CHAPTER 6

Pumping test

When a borehole or a well has been completed, it is essential to verify that its capacity meets the water needs of the population. When a well or borehole is to be exploited, there are recurrent questions as to how much water can be pumped, at what intervals, with what type of pump, and at what depth. A well-conducted pumping test generally provides the answers to these questions.

Also, observation of the effects of pumping is one of the best investigative methods in hydrogeology. Pumping tests enable better knowledge of the aquifer and better targeting of activities.

There are two types of test aiming to fulfil different objectives:

– The aquifer test (also known as the constant-discharge test) estimates the hydraulic parameters of the aquifer. The information obtained is usually the transmissivity of the aquifer (subsequently used to calculate the hydraulic conductivity), the storativity (the storage coefficient if the aquifer is confined, or the specific yield if it is unconfined), the radius of influence of pumping, and the boundary conditions.

This test requires pumping at a constant rate and monitoring of the water level in an observation well over several days. It is therefore difficult and relatively expensive to implement. In the context of humanitarian programmes, it is justified on boreholes intended for high flow-rates, or in investigations to determine the hydrodynamics of a zone.

– The well test (also known as step test or step-drawdown test) evaluates the characteristics of the well and its immediate environment. Unlike the aquifer test, it is not designed to produce reliable information concerning the aquifer, even though it is possible to estimate the transmissivity of the immediate surroundings of the catchment. This test determines the critical flow rate of the well, as well as the various head-losses and drawdowns as functions of pumping rates and times. Finally, it is designed to estimate the well efficiency, to set an exploitation pumping rate and to specify the depth of installation of the pump.

This type of test is especially useful in determining whether the well meets users' needs. It also helps to specify limits of exploitation of the well and to obtain data relevant to the consideration of possible rehabilitation, or of new extraction methods (for example, replacement of a handpump by an electric submersible pump).

Whatever the pumping test, the main field data recorded are the pumping rate, the water level and the time (or duration). These data need to be verified before interpretation. Interpretation consists of comparing the field record with theoretical well-flow equations.

1 Aquifer test

The aquifer test is used to determine the aquifer hydraulic characteristics and, in some instances, boundary conditions :

- transmissivity;
- storativity, that is specific yield for an unconfined aquifer, storage coefficient for a confined aquifer or specific drainage for a confined aquifer that is desaturated by water abstraction;
- boundary conditions such as recharging or barrier boundaries;
- heterogeneity and anisotropy of reservoirs.

An aquifer test involves pumping from a well at a constant discharge rate and measuring the drawdown in the pumping well and in piezometers (observation wells) at known distances from the well. The interpretation of these field measurements involves entering the observed data into an appropriate well-flow equation to calculate the hydraulic characteristics of the aquifer.

There is a wide range of methods and equations that could be used according to the aquifer type, boundary conditions and test procedure. The appropriate method can be selected with the support of diagnostic graphs.

1.1 Diagnostic graphs

Theoretical models used to interpret field data take into account the type of aquifer, the well conditions and the boundary conditions. These parameters affect the drawdown behaviour of the system in their own individual ways, so that to identify an aquifer system, one must compare its drawdown behaviour with that of various models. The model that compares best with the data should be selected to calculate the hydraulic characteristics of the aquifer.

System identification includes the construction of diagnostic log-log and semi-log plots, while interpretation of the data includes construction of specialised semi-log plots. The diagnostic graphs represent drawdowns against time (or against distance); they help to identify the flow regime and their shape leads to selection of the appropriate model of interpretation.

It is therefore recommended that diagnostic graphs are drawn before selecting an interpretation method.

1.1.1 AQUIFER CATEGORIES

For pumping-test analysis, the aquifer can be classified as follows: unconsolidated or fractured; and confined, unconfined or leaky. Figure 6.1 shows diagnostics graphs of the main unconsolidated categories of aquifer.

Graph 6.1A represents an unconsolidated, confined, homogeneous and isotropic aquifer. This represents the ideal curve that is the reference used to understand others. From a semi-log plot, one can see that the time/drawdown relationship becomes linear. This linearity is used to calculate hydraulic characteristics accurately (see Jacob's method).

Graph 6.1B shows diagnostic graphs obtained in an unconfined, homogenous and isotropic aquifer. Initially, typically for the first few minutes of pumping, the curve is the same as that for a

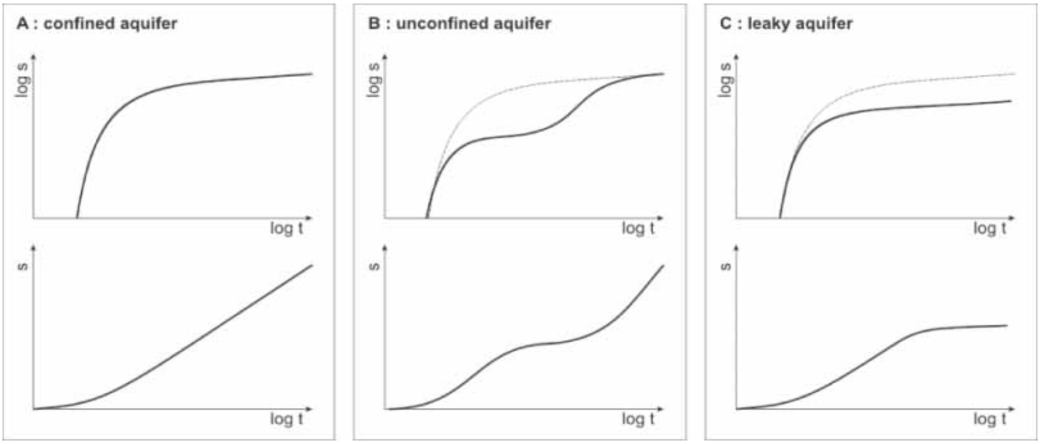

Figure 6.1: Theoretical diagnostic graphs of aquifer type showing drawdown (s) against time (t). The dashed curves are those of the 'ideal confined aquifer' as represented on graph A (Kruseman & de Ridder, 2000).

confined aquifer because the release of water is dominated by the storage coefficient. The flat segment midway along the curve corresponds to the delayed yield-effect characteristic of an unconfined aquifer: this reflects the recharge from overlying horizons by a specific-yield effect that takes more time than the storage coefficient to release water. Finally, the curve follows a similar path to graph 6.1A as the flow is again mainly horizontal.

This drawdown development is also one of a double-porosity system. Initially, the flow comes mainly from storage into fractures until the storage in the matrix starts to feed the fractures.

Graph 6.1C shows a leaky aquifer. After the initial stage, which is similar to that in a confined aquifer, more and more water is produced by the aquitard, and this reduces the development of drawdown.

1.1.2 BOUNDARY CONDITIONS

When field data curves deviate from those of theoretical aquifer types, the deviation is usually due to specific boundary conditions (Figure 6.2).

Graph 6.2A shows the effect of a partially penetrating well. In this case, the condition of horizontal flow in the vicinity of the well does not apply, and vertical flow induces extra head-losses.

The well-capacity effect measured at a piezometer (observation well) is shown in graph 6.2B. This corresponds to the difference between the drawdown due to pumping in an ideal well of negligible diameter, and drawdown in a real well containing a non-negligible volume of water. At the beginning of pumping, the capacity effect is induced by the delay in demand on the aquifer, because it is water stored within the well that is extracted first. The capacity effect therefore results in a delay of drawdown at the beginning of pumping if the water level is measured in a piezometer (observation well). On the other hand, the capacity effect can be seen as an exaggeration of the drawdown at the beginning of pumping if the water level is measured directly in the pumping well. Its duration depends on the dimensions of the well and the transmissivity of the aquifer (see Section 3).

When the cone of depression reaches a hydraulic boundary, the field curve deviates from the theoretical one according to the type of boundary. For a recharge boundary, such as a river for example, the drawdown will stabilise (graph 6.2C); for an impermeable boundary, such as a dike, the slope of the drawdown on the semi-log plot will double (graph 6.2D).

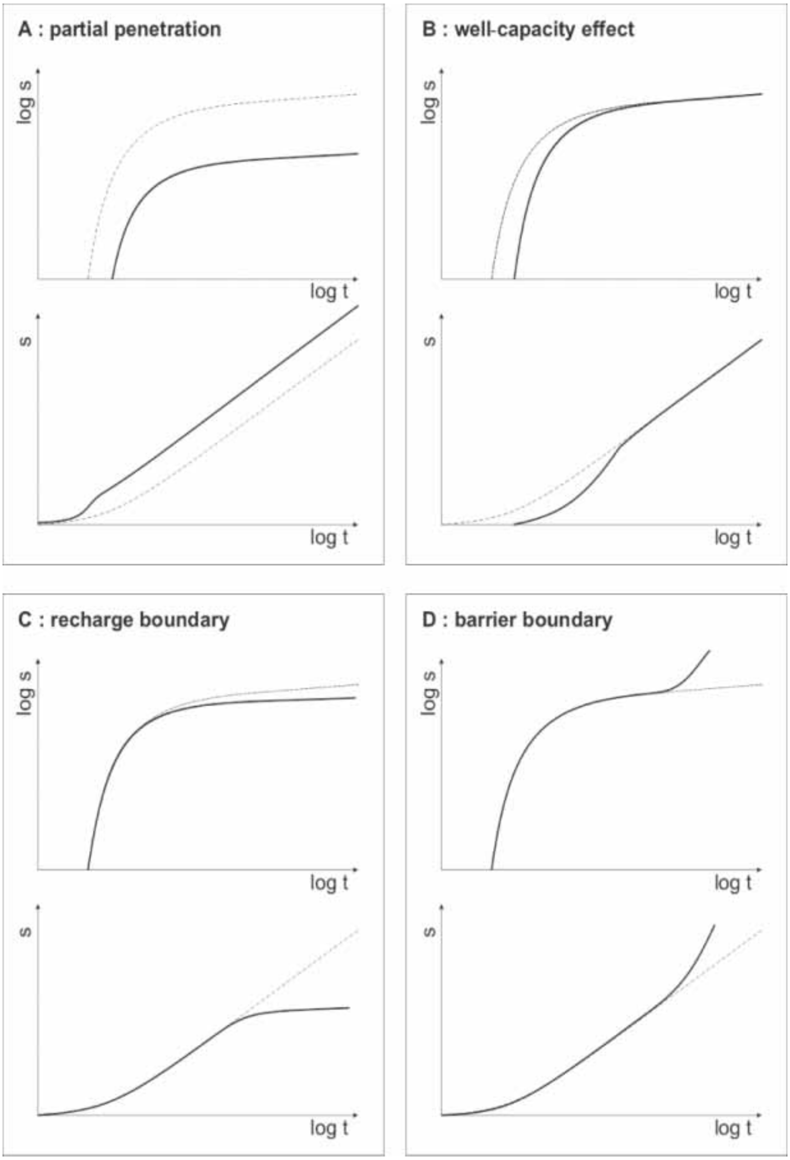

Figure 6.2: Theoretical diagnostic graphs of boundary conditions showing drawdown (s) against time (t). The dashed curve are those of the 'ideal confined aquifer' of Figure 6.1A (Kruseman & de Ridder, 2000).

Heterogeneity and anisotropy of aquifers have effects on drawdown development as the cone of depression reaches zones of different hydraulic characteristics. The effects can be in both directions: either drawdown slows down if the newly reached hydraulic properties are higher, or it speeds up if the hydraulic properties are lower.

1.1.3 DATA VALIDATION

Before interpreting the field data, it should be examined to see if measurements have been affected by external changes other than the test pumping, or if some are obviously wrong.

The observation of the diagnostic graphs s=f(t) together with the plot Q=f(t) is the best way to verify data. The most likely external effects are barometric changes, tidal effects, pumping from other wells and short-term rainfall recharge. These affect the water level and invalidate simple analysis. External effects should be avoided, or if this is impossible (i.e. tides) the measured water levels should be corrected.

1.2 Choice of model

The appropriate interpretation method is selected according to the type of system and the boundary conditions previously known, or shown by the diagnostic plots (Table 6.I).

It is often helpful to test different methods on the same data set to get a feel of the context. For this purpose, the use of software such as AquiferTest Pro is interesting because it is time-saving (http:\\www.flowpath.com). This commercial software is recommended by ACF because it is easy to use and offers several interpretation methods including forward modelling for both well tests and aquifer tests. It allows for the testing of different interpretation solutions with the same data set, and beside the common automatic fitting, the user can always take back the control of the interpretation.

However, manual interpretation by drawing specialised curves and using adapted nomograms is always an efficient and easy process.

Table 6.I: Some of the main methods used for non consolidated aquifer test interpretation.

Flow	Type of aquifer	Boundary conditions	Main methods
Steady -state	Confined	—	Thiem
Unsteady-state	Confined	—	Theis
			Jacob
		Partially-penetrating well	Hantush modification of Theis method
		Large-diameter well	Papadopulos
	Unconfined	—	Neuman
			Jacob with some restrictions
		Partially-penetrating well	Neuman
		Large-diameter well	Boulton-Strelsova
	Leaky	—	Walton
			Hantush
Recovery	Confined	—	Theis recovery
	Unconfined	—	Theis recovery
	Leaky	—	Theis recovery

The methods are described in the main references cited in this chapter, and their detailed explanation is beyond the scope of this book. The only methods which are presented here are the ‘Jacob’ and ‘Theis recovery’ methods because they can be used in several contexts with some precautions.

1.3 Jacob’s method

This method of pumping-test interpretation is frequently used because it is simple to handle: it does not need specific type curves, and the only specific graphs needed for interpretation are semi-log graphs which will already have been drawn for diagnostics. However, the following conditions underlying the method need to apply to obtain realistic interpretation results:

- The method can be used rigorously only if the aquifer is confined. If it is unconfined, Jacob's method can still be used:
  - if the maximum drawdown is negligible compared to the thickness of saturated layers;
  - if the measured drawdowns are corrected with the appropriate formula $s_c = s - (s^2/2 . D)$ where s_c is the corrected drawdown, s is the measured drawdown and D is the original saturated thickness (Kruseman & de Ridder, 2000).
- The aquifer is homogeneous, isotropic, of the same thickness throughout the area affected by pumping and of infinite area extent. These ideal conditions are rarely fulfilled in the field, but the diagnostic graphs can show if this assumption is reasonably met.
- The piezometric surface before pumping is almost horizontal.
- The release of water by the porous environment is instantaneous.
- The well is perfect, in that it penetrates the entire thickness of the aquifer, and its radius is small enough not to be affected by the well-capacity effect. The diagnostic graphs can show if this assumption is reasonably met.
- The pumped flow rate is constant.
- The flow state is unsteady.
- The pumping time is sufficiently long. This condition always needs to be checked (see following section).

These conditions are rarely all fulfilled on site. It is therefore wise to be careful in the application of this method, and to use common sense in the interpretation of diagnostic graphs.

1.3.1 THE LOGARITHMIC APPROXIMATION

Under transient flow conditions (when flow is variable over time and drawdown is not stabilised), drawdown at any point in the aquifer is given by the so called unsteady-state or Theis's equation:

$$s = \frac{Q}{4 \cdot \pi \cdot T} . W(u)$$

where $u = r^2 \cdot S / 4 \cdot T \cdot t$, W(u) is a known and tabulated function (table, nomogram), s is drawdown measured in a piezometer at a distance r from the pumping well (m), Q is pumped flow rate (m^3/h), T is transmissivity (m^2/h), t is pumping time (h), S is the storage coefficient, and r is the distance of a given point from the axis of the pumped well (m).

When t is sufficiently large, a logarithmic approximation known as Jacob's approximation can be applied to the Theis equation such that:

$$s = \frac{0.183 \cdot Q}{T} \cdot \log \left(\frac{2.25 \cdot T \cdot t}{r^2 \cdot S} \right)$$

Jacob's approximation is taken to be satisfactory at 5% from the moment when $t > 10 \cdot r^2 \cdot S / 4 \cdot T$. This condition is easy to verify in the context of an aquifer-test. With a well-test, the storage coefficient is not known and Jacob's approximation can reasonably be considered to be fulfilled when the time/drawdown relationship on the semi-log diagnostic graph becomes linear. Note that the invalidation of Jacob's approximation due to too short a pumping time should not be confused with the well-capacity effect.

1.3.2 ESTIMATION OF THE HYDRAULIC PARAMETERS

According to Jacob's logarithmic approximation, if Q, T and S are constant with reference to the initial assumptions, the plot of drawdown versus the logarithm of time forms a straight line (as

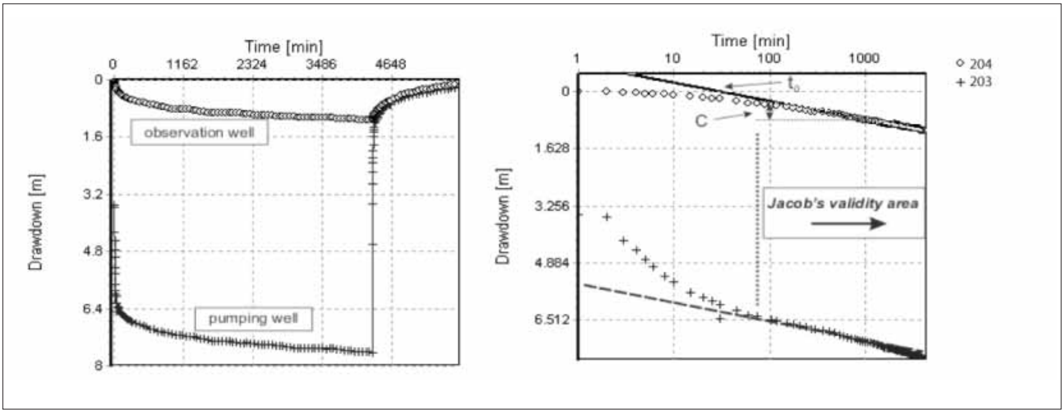

Figure 6.3: Aquifer-test interpretation using Jacob's method.

soon as the duration condition is fulfilled). The slope of this line is:

$$C = \frac{0.183 \cdot Q}{T}$$

$$\Leftrightarrow T = \frac{0.183 \cdot Q}{C}$$

If this line is extended until it intercepts the time axis where s=0, we obtain a value of t called t_0. Substituting this value into Jacob's logarithmic approximation gives:

$$0 = \frac{0.183 \cdot Q}{T} \cdot \log\left(\frac{2.25 \cdot T \cdot t_0}{r^2 \cdot S}\right)$$

$$\rightarrow \frac{2.25 \cdot T \cdot t_0}{r^2 \cdot S} = 1$$

$$\rightarrow S = \frac{2.25 \cdot T \cdot t_0}{r^2}$$

Figure 6.3 illustrates the used of Jacob's method on a borehole drilled in a weathered granitic formation. Well 203 is the pumping well and well 204 is the observation well situated at a distance of 84 m. The test was conducted with a constant discharge of 6 m^3/h. The slope C of the Jacob's straight line is calculated from the observation-well data: when plotted on the same graph as the pumping-well data, it confirms the similar development of both drawdowns. Using the graphical value of C and t_0, the calculated hydraulic characteristics of the aquifer are $T=5.8\ 10^{-4}\ m^2/s$ and $S=1.6\ 10^{-4}$.

The calculation of Jacob's method validity gives $t > 10 \cdot r^2 \cdot S / 4 \cdot t \rightarrow t > 1.3$ hours, that confirms the validity of the interpretation that considers the data point after 80 minutes.

1.3.3 SUPERPOSITION PRINCIPLE

Assuming pumping at flow rate Q for a period t, followed by a pause of duration t', the superposition of flow principle is such that after pumping stops it is as if pumping were to be continued at flow rate Q which would lower the level such that:

$$0.183 \cdot Q \qquad 2.25 \cdot T \cdot t$$

$$s = \frac{}{T} \cdot \log\left(\frac{}{r^2 \cdot S}\right)$$

But at the same time, the well is recharged at flow rate Q which would raise the levels so that:

$$s' = \frac{0.183 \cdot Q}{T} \cdot \log\left(\frac{2.25 \cdot T \cdot t'}{r^2 \cdot S}\right)$$

Table 6.II: Drawdown equations.

Step	Flow	Duration	Equation for theoretical drawdown at end of step
Pumping 1	$+ Q_1$	t_1	$s_1 = [(0.183Q_1)/T] \log [(2.25Tt_1)/(r^2S)]$
Recovery 1	$- Q_1$	t'_1	$s'_1 = [(0.183Q_1)/T] \log [(2.25Tt_1)/(r^2S)] - [(0.183Q_1)/T] \log [(2.25Tt'_1)/(r^2S)]$
			$s'_1 = [(0.183Q_1)/T] \log (t_1/t'_1)$
Pumping 2	$+ Q_2$	t_2	$s_2 = [(0.183Q_1)/T] \log (t_1/t'_1) + [(0.183Q_2)/T] \log [(2.25Tt_2)/(r^2S)]$
Recovery 2	$- Q_2$	t'_2	$s'2 = [(0.183Q_1)/T] \log (t_1/t'_1) + [(0.183Q_2)/T] \log (t_2/t'_2)$
Pumping i	$+ Q_i$	t_i	$s_i = \sum_{j=i-1}^{j=1} [(0.183Q_j)/T] \log (t_j/t'_j) + [(0.183Q_i)/T] \log [(2.25Tt_i)/(r^2s)]$

For pumping in steps of n flow rates, results represented in Table 6.II are obtained, where t_i is the elapsed time since the beginning of pumping Q_i, and t' the elapsed time after pumping Q_i is stopped. It is assumed that the head losses are negligible.

1.4 Theis's recovery method

The transmissivity of the aquifer can be calculated by interpreting the curve of recovery after pumping has ceased. It provides an important check of the transmissivity calculation with Jacob's method, and allows estimation of transmissivity when no observation wells or piezometers are available. Indeed, with well tests the accuracy of transmissivity estimation while pumping (Jacob's method) is not as good because of the variations in flow rate and because of quadratic head losses in the pumping well (see well test information in Section 2).

The analysis of a recovery test is based on the superposition principle: after the pump has been switched off, the well continues to be pumped at the same discharge rate while an imaginary recharge equal to the discharge is injected into the well. Discharge and recharge cancel each other.

The conditions underlying the method are the same as that for Jacob's method. According to Jacob's approximation and superposition principle, the equation for residual drawdown after pumping stops is written:

$$s_r = \frac{0.183 \cdot Q_i}{T} \cdot \log\left(\frac{t_i}{t'_i}\right)$$

where s_r is the residual drawdown (m), Q_i the flow rate at the last pumping i (m^3/h), T the transmissivity (m^2/h), t_i the elapsed time from the beginning of pumping i (h), and t'_i the elapsed time from the end of pumping i (h).

The experimental pairs (s_r,t/t'), plotted on semi-logarithmic paper, are aligned when the Jacob regime is reached. The slope of the fitted straight line is $C = 0.183 \cdot Q / T$.

Figure 6.4 illustrates the Theis recovery procedure. The transmissivity obtained is $3.9\ 10^{-4}\ m^2/s$ for the observation well (204) and $4.2\ 10^{-4}\ m^2/s$ for the pumping well (203). These values are close to

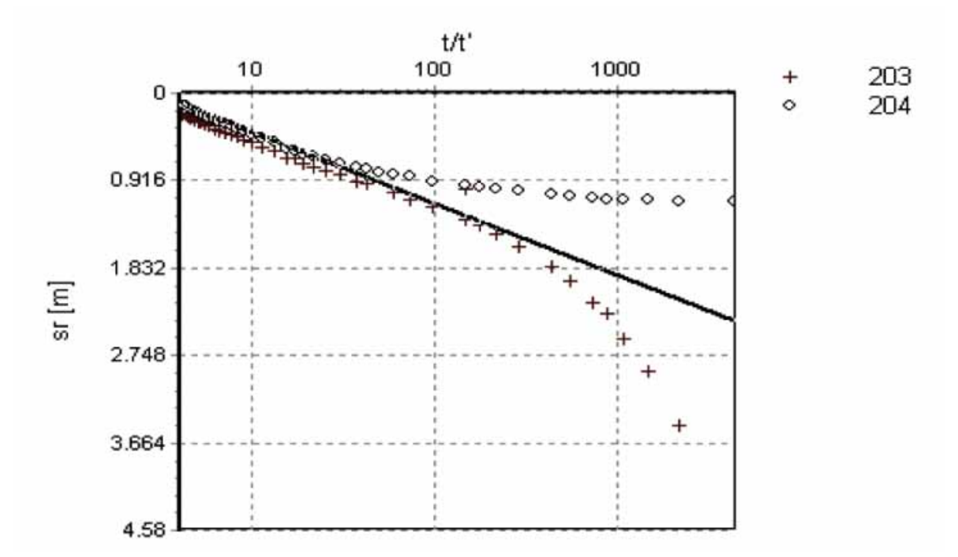

Figure 6.4: Aquifer-test interpretation using Theis's recovery method.

the one obtained with the Jacob method (5.8 10^{-4}m^2/s), and the interpreted transmissivity of the aquifer chosen is the average i.e. 4.6 10^{-4} m^2/s.

2 Well test

The well test is used to determine the conditions of well exploitation:

– operating yield and pumping schedule;
– installation depth of the pump;
– depth of well-borehole connection when a combined well is planned (see Chapter 8B).

Two well-test methods are frequently used. They are based on the same principle: pumping at different flow rates (known as pumping steps) is carried out, and the effect on water level (known as drawdown) is observed.

In the case of pumping in non-connected flow-rate steps, after every pumping step there is an observation time for the rise in water level (known as recovery). This recovery time is at least equal to that of the pumping-step time. It takes an average of 14 hours of field measurements to carry out a test, and the interpretation of field records is easier and more thorough that of the other method.

For pumping in connected flow-rate steps, no recovery time is allowed. This method is quicker than the non-connected method (an average of 6 hours of field measurements), but for accuracy it requires correction of measured drawdowns after the first step. Its interpretation is therefore a bit more difficult and sometimes less thorough.

2.1 Non-connected steps

2.1.1 STANDARD METHOD

A minimum of three successive pumping periods of 2 hours each are carried out at increasing flow rates. Each pumping period is separated by a pause at least as long, in order to allow the initial water level in the well to be approximately recovered (Figure 6.5).

The test includes the following phases:

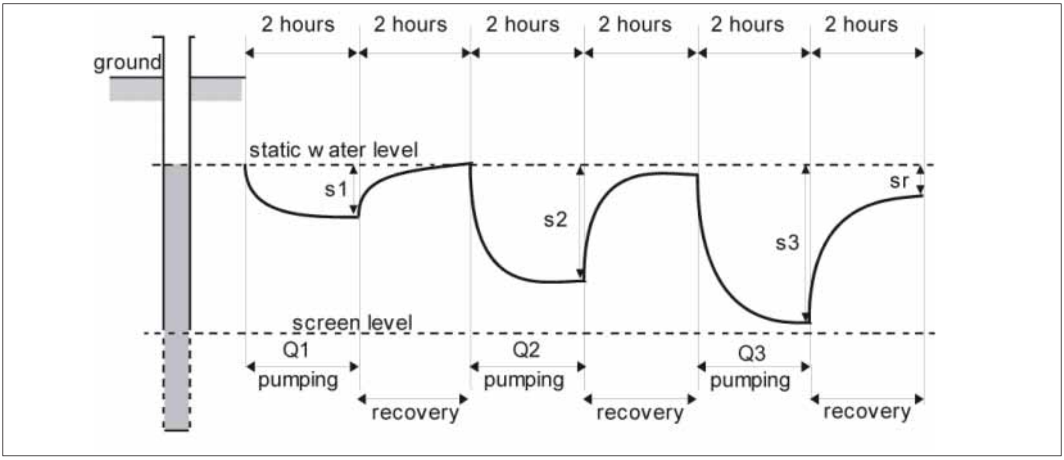

Figure 6.5: Well test with non-connected steps.

0	Rest phase	No work should take place for a period of at least 24 h, so that the level of the water measured before the first pumping step is actually the static level.
1	Pumping step No 1	Flow rate Q_1 of the first step is near to the future operational flow rate. In the case of manual pumping, the flow rate is: $0.7\ m^3/h < Q_1 < 1.0\ m^3/h$ Pumping time is 2 h Drawdown s_1 is the drawdown measured at the end of pumping
	Recovery No 1	The observation time for water-level recovery after pumping is 2 h
2	Pumping step No 2	Flow rate $Q_2 = (Q_1 + Q_3)/2$ Pumping time is 2 h s_2 is the drawdown measured at the end of pumping (2 h)
	Recovery No 2	The observation time for water-level recovery after pumping is 2 h
3	Pumping step No 3	$Q_3 = Q_{max} \cdot Q_{max}$ is the previously-determined maximum flow rate which should not induce the dewatering of the well. In practice Q_{max} can prove to be difficult to evaluate: an arbitrary value of Q_3 is therefore taken as equal to 70% of the value of the maximum flow rate at the time of well development Pumping time is 2 h s_3 is the drawdown measured for a pumping time of 2 h
4	Recovery No 3	The observation time for water-level recovery after pumping is at least 2 h, but should last until the water level approaches the initial static water level The difference between the initial water level and that measured after the observation of recovery is called residual drawdown (sr)

The drawdowns and pumping rates as functions of time are recorded during the whole process. The inter-related flow rate/maximum drawdown pairs (Q_1,s_1) (Q_2,s_2) (Q_3,s_3) are recorded at the end of each step.

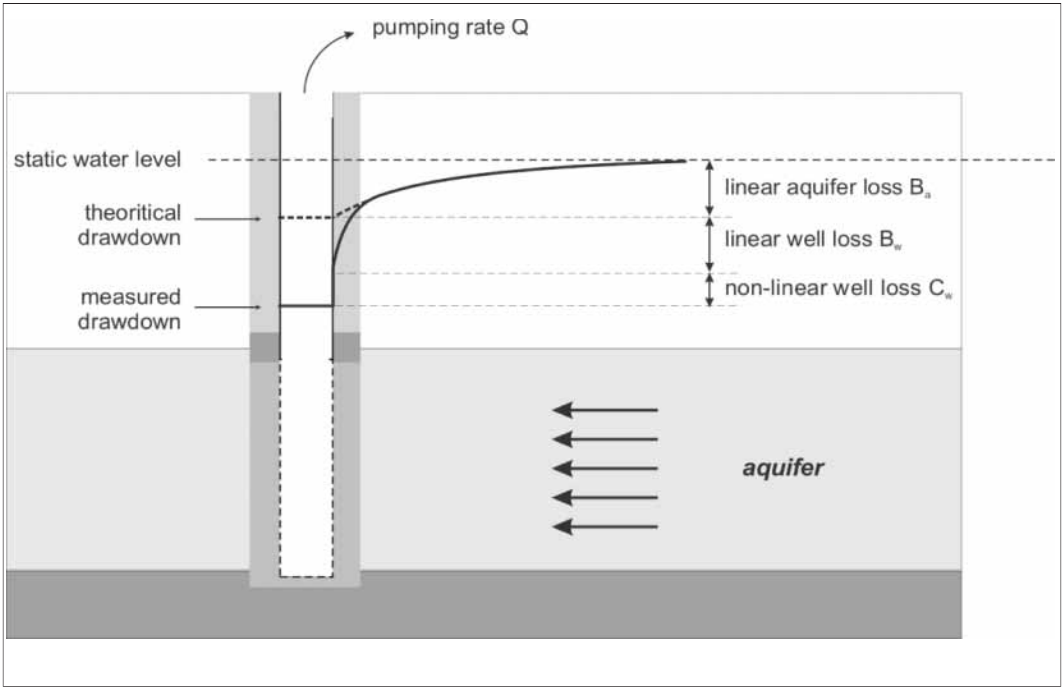

Figure 6.6: Various head-losses in a pumped well.

2.1.2 DATA VALIDATION AND INTERPRETATION

Before interpreting the field data, the records should be verified as presented in Section 1: any external changes, other than the test pumping, should be identified and any obviously wrong records should be removed or corrected.

There are several methods for analysing the data that may be found in the cited references. Two simple and easy-to-use methods are presented in this chapter: the Jacob's drawdown method is used to calculate the head-losses, and the Theis's recovery method is used to estimate the local transmissivity of the aquifer.

The Jacob's drawdown equation

For the drawdown in a pumped well, the Jacob's equation is (Kruseman & de Ridder, 2000):

$$s = (B_a + B_w) \cdot Q + C_w \cdot Q^p$$

where s in the measured drawdown, Q is the pumping yield, B_a is the linear aquifer head-loss coefficient, B_w is the linear well head-loss coefficient, C_w is the non-linear well head-loss coefficient and p can vary between value of 1.5 to 3.5.

Jacob's equation tells us that drawdown measured in a pumped well consists of two components (Figure 6.6): the aquifer head-losses and the well head-losses. Aquifer head-losses occur in an aquifer when the flow is laminar. They are time-dependent and they vary linearly with the pumping rate. They are quantified with B_a coefficient. Well losses are divided into linear and non-linear head-losses. The linear head-losses are caused by damage to the aquifer during drilling and completion of the well (B_w coefficient); the non-linear head-losses occur mainly in the gravel pack and the screen where the flow is turbulent (C_w coefficient).

In practice, it is not possible to differentiate B_a and B_w coefficients and Jacob's equation is simplified as $s = B \cdot Q + C \cdot Q^2$. The interpretation method makes possible to evaluate the linear head-losses coefficient B and the quadratic head-losses coefficient C. Knowing B and C, it is possible to predict the drawdown for any discharge Q at a certain time t (B is time dependant). From the relationship between s and Q, it is also possible to determine an optimum operating yield for the well. Finally, the relative value of C is used to evaluate the well efficiency.

This method is only theoretically valid when the following conditions apply:

– the aquifer is confined, unconfined or leaky;
– the aquifer has an infinite area extent;
– the aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the test;
– the piezometric surface is horizontal over the area influenced by the test, before the beginning of the test;
– the well penetrates the entire thickness of the aquifer so that the flow is horizontal in the aquifer;
– the non-linear head-losses vary according to $C \cdot Q^2$ (p=2).

These ideal conditions are not always encountered in reality: it is thus essential to be vigilant concerning the interpretation of results, and to use common sense and accuracy in taking measurements, in order to remain within an acceptable range of approximation.

The interpretation can be carried out manually (using graph paper), with support software such as Excel (prepared worksheets with formulas), or using specific interpretation software such as WHI AquiferTest Pro (http:\www.flowpath.com).

Well-efficiency estimation: head-loss calculation

According to Jacob's equation, a plot $s_i/Q_i = f(Qi)$ will yield a straight line of slope C and ordinate at the origin B ($s = B \cdot Q + C \cdot Q^2 \leftrightarrow s/Q = B + C \cdot Q$, Figure 6.7). Values of B and C provide the equation of the borehole for all flow rates for which the pumping time is that of the test. Note that this procedure is completely valid when the steady state is reached at the end of each step. In practice, it is important to maintain pumping until the drawdowns vary little with time (quasi-steady state).

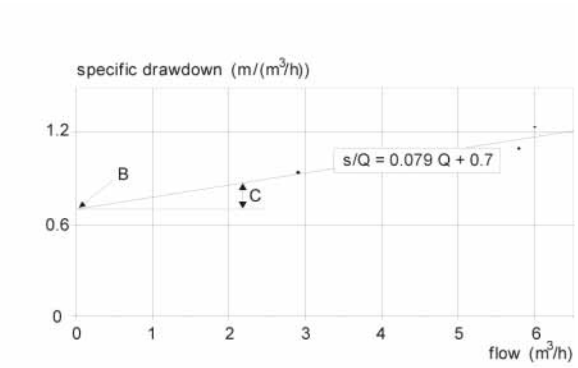

Figure 6.7: Calculation of head losses.
Well test: borehole F1 – Estimation of head-losses using Jacob's method. Linear head-losses: B = 0.7 m/(m³/h). Quadratic head-losses: C = 7.9 10⁻² m/(m³/h)².

Another parameter, called J, is used to estimate the borehole quality (Forkasiewicz 1972). J is a coefficient that represents the ratio between linear and quadratic head-losses as $J = \Delta Q/s \;/\; Q/s$.

B, C, and J cannot be interpreted on their own, but they can be compared between several actual wells. It is useful to estimate the quality of a well in a rehabilitation programme or when planning the installation of a submersible pump. According to De Marsily (1986) and Forkasiewicz (1972) a first approximation of well efficiency can be made from the values in Table 6.III.

Table 6.III: Order of magnitude of head-losses.
C is expressed in $m/(m^3/h)^2$.

C	$C < 1.9 \cdot 10^{-2}$	Good well, highly developed
	$1.9 \cdot 10^{-2} < C < 3.7 \cdot 10^{-2}$	Significant head-losses
	$3.7 \cdot 10^{-2} < C < 1.5$	Clogged or deteriorated well
	$C > 1.5$	Well that cannot be rehabilitated
J	$J < 10\%$	Quadratic head-losses negligible compared to linear head-losses
	$J > 10\%$	Quadratic head-losses significant compared to linear head-losses

Evaluation of maximum pumping rate: the well curve

At the end of every step, the pairs (s_1,Q_1) (s_2,Q_2) and (s_3,Q_3) are recorded. By plotting these values in an linear diagram, with s as ordinate and Q as abscissa, the link between the pumped flow rates and the drawdown created is illustrated (Figure 6.8). From the head-loss equation, $s = BQ + CQ^2$, it is possible to plot on the same graph the straight line $s = BQ$, in order to visualise the linear and quadratic head-losses of the drawdown.

A significant increase in quadratic head-losses creates a point of inflection on the curve, which allows the critical flow rate to be determined. Such a point of inflection is due to an over-pumping that creates important turbulent flow and heavy non-linear head-losses, but it can also be caused by the dewatering of a particularly productive horizon. The maximum flow rate is set slightly lower than the critical flow rate. If there is no clear break in the slope of the well curve, the maximum flow rate is set according to the possible maximum drawdown, that is generally 1 m above the pump screens. Jacob's equation $s = B \cdot Q + C \cdot Q^2$ has a positive real solution

$$Q = \frac{\sqrt{B^2 + 4 \cdot C \cdot s} - B}{2 \cdot C}$$

By inserting the maximum permissible drawdown in place of s, the maximum flow rate is obtained.

Note that if values (s_i, Q_i) are aligned in a slightly concave curve, it may be that the measurements had not been taken properly, or that well development occurred during pumping (gravel-pack clearing, improvement of water circulation in the immediate neighbourhood of the well). In this case, the test must be repeated.

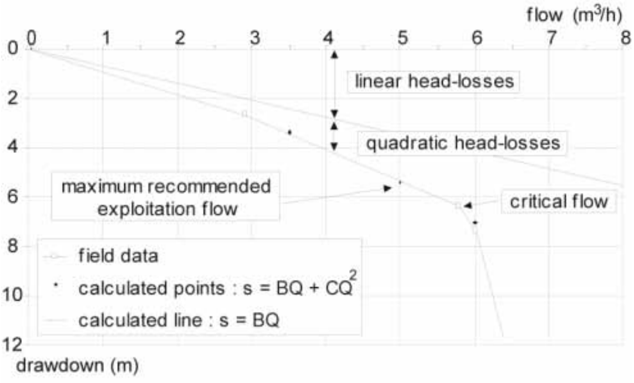

Figure 6.8: Well curve s = f(Q) of borehole F1.

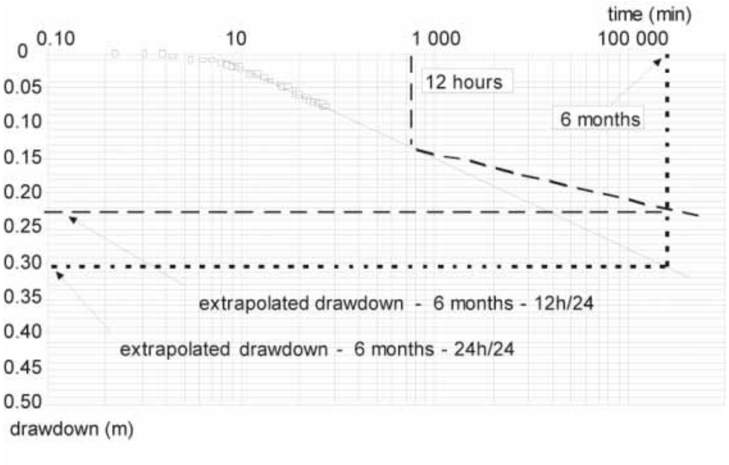

Figure 6.9: Extrapolation of drawdown as a function of time.

Evaluation of possible future drawdown: link between drawdown, yield and time

To estimate drawdown induced by pumped flow-rates differing from those of the tests, it is possible to use the head-loss equation $s = B \cdot Q + C \cdot Q^2$. Drawdowns estimated in this way are only valid for pumping times equivalent to the durations of the test steps.

In a well test, it is not possible to make a reliable estimate of drawdown induced by pumping times longer than those of the tests. Indeed, the effects of several hours' pumping are only appreciable in a restricted part of the aquifer surrounding the pumping well (see Section 3). Nevertheless, various solutions have been proposed and have been used on a large scale in Africa, to optimise information from well tests. Some of these results are presented here because they seem to have been consistent in the field. However, they must be used while being aware of their limitations: the extrapolation of data to predict operations over 6 months from a well test of some hours is not really reliable.

Drawdowns measured during the test (ordinate, linear) are plotted against pumping time (abscissa, logarithmic) on a semi-logarithmic graph. The curve s = f(t) must be a straight line after some time (see the section on Jacob's method). It is possible to extend this straight line to estimate the drawdown induced by the same flow rate but for a longer pumping time (Figure 6.9).

If the pumping period is n hours per day, the drawdown after 6 months can be estimated as follows:

– from test data, extrapolate drawdown induced by n hours of pumping by extending the straight line s = f(t) to n hours;

– extend this straight line beyond n hours (up to 6 months for example) by correcting its slope by the ratio n/24.

The first straight line of Figure 6.4 is an extrapolation of drawdown for a pumping time of 6 months, 24 h per day. The second one is an example of drawdown extrapolation for pumping 12 h per day for 6 months.

Proceeding in this way for the various steps, new pairs (s_i extrapolated, Q_i) are obtained, enabling a new well curve of $s_{extrapolated} = f(Q)$ to be constructed. A theoretical operational flow rate can then be set on the basis of permissible maximum drawdown.

Depth of installation of the pump: prediction of dynamic level

The depth of installation of the pump inlet screen is a function of the predicted dynamic level. This level is given by the drawdown induced by the rate of abstraction, increased by annual piezometric variations. For accuracy, a correction taking into account year-to-year variations of static level should also be applied.

Table 6.IV: Fluctuations (m) in static water level, raised in formations of weathered bedrock in various countries of the Sudan-Sahel zone.

Static level	Foreseeable static level fluctuations									
	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
5 m	6	5.40	4.80	4.20	3.60	3	2.40	1.80	1.20	0.60
10 m	4	3.60	3.20	2.80	2.40	2	1.60	1.20	0.80	0.40
15 m	2.50	2.25	2	1.75	1.50	1.25	1	0.75	0.50	0.26
20 m	1.50	1.35	1.20	1.05	0.90	0.75	0.60	0.45	0.30	0.15
25 m	1	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10

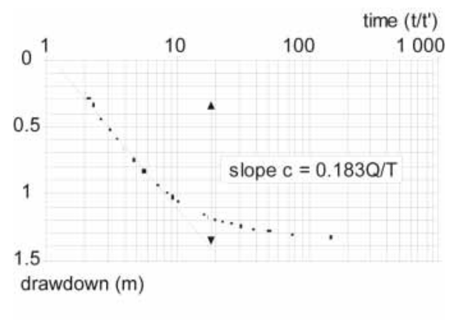

Figure 6.10: Recovery curve, borehole F4 – s = f(t/t').

The drawdown must be estimated for an operational flow rate of a duration equivalent to that of the dry period (4 to 8 months, depending on context) and for a length of daily pumping to be established (4 to 20 h). It must be increased by seasonal variations in piezometric level (Table 6.IV). The pump inlet screen is then generally installed at 2 or 3 m below the dynamic level so established.

For example, in a pumping test on a borehole intended to be equipped with a handpump, interpretation of the test predicts an drawdown of 5.50 m after 8 months of pumping at 1 m^3/h for 8 h per day. The static level measured before the test of February 15 is 17.5 m. According to Table 6.IV, the foreseeable decrease in static level before the next rains (June) is 1 m. The proposed installation of the pump is therefore : 17.5 + 1 + 5.5 + 3 = 27 m

Note that this procedure is also used to estimate the depth of a well when a combined well is under construction (see Chapter 8D). At the time of sinking the well after drilling the borehole, the minimum depth of the well will be about 1 or 2 m lower than the foreseeable dynamic level.

Local transmissivity estimation: recovery analysis

A well test does not provide a representative value of the transmissivity of an aquifer. Pumping times are not long enough to concern a sufficient volume of aquifer. The transmissivity calculated from a well test is therefore a local feature, but it is still of interest in that it gives a comparison between wells.

The most reliable evaluation of transmissivity comes from the interpretation of the recovery curve (rise in water level after the final pumping step). The common interpretation method, called Theis's recovery method (Kruseman & de Ridder, 2000) is presented Section 1. The procedure is to plot the experimental pairs (t/t',s) on semi-logarithmic paper, and to fit a straight line through them considering mainly the late time. The transmissivity is calculated from the slope of this straight line that is $C = 0.183 \cdot Q / T$ where Q is the flow rate of the last pumping i (m^3/h), T is the transmissivity (m^2/h), with t and t' the elapsed times since the beginning and end of pumping i respectively (h). An example of a recovery curve is given in Figure 6.10.

2.1.3 EXAMPLES

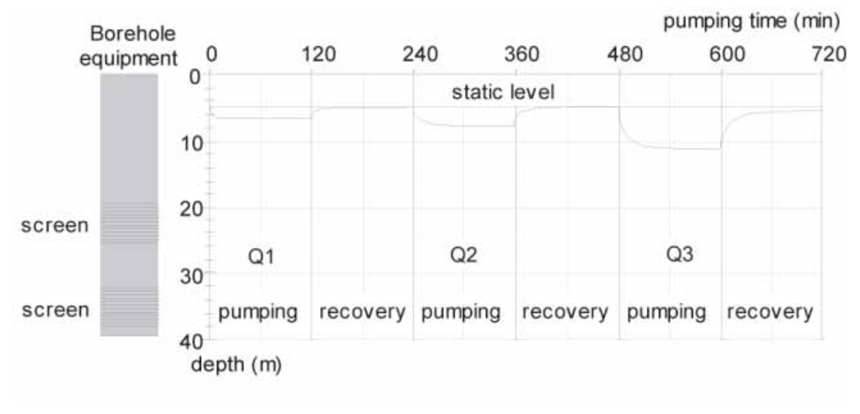

Figure 6.11: Water level as a function of time.

These examples concern Sierra Leonean refugee camps in the Forecaria region of Guinea Conakry. The 1998 ACF borehole programme was implemented to supply the camps with drinking water. The geological context is weathered and fractured crystalline rock (mesocrates, diorites or gabbros).

The objectives of well tests were to decide the installation depth of foot pumps (Vergnet HPV60 type) and to check if boreholes were capable of being equipped with small pumping stations (to provide a rapid increase in water abstraction in case of a new influx of refugees).

High-productivity well: borehole No.1 (Kaleah I)

The main results of this test are shown in Figures 6.11 and 6.12 and Tables V and VI.

This borehole can reliably be equipped with a Vergnet HPV 60 pump. The pump inlet screen is fixed at 12 m deep (taking account of static level fluctuations and allowing a 3-m safety factor).

This borehole can also be selected for the installation of a small pumping station if the number of refugees were to increase over the next months: indeed a flow rate of 6 m^3/h seems to be possible. The final level was achieved at the maximum capacity of the submersible pump used. However, a flow rate greater than 6 m^3/h could be considered if the drawdown does not deviate from the calculated curve s = f(Q) (so as not to exceed the critical flow rate that could not be observed yet) and drawdown does not go below the top of the screens (in order to avoid dewatering of the productive zone).

The top of the borehole screens lies at 19.5 m and the deepest static water level is estimated as 6.5 m; the foreseeable maximum drawdown is 13 m. Taking a safety margin of 3 m, a maximum

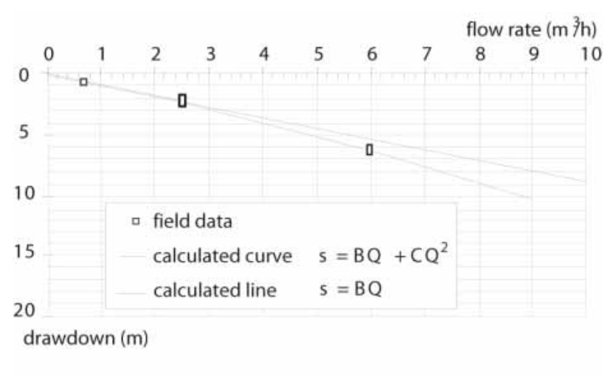

Figure 6.12: Curve of flow rate vs drawdown [s = f(Q)].

Table 6.V: Test conditions.

Date	Water	Turbidity	T	pH	EC	Maximum exploitation flow (m^3/h)
22/01/1998	clear no sand (stain test < 0.5 cm)	< 5 NTU	27.5°C	7.8	205-220 µS/cm	6-8.8

Table 6.VI: Test results.

Flow/step (m^3/h)	Pumping time (h)	Drawdown (m) max at end of step	Drawdown (m) residual after 2 h	Specific capacity ($(m^3/h)/m$)	Value of quadratic head-losses $m/(m^3/h)^2$
0.7	2	0.65	0.02	1.077	$6\ 10^{-3}$
2.5	2	2.33	0.05	1.073	
6	2	6.29	0.09	0.954	

drawdown of 10 m can be estimated. Referring to the curve s = f(Q), this drawdown corresponds to a flow rate of about 8.8 m^3/h. These values must be verified at the time of installation of any possible pumping station, and a regulating valve may have to be used to adjust the flow rate to conform with observations on measured drawdown values.

Low-productivity well: borehole No. 2 (Kaleah I)

The results of this test are shown in Figures 6.13 and 6.14 and Tables 6.VII and 6.VIII.

This borehole is productive enough to be equipped with a Vergnet HPV 60 pump. The pump inlet screen is fixed at 15 m deep.

In spite of a flow rate measured at 5 m^3/h at the time of the borehole drilling, it is not advisable to install a small pumping station at this borehole because the head-losses are relatively significant compared to that of the borehole No.1. The stabilisation of drawdown was not fully reached

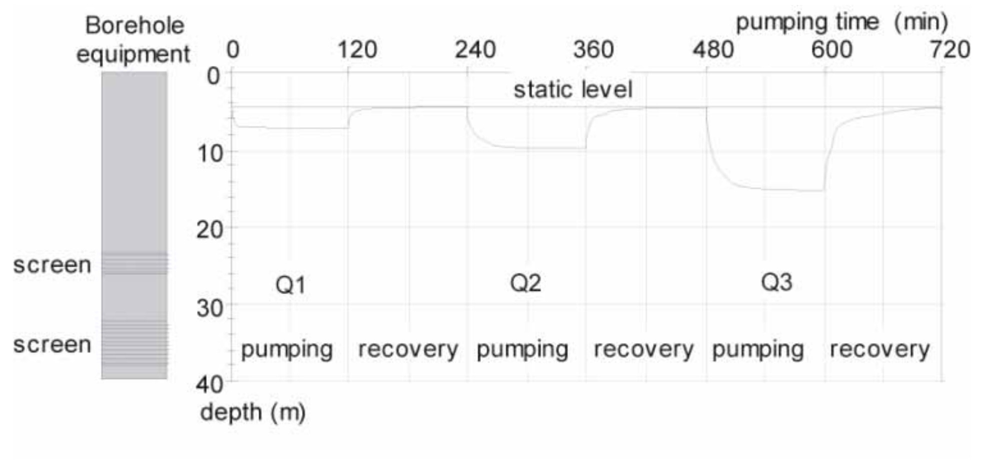

Figure 6.13: Water levels as a function of time.

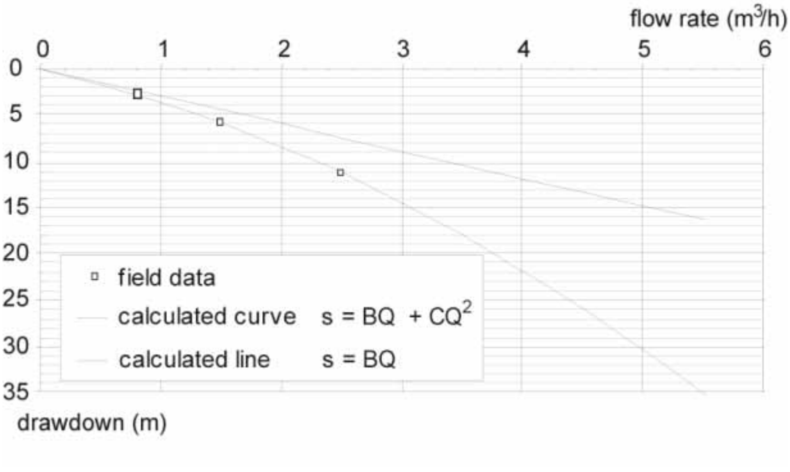

Figure 6.14: Curve of flow rate against drawdown [s = f(Q)].

Table 6.VII:Test conditions.
No variation in these values during the test.

Date	Water	Turbidity	T	pH	EC
22/01/1998	clear no sand (stain test < 0.5 cm)	< 5 NTU	28°C	7.8	205-220 μS/cm

Table 6.VIII: Test results.

Flow/step (m^3/h)	Pumping time (h)	Drawdown (m)		Specific capacity ($(m^3/h)/m$)	Value of quadratic head-losses $m/(m^3/h)^2$
		max at end of step	residual after 2 h		
0.8	2	2.79	0	0.287	$2.2\ 10^{-2}$
1.5	2	5.81	0.09	0.258	
2.5	2	11.34	0.09	0.220	

at the last step, and exploitation flow rates greater than 3.6 m^3/h would induce drawdown lower than screen level (top of screens = 23.1 m, static level = 4.4 m, permissible maximum drawdown = 18.7 m, Q = 3.6 m^3/h if critical flow rate is not reached). Thus the maximum flow rate is estimated at 3 m^3/h.

2.2 Connected steps

Pumping steps are carried out without recovery time in between. This results in the measured drawdown being affected by all the previous pumping series, and not only by the last pumping step. To allow strict interpretation, the measured drawdowns need to be corrected so that they reflect only the current pumping step. There are two main methods to conduct this correction: the mathematical calculation of corrected drawdown and the graphical analysis of drawdown.

Table 6.IX: Test phases.

0	Rest phase	No work should take place for a period of at least 24 h, so that the level measured before the first pumping is actually the static level
1.	Pumping step No 1	Flow rate Q_1 of the first step is near to the future operational flow rate In the case of manual pumping, the flow rate is $0.7\ m^3/h < Q_1 < 1.0\ m^3/h$ Pumping time is 2 h Drawdown s_1 is the drawdown measured at the end of pumping
2	Pumping step No 2	Flow rate $Q_2 = (Q_1 + Q_3)/2$ Pumping time is 1 h s_2 is the drawdown measured at the end of pumping (2 + 1 = 3 h)
3	Pumping step No 3	$Q_3 = Q_{max}$. Q_{max} is the previously-determined maximum flow rate which should produce the maximum drawdown In practice Q_{max} can prove to be difficult to evaluate: an arbitrary value of Q_3 is therefore taken as equal to 70% of the value of the maximum flow rate at the time of well development Pumping time is 1 h s_3 is the drawdown measured for a pumping time of (2 + 1 + 1 = 4 h)
4	Recovery	The observation time for water-level recovery after pumping is at least 2 h, but should last until the water level reaches a level of about the initial static water level The difference between the initial water level and that measured after the observation of recovery is called residual drawdown (sr)

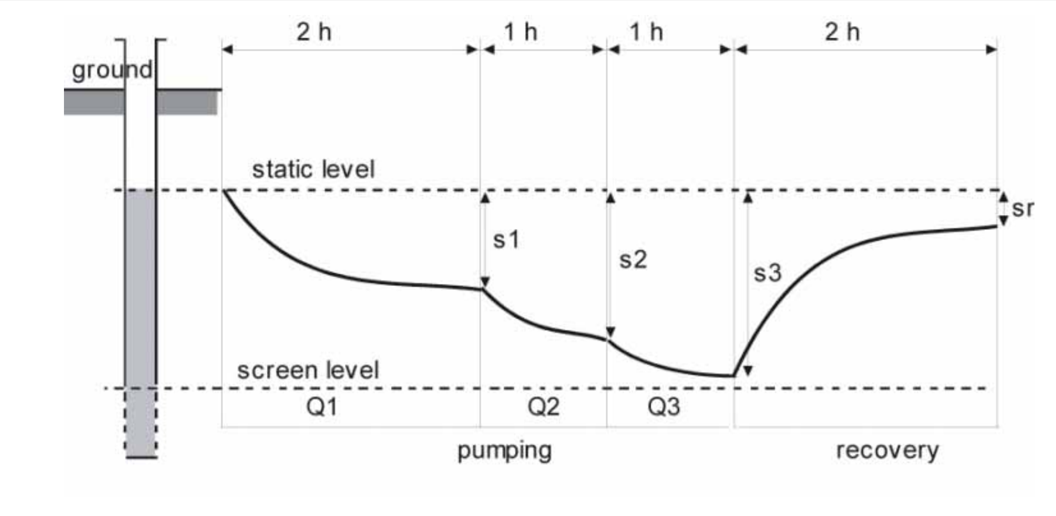

Figure 6.15: Well test in connected steps.

2.2.1 SIMPLIFIED METHOD

Three connected pumping steps are carried out at increasing flow rates, and the recovery in water level in the well is observed until a level close to the static level before the test is reached (Figure 6.15). The test phases are given in Table 6.IX:

2.2.2 CALCULATION OF CORRECTED DRAWDOWNS

To calculate the drawdown corresponding to the one that would have been created by the current step alone, Jacob's method is used according the superposition principle (see Section 1.3.3). Considering a non-connected well test, if recovery times are at least as long as pumping times, and the progression of flow rates is meaningful, terms under the Σ sign of drawdown equation given in Table 6.II rapidly become negligible compared to the isolated term. Equations of drawdown are then simplified $S_i = [(0.183Q_i)/T] \log[(2.25Tt_i)/(r^2S)]$ where i is the step number. The theoretical drawdowns at the end of each step of a non-connected well test are therefore induced only by the last pumping. A set of pairs (s_i/Q_i) is then obtained, measured directly on site and comparable with one another.

When pumping steps are connected, it is no longer possible to disregard the terms under Σ. Drawdowns obtained at the end of steps are therefore induced by the total previous steps, and they

$$s_2 = \frac{0.183 \cdot Q_1}{T} \cdot \log\left(t_2 \frac{2.25 \cdot T}{r^2 \cdot S}\right) - \frac{0.183 \cdot Q_1}{T} \cdot \log\left((t_2 - t_1) \frac{2.25 \cdot T}{r^2 \cdot S}\right) + \frac{0.183 \cdot Q_2}{T} \cdot \log\left((t_2 - t_1) \frac{2.25 \cdot T}{r^2 \cdot S}\right) + J_2$$

$$\rightarrow s_2 = \frac{0.183 \cdot Q_1}{T} \cdot \log\left(\frac{2.25 \cdot T}{r^2 \cdot S}\right) + \frac{0.183 \cdot (Q_2 - Q_1)}{T} \cdot \log\left((t_2 - t_1) \frac{2.25 \cdot T}{r^2 \cdot S}\right) + J_2$$

$$s_3 = \frac{0.183 \cdot Q_1}{T} \cdot \log\left(t_3 \frac{2.25 \cdot T}{r^2 \cdot S}\right) + \frac{0.183 \cdot (Q_2 - Q_1)}{T} \log\left((t_3 - t_1) \frac{2.25 \cdot T}{r^2 \cdot S}\right) + \frac{0.183 \cdot (Q_3 - Q_2)}{T} \cdot \log\left((t_3 - t_2) \frac{2.25 \cdot T}{r^2 \cdot S}\right) + J_3$$

need to be corrected to be compared.

For a well test of three connected steps, the measured drawdowns are:

$$s_1 = \frac{0.183 \,.\, Q_1}{T} \cdot \log\left(t_1 \frac{2.25 \cdot T}{r^2 \cdot S}\right) + J_1$$

By definition the corrected drawdowns are:

$$s_{1-c} = \frac{0.183 \cdot Q_1}{T} \cdot \log\left(t_1 \frac{2.25 \cdot T}{r^2 \cdot S}\right) + J_1$$

$$s_{2-c} = \frac{0.183 \cdot Q_2}{T} \cdot \log\left(t_2 \frac{2.25 \cdot T}{r^2 \cdot S}\right) + J_2$$

$$s_{3-c} = \frac{0.183 \cdot Q_3}{T} \cdot \log\left(t_3 \frac{2.25 \cdot T}{r^2 \cdot S}\right) + J_3$$

By combining the two systems of equation, we obtain:

$$s_{1-c} = s_1$$

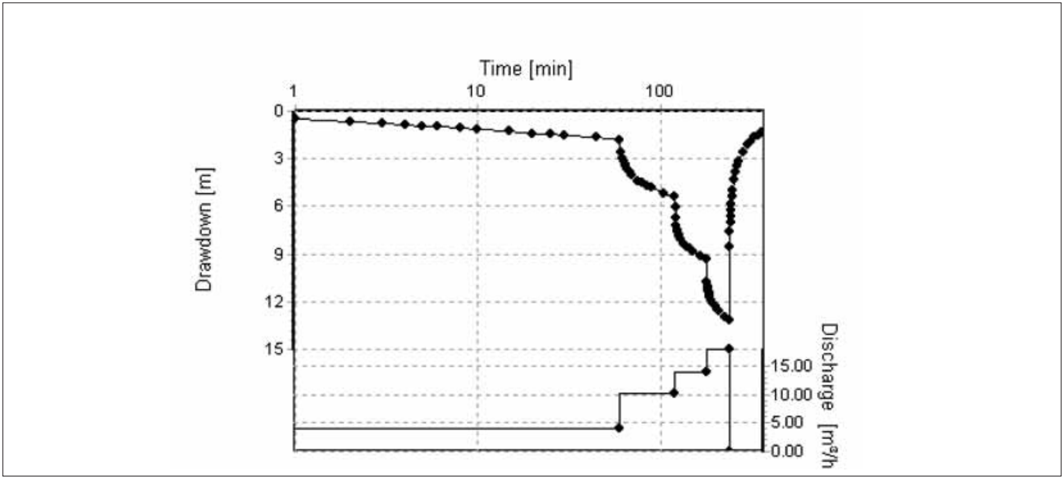

Figure 6.16: Four connected pumping steps, borehole 204.

$$s_{2-c} = s_2 + \frac{0.18}{T} \cdot \left(Q_2 \cdot \log \frac{t_1}{t_2 -} - Q_1 \cdot \log \frac{t_2}{t_2 - t_1} \right)$$

$$s_{3-c} = s_3 \frac{0.183}{T} \cdot \left(Q_3 \cdot \log \frac{t_1}{t_3 - t_2} - Q_2 \cdot \log \frac{t_3 - t_1}{t_3 - t_2} - Q_1 \cdot \log \frac{t_3}{t_3 - t_1} \right)$$

Whatever the test protocol, it is possible to correct the measured drawdowns using the same calculation. For example, the corrected drawdowns of the simplified method of 2 hours for the first step, 1 hour for the second step and 1 hour for the last step:

$$s_{1-c} = s_1$$

$$s_{2-c} = s_2 + \frac{0.183}{T} \cdot (0.3 \cdot Q_2 - 0.48 \cdot Q_1)$$

$$s_{3-c} = s_3 + \frac{0.183}{T} \cdot (0.3 \cdot Q_3 - Q_2 - Q_1)$$

T can be determined using Theis's recovery method (Section 1) or its modified form given in the following section.

2.2.3 GRAPHICAL ESTIMATION OF CORRECTED DRAWDOWNS

A graphical analysis can also be conducted to estimate the corrected drawdowns. This method needs careful data processing to be accurate.

Figure 6.16 presents a test conducted in borehole drilled in a granitic bedrock formation. Four connected steps have been carried out: the last one was stopped because the dynamic water level reached the pump inlet level.

The graphical analysis consists of estimating the drawdown of each particular step using the slope of the previous drawdown development. Figure 6.17 shows the graphical estimation of the cor-

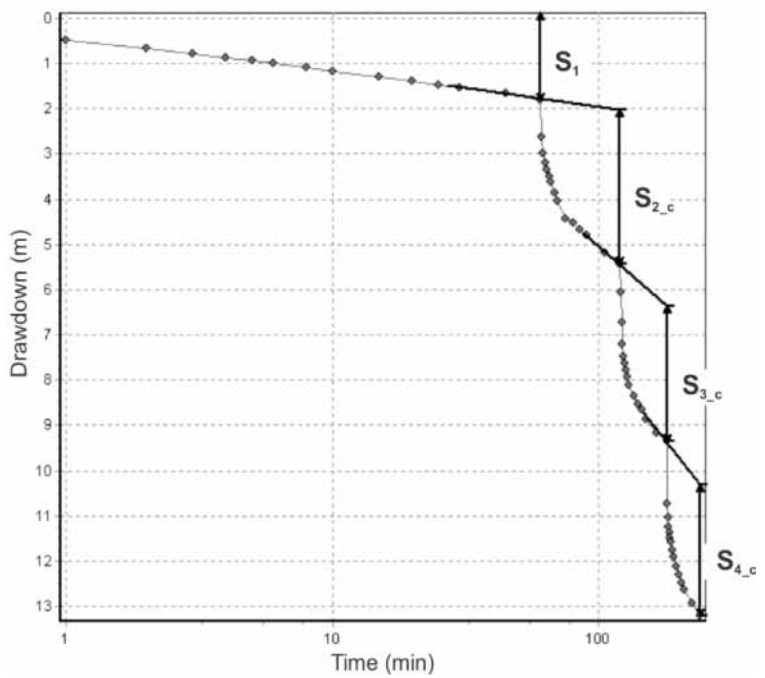

Figure 6.17: Graphical estimation of the corrected drawdown s_{i_C}, borehole 204.

rected drawdown for the borehole test presented Figure 6.16. The slope has to be chosen carefully because it obviously has a great influence on the drawdown estimation.

2.2.4 DATA VALIDATION AND INTERPRETATION

Data validation and interpretation are carried out in a similar manner to that for the non-connected flow-rate tests, but using the corrected drawdowns. However, some differences exist

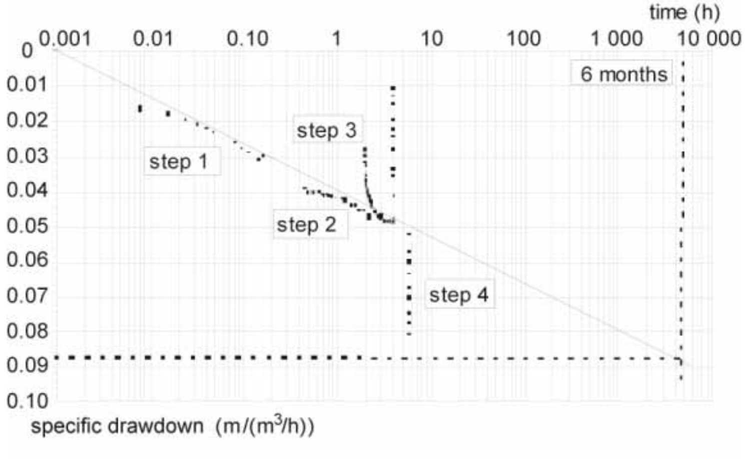

Figure 6.18: Extrapolation of specific drawdown, well P1.

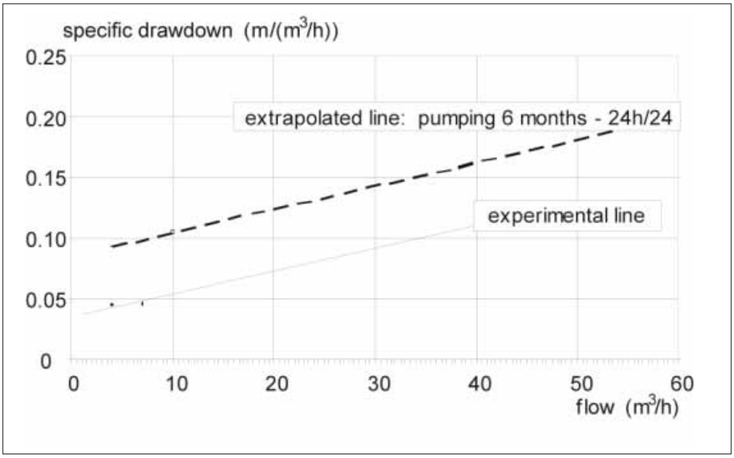

Figure 6.19: Extrapolation of drawdown, well P1.

concerning the dynamic level prediction and the local transmissivity estimation.

Prediction of dynamic level

Recommendations for the extrapolation of data at the time of the interpretation of non-connected well tests also need to be taken into account. It is right, therefore, to be sceptical and to be critical of these somewhat daring extrapolations.

To estimate drawdown induced by a pumping time longer than that of tests, a semi-logarithmic graph of specific drawdown s_i/Q_i (ordinate, linear) of the set of steps against time (abscissa, logarithmic) is used. The theory is that these points should have a same asymptote that can be represented with a well-fitted straight line (Figure 6.18). This straight line can be extended for longer pumping times than those of the tests. A new value s/Q corresponding to a new pumping time is then obtained. Plotting this value in the graph $s/Q = f(Q)$ and drawing a straight line parallel to that obtained in the test gives a new value of B. It is then possible to define the equation of the well ($s = BQ + CQ^2$) for a new pumping time (Figure 6.19).

Estimation of local transmissivity

For pumping periods in non-connected steps, it is recommended that local transmissivity is calculated from a survey of the recovery curve.

It is possible to draw this curve of under the form $(s_3–s) / Q_3 = f(t')$ where t' is time elapsed since the end of pumping, on the same diagram as that for connected steps $s / Q = f(Q)$. The two straight lines (pumping and recovery) must have the same slope C, such that $T = 0.183 \cdot Q / C$.

3 Pumping-test procedure

3.1 Design of test

Before the test is carried out, it is necessary to collect information on the local geology, the well lithology, the aquifer type and the well (diameter, depth, position of screens, estimated flow rate at the time of development and corresponding drawdown).

This information enables the preparation of the programme of the pumping test and the definition of maximum permissible drawdown, pumped flow rates, number and duration of each pumping step for a well test, number and position of piezometers and pumping duration for an aquifer test.

3.1.1 MAXIMUM DRAWDOWN AND PUMPING RATE

Table 6.X: Estimated number and duration of steps according to the maximum pumping yield.

Maximum yield expected (from borehole development or nearby well)	Minimum number of steps	Expected duration of steps
$Q < 2\ m^3/h$	1	4 hours
$2\ m^3/h < Q < 3\ m^3/h$	2	2 + 2 hours
$Q > 3\ m^3/h$	3 and more	1.5 + 1.5 + 1.5 hours +…

Indications obtained at the time of the development of the borehole determine the maximum flow rate (that is the last step of a well test). This must equal the maximum permissible drawdown, so that the thickness of the saturated zone should remain constant all over the test duration if the aquifer is confined, and the final drawdown is less than 60% of the saturated thickness if the aquifer is unconfined.

3.1.2 WELL TEST: NUMBER AND DURATION OF STEPS

The maximum permissible flow rate allows the number of steps to be estimated according to Table 6.X. It also influences the step duration, which depends on the well and aquifer characteristics.

The duration of steps depends on well behaviour during pumping: it is essential that drawdown

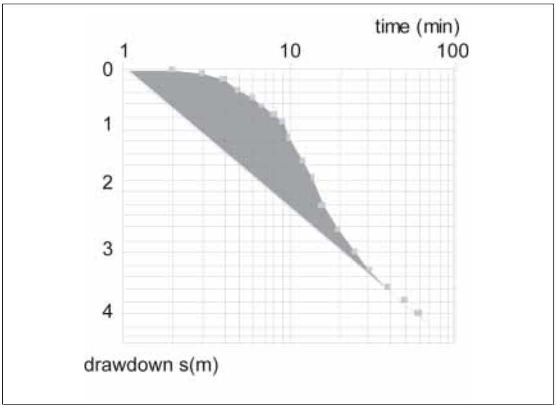

Figure 6.20: Capacity effect (drawdown delay).
The effect is represented in grey; pumping time must be greater that 60 mins.

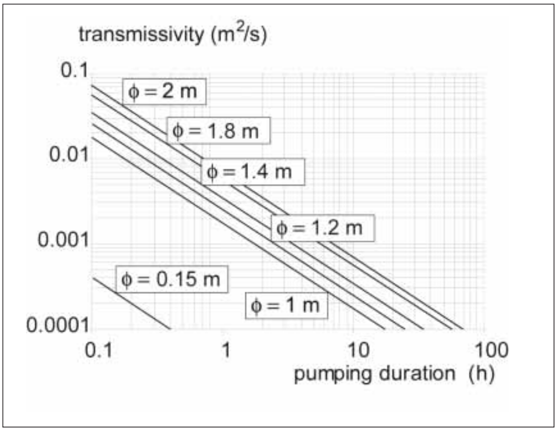

Figure 6.21: Design chart for evaluating pumping time at which the capacity effect is theoretically negligible.
The pumping time must be at least ten times greater than the capacity-effect delay.

at the end of a non-connected well test is nearly stabilised. If the water level continues to fall significantly, it is preferable to prolong the pumping duration. For a connected well test, this condition is less important because the drawdowns will be corrected for interpretation. Also, if the aquifer tested has very low transmissivity and the well has a large diameter, the capacity effect can be significant (Figure 6.20) and the duration of pumping steps should be extended as $t \geq 25 \cdot r^2 / T$ where r is the well radius and T the transmissivity (Figure 6.21, University of Avignon, 1990).

The number of steps needs also to be adjustable. On one hand, if the flow rate of the well is lower than 2 or 3 m^3/h, it is difficult to set three steps with increasing flow rates. Two steps of over 3 h, or even only one step of at least 4 h, can then be considered. The pumped flow rate is chosen so that the well is not dewatered. The observation of recovery of water levels is at least 2 h, until the water level returns to somewhere near the initial static level. On the other hand, if the flow rate has been underestimated, additional steps may be used.

3.1.3 AQUIFER TEST: DURATION OF PUMPING

There are numerous parameters that have to be considered when choosing the pumping duration of an aquifer test. The main ones are the type of aquifer and the degree of accuracy of the interpretation that needs to be reached.

Economising on the pumping duration is not recommended and the general rule is to continue the pumping until a steady state or quasi-steady state is reached. At the beginning of the test, the drawdown develops rapidly and it will deepen more slowly after some time. This apparent stabilisation of the dynamic level is not yet a steady flow state and the cone of depression will continue to extend slowly until the recharge from the aquifer equals the pumping rate.

Under average conditions, the quasi-steady flow state is reached in a confined aquifer after 24 hours, and in an unconfined aquifer after 2 or 3 days. A planned pumping duration of a minimum of 48 hours is recommended in a confined aquifer and 72 hours in an unconfined aquifer.

3.1.4 NUMBER AND POSITION OF PIEZOMETERS

The piezometers considered here are observation wells to monitor water level.

Their number depends on the amount and degree of accuracy of the estimates of aquifer hydraulic parameters needed (Table 6.XI). To carry out a well test, no piezometer is needed because the dynamic level has to be monitored in the pumping well. The local transmissivity of the aquifer can generally be estimated from single well test with Theis's recovery method. However, a piezometer is needed to estimate the storativity of the aquifer because it can not be accurately estimated from the pumping-well data alone.

To carry out an aquifer test, one piezometer is needed to estimate the hydraulic characteristics

Table 6.XI: Estimated number and position of piezometers required.

Test	Objective	Required number of piezometers	Distance from the pumping well
Well test	Well characteristics	0	—
	Well characteristics + local transmissivity	1	10 m – 50 m
Aquifer test	Hydraulic characterisation	1	20 m – 100 m
	High accuracy in hydraulic characterisation	3	10 m – 200 m

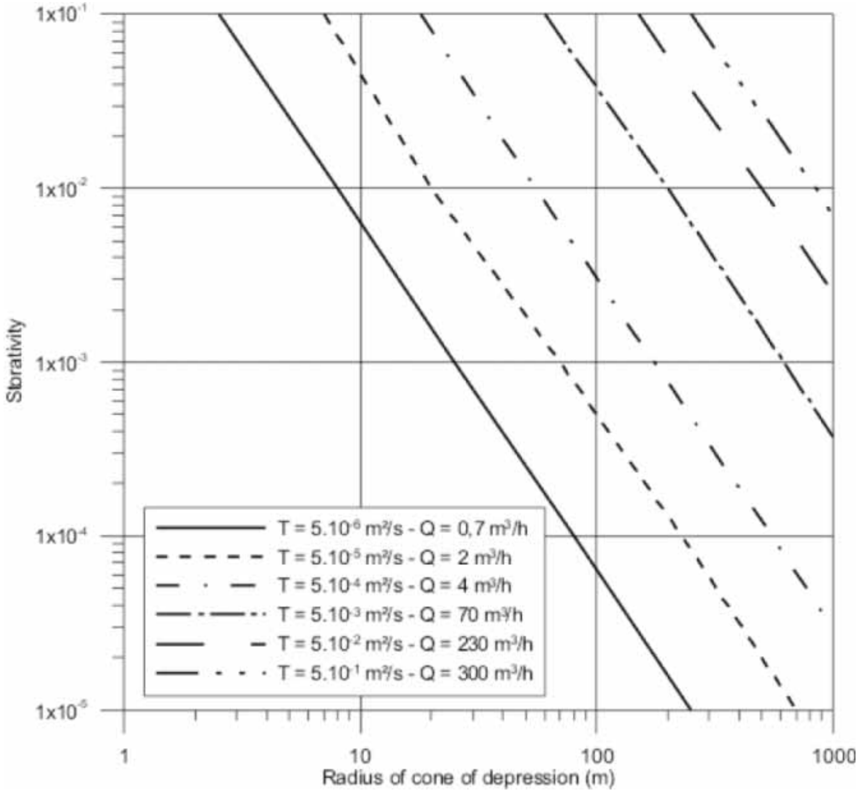

Figure 6.22: Estimation of radius of cone of depression after 2 hours of pumping.

of the aquifer without heavy influence of the pumping process (head-loss in the pumping well). The advantages of having more than one piezometer are that the surface area of aquifer under observation will be larger and that the drawdowns measured in a minimum of 3 piezometers can be analysed in two ways: by time/drawdown and distance/drawdown relationships.

The piezometers should be placed not too near to the well, but also not too far from it. The appropriate distance depends on the way the cone of depression will develop while pumping, and can be easily estimated from forward calculations using software such as AquiferTest Pro. Figure 6.22 presents the estimation of the radius of the cone of depression according to the hydraulic characteristics of the aquifer.

3.2 Test implementation

3.2.1 VERIFICATION OF SITE

Conditions of access to the site and ease of installation of the pumping equipment (pump and generator) need to be assessed.

It is important to verify that there is not another well being exploited in the vicinity of the area under test. If that turns out to be the case, exploitation must stop (if possible 24 h before the beginning of tests) and any operational wells may be used as piezometers during tests.

The water pumped must be deposited as far as possible from the well under test. It is possible that water discharged by the pump can infiltrate quickly enough to recharge the aquifer, giving a false picture of stable drawdown. The point of discharge must be chosen according to site conditions (notably the permeability and thickness of the terrain), but a discharge outlet at about 50 to 100 m from the

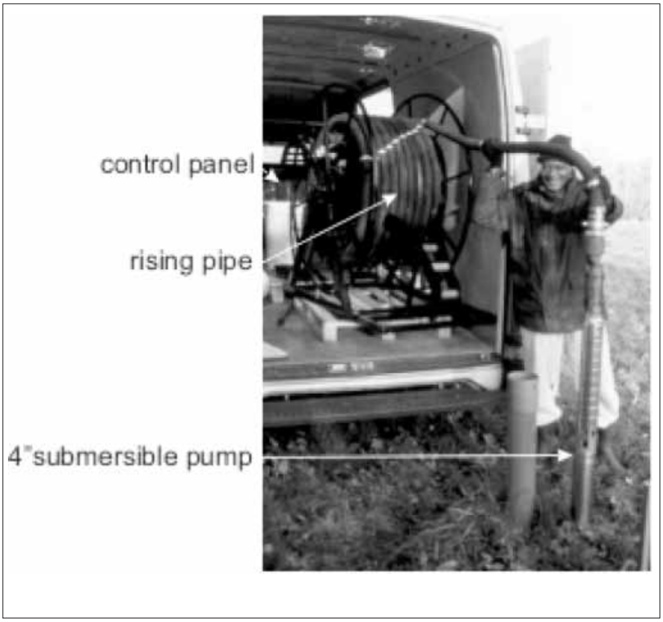

Figure 6.23: ACF pumping-test kit.

pumped well would seem to be a minimum.

3.2.2 EQUIPMENT REQUIRED

A standard ACF pumping test kit has been developed to carry out the whole process of well testing (Figure 6.23). It also includes the necessary equipment for test monitoring.

Basic requirements are a measuring tape of about 3 m (for measuring height of reference marks in relation to ground level, diameter of well etc.), a piezometric probe, two chronometers for time measurements, and one calibrated container for measuring flow rates.

For sufficient accuracy in flow-rate measurements, the container-filling time must be between 30 and 60 s (see Chapter 3). The use of a flow meter greatly facilitates the performance of tests. It is however advisable to check its accuracy using the calibrated container.

The conductivity, temperature and pH of the water should be measured regularly during pumping. In this way, changes in the water quality can be indicated, and then interpreted together with the borehole cuttings and the pumping test.

3.2.3 HUMAN RESOURCES

A team of three people is sufficient to carry out common tests. The team leader is responsible for data-plotting on record sheets, while two operators are put in charge of setting up the equipment and taking measurements (flow rates, water levels, times, water quality).

A hydrogeologist must define the type of tests to be carried out, and interpret the data.

3.2.4 TEST MONITORING

Measurements

During the test, it is necessary to take measurements of time, water level, and flow rate. Record sheets for standard tests are illustrated in Annex 9. Measurements of time are taken very frequently at the beginning of each pumping and recovery period; their frequency is entered in the record sheets.

For every measurement of time, there is a corresponding measurement of water level. Before the beginning of tests, the static level in the well is noted in relation to a reference mark, which then becomes the reference for all level measurements in the operation. Usually, this reference mark is the top of the borehole casing: its height in relation to ground level is also noted. The tip of the electric probe is then located a few cm above the static level. It is strongly advisable to use guide tubes (1" PVC or GI) to slide the probe inside the pumping well. This helps to avoid fouling the probe with the pipe or cable of the pump.

There must be a facility for adjusting the flow rate as quickly and as precisely as possible. The use of two control valves on the discharge pipe is sometimes essential. These valves are pre-set according to the required suction head and flow-rate. A good position for the calibrated container must also be ensured: flow-rate measurements must be able to be taken as easily as possible, without modifying the suction head for every measurement.

Monitoring

The curve s = f(t) must be drawn on semi-logarithmic paper for every pumping step during the tests. The curve is compared to the theoretical ones and if it shows some actual 'anomalies' this helps to decide the progress of the tests (see Section 1).

While conducting the pumping test, one should be flexible and adapt the test design to the well behaviour. A little common sense, sufficiently long pumping times, constant flow rates, and a pump outlet sufficiently distant from the boreholes usually provide the right conditions for a successful test.

3.3 Reporting

The pumping test report should contain the following:
- a location map of the wells and boreholes;
- a summary of main interpretation results and recommendations;
- the lithological and equipment logs of the tested boreholes;
- diagrams of field data and the interpretation process, i.e. diagnostic and specific graphs;
- tables of field measurements.

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