CHAPTER 9

AQUIFER TESTS BY PUMPING

by

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Power and Water Authority
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9.1 BACKGROUND

9.1.1 General

Test pumping is a means by which quantitative information about an aquifer system and the bore may be obtained. Whether flowing or non-flowing conditions are concerned, the process involves the abstraction from the aquifer at a controlled rate whilst monitoring head or change in head (water level or potentiometric) response over time. Consider that the equation relating flow from a well to drawdown consists of three variables - time, discharge and head. Time is continuous and therefore if either of the other two variables can be controlled, the test can centre on monitoring the response of the third variable.

The Australian Standard AS 2368-1990 exists to provide the minimum specification in terms of procedures, measurements and other observations required when designing and performing a pumping test. Basically, the field procedure requires that a pump be installed in the bore or for flowing bores, a valve fitted to control flow. Once discharge has commenced, observations of water levels from the test and observation bores are made. Data is obtained in such a way that it is suitable to plot on a logarithmic time scale. Analysis of plotted data solves for the constants in the flow equation which represent the hydraulic parameters of the aquifer. This may appear to be straightforward, however, many factors including the accuracy and ambiguity of data, and the skill, experience and understanding of the practitioner will determine the success of the analysis.

It is necessary to assess the hydraulic behaviour of a bore, or determine the hydraulic properties of the aquifer in order that the performance of either may be predicted. Such understanding is the basis for determining suitable pumping installations for a bore as well as optimising the utilisation of the groundwater resource.
9.5

9.1.2 Hydrogeological Considerations

The practitioners' development of a conceptual model of the aquifer is the primary requisite to accurate interpretation of the pumping test data. This understanding, in terms of the conditions under which the aquifer has developed and the environment which controls the regime it inhabits, is indeed the key to deciphering or eliminating ambiguity in the data which may have been encountered otherwise.

Background knowledge and research for information relevant to the hydrogeological conditions which exist, should be gained in the initial stages of planning for the test. The model will incorporate geological data, water level and water quality data and perhaps existing test data and historical performance data from other bores in the aquifer. Assessment of this data will enable the formulation of a model which will alert the practitioner of the aquifer type (confined, semi-confined etc), characteristics of the host rock (fractured, unconsolidated), its hydraulic parameters (transmissivity, storativity) and the presence of unusual features (boundaries) so that the resulting test data may be somewhat anticipated. Conversely, a suitable explanation of the response obtained from a pumping test may be offered in terms of the existing conditions.
9.2 AQUIFER TEST PLANNING AND DESIGN

9.2.1 Statement of Test Objectives

The purpose for testing should be defined and clearly understood so as to enable objectives to be met in the most efficient manner. That is, the intended function of the bore should determine the type of test to be performed, its duration and rate of discharge.

Multirate testing of bores is recommended to be applied to small stock or domestic situations or large municipal and irrigation supplies. In these cases, testing will serve to determine the minimum specification for a pumping installation as well as obtain information on aquifer performance. However, even in larger pumping applications, economic constraints may dictate the format of tests, or even whether some are performed or not against the advice that they are relatively inexpensive compared to the consequences of failure.

Bores drilled specifically for resource investigation purposes may only require testing for hydraulic parameters of the aquifer (ie. the hydraulic performance of individual test bores may not need to be considered). In other cases, test bores may serve to develop techniques for construction and monitoring of their performance in terms of efficiency may be considered as important as aquifer information.

9.2.2 Test Format and Design

The aquifer test should be designed such that the result and subsequent analysis address the stated objectives.
9.7

Where comprehensive testing for the aquifer's hydraulic parameters is concerned, planning is necessarily implemented at the initial stages of the investigation. The conditions will need to be anticipated in order to correctly and appropriately construct the discharge bore, allowing for versatility with regards to its capacity and physical design (e.g., screen length and depth, casing size). Considering also that the use of observation bores to determine the suite of possible aquifer parameters is imperative, their strategic location must be determined during investigation drilling. Their construction and distance to the pumped bore are important factors in obtaining and maximising the amount of useful data from the test. If set at appropriate distances, the effects of partial penetration may be neglected, or if strategically placed, will reveal particular effects or boundaries. In general, a pretest modelling exercise by estimating and anticipating hydraulic parameters, boundary conditions and other data will assist in determining the optimal depths, locations and number of observation bores required and in some cases, the optimum duration of the test. Bouwer (1978) discusses the aspect of spacing of observation.

A number of common test types are available as listed below and are described in greater detail in Section 9.3.3. The preference for a particular test type is usually dictated by the condition under which they are applied. That is, whether the bore is flowing or non-flowing.

(a) Preliminary Test
(b) Constant Discharge Test
(c) Step Drawdown Test
(d) Constant Head Test
(e) Recovery Test

Each test type has been developed with certain applicability for the determination of particular parameters. Consequently, acquisition of comprehensive information may require that two or more tests are conducted to
fully establish the suite of parameters to best describe the bore and aquifer performance.

For investigation purposes, the constant discharge test is the most common since values for transmissivity, storage coefficient and other parameters are generally more accurate, the analysis techniques are suited and trends are more discernable.

The duration of the test is a major factor in the strategy to gain maximum data. In most cases, budgetary constraints limit the duration, however, consideration of the bores' intended function and the success or usefulness of the already retrieved data may also determine the length of the test.

It may also be considered that premature curtailment of a test may preclude meaningful or accurate analysis, however, lengthy testing is not universally the best solution. For investigation work, the duration of the test should not normally be pre-set as flexibility should be reserved to on-site management with the advantage of continuous updated analysis. In general, data should be sufficient to provide an adequate platform for unambiguous analysis.

AS 2368-1990 (Table 3.1) recommends the test type and duration of testing for various intended purposes of a well. However, flexibility in the approach is always recommended to be adopted and should be incorporated at the planning stages within the budgetary element.

Production pumping may be regarded and treated as a long term test pumping exercise. With adequate monitoring of water levels regionally, the response of the regime may be interpreted to facilitate aquifer assessment.
9.3 TESTING PROCEDURES AND METHODOLOGY

9.3.1 Pretest Considerations

A number of considerations need to be made prior to the commencement of testing.

Awareness of the environment in which the test is to be conducted is a preliminary issue. Consequences on the environment of pumped discharge, or other by-products should be examined. The legality or the presence of external restrictions on the proposed test should be ascertained initially. In particular, water rights, water quality, land rights, the type of machinery and noise potential may determine the type of test and its duration and the type of equipment to be used. Indeed, neglect to carry out these basic, but necessary checks may jeopardise the operation.

The aquifer should not be influenced by recharge for the duration of the test and hence facility for disposing of the pumped discharge should be made available if there is a likelihood of this occurrence. In any case, it is good practice to ensure adequate drainage from the site simply from the aspect of a safe and comfortable working environment.

The practice of sterilisation and disinfection of equipment and wells should be observed to preclude the transfer of bacteria to subsequent bores.

From the point of view of comprehensive data acquisition, other factors which may influence the data obtained during the test should be noted and monitored accordingly. Such factors may include rainfall, although unlikely to have influence in a short test, the influence of tides and the presence of surface waters. Most commonly, the effects of pumping from a current operational
9.10 bore or borefield nearby will influence data and hence action must be taken to eliminate or compensate for these effects in the pumping test data set.

Antecedent or baseline measurements such as standing water levels with trends monitored as necessary, chemical properties of the water including pH, conductivity and temperature, and properties of the bore such as total depth and water level measuring datum should be noted as a matter of routine.

9.3.2 Setup and Instrumentation

The setup stage involves the installation of the pumping and ancillary equipment, and the appropriate instrumentation to measure time, discharge and water level or pressure head. Where the discharge involves hot water (>40°C), temperature should be measured to enable a correction of pressure heads to be made. If observation bores are monitored, the distance and direction to the pumped bore should also be recorded.

For all measurements, the instrumentation selected should be such that a relative level of accuracy is maintained. For example, when measuring time to the minute, an error of less than 5 seconds is acceptable, whereas when measuring hourly, the error allowed is up to one minute.

Similarly, the magnitude of discharge will dictate the facility for measurement. The error involved will increase with the 'coarser' devices, however, the relative error should be consistent. Examples of discharge measuring devices include flowmeters and buckets or drums of known volume for smaller flows, to orifice tube with piezometer, flowmeters and calibrated sharp crested weirs (eg. "vee" notch) for larger flows. Figure 9.1 illustrates examples of these devices. Allowable limits for errors are discussed by Stallman (1971). Discharge (10%), water level (5mm), time (1%) and distance to observation bores (0.05%) are acceptable.
Figure 9.1 Common Discharge Measuring Devices
9.12

Several common methods for water level (or potentiometric head) measurement are listed below (see Figure 9.2).

(a) electrical contact probe with tape - meter or light indicates closed circuit on contact with water

(b) acoustic device with tape - "plopper" makes sound on contact with water surface

(c) pressure transducers - the magnitude of the electrical signal response of the device is proportional to its depth of immersion. May be connected to a logger for remote and continuous water level recording.

(d) pressure gauge - installed at borehead of flowing bore. Need to convert readings to metres head of water.

(e) float device with tape - floats on water surface

For pumped bores, the type of device utilised will depend firstly on the available clearance in the hole once the pump is installed, and secondly the suitability of the device. The electrical contact device is probably the most common as it is small and inexpensive to make. Conduit to house the device downhole is advised since there is a tendency for the cable to entwine the pump column. For observation bores, pressure transducers may be preferred since once established before commencement of pumping, should provide continuous reliable data throughout the test and presents an avenue for reducing labour intensity on-site.

Instrumentation should also be available to monitor various aspects of the water chemistry. Parameters such as pH, conductivity, temperature, DO, Eh and dissolved CO₂ may require monitoring. Other characteristics of the discharge such as colour, smell and sediment load should be noted.

Primarily, suitable pump selection is based on its capacity to meet the range of drawdown and discharge expected. With appropriate planning, the bore casing size will have been anticipated to adequately house the pump. The nature of
Electronic Water Level Recording System consists of
(a) Logger
(b) Pressure Transducer

Water Level 'Interface Meter'

Figure 9.2 Some Common Water Level Measuring Devices
9.14

the discharge may also need to be considered as some types of pump do not handle heat or sand for example, as well as others. An example pumping installation in a borehole is illustrated on Figure 9.3.

9.3.3 Test Procedures and Data Acquisition

Appropriate procedures for the various test types are described in a number of texts including Hazel (1975) and the Australian Standards Publication AS 2368-1990. The particular test types are designed so that data may be retrieved in a form so as to ascribe to the various analysis methods used for the solution of hydraulic parameters.

The appropriate test type to apply is previously determined during the planning stages and is dependent on the intended use of the bore. In all test types, the frequency of observations remain similar. Such observations are made at gradually increasing intervals since both head and discharge are related to log time and data in this format will facilitate plotting on a logarithmic scale. The Australian Standard for Test Pumping stipulates minimum observations at certain time intervals at the commencement or change of discharge rate. That is, they are represented by successive intervals of 0.5, 1, 2, 3, 4, 6, 8, 10, 15, 20, 25 minutes etc. increasing eventually to 1, 2 then finally 4 hour intervals after two days.

Section 9.2.2 listed a suite of tests which can be performed on either flowing and non-flowing bores. However, each test type is more suited to a particular bore. For example, the constant discharge test is suited to pumped bores since the discharge rate can be readily controlled, whereas closer control of the constantly decreasing flow must be exercised if this particular test were performed on a flowing bore and therefore may not be favoured. As an alternative, the flow recession (or constant drawdown) test is more commonly conducted on flowing bores.
Figure 9.3  Typical Installation in a Test Well
9.16

Tests may generally be performed in a particular order since in many cases, the results of the previous tests will influence the decisions on subsequent tests.

For example, the more common tests on non-flowing bores are

(i) Preliminary
(ii) Step Drawdown
(iii) Constant Discharge
(iv) Recovery

The preliminary test is of short duration and is used as an indicator of the bores' performance. A range of discharge rates are pumped and the associated drawdowns are measured. From the result of this test, rates at which the step and constant discharge tests are to be conducted may be determined. Preliminary pumping also serves to develop the bore.

The step drawdown test is conducted to establish the parameters of the well equation which are used to predict the bores' performance. The discharge rates may be either increased or decreased for subsequent steps. A minimum of three steps are required to enable reliable analysis to be conducted (Refer Hazel (1975) for analysis technique). Drawdown readings are to be taken at the recommended time intervals, recommencing at these intervals at the start of each step. The steps should be continued to a stage when the effects of well losses become negligible (usually 60 to 100 minutes). The results of this test will give an indication of the efficiency of the bore.

Aquifer performance is best tested using the constant discharge test. The discharge rate is maintained for the duration of the test. The recommended duration of the test varies for different applications and may range from 8 hours for stock bores to 7 days or more for investigation testing. It is also dependent on the type of aquifer and degree of accuracy desired in establishing hydraulic properties. Often it is useful to perform preliminary calculations or modelling beforehand based on estimated parameters. It may be considered false...
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economy to terminate a test prematurely, particularly if the bore has been constructed specifically for the purpose of testing. Progressive plotting of the results will enable the optimal duration of the test to be selected.

The type of analysis required will largely determine the duration of testing and pumping rate. If it is considered that 3 log cycles represents in excess of 1 day, and that 4 log cycles represents nearly 7 days, a duration of testing within this time frame will, in many cases, be adequate to allow prediction of aquifer performance over 1 year (5.7 log cycles) to be made with reasonable confidence.

Monitoring of discharge should be vigilant throughout the test. Fluctuations will occur from time to time, and may drift as drawdown increases or atmospheric conditions vary.

The recovery test is usually conducted subsequent to the constant discharge test. The drawdown readings during recovery are termed residuals. Monitoring of residuals should continue until a minimum of 80% recovery. Analysis of this test provides a useful check and may be important when discharge fluctuations are prevalent in the constant discharge test.

Other tests include variable discharge test (constant drawdown), and variations of the step test by extending either the first or last steps.

For flowing wells, the principles remain similar except that the standing water level is essentially above the ground. In deep artesian applications where the water is hot, temperature compensation for decrease in pressure head (and therefore potentiometric head) due to cooling must also be applied. Therefore, temperature of the discharge must also be monitored.

The main tests performed include the preliminary test (as for non-flowing bores), flow recession test where discharge is allowed to free flow from the bore
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and measured at the appropriate time intervals, static tests (recovery) and step tests.

9.3.4 Other Observations and Sampling

Water quality sampling should be included as a routine operation during testing. In addition to the constant monitoring of parameters such as conductivity, pH, temperature etc, a minimum of two samples should be acquired for complete chemical analysis. In some cases, specific samples for heavy metal, radium or specific parameter analysis may also be required. These should be taken at the beginning and the end of the test. It should be understood however, that should a change or feature be detected, then more frequent monitoring or increased sampling will usually be warranted.

In some instances, tidal influences may be evident and therefore tidal movement must be recorded to enable correction of data and allow analysis to proceed. As well, tidal amplitude and period information will facilitate calculation of parameters using the tidal efficiency analysis.

Observation of atmospheric pressure and diurnal movement of the water level may need to be taken in some cases where prominent. The data should be corrected for these effects in the same way as for tidal influences.

Physical factors such as water condition, colour, and the presence of solids or precipitates should be noted. Measurement of the total depth of bore at the completion of the test may indicate movement of fines into the bore.
9.4 DATA REDUCTION AND PRESENTATION

9.4.1 Data Reduction and Presentation

A good quality of presentation of data retrieved from the field is required at all times. It should be clearly set out with all relevant measurements recorded. An example test data sheet is shown on Figure 9.4. Note that the precise details of timing (exact time is noted if usual interval is not possible or missed), discharge and drawdown measurements are required, as well as SWL, measuring point and observation bore distance. Details of the well construction and conditions to be encountered should be studied beforehand and may also be listed.

Reduction of data may be needed under a number of circumstances. Step tests need to be corrected before analysis. This is performed graphically. Development of the bore may also be noticed during this test, particularly if it is the first test performed. Subsequent steps may perform better than predicted, and in extreme cases, drawdown may decrease. Conversely, if for instance, slumping of the bore occurs to produce a sudden increase in drawdown, comment on the discoloration of the water should be made in the field notes.

Well storage capacity effects are common. This effect is usually associated with small discharges and large diameter or deep bores. The discharge is partially derived from water stored in the bore producing a lag in the drawdown.

Adjustments may need to be made if there are changes to the pumping rate during a constant discharge test or if there has been interference from nearby production bores or barometric pressure changes. If not noted during the test, these effects may be erroneously interpreted as boundaries.
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DRAWDOWN SHEET

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<td>Date pumping commenced</td>
<td>Time</td>
<td>am/pm</td>
</tr>
<tr>
<td>Date pumping ceased</td>
<td>Time</td>
<td>am/pm</td>
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Are the measurements below for the pumped well? Distance from pumped well: m

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<th>ground level</th>
<th>m</th>
</tr>
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<tr>
<td>or Static pressure</td>
<td>above</td>
<td></td>
<td>above</td>
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<th>ELAPSED TIME</th>
<th>DRAWDOWN</th>
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<th>DISCHARGE</th>
<th>REMARKS, etc.</th>
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<tr>
<td>h Min am</td>
<td>min.</td>
<td>metres</td>
<td>metres</td>
<td>Piezometer L/s</td>
<td></td>
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Figure 9.4 Example Test Sheet (from AS 2368-1990)
9.21

Barometric effects may be prominent in artesian conditions. Adjustments to the potentiometric head can be made if barometric efficiency is known. Similarly, tidal or river effects should be adjusted.

Under water table conditions, particularly if the drawdown is relatively large compared to aquifer thickness, transmissivity reduction will be experienced and Jacobs correction should be applied to the drawdown data to compensate for this.

Effects of partial penetration and aquifer stratification should also be borne in mind and corrected. The procedure using the Hantush method is complex and available microcomputer software should perhaps be sought for this exercise. Walton (1987) contains some basic software for this purpose.

9.4.2 Data Representation

A graphical presentation is the most effective means of data representation as it facilitates most analysis techniques and also immediate visual interpretation. Data may be plotted once the appropriate corrections (if any) have been applied.

Graphs of drawdown or recovery versus log time for the pumped bore and each observation bore should be plotted for each test. For observation bores, plotting log drawdown against log time (on the same scale as type curve) will enable comprehensive analysis of leakage, drainage etc. parameters to be performed. Drawdown versus log distance may be plotted if there are a number of observation bores.

In addition to this data, plots of barometric pressure, rainfall, river stage, other pumping influences and antecedent water levels may be graphically
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represented. It is also often useful to provide a sketch of the location and
distances of observation bores, boundaries and topography.
9.5 GUIDE TO TEST ANALYSIS AND INTERPRETATION

9.5.1 Approach to Analysis

Aquifer tests by pumping are the most suitable means by which hydraulic characteristics may be quantified. This is mainly because the results obtained are representative of the aquifer over a larger area than possibly obtainable with single point observations. However, aquifer analysis should only be contemplated if a fundamental understanding of the aquifer system and conceptual model has been formulated. The model then serves as a frame of reference for selecting the appropriate type curve or analysis technique. Compared with results of prior modelling or analysis using estimated parameters, the measured response should serve to refine the understanding of the groundwater system. Conversely, the results may serve to explain other phenomena or dispel uncertainties.

Important aquifer and facility conditions which may influence test data must be taken into consideration and corrected where possible (or at least acknowledged). For example, common conditions include boundaries which should be identified, water table decline and associated transmissivity reduction and storativity conversion which will appear as a recharge boundary. This preliminary exercise in data interpretation is the key to successful analysis.

Bouwer (1978), Fetter (1980) and Walton (1970) provide a good general overview of analytical techniques. These methods are subsequently applied to determine the relevant aquifer parameters. However, pumping test analyses do not necessarily provide a unique solution. This is because theoretical solutions do not simulate reality completely. They are based on assumptions which are rarely met under natural conditions. Influences of anisotropic and non-homogeneous aquifer conditions, irregular thicknesses, limitations of extent and combinations of different boundary conditions as well as data inaccuracy mean
that more than one model equation may be solved. Furthermore, it will usually be found that parameters obtained from bores in the same aquifer will represent a range of values which confirm that the aquifer is not ideal. Acceptable analyses will place values of transmissivity within 10% and storativity to 30%. Regardless of the seemingly limited circumstances under which analytical solutions are applied, this theory has generally been proven to be reliable in most cases.

Selection of the applicable method of analysis is basically dependent on the type of aquifer encountered (i.e. confined, semi-confined, semi-unconfined, unconfined). Most analyses are only applicable to observation bore data (since effective radius usually unknown in pumped bore).

Each analysis technique has its advantages. For example, Jacobs method is popular because it only requires a simple plot on a log-linear graph and does not require a curve match. However, it is restricted to small values of 'r' (distance to pumped bore) and large 't' (time). Its requirements are generally satisfied in confined aquifers for moderate distances (1 hour or less response) as compared to an unconfined situation where this condition may be attained after 12 hours of pumping.

The Theis method depends on curve matching and places less value on early time data. With increasing time, the time lag effects of head decline and pumping rate become negligible and the analysis is then best based on later data. Chows method is based on the Theis method, however eliminates the curve fitting. It does not restrict its application to small values of 'r' and large values of 't'.

Other methods applicable for flow in steady and unsteady state semi-confined aquifers include Hantush-Jacob, Ernst Modification of the Theim equation and Hantush's methods. For semi-unconfined (delayed yield), the Boulton method
9.25

is commonly used and the Theim-Dupuit method for unconfined. These techniques are comprehensively treated by Kruseman and De Ridder (1970).

Selection of the analysis type is therefore highly dependent on recognition of the aquifer conditions.

9.5.2 Analysis Software

A large range of software currently exists for the analysis of pumping tests. Included are programs for step drawdown test analysis for well loss to sophisticated type curve match programs via which a comprehensive range of parameters may be determined. It should be emphasised that computer software exists simply to aid in the process of presenting and analysing data. The prerequisite for meaningful analysis of pumping test data is still an understanding and appreciation of the thought processes described in this chapter. The recognition of aquifer types and the selection of the analysis technique applicable to the particular situation is still required before use of the computer is contemplated.

Although software is abundant and in most cases inexpensive, some are not considered user friendly. Before embarking on the purchase of a suite of analysis software, its applicability to the desired analysis, its user friendliness and layout as well as the compatibility to your computer should be checked.

9.5.3 Case Examples

The case examples selected are intended to provide some appreciation of the practical application of the interpretation techniques discussed above. There is an underlying importance in the appreciation of the hydrogeological setting and the informed ability to filter and segment data. These are processes which are
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generally acquired through experience and are major factors in the meaningful interpretation and successful analysis of pumping test data.

Examples of typical drawdown and recovery trends under different situations plotted on semi-log, are shown in Appendix A of AS 2368-1990. Such plots are suitable to be analysed using the 'Jacob' analysis. Recognition of the basic responses of the aquifer types may be regarded as a fundamental skill.

Case 1 Confined Aquifer

An aquifer exists in a sandy bed underlying 90m of clay which forms an aquiclude. The aquifer is 6m thick and a shaly sequence exists beneath it. A constant rate pumping test was conducted for a period of 500 minutes. One observation bore at a distance of 245m was monitored for the duration of the test. The bore was pumped at a rate of 1300 m\(^3/d\) (15 L/s). The responses of both the test and observation bores are shown on Figures 9.5 and 9.6 respectively.

In the pumped bore, well storage effects are discernable up to 10 minutes, and may be neglected in the analysis if a 'Jacob' straight line solution is used to determine transmissivity. Hence the equation below is applied.

\[
T = \frac{2.3 \times Q}{4\pi \Delta s}
\]

Since \(Q = 1300\) m\(^3/d\) and from Figure 9.5,

\[
\Delta s = 1.7\ m
\]

Transmissivity = 140 m\(^2/d\)

For analysis of the observation bore response (Fig. 9.7), a type curve solution is sought. Using a type curve overlay, the match point co-ordinate for \(W(u) = 10^6\) and \(1/u = 10^6\),

is \(s = 0.82\ m\) and \(t = 4.2\ min\)
Figure 9.5  Case Example 1 - Confined Aquifer (Pumped Bore)
Figure 9.6 Case Example 1 - Confined Aquifer (Observation Bore)
9.29

Substituting values for 'Q' and 's' into the equation

\[ T = \frac{Q}{4\pi s} \eta(u) \]

Transmissivity = 130 m\(^2\)/d

Using values for 'r' and 't' in the equation for storage coefficient below,

\[ s = \frac{4Ttu}{r^2} \]

Storage Coefficient = 2.5 x 10\(^{-5}\)

The values for transmissivity obtained from both bores correspond satisfactorily. The hydraulic conductivity is 22 m/d and is typical of medium to coarse sands.

Case 2  Delayed Drainage Curve

A test is conducted on an aquifer of a highly stratified nature containing coarse sand and gravel with silty layers for a depth of 32m. The pumped bore has screened the bottom 8m of the aquifer and pumped at a rate of 5620 m\(^3\)/d (65 L/s). An observation bore at a distance of 62m was monitored for the duration of the test. The resulting response is as shown on Figure 9.7. An adjustment for dewatering and partial penetration effects has been made to the data.

The analysis using Jacob and Theis methods assume an instantaneous release of water. However, due to the presence of the silty layers, there is some delay in the vertical movement of water as the cone of depression spreads laterally. The increasing hydraulic gradient eventually drives flow through the silty beds. This aquifer type may be described as semi-unconfined and this effect is commonly referred to as delayed yield or drainage. Such responses are also characteristic of fine grained aquifers.
Figure 9.7  Case Example 2 - Delayed Drainage
9.31

A Boultion analysis is applicable in this case and a type curve solution is required. The response is analysed for early and late responses. The applicable type curve was found to be \( r/B = 0.6 \) model type curve where \( B \) is the drainage factor (refer Boultion type curves).

The match point for the early time data

\[ W(u_A, r/B) = 10^9 \quad \text{and} \quad 1/u_A = 10^l, \]

is

\[ s = 0.11 \quad \text{and} \quad t = 9 \text{ min} \]

Therefore, since \( Q = 5620 \text{ m}^3/\text{d}, \quad r = 62\text{m}, \) and substituting into the equation

\[ T = \frac{Q}{4\pi s} \cdot \mathcal{H}(u_A, \frac{r}{B}) \]

Transmissivity = 4070 m²/d

Therefore, substituting into the equation below for the early time storage coefficient,

\[ S_A = \frac{4 T u_A}{r^2} \]

\[ S_A = 2.6 \times 10^3 \]

Similarly, the match point for the late time data representing the delayed yield portion of the response

\[ W(u_Y, r/B) = 10^9 \quad \text{and} \quad 1/u_Y = 10^l, \]

is

\[ s = 0.12 \quad \text{and} \quad t = 80 \text{ min} \]

Again using the values of \( Q = 5620 \text{ m}^3/\text{d}, \quad r = 62\text{m}, \) and substituting into the equation

\[ T = \frac{Q}{4\pi s} \cdot \mathcal{H}(u_Y, \frac{r}{B}) \]

Transmissivity = 3730 m²/d
9.32

\[ S_y = \frac{4T\tau u}{r^2} \]

Therefore, the specific yield,

\[ S_Y = 0.22 \]

The validity of this solution should be checked by calculating the value of

\[ \gamma = 1 + \frac{S_Y}{S_A} \]

A value >100 is considered very good for a practical solution, however, a value between 10 and 100 is acceptable. Since this value is calculated to be 86, the solution is acceptable, although the transitional segment is not strictly horizontal.

The time that delayed yield ceases to affect drawdown \( (t_m) \) can also be calculated. The drawdown response subsequent to this point should follow the Theis curve and long term prediction of drawdown is therefore possible. For this calculation, Boulton's Delay Index Curve is required (refer Hazel (1975)). The value corresponding to \( r/B \) = 0.6 is

\[ \alpha \tau_m = 3.5 \]

Since \( B = 217 \) m, and given the equation

\[ \alpha = \frac{T}{S_Y B^3} \]

\[ t_m = 9.7 \text{ days} \]

Case 3 Casing Storage Effect

A 203mm bore is constructed in alluvial sediments to a depth of 60m. There are no evident sources of recharge in the vicinity. The bore is tested at a rate of 28 m\(^3\)/d (0.3 L/s). The pumped bore response is shown in Figure 9.8.
Figure 9.8 Case Example 3 - Casing Storage Effect
9.34

The response appears as a recharge boundary at about 80 minutes. Otherwise it may be interpreted as the result of a decrease in the pumping rate. In this analysis, the effect persists longer than 10 minutes, and if not for the length of the test, the later slope indicating the correct trend, may not have been detected.

For a bore of low specific capacity, casing storage effects may be significant. The Jacob equation assumes that all water being pumped is derived from the aquifer. However, due to a number of factors, including the casing diameter, the pumping rate, the size of pump column and the permeability of the formation, this may only occur after a finite period. The Papadopulous-Cooper analysis (or Schafer derivation of this equation) may be used to determine the time when casing storage effects become negligible on the time/drawdown graph.

The Papadopulous-Cooper (1967) equation below, is only valid for 100% efficient wells.

\[
t_c = \frac{50.13 (r_c^2 - r_p^2)}{T}
\]

where
- \( t_c \) = time (days) when casing storage effects become negligible
- \( r_c \) = radius of casing (m) over which the water level changes are occurring
- \( r_p \) = radius of pump column (m)
- \( T \) = transmissivity (m²/d)

For other wells, and where transmissivity is not known, Schafer (1978) has derived the following equation.
9.35

\[ t_c = \frac{11.55 \left( d_c^2 - d_p^2 \right)}{Q/s} \]

where
- \( t_c \) = time (mins) when casing effects become negligible
- \( d_c \) = inner diameter of casing (m)
- \( d_p \) = outer diameter of pump column (m)
- \( Q/s \) = specific capacity of the well in \( m^3/min \) of drawdown at time \( t_c \)

For this example, where the pumping rate was 28m\(^3/d\), the casing diameter 203mm and the pump column used was 75mm diameter, the Schafer equation gives \( t_c \) to be 253 minutes. This may be surprising since visually, the plot suggests this should be around 100 minutes.

Case 4 River Recharge and Boundary Effects

An investigation bore is drilled in a deep alluvial basin within a canyon. A river lies between the test bore and the canyon wall to the north-west at a distance of 300m. The site plan is shown on Figure 9.9.

Two deep observation bores were also drilled so as to enable comprehensive data to be obtained. A third observation bore monitoring the shallow response above the clay layer has also been constructed. Section X-Y (Figure 9.10) presents the stratigraphic model of the aquifer system. A clayey bed between 50 and 53 metres is suspected to confine the lower sand aquifer. The first observation bore was constructed with screens between 70 and 76 metres, and 72 to 78 metres in the second. The third, at a distance of 30m, has screened the interval between 35 and 40m. The test bore is 254mm in diameter and 85 metres deep. Screens were placed between 63 and 83 metres.
Figure 9.9 Case Example 4 - Site Plan

Figure 9.10 Case Example 4 - Cross Section X-Y
Figure 9.11  Case Example 4 - River Recharge and Boundary Effect
9.38

A constant discharge test is conducted for a period of 72 hours at a rate of 80 L/s. During the early stages of the test, a rainfall event caused the river stage to rise by 0.6m. Figure 9.11 is the response of the first observation bore at 60m. Analysis of this test should be approached by segmenting the response curve to isolate the effects of each boundary. A semi-log plot using 'Jacobs' analysis is best suited since analysis using type curve match is not possible due to the complexity of the behaviour.

The initial 10 minutes of data have been omitted since this data is not applicable to 'Jacobs' technique. Slope 1 exhibits the aquifer’s true transmissivity value since boundary effects have not yet been intersected. Slope 2 shows the influence of a recharge boundary as the cone of depression intercepts the river. A value for transmissivity calculated from this slope would be too high. Slope 3 indicates the effect of the rise in river level caused by the rainstorm. Slope 4 indicates that the cone of depression has now intersected a discharge boundary, presumably the canyon wall. Examination of data from another observation bore would verify this. The eventual subsidence in the river level has resulted in a steepening of the response (Slope 5).

Analysis and determination of representative transmissivity and storage coefficient values is only possible if the nature of the aquifer and hydrogeological constraints are understood. The understanding of the aquifer may be enhanced through thoughtful examination of the data to hand. For example, since river recharge is detected, the effectiveness of the clay layer as a confining bed is questioned. The response of the shallow observation bore confirms that the clay exists probably as a lens, and not to the extent as initially perceived as shown in the cross section. The precise positioning of the boundary may be calculated using information from all observation bores. The relative response times indicate that the discharge boundary is further than the river, and not an outlier as may possibly be the case.
9.39

9.5 REFERENCES


