13 Recovery tests

When the pump is shut down after a pumping test, the water levels in the well and the piezometers will start to rise. This rise in water levels is known as residual drawdown, s′. It is expressed as the difference between the original water level before the start of pumping and the water level measured at a time t′ after the cessation of pumping. Figure 13.1 shows the change in water level with time during and after a pumping test.

It is always good practice to measure the residual drawdowns during the recovery period. Recovery-test measurements allow the transmissivity of the aquifer to be calculated, thereby providing an independent check on the results of the pumping test, although costing very little in comparison with the pumping test.

Residual drawdown data are more reliable than pumping test data because recovery occurs at a constant rate, whereas a constant discharge during pumping is often difficult to achieve in the field.

The analysis of a recovery test is based on the principle of superposition, which was discussed in Chapter 6. Applying this principle, we assume that, after the pump has been shut down, the well continues to be pumped at the same discharge as before, and that an imaginary recharge, equal to the discharge, is injected into the well. The recharge and the discharge thus cancel each other, resulting in an idle well as is required for the recovery period. For any of the well-flow equations presented in the previous chapters, a corresponding 'recovery equation' can be formulated.

The Theis recovery method (Section 13.1.1) is widely used for the analysis of recovery tests. Strictly speaking, this method is only valid for confined aquifers which are fully penetrated by a well that is pumped at a constant rate. Nevertheless, if additional limiting conditions are satisfied, the Theis method can also be used for leaky aquifers (Section 13.1.2) and unconfined aquifers (Section 13.1.3), and aquifers that are only partially penetrated by a well (Section 13.1.4).

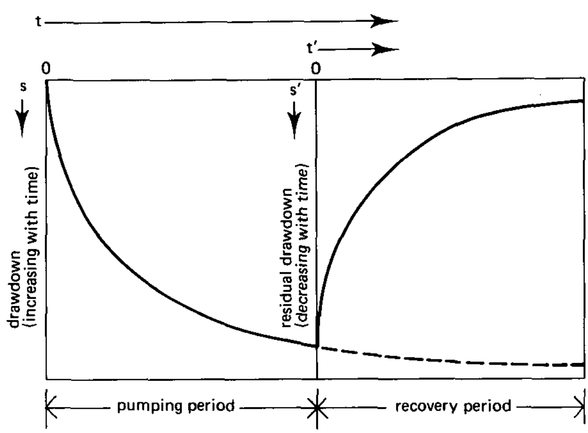

Figure 13.1 Time drawdown and residual drawdown

If the recovery test is conducted in a free-flowing well, the Theis recovery method can also be used (Section 13.2).

If the discharge rate of the pumping test was variable, the Birsoy-Summer recovery method (Section 13.3.1) can be used.

13.1 Recovery tests after constant-discharge tests

13.1.1 Confined aquifers, Theis's recovery method

According to Theis (1935), the residual drawdown after a pumping test with a constant discharge is

$$s' = \frac{Q}{4\pi KD}\{W(u) - W(u')\} \tag{13.1}$$

where

$$u = \frac{r^2S}{4KDt} \text{ and } u' = \frac{r^2S'}{4KDt'}$$

When u and u′ are sufficiently small (see Section 3.2.2 for the approximation of W(u) for $u < 0.01$), Equation 13.1 can be approximated by

$$s' = \frac{Q}{4\pi KD}\left(\ln\frac{4KDt}{r^2S} - \ln\frac{4KDt'}{r^2S'}\right) \tag{13.2}$$

where

s' = residual drawdown in m
r = distance in m from well to piezometer
KD = transmissivity of the aquifer in m^2/d
S' = storativity during recovery, dimensionless
S = storativity during pumping, dimensionless
t = time in days since the start of pumping
t' = time in days since the cessation of pumping
Q = rate of recharge = rate of discharge in m^3/d

When S and S′ are constant and equal and KD is constant, Equation 13.2 can also be written as

$$s' = \frac{2.30Q}{4\pi KD}\log\frac{t}{t'} \tag{13.3}$$

A plot of s′ versus t/t′ on semi-log paper (t/t′ on logarithmic scale) will yield a straight line. The slope of the line is

$$\Delta s' = \frac{2.30Q}{4\pi KD} \tag{13.4}$$

where $\Delta s'$ is the residual drawdown difference per log cycle of t/t′.

The Theis recovery method is applicable if the following assumptions and conditions are met:
- The assumptions listed at the beginning of Chapter 3, adjusted for recovery tests.

The following conditions are added:
- The flow to the well is in an unsteady state;
- $u < 0.01$, i.e. pumping time $t_p > (25\,r^2S)/KD$
- $u' < 0.01$, i.e. $t' > (25\,r^2S)/KD$, see also Section 3.2.2.

Procedure 13.1
- For each observed value of s', calculate the corresponding value of t/t';
- For one of the piezometers, plot s' versus t/t' on semi-log paper (t/t' on the logarithmic scale);
- Fit a straight line through the plotted points;
- Determine the slope of the straight line, i.e. the residual drawdown difference $\Delta s'$ per log cycle of t/t';
- Substitute the known values of Q and $\Delta s'$ into Equation 13.4 and calculate KD.

Remark
- When S and S' are constant, but unequal, the straight line through the plotted points intercepts the time axis where $s' = 0$ at a point $t/t' = (t/t')_o$. At this point, Equation 13.2 becomes

$$0 = \frac{2.30Q}{4\pi KD}\left[\log\left(\frac{t}{t'}\right)_o - \log\frac{S}{S'}\right]$$

Because $2.30\,Q/4\pi KD \neq 0$, it follows that $\log(t/t')_o - \log(S/S') = 0$. Hence $(t/t')_o = S/S'$, which determines the relative change of S.

13.1.2 Leaky aquifers, Theis's recovery method

After a constant-discharge test in a leaky aquifer, Hantush (1964), disregarding any storage effects in the confining aquitard, expresses the residual drawdown s' at a distance r from the well as

$$s' = \frac{Q}{4\pi KD}\{W(u,r/L) - W(u',r/L)\} \qquad (13.5)$$

Taking this equation as his basis and using a digital computer, Vandenberg (1975) devised a least-squares method to determine KD, S, and L. For more information on this method, we refer the reader to the original literature.

If the pumping and recovery times are long, leakage through the confining aquitards will affect the water levels. If the times are short, i.e. if $t_p + t' \leq (L^2S)/20KD$ or $t_p + t' \leq cS/20$, the Theis recovery method (Section 13.1.1) can be used, but only the leaky aquifer's transmissivity can be determined (Uffink 1982; see also Hantush 1964).

13.1.3 Unconfined aquifers, Theis's recovery method

An unconfined aquifer's delayed watertable response to pumping (Chapter 5) is fully reversible according to Neuman's theory of delayed watertable response, because hysteresis effects do not play any part in this theory. Neuman (1975) showed that the Theis recovery method (Section 13.1.1) is applicable in unconfined aquifers, but only for late-time recovery data. At late time, the effects of elastic storage, which set in after pumping stopped, have dissipated. The residual drawdown data will then fall on a straight line in the semi-log s' versus t/t' plot used in the Theis recovery method.

13.1.4 Partially penetrating wells, Theis's recovery method

The Theis recovery method (Section 13.1.1) can also be used if the well is only partially penetrating. For long pumping times in such a well, i.e. $t_p > (D^2S)/2KD$, the semi-log plot of s versus t yields a straight line with a slope identical to that of a completely penetrating well (Hantush 1961b). Thus, if the straight line portion of the recovery curve is long enough, i.e. if both t_p and t' are greater than $(10\ D^2S)/KD$, the Theis recovery method can be applied (Uffink 1982).

13.2 Recovery tests after constant-drawdown tests

If the recovery test follows a constant-drawdown test instead of a constant-discharge test, the Theis recovery method (Section 13.1.1) can be applied, provided that the discharge at the moment before the pump is shut down is used in Equation 13.4 (Rushton and Rathod 1980).

13.3 Recovery tests after variable-discharge tests

13.3.1 Confined aquifers, Birsoy-Summers's recovery method

To analyze the residual drawdown data after a pumping test with step-wise or intermittently changing discharge rates, Birsoy and Summers (1980) proposed the following expression

$$\frac{s'}{Q_n} = \frac{2.30}{4\pi KD} \log\left\{\beta_{t(n)}\left(\frac{t-t_n}{t-t'_n}\right)\right\} \qquad (13.6)$$

where

s' = residual drawdown at $t > t'_n$
Q_n = constant discharge during the last (= n-th) pumping period
t_n = time at which the n-th pumping period started
$t-t_n$ = time since the n-th pumping period started
t'_n = time at which the n-th pumping period ended
$t-t'_n$ = time since the n-th pumping period ended
$\beta_{t(n)}$ is defined according to Equation 12.2

A semi-log plot of s'/Q_n versus the corresponding adjusted time of recovery: $\beta_{t(n)}(t-t_n/t-t'_n)$ yields a straight line. The slope of the straight line $\Delta(s'/Q_n)$ is equal to $2.30/4\pi KD$, from which the transmissivity can be determined.

The Birsoy-Summers recovery method can be used if the following assumptions and conditions are met:
- The assumptions listed at the beginning of Chapter 3, as adjusted for recovery tests, with the exception of the fifth assumption, which is replaced by:
  - Prior to the recovery test, the aquifer is pumped at a variable discharge rate.

The following conditions are added:
- The flow to the well is in an unsteady state;
- $u < 0.01$ $[u = r^2S/4KD\{\beta_{t(n)}(t_p-t_n)\}]$, see also Section 3.2.2;
- $u' < 0.01$ $[u' = r^2S/4KD\{\beta_{t(n)}(t-t_n/t-t'_n)\}]$.

Procedure 13.2
- For a single piezometer, calculate the adjusted time of recovery, $\beta_{t(n)}(t-t_n/t-t'_n)$, by applying Equation 12.2 for the calculation of $\beta_{t(n)}$, and by using all the observed values of the discharge rate and the appropriate values of time;
- On semi-log paper, plot the observed specific residual drawdown s'/Q_n versus the corresponding values of $[\beta_{t(n)}(t-t_n/t-t'_n)]$ (the adjusted time of recovery on the logarithmic scale);
- Draw a straight line through the plotted points;
- Determine the slope of the straight line, $\Delta(s'/Q_n)$, which is the difference of s'/Q_n per log cycle of adjusted time of recovery;
- Calculate KD from $\Delta(s'/Q_n) = 2.30/4\pi KD$.

Remark
- See Section 12.1 for simplified expressions of $\beta_{t(n)}(t-t_n)$ which can be introduced into the expression for the adjusted time of recovery.