TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC INVESTIGATIONS AND GROUND WATER MONITORING

CHAPTER 4

SLUG AND PUMPING TESTS

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TABLE OF CONTENTS

CHAPTER 4

SLUG AND PUMPING TESTS

Slug and pumping tests are used to determine in-situ properties of water-bearing formations and define the overall hydrogeologic regime. Such tests can determine transmissivity (T), hydraulic conductivity (K), storativity (S), connection between saturated zones, identification of boundary conditions, and the cone of influence of a pumping well in a ground water extraction system. To enable proper test design, it is important to define objectives and understand site hydrogeology as much as possible. Methods, instruments, and operating procedures should be specified in a workplan. The results of tests, methods, and any departures from the work plan that were necessary during implementation should be documented in a report.

This chapter covers various types of tests, including single well and multiple well. Their advantages and disadvantages and the minimum criteria that should be considered prior to, during, and after implementation are summarized. It is beyond the scope of this document to address all details on test design and analysis; therefore, additional sources have been referenced.

SINGLE WELL TESTS

A single well test involves pumping, displacing, or adding water and measuring changes in water levels in the well. This type of test allows a rapid and economical calculation of K and T of the zone of interest at a single location. Single well tests also can determine response criteria for observation wells in multiple well pumping tests.

Single well tests should be conducted in properly designed and developed wells or piezometers. If development is inadequate, the presence of drilling mud filter cake (use of mud is not recommended) or the smearing of fine-grained material along the borehole wall may result in data that indicate an artificially low K. This may lead to underestimation of contaminant migration potential. Drilling methods, well design and installation, and well development are covered in Chapters 6, 7 and 8, respectively. The various types of tests are discussed briefly below. Additional information can be found in documents by Black (1978), Chirlin (1990), Dawson and Istok (1991), Kruseman and de Ridder (1991), and Lohman (1972).

SLUG TESTS

A slug test involves the abrupt removal, addition, or displacement of a known volume of water and the subsequent monitoring of changes in water level as equilibrium conditions return. The measurements are recorded and analyzed by one or more methods. The rate of water level change is a function of the K of the formation and the geometry of the well or screened interval.

Slug tests generally are conducted in formations that exhibit low K. They may not be appropriate in fractured rock or formations with T greater than 250 m^2/day (2, 690 ft^2/day) (Kruseman and de Ridder, 1991); however, in some instances, a vacuum or slug test conducted with a pressure transducer or electronic data logger may be warranted.

Hydraulic properties determined by slug tests are representative only of the material in the immediate vicinity of the well; therefore, slug tests should not be considered a substitute for conventional multiple well tests. Due to the localized nature of hydraulic response, the test may be affected by the properties of the well filter pack. Therefore, the results should be compared to known values for similar geologic media to determine if they are reasonable.

If slug tests are used, the designer should consider the amount of displaced water, design of the well, number of tests, method and frequency of water level measurements, and the method used to analyze the data.

Design of Well

Well depth, length of screen, screen slot size and length, and distribution of the filter pack must be known and based on site-specific boring information in order for a well to be used as a valid observation point. For example, equations used in data analysis make use of the radii of the well and borehole. The nature of the materials comprising the screened interval (i.e., thickness, grain size, and porosity of the filter pack) also must be known.

Number of Tests

Properties determined from slug tests at a single location are not very useful for site characterization unless they are compared with data from tests in other wells installed in the same zone. When conducted in large number, slug tests are valuable for determining subsurface heterogeneity and isotropy. The appropriate number depends on site hydrogeologic complexity.

Test Performance and Data Collection

Data collection should include establishment of water level trends prior to and following the application of the slug. Pre-test measurements should be made until any changes have stabilized and should be taken for a period of time, at least as long as the expected recovery period. Water level measurements in low-permeability zones may be taken with manual devices. Automatic data loggers should be used for tests of high permeability zones. Slug tests should be continued until at least 85-90 percent of the initial pre-test measurement is obtained (U.S. EPA, 1986).

Whenever possible, water should either be removed by bailing or it should be displaced by submerging a solid body. According to Black (1978), an addition of water invariably arrives as an initial direct pulse followed by a subsequent charge that runs down the sides of a well. This may result in a response that is not instantaneous, which may subsequently influence the data (Figure 4.1). An advantage of displacement is that it allows for collection and analysis of both slug injection and slug withdrawal data. However, slug injection tests should not be conducted in wells where the screened interval intercepts the water table.

The volume of water removed or displaced should be large enough to insure that build-up or drawdown can be measured adequately, but it should not result in significant changes in saturated zone thickness (Dawson and Istok, 1991). It should be large enough to change water level by 10 to 50 centimeters (Kruseman and de Ridder, 1991). Field procedures for slug tests are also described in ASTM D 4044-91 (1992).

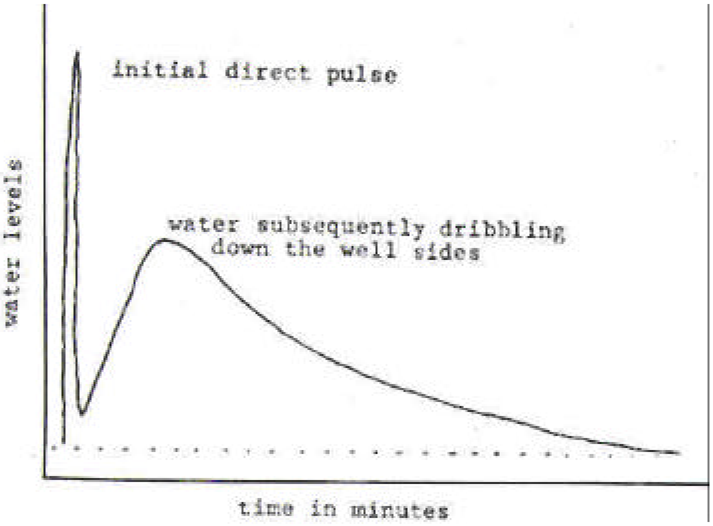

Figure 4.1 Results of a slug test with addition of water. Water arrives as an initial direct pulse followed by a subsequent charge that runs down the sides of the well (Source: Adapted from Black, 1978).

Modified Slug Tests

In addition to removal or displacement of water, a change in static water level can be accomplished by pressurizing a well with air or water or by creating a vacuum. Packers are often used to seal the zone to be tested.

Packer Tests Within A Stable Borehole

Horizontal K for consolidated rock can be determined by a packer test conducted in a stable borehole (Sevee, 1991). A single packer system can be used when testing between a packer and the bottom of the borehole (Figure 4.2A). Two packer systems can be utilized in a completed borehole at any position or interval (Figure 4.2B). A packer is inflated using water or gas. Water should be injected for a given length of time to test the packed-off zone.

Pressure Tests

A pulse or a pressure test may be appropriate in formations where K can be assumed to be lower than 10^{-7} cm/sec. In a pulse test, an increment of pressure is applied into a packed zone. The decay of pressure is monitored over a period of time using pressure transducers with electronic data loggers or strip-chart recorders. The rate of decay is related to the K and S of the formation being tested. This test generally is applied in rock formations characterized by low K. Compensation must be made for skin effects[1] and packer adjustments during the test. An understanding of the presence and orientation of fractures is necessary to select an appropriate type curve to analyze test data (Sevee, 1991).

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[1] Skin effects result from locally increasing the K near the well by opening fractures (positive skin) or decreasing the K (negative skin) by filling voids or coating borehole walls with drilling cuttings (Sevee, 1991).

Vacuum Tests

According to Orient et al. (1987), vacuum tests can be used to evaluate the K of glacial deposits and compare favorably to more conventional methods. Figure 4.3 shows typical test design. In general, water level is raised by inducing vacuum conditions. Once it reaches the desired height and sufficient time has been allowed for the formation to return to its previous hydrostatic equilibrium, the vacuum is broken and the recovery is monitored. The data is evaluated using the same techniques that are used to evaluate conventional slug test data.

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Figure 4.2 In-Situ packer testing. A - Single packer system, test conducted during drilling. B - Double packer system, test conducted after borehole is complete (Source: Design and Installation of Ground Water Monitoring Wells by D.M. Nielsen and R. Schalla, *Practical Handbook of Ground Water Monitoring*, edited by David M. Nielsen, Copyright © 1991 by permission.)Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida. With permission.)

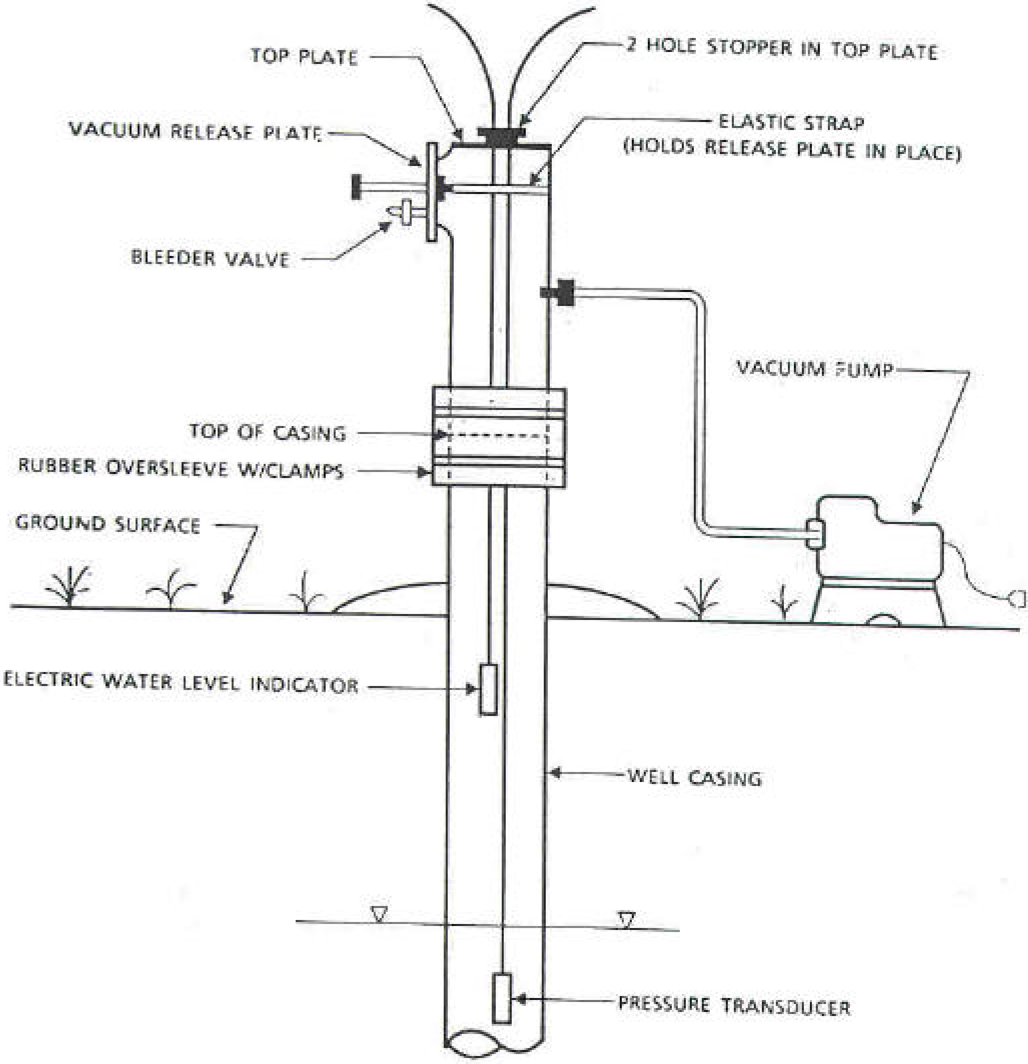

Figure 4.3 **Vacuum testing setup** (Source: Vacuum and Pressure Test Methods for Estimating Hydraulic Conductivity by J.P. Orient, A. Nazar and R.C. Rice. Ground Water Monitoring Review. Volume 7, No. 1, Page 50 (Figure 5). 1987. Reprinted from Ground Water Monitoring Review with permission from the National Ground Water Association. Copyright 1987.)

Analysis of Slug Test Data

Mathematical models for slug test data analysis are summarized in Table 4.1. Models have been developed to deal with confined, unconfined, partial penetration, and skin effects. Calculation of K for a fully screened zone is achieved by dividing T by the entire thickness of the zone. A test of a partially penetrating well yields a T value that is only indicative of that portion of the zone that is penetrated by the well screen. Results from slug tests should not be "over-interpreted". The values obtained are for the geologic material immediately surrounding the well intake, which invariably has been altered to some degree by the installation process.

SINGLE WELL PUMPING TESTS

A single well pumping test involves pumping at a constant or variable rate and measuring changes in water levels during pumping and recovery. Such tests are used to determine T and K when water level recovery is too rapid for slug tests and no observation wells or piezometers are available.

A simplistic single well test consists of pumping at a constant rate and measuring drawdown. When the water level has stabilized, steady flow conditions can be assumed and the following variation of the Theim equation can be used for estimating T (modified from Boonstra and de Ridder, 1981):

$$T = \frac{43.08\,Q}{S_w}$$

where: Q = the constant well discharge in feet^3/day.
S_w = the stabilized drawdown inside the well at steady flow in feet.
T = the transmissivity.

The equation can be applied to data for both confined and unconfined zones; however, for unconfined zones, drawdown (s_w) must be corrected to $s_w' = s_w - (s^2_w/2D)$, where D is the saturated zone thickness in feet. Appreciable error can be made in calculating for T using this equation, especially if well construction is unknown or inaccurate or if the screen is partially clogged (Boonstra and de Ridder, 1981). The equation, T = KD can be utilized to determine K.

The drawdown in a pumped well is influenced by well loss and well-bore storage. Well loss is responsible for drawdown being greater than expected from theoretical calculations and can be classified as linear or non-linear. Linear loss is caused by compaction and/or plugging of subsurface material during well construction and installation and head loss in the filter pack and screen. Non-linear loss includes head loss from friction within the screen and suction pipe. Since well-bore storage is large when compared to an equal volume of formation material, it must be considered when analyzing drawdown data from single well pumping tests (Kruseman and de Ridder, 1991). However, Papadopulos and Cooper (1967) observed that the influence of well-bore storage on drawdown decreases with time (t) and becomes negligible at $t > 25r_c^2$, where r_c is the radius of the unscreened part of the well where the water level is changing. The effects of well-bore storage on early-time drawdown data can be determined by a log-log plot of drawdown (s_w) verses time (t). Borehole storage effects exist if the early-time drawdown data plots as a unit-slope straight line (Kruseman and de Ridder, 1991).

Table 4.1 Analysis methods for slug tests.

GENERAL ASSUMPTIONS

1. The aquifer has an apparently infinite areal extent.
2. The zone is homogeneous and of uniform thickness over the area influenced by the test (except when noted in application column).
3. Prior to the test, the water table or piezometric surface is (nearly) horizontal over the area influenced and extends infinitely in the radial direction.
4. The head in the well is changed instantaneously at time $t_o = 0$.
5. The inertia of the water column in the well and the linear and non-linear well losses are negligible (i.e., well installation and development process are assumed to have not changed the hydraulic characteristics of the formation).
6. The well diameter is finite; hence storage in the well cannot be neglected.
7. Ground water density and viscosity are constant.
8 No phases other than water (such as gasoline) are assumed to be present in the well or saturated portion of the aquifer.
9. Ground water flow can be described by Darcy's Law.
10. Water is assumed to flow horizontally.

	APPLICATION						
METHOD	**"Aquifer" Type**	**Flow Condition**	**Can account for**		**ADDITIONAL ASSUMPTIONS**	**PROCEDURE/ANALYSIS**	**REMARKS**
			Partial Penetration	Anisotropic			
Cooper et al. (1967) (a,b)	Confined	Transient	No	No	- The rate at which the water flows from the well into the aquifer (or vice versa) is equal to the rate at which the volume of water stored in the well changes as the head in the well falls or rises	- Conventional[**] - Type curve analysis	Difficult to match due to similarities of type curve. - Also described in ASTM D4104-91 (1992)
Bouwer and Rice (1976) Bouwer (1989) (a,b)	Unconfined or leaky[*]	Steady state	Yes	No	- Aquifer is incompressible - Buildup of the water table is small compared to aquifer thickness	- Conventional[**] - Calculations based on modified Theim equation and geometric parameters	- Can be used to estimate the K of leaky aquifers that receive water from the upper-semi confining layer through recharge or compression

Table 4.1 (continued): Analysis Methods of Slug tests.

METHOD	**APPLICATION**				**ADDITIONAL ASSUMPTIONS**	**PROCEDURE/ANALYSIS**	**REMARKS**
	"Aquifer" Type	**Flow Condition**	**Can account for**				
			Partial Penetration	Anisotropic			
Hvorslev (1951) (a)	Confined or Unconfined*	Transient	Yes	Yes	- The injection well is considered to be a slot (line source) with infinitesimal width	- Conventional - Analytical equations and calculations of hydraulic equation based on test conditions	- Differences of 0.3X to 0.5X can be observed when comparing the K calculated from other methods - In some cases can be applied to unconfined aquifers, Fetter (1988)
Bredehoeft and Papadopulos (1980)	Confined	Transient		Yes		- Modified - Measure decay of head change by pressurizing a volume of water in the well - Type curves - Type curves	- Low to extremely low K (i.e. silts, clays, shales)
Uffink (1984) (Oscillation Test) (b)	Confined	Transient		No	-Inertia of water column is not negligible, the head change in the well at $t > t_o$ can be described as an exponentially damped cyclic fluctuation - Storativity (s) and the skin factor are already known or can be estimated	- Modified - Stress zone by lowering water table by compressed air. Calculate K by Hvorslev method.	

* see remarks

** conventional refers to either injecting or withdrawing or displacing using a solid slug

a Described in Dawson and Istok (1991)

b Described in Kruseman and de Ridder (1991)

A step-drawdown test can be conducted to account for well loss. This test involves pumping at a constant rate until drawdown has stabilized. The rate of pumping is then increased. This process should be repeated through a minimum of three steps. Methods for analyzing the data have been summarized by Kruseman and de Ridder (1991).

Table 4.2 presents several methods for analyzing the drawdown data for constant discharge, variable discharge, and step-discharge single well tests. Analysis of recovery test data (residual drawdown) is invaluable with a single well pumping test. Methods for analysis are straight line methods, which are the same as for conventional pumping tests. However, with single well tests, one must account for the effects of well-bore storage when evaluating recovery (Kruseman and de Ridder, 1991). Available methods to analyze recovery are discussed in the Multiple Well Pumping Tests section of this chapter.

MULTIPLE WELL PUMPING TESTS

A multiple well test is implemented by pumping a well continuously and measuring water level changes in both the pumped and observation wells during pumping or subsequent recovery. Properly designed and conducted multiple well tests can be used to define the overall hydrogeologic regime of the area being investigated, including T, S and/or specific yield of a zone. They also can help design municipal well fields, predict rates of ground water flow, determine interconnectivity between saturated zones, and design a remediation system.

Two basic types are constant discharge and variable discharge. The former is performed by pumping at a constant rate for the duration of the test, while the latter is distinguished by changes in rate. Measurements obtained from the pumping well generally are less desirable for calculating hydraulic properties because of the irregularities induced from the operation of the pump and well bore storage. Obtaining data from observation well(s) allows for characterization of the pumped zone over a larger area.

Test design and data analysis are dependent on the characteristics of the zone tested, the desired/required information, and available funds. Design and analysis are summarized below. References suggested for more detailed information include Lohman (1972), Walton (1987), Dawson and Istok (1991), and Kruseman and de Ridder (1991).

PRELIMINARY STUDIES

Prior to initiating a test, the following data should be gathered:

- The geologic characteristics of the subsurface that may influence ground water flow.
- The type of water-bearing zone and its lateral and vertical extent.
- The depth, thickness, and lateral extent of any confining beds.
- Location of recharge and discharge boundaries.
- Horizontal and vertical flow components (e.g., direction, gradient)
- Location, construction, and zone of completion of any existing wells in the area.
- Location and effects of any pumping wells.
- Approximate values and spatial variation of formation T and S.
- Determination of seasonal ground water fluctuations and any regional water level trends.

Table 4.2 Single well pumping tests.

GENERAL ASSUMPTIONS

1. The aquifer is infinite in areal extent.
2. The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test.
3. Prior to pumping, the piezometric surface is horizontal, or nearly so, over the area to be influenced by the test.
4. The well penetrates the entire thickness of the aquifer and, thus, receives water by horizontal flow.
5. The water removed from storage in the aquifer is discharged instantaneously with decline of head.
6. Non-linear well losses are negligible.

The following assumptions/conditions apply to leaky confined aquifers.

1. The aquitard is infinite in areal extent.
2. The aquitard is homogeneous, isotropic and of uniform thickness.
3. The water supplied by leakage from the aquitard is discharged instantaneously with decline in head.

METHOD	APPLICATION		ADDITIONAL ASSUMPTIONS/CONDITIONS	ANALYSIS/PROCEDURE	REMARKS
	"Aquifer" Type	Flow Condition			
Papadopulos and Cooper (1967) (a & b)	Confined	Transient	The well diameter cannot be considered infinitesimal, hence, storage in well cannot be neglected	Constant discharge Equations take storage capacity of well into account Type curves, data curve, log/log	- Early time data does not adequately reflect aquifer characteristics - May be difficult to match the data curve with appropriate type curves because of similarities of curves
Rushton and Singh (1983) (b)	Confined	Transient	The well diameter cannot be considered infinitesimal, hence storage in well cannot be neglected	Constant discharge Type curve fitting, data curve semi-log	More sensitive curve fitting than Papadopulos and Cooper method
Birsoy and Summers(1980) (b)	Confined	Transient	Storativity is known or can be estimated with reasonable accuracy	Variable discharge (aquifer is pumped stepwise or is intermittently pumped at constant discharge)	
Hurr-Worthington (Worthington, 1981) (b)	Confined or leaky confined	Transient	Storage in well cannot be neglected. Storativity is known or can be estimated with reasonable accuracy	Constant discharge Modified Theis Equation	

Table 4.2 (Continued): Single well pumping tests.

METHOD	APPLICATION		ADDITIONAL ASSUMPTIONS/CONDITIONS	ANALYSIS/PROCEDURE	REMARKS
	"Aquifer" Type	Flow Condition			
Jacob's Straight Line Method (b)	Confined or leaky confined	Transient	For confined, $t < 25\frac{r_c^2}{KD}$ if net effect of well borestorage can be neglected. For leaky, $25\frac{r_c^2}{KD} < t < \frac{cS}{20}$ as long as the influence of leakage is negligible. $t < \frac{cS}{20}$	Constant discharge T determined by drawdown differences	Sensitive to minor variations in discharge rate May be able to account for partial penetration if late-time data is used
Hantush (1959b) (b)	Leaky confined/artesian	Transient	Flow through aquitard is vertical Aquitard is incompressible (i.e. changes in aquitard storage are negligible) At the beginning of the test (t=0), the water level in the well is lowered instantly, at t>0, the drawdown in the well is constant and its discharge is variable	Variable discharge Type curve matching	
Jacob and Lohman (1952)(b)	Confined/artesian	Transient	At the beginning of the test (t=0), water levels screened in the artesian aquifer are lowered instantaneously. At t>0, the drawdown is constant and discharge is variable Uw <0.01	Variable discharge (drawdown is constant)	If value of the effective radius is not known then storativity cannot be determined

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a Described in Dawson and Istok (1991), b Described in Kruseman and deRidder (1991)

t = time since start of pumping, KD =transmissivity of the aquifer, r_c = radius of the unscreend part of the well where water level is changing, c = hydraulic resistance of the aquitard, S = storativity, Uw = equation function

This preliminary information can assist in the proper design of the test and the choice of a conceptual model. Test design also can be facilitated by preminary conceptual modeling efforts that predict the outcome of the test beforehand (Walton, 1987). This serves two purposes. First, it describes the aquifer so that an appropriate data analysis method is evident. Secondly, it suggests deficiencies in observation well locations.

Costs frequently are reduced by using existing wells rather than installing new ones; however, few existing configurations are suitable. Evaluation of existing wells to identify ones that are potentially useable is the first step in design (Stallman, 1983). Single well tests should be conducted on the existing wells to determine whether they will respond appropriately.

PUMPING TEST DESIGN

As indicated, the design of a pumping test is dependent on the hydrogeologic environment and the purpose of the test. The designer must determine pumping well location and design, pumping rate, pump selection, location and depth of observation wells, test duration, discharge rate measurements and devices, interval and method of water level measurements, and method of analyzing data.

Pumping Well Location

A pumping well should be located far enough away from hydraulic boundaries to permit recognition of drawdown trends before boundary conditions influence the drawdown data (Sevee, 1991). To minimize the effect of stream, river or lake bed infiltration, it should be located at a distance equal to or exceeding the aquifer thickness from the possible boundary (Walton, 1987). However, if the intent is to induce recharge, then the pumping well should be located as close to the boundary as possible (Sevee, 1991). The appropriate depth should be determined from exploratory boreholes or logs from nearby wells.

Pumping Well Design

The design of a pumping well is dependent on the hydrogeologic environment, the choice of conceptual model, and economics. Components that must be considered include diameter, length and depth of the screened interval, and screen slot configuration.

A general rule is to screen the well over at least 80 percent of the aquifer thickness. This makes it possible to obtain about 90 percent or more of the maximum yield that could be obtained if the entire aquifer were screened, and also allows horizontal flow toward the well to be assumed, which is an assumption that underlies almost all well-flow equations. Pumping wells completed in thick zones often have intake lengths less than 80 percent of the thickness. These wells are considered partially-penetrating (Kruseman and deRidder, 1991), and pumping would be expected to induce vertical flow components. As a result, corrections to the drawdown data may be necessary. Corrections are discussed later in this chapter.

The diameter of a pumping well is dependent on the conceptual model and the estimated hydraulic properties. It must accommodate the pump, assure hydraulic efficiency, and allow measurement of depth to water before, during and after pumping. Table 4.3 recommends casing diameters based on pumping rates; however, the final selection should be based on consultation with the pump manufacturer.

The screen slot size and filter pack material should be based on the grain size distribution of the zone being pumped. The screen should be factory-slotted or perforated over no more than 30 to 40 percent of its circumference to keep entrance velocity less than 3 cm/sec (Kruseman and de Ridder, 1991). At this velocity, friction losses in the screen are small and may be considered negligible. Slots should be long and narrow or continuous. The screen should be factory-produced. Slots produced manually are not appropriate under any circumstances.

Table 4.3 Recommended pumping well diameter for various pumping rates. (Dawson and Istok, 1991, after Driscoll, 1986).

PUMPING RATE		*DIAMETER*	
gal/min	*m^3/day*	*(in)*	*(mm)*
<100	<545	6	152
75-175	409-954	8	203
150-350	818-1910	10	254
300-700	1640-3820	12	305
500-1000	2730-5450	14	365
800-1800	4360-9810	16	406
1200-3000	6540-16400	20	508

Pumping Rate

Insufficient pumping rates may result in underestimation of the hydraulic parameters of both the zone tested and confining layers. Likewise, excessive rates for too short a duration may lead to calculation of erroneously large hydraulic properties. The rate(s) should be sufficient to ensure that the aquifer is stressed and that drawdown can be measured accurately. The water table in an unconfined zone should not be lowered by more than 25 percent. This is the largest drawdown that can be corrected and analyzed with an analytical solution of the ground water flow equation (Dawson and Istok, 1991). The pumping rate for tests conducted in confined zones should not readily dewater the pumping well.

Well efficiency and an appropriate pumping rate for a constant discharge test can be determined by conducting a step-drawdown test. A step test involves pumping a single well at a low constant rate until the drawdown within the well has stabilized. The rate is then increased to a higher constant discharge until the water level has stabilized once more. At a minimum, to insure that an appropriate rate can be determined from the data, three successively greater rates of equal duration should be utilized. The duration of each step generally should be at least 2 hours; however, the required time is dependent on aquifer characteristics. References detailing the mechanics of a step test include Kruseman and de Ridder (1991), Driscoll (1986), and Dawson and Istok (1991).

Other methods that may be useful to estimate an appropriate pumping rate for a constant head test include: 1) using an empirical formula to predict well specific capacity, and 2) predicting drawdown using analytical solutions. These methods are described by Dawson and Istok (1991). It should be noted that these techniques predict discharge rates that can be utilized to determine hydraulic parameters and should not be utilized to estimate an appropriate rate for capturing a contaminant plume.

Pump Selection

The pump and power supply must be capable of operating continuously at an appropriate constant discharge rate for at least the expected duration of the test. Pumps powered by electric motors produce the most constant discharge (Stallman, 1983).

Observation Well Number

The appropriate number of observation wells depends on the goals of the test, hydrogeologic complexity, the degree of accuracy needed, and economics. Though it is always best to have as many wells as conditions permit, at least three should be employed in the pumping zone (Kruseman and de Ridder, 1991). If two or more are available, data can be analyzed by both drawdown versus time and drawdown versus distance relationships. Using both and observing how wells respond in various locations provides greater assurance that: 1) the calculated hydraulic properties are representative of the zone being pumped over a large area, and 2) any heterogeneities that may affect the flow of ground water and contaminants have been identified. In areas in where several complex boundaries exist, additional wells may be needed to allow proper interpretation of the test data (Sevee, 1991).

Observation Well Design

In general, observation wells need to be constructed with an appropriate filter pack, screen slot size, and annular seal, and must be developed properly. Practices for design and development of observation wells can be similar to those for monitoring wells (see Chapters 7 & 8). The observation wells/piezometers must be of sufficient diameter to accommodate the measuring device, but should not be so large that the drawdown cannot be measured.

Observation Well Depth

Fully-penetrating wells are desirable. The open portion of an observation well generally should be placed vertically opposite the intake of the pumping well. When testing heterogeneous zones, it is recommended that an observation well be installed in each permeable layer. Additional wells should be placed in the aquitards to determine leakage and interconnectivity (Kruseman and de Ridder, 1991).

Observation Well Location

Observation well location is dependent on the type of aquifer, estimated transmissivity, duration of the test, discharge rate, length of the pumping well screen, whether the aquifer is stratified or fractured, and anticipated boundary conditions. Placing observation wells 10 to 100 meters (33 to 328 feet) from the pumping well is generally adequate for determining hydraulic parameters. For thick or stratified, confined zones, the distance should be greater (Kruseman and de Ridder, 1991). It also is recommended that additional observation wells be located outside the zone of influence of the pumping well to monitor possible natural changes in head.

In general, observation wells completed in a confined zone can be spaced further from the pumping well than those completed in an unconfined aquifer. The decline in the piezometric surface of confined zones spreads rapidly because the release of water from storage is entirely due to compressibility of water and the aquifer material. Water movement in unconfined zones is principally from draining of pores, which results in a slower expansion.

Under isotropic conditions, the distribution of the observation wells around the pumping well can be arbitrary. However, an even distribution is desirable so that drawdown measurements are representative of the largest volume of aquifer possible (Dawson and Istok, 1991). If feasible, at least three wells should be logarithmically spaced to provide at least one logarithmic cycle of distance-drawdown data (Walton, 1987). If anisotropic conditions exist or are suspected, then a single row of observation wells is not sufficient to estimate the directional dependence of transmissivity. A minimum of 3 observation wells, none of which are on the same radial arc, is required to separate the anisotropic behavior.

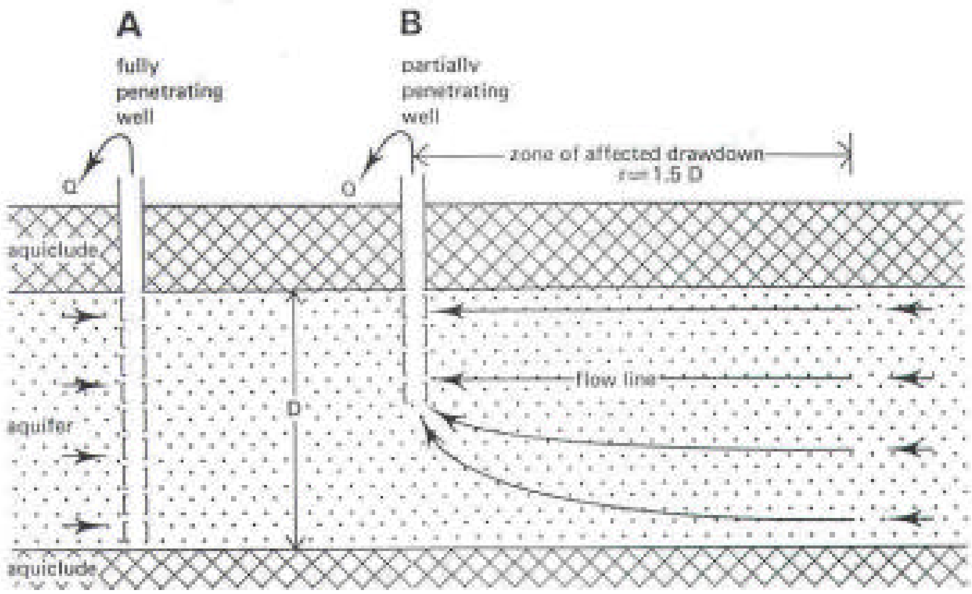
The length of the pumping well screen can have a strong influence on the distance of the observation wells from the pumping well. Partially-penetrating pumping wells will induce vertical flow, which is most noticeable near the well (Figure 4.4). As a result, water level measurements taken from these wells need to be corrected; however, the effects of vertical flow become more negligible at increasing distances from the pumping well. For partially-penetrating pumping wells, corrections to the drawdown data may not be necessary if the following relation holds true (Sevee, 1991; and Dawson and Istok, 1991):

$$M.D. \$\ 1.5\ D \sqrt{\frac{K_H}{K_V}}$$

M.D. = minimum distance between pumping well and observation well.
D = thickness of the aquifer.
K_H = horizontal K.
K_V = vertical K.

Drawdown measured in observation wells located less than the minimim distance should be corrected. Typically, horizontal K is ten times greater than vertical K. If this ratio is used, then the minimum distance becomes 1.5D **/** 10. It should be noted that partially-penetrating wells located at or greater than the minimum distance may be too far away to show drawdown.

Anticipated boundary conditions (e.g., an impervious zone or a recharging river) also can affect the placement of observation wells. Wells can be placed to either minimize the effect of the boundary or more precisely locate the discontinuity (Dawson and Istok, 1991). According to Walton (1987), to minimize the effect of the boundary on distance-drawdown data, wells should be placed along a line through the pumping well and parallel to the boundary. Observation wells also should be placed on a line perpendicular to the boundary. If more than one boundary is suspected or known, the wells should be located so that the effects on drawdown data encountered by the first boundary have stabilized prior to encountering the second boundary (Sevee, 1991).



4.4 (A) Flow to a fully penetrating well. (B) Flow to a partially penetrating well. (Source: *Analysisand Evaluation of Pumping Test* by G. P. Kruseman and N.A. de Ridder, Copyright © 1991 by International Institute for Land Reclamation and Improvement, publication 47, 377 pp. Printed with permission).

Duration of Pumping

It is difficult to predict how long a pumping test should be conducted. The duration depends on the hydrogeologic setting, boundary conditions, and degree of accuracy desired. Economic factors and time constraints also may be influential; however, economizing the period of pumping is not recommended. The cost of continuing a test is low compared to total costs, particularly when the wells have been specially constructed and positioned for test purposes (Kruseman and de Ridder, 1991).

Pumping tests commonly last from five hours to five days (Walton, 1962). Though not absolutely necessary, it is recommended that tests be continued until the cone of depression has stabilized and does not expand as pumping continues. Such a steady state or equilibrium can occur within a few hours to weeks or never. According to Kruseman and de Ridder (1991), the average time to reach steady state in leaky aquifers is 15 to 20 hours. A test of a confined aquifer should last a minimum of 24 hours. Three days or more should be allowed for tests conducted in unconfined aquifers because of the slow expansion of the cone of depression. The duration necessary to define the hydraulic parameters depends on the regional and local geologic/hydrogeologic setting. Plotting drawdown data during tests often reveals anomalies and the presence of suspected or unknown boundaries, and assists in determining test duration.

Discharge Rate Measurement

Variation in discharge rates produces aberrations in drawdown that are difficult to treat in data analysis. Engines, even those equipped with automatic speed controls, can produce variations up to 20 to 25 percent over the course of a day. The rate should never vary by more than five percent (Osborn, 1993). In order to obtain reliable data, discharge should be monitored and adjustments made as needed.

The frequency of measurements is dependent on the pump, engine power characteristics, the well, and the zone tested. Discharge from electric pumps should be measured and adjusted (if necessary) at 5, 10, 20, 30, 60 minutes, and hourly thereafter. Other types of pumps may require more frequent attention; however, no "rule of thumb" can be set because of the wide variation in equipment response (Stallman, 1983).

Discharge Measuring Devices

Some discharge measurement techniques are more accurate than others and some allow for a convenient means of adjusting rate. A ***commercial water meter*** of appropriate capacity can be utilized. It should be connected to the discharge pipe in a way that ensures accurate readings. A disadvantage is the unavoidable delay in obtaining values at the start of the test, when pumping rate is being adjusted to the desired level (Driscoll, 1986). When discharge is low, the rate can be measured as a function of time to fill a ***container of known volume***. The ***orifice weir*** is commonly used to measure discharge from high capacity pumps. A manometer is fitted into the discharge pipe. The water level in the manometer represents the pressure in the pipe when the water flows through the orifice. Figure 4.5 shows a diagram of a typical circular orifice weir. Details on orifice design and interpretation of results can be found in Driscoll (1986). Finally, discharge rate can be obtained by water level measurements taken from ***weirs and flumes***. The rate of flow is determined within known constriction dimensions placed in the discharge channel originating at the well head (Driscoll, 1986).

Interval of Water Level Measurements

Pretest Measurements

Prior to the start of tests, water level data should be collected from the pumping and observation wells to determine existing trends for all zones to be monitored. The pumping phase should begin only if identified and recorded trends are expected to remain constant. As a general rule, the period of observation should be at least twice the length of the estimated time of pumping (Stallman, 1983). Water levels should be measured and recorded hourly for all zones. In addition, the barometric pressure should be monitored, at least hourly, to determine the barometric efficiency of saturated zone(s), which may be useful in correcting the drawdown data. Barometric efficiency is discussed later in this chapter.

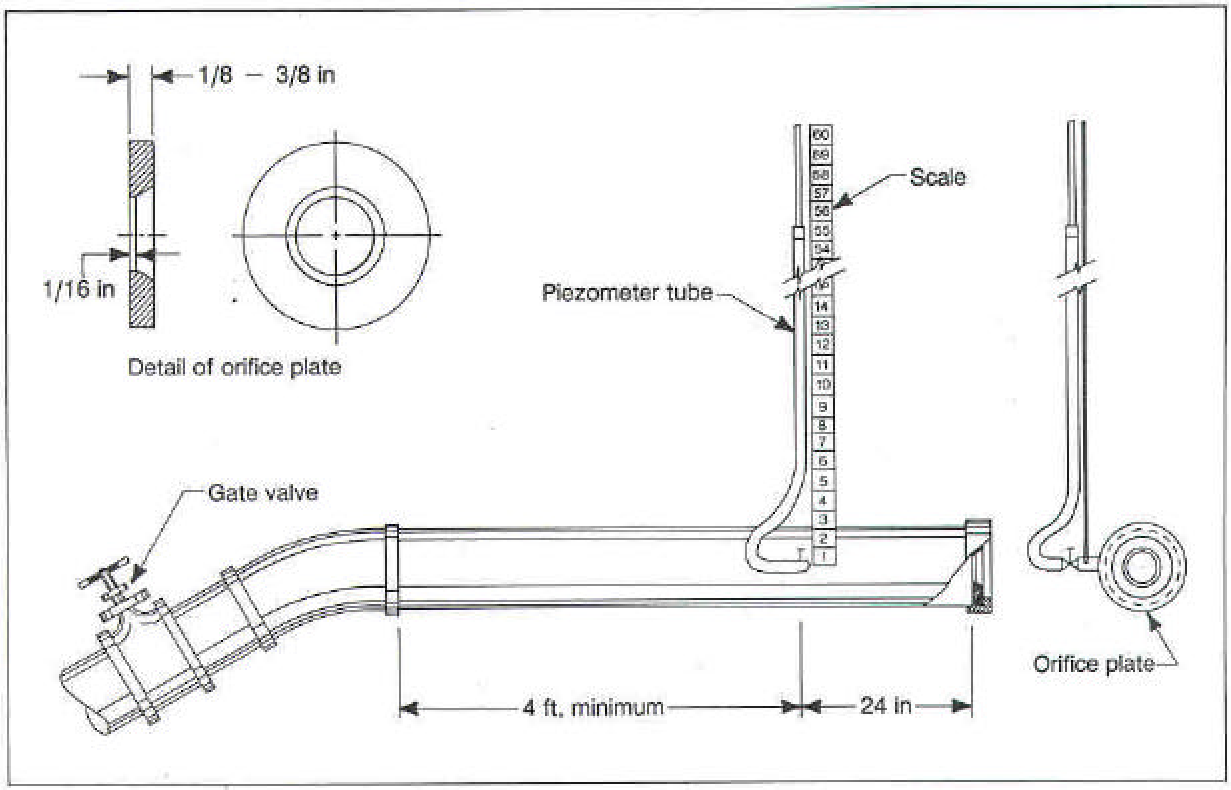


Figure 4.5 Construction diagram of a circular orifice weir commonly used for measuring rates of a high capacity pump. (Source: *Ground Water and Wells* by E.G. Driscoll. Copyright , © 1986; Johnson screens. Printed with permission).

Measurements During Pumping

The appropriate time interval for water level measurements varies from frequent at the beginning of a test, when water-levels are changing rapidly, to long at the end of the test, when change is slow. Typical intervals for the pumping well and observation wells located close to the pumping well are given in Tables 4.4 and 4.5, respectively. Though specified intervals need not be followed rigidly, each logarithmic cycle of time should contain at least 10 data points spread through the cycle (Stallman, 1983). Frequent readings are essential during the first hour since the rate of change is faster. For wells further away and those located in zones above or below the pumping zone, the frequent measurements recommended by Table 4.5 for the first few minutes of the pumping tests are less important (Kruseman and de Ridder, 1991).

Table 4.4 Range of interval between water-level measurements in the pumping well (Kruseman and de Ridder, 1991).

TIME SINCE START OF PUMPING	TIME INTERVAL
0 to 5 minutes	0.5 minutes
2 to 60 minutes	5 minutes
60 to 120 minutes	20 minutes
120 to shutdown of the pump	60 minutes

Table 4.5 Range of intervals between water-level measurements in observation wells (Kruseman and de Ridder, 1991).

TIME SINCE START OF PUMPING	TIME INTERVAL
0 to 2 minutes	approx. 10 seconds
2 to 5 minutes	30 seconds
5 to 15 minutes	1 minute
50 to 100 minutes	5 minutes
100 minutes to 5 hours	30 minutes
5 hours to 48 hours	60 minutes
48 hours to 6 days	3 times a day
6 days to shutdown of the pump	1 time a day

According to Stallman (1983), it is not necessary to measure water levels in all wells simultaneously, but it is highly desirable to achieve nearly uniform separation of plotted drawdowns on a logarithmic scale. All watches used should be synchronized before the test is started, and provisions made to notify all participants at the instant the test is initiated.

Measurements During Recovery

After pumping is completed, water level recovery should be monitored with the same frequency used during pumping.

Water Level Measurement Devices

The most accurate recording of water level changes is made with fully automatic microcomputer-controlled systems that use pressure or acoustic transducers for continuous measurements. Water levels can also be determined by hand, but the instant of each reading must be recorded with a chronometer. Measurements can be performed with floating steel tape equipped with a standard pointer, electronic sounder, or wet-tape method. For observation wells close to the pumped well, automatic recorders programmed for frequent measurements are most convenient because water level change is rapid during the first hour of the test. For detailed descriptions of automatic recorders, mechanical and electric sounders, and other tools, see Driscoll (1986), Dalton et al. (1991), and ASTM D4750-87 (1992). Chapter 10 of this document contains a summary of manual devices.

The measurement procedure should be standardized and calibrated prior to the start of the test. Transducers should be calibrated by a direct method, and the calibration should be checked at the conclusion of the recovery test.

Discharge of Pumped Water

Water extracted during a pumping test must be discharged properly and in accordance with any applicable laws and regulations. At sites with contaminated ground water, the discharge may need to be containerized and sampled to assess the presence of contaminants and, if necessary, treated and/or disposed at an appropriate permitted facility.

It is not the intent of this document to define Agency policy on disposal of pumped water. In general, the water should be evaluated to determine if it is characteristically a waste. If the ground water has been contaminated by a listed hazardous waste, the ground water is considered to "contain" that waste, and must therefore be managed as such. Disposal must be at a permitted hazardous waste facility. Treatment must be in a wastewater treatment system that is appropriate for the waste and meets the definitions contained in OAC rule 3745-50-10.

If containerization is not necessary, then pumped water must be discharged in a manner that prevents recharge into any zone being monitored during the test. At a minimum, the water should be discharged 100 to 200 meters from the pumped well. This is particularly important when testing unconfined zones. At no time should the discharge water be injected back into the subsurface. A permit for discharge via stream or storm sewer may be required (contact the Division of Surface Water, Ohio EPA).

Decontamination of Equipment

Decontamination of equipment is important throughout an in-situ test. Contact of contaminated equipment with ground water (or a well) may cause a measuring point to be unsuitable for water quality investigations. Details on appropriate methods can be found in Chapter 10.

CORRECTION TO DRAWDOWN DATA

Prior to using the drawdown data collected from a pumping test, it may be necessary to correct for either external sources or effects induced by the test. Barometric pressure changes, tidal or river fluctuations, natural recharge and discharge, and unique situations (e.g., a heavy rainfall) may all exert an influence. In confined and leaky aquifers, changes in hydraulic head may be due to influences of tidal or river-level fluctuations, surface loading, or changes in atmospheric pressure.

Diurnal fluctuations in water levels can occur in unconfined aquifers due to the differences between night and day evapotranspiration. Corrections to measurements may be needed for unconfined aquifer data due to a decrease in saturated thickness caused by the pumping test. Also, corrections may be necessary if the pumping well only partially penetrates the zone tested. By identifying pre-test water level trends in zone(s) of interest, long and short-term variations can be eliminated from the data if their impacts are significant during the pumping phase (Figure 4.6).

In order to determine if corrections are necessary, measurements should be taken during the test in observation wells unaffected by the pumping. Hydrographs of the pumping and observation wells covering a sufficient period of pre-test and post-recovery periods can help determine if the data needs to be corrected and also to correct the drawdown data. If the same constant water level is observed during the pre-testing and post-recovery periods, it can safely be assumed that no external events exerted an influence (Kruseman and de Ridder, 1991).

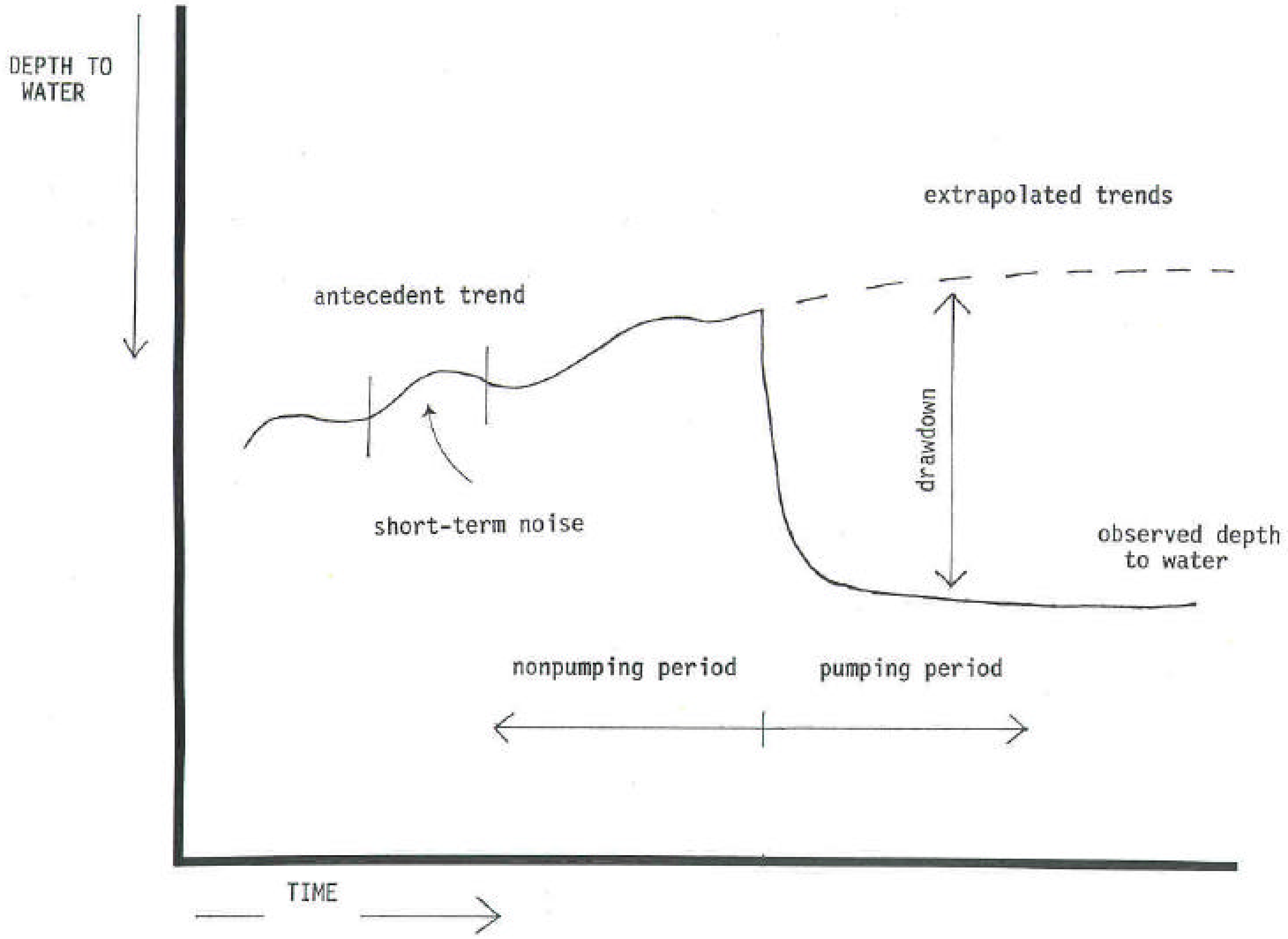


Figure 4.6 Hydrograph for hypothetical observation well showing definition of drawdown (adapted from Stallman, 1983).

Barometric Pressure

Data for confined and leaky zones needs to be corrected for the amount of rise in water levels resulting from a decrease in atmospheric pressure and/or the amount of fall resulting from an increase. To make the correction, the barometric efficiency (BE) of the zone needs to be determined. The BE can be calculated by the following equation [Dawson and Istok (1991) and Kruseman and de Ridder (1991)]:

$$BE \;'\; \frac{Mh}{Mk_a \,/\, \tilde{a}_w} \; x \; 100\%$$

where: Mh = change of head in the observation well.
$(Mk_a/\tilde{Q}_w)$ = change in atmospheric pressure expressed as a height of water.
k_a = change in atmospheric pressure.
$\tilde{Q}_w$ = specific weight of water.

If the change in hydraulic head is plotted versus the change in pressure (measured column height) and a best-fit straight line is drawn, then the slope of the line is the BE. From changes in atmospheric pressure observed during the test and the BE, the change in water level due to changes in barometric pressure can be calculated and the drawdown data can be corrected. When artesian zones are tested, barometric pressure (to a sensitivity of +/- 0.01 inch of mercury) should be recorded continuously throughout the testing period. Barometric efficiency typically ranges between 0.20 and 0.75 (Kruseman and de Ridder, 1991).

Saturated Thickness

The saturated thickness of an unconfined zone decreases during pumping tests; however, most conceptual models are based on the assumption that it remains constant. This assumption can be accepted if the saturated thickness does not decrease more than 25 percent. If the decrease is greater then 25 percent, then the drawdown data should be corrected prior to analysis (Dawson and Istok, 1991).

According to Jacob (1944), data for unconfined zones can be corrected for saturated thickness change with the following equation:

$$s_{corrected} = s - s^2/2m$$

where: $s_{corrected}$ = corrected drawdown.

s = observed drawdown.

m = initial saturated thickness.

However, this correction is based on the Dupuit-Forchheimer assumption (ground water flows horizontally and hydraulic gradient is equal to the slope of the water table). Neuman (1975) showed that this assumption is not valid for an unconfined aquifer until the later portion of the test when the drawdown matches the Theis type curve. Therefore, the correction is not recommended with early and intermediate data (Dawson and Istok, 1991).

Unique Fluctuations

Data cannot be corrected for unique events such as a heavy rain or sudden fall or rise of a nearby river that is hydraulically connected to the zone tested. However, in favorable circumstances, some allowances can be made for the resulting fluctuations by extrapolating data from a controlled piezometer outside the zone of influence. In most cases, the data collected is rendered worthless and the test has to be repeated when the situation returns to normal (Kruseman and de Ridder, 1991). It is also important to understand the effects of nearby industrial or municipal pumping wells prior to conducting a pumping test.

Partially-Penetrating Wells

In some cases, a saturated zone is so thick that it is not justifiable to install a fully-penetrating well, and the aquifer must be pumped by a partially-penetrating well. Partial-penetration causes vertical flow in the vicinity of the well, which results in additional head loss. As indicated earlier, this effect decreases with increasing distance from the pumping well and no correction is necessary if the observation well is at a distance greater than $1.5\ D\ / K_H/K_V$. Various methods have been developed to correct data for the effects of partially-penetrating wells. These were discussed in detail by Kruseman and de Ridder (1991). Table 4.6 lists the methods and their general applications.

ANALYSIS OF MULTIPLE WELL PUMPING TEST DATA

Many conceptual models exist for interpreting multiple well pumping test data. The hydraulic properties computed by a particular method can only be considered correct if the assumptions included in the conceptual model on which the method is based are valid for the particular system being tested. Because the computed values depend on the choice of conceptual model used to analyze the data, the selection of an appropriate model is the single most important step in analysis (Dawson and Istok, 1991).

IIt is beyond the scope of this document to detail or discuss all conceptual models. Tables 4.7 through 4.11 can be used for a preliminary selection. In addition, the ASTM Method D4043-91 (1992) provides a decision tree for the selection of an aquifer test method and ASTM Methods D4106-91 (1992) and D4105-91 (1992) offer information on determining hydraulic parameters. Additional references are provided in the tables that should serve as a guide for choice and use of conceptual models. It should be noted that additional models may exist that are not listed here. Any model utilized must be shown to be appropriate for site conditions.

Data collected during a pumping test are subject to a variety of circumstances that may be recognized in the field or may not be apparent until data analysis has begun. In either case, all information (including field observations) must be examined during data correlation and analysis.

Table 4.6 Corrections for partially penetrating effects (information derived from Kruseman & de Ridder, 1991.)

METHOD	*APPLICATION*	*ORIGINAL SOURCE*
Huisman Method I	- confined aquifer - steady state	Anonymous, 1964
Huisman Method II	- confined - unsteady state - time of pumping relatively short	Hantush (1961 a, 1961 b)
Hantush Modification of Theis Method	- confined - unsteady state - time of pumping relatively short	Hantush (1961 a, 1961 b)
Hantush, Modification of Jacob Method	- confined - unsteady state - time of pumping relatively long	Hantush (1961 b)
Weeks', "Modification of Walton and the Hantush Curve Fitting Methods"	- leaky aquifers - steady state flow	Weeks (1969)
Streltsova's Curve Fitting Method	- unconfined - anisotropic - unsteady state	Streltsova (1974)
Neuman's Curve-Fitting Method	- unconfined - anisotropic	Neuman (1974, 1975, 1979)

RECOVERY TESTS

Recovery tests (also called residual drawdown tests) involve measuring water level rise after the pump is shut down. These tests provide an independent check on the transmissivity determined from a pumping test. Results of a recovery test conducted on confined and leaky confined zones can be more reliable than pumping test results because recovery occurs at a constant rate that is not influenced by the erratic fluctuations that can be characteristic of pumping rate. Hysteresis effects must be accounted for when evaluating recovery data collected from unconfined aquifers. Table 4.12 provides methods for analyzing recovery data.

Table 4.7 Multiple-Well, Constant Discharge Pumping Tests, Unconfined Aquifer.

GENERAL ASSUMPTIONS

1. The aquifer is unconfined. The aquifer is bounded below by an aquiclude.
2. All layers are horizontal and extend infinitely in the radial extent.
3. The aquifer is homogeneous, isotropic (unless noted) and of uniform thickness over the area influenced by the test.
4. Prior to pumping, the water table is horizontal over the area that will be influenced by the test.
5. Ground water density and viscosity are constant.
6. Ground water flow can be described by Darcy's Law.
7. Head losses through well screen and pump intake are negligible.
8. The aquifer is compressible and completely elastic.
9. The aquifer has been pumped long enough that equalibrium has been reached (drawdown is not changing with time).
10. Drawdown is small compared to the saturated thickness of the aquifer (i.e., no more than 25 percent).
11. Pumping and observation wells are screened over the entire saturated thickness and receives water from the entire aquifer (unless noted).
12. Ground water flow above the water table is negligible.

METHOD	CAN ACCOUNT FOR			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/ PROCEDURES	REMARKS
	Flow Conditions	Partial Penetration	Other			
Neuman's Curve Fitting Method (Neuman, 1972) (a,b)	Transient	No	anisotropic conditions	The influence of the unsaturated zone upon drawdowns of the aquifer is negligible The diameters of the pumped and observation wells are small, i.e., storage in them can be neglected The ratio of the specific yield versus the elastic early-time storativity is greater than 10, i.e., $\frac{S_y}{S_A} > 10$	Curve fitting method	Theory should be valid for piezometers with short screens provided that the drawdowns are averaged over the aquifer (Van der Kamp, 1985)

Table 4.7 (continued). Multiple-well, constant discharge pumping tests, unconfined aquifers.

METHOD	CAN ACCOUNT FOR			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/ PROCEDURES	REMARKS
	Flow Conditions	Partial Penetration	Other			
Thiem-Dupuit's Method, (Thiem, 1906) (b)	Steady state	No		Velocity of flow is proportional to the tangent of the hydraulic gradient instead of the sine as it is in reality Flow is horizontal and uniform everywhere in a vertical section through the well axis The aquifer has been pumping long enough that equilibrium has been reached	Plot drawdown versus time and substitute values into analytical equations	Steady state will only be achieved after long pumping time Does not give accurate description of drawdown near the well Assumptions ignore the existence of a seepage face at the well and the influence of the vertical velocity component
Boulton and Streltsova (1976) a	Transient	Yes	storage in the well Anisotropy		Type curve fitting	The affects of well storage on drawdown can be neglected if either $t > \frac{2.5x10^{\&3} r_c^2}{Ô}$ or $r > 3\ 00\& r_w$ Other models may be more applicable.
Neuman (1974) a	Transient	Yes	Anisotropy		Type curve fitting	

a Described in Dawson and Istok, 1991
b Described in Kruseman and de Ridder, 1991
t = time, Ô= transmissivity, r = radial distance from the pumping well, r_w = effective radius of the pumping well, r_c= inside radius of the pumping well within the range of water fluctuations

Table 4.8 Multiple-well, constant-discharge pumping tests, confined aquifers.

GENERAL ASSUMPTIONS

1. The aquifer is confined. The aquifer is bounded above and below by aquicludes.
2. The aquifer is homogeneous, isotropic (unless noted in special conditions) and of uniform thickness over the area influenced by the test.
3. All layers are horizontal and extend infinitely in the radial extent.
4. Prior to pumping, the piezometric surface is horizontal and extends infinitely in the radial direction.
5. Ground water density and viscosity are constant.
6. Ground water can be described by Darcy's Law.
7. Head losses through well screen and pump intake are negligible.
8. Ground water flow is horizontal and is directed radially to the well.
9. Pumping well and observation wells are screened over the entire thickness of the aquifer.

Additional assumptions for unsteady state flow.

10. The water removed from storage is discharged instantaneously with decline of head.
11. The diameter of the well is small, i.e., the storage in the well can be neglected.

METHOD	APPLICATION			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/ PROCEDURES	REMARKS
	Flow Condition	CAN ACCOUNT FOR				
		Partial Penetration	Other			
Thiem (1906) (a, b)	Steady state	No		The aquifer has been pumped long enough that equilibrium has been reached (drawdown is not changed with time)	Drawdown versus time plotted on semi-log paper and substitution of values into analytical equations.	Equation should be used with caution and only when other methods cannot be applied Drawdown is influenced by well losses, screen and pump intake
Theis (1935) (a,b)	Transient	No		The aquifer is compressible and completely elastic	Type curve analysis	Because there may be a time lag between pressure decline and release of stored water, early drawdown data may not closely represent theoretical drawdown data
Hantush (1964) (b)	Transient	Yes	Anisotropy in the horizontal plane	No vertical flow at the top and bottom of the aquifer	Solutions involve type curve analysis or inflection point method	Inflection point method can be used when the horizontal and vertical hydraulic conductivities can be reasonably estimated.

Table 4.8 (continued): Multiple-well tests, constant discharge pumping tests, confined aquifers.

METHOD	APPLICATION			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/ PROCEDURES	REMARKS
	Flow Condition	CAN ACCOUNT FOR				
		Partial Penetration	Other			
Jacob's Method (Cooper and Jacob, 1946) (b)	Transient	No		u < 0.01 where $u \ ' \ r^2 \frac{S}{4KDt}$	Based on Theis Equation, straight line method based on drawdown versus time on semi-log paper	Can also be applied to single well pump tests Condition that u values are small usually is satisfied at moderate distances from the well within a hour or so. at u < 0.05 or 0.10, error introduced is 2 and 5% respectively
Weeks (1969) (b)	Transient	Yes	Anisotropy in the vertical plane	$t > \frac{SD}{2K_v}$ Must have at least two piezometers, one which is at a distance of at least $r > 2D\sqrt{\frac{K_h}{K_v}}$	Apply methods for fully penetrating wells to determine T and S, then determine K_h & K_v by data plots and substitutions into equations	Similar procedure can be applied to leaky aquifers
Papadopulos (1965) (a)	Transient	No	Anisotropy in horizontal plane		Curve fitting	Two dimensional coordinate system Min. of three observation wells
Papadopulos and Cooper (1967) (a)	Transient	No	Well Storage		Curve fitting	Pumping rate is the sum of the ground water entering in the pumping well from the aquifer and the rate of decrease of water stored in well casing.

METHOD	APPLICATION			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/ PROCEDURES	REMARKS
	Flow Condition	CAN ACCOUNT FOR				
		Partial Penetration	Other			
Neuman's Extension of Papadopulos (Neuman et al., 1984) (b)	Transient	No	Anisotropy in the horizontal plane	Aquifer is penetrated by at least three wells, which are not on the same ray.	Requires drawdown data from at least 3 wells on different rays from the pumping well Requires two pumping tests conducted in sequence	More reliable results can be obtained by conducting 3 pumping tests.
Hantush (1966) (b)	Transient	No	Anisotropy in the horizontal plane		Use of Theis (1906) or Cooper and Jacob (1946) Substitution into various equations	If the principal direction of anisotropy is known, drawdown data from two piezometers on different rays is sufficient. If not, 3 wells on different rays will be needed.
Hantush and Thomas (1966) (b)	Transient	No	Anisotropy in the horizontal plane		Apply methods for confined isotropic aquifers to the data for each ray of piezometers Calculation of T in the major and minor directions of anisotropy involves substitution	

a Described in Dawson and Istok (1991)
b Described in Kruseman and de Ridder (1991)
S = Storativity, K = hydraulic conductivity, D = thickness of saturated zone, r = distance to observation well, t = time since start of pumping

Table 4.9 Multiple-well, Constant discharge pumping tests, leaky aquifers.

GENERAL ASSUMPTIONS

1. The aquifer is leaky.
2. The aquifer and aquitard have seemingly infinite and areal extent.
3. The aquifer and aquitard are homogeneous, isotropic (unless noted), and of uniform thickness over the area influenced by the test.
4. Prior to pumping, the piezometric surface and the water table are horizontal over the area that will be influenced by the test.
5. The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow (unless noted).
6. The flow in the aquitard is vertical.
7. The drawdown in the unpumped aquifer (or aquitard) is negligible.
8. Ground water flow can be described by Darcy's Law.

Additional assumptions for transient conditions:

9. Water removed from storage in the aquifer and the water supplied by leakage from the aquitard is discharged instantaneously with decline of head.
10. The diameter of the well is very small, i.e., the storage in the well can be neglected.

METHOD	CAN ACCOUNT FOR			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/PROCEDURES	REMARKS
	Flow Conditions	Partial Penetration	Other			
DeGlee (1930 & 1951) (b)	steady state	No		L > 3D: where L represents a leakage factor and D is the saturated thickness of the aquifer	Substitution into equations	
Hantush (1960) (b)	Transient	No	Takes into account storage changes in the aquitard	The aquitard is compressible, i.e., the changes in the aquitard storage are appreciable $t < S'\frac{D'}{10K'}$	Type curve analysis Generally is Theis equation plus an error function	Only the early-time drawdown should be used to satisfy the assumption that the drawdown in the aquitard is negligible

Table 4.9 (continued): Multiple-well, constant discharge pumping tests, leaking aquifers.

METHOD	CAN ACCOUNT FOR			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/PROCEDURES	REMARKS
	Flow Conditions	**Partial Penetration**	**Other**			
Hantush-Inflection Point (1956) (a,b)	Transient	No		The aquitard is incompressible, i.e., changes in aquitard storage are negligible It must be possible to extrapolate the steady-state drawdown for each observation well	Plotting drawdown versus time on semi-log paper, substitution of values into equation	Accuracy depends on accuracy of extrapolating the maximum drawdown Two different methods, one requires one piezometer, and the other requires data from two piezometers
Hantush-Jacob (1955) (b)	Steady state	No		aquitard is incompressible L > 3D r/L # 0.05 L = leakage factor r = distance from pumping well D = saturated thickness of aquifer	Best fit straight line, substitution into equation	Results are an approximation because method only can be used for values of $r/L \leq 0.05$ which is a restrictive limiting condition If errors in hydraulic parameters are to be less than 7%, r/L should be less than 0.16
Lai and Su (1974) (a,b)	Transient	No		The aquitard is incompressible, i.e., changes in aquitard storage are negligible	Type - curve fitting method	

Table 4.9 (continued): Multiple-well, constant discharge pumping tests, leaking aquifers.

METHOD	CAN ACCOUNT FOR			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/PROCEDURES	REMARKS
	Flow Conditions	Partial Penetration	Other			
Neuman-Witherspoon (1972) (b)	Transient	No	Determines the hydraulic characteristics of the aquitard	The aquitard is compressible i.e., changes in aquitard storage are appreciable The radial distance from the well to the piezometer should be small (<100m)	Substitution of values into Neuman Witherspoon equations (derived from Hantush-Jacob Equation)	Need to calculate for transmissivity using one of the other methods for leaky aquifers
Hantush-Jacob (1955) (a)	Transient	No		Ground water flow in the aquitard is vertical Aquifer is bounded above by aquitard and an unconfined aquifer and bounded below by an aquiclude	Curve fitting and substitution of values into equation	Drawdown in the source bed can be neglected when $t < \frac{S'(D')^2}{10DK'}$ or KD of source bed is >100 KD of aquifer
Walton (1962) (b)	Transient	No		- The aquitard is incompressible, i.e., changes in aquitard storage are negligible	- Type curve fitting	- To obtain the unique fitting position of the data plot with one of the type curves, enough of the observation data should fall within the period when leakage effects are negligible

Table 4.9 (continued): Multiple-well, constant discharge pumping tests, leaking aquifers.

METHOD	CAN ACCOUNT FOR			ADDITIONAL ASSUMPTIONS AND CONDITIONS	ANALYSIS/PROCEDURES	REMARKS
	Flow Conditions	Partial Penetration	Other			
Hantush (1966) (b)	Transient	No	Anisotropic in horizontal plane		Substitution into equations	- Similar to Hantush's methods for confined aquifers except initial step uses methods to calculate the hydraulic parameters
Weeks (1969) (b)	Transient	Yes	Anisotropic in the vertical plane	- Large values of pumping time: $t > \frac{SD}{2K_v}$ - Drawdown data from at least two piezometers, with one piezometer at a distance greater than $2D\sqrt{\frac{K_h}{K_v}}$ -Aquitard is incompressible	- Apply methods for leaky confined aquifers, to determine transmissivity and storativity, then determine K_h and K_v from data plots and substitutions into equations	- Similar process can be conducted for confined aquifer

a Described in Dawson and Istok, 1991

b Described in Kruseman and de Ridder, 1991

t = time since start of pumping, S' = aquitard storativity, D'= saturated thickness of aquitard, D = saturated thickness of the aquifer, K'= hydrualic conductivity of aquitard

Table 4.10 Pumping tests, variable discharge.

METHOD*	APPLICATION	ASSUMPTIONS	PROCEDURE	REMARKS
Birsoy and Summers (1980)	-Confined - Transient - Aquifer pumped step-wise or intermittently at variable rates	- General assumptions for confined aquifers $\frac{r^2 S}{4KD} \times \frac{1}{B_{t(n)}(t - t_n)} < 0.01$	Analytical solution Apply the principle of superposition to Jacob's approximation rates	Tedious process
Aron and Scott (1965)	-Confined -Transient Discharge rate decreases	- Same general assumptions as above - Discharge rate deceases with time sharpest decrease occurring soon after the start of pumping	Curve fitting and analytical solutions	Analogous to the Jacob Method
Hantush (1964)	- Confined - Transient	- Standard assumptions for confined aquifers - At the start of the tests, the water level in the free flowing well drops instantaneously. At t> 0 drawdown is constant and its discharge rate is variable	- Type curve analysis	
Hantush-DeGlee Method (Hantush, 1959b)	- Leaky aquifers - Transient - Fully penetrating well	- Standard assumptions for leaky aquifers (see leaky section) - L > 3D - At the start of the tests, the water level in the free flowing well drops instantaneously. At t >0 drawdown is constant and its discharge rate is variable	DeGlee's method using Hantush Equation	

* Methods described in Kruseman and de Ridder (1991).

R = distance of piezometer from pumping well, S = storativity, D = thickness of aquifer, K = hydraulic conductivity, $B_{u(n)}$ is a time function, and L = leakage factor

Table 4.11 Methods of analysis for pumping tests with special conditions.

CONDITION	*FLOW*	*AQUIFER TYPE*	*MODELS & SOURCES*[2]
One or more recharge boundaries	Steady State	Confined or Unconfined	Dietz (1943)
One or more straight recharge boundaries	Unsteady State	Confined or Unconfined	Stallman (in Ferris et al., 1962)
One recharge boundary	Unsteady State	Confined or Unconfined	Hantush (1959a)
Aquifer bounded by two fully penetrating boundaries	Unsteady State	Leaky or Confined	Vandenberg (1976 and 1977)
Wedge shaped aquifer	Unsteady State	Confined	Hantush (1962)
Water table slopes	Steady State	Unconfined	Culmination Point Method (Huisman, 1972)
	Unsteady State	Unconfined	Hantush (1964)
Two layered aquifer, unrestricted cross flow Pumping well does not penetrate entire thickness	Unsteady State	Confined	Javandel-Witherspoon (1983)
Leaky two-layered aquifer, separated by aquitard with cross-flow across aquitard	Steady State	Leaky	Bruggeman (1966)
Large diameter well	Unsteady State	Confined	Papadopulos (1967), Papadopulos and Cooper (1967)
Large diameter well	Unsteady State	Unconfined	Boulton and Streltsova, (1976)

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[2] Methods are described in Kruseman and de Ridder, 1991.

Table 4.12 Recovery test methods (discussed in Kruseman and de Ridder, 1991).

METHOD	*APPLICATION*	*SOURCE*
Theis Recovery Methods	C Confined C Unsteady state C Recovery after constant discharge	C Theis (1935)
	C Leaky C Unsteady state C Recovery after constant discharge	C Vandenberg (1975) C Hantush (1964)
	C Unconfined C Recovery after constant discharge C Late recovery data	C Neuman (1975)
	C Unconfined C Recovery after constant drawdown	C Rushton and Rathod (1980)
Birsoy and Summers	C Unconfined C Recovery after variable discharge	C Birsoy and Summers (1980)

PRESENTATION OF DATA

The specifics of an in-situ test should be described in a report to demonstrate that the test was conducted properly and that the data and interpretations are representative of site conditions. Work plans should be submitted prior to conducting tests to ensure that the results will be relevant to regulatory and program goals.

SINGLE WELL TESTS

At a minimum, the following should be specified in a workplan for a single well or slug test:

- Preliminary evaluation of hydraulic conductivity (i.e., data used to plan the test).
- Design or proposed design of the well (e.g., depth and length of screen and filter pack).
- Proposed amount and method to displace the water, such as:
    -Dimension and weight of slug.
    -Composition of slug.
    -Manner in which the slug will be lowered and raised from the well.
    -Use of packers, and manner in which pressure will be delivered to packed-off zone.
    -Chemical quality of water to be added.
- Proposed frequency of water level measurements.
- Proposed number and location of tests.
- Proposed method of analysis.

To provide adequate documentation that the test was conducted and interpreted correctly, the following should be provided in a report:

- The design and implementation of the test (workplan content items as specified above).
- All raw data (including type curves, if used).
- Sample calculations.
- Any field conditions or problems noted during the test that may influence the results.
- An evaluation and interpretation of the data (relating it to overall site conditions).

MULTIPLE WELL PUMPING TESTS

At a minimum, the following should be provided in a workplan for a conventional multiple well pumping test:

- Preliminary evaluation of hydrogeologic conditions, including all data used to plan and design the test.

- Proposed test and rationale for design, including but not limited to:

    - Geologic zone into which the pumping well is completed (i.e. areal extent, thickness, lateral and vertical extent).

    - Pumping well construction (justification should be provided if the well screen is partially penetrating).

    - Duration of pumping.

    - Rate of pumping and method for determination.

    - Location of all proposed observation wells.

    - Geologic zone(s) to be monitored (including depths, thickness, spatial relationship to the pumped zone).

    - Observation well construction.

    - Method of water level measurements (for each well).

    - Methods for gathering data used to correct drawdown and establishment of existing trends in water levels.

    - Method of data analysis.

    - Procedures for the discharge of pumped water.

After completion of a pumping test, the following should be included in a report to document that the test was conducted and interpreted correctly:

- Specific design of the test (workplan content items as specified above), including modifications from the planned configuration and rationale for any deviations.
- Date and time pumping began and ended.
- Raw data, including water level measurements, time of measurement in minutes after pumping started or ended, drawdown, pumping rates, etc. All data should be expressed in consistent units.
- Data plots and type curves, if used. All graphs and data plots should be labeled clearly.
- Calculations.
- Comments noting any external events (e.g., change in weather patterns, passage of train or heavy machinery).
- Data plots, graphs, and equations used to determine drawdown corrections.
- Data analysis method, including assumptions, limitations and references.
- Interpretation of the data using both results of the test and other available hydrogeologic information.

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