UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

ATOMIC SAFETY AND LICENSING BOARD

In the Matter of	Docket No. 40-8943-MLA-2
CROW BUTTE RESOURCES, INC.	ASLBP No. 13-926-01-MLA-BD01
(Marsland Expansion Area)	

Hearing Exhibit

Exhibit Number: NRC016

Exhibit Title: Excerpts from Driscoll, "Groundwater and Wells", 2d ed. (1986)

Groundwater and Wells

Second Edition

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R = radius of the cone of depression, in ft
r = radius of the well, in ft

R = radius of the cone of depression, in m
r = radius of the well, in m

Equation 9.1 is often called the equilibrium, or Thiem, equation.

Figure 9.9 is a vertical section of a well pumping from a *confined* aquifer. The equation for a well operating under confined conditions is:

$$Q = \frac{K\,b\,(H - h)}{528 \log R/r} \qquad\qquad Q = \frac{2.73\,K\,b\,(H - h)}{\log R/r} \qquad (9.2)$$

where
b = thickness of aquifer, in ft
All other terms are as defined for Equation 9.1

where
b = thickness of aquifer, in m
All other terms are as defined for Equation 9.1

Derivations of the foregoing equations are based on the following simplifying assumptions:

1. The water-bearing materials have a uniform hydraulic conductivity within the radius of influence of the well.
2. The aquifer is not stratified.
3. For an unconfined aquifer, the saturated thickness is constant before pumping starts; for a confined aquifer, the aquifer thickness is constant.
4. The pumping well is 100-percent efficient, that is, the drawdown levels inside and just outside the well bore are at the same elevation (see Chapter 16). (Head losses in the vicinity of the well are minimal.)
5. The intake portion of the well penetrates the entire aquifer.
6. The water table or potentiometric surface has no slope.
7. Laminar flow exists throughout the aquifer and within the radius of influence of the well.
8. The cone of depression has reached equilibrium so that both drawdown and radius of influence of the well do not change with continued pumping at a given rate.

These assumptions appear to limit severely the use of the two equations. In reality, however, they do not. For example, uniform hydraulic conductivity is rarely found in a real aquifer, but the average hydraulic conductivity as determined from pumping tests has proved to be reliable for predicting well performance. In confined aquifers where the well is fully penetrating and open to the formation, the assumption of no stratification is not an important limitation.

Assumption of constant thickness is not a serious limitation because variation in aquifer thickness within the cone of depression in most situations is relatively small, especially in sedimentary rocks. Where changes in thickness do occur, as in glacial sediments, for example, they can be taken into account. The assumption that a well is 100-percent efficient can cause the calculated well yield to be seriously in error if the real well is inefficient because of improper design or construction. Factors contributing to inefficiency are discussed in Chapter 16.

The assumption that the water table or potentiometric surface is horizontal before pumping begins is not correct. The slope or hydraulic gradient, however, is usually almost flat and the effect on calculation of well yield is negligible in most cases. Slope

of the water table or potentiometric surface does cause distortion of the cone of depression, making it more elliptical than circular.

Flow in all regions of an aquifer is considered to be laminar. Some investigators have theorized that turbulent flow near a well could result in relatively high head losses. Laboratory and field tests show, however, that some departure from laminar flow near a well causes only small additional head losses (Mogg, 1959).

Determining Aquifer Hydraulic Conductivity

Equations 9.1 and 9.2 can be modified to calculate hydraulic conductivity if Q, H, and R are determined from a pumping test, and b is known from the driller's log. For an unconfined aquifer, the equation for calculating K is:

$$K = \frac{1055\ Q \log r_2/r_1}{(h_2^2 - h_1^2)} \qquad K = \frac{Q \log r_2/r_1}{1.366\ (h_2^2 - h_1^2)} \qquad (9.3)$$

where
r_1 = distance to the nearest observation well, in ft
r_2 = distance to the farthest observation well, in ft
h_2 = saturated thickness, in ft, at the farthest observation well
h_1 = saturated thickness, in ft, at the nearest observation well
All other terms are as defined in Equation 9.1

where
r_1 = distance to the nearest observation well, in m
r_2 = distance to the farthest observation well, in m
h_2 = saturated thickness, in m, at the farthest observation well
h_1 = saturated thickness, in m, at the nearest observation well
All other terms are as defined in Equation 9.1

All the parameters on the right-hand side of Equation 9.3 can be determined from a pumping test. Two observation wells, located at distances r_1 and r_2 from the pumped well, are required to determine h_1 and h_2.

Figure 9.10 shows a sectional view of a pumping test layout in an unconfined formation for determining the hydraulic conductivity of the formation. All pertinent factors are easily measured in this kind of test, and the hydraulic conductivity of the aquifer can be determined accurately.

For confined conditions, the equation for determining the hydraulic conductivity from a test installation similar to Figure 9.10 is:

$$K = \frac{528\ Q \log r_2/r_1}{b\ (h_2 - h_1)} \qquad K = \frac{Q \log r_2/r_1}{2.73\ b\ (h_2 - h_1)} \qquad (9.4)$$

where
all terms except the following are the same as for Equation 9.3
b = thickness of the aquifer, in ft
h_2 = head, in ft, at the farthest observation well, measured from the bottom of the aquifer
h_1 = head, in ft, at the nearest obser-

where
all terms except the following are the same as for Equation 9.3
b = thickness of the aquifer, in m
h_2 = head, in m, at the farthest observation well, measured from the bottom of the aquifer
h_1 = head, in m, at the nearest obser-

NONEQUILIBRIUM WELL EQUATION

Theis developed the nonequilibrium well equation in 1935. The Theis equation was the first to take into account the effect of pumping time on well yield. Its derivation was a major advance in groundwater hydraulics. By use of this equation, the drawdown can be predicted at any time after pumping begins. Transmissivity and average hydraulic conductivity can be determined during the early stages of a pumping test rather than after water levels in observation wells have virtually stabilized. Aquifer coefficients can be determined from the time-drawdown measurements in a single observation well rather than from two observation wells as required in Equations 9.3 and 9.4.

Derivation of the Theis equation is based on the following assumptions:

1. The water-bearing formation is uniform in character and the hydraulic conductivity is the same in all directions.
2. The formation is uniform in thickness and infinite in areal extent.
3. The formation receives no recharge from any source.
4. The pumped well penetrates, and receives water from, the full thickness of the water-bearing formation.
5. The water removed from storage is discharged instantaneously when the head is lowered.
6. The pumping well is 100-percent efficient.
7. All water removed from the well comes from aquifer storage.
8. Laminar flow exists throughout the well and aquifer.
9. The water table or potentiometric surface has no slope.

These assumptions are essentially the same as those for the equilibrium equation except that the water levels within the cone of depression need not have stabilized or reached equilibrium.

In its simplest form, the Theis equation is:

$$s = \frac{114.6\, Q\, W(u)}{T} \qquad\qquad s = \frac{1}{4\pi}\frac{Q}{T} W(u) \qquad (9.5)$$

where

s = drawdown, in ft, at any point in the vicinity of a well discharging at a constant rate

Q = pumping rate, in gpm

T = coefficient of transmissivity of the aquifer, in gpd/ft

$W(u)$ = is read "well function of u" and represents an exponential integral

where

s = drawdown, in m, at any point in the vicinity of a well discharging at a constant rate

Q = pumping rate, in m^3/day

T = coefficient of transmissivity of the aquifer, in m^2/day

$W(u)$ = is read "well function of u" and represents an exponential integral

In the $W(u)$ function, u is equal to:

$$u = \frac{1.87 r^2 S}{Tt} \qquad\qquad u = \frac{r^2 S}{4Tt} \qquad (9.5a)$$

where

r = distance, in ft, from the center of a

where

r = distance, in m, from the center of a

pumped well to a point where the drawdown is measured	pumped well to a point where the drawdown is measured
S = coefficient of storage (dimensionless)	S = coefficient of storage (dimensionless)
T = coefficient of transmissivity, in gpd/ft	T = coefficient of transmissivity, in m^2/day
t = time since pumping started, in days	t = time since pumping started, in days

The well function of u [$W(u)$] originated as a term to represent the heat distribution in a flat plate with a heating element at its center. Theis recognized that this same concept could be applied to the regular distribution of the groundwater head around a pumping well even though water flows toward the point source rather than away from it. The mathematical principles remain the same.

Analysis of pumping test data* using the Theis equation can yield transmissivity and storage coefficients for all nonequilibrium situations. In actual practice, however, the Theis method is often avoided because it requires curve-matching interpretation and is somewhat laborious. In fact, the work of applying the Theis method can be avoided in most cases. For example, if the pumping test is sufficiently long or the distance from the well to where the drawdown is measured is sufficiently small, the $W(u)$ function can be replaced by a simpler mathematical function which makes the analysis easier. The Theis method is developed at the end of this chapter, but at this point the simplified version is examined because it serves well in most cases.

MODIFIED NONEQUILIBRIUM EQUATION

In working with the Theis equation, Cooper and Jacob (1946) point out that when u is sufficiently small, the nonequilibrium equation can be modified to the following form without significant error:

$$s = \frac{264Q}{T} \log \frac{0.3\ Tt}{r^2S} \qquad s = \frac{0.183Q}{T} \log \frac{2.25\ Tt}{r^2S} \tag{9.6}$$

where the symbols represent the same terms as in Equation 9.5 and 9.5a.

For values of u less than about 0.05, Equation 9.6 gives essentially the same results as Equation 9.5. The value of u becomes smaller as t increases and r decreases. Thus, Equation 9.6 is valid when t is sufficiently large and r is sufficiently small. Equation 9.6 is similar in form to the Theis equation except that the exponential integral function, $W(u)$, has been replaced by a logarithmic term which is easier to work with in practical applications of well hydraulics.

For a particular situation where the pumping rate is held constant, Q, T, and S are all constants. Equation 9.6 shows, therefore, that the drawdown, s, varies with log t/r^2 when u is less than 0.05. From this relationship, two important relationships can be stated:

1. For a particular aquifer at any specific point (where r is constant), the terms s and t are the only variables in Equation 9.6. Thus, s varies as log C_1t, where C_1 represents all the constant terms in the equation.

2. For a particular formation and at a given value of t, the terms s and r are the

*The performance of newly completed wells is often checked by pumping tests. During the test, the drawdown in the pumping well and observation wells is measured at a constant discharge rate. When properly conducted, these tests yield information on transmissivity and storage capability. See Chapter 16 for a detailed analysis of pumping test procedures.

It is also pertinent to note the reason for the earlier suggestion that pumping tests last at least 1 day for wells in confined aquifers and at least 3 days for wells in unconfined aquifers. Figure 9.20 shows evidence of a boundary effect 100 minutes after the pump was started. If the test had been conducted for only 100 minutes, the boundary would not have been revealed. Moreover, extension of the initial slope indicates a drawdown of 62 ft (18.9 m) after 7 days (10,000 minutes) of pumping at 250 gpm (1,360 m^3/day), whereas the correct estimate is 73 ft (22.3 m) as determined from the extension of the second leg of the curve.

In a confined aquifer, enlargement of the cone of depression during a 24-hour pumping period is usually extensive enough to encounter boundaries that could appreciably affect drawdown predictions from the semilog diagram. In an unconfined aquifer, the cone of depression expands more slowly, and so a longer pumping period is required to detect boundaries that may exist.

Casing Storage

Schafer (1978) suggests that in many instances early pumping test data may not fit Jacob's modification of the nonequilibrium theory, and that calculations based on this early Δs value will be erroneous. These early data reflect the removal of water stored in the casing. When pumping begins, water in the casing is removed first. As the water level in the casing falls, water begins to enter the well from the surrounding formation. Gradually, a greater percentage of the well's yield will be from the aquifer. The Δs value will be higher during the time required to exhaust the casing storage, giving an erroneously low transmissivity value in the early stages of the pumping test. Figure 9.21 shows data from a typical pumping test in which casing storage has

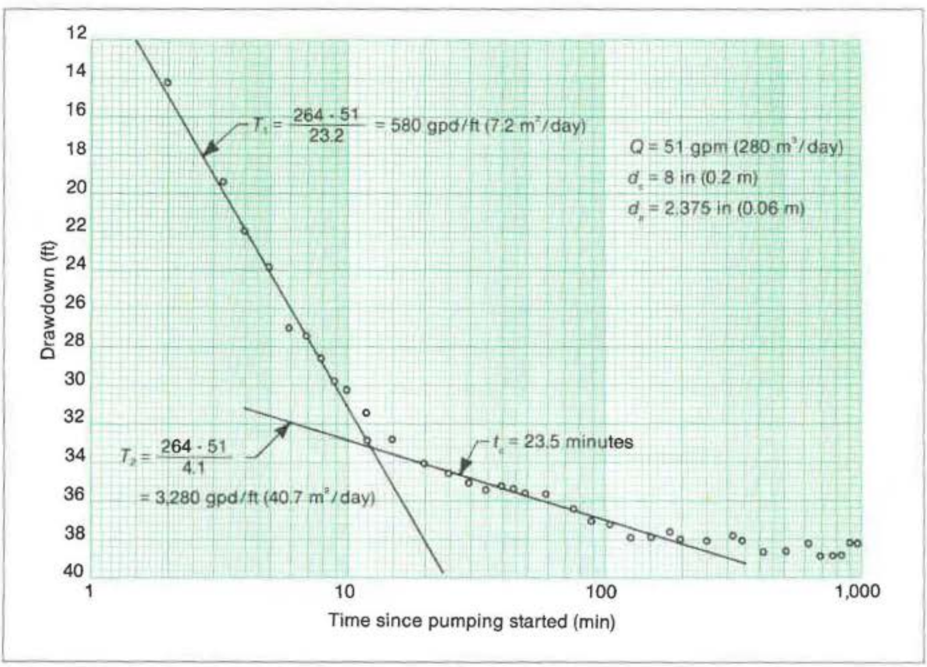

Figure 9.21. Pumping test data in which casing storage has altered the early part of the time-drawdown plot.

-8-

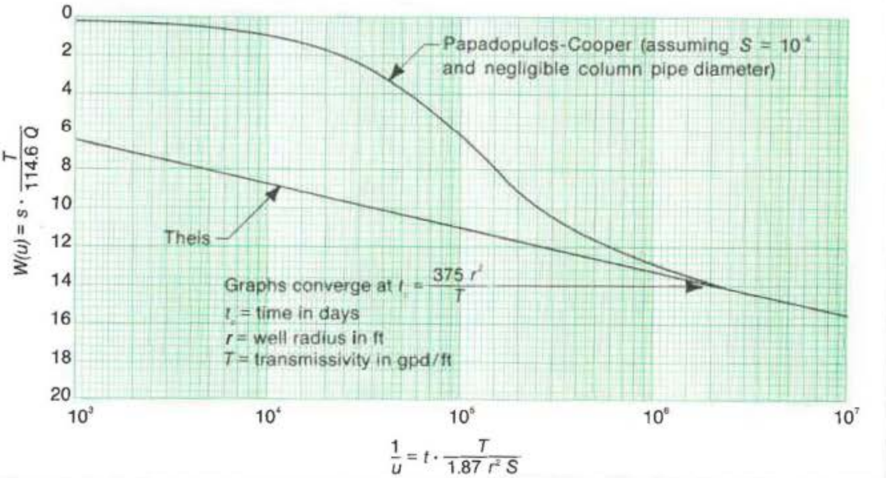

Figure 9.22. Graphic representation of the Papadopulos-Cooper equation which takes into account casing storage.

distorted the early part of the time-drawdown curve.

Before the effect of casing storage on pumping test data was recognized, an interpreter might have mistaken the flattened or second part of the drawdown curve as an indication of aquifer recharge. The duration of the casing storage effect varies greatly from well to well depending on the casing diameter and specific capacity. In general, the storage effect will last longer for wells with large diameters and low specific capacities.

Papadopulos and Cooper (1967) and Ramey et al. (1973) present equations that modify the early part of the Jacob and Theis curves by taking into account casing storage (Papadopulos-Cooper equation for determining t_c is shown in Figure 9.22). These equations indicate the critical time after which casing storage no longer contributes to the yield of a well. Presumably, drawdown data collected after this time will represent the true physical conditions within an aquifer. Unfortunately, these equations can be used only if the transmissivity and well efficiency are known in advance.

Schafer suggests that the critical time can be calculated by the equation:

$$t_c = \frac{0.6\,(d_c^2 - d_p^2)}{Q/s}$$

where

t_c = time, in minutes, when casing storage effect becomes negligible

d_c = inside diameter of well casing, in inches

d_p = outside diameter of pump column pipe, in inches

Q/s = specific capacity of the well in gpm/ft of drawdown at time t_c

$$t_c = \frac{0.017\,(d_c^2 - d_p^2)}{Q/s} \qquad (9.9)$$

where

t_c = time, in minutes, when casing storage effect becomes negligible

d_c = inside diameter of well casing, in mm

d_p = outside diameter of pump column pipe, in mm

Q/s = specific capacity of the well in m^3/day/m of drawdown at time t_c