired depth and diameter of the well. Bits and drill stems vary in length depending upon the weight needed to furnish the desired impact. The bits need not be very sharp but the drill end must be kept considerably larger than the shank to allow free movement of the bit in the hole. The bit is connected to a cable and by means of a rocker arm on the drill rig it is raised and released to exert its energy on the bottom of the hole. To remove the drill cuttings, water is introduced to make mud that can be removed by means of a bailer.

The cable tool method must rely upon casing when the hole begins to cave. The hole often caves when the drill enters or passes through a non-cohesive water-bearing stratum. In order to penetrate some water-bearing formations it becomes necessary to introduce casing into the well and by means of the bailer remove sand that enters the casing. The casing will usually settle by its own weight for a short distance before it becomes necessary to drive it to penetrate the water-bearing stratum.

This method of drilling is designed primarily for hard rock and cobbly or bouldery materials. It tends to compact the unconsolidated sediments so that the walls of the hole become dense and tight.

Jetting

The jetting method of drilling wells is usually employed in sandy formations where water is developed by entry from the bottom of the casing. Perforated casing is not used. The casing, usually a two-inch diameter galvanized or black iron pipe, is used to drill the hole. Jagged edges are cut into the lower end for chopping purposes. The drill stem is lifted and dropped in the operation and water is forced under pressure through the drill stem to remove cuttings. When the drill pipe has entered the zone of saturation far enough to have several feet of water in the casing it is then considered to be in proper place and jetting is terminated. A cylinder is then lowered into the well with sand point or screen on the lower end of the tail pipe to complete the installation. This method is never used for test drilling that requires collection of representative samples.

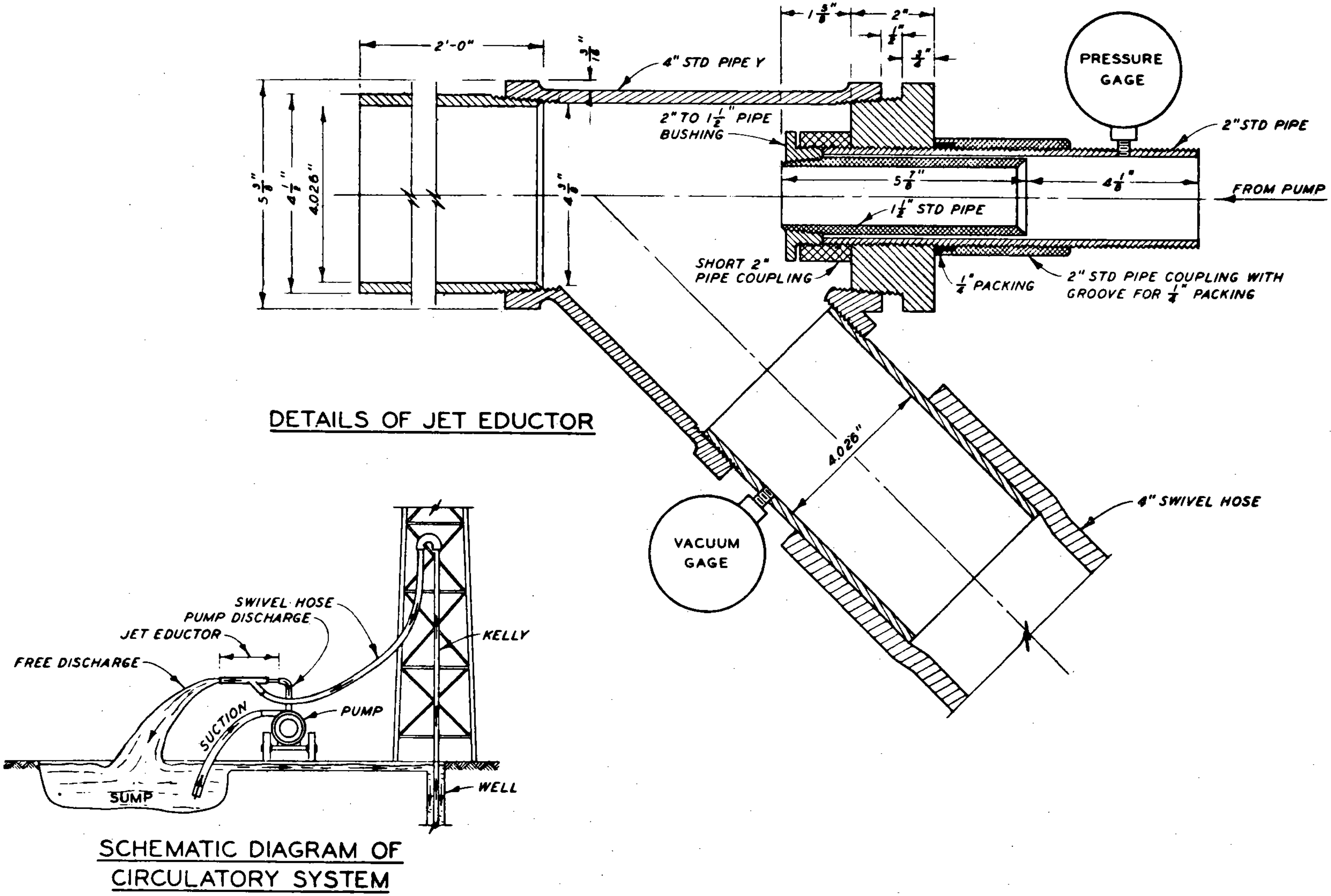


Figure 6–1. Reverse Circulation Drilling

Boring
The boring method of well drilling is based upon the principle of the Iwan Auger. It is designed for unconsolidated sediments and successfully used where water-bearing formations are very fine-textured and permeabilities are low. The auger is connected to a shaft that is rotated slowly. It is designed to retain drill cuttings and pulled out of the hole to empty the bucket. Diameters may vary from 12 to about 36 inches and will usually average about 18 to 20 inches.

These wells can be bored up to depths of 100 to 150 feet providing rock or caving soils are not encountered. They have the advantage of developing reservoir capacity within the dug space where water-bearing formations release water at a relatively slow rate. Where diameter is important to storage within the augered portion of the zone of saturation it may be the basis for selecting a given diameter. The volume of water in a cylinder 12 inches long is given by the formula:

$$0.0408\ d^2 = \text{gallons}$$

with d in inches

or

$$5.8752\ d^2 = \text{gallons}$$

with d in feet.

Table 6-2 lists the capacity of cylinders of various sizes.

Other Methods
Dug wells are best suited to areas with a shallow water table and where thickness of the water-bearing material is not great. They present problems in construction. There is little possibility of improving them by development (see p. 6-34 for discussion of development) because only a limited area of openings may be left in the sidewalls. Their large diameter makes it difficult to apply usual development methods. They may be unsanitary because it is difficult to seal out surface contamination and subject to failure because of yielding foundations. Dug wells usually are more expensive than wells constructed with drilling equipment.

Wells constructed by driving are useful under certain conditions for developing water and draining areas. Their use is limited to areas underlain by unconsolidated clay, silt and sand relatively free of gravel, cobbles or boulders. Depth to water, including drawdown, must be less than the suction limit at the elevation of the well. The practical limit of suction lift for pumps is 22 feet at sea level, 17 feet at 5,000 feet elevation and 14 feet at 10,000 feet elevation (Rohwer, 1940).

Driven wells are constructed by driving pipe fitted with a sand point sufficiently below the water table so that fluctuations, and drawdown from pumping will not lower water below the point.

A sand point consists of a forged steel point attached to a short length of perforated pipe. The perforated pipe is wrapped with either brass screen or spiral wound brass bands having a trapezoidal cross section.

Table 6-2. Capacity of Cylinders in Gallons per Lineal Foot

Diameter in inches	Gallons	Diameter in feet	Gallons for pipes and tanks
2	0.16	2	24
4	0.65	3	53
6	1.5	4	94
8	2.6	5	147
10	4.1	6	212
12	6.0	7	288
		8	376
		9	477
		10	590
		12	846
		15	1278
		20	2350
		25	3671

The bands form a relatively non-clogging slot that is narrowest at the outside.

In driving the point through materials containing considerable amounts of clay, the openings often become clogged. It may prove advisable to auger or jet the hole through the clay layers.

Single driven wells are an efficient and economical means of obtaining small amounts of water under conditions outlined. Multiple driven wells connected to a common pump manifold are useful in developing irrigation supplies and for drainage.

Well Logs

A great deal of information needed in the design and construction of an efficient well, as well as information for locating new wells, is available from the various types of well logs.

Many types of logs can be constructed or obtained on wells. The information for sample logs and drilling time logs can be obtained at a minimum expenditure of time and funds when the well is drilled. The various types of electric and radioactive logs require additional time and equipment to run but in almost all cases are worth the cost.

The following discussion will describe some of the various types of logs, how they are obtained, and their use in correlation and delineating favorable water-bearing horizons.

The quantitative procedures for determining specific formational constants such as true rock resistivities and true formation fluid resistivities which is a function of the chemical quality of the water will not be explained. If this type of interpretation is desired, reference should be made to LeRoy (1951), Patten and Bennett (1963), Maher (1954), and equipment manufacturers manuals.

Sample Logs

Good representative samples are necessary for the preparation of an accurate *sample log* and are required for proper screen and filter pack design.

Samples should be collected for at least each five foot interval of hole drilled and at every change in formation that is discernable by the action of the drilling rig.

Rotary hydraulic samples are subject to some contamination by caving and recirculation of material in the drilling mud. With proper construction and location of the mud pits, recirculation of material can be minimized. Proper mud consistency can keep caving at a minimum. A sample box, as shown in Figure 6-2, placed between the well and the mud pit is a satisfactory method of obtaining representative samples.

When drilling in the aquifer, penetration of the bit should be stopped every five feet and the mud circulated until all cuttings are removed from the hole. The sample is then removed from the sample box and the box washed clean before another increment of five feet is drilled.

Undisturbed core samples are best if the additional cost can be justified. Push tube or drive samplers also provide excellent samples.

When reverse circulation rotary hydraulic drilling is used, the high velocity of the drilling fluid, for practical purposes, eliminates sample lag time and the samples are contaminated very little from caving. The large volume of drilling fluid used in this method makes the sample box used in the standard rotary method impractical. Diverting part of the return flow into the sample box may be adequate or the sample catching system shown in Figure 6-3 can be used.

Samples from wells drilled by cable tool can be quite variable. In consolidated formations samples are good. In unconsolidated formations, if the casing follows closely behind the bit the samples are usually good and if the casing is bailed down they are excellent. All the cuttings from sampling interval should be collected and then split to obtain the sample to be retained.

Samples are inadequate or not available from wells that are jetted or driven. Bored or dug wells are usually very shallow but yield adequate samples.

The samples that have been collected are described for mineral composition, grain size, USCS classification, color, and any other feature that can be seen. They are usually observed with a hand lens or a binocular microscope. Mechanical analysis of the aquifer samples is necessary for screen slot and filter pack design. The descriptive information is plotted on a strip log. The vertical scale should be the same as the scale of any other logs to be run on the well and the same as other wells in the vicinity to aid in correlation and comparison.

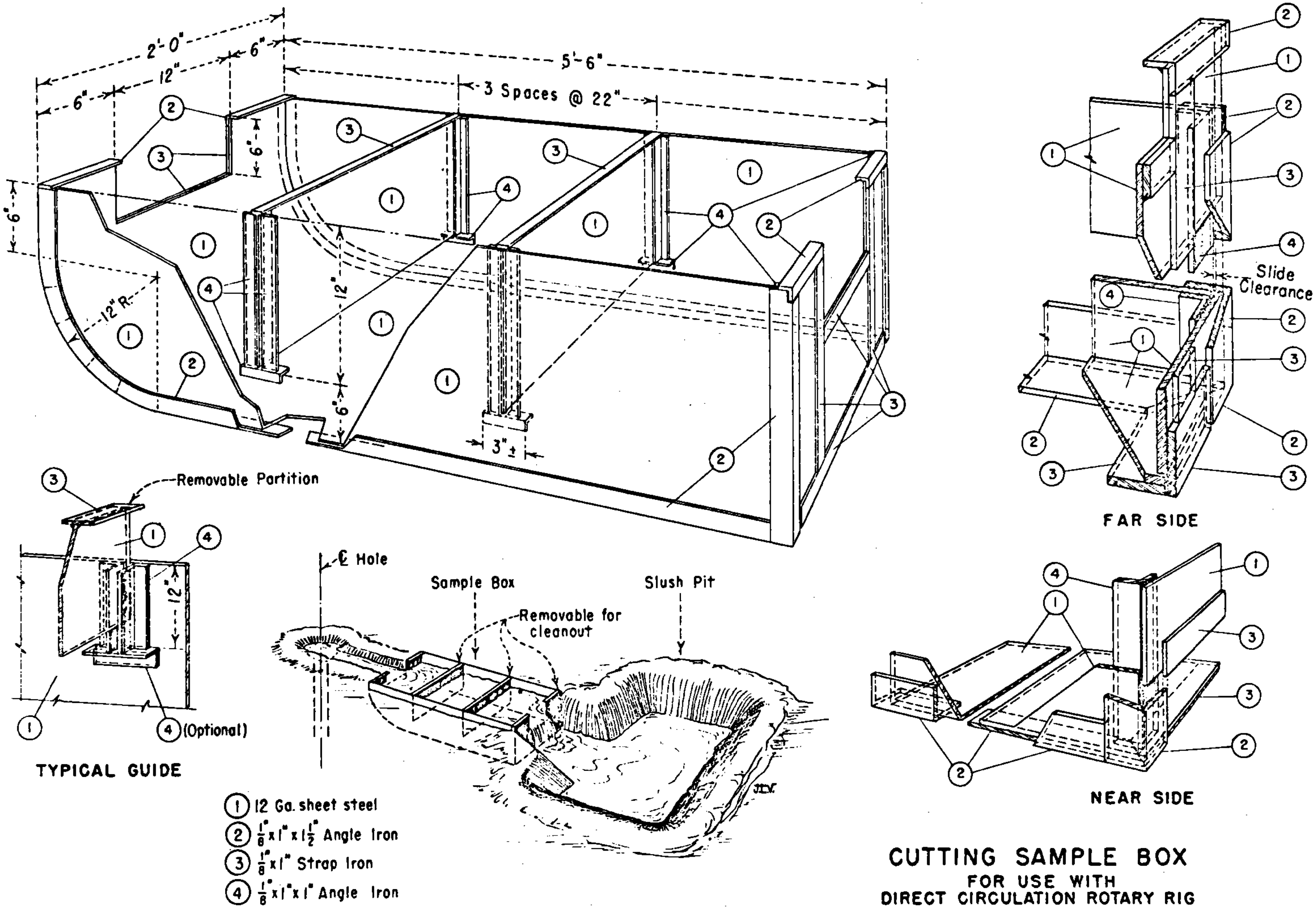
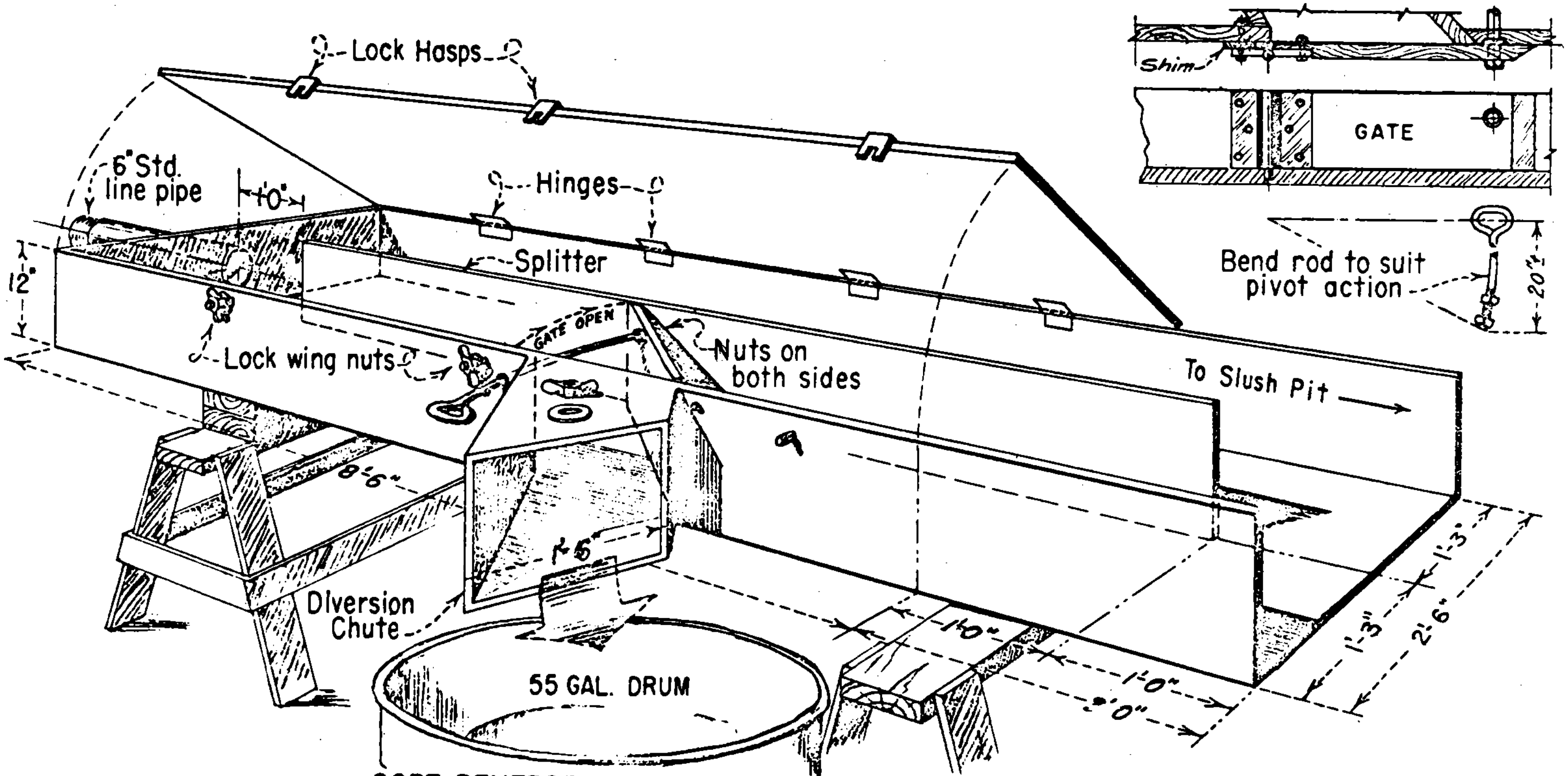


Figure 6–2. Cutting Sample Box

(From U.S. Bur. Rec., 1964)



COPE REVERSE CIRCULATION FORMATION SAMPLER

Original Model was made of welded 3/16" steel plate, but if general measurements are followed, model could be made from wood.

Discharge Hose from Reverse Circulation Pump is connected to 6" pipe so all materials go thru Sampler. Materials can be observed in open 2-foot discharge without cover.

Sampler is mounted on heavy horses or similar supports with about a 6" slope towards the Slush Pit into which material is discharged.

To obtain sample, Control Gate is thrown open against Splitter to divert sample thru Chute and into 55-gal. oil drum.

Figure 6–3. Sample Catching System

(From U.S. Bur. Rec., 1964)

Drilling Time Logs
The *drilling time log* is an aid in correlating other logs. Slow drilling time may indicate a hard indurated zone. Fast, smooth drilling could indicate fine sands and vibration of the drill stem could indicate sand and gravel.

Electric Logs
The two types of electric logs generally used in ground water work are the *spontaneous potential logs* and *resistivity logs.*

Electric logs can only be run in bore holes filled with drilling fluid.

Spontaneous potential logs.--The *spontaneous potential* is a quantitative tool and is the measure of the spontaneous electromotive force generated between the drilling mud and the fluid in the permeable zones and shale layers surrounding the permeable zones.

The spontaneous potential (SP) is measured by an electrode suspended in the well bore and another electrode at the ground surface. The amplitude of the SP curve is a function of several factors such as the resistivity of the mud and ground water, hole diameter, bed thickness, etc. Figure 6-4 is an SP logging arrangement.

In general, when the resistivity of the drilling mud is higher than the formation fluid the SP is negative; when the resistivity of the formation fluid and drilling mud are about the same, the SP is very small or zero; and when the resistivity of the drilling mud is lower than the formation fluid the SP is positive.

With a fresh-water drilling mud, the SP across a fresh-water aquifer would be very small; the SP across an aquifer containing highly mineralized water would be high and negative. Increasing clay content in an alluvial aquifer would give a negative SP also. Correlation with a good sample log aids in interpretation.

Resistivity logs.--The *resistivity log* differs from the SP in that an induced current is used. Commonly two current and two potential electrodes are used. The arrangement and spacing of the electrodes determine whether the type or curve obtained is *normal* or *lateral.* Figure 6-5 shows the electrode arrangement for normal and lateral types of resistivity logs.

In the *normal* curve the distance between one potential and one current electrode (AM) is the significant interval. The position of the current electrode B is not important as long as it is large compared to AM.

In the *lateral* curve the interval AO, the distance between one potential electrode and a point midway between the two current electrodes is the significant interval, the interval AB must be small compared to AM.

The resistivity log can be used to determine the boundaries between beds or zones of differential resistance. A sand or gravel containing

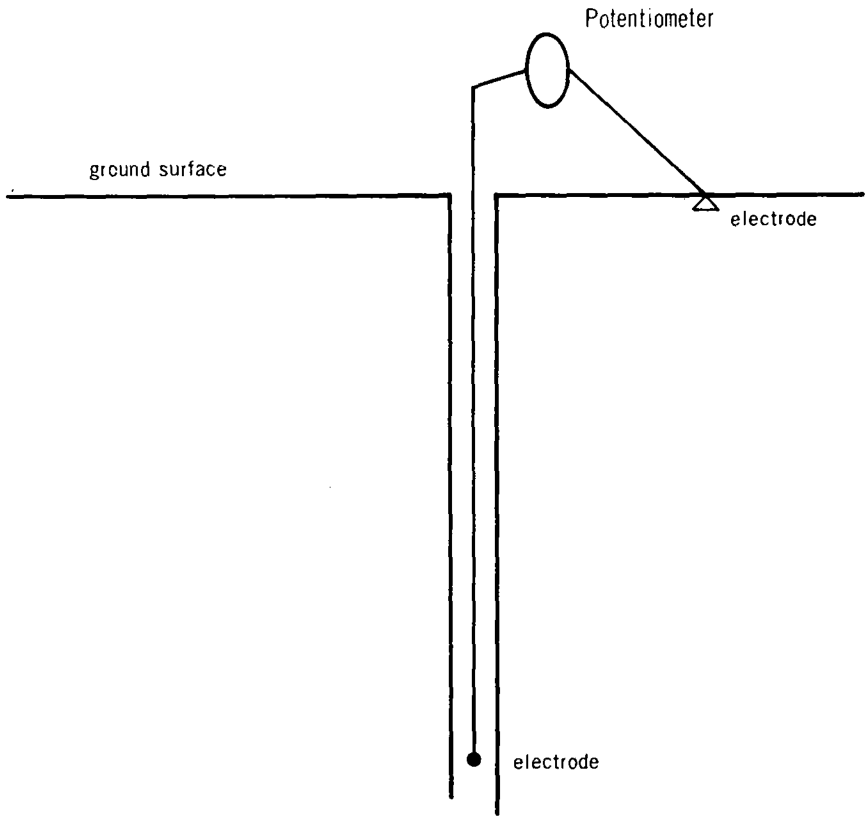


FIGURE 6-4. SP Logging Arrangement

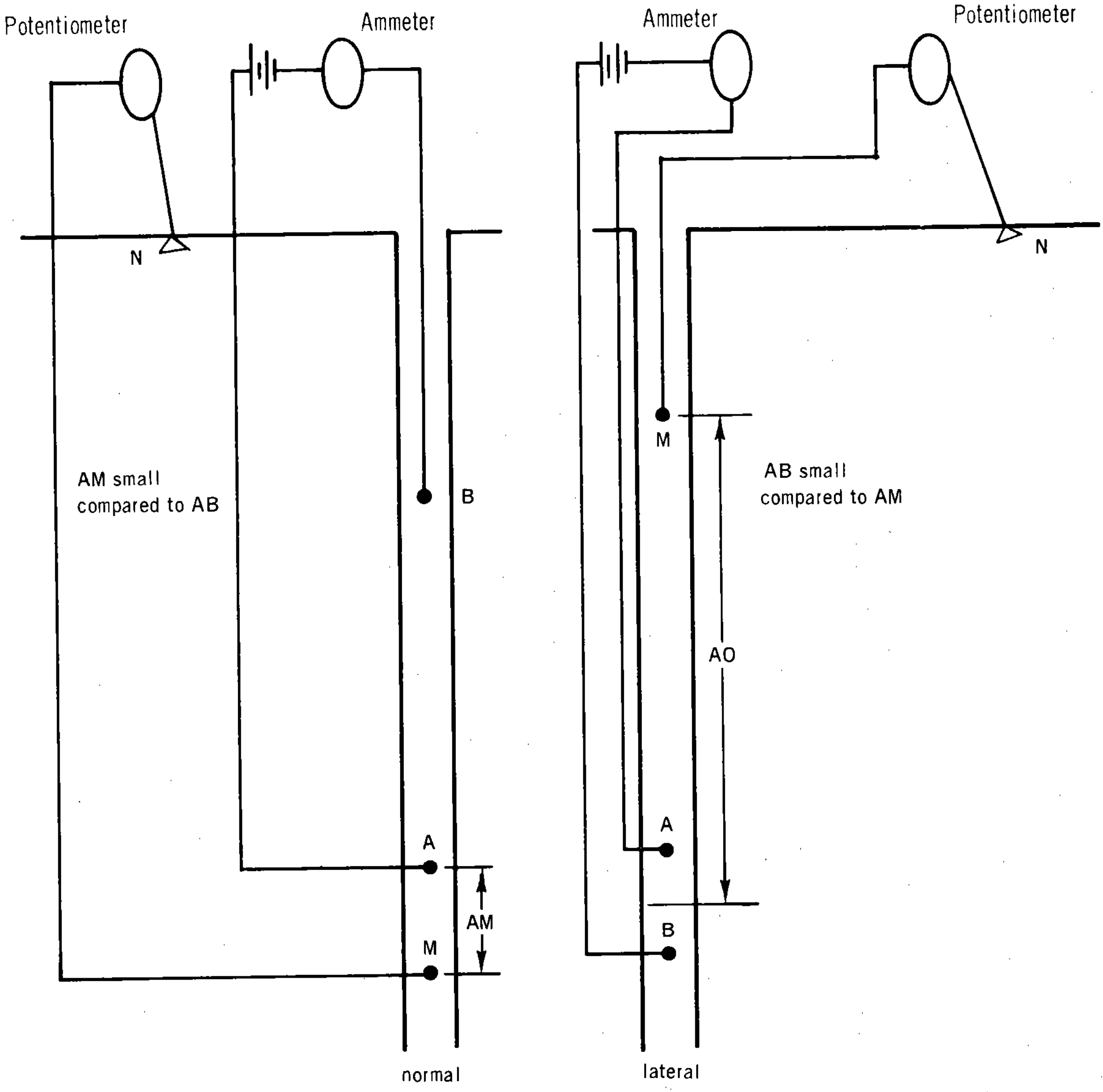
fresh or only slightly mineralized ground water has a much higher resistance than clay or shale where the interstitial water is highly mineralized with dissolved salts from the clay particles.

The normal resistivity log is usually run with at least two electrode spacings. Resistive beds thicker than the electrode spacing will show as a deflection in a positive (higher resistance) direction, resistive beds thinner than the electrode spacing will show as a negative deflection, and beds the same thickness as the electrode spacing will show no deflection.

The lateral resistivity curve shows resistive beds of all thickness. The upper boundary of beds whose thickness is greater than the AO interval is indefinite and true resistivity values are masked for a distance equal to the AO spacing. The thickness of beds less than the AB interval is exaggerated by an amount equal to the AB interval.

Radioactive Logs

There are two kinds of radioactive logging generally done. They are *gamma-ray* logging and *neutron* logging.



AB current electrodes
MN potential electrodes

FIGURE 6–5. Resistivity Electrode Arrangement

Gamma-ray logs.--*Gamma-ray* logging measures the amount of natural gamma radiation, in the vicinity of the bore hole, of the material penetrated by a well. It is recorded by lowering a detecting instrument (Geiger-Mueller or scintillation counter) into the well and recording the readings at the surface. Experience in logging thousands of wells has shown that natural gamma radiation is higher in shales and clays than in sands and gravels. Figure 6-6 indicates the natural gamma radiation of various types of formations.

Neutron logs.--In *neutron* logging the formation is bombarded by a strong source of fast-moving neutrons. The secondary gamma rays that have been excited by the bombardment are recorded on the log. Hydrogen is the controlling factor in neutron logging. When hydrogen is present the neutrons are slowed down or stopped giving a low value on the curve. The activity recorded on the log is inversely proportional to the hydrogen present. Since ground water is the source of most large quantities of hydrogen, a low value on the log would indicate a water-bearing zone. Conversely, a high value on the log would indicate no water and, therefore, dense or non-porous rocks. Correlation with other logs is necessary because shale or clay could contain water giving a low value on the log but they are not usually aquifers.

Correlation and Interpretation

Correlation and interpretation of the various types of well logs provide excellent information for well design.

Correlation of logs of a test well with logs from production wells with known aquifer characteristics will permit rapid identification of the most favorable water-producing zones in the test well.

Interpretations of the different types of logs on the same well indicate formational changes and major differences in water quality. Figure 6-7 is an example of the characteristic curves of the various types of logs run in a fresh water drilling mud.

In this figure, the SP curve gives a positive deflection opposite clay beds, negative deflection opposite salt-water aquifers, and no deflection opposite fresh-water aquifers.

The resistivity curves show high resistance opposite fresh-water alluvial aquifers and dense rock and low resistance opposite clay, shale and saline aquifers.

The gamma ray and neutron logs are helpful in differentiating between permeable zones and clay beds. A low or negative deflection on both curves would indicate a permeable water-bearing zone. A high or positive deflection of the gamma-ray curve and a low or negative deflection of the neutron curve would indicate clay or shale.

Well Design

Many factors must be considered in the proper design of a well. The purpose of the well (livestock, irrigation, etc.) and the required yield will determine the optimum size of the well. The potential

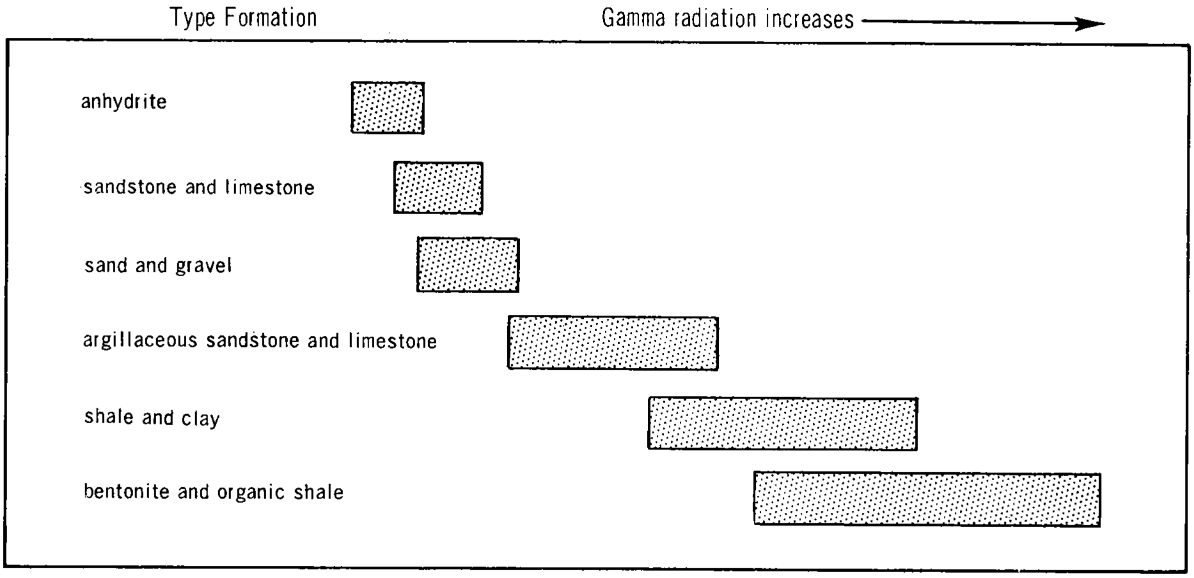


FIGURE 6-6. Relative Natural Gamma Radiation of Rocks

corrosion will indicate the type of casing and screen that should be used and the method of installation. Mechanical analysis of alluvial aquifers will guide the design of filter packs and well screens. The ultimate aim in well design and construction is to provide an efficient well that will produce the required amount of water at the least cost.

Drawdown - Yield

The best design for a well that must produce at or near its maximum rate is one that fully penetrates the aquifer. In this case the flow to the well is radial as shown in Figure 6-8 A and C. In a partially penetrating well, the flow path is curvilinear (B and D in Figure 6-8) and, therefore, longer and encounters more resistance than in radial flow. Wells A and C will produce the same amount of water with less drawdown than wells B and D.

When constructing a well in an artesian aquifer, the screen should extend through the full thickness of the aquifer and the maximum drawdown should not be below the top of the screen for optimum production.

For non-artesian aquifers the lower one-third of the aquifer should be screened and the drawdown again should not be below the top of the screen for optimum production. Figure 6-9 shows that for non-artesian aquifers about 85 percent of the yield will occur at about 60 percent drawdown.

Exceptions to the full penetration of an aquifer are in areas where there is a possibility that sea water or saline water may lie beneath the fresh ground water. This is likely in coastal areas, on islands, and in arid areas where evaporite or brine deposits are common in the geologic section. In these areas, a study of geology and conditions under which ground water occurs, should be made to determine the maximum depth of wells (Todd, 1959).

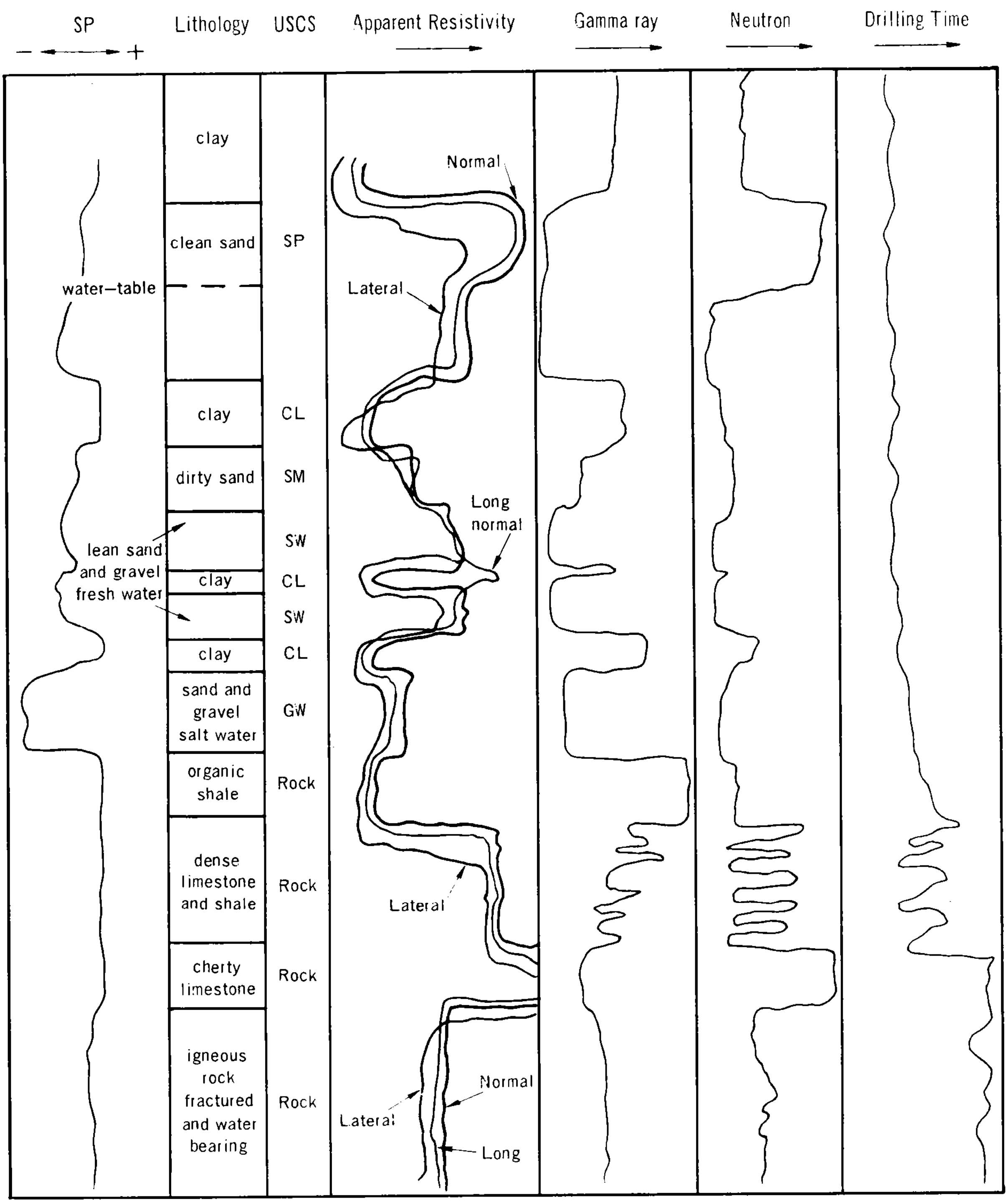


FIGURE 6-7. Examples of Well Logs

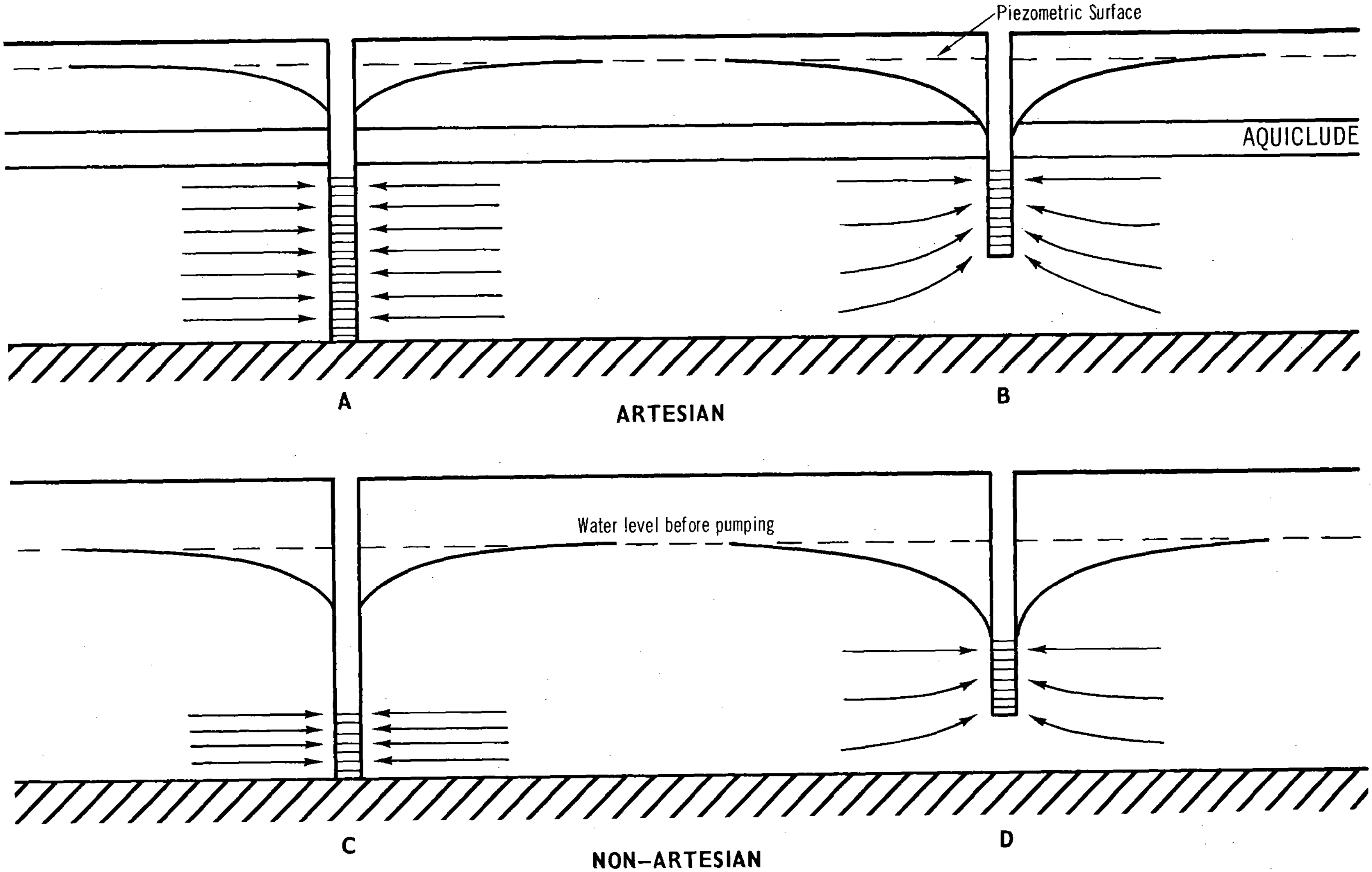
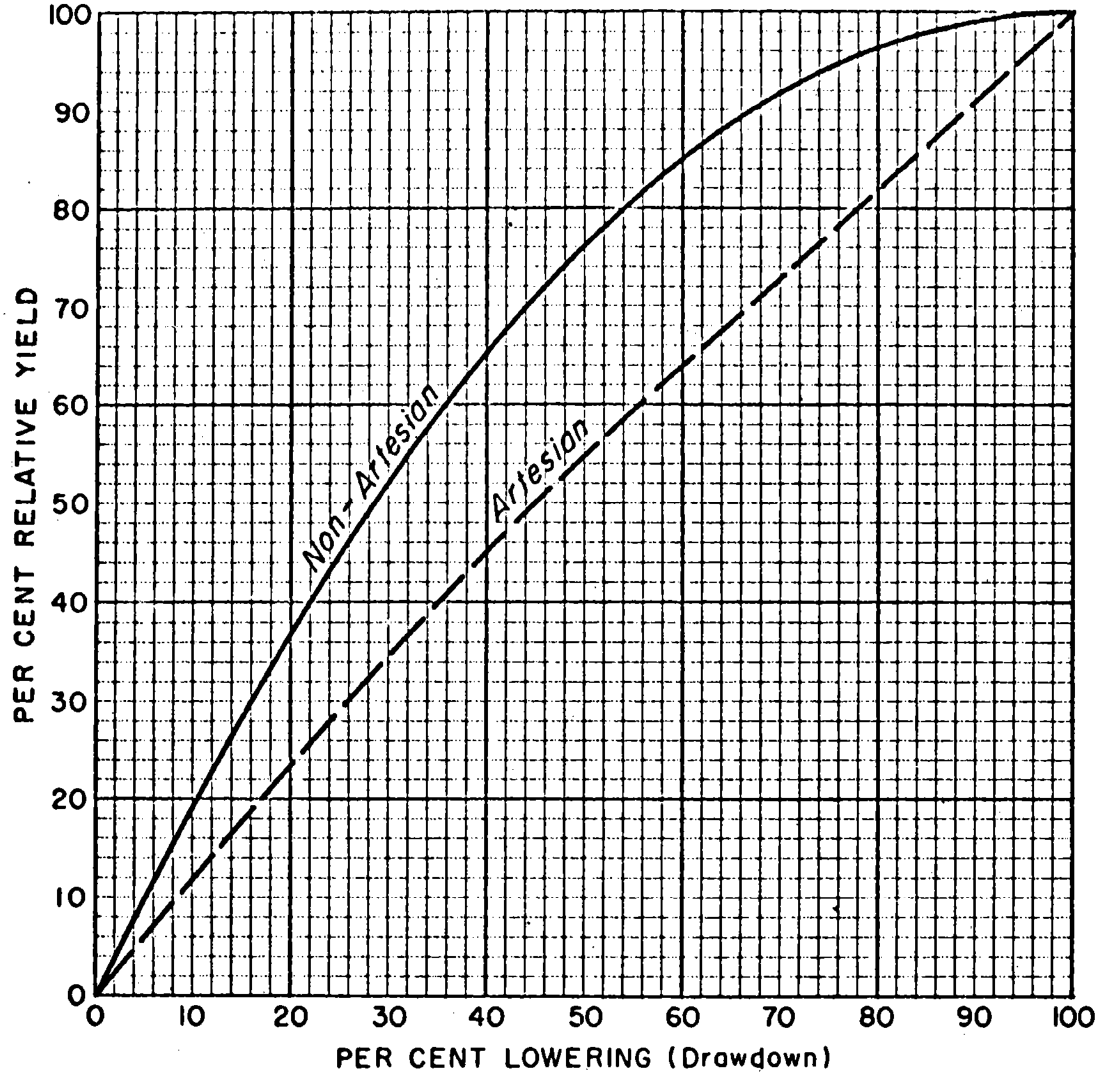


Figure 6-8. Full and Partial Penetration of Wells



EXAMPLE: The water stands 75 feet in a well and the pumping test yielded 1470 g.p.m. with a drawdown of 23 feet. This is 30% of the total possible drawdown. The curve shows that at 30% of the maximum drawdown, the well will produce 52% of the maximum yield. 1470 g.p.m. is 52% so the maximum yield or 100% would be $\frac{1470}{.52}$ = 2827 g.p.m. The curve shows that 77% of the maximum capacity can be obtained with a 50% (38 feet) drawdown. 2827 x .77 = 2253 g.p.m. yield with a 38 foot drawdown.

Figure 6–9. Relation of Drawdown to Yield

(From E. E. Johnson, Inc., The Yield of Water Wells, Bull. 1238 (Rev.), 1955. Used by permission of E. E. Johnson, Inc.)

Beneath coastal areas, movement of fresh ground water toward the sea usually prevents landward intrusion of the slightly denser salt water. Hydrostatic equilibrium is established between these fluids of different densities, when, for each foot of fresh water above sea level, there are about 40 feet of fresh water lying below sea level. The fresh water--salt water interface thus slopes downward away from the ocean as the water table rises. This is known as the Gyhben-Herzberg relation between fresh and saline waters.

As a general guide for use in planning, wells in proximity of the coast should not pump from below mean sea level. Interior basin wells should bottom above the fresh water--salt water interface with the anticipated drawdown (interface may rise as much as 40 feet for each foot of drawdown). Wells should be designed and developed for minimum drawdown and located so that drawdown is distributed as widely as possible.

Well Casing

Casing maintains the hole through loose, caving or flowing materials and seals out contaminated or undesirable waters. It must be strong enough to resist earth pressure and, depending upon method of placement, may have to withstand considerable shock and compressive stress. Casing should also be sufficiently resistant to corrosion to last 25 to 50 years.

Materials.--Most wells are cased with steel or wrought iron pipe using welded or threaded and coupled joints. When casing is to be driven, a steel drive shoe is riveted or welded to the bottom of the pipe to ream the hole and prevent crimping the casing. Casings of other materials and designs are used with special drilling methods adapted to specific geologic conditions.

"Stovepipe" or double casing made up of telescoping sheet iron sections, 8 to 16 gauge in thickness, 2 to 4 feet in length, and 4 to 36 inches in diameter, is used in sediment-filled valleys in California and Arizona. It was designed for use with the mud-scow, orange peel bucket, and hollow rod drilling methods. Casings and screens of concrete, tile, and wood have also been successfully used. Riveted, single thickness sheet iron casing joined by telescoping or welded joints is sometimes used.

Soil corrosion investigations were begun by the National Bureau of Standards in 1922 and results reported in Research Paper 945 by Kirk H. Logan in 1934. It was found no one metal or alloy resists corrosion better than all others in all soils, but suitable material may be obtained for each condition. Copper and alloys high in copper corrode slowly in most soils but corrode at their highest rate in soils containing sulfides. For all copper alloys the rates of corrosion were higher in cinders than in any soil tested. Aluminum and some of its alloys corroded rapidly under most of the soil conditions to which they were exposed.

Steel or wrought iron pipe, while not corrosion resistant, has adequate life as well casing under most conditions because it is over strength.

The use of heavy pipe is an economical means of obtaining long life even in fairly corrosive materials.

Under especially corrosive conditions, pipe and tubing of stainless steel, brass and copper alloys containing manganese, nickel and silicon have been used. The relative corrosion resistance of these metals is shown under Well Screens on page 6-21. Joints are welded because the wall thickness is less than for steel or wrought iron pipe. Asbestos-cement pipe is suitable for casing and plastic pipe has recently been used in wells up to 6 inches in diameter. Use of cast iron casing is increasing. Pipe lined with cement, various enamels, and rubber is available and may prove useful in some situations. Asbestos-cement, plastic, and cast iron pipes have slip joints. Lined pipes have flanged joints. Well construction must allow these casings to be set in place without driving.

The American Water Works Association (1958) recommends thickness of steel or wrought iron casing considered "best practice" as shown in Table 6-3.

Size.--Steel and iron pipe have standard dimensions, weight and threads. Refer to ASTM A-53, ASTM A-120, and AWWA (1958) and Anderson (1947) for commonly used details and specifications.

Pipe is furnished in 20 foot lengths. Sizes up to 12 inches are designated by nominal inside diameter. Sizes 14 inches and over are designated by outside diameter. When ordering, specify the desired wall thickness, or weight per foot. In some areas, inside diameter and wall thickness are specified for pipe made to order. Galvanized pipe may be purchased in 6-inch to 12-inch diameters. Larger sizes may be galvanized by arrangement with the manufacturer.

Pipe 6 inches in diameter and smaller is referred to as "standard weight pipe." Sizes over 6 inches are called line pipe and pipe 8 inches in diameter and over is made in more than one wall thickness. Consider the method of placement and conditions of service in selecting the weight of pipe to use. Heavier walls are needed for hard driving and corrosive environment. Lighter pipe may be used where conditions are unusually favorable. Threading data must be specified for diameters 14 inches and over as these are generally stocked with plain ends. Welded joints are advocated for pipe larger than 20 inches in diameter and also for smaller sizes, where applicable, to obtain hole clearance or maintain uniform grout thickness (AWWA, 1958).

Diameter - Yield.--The diameter of the well will depend on the nature and thickness of the water-bearing material, the area of openings or perforations necessary to allow for water entrance velocity at about 0.10 feet per second and the size of the pump required (E. E. Johnson, Inc., 1966). Increasing the diameter of a well increases its yield but not in direct proportion to the increase in diameter. In other words, doubling the diameter of a well increases but does not double its yield.

Table 6-3. AWWA Casing Thickness

6" diameter	0.280 inches
10" "	0.365 "
12-20" "	0.375 "
22-36" "	0.500 "

Table 6-4 shows the relationship between the increase in diameter to increase in yield for wells of the same depth in the same formation, all other things being equal. For example, an 8-inch well will yield about 10 percent more water than a 4-inch well (see underscores on Table 6-4), or a 48-inch well will yield about 30 percent more water than a 12-inch well.

The diameter of wells in which aquifer characteristics are not a critical factor may be based on the diameter of the pump bowls required to lift the desired volume of water.

If the well is to be pumped by a turbine pump, the diameter of the casing down to the lowest anticipated bowl setting should be at least two inches larger than the diameter of the pump bowls. This will allow water to flow past the bowls to the intake with minumum head loss and also allow for some deviation of the well from the vertical.

A submersible pump is one in which the pump and motor are an integral unit. The motor and pump are submerged below the expected drawdown in the well and the motor is below the pump. Pump manufacturers recommendations must be followed for an efficient installation of a submersible pump.

Installation.--Most states have state codes or laws on the requirements for installation of water wells. These minimum requirements must be met, but it should be emphasized that they are minimum requirements and can be exceeded if necessary or desirable.

During the development of a well, fines are removed from the aquifer adjacent to the well bore. This tends to form a cavity near the top of the aquifer which may result in the caving of the overlying material. If this happens the casing could settle. To prevent this, it is desirable where possible to seat the casing on hard rock or stiff clay.

All or part of the casing should be grouted in place. The grout forms a seal between the casing and the disturbed formation. This prevents surface water from entering and possibly contaminating the well. The grout should also extend deep enough to seal off any undesirable water zones between the ground surface and the top of the aquifer to prevent co-mingling of undesirable water.

In a corrosive environment a grout seal the entire length of the casing will protect it from attack. In this case the minimum grout thickness at any point is 1-1/2 inches.

Table 6-4. Relation of Diameter to Yield of Wells
(Used by permission of E. E. Johnson, Inc, 1947[Rev.], Bull. No. 1238, St. Paul)

	Well Diameters								
	2"	4"	6"	8"	12"	18"	24"	36"	48"
Percent Increase in Yield	0	10	15	20	25	33	38	48	55
		0	5	10	15	23	28	38	45
			0	5	10	18	23	33	40
				0	5	13	18	28	35
					0	8	13	23	30
						0	5	15	22
							0	10	17
								0	7
									0

Grout can be placed either through the casing or through the annular space outside the casing. The important points in placing grout are: (1) sufficient grout is available to complete the job in one continuous operation; (2) any temporary casing is removed so that the grout is in intimate contact with the casing and formation; and (3) the grout be allowed to "set up," usually about 72 hours, so that it is not damaged by vibration when drilling is resumed.

Well Screens

The most important part of any well is that area where the water flows from the aquifer into the well. The proper construction and development of this section of the well is necessary for the efficient production of the optimum amount of ground water.

Consolidated rock aquifers often may be completed as "open-hole," that is, no perforated casing or screen is required. If caving or ravelling from joints or bedding planes occurs or is likely to occur, short sections of liner can be set by squeezing or other stabilizing measures used.

In unconsolidated sand and gravel aquifers a screen or perforated casing is necessary to allow the water from the aquifer to enter the well and to stabilize the aquifer material.

Types of screens.--Screens are manufactured according to several designs and from a variety of corrosion resistant materials. One popular type features a continuous horizontal slot formed by wrapping and welding trapezoidal wire about a cylindrical frame of rods. The slot opening is determined by the spacing between the trapezoidal wire wraps and is varied according to specifications. The wire is placed with the wide side out resulting in an opening that widens toward the inside of the screen. This inward flaring slot reduces clogging of the screen to a minimum. A type having sectioned horizontal slots is made by wrapping trapezoidal wire over metal strips on perforated steel tubing. The trapezoidal wire is formed with lateral lugs at intervals to maintain the slot width. Another perforated pipe design is like a sand point but much larger. It consists of woven screen of varied gauge wrapped on casing perforated with 5/8-inch holes. The screen is protected by 1/2-inch mesh galvanized iron hardware cloth. Other screens are galvanized iron casing with punched openings in lattice, crowfoot, shutter or louvered slit design. Louvered horizontal openings are reported more effective in controlling unconsolidated materials than vertical slots.

Perforations can also be made in the field with a cutting torch or the casing can be perforated in place in the aquifer with a casing perforator or knife. Openings made in this manner are ragged, uneven, and the open area is small.

Perforations can also be made with a hacksaw either in the shop or in the field. Perforations made in this manner should be oriented transverse to the casing length. Lengths of perforations should be governed by the need for maintaining casing strength and increasing the void ratio to about 20 percent of the area if possible. They may be 1/6 to 1/8 the circumference of the pipe depending upon requirements and needs. Perforations can be placed in rows the full length of an aquifer and separated by equal spacings of unperforated casing. They can be as close together as the width of the slotted voids thus making it possible to approach 20 percent of the area for a favorable void ratio.

In most cases, if optimum production from the aquifer is required, spiral-wound well screen is necessary. If less than optimum production is acceptable, one of the less costly mechanically or field perforated well screens can be used.

Materials.--Well screens are subject to corrosion that reduces their effectiveness and may eventually weaken them to the point of failure. All ground water contains some corrosive or encrusting elements depending on the materials with which it has been in contact. Seldom do both occur in the same water. Corrosion is chemical erosion or removal of metal from the screen.

Rate of corrosion depends on characteristics of both metal and water. The best way to guard against corrosion is to use a metal resistant to attack. A screen constructed of a single metal avoids the possibility of galvanic action and electrolytic corrosion. Another method of protecting against electolysis is the introduction in the system of a metal low on the electrochemical scale that will be corroded instead of the casing or screen. Rods of magnesium suspended in the water are excellent for this purpose (Todd, 1959).

An analysis of the water will aid in selecting a metal for the screen best suited to the conditions. The following tabulation lists the various metals and their recommended usage:

1. Monel Metal (approximately 70 percent nickel and 30 percent copper). Use where waters are extremely aggressive or frequent acidizing will be required.

2. Stainless Steel (74 percent low carbon steel, 18 percent chromium, 8 percent nickel).
   Super-Nickel Metal (30 percent nickel and 70 percent copper).
   Use where the pH value of the water is below 5 or above 8 when the bicarbonate, chloride, and sulfate ions exceed about 60 ppm. They will stand acidizing treatment but inhibited acids are recommended.

3. Everdur Metal (96 percent copper, 3 percent silicon, 1 percent manganese).
   Silicon Red Brass (83 percent copper, 1 percent silicon, 16 percent zinc).
   Anaconda Red Brass (85 percent copper, 15 percent zinc).
   Common Yellow Brass (approximately 67 percent copper and 33 percent zinc).
   Use when the pH value of the water is between 5 and 6 or above 8. Acidizing with inhibited acid is preferred.

4. Armco Iron. Use in water with pH between 6 and 8 where mild carbonate deposition on the screen is anticipated. It will stand two or three light acidizing treatments.

5. Mild steel, soft iron, galvanized iron or steel and bitumen or enamel-coated iron or steel have poor to fair resistance to corrosion. The bitumen and enamel coatings usually break and chip during shipment and installation, thereby reducing their effectiveness. These materials can be used where the pH of the water is between 6 and 8 and light carbonate deposition is expected. They will stand one or two light acidizing treatments.

Normally, the more corrosion resistant the screen material is, the more expensive it is. When recommending the type of screen to install in a corrosive environment, comparison of the cost of removal and replacement of a less costly screen with the cost of a corrosion resistant screen should be made.

Slot size - natural filter pack.--The well screen is the intake area of a well. It should be designed so that it will provide sand-free water at its maximum rate of production. This can usually be accomplished by developing a natural or artificially produced sand and gravel filtering zone around the screen.

This zone is commonly called a *gravel pack.* This term is misleading because packs may consist of different size particles--from fine sand to coarse gravel--depending on the size and gradation of the aquifer materials. The terms *natural filter pack* and *artificial filter pack* are more precise and will be used in this section of the National Engineering Handbook.

The filter pack, in effect, increases the diameter of the well, thereby reduces head loss which results in a more efficient well. A natural filter pack is developed by removing, through the screen, the fine material of the aquifer adjacent to the screen. An artificial filter pack is placed, from the surface, in the annular space between the aquifer and the screen.

The width or diameter of the openings in the well screen are commonly called *slot size*. The optimum slot size is the largest size that will maintain the stability of the aquifer or pack material and is determined by analysis of the grain size distribution curve.

The uniformity coefficient *(Cu)* of aquifer or pack material is the ratio of the 60 percent finer material (D_{60}) to the 10 percent finer material (D_{10}).

$$Cu = \frac{D_{60}}{D_{10}}$$

It is a means of grading or rating uniformity of grain size. A *Cu* of unity means the grains of the material are practically all of the same size while a large *Cu* indicates a large range in sizes.

If the uniformity coefficient of the aquifer material is 2.0 or less an artificial filter pack will usually be required. If no coarse particles (between 0.5 and 1.0 mm) are present, an artificial filter pack will usually be required even though *Cu* is greater than 2.0.

The *Cu* of aquifer materials is a guide but there are no hard and fast rules on when an artificial filter pack is or is not required. Three wells constructed in a fine sand aquifer at Coos Bay, Oregon, seen to substantiate this point (E. E. Johnson, 1966, pp. 153-154). One well was constructed with slotted wood pipe and a double artificial filter pack, the second with a slotted wire well screen and artificial filter pack, and the third with a slotted wire well screen and naturally developed filter pack. The specific capacity of the three wells in gallons per minute per foot of drawdown was: wood pipe--6.7; well screen with artificial filter pack--19.6; and well screen with natural filter pack--17.9. In this case the well with the artificial filter pack and wire well screen was slightly better than the well with the naturally developed filter pack and both were much better wells than the well with the slotted wood pipe and artificial filter pack.

Experience with other wells in the same area with similar conditions will help in determining if an artificial filter pack is required in borderline cases.

The slot size for a naturally developed filter pack in a sand aquifer should be such that about 60 percent (D_{60}) of the aquifer material will enter the screen (E. E. Johnson, 1966). If the water is corrosive, a slot size to pass 50 percent (D_{50}) is recommended because corrosion may eventually increase the slot size enough to allow the well to produce sand.

Figure 6-10 is an example of a grain size distribution graph of a sand aquifer. The *Cu* is 2.1 which is on the borderline of requiring an artificial filter pack. Most well screen slots are fabricated in even increments of 0.01 inches. In this case the actual design size is 0.024 which is between fabricated sizes 0.020 and 0.030. In practice the next smaller (0.020) size is installed.

Form SCS- 353a

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

GRAIN SIZE DISTRIBUTION GRAPH

Project ______________________ Location ______________________

DESIGN DATA for Well No. 1

Sieve No	% Passing
3/8	99
4	97
10	90
20	72
40	19
60	4

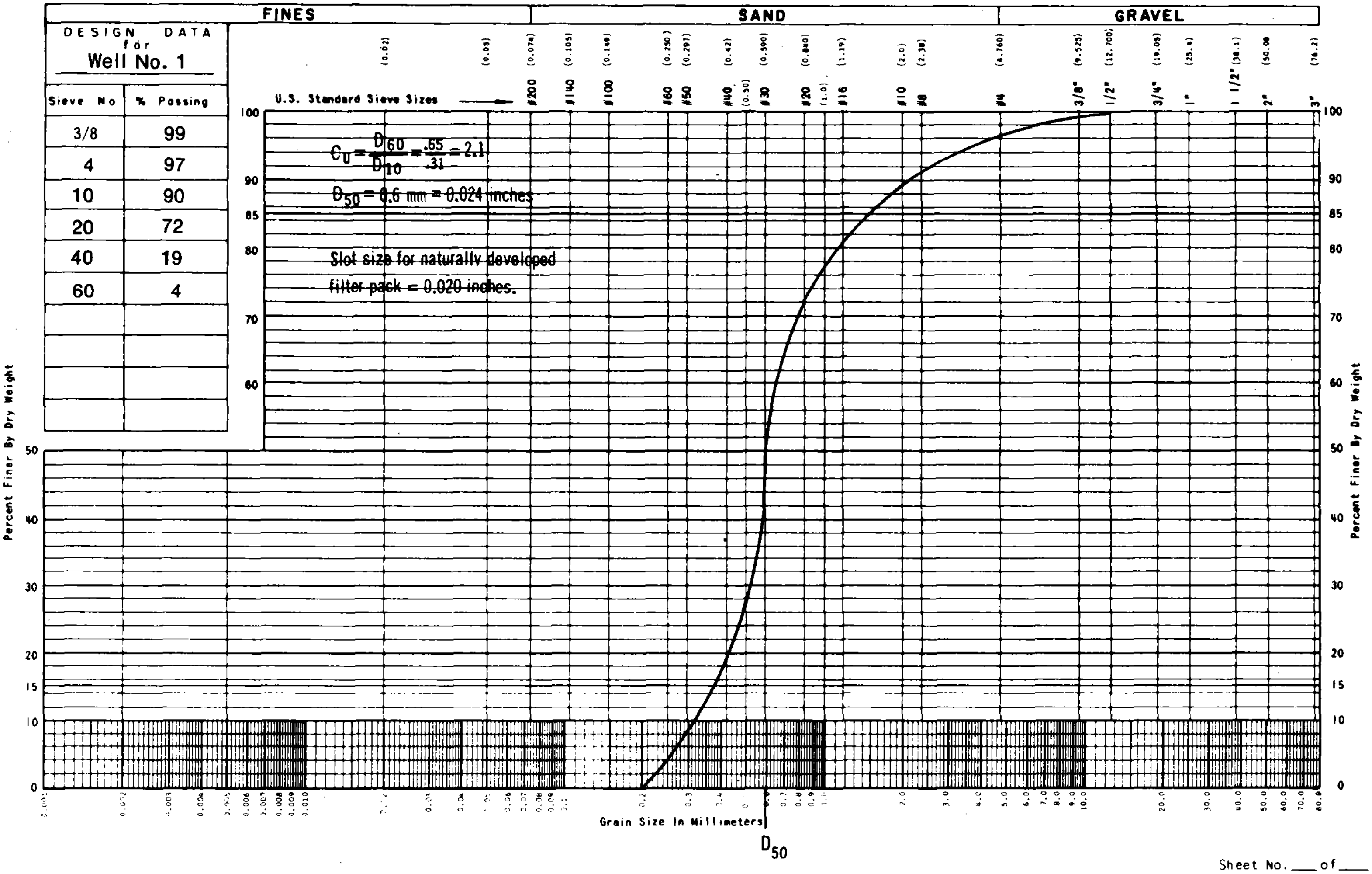


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FIGURE 6–10. Natural Filter Pack Design

If the aquifer is coarse sand and gravel a slot size to pass 50 to 70 percent (D_{50} to D_{70}) of the aquifer material is recommended. The 70 percent size allows more of the aquifer material to enter the well and, therefore, development of the well takes longer and is more expensive. Figure 6-11 is a grain size distribution graph of a sand and gravel aquifer.

The Bureau of Reclamation (1964) recommends for a naturally developed filter pack, a slot size equal to one-half the D_{85} size of the aquifer material. They also make adjustments in grain size distribution curve if there is a sharp break in the curve where some sizes are missing or if *Cu* is large. In most cases the Bureau's method and the method described above give about the same designed slot size.

Artificial filter pack (gravel pack).--The following tabulation lists conditions when it may be desirable to install an artificial filter pack:

1. To stabilize fine-grained, poorly-sorted sand aquifers to avoid sand pumping.
2. To permit the use of larger slot openings and resultant better well efficiency in fine-grained aquifers.
3. In formations of thin alternating zones of coarse and fine aquifer material it is difficult to position screens of various slot sizes accurately. The use of an artificial filter pack will permit use of a single slot size screen and eliminate the positioning problem.
4. In deep-lying aquifers it may be less costly to set a small diameter artificially filter packed screen in an underreamed section of hole than to drill the full diameter hole to total depth.
5. Loosely-cemented, fine-grained sandstone aquifers that cannot be completed open hole because of sand pumping and require very fine slot openings to properly retain the sand can advantageously be constructed with an artificial filter pack.

One indication of the need for an artificial filter pack may be determined from the uniformity coefficient of the aquifer materials. If *Cu* is less than 2.0 and D_{10} size is less than 0.01 inches (0.25 mm), a filter envelope may be necessary. An artificial filter pack may also be installed in an aquifer containing fine materials when it is desirable to use larger well screen openings than are indicated by the sieve analysis. This usually occurs when *Cu* is between 2.0 and 3.0 and D_{60} is less than 0.017 inches (0.42 mm).

The most satisfactory size of filter material is that size which minimizes head losses through the pack and at the same time prevents excessive sand movement into the well. A filter pack mixture of varying sizes is unsatisfactory because the smaller particles fill the spaces between the larger ones thereby reducing the voids and increasing resistance to water flow.

The sizes of filter material to be used are determined from a sieve analysis of the aquifer material. They are based on a relationship

Form SCS-353a

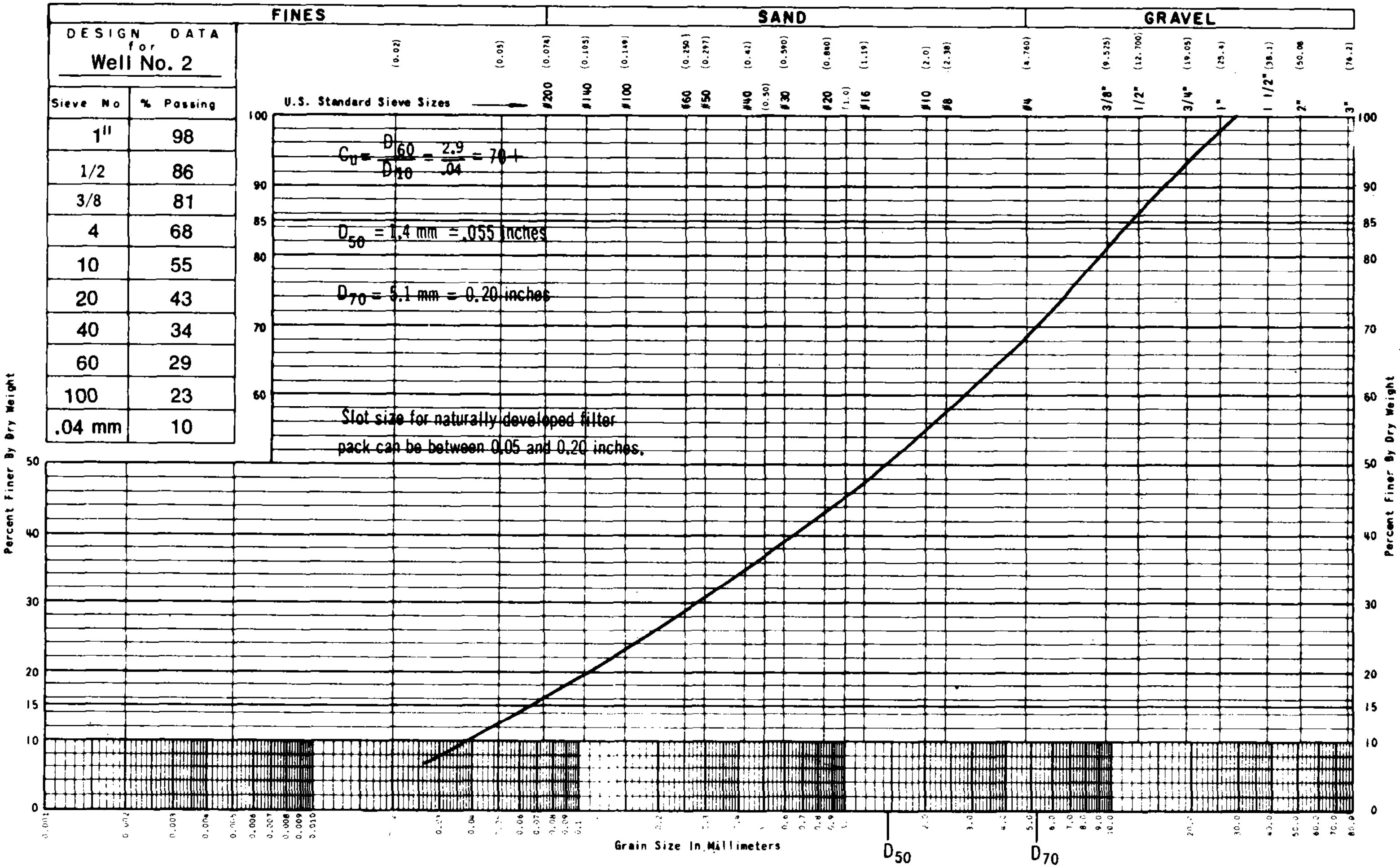
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

GRAIN SIZE DISTRIBUTION GRAPH

Project ______________________ Location ______________________

DESIGN DATA for Well No. 2

Sieve No	% Passing
1"	98
1/2	86
3/8	81
4	68
10	55
20	43
40	34
60	29
100	23
.04 mm	10



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58M-35

FIGURE 6-11. Natural Filter Pack Design

between the material used in the pack and the size of sand found in the aquifer. This relationship is known as the Pack-Aquifer (P-A) ratio and is defined as the size of sieve opening that will pass 30 percent of the filter material in the pack divided by the size of sieve opening that will pass 30 percent of the aquifer material (E. E. Johnson, 1966). Thus:

$$\text{P-A ratio} = \frac{D_{30} \text{ for the pack}}{D_{30} \text{ for the aquifer}}$$

Experiments have shown that head losses through filter packs increase as P-A ratios decrease. In order to minimize these losses, the lower limit of the P-A ratio should be 4.0. It has also been found that sand movement increases as P-A ratios increase and that ratios exceeding 9.0 become unstable. For this reason the upper limit of the P-A ratio is 9.0.

The design of the filter pack is done in the following steps:

1. Construct a grain size distribution graph of the aquifer material. The filter pack design is based on the gradation of the finest aquifer material that is to be screened.
2. Multiply the D_{30} size by a factor of four to nine. A factor of four is used if the formation is fine and uniform (*Cu* less than 3.0); six if it is coarse and non-uniform; and up to nine if it is highly non-uniform and contains silt.
3. Plot the point from step 2 on the 30 percent abscissa and draw a smooth curve with a uniformity coefficient of about 2.5 through it. This is the gradation of the optimum filter pack.
4. An envelope curve of the permissible limits of the filter pack is drawn plus or minus eight percent of the optimum curve.
5. Select well screen slot openings that will retain 90 percent of the filter material.
6. Gravel or sand for the artificial filter pack should be of washed, well-rounded, hard and insoluble particles.

The method of selecting filter pack sizes and determining screen opening limits is illustrated in Figures 6-12 and 6-13. The screen opening limits without an artificial filter pack are given for comparison. The opening limits with the artificial envelope are two to three times those without.

Natural subrounded material and crushed rock have been tested by Karpoff (1955) to develop design criteria for protective filters draining foundations of engineering structures. The following criteria are given as a guide for filters used in canal structures or other hydraulic structures involving high water heads where rapid dissipation of uplift pressure is desired. In the following ratios, FM represents the filter material, BM the base material, and R the FM-BM ratio (equivalent to P-A ratio discussed above).

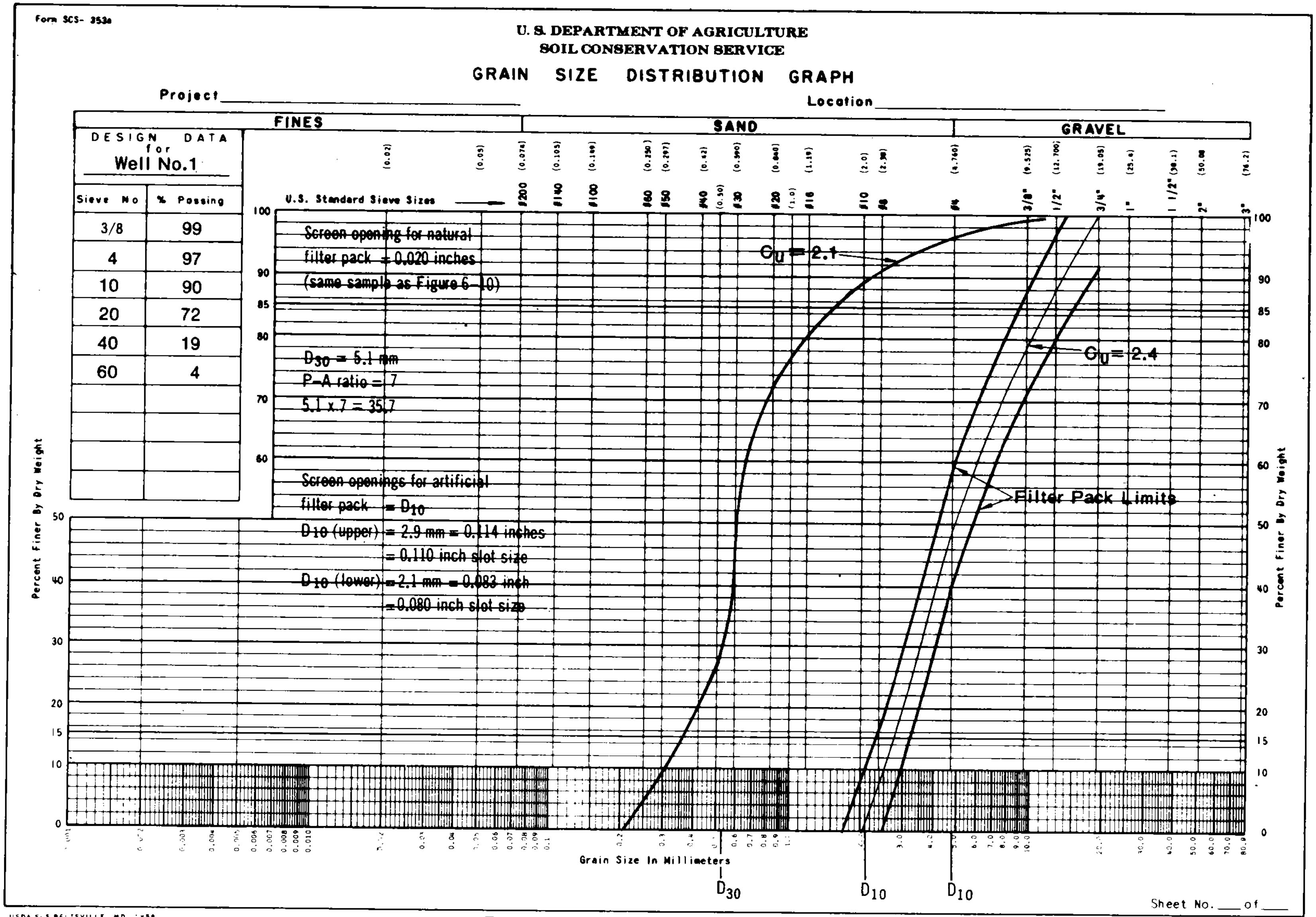


FIGURE 6–12. Artificial Filter Pack Design

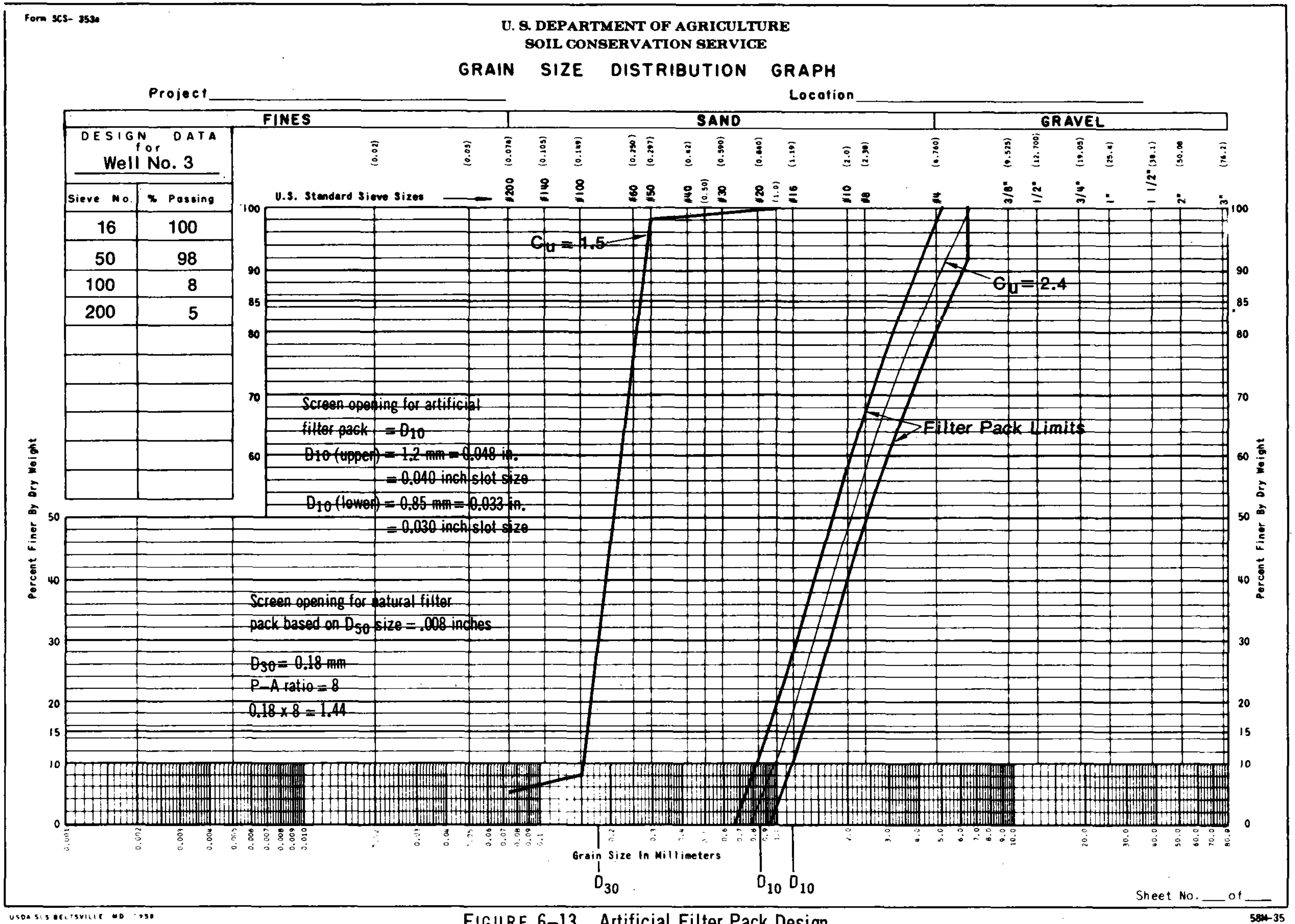


FIGURE 6–13. Artificial Filter Pack Design

For uniform grain size filters:

$$R_{50} = \frac{50 \text{ percent size FM}}{50 \text{ percent size BM}} = 5 \text{ to } 10$$

For graded filters of subrounded particles:

$$R_{50} = \frac{50 \text{ percent size FM}}{50 \text{ percent size BM}} = 12 \text{ to } 58$$

$$R_{15} = \frac{15 \text{ percent size FM}}{15 \text{ percent size BM}} = 12 \text{ to } 40$$

For graded filters of angular particles:

$$R_{50} = \frac{50 \text{ percent size FM}}{50 \text{ percent size BM}} = 9 \text{ to } 30$$

$$R_{15} = \frac{15 \text{ percent size FM}}{15 \text{ percent size BM}} = 6 \text{ to } 18$$

The ratio range (5-10) for uniform grain size filters agrees fairly closely with the ratio range (4-9) recommended herein for filter envelopes.

The ratio range for graded filters of subrounded particles has higher limits than Pack-Aquifer ratios for non-uniform gravel packs of well-rounded particles recommended by Kruse (1960) who reports: "Test results indicated the following values as the upper limits of pack-aquifer ratios if a stable filtering action was to be maintained.

Aquifer	Gravel Pack	Limiting P-A Ratio
Uniform	Uniform	9.5
Non-uniform	Uniform	13.5
Uniform	Non-uniform	13.5
Non-uniform	Non-uniform	17.5

"Materials with uniformity coefficients of 1.3 to 2.0 were considered uniform and from 3.0 to 5.0 non-uniform."

Filters for foundations are designed to permit water flow and relieve pressure while permitting no movement of base materials. High permeability, allowing large water flow, is usually a secondary consideration. Filter envelopes for wells, however, must have high permeability and permit very little to no aquifer (base material) movement. Methods of blending aggregates into a filter of the proper gradation are given in National Engineering Handbook, Section 19, Construction Inspection.

To meet well requirements, pack-aquifer ratios for graded, subrounded materials or crushed rock should, if Bureau of Reclamation criteria is used, be selected at or near their minimum ratios. These minimum ratios agree closely with, though are slightly lower than, P-A ratios for non-uniform well-rounded materials recommended by Kruse.

Screen diameter and entrance velocity.--The ability of water to transport sand varies as a power of the water's velocity. This power is possibly as much as the cube of velocity (Rubey, 1938). An entrance velocity of water into a well screen that approaches but does not exceed 0.1 foot per second is desirable. It has a marked effect on the amount of sand carried into the well, head losses in the screen and the rate of incrustation or corrosion.

The diameter of the screen can be determined to provide enough total area of screen openings so that entrance velocity will approach 0.1 foot per second after the length and slot size are fixed.

Most screen manufacturers furnish tables of open area per foot of screen for the various slot openings and diameters they manufacture. With these tables the transmitting capacity of the screen can readily be calculated. An example of this calculation follows.

The desired discharge of a well is 400 gallons per minute through a ten-foot section of 0.040 inch slot screen. What is the minimum diameter screen that will provide this yield at the desired 0.1 foot per second or less entrance velocity?

An 8-inch telescoping screen has 87 square inches of open area per foot of screen and:

$$Q = AV \text{ or } V = \frac{Q}{A}$$

$$V = \frac{400 \text{ gpm}}{870 \text{ in}^2} \times 0.32 = 0.15 \text{ ft/sec}$$

0.32 is a conversion factor obtained as follows:

$$\frac{gal}{min} \times \frac{1}{in^2} \times \frac{ft^3}{7.48\ gal} \times \frac{1\ min}{60\ sec} \times \frac{144\ in^2}{1\ ft^2} = 0.32$$

An alternate method is to calculate the quantity of water that will flow through the screen at the permissible velocity of 0.1 foot per second and compare it to the required quantity. This is done by multiplying the open area per foot of screen times the conversion factor 0.31.

$$87\ in^2 \times 10\ ft\ long \times 0.31 = 270\ gal/min$$

The conversion factor 0.31 is obtained from

$$Q = AV = in^2 \times \frac{0.1\ ft}{sec} \times \frac{1\ ft^2}{144\ in^2} \times \frac{60\ sec}{min} \times \frac{7.48\ gal}{ft^3} = 0.31$$

The analysis by the two methods shows the entrance velocity is too high and a larger diameter screen is required.

A 12-inch, 0.040-inch slot screen has 130 square inches of open area per foot. The entrance velocity for 400 gallons per minute is:

$$V = \frac{400}{1300}(0.32) = 0.099\ ft/sec$$

The quantity of water flowing through the screen at the permissible velocity is:

$$Q = 130\ in^2 \times 10\ ft \times 0.31 = 400 + gal/min$$

A twelve-inch screen is minimum size that will provide the required quantity of water at the permissible velocity.

It must be emphasized that these calculations are an analysis of the hydraulic characteristics of the screen itself at an arbitrary entrance velocity and have nothing whatever to do with hydraulic characteristics of the aquifer.

Placing well screen.--Any commercial well driller should have adequate knowledge, skill, and tools to properly install well screens and filter packs. The details of the various methods and techniques are discussed in E. E. Johnson (1966). Some general guidelines and criteria will be outlined here.

There are two methods generally used in installing well screens.

Under most conditions it is desirable to telescope the screen through the casing. In this technique, at least five feet of blank casing the same diameter as the screen is attached to the top of the screen and extends into the bottom of the casing when the screen is in place. The space between the top of the screen assembly and casing is sealed by a lead packer or other suitable material. In all cases, the blank casing should be long enough so that the top of the screen is at least two feet and preferably five feet below the top of the aquifer. This will allow for the caving of overlying material due to removal of fines from the aquifer during development of the well.

The other technique is to fasten the screen to the bottom of the casing and install them as one unit. This makes removal and repair or replacement of the screen impractical. In all cases the vertical relationship of the top of the screen and aquifer explained above must be maintained.

Most aquifers are not isotropic and contain alternating beds or zones of different gradation. Well screen slot sizes should be designed for this variable gradation. Installing a multiple slot size well screen where fine material overlies coarse, the fine-slotted screen should extend two to five feet into the coarse zone. This will prevent fine material from entering the coarse screen when the formation slumps during development. If very fine sand, silt, or clay zones are present in an aquifer, blank casing should be set opposite them.

To prevent aquifer material from entering the screen from the bottom, it must be closed. This can be accomplished by welding a metal plate in a section of blank casing on the bottom of the screen or by cement grout. If bail-down or wash-down shoes are used, they should incorporate a device for closing the bottom opening after the screen is in place.

Metals used in screen assemblies should be the same insofar as possible. Dissimilar metals below the water table create galvanic currents which may accelerate corrosion.

In theory, a filter pack thickness of only two or three grain diameters will successfully control the aquifer material. In practice three inches is about the minimum thickness of an artificial filter pack that can be installed. A filter pack greater than about eight inches does not increase the yield of the well and makes development more difficult.

Artificial filter packs may be placed by tremie, pumped, or other suitable method. Care should be taken to insure that the screen is centered in the well so the filter pack is placed on all sides of the screen. The method of placing the filter pack must not result in segregation of the sizes of the pack material. This is extremely important in non-uniform material.

In wells drilled by the rotary method it is necessary to make the diameter of the hole a few inches larger than the diameter of the screen. This provides clearance for setting the screen. After the screen has been set it is often advantageous to fill this annular space to prevent fines overlying the aquifer from caving. The material used in this procedure is called a formation stabilizer. The gradation is not too important, but it should be about the same as the aquifer or slightly larger. The size of the slot openings of the screen are based on the gradation of the aquifer.

Centering the well screen and careful placement of the formation stabilizer to prevent segregation is not required.

Well Development

Well development is the process of removing clay, silt, fine sand, drilling mud and other deleterious material from the vicinity of the well screen and from behind the filter pack. This increases the permeability of the material surrounding the screen, thus increasing the efficiency of the well. Development has proved beneficial in consolidated deposits in some instances but the following discussion relates to development in unconsolidated deposits.

Wells may be developed using one or a combination of several methods including surging, backwashing, jetting, use of compressed air, pumping, use of dry ice, acid, and dispersing agents. Some are more effective under certain conditions than others. Knowledge of drilling methods and how particular formations react to development are requisites for proper selection.

Care must be taken in developing wells. As in other phases of design, use information from the record of materials penetrated to guide development work. Operations such as pumping, surging, jetting and backwashing should start slowly. Results should be carefully observed and the tempo of operations increased only if the method is operating as expected. If the aquifer is overlain by fine sand or silt, there is danger these materials may be washed down into the aquifer by surging and spoil the well or prolong development work.

Bridging of fine sand in the aquifer close to the well may result from too violent actions at the beginning of work. Bridging of sand in water-bearing formations is important and knowledge of the process of bridging is necessary to an understanding of development work. When water is pumped from a well, there is a tendency for sand particles in the formation to move toward the well. Because the steady pull of pumping is in one direction, finer sand grains wedge against each other and bridge across openings between coarser grains. The only way bridging can be prevented and fine grains removed is by keeping the water agitated by reversing the direction of flow.

Development by Surging

Surging is one of the most effective and commonly used methods of developing wells in sand and gravel formations. Surging is working some type of block or plunger up and down in the well so that water is alternately forced out into the surrounding formation and then allowed to flow back into the well. This action loosens fine sand or gravel particles near perforations in the casing and carries finer particles into the well where they can be removed. Surge blocks are illustrated in Figure 6-14.

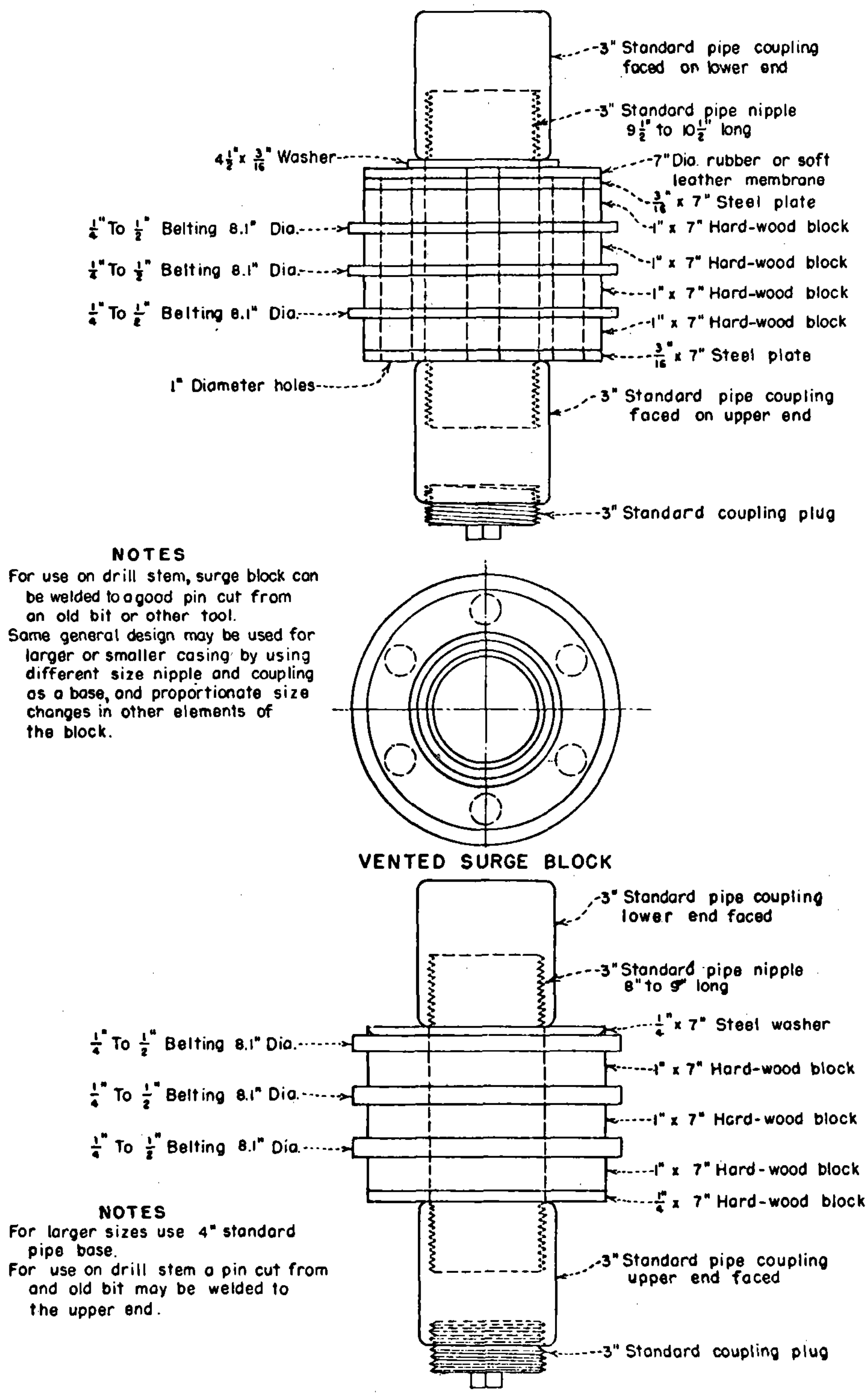
Development by Backwashing

Several procedures are used in backwashing and all produce a surging effect at the perforations or screen. They include use of water and compressed air, and while usually not as forceful as surging with a plunger, are in some instances very effective. Backwashing under pressure or with large volumes of water should be done with caution if the casing is not tight, or the aquifer is overlain by fine sand, silt or clay. Provision must be made for frequent removal of fines washed into the well. Backwashing is quick, inexpensive, and effective when there is not a great quantity of fines to be removed.

The simplest method of backwashing is to pour a large volume of water into the well as rapidly as possible and remove it with bailer or sand pump as soon as possible. The wash water can be re-used if screened or dumped into a tank having a settling compartment. The larger the volume of water and the quicker the bailing, the greater is the effectiveness of this method. It is often surprisingly effective.

A more forceful method of backwashing is to pump a large volume of water into the well under pressure. The water is pumped to the perforations or screen through a wash line passing through a cap or bushing at the top of casing. Pumping is continued for two to five minutes to establish flow into the aquifer. The cap is then removed and the well bailed as quickly as possible. Instead of bailing, the well may be flushed hydraulically by addition of a side outlet valve at the top of casing. After application of pressure, this valve is opened and sufficient water pumped down the wash line to bring up the fine materials drawn through the screen. This method is fairly effective where conditions are favorable, and has been used successfully by many drillers on large and small wells.

Backwashing and removal of fines may be accomplished with a turbine pump installed without a foot valve. The procedure is called "rawhiding"



SOLID SURGE BLOCK
FOR USE IN 8" DIAMETER CASING

Figure 6–14. Surge Blocks

(From U.S. Bur. Rec., 1964)

the well and consists of intermittently operating the pump so as to produce relatively rapid changes in pressure head in the well.

Meeks (1952) states, "The well should be pumped slowly at first, with a gradual increase in rate. At each rate, pumping should be continued until no more sand is discharged by the well. This procedure should be continued until maximum capacity of the pump or well is reached. The pump should not be shut down until this preliminary pumping is completed. If pumping is stopped during this stage, there is danger of sand clogging the well or locking the pump. If pumping is started at maximum rate, there will be a tendency for sand particles to bridge."

When the preliminary pumping has been completed the well is ready for treatment. Three distinct reactions may be obtained by operating the pump in different ways. The methods are summarized here from E. E. Johnson (1959):

1. Pump well at fullest capacity until greatest drawdown is obtained. Stop pump and allow water to return to full static water level. Repeat this procedure many times until well shows no further improvement. This method develops the maximum difference in pressure head and an appreciable surge at the well end by return of water in the pump column when the pump is shut down. This method is not as vigorous as the following methods nor as severe on the pumping equipment.

2. Pump well at fullest capacity until maximum drawdown is obtained. Then stop and start pump alternately at short intervals. This procedure holds the water level down and forcefully agitates the materials at the well end by backwash of water in the pump column. Care must be taken not to start the pump while the shaft is still turning backward.

3. Run pump until water is lifted to the surface. Stop until water drains back down the pump column. Repeat this process. No effort is made to draw water level down. The object is agitation by starting and then reversing flow.

Most drillers who develop wells by rawhiding use a combination of these procedures. Only experiment and experience can determine which will apply at a given location. Rawhiding is not vigorous enough where heavy development is needed and it is hard on pumping equipment. It is inexpensive, speedy and effective under proper conditions.

In backwashing wells with compressed air, water is forced out through the perforations or screen by the pressure of air. This method cannot be used unless the water in the well stands at a considerable height above the perforated part of the casing. When this method is used, the top of the casing is sealed with an airtight cap through which an air line extends. The air line is equipped with a three-way valve so that the pressure in the well can be released at any time. When air is turned into the air line, the pressure forces water in the well out through the perforations. When air begins to escape through the perforations, it is shut off and pressure in the well released by opening the valve. A pressure gage on the air line shows when the pressure has built up enough to force air through the perforations. When air starts to escape, the pressure will no longer rise. When pressure is released, water will flow back into the well, carrying fine sand with it. Periodically, the cap is then removed and sand is removed with the bailer. The process should be repeated until no more sand is brought in. To make this method more effective, it should be combined with pumping by air. See Figure 6-15.

Development by Jetting

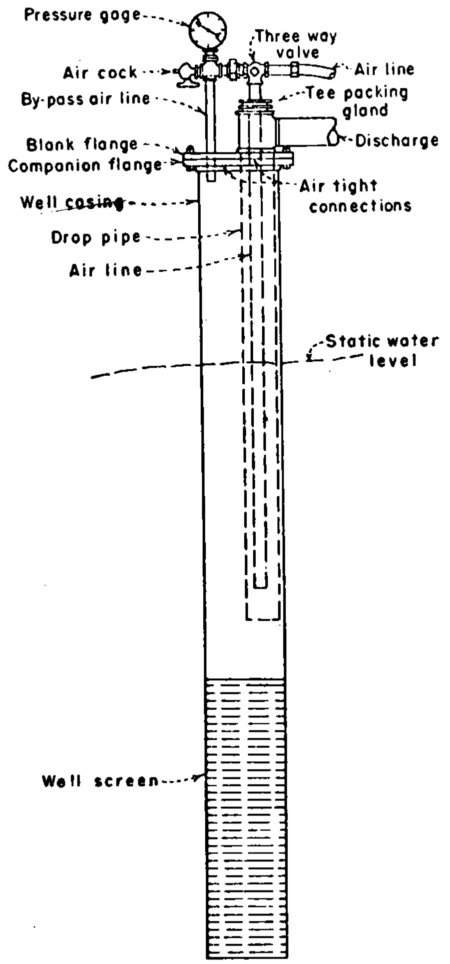
Jetting is a recent addition to the usual procedures for completing wells. It is described in detail in E. E. Johnson (1966). The procedure consists of operating 2 or 4 horizontal water jets inside the well so that high velocity streams of water shoot out through the screen openings. The jetting tool has an outside diameter 1 inch less than the inside diameter of the screen. Horizontal nozzles on its perimeter have orifices 1/4 inch, 3/8 inch, or 1/2 inch in diameter. The tool is slowly rotated and gradually raised and lowered so that the entire surface of the screen is jetted. Fine sand, silt, and clay are washed out of the formation around the screen and brought into the well above or below the jet. It is desirable that light pumping to remove fines continue while jetting.

Reports indicate the continuous slot type well screen permits effective development by jetting. Louvered or shutter type screens and pipe-base screens present too little open area for the horizontal jet to be effective.

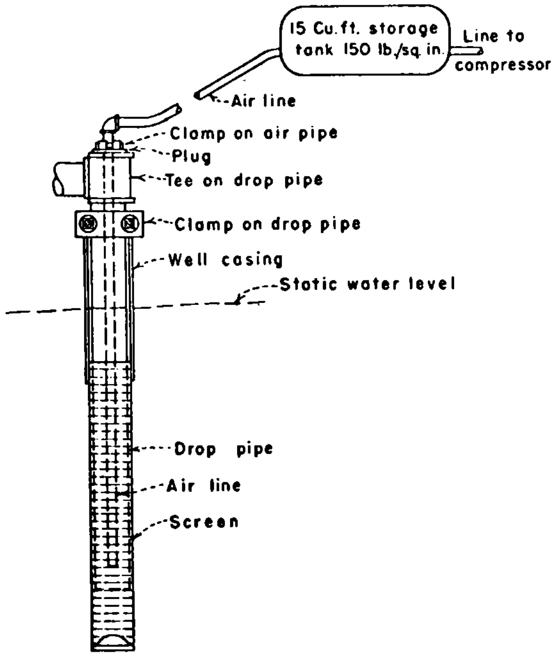
Development by Use of Air ("Open Well" Method)

Meeks (1952) states, "Use of air is an effective means of developing a well when properly done. Development with air is a combination of surging and pumping. Large volumes of compressed air are suddenly released at the bottom of the well, producing a strong surging action and pumping at the same time, as with an ordinary air lift pump. Developing with air is best suited to wells of small diameter where depth of water in the well exceeds two-thirds of the total depth of well.

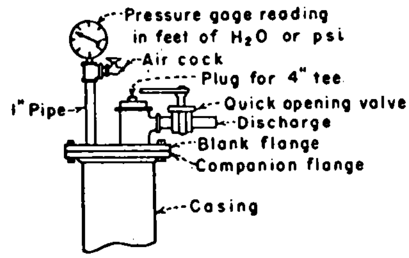
"In using air for development, a drop pipe and an air line are necessary. The drop pipe is lowered to within about two feet of the bottom of the well and the air line placed so it is a foot or two up in the drop pipe. The well is pumped by air until the water is free from sand. A valve on the air line is then closed and pressure in the tank built up to 100 or 150 pounds. The air line is lowered a foot or so below the drop pipe and the valve opened quickly, allowing air to rush into the well under full pressure. There will be a brief forceful surge of water; and if the air line is then pulled back into the drop pipe, a strong reverse flow will be produced up the drop pipe, effectively agitating the water-bearing formation. The cycle of surging and pumping is continued until the water is free from sand, indicating that development work is complete." See Figure 6-15.



ARRANGEMENT FOR BACKWASH DEVELOPMENT OF WELL USING COMPRESSED AIR



ARRANGEMENT FOR SURGE DEVELOPMENT OF WELL USING COMPRESSED AIR



ARRANGEMENT AT CASING HEAD FOR DEVELOPMENT WITH DRY ICE

Figure 6–15. Development with Air or Dry Ice

(From U.S. Bur. Rec., 1964)

Development by Over Pumping

This is the simplest and probably most common method of finishing wells ending in sand or gravel. It consists of pumping the well at a capacity that will develop excessive or at least greater drawdown than is planned for regular operation. Over pumping clears the well at or above its natural capacity but accomplishes little actual development because it produces no reversal of flow and little agitation of aquifer materials. It has three weaknesses: (1) It is not effective for increasing production because few fines are removed; (2) Over pumping tends to cause bridging of fine sand in the formation and reduction of permeability in vicinity of the well; (3) It often requires larger pumping equipment than may be conveniently available. A more effective method should be used if permeability of the aquifer can be increased by development.

Development by Use of Dry Ice (solid carbon dioxide)

The surge produced is similar to backwashing with compressed air in a closed well except that pressure is built up by evaporation of the dry ice. Light surging in wells 6 inches to 10 inches in diameter may be accomplished by using 10 or 15 pounds of dry ice broken into small pieces, while 25 to 50 pounds will produce a heavy surge. The casing should be open at the top to allow escape of gas and possibly a geyser of muddy water. A rule of the Illinois State Water Survey states, "There is no danger of freezing as long as there are 11 pounds of water in the well for each pound of dry ice used." See Figure 6-15.

Dry ice is usually not effective if the depth of water in the well is small in proportion to depth of well. If clay is present, use of a polyphosphate dispersing agent beforehand will improve the effectiveness of treatment. This method is inexpensive and convenient. It has met with considerable success under some conditions, has been ineffective under others, and in a few cases has damaged wells by its violent reaction.

Use of Acids

If the water-bearing sands or gravels are partially cemented by $CaCO_3$, the use of acid with the several methods of well development will assist in improving yield. Acids act to free fine materials and increase void space by dissolving the cement. Dilute hydrochloric acid, HCl (usually a 15 percent solution) is commonly used. Sulphuric acid, H_2SO_4, is used less frequently because products of its reaction (sulphates) are not as soluble in water as chlorides. A recent development, sulfamic acid, a granular material that forms a strong acid when dissolved in water, has many advantages. Its use is described in E. E. Johnson (1966). Sulfamic acid should not be confused with sulphuric acid. It reacts to form sulfamates which are soluble in water. Granular sulfamic acid is shipped in dry form and is convenient and safe to handle. In dry form it is not irritating to dry skin, but in water solutions it becomes a strong acid and should be handled the same as other strong acids.

The kind, method, and quantity of acid needed to facilitate well development depend on the amount of cementing material in the aquifer, the size, depth, and construction of the well.

Use of Dispersing Agents

Use of glassy phosphates (polyphosphates) in well development will assist in removing silt, clay, iron oxide, and manganese oxide. Polyphosphates have ability to loosen and disperse these materials permitting their removal by surging and backwashing. Glassy phosphates can be handled safely and are not injurious to pumps.

Explosives

Explosives are used in some instances in an attempt to increase the yield of wells in rock aquifers.

The following items have to be considered in dynamiting wells:

1. Diameter of the hole;
2. character of the rock;
3. rate of drilling;
4. depth of placement of shot under water.

In addition, the log of the hole should be evaluated and the size of the shot be limited to 50 pounds of 60 percent dynamite unless the formation or stratum being shot is 200 feet or more in thickness. Milaeger (1942) discusses this procedure in detail.

Mylander (1952) has developed a method of using what is called vibratory explosives. This involves using special explosives that are spaced on various leads that correspond to permeable areas. The charges are detonated at predetermined intervals and produce a continuous series of shock waves of relatively long duration. This method is said to use explosives only 1/9 as powerful as primacord and produce beneficial shock waves for a period 500 times as long.

Livestock and Domestic Wells

The criteria discussed in this chapter has been mainly for large yielding irrigation-type wells. Much of this criteria is also applicable to livestock and domestic wells where the required yield is much less.

The criteria on selection of well screen openings, types of metal, entrance velocity, and well development are all valid for small wells.

There are several points to consider when designing small yielding wells. The top of the screen should be far enough below the water table to allow for seasonable and long-term fluctuations of the water table. Screen a short interval of a coarse-grained zone in the aquifer in preference to a longer section of a fine-grained zone. (See the section on entrance velocity.) To increase the yield of a well, increase the length of the screen and not the diameter. Doubling the length will about double the yield while doubling the diameter will not increase the yield significantly.

Always consider sanitary protection. All drainage should be away from the well. Locate the well up the hydraulic gradient from potential sources of contamination such as barns, septic fields, etc. The casing should be grouted in place to prevent contaminated surface or ground water from co-mingling with the water in the aquifer.

Pumping Tests

Pumping tests are usually conducted for one of two reasons: (1) to obtain information on performance and efficiency of the well from which to base pump and power requirements; or (2) to determine the physical characteristics of the aquifer which furnishes valuable information for water management developments.

Test results show well characteristics and permit estimating optimum pumping rate, pump setting, pump capacity, and power required. Testing is done after completing development and preferably after 30 days steady pumping. It consists of: (1) measuring the static water level; (2) determining whether well is artesian or non-artesian; (3) determining height of static water column; (4) measuring water level and yield while pumping at a near maximum rate.

The optimum yield and required lift may be estimated by converting drawdown obtained from test to percent of possible drawdown and reference to Figure 6-9. The curves shown are average drawdown-yield relations for a large number of wells. It is noteworthy that non-artesian wells obtain about 77 percent of possible yield at 50 percent drawdown and artesian wells produce about 55 percent yield at 50 percent drawdown.

Procedure:

1. Measure depth to static water level and record. (See chapter 3 for methods of measuring.)

2. Determine if well is artesian or non-artesian by reference to well log for presence of a confining layer. If static water level is above bottom of confining layer, the well is artesian.

3. Figure height of static water column or 100 percent drawdown. For non-artesian wells, 100 percent drawdown is depth from static water level to bottom of aquifer, or to bottom of well if aquifer is not completely penetrated. For this purpose, 100 percent drawdown in artesian wells is the depth from the piezometric surface to the top of the aquifer. (If drawdown extends below the top of the aquifer and part of the artesian aquifer is dewatered, the procedure in step 5 must be proportioned for artesian and non-artesian drawdown.)

4. Pump well at near maximum rate (50 percent drawdown or slightly more) until drawdown and yield are constant at that rate. Drawdown may be considered constant when three measurements one hour apart are the same or very nearly so. Several hours to several days of continuous pumping may be required. Record drawdown and yield.

5. Convert measured drawdown to percent drawdown and refer to Figure 6-9 to estimate optimum drawdown and yield.

6. Furnish information on yield, drawdown, etc., to pump supplier for recommendations on pump and power requirements.

A check on the efficiency of the well screen can be made by installing an observation well in the annular space between the well casing and sides of the drill hole. If the water level in the observation well during a pump test is at a higher elevation than the water in the pumping well, the well screen is not transmitting the water efficiently. It may be desirable, if possible, to rework the well to improve the efficiency of the screen or filter pack.

The procedures and methods of conducting pump tests and examples of the calculations to determine aquifer characteristics are given in Chapter 3.

Maintenance

Maintenance properly performed can maintain well yields and increase the life of a well. The two main causes of decreasing well capacities are corrosion and deposition or incrustation.

Corrosion

Corrosion is the removal of metal in water by chemical or electrolytic action. Methods of protecting against corrosion have been discussed in this chapter under the heading Well Design. If corrosion does occur severe enough to impair the well, the only solution is to remove and replace the corroded well screen or casing.

Incrustation

Incrustation is deposition of foreign material on or around the screen. Corrosive or incrusting salts occur to some extent in all ground water. Unlike corrosion, incrustation reduces and will in time close screen openings.

Incrustations are usually hard and cement-like but may have the consistency of paste or jelly until exposed to air. The causes of incrustation in approximate order of importance are: (1) precipitation of calcium and magnesium carbonate and other materials carried in solution (9 instances out of 10); (2) deposition of suspended silt and clay; (3) growth of bacteria (crenothrix) that feeds on iron in the water and closes voids in sediments and screen openings with a jelly-like substance; and (4) the growth of slime-forming organisms that feeds on ammonia and decomposing organic matter.

Carbonate incrustation occurs because pumping causes a reduction of pressure in the vicinity of the well and liberates carbon dioxide. The water is then unable to carry in solution the former amount of calcium, magnesium and other metal salts. They are deposited as carbonates and oxides on the screen and in the adjacent aquifer. Eventually they cement an area about the well.

Reduction of drawdown is the most effective means of slowing deposition of carbonate encrusting materials. Drawdown may be reduced in several ways: (1) by design of the screen to keep entrance losses at a minimum; (2) by thorough well development to increase effective diameter of the well; (3) by pumping at a reduced rate for a longer period of time; and (4) by use of a greater number of smaller wells.

Treatment with acid.--When incrustation is rapid, periodic treatment with hydrochloric or other strong acid is required even though all possible measures to reduce drawdown are taken. The following procedure for treatment with hydrochloric acid is summarized from E. E. Johnson (1955a).

Determine reason for production decline if possible. Make pumping test to have basis for determining effectiveness of treatment.

Conditions necessary for acid treatment of wells:

1. Well screen must be constructed of metal that will not be damaged by the acid.
2. Well screen should be constructed of one metal so that electrolytic corrosion will not become established.
3. The kind of material encrusting screen should be determined. Analyze water. If not able to determine nature, try single acid treatment.
4. Prepare well and area in vicinity. Shut down all wells within 100 feet.

Method of single acid treatment:

If muriatic (hydrochloric) acid is used, it should be 18° Baume which is 27.92 percent acid. It is better practice to buy an inhibited acid from a chemical supply house. The acid should be introduced at the bottom of the screen using black iron or plastic pipe and fittings. Fill 5 to 7 feet of screen at a time and raise pipe 5 feet and repeat as necessary, add 20 percent extra at last setting. Use glass, earthenware or plain steel pitcher to pour acid into funnel. Do not breathe fumes of HCl or reaction. Keep work area ventilated. Water-slaked lime (CaO) is useful to neutralize spilled acid. Pump and waste water for 2 hours on completion. Check water with litmus paper or determine pH.

Outline of procedure for single acid treatment:

1. Fill screen with acid.
2. Let stand 30 minutes to 1 hour.
3. Stir with pipe for about 1 minute.
4. Let stand for 2-3 hours.
5. Surge lightly for about 10 minutes with surge block. (Run small stream of water into well while surging, if convenient.)

6. Surge moderately with solid surge block.
7. Bail well clean.
8. Pump for at least 2 hours.

This method will be successful in a majority of wells where principal cementing agent is calcium carbonate ($CaCO_3$). It may need to be repeated two or three times. If it is to be repeated, place acid in screen, agitate, and remove by pumping or bailing after 30 minutes to 1 hour. The second treatment should then proceed as above.

Treatment with polyphosphate.--Accumulations of silt, clay, and oxides of iron and manganese incrusting screens may be dispersed by use of glassy phosphates and pumped from the well. Phosphates work in the same manner as household detergents. The following notes are a summary of instructions for use of glassy phosphates from E. E. Johnson (1955):

> Make pumping test at start to have basis for evaluating treatment. Use 15 to 30 pounds of glassy phosphates and 1 to 2 pounds of calcium hypochlorite for each 100 gallons of water in well. The calcium hypochlorite is used with the polyphosphate to kill iron bacteria. The phosphate should be dissolved from a wire basket or burlap bag and not dumped in a tank.
>
> Pour solution into well. Surge vigorously to work chemicals in and out through screen openings. Surge with pump for 4 hours, idle 2 hours, surge for 2 to 4 more hours. After chemicals have been in the well 24 hours, they should be surged several times and pumped out to waste. During flushing period the well should be surged 3 or 4 times at about 10-minute intervals. Pumping should continue until water comes fairly clean. This treatment should be repeated with a new charge. Two or more repetitions of treatment are usually required. A pumping test should be made to determine need for repetition.
>
> The effectiveness of treatment can be improved by removing the pump and surging with blocks for more positive circulation of chemicals. Better opportunity is thus offered for breaking up and dispersing encrusting materials and well may be cleaned by bailing. If this is done, time of surging may be cut in half but dispersing agent should be left in well about 24 hours.

Treatment with chlorine.--Chlorine has been found effective in "burning up" organic slimes that cause stoppage in some localities. Good results have been produced by adding 30 to 40 pounds liquid chlorine to a large well over a period of 10 to 12 hours. The pump need not be removed and may be used to surge well occasionally. A small amount of corrosion inhibitor should be added to the water to avoid corrosion of the pump.

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