♦EPA Ground Water Issue

Suggested Operating Procedures for Aquifer Pumping Tests

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The Regional Superfund Ground Water Forum is a group of ground-water scientists, representing EPA's Regional Superfund Offices, organized to exchange up-to-date information related to ground water remediation at Superfund sites.

A very important aspect of ground water remediation is the capability to determine accurate estimates of aquifer hydraulic characteristics. This document was developed to provide an overview of all the elements of an aquifer test to assist RPMs and OSCs in the initial design of such tests or in the review of tests performed by other groups.

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INTRODUCTION

In recent years, there has been an increased interest in ground water resources throughout the United States. This interest has resulted from a combination of an increase in ground water development for public and domestic use; an increase in mining, agricultural, and industrial activities which might impact ground water quality; and an increase in studies of already contaminated aquifers. Decision-making agencies involved in these ground water activities require studies of the aquifers to develop reliable information on the hydrologic properties and behavior of aquifers and aquitards.

The most reliable type of aquifer test usually conducted is a pumping test. In addition, some site studies involve the use of short term slug tests to obtain estimates of hydraulic conductivity, usually for a specific zone or very limited portion of the aquifer. It should be emphasized that slug tests provide

very limited information on the hydraulic properties of the aquifer and often produce estimates which are only accurate within an order of magnitude. Many experts believe that slug tests are much too heavily relied upon in site characterization and contamination studies. This group of professionals recommends use of slug testing during the initial site studies to assist in developing a site conceptual model and in pumping test design.

This document is intended as a primer, describing the process for the design and performance of an "aquifer test" (how to obtain reliable data from a pumping test) to obtain accurate estimates of aquifer parameters. It is intended for use by those professionals involved in characterizing sites which require corrective action as well as those which are proposed for ground water development, agricultural development, industrial development, or disposal activities. The goal of the document is to provide the reader with a complete picture of all of the elements of aquifer (pumping) test design and performance and an understanding of how those elements can affect the quality of the final data.

The determination of accurate estimates of aquifer hydraulic characteristics is dependent on the availability of reliable data from an aquifer test. This document outlines the planning, equipment, and test procedures for designing and conducting an accurate aquifer test. The design and operation of a slug test is not included in this document, although slug tests are often run prior to the design and implementation of an aquifer test. The slug test information can be very useful in developing the aquifer test design (see ASTM D-18

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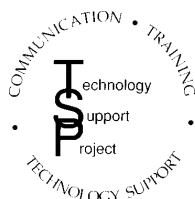
Committee, D4050 and D4104). If an accurate conceptual model of the site is developed and the proper equipment, wells, and procedures are selected during the design phase, the resulting data should be reliable. The aquifer estimates obtained from analyzing the data will, of course, depend on the method of analysis.

This document is not intended to be an overview of aquifer test analysis. The analysis and evaluation of pumping test data is adequately covered by numerous texts on the subject (Dawson and Istok, 1991; Kruseman and de Ridder, 1991; Walton, 1962; and Ferris, Knowles, Brown, and Stallman, 1962). It should be emphasized, however, that information on the methods for analyzing test data should be reviewed in detail during the planning phase. This is especially important for determining the number, location, and construction details for all wells involved in the test.

A simple "pump" (specific capacity) test involves the pumping of a single well with no associated observation wells. The purpose of a pump test is to obtain information on well yield, observed drawdown, pump efficiency, and calculated specific capacity. The information is used mainly for developing the final design of the pump facility and water delivery system. The pump test usually has a duration of 2 to 12 hours with periodic water level and discharge measurements. The pump is generally allowed to run at maximum capacity with little or no attempt to maintain constant discharge. Discharge variations are often as high as 50 percent. Short-term pump tests with poor control of discharge are not suitable for estimating parameters needed for adequate aquifer characterization. If the pump test is, however, run in such a way that the discharge rate varies less than 5 percent and water levels are measured frequently, the test data can also be used to obtain some reliable estimates of aquifer performance. It should be emphasized that an estimate of aquifer transmissivity obtained in this manner will not be as accurate as that obtained using an aquifer test including observation wells.

By controlling the discharge variation and pumping for a sufficient duration, it is possible to obtain reliable estimates of transmissivity using water level data obtained during the pump test. However, this method does not provide information on boundaries, storativity, leaky aquifers, and other information needed to adequately characterize the hydrology of an aquifer. For the purpose of this document, an aquifer test is defined as a controlled field experiment using a discharging (control) well and at least one observation well.

The aquifer test is accomplished by applying a known stress to an aquifer of known or assumed dimensions and observing the water level response over time. Hydraulic characteristics which can be estimated, if the test is designed and implemented properly, include the coefficient of storage, specific yield, transmissivity, vertical and horizontal permeability, and confining layer leakage. Depending on the location of observation wells, it may be possible to determine the location of aquifer boundaries. If measurements are made on nearby springs, it may also be possible to determine the impact of pumping on surface-water features.

TEST DESIGN

Adequate attention to the planning and design phase of the

aquifer pumping test will assure that the effort and expense of conducting a test will produce useful results. Individuals involved in designing an aquifer test should review the relevant ASTM Standards relating to: 1) appropriate field procedures for determining aquifer hydraulic properties (D4050 and D4106); 2) selection of aquifer test method (D4043); and 3) design and installation of ground water monitoring wells (D5092). The relevant portions of these standards should be incorporated into the design.

All available information regarding the aquifer and the site should be collected and reviewed at the commencement of the test design phase. This information will provide the basis for development of a conceptual model of the site and for selecting the final design. It is important that the geometry of the site, location and depth of observation wells and piezometers, and the pumping period agree with the mathematical model to be used in the analysis of the data. A test should be designed for the most important parameters to be determined, and other parameters may have to be de-emphasized.

Aquifer Data Needs

The initial element of the test design, formulating a conceptual model of the site, involves the collection and analysis of existing data regarding the aquifer and related geologic and hydrologic units. All available information on the aquifer itself, such as saturated thickness, locations of aquifer boundaries, locations of springs, information on all on-site and all nearby wells (construction, well logs, pumping schedules, etc.), estimates of regional transmissivities, and other pertinent data, should be collected. Detailed information relating to the geology and hydrology is needed to formulate the conceptual model and to determine which mathematical model should be utilized to estimate the most important parameters. It is also important to review various methods for the analyses and evaluation of pumping test data (Ferris, Knowles, Brown, and Stallman, 1962; Kruseman and De Ridder, 1991; and Walton, 1962 and 1970). Information relating to the various analytical methods and associated data needs will assist the hydrologist in reviewing the existing data, identifying gaps in information, and formulating a program for filling any gaps that exist.

The conceptual model of the site should be prepared after carrying out a detailed site visit and an evaluation of the assembled information. The review of available records should include files available from the U. S. Geological Survey, appropriate state agencies, and information from local drillers with experience in the area. Formulation of a conceptual model should include a brief analysis of how the local hydrology/geology fits into the regional hydrogeologic setting.

Aquifer Location

The depth to, thickness of, areal extent of, and lithology of the aquifer to be tested should be delineated, if possible.

Aquifer Boundaries

Nearby aquifer discontinuities caused by changes in lithology or by incised streams and lakes should be mapped. All known and suspected boundaries should be mapped such that

observation wells can be placed (chosen) where they will provide the best opportunity to measure the aquifer's response to the pumping and the boundary effects during the pumping test.

<u>Hydraulic Properties</u>

Estimates of all pertinent hydraulic properties of the aquifers and pertinent geologic units must be made by any means feasible. Estimates of transmissivity and the storage coefficient should be made, and if leaky confining beds are detected, leakage coefficients should be estimated. The estimation of transmissivity and the storage coefficient should be carried out by making a close examination of existing well logs and core data in the area or by gathering information from nearby aquifer tests, slug tests, or drill stem tests conducted on the aquifer(s) in question. It may also be feasible to run a slug test on the wells near the site to get preliminary values. (See ASTM Committee D-18 Standards D4044 and D4104). It should be noted that some investigators have found that slug tests often produce results which are as much as an order of magnitude low. Although some investigators have reported results which are two orders of magnitude high because the sand pack dominated the test. Such tests will, however, provide a starting point for the design. If no core analyses are available, the well log review should form a basis for utilizing an available table which correlates the type of aquifer material with the hydraulic conductivity. If detailed sample results from drill holes are available and they have grain size analyses, there are empirical formulas for estimation of transmissivity. Estimation of storage coefficient is more difficult, but can be based on the expected porosity of the material or the expected confinement of the aquifer. It is recommended that a range of values be chosen to provide a worst case and best case scenario (Freeze and Cherry, 1979). Trial calculations of well drawdown using these estimated values should be made to finalize the design, location, and operation of test and observation wells (Ferris and others, 1962; Campbell and Lehr, 1972; and Stallman, 1971).

If local perched aquifers are of a significant size and location to impact the pump test, this impact should be estimated if possible. The final test design should include adequate monitoring of any perched aquifers and leaky confining beds. This might involve the placing of piezometers into and/or above the leaky confining zone or into the perched aquifer.

Evaluation of Existing Well Information

Because the drilling of new production wells and observation wells expressly for an aquifer test can be expensive, it is advisable to use existing wells for conducting an aquifer test when possible. However, many existing wells are not suitable for aquifer testing. They may be unsuitably constructed (such as a well which is not completed in the same aquifer zone as the pumping well) or may be inappropriately located. It is also important to note that well logs and well completion data for existing facilities are not always reliable. Existing data should be verified whenever possible. The design of each well, whether existing or to be drilled, must be carefully considered to determine if it will meet the needs of the proposed test plan and analytical methods. Special attention must be paid to well location, the depth and interval of the well screen or perforation, and the present condition of existing perforations.

After the process of developing the site model and determining which analytical methods should be used, it is possible to move to the final design stage. The final stage of the design involves development of the key elements of the aquifer test: 1) number and location of observation wells; 2) design of observation wells; 3) approximate duration of the test; and 4) discharge rate.

Design of Pumping Facility

There are seven principal elements to be considered during the pumping facility design phase: 1) well construction; 2) the well development procedure; 3) well access for water level measurements; 4) a reliable power source; 5) the type of pump; 6) the discharge-control and measurement equipment; and 7) the method of water disposal. These elements are discussed in the following sections.

<u>Well Construction</u>

The diameter, depth and position of all intervals open to the aquifer in the pumping well should be known, as should total depth. The diameter must be large enough to accommodate a test pump and allow for water level measurements. All openings to the aquifer(s) must be known <u>and only those openings located in the aquifer to be tested should be open to the well during the testing</u>. If the pumping well has to be drilled, the type, size, and number of perforations should be established using data from existing well logs and from the information obtained during the drilling of the new well itself. The screen or perforated interval should be designed to have sufficient open area to minimize well losses caused by fluid entry into the well (Campbell and Lehr, 1972; and Driscoll, 1986).

A well into an unconsolidated aquifer should be completed with a filter pack in the annular space between the well screen and the aquifer material. To design an adequate filter pack, it is essential that the grain size makeup of the aquifer be defined. This is generally done by running a sieve analysis of the major lithologic units making up the aquifer. The sizing of the filter pack will depend on the grain size distribution of the aquifer material. The well screen size would be established by the sizing of the chosen filter pack (Driscoll,1986). The filter pack should extend at least one (1) foot above the top of the well screen. A seal of bentonite pellets should be placed on top of the filter pack. A minimum of three (3) feet of pellets should be used. An annulus seal of cement and/or bentonite grout should be placed on top of the bentonite pellets. The well casing should be protected at the surface with a concrete pad around the well to isolate the wellbore from surface runoff (ASTM Committee D-18, D5092; and Barcelona, Gibb, and Miller, 1983).

<u>Well Development</u>

Information on how the pumping well was constructed and developed should be collected during the review of existing site information. It may be necessary to interview the driller. If the well has not been adequately developed, the data collected from the well may not be representative of the aquifer. For instance, the efficiency of the well may be reduced, thereby causing increased drawdown in the pumping well. When a well is pumped, there are two components of

drawdown: 1) the head losses in the aquifer; and 2) the head losses associated with entry into the well. A well which is poorly constructed or has a plugged well screen will have a high head loss associated with entry into the well. These losses will affect the accuracy of the estimates of aquifer hydraulic parameters made using data from that well. If the well is suspected to have been poorly developed, or nothing is known, it is advisable to run a step drawdown test on the well to determine the extent of the problem. The step drawdown test entails conducting three or more steps of increasing discharge, producing drawdown curves such as shown in Figure 1. The data provided by the step drawdown test (multiple discharge test) can be analyzed using various techniques (Rorabough, 1953; and Driscoll, 1986) to obtain an estimate of well entry losses. If a determination is made that plugging results in significant losses, the well should be redeveloped prior to the pumping test using a surge block and/ or a pump until the well discharge is clear: i. e. the development results in the well achieving acceptable turbidity unit limits (Driscoll, 1986). In many cases, running a step drawdown test to determine well efficiency after the well has been surged is needed to assess the results of the development process. The results of the post development test should be compared with the step-drawdown test run prior to development. This analysis will provide a means of verifying the success of the well development.
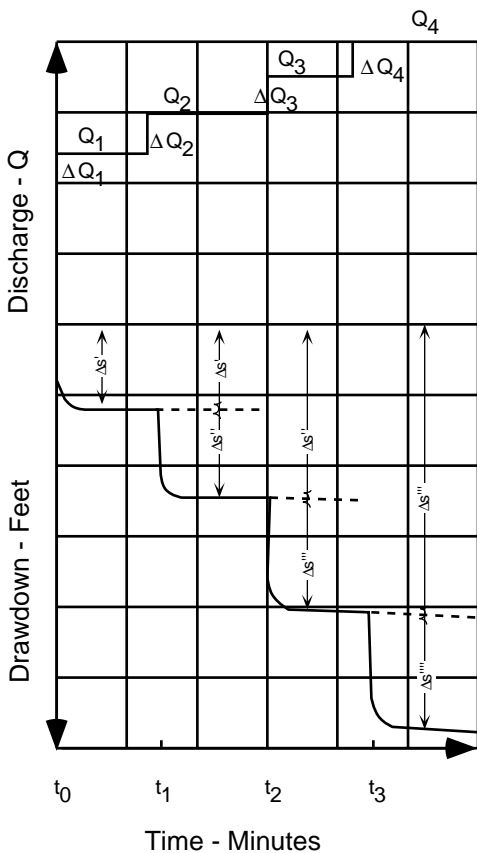

Figure 1. Variation of discharge and drawdown in multiple discharge tests (step drawdown tests).

Water Level Measurement Access

It must be possible to measure depth to the water level in the pumping well before, during, and after pumping. The quickest and generally the most accurate means of measuring the water levels in the pumped well during an aquifer test is to use an electric sounder or pressure transducer system. The transducer system may be expensive and may be difficult to install in an existing well. It may be possible to run a 1/4 inch copper line into the well as an air line. If the control well is newly constructed, the continuous copper line should be strapped to the pump column as it is being installed. If it is correctly installed, an air line can be used with somewhat less accuracy than an electric sounder or steel tape. An air line with a bubbler and either a transducer or precision pressure gage should be adequate for running an aquifer test.

With adequate temperature compensation, a surface mounted pressure transducer is as precise as one that is submerged. Steel tapes cannot always be used quickly enough in a pumping well, except in wells with a small depth to water (less than 100 feet) where the pump test crew has a fair amount of experience and the well is modified for access of the steel tape. Such modification often involves hanging a 3/4 inch pipe in the well as access for the steel tape. The pipe should be capped at the bottom with numerous 1/16 to 1/8 inch holes drilled in the pipe and cap (especially needed for wells subject to cascading water or surging). This will dampen water-level surging caused by the pump and will eliminate the problems caused by cascading water. In general, the use of a steel tape is usually confined to the later stages of the pump test where rapid changes in water levels are not occurring.

In cases where the pump is isolated by a packer to allow production from a particular zone, a transducer system should be used to monitor pumping hydraulic heads. It is important, however, to calibrate the transducers before and after the test. In addition, reference checks with an electric sounder or steel tape should be made before, during, and after the test. The ASTM Standard Test Method for determining subsurface liquid levels in a borehole or monitoring well (D4750) should be reviewed as part of the design process.

Reliable Power Source

Having power continuously available to the pump, for the duration of the test, is crucial to the success of the test. If power is interrupted during the test, it may be necessary to terminate the test and allow for sufficient recovery so that pre-pumping water-level trends can be extrapolated. At that point, a new test would be run. If, however, brief interruptions in power occur late in the test, the affect of the interruption can be eliminated by pumping at a calculated higher rate for some period so that the average rate remains unchanged. The increased rate must be calculated such that the final portion of the test compensates for the pumpage that would have occurred during the interruption of pumping.

Pump Selection

A reliable pump is a necessity during an aquifer test. The pump should be operated continuously during the test. Should a pump fail during the pumping period of the test, the time, effort, and expense of conducting the test could be

wasted. Electrically powered pumps produce the most constant discharge and are often recommended for use during an aquifer test. However, in irrigation areas, line loads can fluctuate greatly, causing variations in the pumping rate of electric motors. Furthermore, electric motors are nearly constant-load devices, so that as the lift increases (water level declines), the pumping rate decreases. This is a particular problem for inefficient wells or low transmissivity aquifers.

The discharge of engine-powered (usually gasoline or diesel) pumps may vary greatly over a 24 hour period, requiring more frequent monitoring of the discharge rate during the test. For example, under extreme conditions a diesel-powered turbine pump may have more than a 10 percent change in discharge as a result of the daily variation in temperature. The change in air temperature affects the combustion ratio of the engine resulting in a variation in engine revolutions per minute (rpm). The greater the daily temperature range,the greater the range in engine rpm. Variations in barometric pressure may also affect the engine operation and resulting rpm. Running the engine at full throttle will reduce operational flexibility for adjusting engine rpm and the resulting discharge. In areas where outside temperatures are extreme, such as the desert or a very cold region, it may be advisable to undertake measures to prevent the engine from overheating or freezing.

In order to obtain good data during the period of recovery at the end of pumping, it is necessary to have a check valve installed at the base of the pump column pipe in the discharging well. This will prevent the back flow of water from the column pipe into the well when the pumping portion of the test is terminated and the recovery begins. Any back flow into the well will interfere with or totally mask the water level recovery of the aquifer and this would make any aquifer analysis based on recovery data useless or, at best, questionable (Schafer, 1978).

Discharge-Control and Measurement Equipment

The well bore and discharge lines should be accessible for installing discharge control and monitoring equipment. When considering an existing well for the test well to be pumped (control well), the well must either already be equipped with discharge measuring and regulating equipment, or the well must have been constructed such that the necessary equipment can be added.

Control of the pumping rate during the test requires an accurate means for measuring the discharge of the pump and a convenient means of adjusting the rate to keep it as nearly constant as possible. Common methods of measuring well discharge include the use of an orifice plate and manometer, an inline flow meter, an inline calibrated pitot tube, a calibrated weir or flume, or, for low discharge rates, observing the length of time taken for the discharging water to fill a container of known volume (e.g. 5 gallon bucket; 55 gallon drum).

In addition to the potentially large variation in discharge associated with the pump motor or engine, the discharge rate is also related to the drop in water level near the pumping well during the aquifer test. As the pumping lift increases, the rate of discharge at a given level of power (such as engine rpm) will decrease. The pump should not be operated at its maximum rate. As a general rule, the pumping unit, including the engine, should be designed so that the maximum pumping

rate is at least 20 percent more than the estimated long term sustainable yield of the aquifer. The long term yield of the aquifer should be determined by collecting data on pumping rates in nearby wells. If possible, a short term test of one to two hours should be run when the pump is installed. This test data should be compared to the historic data as part of the estimation process.

The pumping rate can be controlled by placing valves on the discharge line and/or by placing controls on the pump power source. A valve installed in the discharge line to create back pressure provides effective control of the discharge rate while conducting an aquifer test, especially when using an electric-powered pump. A rheostatic control on the electric pump will also allow accurate control of the discharge rate. When an engine-powered pump is being utilized, installation of a micrometer throttle adjustment device to accurately control engine rpm is recommended in addition to a valve in the line.

Water Disposal

Discharging water immediately adjacent to the pumping well can cause problems with the aquifer test, especially in tests of permeable unconfined alluvial aquifers. The water becomes a source of recharge which will affect the results of the test. <u>It is essential that the volumes of produced water, the storage needs, the disposal alternatives, and the treatment needs be assessed early in the planning process</u>. The produced water from the test well must be transported away from the control well and observation wells so it cannot return to the aquifer during the test. This may necessitate the laying of a temporary pipeline (sprinkler irrigation line is often used) to convey the discharge water a sufficient distance from the test site. In some cases, it may be necessary to have on-site storage, such as steel storage tanks or lined ponds. This is especially critical when testing contaminated zones where water treatment capacity is not available. The test designer should carefully review applicable requirements of the RCRA hazardous waste program, the underground injection control program, and the surface water discharge program prior to making decisions about this phase of the design. It may be necessary to obtain permits for on-site storage and final disposal of the contaminated fluids. Final disposal could involve treatment and reinjection into the source aquifer or appropriate treatment and discharge.

Design of Observation Well(s)

Verification of well response

As part of the process of selecting the location of the observation wells needed for the chosen aquifer test design, existing wells should be tested for their suitability as observation wells. The existing information regarding well construction should be reviewed as a screening mechanism for identifying suitable candidates. The wells that are identified as potential observation wells should be field tested to verify that they are suitable for monitoring aquifer response. The perforations or well screens of abandoned wells tend to become restricted by the buildup of iron compounds, carbonate compounds, sulfate compounds or bacterial growth as a result of not pumping the well. Consequently, the response test is one of the most important pre-pumping examinations to be made if such wells are to be used for observation (Stallman, 1971; and Black and Kip, 1977). The

reaction of all wells to changing water levels should be tested by injecting or removing a known volume of water into each well and measuring the subsequent change of water level. Any wells which appear to have poor response should be either redeveloped, replaced, or dropped from consideration in favor of another available well selected.

Total Depth

In general, observation wells should penetrate the tested aquifer to the same stratigraphic horizon as the well screen or perforated interval of the pumping well. This will require close evaluation of logs to adjust for dipping formations. This assumes the observation well is to be used for monitoring response in the same aquifer from which the discharging well is pumping. Actual screen design will depend on aquifer geometry and site specific lithology. If the aquifer test is designed to detect hydraulic connection between aquifers, one observation well should be screened in the strata for which hydraulic inter-connection is suspected. Depending on how much information is needed, additional wells screened in other strata may be needed (Bredehoeft and others, 1983; Walton, 1970; Dawson and Istok, 1991; and Hamlin, 1983).

Well Diameter

In general, observation well casing should have a diameter just large enough to allow for accurate, rapid water level measurements. A two-inch well casing is usually adequate for use as an observation well in shallow aquifers which are less than 100 feet in depth. They are, however, often difficult to develop. A four- to six-inch diameter well will withstand a more vigorous development process, and should have better aquifer response when properly developed. Additionally, a four or six inch diameter well may be required if a water-depth recorder is planned, depending on the type of recording equipment to be used. The difficulties in drilling a straight hole usually dictate that a well over 200 feet deep be at least four inches in diameter.

Well Construction

Ideally, the observation well(s) should have five to twenty feet of perforated casing or well screen near the bottom of the well. The final well screened interval(s) will depend on the nature of geologic conditions at the site and the types of parameters to be estimated. Any openings which allow water to enter the well from aquifers which are not to be tested should be sealed or closed off for the duration of the test. Ideally, the annular space between the casing and the hole wall should be gravel packed adjacent to the perforated interval to be tested. The use of a filter pack in wells with more than one screened interval will, however, create a problem. There is no reliable method for sealing the annular space of any unwanted filter packed interval even though the screen can be isolated. The size of the filter material should be based on the grain size distribution of the zone to be screened (preferably based on a sieve analysis of the material). The screen size should be determined based on the filter pack design (Driscoll, 1986). The space above the gravel should be sealed with a sufficient amount of bentonite or other grout to isolate the gravel pack from vertical flow from above. If the bentonite does not extend to the surface, it will be necessary to put a cement seal on top of the bentonite prior to back filling the remaining annular space. A concrete pad should be placed around the well to prevent surface fluids from entering the annular material. After installation is finished, the observation well should be developed by surging with a block, and/or submersible pump (Campbell and Lehr, 1972; and Driscoll, 1986) for a sufficient period (usually several hours) to meet a pre-determined level of turbidity.

Radial Distance and Location Relative to the Pumped Well

If only one observation well is to be used, it is usually located 50 to 300 feet from the pumped well. However, each test situation should be evaluated individually, because certain hydraulic conditions may exist which warrant the use of a closer or more distant observation well. If the test design requires multiple observation wells, the wells are often placed in a straight line or along rays that are perpendicular from the pumping well. In the case of multiple boundaries or leaky aquifers, the observation wells need to be located in a manner which will identify the location and effect of the boundaries. If the location of the boundary is suspected before the test, it is desirable to locate most of the wells along a line parallel to the boundary and running through the pumping well, as shown in Figure 2. If aquifer anisotropy is expected, the observation wells should be located in a pattern based on the suspected or known anisotropic conditions at the site (Bentall and others, 1963; Ferris and others, 1962; Walton, 1962 and 1970; and Dawson and Istok, 1991). If the principal directions of anisotropy are known, drawdown data from two wells located on different rays from the pumping well will be sufficient. If the principal directions of anisotropy are not known, at least three wells on different rays are needed.

FIELD PROCEDURES

Well thought out field procedures and accurate monitoring equipment are the key to a successful aquifer test. The following three sections provide an overview of the methods and equipment for establishing a pre-test baseline condition and running the test itself.

Necessary Equipment for Data Collection

During an aquifer test, equipment is needed to measure/ record water levels, well discharges, and the time since the beginning of the test, and to record accumulated data. Appendix One contains a detailed description of the types of equipment commonly used during an aquifer test. Appendix Two is an example form for recording test data.

Establish Baseline Trend

Collecting data on pre-test water levels is essential if the analysis of the test data is to be completely successful. The baseline data provides a basis for correcting the test data to account for on-going regional water level changes. Although the wells on-site are the main target for baseline measurements, it is important to measure key wells adjacent to the site and to account for off-site pumping which may affect the test results.

Baseline water levels

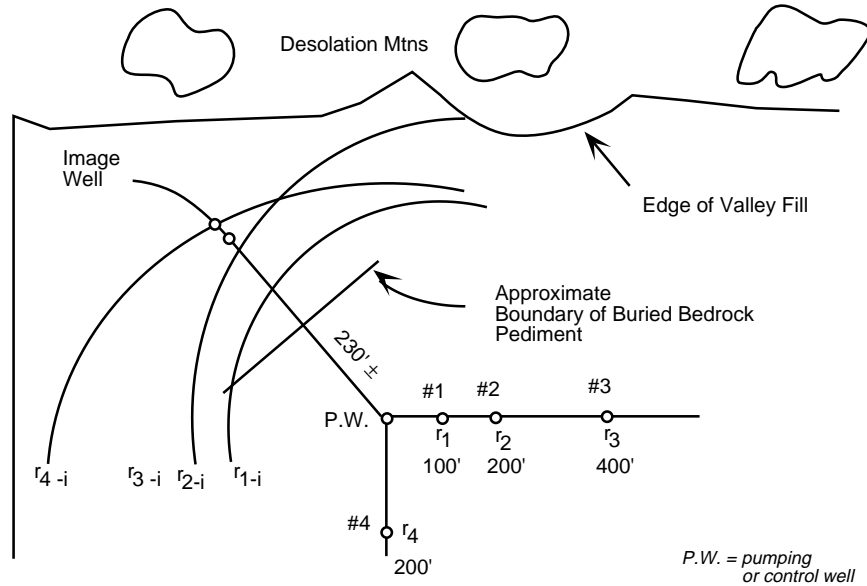Prior to beginning the test, it will be necessary to establish a

Figure 2.   Observation well/pumping well location to determine buried impermeable boundary.

baseline trend in the water levels in the pumping and all observation wells. As a general rule, the period of observation before the start of the test (t_0), should be at least one week. Baseline measurements must be made for a period which is sufficient to establish the pre-pumping water level trends on site (see Figure 3). The baseline data must be sufficient to explain any differences between individual observation wells. As shown in Figure 3, the water levels in on-site wells were declining prior to the test. The drawdown during the test must be corrected to account for the pre-pumping trend.

Nearby pumping activities

During the baseline measurements, the on-off times should be recorded for any nearby wells in use. The well discharge rates should be noted as should any observed changes in the proposed on-site control well and observation wells. Baseline water level measurements should be made in all off-site wells within the anticipated area of influence. As shown in Figure 3, the baseline period should be sufficient to establish the pretest pumping trends and to explain any differences in trends between individual off-site wells.

Significant effects due to nearby pumping wells can often be removed from the test data if the on-off times of the wells are monitored before and during the test. Interference effects may not, however, always be observable. In any case, changes associated with nearby pumping wells will make analysis more difficult. If possible, the cooperation of nearby well owners should be obtained to either cease pumping prior to and during the test period or to control the discharge of these wells during the baseline and test period. The underlying principle is to minimize changes in regional effects during the baseline, test and recovery periods.

Barometric pressure changes

During the baseline trend observation period, it is desirable to

monitor and record the barometric pressure to a sensitivity of plus or minus 0.01 inches of mercury. The monitoring should continue throughout the test and for at least one day to a week after the completion of the recovery measurement period. This data, when combined with the water level trends measured during the baseline period, can be used to correct for the effects of barometric changes that may occur during the test (Clark, 1967).

Local activities which may affect test

Changes in depth to water level, observed during the test, may be due to several variables such as recharge, barometric response, or "noise" resulting from operation of nearby wells, or loading of the aquifer by trains or other surface disturbances (King, 1982). It is important to identify all major activities (especially cyclic activities) which may impact the test data. Enough measurements have to be made to fully characterize the pre-pumping trends of these activities. This may necessitate the installation of recording equipment. A summary of this information should be noted in the comments section of the pumping test data forms.

Test Procedures

Initial water level measurements

Immediately before pumping is to begin, static water levels in all test wells should be recorded. Measurements of drawdown in the pumping well can be simplified by taping a calibrated steel tape to the electric sounder wire. The zero point of the tape may be taped at the point representing static water level. This will enable the drawdown to be measured directly rather than by depth to water.

Measuring water levels during test

If drawdown is expected in the observation well(s) soon after

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Map of Aquifer Test Site

Change of Water Level in Well B
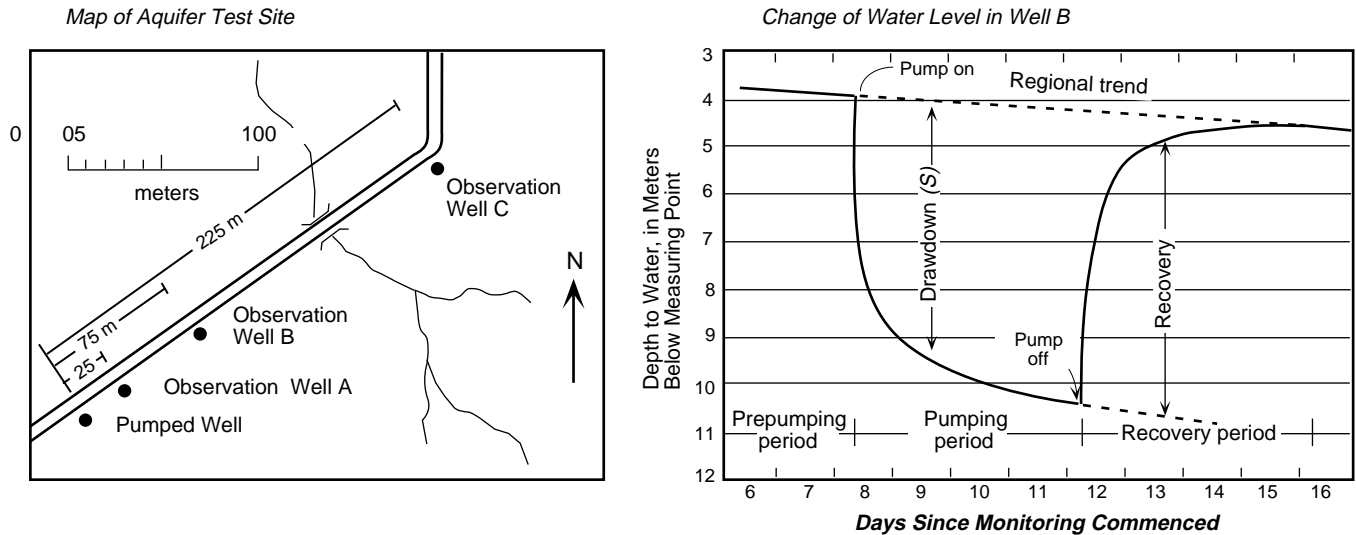
Figure 3. **Example test site showing baseline, pumping test, and recovery water level measurements in one of the wells.**

testing begins and continuous water level recorders are not installed, an observer should be stationed at each observation well to record water levels during the first two to three hours of testing. Subsequently, a single observer is usually able to record water levels in all wells because simultaneous measurements are unnecessary. If there are numerous observation wells, a pressure transducer/data-logging system should be considered to reduce manpower needs.

Time frame for measuring water levels

Table 1 shows the recommended maximum time intervals for recording water levels in the pumped well. NOTE: the times provided in Table 1 are only the maximum recommended time intervals--more frequent measurements may be taken if test conditions warrant. For instance, it is recommended that water level measurements be taken at least every 30 seconds for the first several minutes of the test (see ASTM Committee D-18, D 4050). Figure 4 is a hypothetical logarithmic plot of drawdown versus time for an observation well. This plot illustrates the need for the frequency of measurements given in Table 1. As shown on the plot, frequent measurements during early times are needed to define the drawdown curve. The data used in Figure 4 was collected with a downhole pressure transducer and electronic data recording equipment. Thus, water levels could be collected about every 6 seconds initially and less frequently as the test progresses. As time since pumping started increases, the logarithmic scale dictates that less frequent measurements are needed to adequately define the curve.

Measurements in the observation well(s) should occur often enough and soon enough after testing begins to avoid missing the initial drawdown values. Actual timing will depend on the aquifer and well conditions which vary from test area to test area. Estimates for timing should be made during the planning stages of aquifer testing using estimated aquifer parameters based on the conceptual model of the site.

Table 1. **Maximum Recommended Time Intervals for Aquifer Test Water Level Measurements***

0 to 3 minutes	every 30 seconds
3 to 15 minutes	every minute
15 to 60 minutes	every 5 minutes
60 to 120 minutes	every 10 minutes
120 min. to 10 hours	every 30 minutes
10 hours to 48 hours	every 4 hours
48 hours to shut down	every 24 hours

* Dr. John Harshbarger, personal communication, 1968.

Monitoring discharge rate

During the initial hour of the aquifer test, well discharge in the pumping well should be monitored and recorded as frequently as practical. Ideally, the pretest discharge will equal zero. If it does not, the discharge should be measured for the first time within a minute or two after the pump is started.

It is important when starting a test to bring the discharge up to the chosen rate as quickly as possible. How frequently the discharge needs to be measured and adjusted for a test depends on the pump, well, aquifer, and power characteristics. Output from electrically driven equipment requires less frequent adjustments than from all other pumping equipment. Engine-driven pumps generally require adjustments several times a day because of variation that occurs in the motor performance due to a number of factors, including air temperature effects. At a minimum, the discharge should be checked four times per day: 1) early
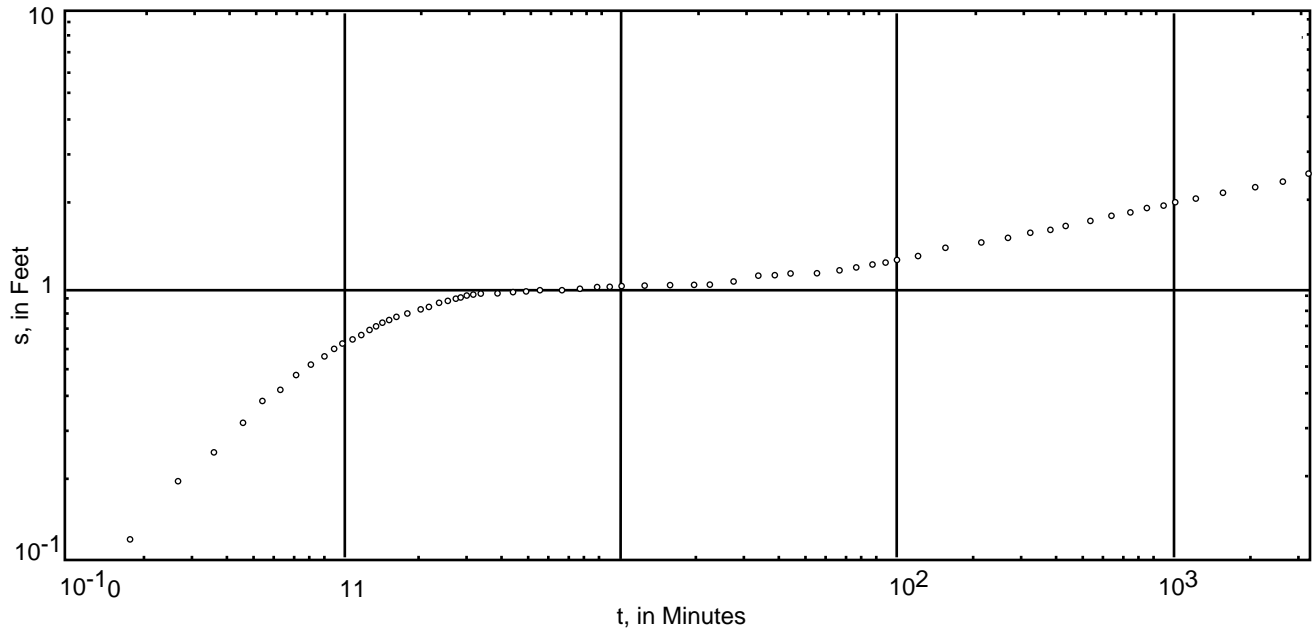
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Figure 4. Logarithmic plot of s vs t for observation well.

morning (2 AM); 2) mid-morning (10 AM); 3) mid-afternoon (3 PM); and 4) early evening (8 PM). <u>The discharge should never be allowed to vary more than plus or minus 5 percent</u> (Ferris, J. G., personal communication, 1/19/68). The lower the discharge rate, the more important it is to hold the variation to less than 5 percent. The variation of discharge rate has a large effect on permeability estimates calculated using data collected during a test. The importance of controlling the discharge rate can be demonstrated using a sensitivity analysis of pumping test data. An analysis of this type indicates that a 10 percent variation in discharge can result in a 100 percent variation in the estimate of aquifer transmissivity. Thus, short-term pumping tests with poor control of discharge are not suitable for estimating parameters needed for adequate site characterization. If, however, the pumping test is run in such a way that the discharge rate varies less than 5 percent and water levels are measured frequently, the short-term pumping test data can be used to obtain some reliable estimates of aquifer performance.

It should be emphasized, however, that some random, short-term variations in discharge may be acceptable, if the average discharge does not vary by more than plus or minus 5 percent. A systematic or monotonic change in discharge (usually, a decrease in discharge with increasing time) is, however, unacceptable.

Water level recovery

Recovery measurements should be made in the same manner as the drawdown measurements. After pumping is terminated, recovery measurements should be taken at the same frequency as the drawdown measurements listed above in Table 1.

Length of test

The amount of time the aquifer should be pumped depends on the objectives of the test, the type of aquifer, location of suspected boundaries, the degree of accuracy needed to establish the storage coefficient and transmissivity, and the rate of pumping. The test should continue until the data are adequate to define the shape of the type curve sufficiently so that the parameters required are defined. This may require pumping for a significant period after the rate of water level change becomes small (so called water level "stabilization"). This is especially the case when the locations of boundaries or the effects of delayed drainage are of interest. Their influence may occur a few hours after pumping starts (see Figure 3), or it may be days or weeks. Some aquifer tests may never achieve equilibrium, or exhibit boundary effects.

Although it is not necessary for the pumping to continue until equilibrium is approached, it is recommended that pumping be continued for as long as possible and at least for 24 hours. Recovery measurements should be made for a similar period or until the projected pre-pumping water level trend has been attained. The costs of running the pump a few extra hours are low compared with the total costs of the test, and the improvement in additional information gained could be the difference between a conclusive and an inconclusive aquifer test.

Water disposal

As discussed previously, the water being pumped must be disposed of legally within applicable local, State, and Federal

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rules and regulations. This is especially true if the ground water is contaminated or is of poor quality compared to that at the point of disposal. During the pumping test, the individuals carrying out the test should carry out water quality monitoring as required by the test plan and any necessary disposal permits. This monitoring should include periodic checks to assure that the water disposal procedures are following the test design and are not recharging the aquifer in a manner that would adversely affect the test results. The field notes for the test should document when and how monitoring was performed.

Recordkeeping

All data should be recorded on the forms prepared prior to testing (See Appendix 2). An accurate recording of the time, water level, and discharge measurements and comments during the test will prove valuable and necessary during the data analyses stage following the test.

Plotting data

During the test, a plot of drawdown versus time on semi-log paper should always be prepared and updated as new data is collected for each observation well. A plot of the data prepared during the actual test is essential for monitoring the status and effectiveness of the test. The plot of drawdown versus time will reveal the effects of boundaries or other hydraulic features if they are encountered during the test, and will indicate when enough data for a solution have been recorded. A semi-log or log-log mass plot of water level data from all observation wells should be prepared as time allows. Such a plot can be used to show when aquifer conditions are beginning to affect individual wells. More importantly, it enables the observer to identify erroneous data. This is especially important if transducers are being used for data collection. The utilization of a portable PC with a graphics package is an option for use in carrying out additional field manipulation of the data. It should not, however, be a substitute for a manual plot of the data.

Precautions

(a) Care should be taken for all observers to use the same measuring point on the top of the well casing for each well. If it is necessary to change the measuring point during the test, the time at which the point was changed should be noted and the new measuring point described in detail including the elevation of the new point.

(b) Regardless of the prescribed time interval, the actual time of measurement should be recorded for all measurements. It is recognized that the measurements will not be taken at the exact time intervals suggested.

(c) If measurements in observation well(s) are taken by several individuals during the early stages of testing, care should be taken to synchronize stop watches to assure that the time since pumping started is standardized.

(d) It is important to remember to start all stop watches at the time pumping is started (or stopped if performing a recovery test).

(e) Comments can be valuable in analyzing the data. It is important to note any problems, or situations which may alter the test data or the accuracy with which the observer is working.

(f) If several sounders are to be used, they should be compared before the start of the test to assure that constant readings can be made. If the sounder in use is changed, the change should be noted and the new sounder identified in the notes.

PUMPING TEST DATA REDUCTION AND PRESENTATION

All forms required for recording the test data should be prepared prior to the start of the test and should be attached to a clip board for ease of use in the field. It is an option to have a portable PC located on-site with appropriate spreadsheets and graphics package to allow for easier manipulation of the data during the test. The hard copy of the forms should be maintained for the files.

Tabular Data

All raw data in tabular form should be submitted along with the analysis and computations. The data should clearly indicate the well location(s), and date of test and type of test. All data corrections, for pre-pumping trends, barometric pressure fluctuations and other corrections should be given individually and clearly labeled. All graphs used for corrections should be referenced on the specific table. These graphs should be attached to the data package.

Graphs

All graphs or plots should be drafted carefully so that the individual points which reflect the measured data can be retrieved. Semi-logarithmic and logarithmic data plots (see Figures 5 and 6) should be on paper scaled appropriately for the anticipated length of the test and the anticipated drawdown. All X-Y coordinates shall be carefully labeled on each plot. All plots must include the well location, date of test, and an explanation of any points plotted or symbols used.

ANALYSIS OF TEST RESULTS

Data analysis involves using the raw field data to calculate estimated values of hydraulic properties. If the design and field-observation phases of the aquifer test are conducted successfully, data analyses should be routine and successful. The method(s) of analysis utilized will depend, of course, on particular aquifer conditions in the area (known or assumed) and the parameters to be estimated.

Calculations

All calculations and data analyses must accompany the final report. All calculations should clearly show the data used for input, the equations used and the results achieved. Any assumptions made as part of the analysis should be noted in the calculation section. This is especially important if the data were corrected to account for barometric pressure changes, off-site pumping changes, or other activities which have affected the test. The calculations should reference the appropriate tables and graphs used for a particular calculation.
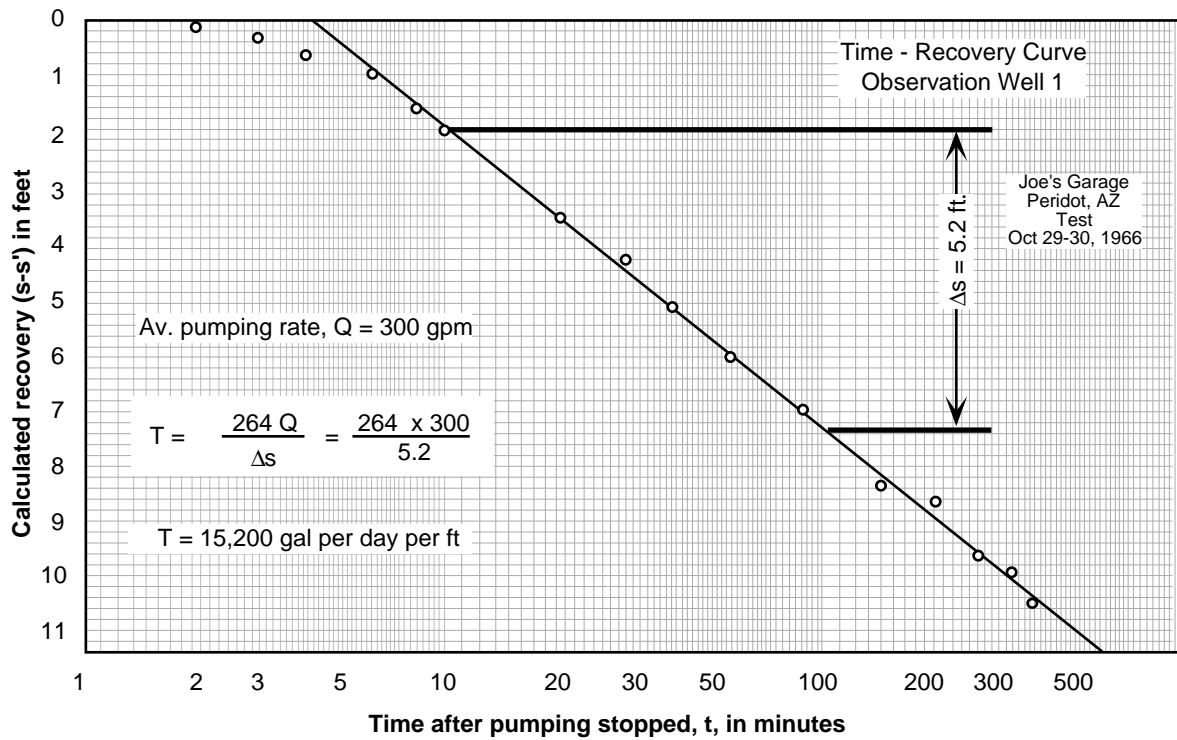
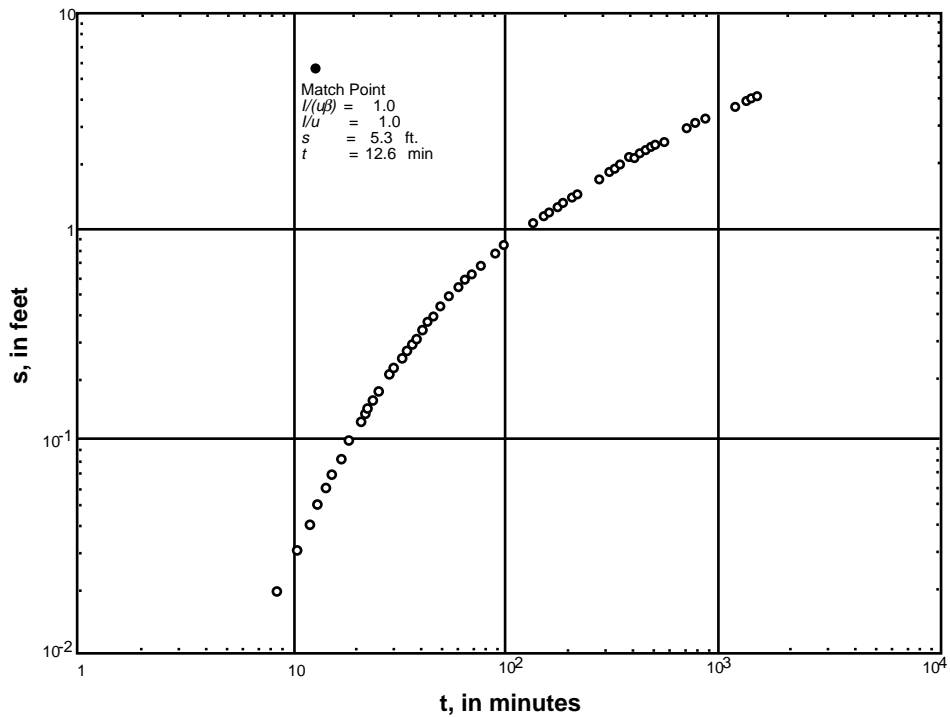**Figure 5. Time recovery curve for observation well - October 30, 1966.**

Figure 6. Logarithmic plot of s vs t for Observation Well 23S/25E-17Q$_2$ at Pixley, CA.

Aquifer Test Results

The results of an aquifer pumping and recovery test should be submitted in narrative format. The narrative report should include the raw data in tabular form, the plots of the data, the complete calculations and a summary of the results of the test. The assumptions made in utilizing a particular method of analysis should also be included.

SUMMARY-EXAMPLE FACILITY DESIGN

As a means of focusing the discussions presented in the preceding sections, the following example of an aquifer pumping test is described. The facility layout is shown in Figure 7. The site is located near a normally dry river channel which is subject to flood flows. The site was constructed for the purpose of carrying out experiments relating to artificial recharge of a shallow alluvial aquifer. The proposed methods of recharge involved use of a pit and a well.

The aquifer at the site is comprised of unconsolidated basin fill material, mainly silty sand and gravel with some clay lenses. The depth to water is generally greater than 50 feet and the river is a source of recharge when it flows. There are extensive gravel lenses above the water table which outcrop at the base of the river channel. These lenses occur beneath the site.

Figure 7 shows the locations of the various monitoring wells relative to the recharge facilities and the river. The well locations were selected to facilitate both characterization of the site and subsequent evaluation of the various recharge tests. The recharge well (used as the pumping well during the site aquifer tests) and the eight inch observation wells were completed to a depth of 150 feet in the upper water bearing unit of a basin fill aquifer. The depth to water in the area was about 75 feet. The recharge and observation wells were screened from about 80 feet to 140 feet. The 1-3/4 inch access tubes were 80-100 feet deep with a five-foot well screen on the bottom of each tube.

The eight-inch observation wells were placed in a line parallel to the river to assess both the effect of flood flows on the aquifer and the hydraulic characteristics of the recharge site itself. The 1-3/4 inch access tubes were positioned for monitoring ground-water movement near the top of the water table in response to aquifer recharge and discharge (pumping) tests. The two inch piezometers at varying depths were constructed to evaluate shallow ground-water movement in response to recharge.

Figure 8 is a plan view of the recharge facility showing the pumping/recharge well and the water distribution system. The pumping well was equipped with a downhole turbine pump powered by a methane driven, 6-cylinder engine. As indicated
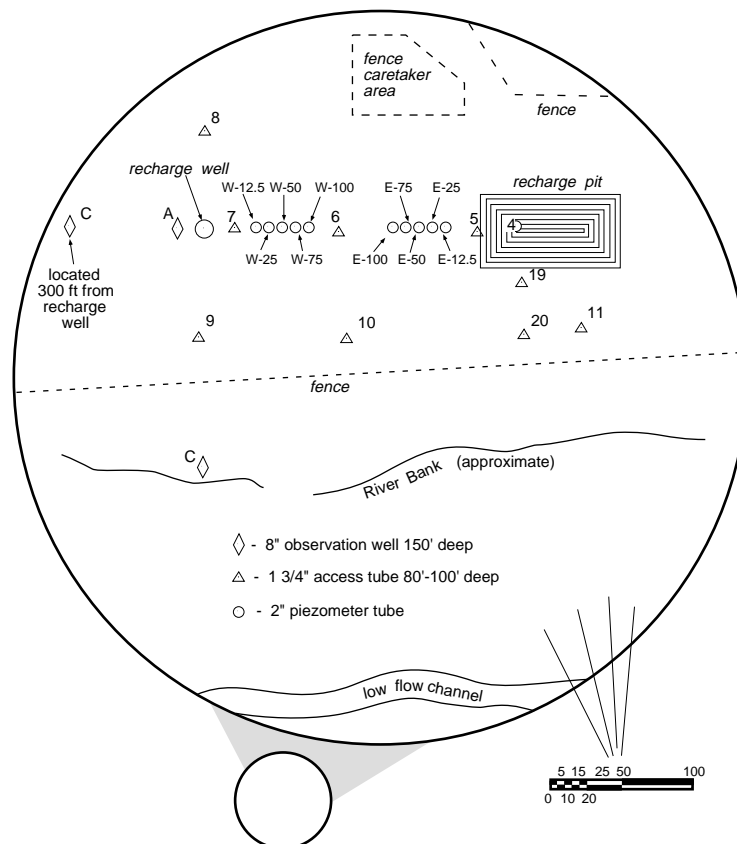

Figure 7. Recharge facility well layout.

on Figure 8, the pump discharge was measured using a Parshall flume (see Figure 9). The water from pumping tests was discharged off-site via the concrete box and distribution line. To prevent interference with test results from nearby recharge of the pumping test water, a temporary pipeline was constructed from irrigation pipe. This temporary line ran from the end of the river drain line to a point 1200 feet down stream out of the estimated area of influence. The ground water was not contaminated. Thus, special water quality monitoring was not required.

The pumping tests for site characterization involved the following monitoring procedure:

1. The eight-inch observation well closest to the recharge well (Well A) was equipped with a Stevens water stage recorder with an electric clock geared for a 4-hour chart cycle;

2. The other two eight-inch observation wells (Wells B and C) were equipped with Stevens water stage recorders with an electric clock geared for a 12-hour chart cycle;

3. The pumping well was equipped with a stilling well composed of a 3/4-inch pipe strapped to the pump column. The stilling well was drilled with 1/4-inch holes through the length. The stilling well was used for assessing the well for water level measurements with a 150-foot steel tape. The steel tape was marked in 0.01 ft. increments for the first 100 feet and in 0.1 ft. increments for the remaining 50 feet;

4. The 1-3/4 inch access wells were monitored at least once a day with a neutron moisture logger to assess changes in saturation as the water level declined in response to the test. This information was used to verify the water level declines in the regular monitoring wells and to aid in assessing the delayed drainage effects which were to be estimated using the water level response data from the eight-inch observation wells;

5. A continuous recording barograph was located in a standard construction, USDA weather station shed located between access Wells 9 and 10; and

6. The pump engine was equipped with an rpm gage to monitor pump performance and a micrometer adjustment on the throttle.

A step drawdown test and several short-term pumping tests were run at the site prior to running the principal aquifer characterization test.   The step drawdown test was used as a means of selecting the final pumping test design. The short term tests were used to obtain an initial picture of aquifer response.

The results of the step drawdown test run on the recharge well after development indicated that the well was suitable for use as a test well. The results of the step test were also used to estimate well efficiency at different rates. Table 2 gives the efficiencies for three (3) discharge rates. As indicated, the well efficiency was greater than 90% for a rate of about 200
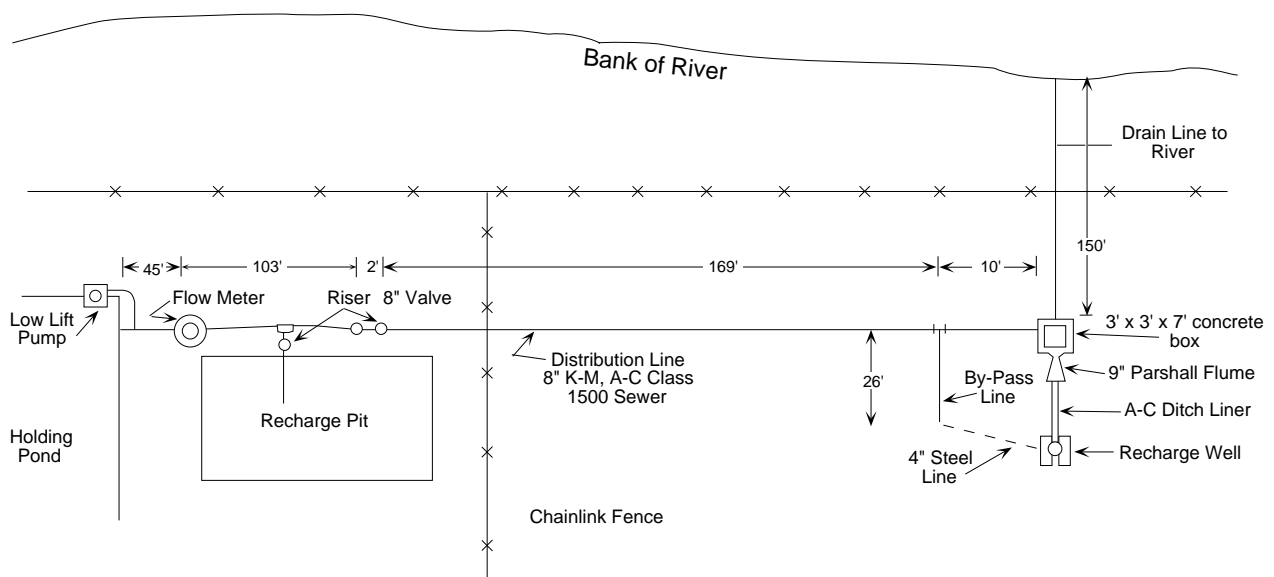

Figure 8.   Water distribution and drainage facilities at the artificial recharge site.
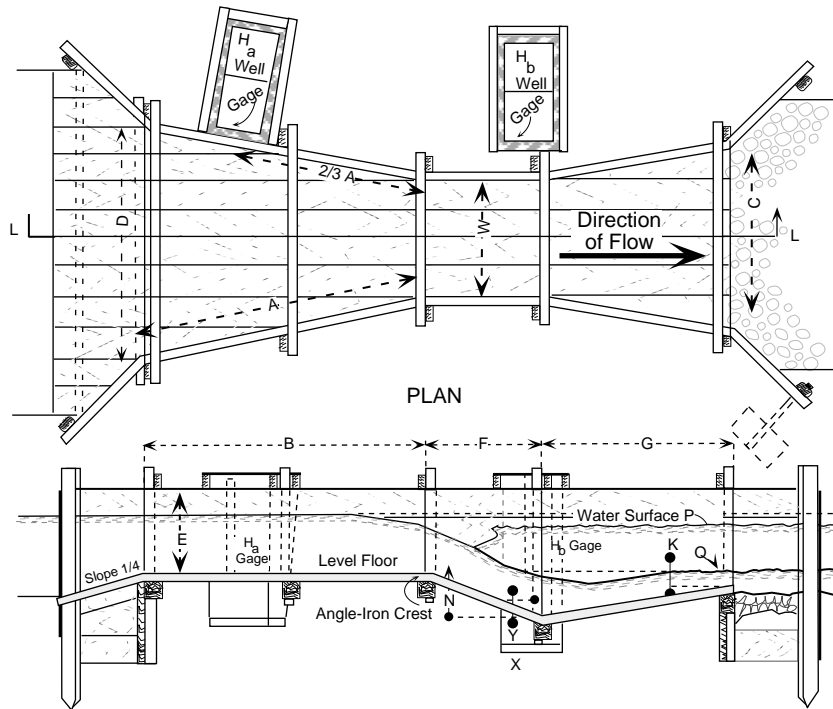
Figure 9. Parshall flume dimensions.

gpm. Based on this data, the design rate for the long-term test was set at about 200 gpm (actual average was 204 gpm).

Table 2. Well Efficiency of R#1 after 200 Minutes of Pumping

Discharge	Theoretical Drawdown	Actual Drawdown	Well Efficiency
gpm	*ft*	*ft*	*percent*
189	7.00	7.51	92
326	11.88	14.71	81
474	17.27	25.41	68

Because the initial short-term tests indicated that delayed drainage was an issue at the site, the main test was designed to run for a continuous period of at least 20 days. The actual scheduling of the test was established to try to avoid flow in the river as a result of a major precipitation event during the background, pumping, and recovery periods. The chosen test period was in the fall after the end of the irrigation season, which also minimized off-site pumping that might affect the results. It should be noted that two short-term tests were planned to follow the main pumping test during the winter rainy season when flow in the river was possible. This was

done to allow the impacts of an uncontrolled recharge event on the system to be assessed. The main pumping test would provide a basis for comparison.

The discharging well was measured on a time schedule per the criteria in Table 1, except that measurements for the initial 10 minute period were taken every 30 seconds. The observation wells were observed manually on the same schedule for the initial 30 minute period and then the recorders were utilized. Discharge measurements were monitored at least every 5 minutes for the first 30 minutes and then were monitored with water levels for the first 12 hours. Discharge measurements were monitored at least four times daily until the end of the test. The access tubes were monitored twice daily to assess changes in saturation near the water table.

The results from the long term pumping test are shown on Figure 10 as a semi-log data mass plot (drawdown versus log time) of the data for the three (3) observation wells. The large initial water level decline for Observation Well A is due to its close proximity to the pumping well (15 feet). The rise in water level at the end of the test was caused by a slight decrease in discharge rate.

Values of T and S were obtained by the non-equilibrium method. The plots of drawdown as a function of log time did not give a good overlay on the non-equilibrium type curve for early times. For later times, it was possible to obtain a good match. The match points obtained for the three observation wells are listed in Table 3. The values of T and S are also shown in Table 3. As indicated, the estimates of T and S were in close agreement.
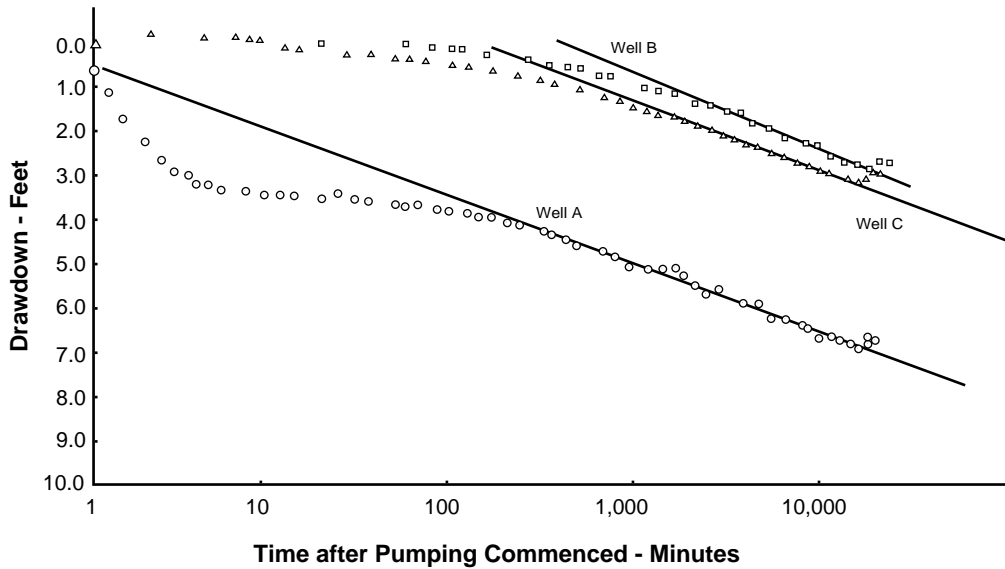
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Figure 10. Drawdown versus log of time in observation wells A, B, and C during pumping of R#1.

Table 3. Values of T and S Obtained by Non-Equilibrium Equation for Discharge Conditions.

Location	w(u)	l/u	s	t	r	T	S
			ft	*min*	*ft*	*gpd/ft*	
Well A	110	10^5	0.62	14900	14.7	37,600	0.01
Well B	1	10	0.62	1780	280.0	37,600	0.03
Well C	1	10	0.58	530	175.4	40,200	0.03

The estimates for storativity were also in reasonable agreement. It is important to note that the test results showed delayed drainage to be a significant factor at this site. The initial estimates of storativity using data from the early part of the test were about 1 x 10^{-5} rather than 3 x 10^{-2} estimated after 20 days of pumping. This effect was expected because of the heterogeneous nature of the basin fill. As a means of comparison, water balance studies on a large well field located 15 miles away (completed in the same material) were reviewed. These studies provided an estimate of storage coefficient (based on 10 years of pumpage) of about 0.15. Thus, it was concluded that the aquifer at the site was under water table conditions, but significant delayed drainage effects were present.

The results of the pumping tests at the site were used to characterize the site and design several long-term recharge experiments. This included monitoring design for evaluation of the effect of river flows on the regional aquifer.

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Appendix One

Equipment for Data Collection

a. Water Levels

Water level measurements can be made with electric sounders, air line and pressure gages, calibrated steel tapes, or pressure transducers (Garber and Koopman, 1968; and Bentall and others, 1963).

(1) Electric Sounders

    (a) An electric sounder is recommended for measuring water levels in the pumping well because it will allow for rapid, multiple water level readings, especially important during the early stages of aquifer pumping and recovery tests.

    (b) A dedicated sounder should be assigned to each observation well throughout the duration of the test. This is particularly important in ground-water quality studies to prevent cross contamination.

    (c) Each sounder should be calibrated prior to the commencement of testing to assure accurate readings during the test.

(2) Air Lines and Pressure Gages

    (a) Air lines are only recommended when electric sounders or steel tapes cannot be used to obtain water level measurements. Their usefulness is limited by the accuracy of the gage used and by difficulties in eliminating leakage from the air line. A gage capable of being read to 0.01 psi will be needed to obtain the necessary level of accuracy for determining water level change. A continuous copper or plastic line of known length should be strapped to the column pipe when the pump is installed. This will minimize the potential for leaks.

    (b) When air lines are used, the same precision pressure gage should be used on all wells.

    (c) Each pressure gage should be calibrated immediately prior to and after the test to assure accurate readings.

    (d) The air line and pressure gage assembly should also be calibrated prior to the test by obtaining static water level by another method, if possible.

(3) Calibrated Steel Tapes

    (a) Steel tapes marked to .01 ft. are preferred unless rapid water level drawdown or buildup is anticipated. If rapid drawdown, cascading water, or high frequency oscillation are anticipated, electric sounders, float actuated recorders or pressure transducers are preferred.

    (b) Steel tapes are not recommended for use in the pumping well because of fluctuating water levels caused by the pump action, possible cascading water and the necessity for obtaining rapid water level measurements during the early portions of the aquifer pumping and recovery tests. If tapes are used, and the water level fluctuates, the well must be equipped with a means of dampening fluctuating water levels. Additional manpower will be needed during the initial stages of the test.

(4) Pressure Transducers

Pressure transducers are often used in situations where access to the well is restricted, such as a well where packers are being used to isolate a certain zone. They may also be applicable in large-scale tests using a computerized data collection system. Such a system will significantly reduce the manpower needed during the initial stages of a multiple well test. The most common installation uses down hole transducers with recording of the results taking place on the surface.

    (a) Transducers should be calibrated prior to installation, and should be capable of accurately detecting changes of less than .005 psi. Transducer systems which will accurately record water level changes of .001 feet are available. The resolution of transducers, however, depends on the full scale range. Where large drawdowns are expected, such resolution is not possible.

    (b) After installation, the transducers and recording equipment should be calibrated by comparing pressure readings to actual water level measurements taken with a steel tape. Periodic measurements of the water level should be made during the test to verify that the transducers are functioning properly.

    (c) The effect of barometric changes on the transducers should be determined prior to and during the test. This will require continuous monitoring of the barometric pressure at the site as well as periodic comparisons of water level and transducer readings (Clark, 1967).

b. Discharge Measurement

The equipment commonly used for measuring discharge in the pumping well includes orifice plates, in-line water meters, Parshall flumes and recorders, V-notch weirs, or, for low discharge rates, a container of known volume, and a stop watch (Driscoll, 1986). The choice of method will depend upon a combination of factors, including i) accuracy needed, ii) planned discharge rate, iii) facility layout, and iv) point of discharge. If, for instance, it is

necessary to discharge the water a half mile from the pump, a flume or weir will probably not be used, because the distance between the point of discharge control and the point of discharge would make logistics too difficult. An in-line flow meter or a pitot tube would be the most likely calibrated devices (U.S. Bureau of Reclamation, 1981; King, 1982; U.S. EPA, 1982; and Leopold and Stevens, 1987).

(1) Orifice Plate

(a) Orifice plates with manometers (see Figure 11) are an inexpensive and accurate means of obtaining discharge measurements during testing. The thin plate orifice is the best choice for the typical pump test. An orifice plate has an opening smaller than that of the discharge pipe. A manometer is installed into and onto the end of the discharge pipe. The diameter of the plate opening must be small enough to ensure that the discharge pipe behind the plate is full at the chosen rate of discharge. The reading shown on the manometer represents the difference between the upstream and downstream heads.

(b) Assuming the devices are manufactured accurately and are installed correctly, an orifice plate will provide an accuracy of between two and five percent. The orifice tube must be horizontal and full at all times to achieve the design accuracy.

(c) The accuracy should be established prior to testing by pumping into a container of known volume over a given time. This should be repeated for several rates.

(2) In-line Flow Meter

(a) In-line flow meters can give accurate readings of the flow if they are installed and calibrated properly. The meter must be located sufficiently far from valves, bends in the pipe, couplings, etc., to minimize turbulence which will affect the accuracy of the meter. **The meter must be installed so that it is completely submerged during operation.**

(b) Use of a meter is an easy way to monitor the discharge rate by recording the volume of flow through the meter using a totalizer or other means at one minute intervals and subtracting the two readings. Some meters register instantaneous rate of flow and total flow volume.

(c) The meter should be calibrated after installation (prior to the test) to insure its accuracy.

(3) Flumes and Weirs

(a) There are numerous accurate flumes and weirs on the market. The choice depends mainly on the approximate discharge anticipated, the location of the discharge point and the nature of the facility. The cost of installation will preclude use at many non-permanent facilities.

(b) The weir (see Figure 12) or flume should be located close to the pump. There should be a permanent recorder on the device as well as means of making manual measurements (e.g., staff gage).

(c) The discharge canal should have a sufficient length of unobstructed upstream channel so as not to affect the accuracy of the chosen weir or flume.

(4) Pitot Tube

(a) The pitot tube is a velocity meter which is installed in the discharge pipe to establish the velocity profile in the pipe. Commercially available devices consist of a combined piezometer and a total head meter.

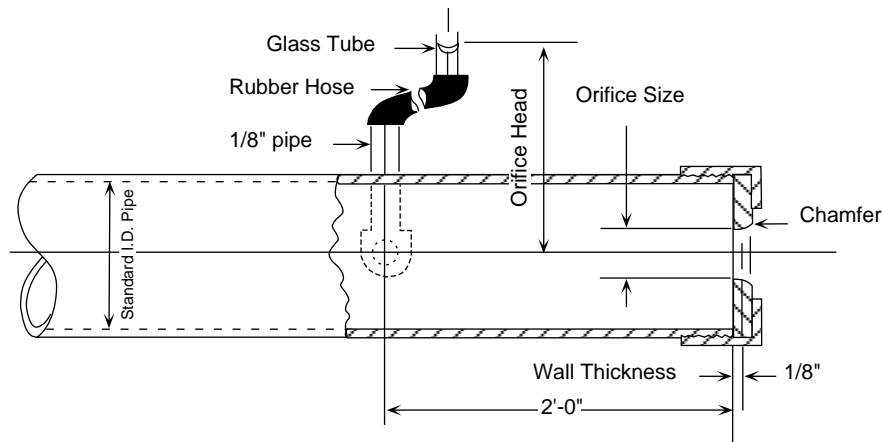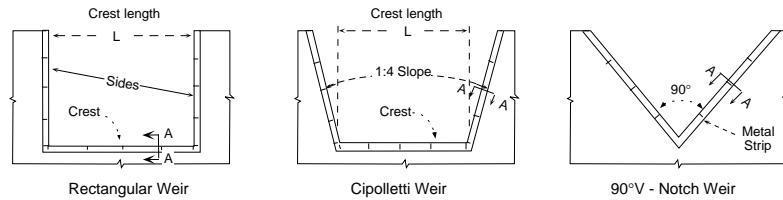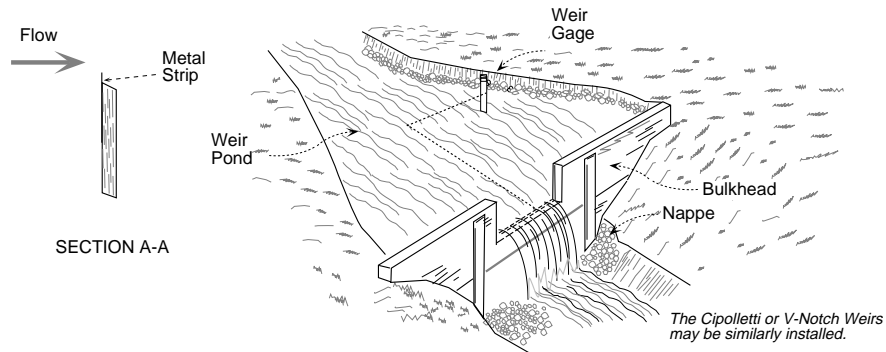(b) The tube must be installed at a point such that the upstream section is free of valves, tees,

Figure 11. Diagram of orifice meter.

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Standard Contracted Weirs
(Upstream Face)

Rectangular Weir — Crest length L, Sides, Crest, A-A

Cipolletti Weir — Crest length L, 1:4 Slope, Crest, A

90°V - Notch Weir — 90°, Metal Strip, A

Flow — Metal Strip

SECTION A-A

Weir Gage

Weir Pond

Bulkhead

Nappe

The Cipolletti or V-Notch Weirs may be similarly installed.

Figure 12.   Standard contracted weirs, and temporary discharging at free flow.

elbows, etc., for a minimum distance equal to 15 to 20 times the pipe diameter to minimize turbulence at the location of the tube.

(c) Since the pitot tube becomes inaccurate at low velocities, the diameter of the pipe should be small enough to maintain reasonably high velocities.

(5) Container of Known Volume and Stop Watch

(a) The use of a container of known volume and a stop watch is a simple way to measure the discharge rate of a low volume discharging well.

(b) By recording the length of time taken for the discharging water to fill a container of known volume, the discharge rate can be calculated.

(c) This method can be used only where it is possible to precisely measure the time interval required for a known volume to be collected. If rates are sufficiently high so that water "sloshes" in the container, or they prohibit development of a relatively smooth surface on the water in the container, this method is likely to be inaccurate. Restricting use of this method to flows of less than 10 gpm is probably a conservative rule of thumb.

c. Discharge Regulation

(1) The size of the discharge line and the gate valve

should be such that the valve will be from one-half to three-fourths open when pumping at the desired rate (during the initial phase of the test) with a full pipe.

(2) The valve should be placed a minimum of five (5) pipe diameters down-stream from an in-line flow meter, to ensure that the pipe is full and flow is not disturbed by excessive turbulence. In the case of some meters, such as a pitot tube, an in-line manometer, or an orifice plate, the valve would need to be upstream. (In this case the pipe downstream of the valve must be sized to be full at all times.)

d. Time

(1) A stop watch is recommended for use during an aquifer pumping and recovery test. Time should be recorded to the nearest second while drawdown is rapid, and to the nearest minute as the time period between measurements is increased beyond 15 minutes.

(2) If more than one stop watch is to be used during the testing, then all watches should be synchronized to assure that there is no error caused by the imprecise measurements of elapsed time.

(3) Accuracy of time is critical during the early stage of a pump or aquifer test and it is crucial to have all stop watches reflect the exact time. Later in the test the time recorded to the nearest minute becomes less critical.

(4) A master clock should be kept on site for tests longer than one day. This will provide a backup in case of

stop watch problems.

Appendix Two

Recording Forms

It is very important that each well data form stand alone. The data forms must contain all information which may have a bearing on the analysis of the data. See the suggested format for pumping test data recording sheets located at the end of this appendix. The form should allow for the following data to be recorded on the data sheet for each well:

(a) date
(b) temperature
(c) discharge rate
(d) weather
(e) well location
(f) well number
(g) owner of the well
(h) type of test (drawdown or recovery)
(i) description of measuring point

(j) elevation of measuring point
(k) type of measuring equipment
(l) radial distance from center of pumped well to the center of the observation well
(m) static depth to water
(n) person recording the data
(o) page number of total pages

In addition to the above information to be recorded on each page, the forms should have columns for recording of the following data:

(a) the elapsed time since pumping started, shown as the value (t)
(b) the elapsed time since pumping stopped, shown as (t')
(c) the depth in feet to the water level
(d) drawdown or recovery of the water level in feet
(e) the time since pumping started divided by the time since pumping stopped, shown as (t/t')
(f) the discharge rate in gallons per minute
(g) a column for comments to note any problems encountered, weather changes (i.e. barometric changes, precipitation), natural disasters, or other pertinent data.

AQUIFER TEST FIELD DATA SHEET

Page___ of____

_____ Pumped Well No._____   Date _____

_____ Observation Well No._____   Weather _____

Owner _____   Location _____

Observers: _____

Measuring Point is _____ which is _____ feet above/below surface.

Static Water Level _____ feet below land surface.

Distance to pumped well _____ feet.   Type of Test _____

Discharge rate of pumped well _____ gpm (gallons per minute).

Total number of observation wells _____ .

Water Measurement Technique _____ .

Recorded by _____ .   Temperature during test _____ .

Clock Time	Elapsed Time Since Pump Started or Stopped (min)	Depth to Water Below Land (feet)	Drawdown or Recovery (feet)	Discharge or Recharge (GPM)	t/t'	Comments

AQUIFER TEST FIELD DATA SHEET

Continuation Sheet

Distance to pumped well _____   Bearing _____   Page _____ of _____

_____ Pumped Well No._____   Date _____

_____ Observation Well No._____   Recorded by _____

Clock Time	Elapsed Time Since Pump Started or Stopped (min)	Depth to Water Below Land (feet)	Drawdown or Recovery (feet)	Discharge or Recharge (GPM)	t/t'	Comments

Glossary

Aquifer: A unit of geologic material that contains sufficient saturated permeable material to conduct ground water and to yield economically significant quantities of ground water to wells and springs. The term was originally defined by Meinzer (1923, p. 30) as any water-bearing formation. Syn: water horizon; ground-water reservoir; nappe; aquafer.

Aquifer Test: A test involving the withdrawal of measured quantities of water from, or addition of water to, a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition.

Aquitard: A confining bed that retards but does not prevent the flow of water to or from an adjacent aquifer; a leaky confining bed. It does not readily yield water to wells or springs, but may serve as a confining bed storage unit for ground water. Cf: aquifuge; aquiclude.

Capillary Fringe: The lower subdivision of the zone of aeration, immediately above the water table in which the interstices contain water under pressure less than that of the atmosphere, being continuous with the water below the water table but held above it by surface tension. Its upper boundary with the intermediate belt is indistinct, but is sometimes defined arbitrarily as the level at which 50 percent of the interstices are filled with water. Syn: zone of capillarity; capillary-moisture zone.

Confined Aquifer: An aquifer bounded above and below by impermeable beds or beds of distinctly lower permeability than that of the aquifer itself; an aquifer containing confined ground water. Syn: artesian aquifer.

Confining Bed: A confining bed is a unit of distinctly less permeable geologic material stratigraphically adjacent to an aquifer. "Aquitard" is a commonly used synonym. Confining beds can have a wide range of hydraulic conductivities and a confining bed of one area may have a hydraulic conductivity greater than an aquifer of another area.

Drawdown: The vertical distance between the static water level and the surface of the cone of depression at a given location and point of time.

Effective Porosity: Effective porosity refers to the amount of interconnected pore space and fracture openings available for the transmission of fluids, expressed as the volume of interconnected pores and openings to the volume of rock.

Ground Water: Subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated.

Hydraulic Conductivity: Hydraulic conductivity, K, replaces the term "coefficient of permeability" and is a volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Hydraulic conductivity is a function of the properties of the medium and the fluid viscosity and specific gravity; intrinsic permeability times specific gravity divided by viscosity. Dimensions are L/T with common units being centimeters per second or feet/day.

Hydraulic Gradient: Hydraulic gradient is the change in head per unit of distance in the direction of maximum rate of decrease in head.

Hydraulic Head: Hydraulic head is the sum of two components: the elevation of the point of measurement and the pressure head.

Intrinsic Permeability: Intrinsic permeability, k, is a property of the porous medium and has dimensions of L^2. It is a measure of the resistance to fluid flow through a given porous medium. It is, however, often used incorrectly to mean the same thing as hydraulic conductivity.

Porosity: Porosity of a rock or soil expresses its property of containing interstices or voids and is the ratio of the volume of interstices to the total volume, expressed as a decimal or percentage. Total porosity is comprised of primary and secondary openings. Primary porosity is controlled by shape, sorting and packing arrangements of grains and is independent of grain size. Secondary porosity is that void space created sometime after the initial formation of the porous medium due to secondary solution phenomena and fracture formation.

Potentiometric Surface: Potentiometric surface is an imaginary surface representing the static head of ground water and defined by the level to which water will rise in a well under static conditions. The water table is a particular potentiometric surface for an

unconfined aquifer representing zero atmospheric gage pressure.

Recharge Zone: A recharge zone is the area in which water is absorbed and added to the saturated soil or geologic formation, either directly into a formation, or indirectly by way of another formation.

Residual Drawdown: The difference between the original static water level and the depth to water at a given instant during the recovery period.

Saturated Zone: The saturated zone is that part of the water-bearing material in which all voids are filled with water. Fluid pressure is always greater than or equal to atmospheric, and the hydraulic conductivity does not vary with pressure head.

Specific Capacity: The rate of discharge of a water well per unit of drawdown, commonly expressed in gpm/ft. It varies with duration of discharge.

Specific Storage: Specific storage, S, is defined as the volume of water that a unit volume of aquifer releases from storage because of expansion of the water and compression of the matrix or medium under a unit decline in average hydraulic head within the unit volume. For an unconfined aquifer, for all practical purposes, it has the same value as specific yield. The dimensions are L^1. It is a property of both the medium and the fluid.

Specific Yield: Specific yield is the fraction of drainable water yielded by gravity drainage when the water table declines. It is the ratio of the volume of water yielded by gravity to the volume of rock. Specific yield is equal to total porosity minus specific retention. Dimensionless.

Storage Coefficient: The storage coefficient, S, or storativity, is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in hydraulic head. It is dimensionless.

Transmissivity: Transmissivity, T, is defined as the rate of flow of water through a vertical strip of aquifer one unit wide extending the full saturated thickness of the aquifer under a unit hydraulic gradient. It is equal to hydraulic conductivity times aquifer saturated thickness. Dimensions are L^2/t.

Unconfined Ground Water: Unconfined ground water is water in an aquifer that has a water table. Also, it is aquifer water found at or near atmospheric pressure.

Unsaturated Zone: The unsaturated zone (also referred to as the vadose zone) is the soil or rock material between the land surface and water table. It includes the capillary fringe. Characteristically this zone contains liquid water under less than atmospheric pressure, with water vapor and other gases generally at atmospheric pressure.

Water Table: The water table is an imaginary surface in an unconfined water body at which the water pressure is atmospheric. It is essentially the top of the saturated zone.

Well Efficiency: The well efficiency is the theoretical

drawdown divided by the measured drawdown. The theoretical drawdown is estimated by using pumping test data from several observation wells to construct a distance drawdown graph to estimate drawdown in the pumping well if there were no losses.

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