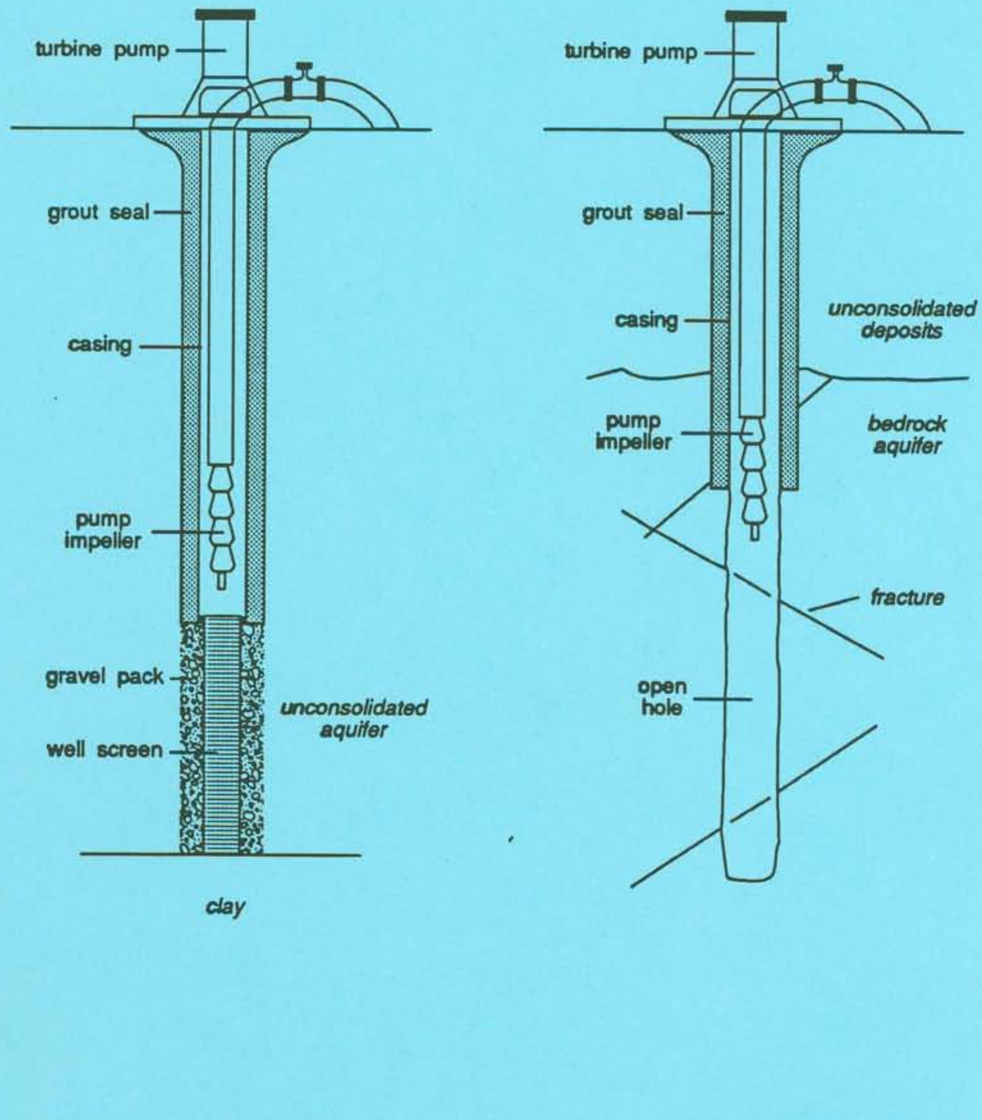
New Jersey Geological Survey
Geological Survey Report GSR 29

GUIDELINES FOR PREPARING HYDROGEOLOGIC REPORTS FOR WATER-ALLOCATION PERMIT APPLICATIONS, WITH AN APPENDIX ON AQUIFER-TEST ANALYSIS PROCEDURES



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All questions regarding the subject matter and use of this report should be addressed to the Bureau of Water Allocation, Water Supply Element, New Jersey Department of Environmental Protection and Energy at (609) 292-2957.

Questions concerning well permits, well construction practices, and driller licensing requirements should be directed to the Well Permit Section at (609) 984-6831.

Questions concerning water-allocation applications, aquifer tests, and hydrogeologic-report requirements should be directed to the Water Resources Management Section at (609) 292-2957.

Cover illustration: Schematic diagrams of wells drawing water from unconsolidated and bedrock aquifers. Modified from Heath, 1983, p. 52.

New Jersey Geological Survey
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Guidelines for Preparing Hydrogeologic Reports for Water-Allocation Permit Applications, with an Appendix on Aquifer-Test Analysis Procedures

by
Jeffrey L. Hoffman, Robert Canace, James Boyle, George Blyskun

Revision of "Guidelines for Preparing Hydrogeologic Reports for Water-Allocation Permit Applications"
(New Jersey Geological Survey Technical Memorandum TM 89-3)

New Jersey Department of Environmental Protection and Energy
Division of Science and Research
New Jersey Geological Survey
CN-029
Trenton, NJ 08625

1992

Conversion Factors

Multiply inch-pound units	by	to obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per mile (ft/mi)	0.189	meter per kilometer (m/km)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
square foot (ft^2)	0.0929	square meter (m^2)

Sea Level

In this report sea level refers to the National Geodetic Vertical Datum of 1929 (NGVD 1929)

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APPENDIX

Aquifer-test-analysis procedures

Guidelines for preparing Hydrogeologic Reports for Water-Allocation Permit Applications, with an Appendix on Aquifer-Test Analysis Procedures

page

"The purpose of design is to improve the probability that a test will yield acceptably accurate values of the hydraulic coefficients."
(Stallman, 1971, p. 16.)

FIGURES

TABLES

GUIDELINES FOR PREPARING HYDROGEOLOGIC REPORTS FOR WATER-ALLOCATION PERMIT APPLICATIONS

I. INTRODUCTION

I.A. Purpose

The New Jersey Department of Environmental Protection and Energy (NJDEPE), through the Bureau of Water Allocation (BWA), reviews hydrogeologic reports submitted in support of applications for major water-supply allocations (more than 100,000 gallons per day). One frequent problem is inappropriate investigational and data-analysis techniques. This report presents guidelines for preparing a hydrogeologic report acceptable to BWA. It is a guide for designing a hydrogeologic investigation and then preparing and submitting the resulting report to NJDEPE.

This report does not cover all details of aquifer-testing procedures and ground-water hydraulics. Many ground-water texts do this; some are listed in the references. This report presents guidelines considered minimally acceptable by BWA and briefly describes appropriate methods of data analysis. Responsibility for the accuracy of the data and appropriateness of the analysis techniques lies with the applicant.

High-capacity wells can supply a large population. The wells may have regional effects on ground-water levels and flow patterns. Additionally, drilling, testing, and installing pumps and water lines can be expensive. Ensuring that such a well is properly located so as to provide the required volume of water without affecting other ground-water users justifies requiring an accurate and thorough hydrogeologic evaluation.

Figure 1 (page 3) is a flow chart summarizing the entire process of obtaining a water-allocation permit. This report does not cover the entire process, only those steps involving planning, conducting, and reporting acceptable aquifer tests.

This report was written at the request of, and with guidance from, the Bureau of Water Allocation. The guidelines reflect BWA's current (1992) practices. These are subject to change. An applicant should contact the BWA to learn of any such changes.

Temporary dewatering operations require a special permit. The process for applying for a dewatering permit is different from the process outlined in this report. The BWA will provide guidence when applying for a dewatering permit.

I.B. Overview

This report presents guidance in several different areas. These include the types of aquifer tests available, the appropriateness of each, some details on field procedures, appropriate analysis techniques and reporting requirements.

. . . I.B.1. Hydrogeologic tests

A hydrogeologic test provides information about the ground-water system. Three different hydrogeologic tests may be necessary to fully evaluate the feasibility and impact of a ground-water diversion. They are: (1) a step-drawdown test; (2) an aquifer test, and; (3) a multiple-well (aquifer-stress) test. BWA does not require the step-drawdown test, but recommends it. *BWA requires either an aquifer test or a multiple-well test for all allocation requests for new wells, increases in allocation for an existing pumping well, and requests for a larger pump size in an existing well. Under certain conditions both tests may be required.* For other cases a decision on the necessity of a hydrogeologic test is made on a case-by-case basis by BWA.

The applicant should notify the Bureau of Water Allocation, by telephone, of the intent to submit an aquifer-test proposal. The applicant is, at this initial contact, informed of the general acceptability of the concept of the proposed test. This helps prevent submission of inadequate or unnecessary aquifer-test proposals. Table 1 (page 5) outlines the items required in an aquifer-test proposal.

. . . I.B.2. Field procedures

In order for a hydrogeologic test to provide accurate and appropriate data, certain procedures must be followed. This report presents minimum standards for collection of data in section II, 'Testing procedures'. Selected references on well and aquifer test procedures are listed in the reference section of this document.

. . . I.B.3. Test-procedures proposal

An informal proposal detailing the procedures planned for a hydrogeologic test of a proposed production well, or for a multiple-well test of a well field, must be submitted to BWA. *The test-procedures proposal must be specific enough to enable an evaluation of the proposed field procedures.* Following approval, BWA must be notified before the test begins.

... I.B.4. Analysis and interpretation of data
Test data must be analyzed to determine the aquifer characteristics which govern ground-water flow, including transmissivity, storativity, vertical leakage, delayed yield, and anisotropy. Tests should be analyzed using techniques designed for the specific type of aquifer and test conditions. The appendix presents an overview of analytical techniques and situations appropriate for their use.

The applicant must also evaluate the diversion's possible effect on other aquifers and on ground-water users, contaminated areas, surface-water bodies and environmentally sensitive areas. More detailed descriptions of these and other considerations are detailed in section III, below.

BWA recognizes the need for flexibility under certain hydrogeologic, geologic and cultural conditions. When extenuating circumstances exist, adjustments are considered. These adjustments must be requested prior to the field tests. Under some conditions, one or more of the tests may be waived if they would not provide any new or relevant information. All requests for waivers must be in writing.

... I.B.5. Final hydrogeologic report
After all tests are conducted and analyzed, the final interpretive hydrogeologic report is submitted as part of the full water-supply diversion application. The final report must include a discussion of the field procedures, a listing of all data gathered, an analysis of the data, and an evaluation of the effect of the proposed diversion on the aquifer and all other ground-water and surface-water users.

... I.B.6. Analysis techniques
The appendix presents an overview of techniques for analyzing hydrogeologic test data. It is not comprehensive but covers the most common methods. Its primary purpose is to guide the investigator toward the most appropriate analytical method for particular hydrogeologic and testing situations. There is not a one-to-one relationship between aquifer types and analytical techniques, but the techniques chosen should adequately and accurately address the test conditions.

I.C. Regulatory Basis
The regulations which govern the application procedure are found in N.J.A.C. 7:19-1, 2, 3 *et seq*. Copies of these regulations are available upon request from the Bureau of Water Allocation. This report expands on the technical detail necessary to satisfy these regulations. Other regulatory information is presented in table 5 (page 23).

I.D. Acknowledgments
Bureau of Water Allocation staff, especially Diane Zalaskus, Rachel O'Brien and Andrew Hildick-Smith, provided guidance and very useful information for this report. The comments of John Cagnassola and James Schultes were very informative and much appreciated.

II. TESTING PROCEDURES

In planning and conducting hydrogeologic tests a series of steps should be followed. These are:

A) Identify potential well site(s);
B) Obtain well permit(s) and drill initial test well(s);
C) Perform and evaluate preliminary, short-duration well test;
D) Conduct hydrogeologic test(s), and;
E) Evaluate hydrogeologic test(s).

Some of the steps would be omitted under certain conditions. Each of these items is discussed in more detail below. This section is structured to follow the actual steps of preparing for, conducting, and analyzing an aquifer test. Each of its subsections is designed to be independent and some, of necessity, repeat information.

A useful technical reference on the proper field methods for measuring ground-water data is the 'National Handbook of Recommended Methods for Water-Data Acquisition' (United States Geological Survey, 1977). This document also provides technical guidance on field procedures for taking water-quality samples and surface-water measurements.

II.A. Identify Potential Well Site(s)
Before application is made for a major diversion, the applicant should conduct an initial investigation to identify a suitable test-well site. In general, it is desirable to select a site with reasonably uniform geology where the likelihood of ground-water contamination is low, the depletion of nearby streams and wetlands is unlikely and interference with nearby wells is not likely.

Well-site selection may be based on previous investigations, if the proposed diversion is in an area where the hydrogeology is well known. In unexplored areas, field studies may be needed to establish the probability of

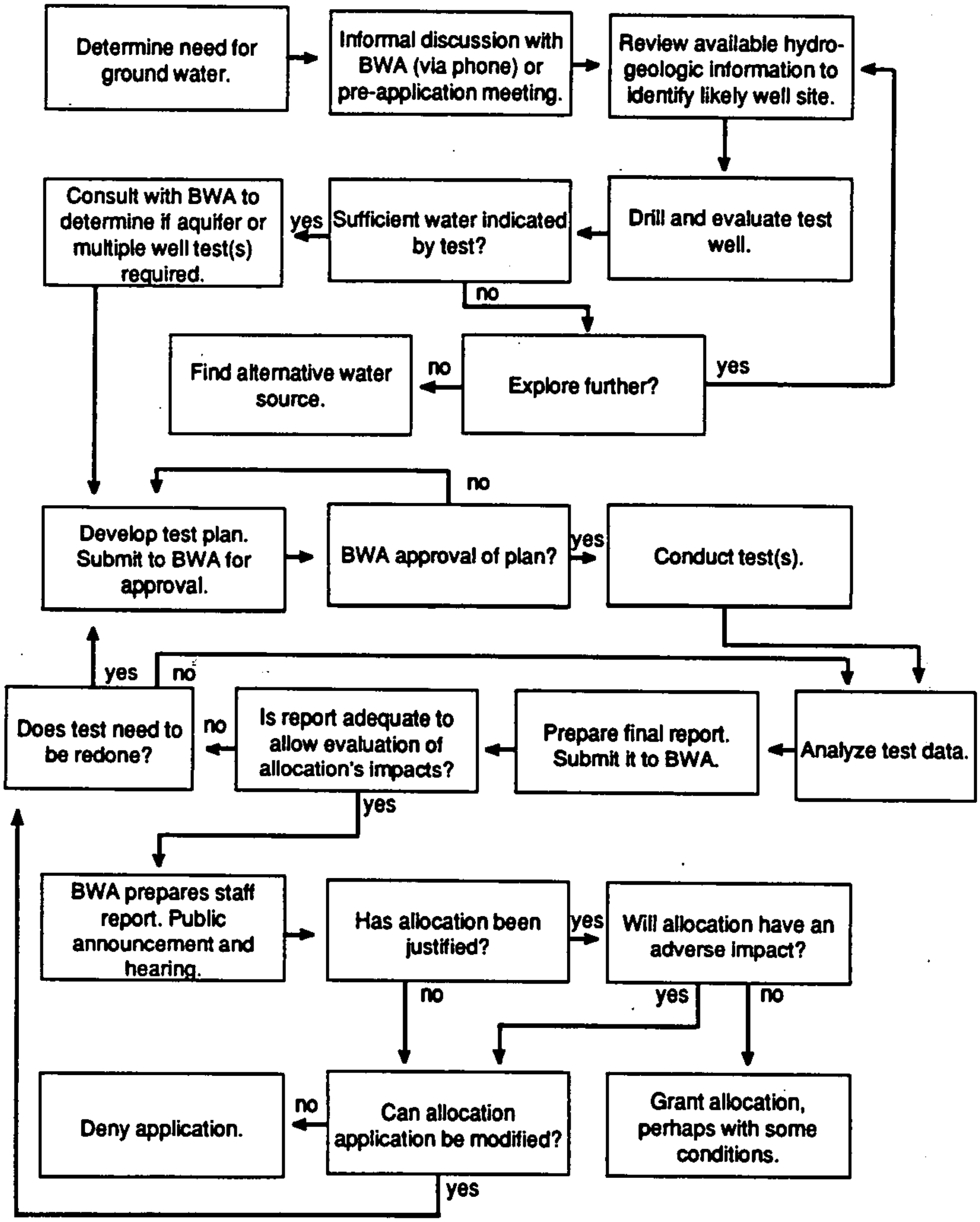


Figure 1. Steps required to complete application procedure.

drilling a successful test well. Published and unpublished geologic maps and reports on file with the New Jersey and United States Geological Surveys may assist the applicant in identifying a suitable well site.

Applicants should contact the Bureau of Safe Drinking Water to insure that the site selected for a public community supply well will satisfy all requirements under N.J.A.C. 7:10-11 *et seq.*, governing construction of water-supply facilities. These regulations cover minimum setback distances and other requirements.

II.B. Install Test Well(s)

A test well, commonly of six-inch diameter, is installed at the location believed most appropriate for a new major water supply. This well's major purpose is to help determine if the aquifer is suitable as a water-supply source. If properly located and constructed the test well may serve as an observation well during a subsequent aquifer and/or multiple-well test.

A review of the test well's geologic log and its discharge during drilling may indicate whether or not the site is suitable for further consideration. In some instances the site may clearly be unsuitable for a major water-supply well and thus a preliminary hydrogeologic test would be wasteful. In these cases more exploration work is needed to identify more productive sites.

If the test well is later converted to a production well a second well permit is required by BWA prior to conversion.

II.C. Design and Submit Hydrogeologic-Test Proposal

The purpose of the hydrogeologic test is to determine the performance and radius of influence of the proposed production well and the hydrogeologic characteristics of the aquifer. One or more of three hydrogeologic tests may be conducted: (1) step-drawdown tests; (2) aquifer tests, and; (3) multiple-well (or aquifer-stress) tests. A step-drawdown test evaluates well hydraulics. The aquifer test evaluates the hydrogeologic characteristics (transmissivity and storage coefficient, in particular) of the aquifer. Properly performed tests can also indicate aquifer boundaries, anisotropic conditions, sustainable yield, leakance, vertical flow and interference effects. The multiple-well test evaluates drawdown in the aquifer when the proposed withdrawal and all nearby withdrawals are taking place.

BWA normally requires either the aquifer test or a multiple-well test. Under certain conditions both may be required, or neither. The step-drawdown test is done at the discretion of the applicant.

When a hydrogeologic test is required the applicant must submit, for approval, a proposal fully describing the proposed test. If the proposal is adequate BWA will give written approval. The purpose of the proposal is to decrease the chances of an unacceptable test that will subsequently be rejected. Following approval, BWA must be notified before the test begins.

Table 1 outlines the items which should be included in the test-procedures proposal.

Producing accurate, continuous data from the tests requires detailed planning. It is important that all test procedures include contingency plans for emergencies. Common emergencies include malfunction of the pump, failure of water-level measurement devices, poor response of observation wells, discharge of water of unacceptable quality, unanticipated nearby pumpage, and adverse weather conditions. Emergencies which result in impairment of the data do not relieve the applicant of the duty to submit an accurate and adequate analysis of the aquifer. In some cases the test may have to be redone.

The following sections deal with the factors which must be addressed in planning the tests.

. . . II.C.1. Permits and approvals

The applicant may be required to obtain one or more permits before a hydrogeologic test can be conducted. A description of some possible permit requirements follows. Other state and local ordinances may apply to road building, emplacement of fill, sediment control and utility disruption, to name a few possibilities. It is the responsibility of the applicant to obtain all necessary permits before conducting an aquifer test.

. . . . . . II.C.1.a. Well-drilling permits

A well-drilling permit must be obtained for all wells drilled in New Jersey (N.J.S.A. 58:4A-5 *et seq.*). As part of this process, information on proposed wells must be submitted to BWA. Obtaining well permits is the responsibility of the well owner. Permit applications must be submitted by a licensed well driller.

BWA issues a unique well-permit number to each well. *This number must be shown on all logs and data sheets to avoid the confusion that arises when using informal names alone for wells.*

As a followup to drilling the well, the driller is required to submit a well record within 60 days of completion. This record includes information on the well location,

Table 1. Essential items in a hydrogeologic test proposal.

1. Site data
   - -location of all wells
   - -location of pertinent features
   - -maps at appropriate scales (U.S. Geological Survey topographic map, detailed site map at 1:6,000 or larger)

2. Hydrogeologic data
   - -estimates of transmissivity, storage, and other aquifer hydraulic characteristics
   - -hydrogeologic setting of area
   - -local recharge/discharge estimates
   - -nearby wells and their pumpage

3. Well data (pumping and observation wells)
   - -permit number
   - -construction details
   - -screened intervals and formation(s) tapped
   - -well logs

4. Test description
   - -step-drawdown
   - -aquifer
   - -multiple-well

5. Identification of external influences
   - -precipitation
   - -barometric pressure
   - -tidal influences
   - -external pumpages
   - -surface waters

6. Monitoring schedule for pre-pumping (background) period
   - -length of period
   - -monitoring of relevant external influences
   - -monitoring frequency

7. Monitoring schedule for observation wells
   - -background, test and recovery-period monitoring schedules
   - -monitoring techniques

8. Monitoring schedule for pumping well
   - -monitoring schedule
   - -techniques for measuring water levels
   - -planned pumping rate
   - -discharge-measuring method and frequency
   - -discharge locations and description

9. Monitoring schedule for relevant external influences and concerns
   - -precipitation
   - -barometric pressure
   - -tidal influences
   - -external pumpages
   - -surface waters
   - -monitoring techniques

10. Monitoring schedule for post-pumping (recovery) period
    - -length of period
    - -monitoring of relevant external influences
    - -monitoring frequency

11. Applicable federal, state and local regulations and permits
    - -list of necessary permits
    - -status of permit applications

subsurface geology, hydrology, construction and pump characteristics.

Prior to applying for a permit, the applicant should contact the BWA well-permit section to ascertain exactly what information BWA requires. If a well drilled for one purpose is converted to another (for example a test well into a production well) an additional well permit is required. BWA's well-permit section can provide guidance.

Counties and municipalities may require that well owners obtain a permit. This permit may be issued by the local health department or the engineering office.

......II.C.1.b. Water-allocation permits

All major water users are assigned a water-allocation permit number. If the application is for a change or renewal of a previous allocation, then this allocation permit number should appear on all correspondence. The water purveyor must also be accurately identified.

An aquifer test which is shorter than one month does not normally require an allocation permit.

......II.C.1.c. Discharge permits

The water withdrawn from the aquifer during a hydrogeologic test must be discharged so as not to interfere with the test. A discharge permit may be required to dispose of water withdrawn from the aquifer during the test.

If the pumping rate during a hydrogeologic test will be greater than 100,000 gallons per day and the test duration will be less than 31 days then BWA does not require a separate withdrawal permit for the test. However, BWA does require notification of the test before it begins and a report on the volume of water pumped submitted after the test. BWA will supply two forms for these reports.

If discharge is to a nearby stream, or to a storm drain that discharges directly to a stream, a permit is not normally needed if the water is uncontaminated. In this case the applicant must submit a letter to the Bureau of Industrial Water Discharge Permits stating the duration of pumping, pumping rate, and discharge point, along with a chemical analysis of the water.

If discharge of water is to a sanitary sewer, then only the approval of the sewage treatment plant operator is required.

If the ground water contains contaminants, a New Jersey Pollution Discharge Elimination System (NJPDES) permit is required. The Bureau of Ground-Water Discharge Control must be notified in advance of a discharge of contaminated ground water to the ground. The Bureau of Industrial Water Discharge Permits must be notified for a discharge of contaminated water to a surface water body.

......II.C.1.d. Wetlands permits

Any development in a wetland or its transition zone must be reviewed by the Bureau of Freshwater Wetlands Permits (N.J.A.C. 7:7A).

...II.C.2. Nearby pumpage

To yield usable information, the test must be conducted with some understanding and control of existing nearby pumpage. The effect of other pumping wells should be minimized, either by having them turned off or, failing that, maintaining their pumpage at a constant rate. The aquifer test proposal must identify all nearby pumping centers which might affect water levels at the observation points. The proposal must detail what steps will be taken to monitor or control nearby pumpages.

...II.C.3. Observation wells

The number, placement and depth of observation wells must be determined based upon the hydrogeology of the site (confining layers, for example), practical conditions (accessibility, for example) and test conditions (pumping rate, nearby wells). In most cases, the more observation wells available, the better the final analysis of aquifer properties. However, too many wells may be redundant and expensive. In some cases existing wells can serve as observation wells.

For a major water-supply well a minimum of three (3) observation wells is suggested. Two observation wells are required in all cases. Additional wells may be required by BWA depending on hydrogeologic conditions.

No minimum diameter is set on observation wells. Best results are often obtained from small-diameter wells, because they store little water inside the well; storage effects are thus minimal or rapidly eliminated. All observation wells, especially those of small diameter, must be constructed and developed to permit unhampered response to changes in aquifer water levels and to allow for monitoring of water levels by an appropriate technique.

All observation wells finished in unconsolidated material must have at least 5 feet of screen. Screens of the first and second observation wells (those closest to the pumping well and completed in the same aquifer) should be centered at the same elevation as the center of the pumping well's screen.

If multiple units are being screened by the pumping well, then the number of observation wells and the depth, placement and screened interval may change. BWA will offer detailed guidance in these cases.

Information on observation-well placement is summarized in table 2.

The first observation well is ideally placed at a distance of 1.5 times the saturated thickness of the aquifer from the pumping well, but not less than 50 feet and not more than 200 feet. For instance, if the aquifer being tested is 80 feet thick, then the first observation well should be placed 120 feet away from the pumping well. If the aquifer is 150 feet thick, the observation well should be placed 200 feet (the maximum distance) away. In a consolidated formation, the location and depth of the first observation well may be influenced by the dip of the formation.

The second observation well should also be completed in the aquifer being pumped. It should be placed a distance from the pumped well equal to approximately 5 times the saturated thickness of the aquifer, up to a maximum of 1,000 feet. At a minimum, it should be twice as far from the pumping well as is the first observation well.

The third well is used to determine vertical leakage of ground water, if leakage from overlying units is a concern. The third well should be located within 10 feet of the pumping well, but at a shallower depth. The depth of the third well should be based on an analysis of the site's hydrogeologic conditions.

If the aquifer being pumped is unconfined, then the screen of the third monitoring well may be more advantageously placed at a lower elevation than the screen of the pumping well. The goal then would be to determine if any water was leaking upward into the water table aquifer from a lower unit.

If geologic conditions are such that a confining layer is suspected, but not confirmed, then the third observation well must be placed so as to make an estimate of vertical flow of water. For a confined aquifer the third observation well should be finished directly above the confining unit that forms the top of the aquifer. The well should not pierce the confining unit. This minimizes the possibility that a disturbed zone around the well casing will hydraulically connect the aquifer and overlying units. If such a connection is inadvertently created by the observation well, then water levels measured in this

Table 2. Observation-well placement.

Note: The first observation well is required. Some or all of the remaining observation wells may be required at the discretion of the Department. More wells may be required in some cases.

Observation well no.	Distance from pumping well	Vertical placement of screen opening
1	Ideally 1.5 x saturated aquifer thickness; in any case, >50 ft. away and<200 ft. away	in aquifer being pumped
2	Ideally 5 x saturated aquifer thickness; in any case <1,000 ft. away	in aquifer being pumped
3	within 10 ft. of pumping well	shallower than pumping well to estimate vertical leakage from above
4	within 10 ft. of pumping well	deeper than pumping well to estimate vertical leakage from below
5	same distance as first	in aquifer being pumped but perpendicular to a line drawn between the pumping well and the first observation well
6	as needed to investigate any hydrogeologic boundaries	where needed

well will yield misleading values for the actual overall vertical leakage rate.

If upward leakage from an underlying unit is believed to be an important consideration, as in the case of upconing of saltwater or depletion of an underlying aquifer, then the third well should be completed in the lower aquifer, or a fourth observation well may be required.

A separate observation well is needed to analyze for anisotropy in an aquifer. The third observation well may be dedicated to this purpose if anisotropy is a more important consideration than vertical leakage of water. An observation well to measure anisotropy may prove advantageous in some situations, particularly in bedrock aquifers. This additional well would be placed at the same distance from the pumping well as either the first or second observation wells, but in a different compass direction. In most cases, if practical, the first observation well and this additional well will form a right angle, with the pumping well at the vertex. In consolidated aquifers, the orientation of bedding and fractures can have a great influence on the degree of anisotropy. Understanding these geological characteristics is critical in order to accurately locate observation wells.

If a hydrogeologic boundary is known or suspected, an additional monitoring well may be required to monitor the effect of the boundary on water levels. Examples of this would include an observation well on the opposite side of a stream or fault from the pumping well, or near bedrock bounding a glacial valley-fill aquifer.

BWA reserves the right to require more observation wells in complex hydrogeologic settings. For this reason, the applicant is encouraged to contact BWA as soon as possible to determine the appropriate number and location of observation wells. BWA may invoke additional requirements over and above the aforementioned guidelines.

After the aquifer tests have been completed, any observation and test wells which will not be used must be properly sealed in accordance with state regulations (N.J.A.C. 58:4A-4.1, *et seq.).*

. . . II.C.4. Background-monitoring period

Monitoring pretest conditions at a site is important. Natural fluctuations in water levels, if not identified before pumping begins, can seriously complicate analysis of drawdown data. All observation points (wells, streams, wetlands, barometric pressure, and so on) should be monitored at 6-hour intervals during a 48-hour background period just prior to the start of pumping. Data measured during this period will establish base conditions. A longer background monitoring period may be appropriate in some instances to clarify questionable fluctuations. In special cases, measurements may be required more frequently than every 6 hours.

The background period is most important for the aquifer and multiple-well tests. It is usually not important for the step-drawdown test.

. . . II.C.5. Recovery period

A recovery period is required to permit measurement of water-level rises. Water-level recovery in the pumping and observation wells must be measured. Recovery data can be analyzed for information on aquifer parameters. In some cases recovery data are superior to drawdown data because they can lack erratic readings caused by fluctuations in the pumping rate.

The recovery-monitoring period must last a minimum of 8 hours. Beyond this, the recovery period must continue until water levels have recovered 90 percent of the drawdown observed in the pumping well. If feasible, pumping in the immediate vicinity should be controlled so as not to complicate interpretation of the recovery. Where this is not practical, it must be demonstrated that the water-level drawdowns caused by the well being tested have recovered by 90 percent.

During recovery, water levels should be measured in the pumping and observation wells according to the same schedule as was used for measuring drawdowns, using the time at which the pump was turned off as the starting time. This generates many data points during the early part of the recovery.

During the recovery period, all other monitoring points (streams, wetlands, tides, barometric pressure, and so on) should be observed at 6-hour intervals or shorter where appropriate.

If questionable fluctuations were observed during the pretest background monitoring period, extending the recovery period and taking measurements more often may help identify the fluctuations.

. . . II.C.6. Determining the pumping rate

During a hydrogeologic test the well should be pumped so as to simulate operation of the well. The rate is determined by the expected pumpage rate under normal operation. If, however, a higher rate would be necessary in order to pump the requested maximum monthly allocation, this higher pumpage rate may be required by BWA.

An important consideration is that for all public community supply wells the Bureau of Safe Drinking Water (BSDW) requires a test pumping rate "at least 20% above the designed pumping rate" (N.J.A.C. 7:10-11.4n.1). If this latter rate is not achieved during the test, an additional test may be required by BSDW.

Information from any preliminary short-term well tests, and also from any step-tests, may be useful in indicating what pumping rate a site can sustain. Analysis of the preliminary tests, along with other hydrogeologic, regulatory and institutional considerations, will lead to an estimated maximum pumping rate (Q_{max}). Once application has been made to the Bureau of Water Allocation for an allocation pumping at Q_{max}, all aquifer tests (except the step-drawdown tests) should be done at this pumping rate. This is in order to more accurately predict the response of the aquifer to the anticipated pumpage.

The pumping rate must be kept constant throughout an aquifer test. Determining at what rate the aquifer can supply water to the production well may be a trial-and-error process. It is far better to determine an appropriate rate during a step-drawdown test than during the aquifer test.

... II.C.7. Measuring and sustaining the pumping rate

It is very important that the pumping rate be accurately measured and held as steady as possible. Fluctuations in the pumpage may be grounds for rejecting the aquifer test. Fluctuations certainly make analysis of the data more difficult.

Flow must be monitored by means of an automatic data recorder (ADR). The discharge rate must be measured at least once every 10 minutes during the first hour of the test and every 60 minutes thereafter.

As a backup to the ADR, the flow rate should be manually monitored. Measuring procedures include, but are not limited to, flow meters, totaling flow meters, weirs, orifice weirs and flumes.

A decrease in discharge will normally occur with increasing drawdowns as the pump works against a greater hydraulic head and increasing friction in the system. This tendancy for a reduction in the pumpage rate during the course of an aquifer test must be compensated for.

The pumpage rate should not be allowed to vary by more than 10 percent from the initial rate. Tests which have significant pumpage variations not accounted for in the data analysis will be rejected.

If, for some reason, the pump must be turned off during the test, it must be restarted within 10 minutes. No more than one 10-minute break should be allowed for every 6 hours of pumping. Owing to the extreme importance of the early-time data, no halting of the pump is allowed during the first two hours of the test. If the pump is halted during this period for any reason, the test must be restarted after allowing water levels in the pumped and observation wells to return to within 95 percent of pre-test levels.

The longer the pump is down the greater the chance that the data set will be unacceptably affected. This will result in a rejected aquifer test and rerunning the aquifer test.

... II.C.8. Discharge of pumped water

Water pumped from a well should be discharged to a point where it cannot infiltrate into the ground and flow back to the well during the test. If the pumped water were to be accidentally "recycled" this would create the appearance of recharge to the aquifer where none actually exists. In some cases (for instance, a deep aquifer with an overlying confining unit) this may not be a concern. In other cases (a carbonate rock aquifer with minimal overburden and sinkholes, or a shallow, unconfined sand aquifer) this could be a significant problem.

... II.C.9. Ground-water-level measurements

Accurate measurement of water levels in all wells is important. Levels must be measured with an accuracy of 0.05 foot. Depth to water is measured from an established reference point. The same reference point should be used each time a measurement is taken. The reference point's elevation relative to mean sea level (msl) must be measured if water-level contour maps of the area are to be made. If only drawdown data are desired, the elevation relative to mean sea level does not need to be determined.

Drawdowns must be reported in decimal feet. If original measurements were taken in different units (for example, pounds, psi, or inches) they must be converted to decimal feet. The original data, along with a description of any necessary conversion process, should be included in an appendix.

The frequency with which measurements are taken is very important. Water levels decline more rapidly at the beginning of the test than later. The sampling schedule accounts for this. Water levels in the observation wells should be monitored according to the schedule in table 3. Figure 2 is a sample form suitable for recording of water levels.

Observation wells far from the pumping well may not require monitoring as frequently as closer wells. At BWA's discretion, a different measurement schedule may be used for distant observation wells.

Although levels in the pumping well are not as critical as those in the observation wells, they should be measured as accurately as possible. Water levels in the pumping well should be measured as scheduled in table 3.

Table 3. Schedule of water-level measurements in wells during an aquifer test.

Time since pumping began	Time between measurements in:	
	Observation wells *	Pumping well
0 - 2 minutes	10 seconds	30 seconds
2 - 5 minutes	30 seconds	30 seconds
5 - 15 minutes	1 minute	1 minute
15 minutes - 1 hour	5 minutes	5 minutes
1 - 2 hours	10 minutes	10 minutes
2 - 8 hours	30 minutes	30 minutes
8 - 24 hours	1 hour	1 hour
24 - 72 hours	2 hours	2 hours

*Longer intervals may be used in observation wells farther from the pumping well at BWA's discretion.

Data collected during the initial part of the pumping and recovery period are needed to accurately calculate the transmissivity and storage coefficient of the aquifer, as well as to quantify the effects of well-bore storage, fractures, and partial penetration of the aquifer by the pumping well. Late-time data are useful for analyzing the effects of vertical leakage and aquifer boundaries, and for determining the specific yield of unconfined aquifers.

During a 72-hour aquifer test the monitoring schedule produces many data points. The frequency with which water levels must be measured during the early part of the test may necessitate use of an automated recording system in one or more wells. In such cases manual measurements should be made occasionally as a check on the automatic system. Loss of data due to the mechanical malfunction of a recording system, with no manual "backup" measurements, is grounds for rejecting the results of an aquifer test.

...II.C.10. Wetland and surface-water-body measurements

If the proposed diversion's effect on nearby wetlands or water bodies is of concern, then these should be monitored. Several possible monitoring procedures could be used. Two are described here.

The first monitoring process involves installing two very shallow well points, with short (< 1 foot) screens centered approximately 3 and 6 feet into the saturated zone, in or next to the surface-water body. Water levels in these well points should be measured hourly during the test period and at 6-hour intervals during the background and recovery periods. The relative heights of water in the well points, and how they change during the test, can indicate whether there is sufficient head decline to deplete surface water during the test.

The second method, appropriate to small standing bodies of water such as ponds, involves placing a staff gauge or measuring stake into the water and measuring the water height hourly during the test. Measurements should be taken at 6-hour intervals during the background and recovery period.
All measurements must be taken with an accuracy of 0.05 foot or better. Results must be reported in units of decimal feet.

Any action which may affect the status of a wetland or its buffer zone must be reviewed by the Bureau of Freshwater Wetlands Permits.

...II.C.11. Streamflow measurements

If the effect of the proposed diversion on nearby streamflow is of concern, then streamflow must be monitored. Two methods may help establish whether pumpage is affecting streamflow.

The first monitoring process involves measuring ground-water levels under the stream in exactly the same manner as was described for surface-water bodies in the previous section.

The second method is by gauging streamflow. However, in all but the most extreme cases, it is expected that the diversion's effect on streamflow will be a small percentage of total stream flow. Stream depletion during the test period is likely to be smaller than the error associated with gauging flow in a stream. This method thus is unlikely to accurately measure stream depletion.

If the applicant monitors stream discharge, then streamflow should be measured during the background monitoring period, again approximately 24 hours after the

WELL-DRAWDOWN DATA

PROJECT ________________________________
LOCATION ________________________________
WELL NUMBER OR DESIGNATION ________________
NJ WELL PERMIT NUMBER ____________________
DATUM ________________________________
DATE ________________________________

STATIC-WATER-LEVEL: Depth to water ____________ ft.
Gauge reading ____________ and units measured ________
Gauge measures ________________________________
Airline length below datum ____________________ ft.
Datum elevation ____________________ (ft. above sea level)
Observer ________________________________

Date	Clock Time	Pumping Time	Water-Level Reading	Drawdown	Flow Meter Reading	Discharge Rate	Remarks

Figure 2. Sample form for reporting drawdown data.

start of the test, and again 48 hours after the start. Flow should be measured both upstream and downstream of the area thought to be affected by the pumpage.

Precipitation can significantly affect streamflow and make it difficult to isolate the effect of the pumping well.

. . . II.C.12. Barometric-pressure effects

Changes in barometric pressure may affect ground-water levels, especially in confined aquifers. Measuring the air pressure, and correcting water-level data for observed changes will increase the accuracy of the water-level data. Measurements every 6 hours are adequate during the background and recovery periods. Hourly measurements are needed during the test period.

The barometric pressure must be measured at the test site.

. . . II.C.13. Tidal effects

Tidal cycles may significantly affect ground-water levels. This cyclic change can be partially accounted for, but will introduce some error into the measurements. If tidal effects are present, a gauge should be installed in the tidal water body. Correction of observed ground-water data can be based on the tide readings (Serfes, 1987). The correction technique can be a simple graphical correction or a more complicated tidal-frequency analysis with a correlated ground-water response function for each well.

Tidal measurements every 2 hours are adequate during the background and recovery periods, but hourly measurements are required during the test period.

II.D. Conduct Hydrogeologic Tests

Once approval is obtained to proceed with testing of the proposed production well, the step-drawdown test is done first, followed by the full-scale aquifer test and/or multiple-well test. BWA does not require the step-drawdown test. It is, however, extremely useful in determining the appropriate pump size and pumping rate for the well. If a step-drawdown test is not done and the test well cannot maintain a constant pumpage rate during the aquifer test, then the allocation request may be denied.

Both the aquifer test and multiple-well test are assigned at the discretion of BWA. Usually one of them is required, but in special cases both or neither may be necessary.

Hydrogeologic tests are conducted to measure site-specific hydrogeologic characteristics. These tests must be conducted properly to maximize the information derived from them. The general procedure is to pump water from the well, measure pump discharge, and measure drawdown and recovery of water levels in the observation wells and pumped well.

The following sections briefly outline the steps necessary to conduct the hydrogeologic tests.

. . . II.D.1. Production and observation wells

The production well is drilled at a site believed to be the most productive and that will interfere least with other ground-water users. Production wells must be constructed in accordance with state regulations administered by the Bureau of Safe Drinking Water (N.J.A.C. 7:10-11.1 and 12.1). Careful attention should be paid to the lithology of the aquifer. Reasonable estimates of aquifer permeability can sometimes be made on the basis of laboratory analysis of core samples and grain-size distribution.

The number and placement of observation wells is covered in detail in section II.D.3. above.

A special type of production well involves a series of horizontal bore holes radiating out from the bottom of a large-diameter vertical shaft (for example, a Ranney well). Water flows horizontally through the bore holes into the vertical shaft and is then pumped to the surface. The hydrogeologic tests described in this report cannot be performed on this type of well. BWA will provide specific guidance on applications for allocation permits for these wells.

. . . II.D.2. Step-drawdown test

A step-drawdown test is intended to provide information on the relationship between yield and drawdown in a well. It is used to calculate additional drawdown caused by frictional and turbulent effects at different pumping rates. It is usually employed to evaluate well construction and pumping efficiency but can also provide a means of predicting well performance during more sustained pumping tests. The results are analyzed to determine if well losses in the production well indicate the need for additional well development. The step-drawdown analysis is useful in evaluating the sustainability of the planned pumping rate for the long-term aquifer test, selecting performance specifications for the permanent pumping equipment, and devising a pumping schedule for optimum efficiency.

The step-drawdown test can be done on the test well to estimate the aquifer yield. In this case it probably would be performed before the aquifer test. This test could also be done on the supply well to estimate the most efficient pump size. In this case it would probably be done after the aquifer test.

A step-drawdown test involves increasing pumpage from a well in successive equal steps or stages. Drawdown at each pumping level is measured. Pumping begins at a low rate and then increases in successive steps. It is suggested that for wells in an unconsolidated formation the well be pumped at a minimum of four different rates or steps: 25, 50, 75, and 100 percent of the proposed production pumping rate. (Pumping at higher rates could yield useful information and should be considered if the higher rates will not damage the well's screen or gravel pack.) For wells in a consolidated aquifer (without a well screen), an additional two steps, 125 and 150 percent, should be added. At each step the pumpage rate is held constant for 1 hour or longer. If the highest pumping rate cannot be achieved, then a rate as high as possible should be used.

Alternative pumping-rate and duration schedules may be appropriate in certain situations. BWA will provide guidance in these cases.

Water levels in the pumping well should be measured as frequently as necessary to observe significant changes in water levels. At a minimum, they should be monitored every 5 minutes.

If the aquifer test is run immediately after the step-drawdown test, the water levels must be allowed to fully recover after the first test before running the second. The aquifer test may not be a continuation of the last pumping step of the step-drawdown test.

. . . II.D.3. Aquifer test

An aquifer test is designed to yield information on the hydrogeologic parameters of the ground-water system. The term 'aquifer test' is used because it is principally the aquifer, rather than the well, which is being evaluated. Water is withdrawn from one well and drawdowns are measured in several observation wells. Measurements must be taken at the observation points during the background period (before pumping begins), during the test, and during the recovery period. Other influences on drawdowns (for example, outside pumping, barometric changes, or tidal effects) should either be eliminated or quantified. Time schedules for measuring water levels during these periods, as well as the lengths of the periods, are given in table 3 (page 10). The test should last for a minimum of 72 hours. Longer test periods may be required in certain cases, such as for aquifers in which delayed drainage is of concern, leaky aquifers, or confined aquifers near hydrogeologic boundaries.

The duration of the pumping period beyond the required minimum is decided by the applicant. At the end of 72 hours, the applicant should examine the drawdown data and decide if they are analyzable. If the drawdown in the well has stabilized, then equilibrium-type solutions can be applied. The applicant should extend the test if data observed during the first 72 hours warrant the extension.

To be consistent with requirements in "Standards for Construction of Public Community Water Systems" (N.J.A.C. 7:10-11, *et seq.*), public community wells being tested should be pumped at 120 percent of the maximum requested diversion rate. Any request for waivers from this volume for these types of wells must be addressed to the Bureau of Safe Drinking Water.

If the drawdown in the well has not stabilized, it is exhibiting nonequilibrium behavior. A subsurface barrier to ground-water flow retards stabilization of the cone of depression as it impedes recharge to the well. Whenever discharge from the well exceeds recharge to the drawdown cone, the cone will not stabilize. In the case of nonequilibrium pumping, the applicant should make a decision on continued monitoring of the drawdown. The decision to cease pumping after the required minimum 72-hour pumping period, therefore, is largely a function of the confidence of the applicant in successfully analyzing the test data to yield aquifer parameters.

A full-scale aquifer test requires careful planning. Most of the design considerations mentioned previously deal specifically with aquifer tests. Field personnel must install, service, and monitor all observation devices during the background, testing, and recovery periods. Backup equipment may be needed to insure an uninterrupted test. Planning for adverse weather conditions and mid-test interruptions is advised.

. . . II.D.4. Multiple-well (aquifer-stress) test

The purpose of a multiple-well test is to determine the effect of the proposed withdrawal in conjunction with any other ground-water withdrawals already occurring at or near the site. Whereas the aquifer test is aimed at determining aquifer hydraulic characteristics which permit calculation of drawdown, the multiple-well test is conducted to determine actual water levels in the aquifer under short-term, highly-stressed conditions, when the proposed well is operational. It is assumed that existing pumpage already has a quantifiable effect on water levels. The purposes of the stress test are to determine if the proposed additional pumpage will create additional drawdown, and to assess any associated impact.

The procedure for a multiple-well test involves simulating conditions of maximum planned water use. First, all nearby production wells are pumped at their maximum allowed pumpage rate for a 'background' period of 24 hours. (This is to simulate the maximum anticipated drawdowns already experienced in the area during peak use. If the test is performed during a period of less than peak use, the wells may have to be pumped at more than the current system demands. The additional water should be diverted to a storm drain or stream at a point that precludes recharge to the aquifer of interest in the test area.) Measurements are taken at all points of concern (observation wells, pumping wells, lakes, wetlands, and so on) every 6 hours during this background period.

Next, after the background period, the proposed well is pumped at its maximum allowable pumpage rate for 24 hours, the 'stress' period. During this time pumpage continues at all nearby production wells. Measurements continue to be taken at all points of concern, but at 2-hour intervals.

After the stress period, the pump in the proposed well is turned off, but pumpage continues in all nearby production wells for an additional 12 hours. During this 'recovery' period, measurements are taken at all points of concern every 2 hours.

During the entire multiple-well test, nearby production wells are pumped for a total of 60 hours. During this time pumpage should be kept constant. Pumpage variations create water-level fluctuations that complicate interpretation of the effect due only to the proposed new allocation.

In the special case where the requested new pumpage is to be supplied by more than one well, BWA will give guidance on exactly how to add the total new pumpage.

Analysis of the multiple-well test gives necessary information as to the combined impact of the total pumpage in an area before and after the introduction of a new diversion. Separating the effects of individual wells is complex, and is not necessarily the object of the stress test.

An informal report detailing the planned procedures for a multiple-well test must be submitted to BWA before the test is performed. After approval, BWA must be notified before the test begins.

II.E. Evaluate Hydrogeologic Tests

Interpreting test data requires an understanding of the hydrogeologic system and the conditions under which the test was conducted. Evaluation of the hydrogeologic setting and analysis of the data derived from the step-drawdown, aquifer, and multiple-well tests should be done by a hydrogeologist. The acceptance of an applicant's well-test report will depend, in part, on the competency of those conducting and analyzing the test.

Evaluating the hydrogeologic tests is complicated by many factors. The geologic conditions rarely match all of the assumptions required by the available analytical techniques. The hydrogeologist usually must evaluate the data using several methods and, based on professional judgment, provide a range of values for aquifer hydraulic parameters. The appendix of this report discusses selected analytical methods appropriate for various hydrogeologic settings.

. . . II.E.1. Step-drawdown analysis

Several methods are available to analyze the results of the step-drawdown test. The well-loss coefficient and well efficiency value can be calculated from the results of the test. Well efficiency is an often-confused term. Simplified, it is the ratio between the theoretical and actual specific capacity of the well. References are provided in the appendix of this report.

The pumping rate and pump size for optimum well efficiency are based on analysis of the well loss, well efficiency, drawdown, required water volume, depth of installed pump, and other engineering factors.

. . . II.E.2. Aquifer-test analysis

Numerous methods are available for analyzing aquifer-test data. Specifying which method is appropriate for all possible combinations of geologic conditions is beyond the scope of this document. Analytical techniques appropriate for the most common hydrogeologic conditions are outlined in tables 6, 7 and 8 (pages 31-33). References that discuss the analysis of aquifer-test data are in the appendix.

Aquifers can generally be grouped into three types: (1) confined (or artesian); (2) unconfined (or water table); and (3) semiconfined (or leaky-artesian). Aquifer tests, furthermore, are divided into unsteady-state (before drawdown has stabilized) and steady-state (after drawdown has stabilized). Behavior of the time/drawdown data can indicate which analytical method is most suitable for prevailing hydrogeologic conditions. A preliminary analysis of the data using more than one technique is often required before the appropriate analytical solution becomes evident.

. . . II.E.3. Multiple-well-test analysis
Conducting and analyzing a multiple-well (aquifer-stress) test is straightforward. All existing wells in an area are pumped at maximum allowable rates. Drawdown is measured at a series of observation points. (Observation points can include nearby domestic wells, other major pumping wells, streams, and surface wetlands.) Pumpage from the proposed production well is then added, keeping all other pumpage constant. Drawdown is again measured at the observation points. The entire test should last long enough to allow any additional drawdown caused by the new pumpage enough time to affect the observation points.

Analysis assumes that all additional drawdown is caused by the incremental pumpage. The total drawdown at the observation points is evaluated to determine the additional drawdown attributable to the proposed pumpage.

The additional drawdown in nearby existing wells attributable to a new allocation may or may not be significant. BWA determines significant impact on a case-by-case basis.

Another possible problem is that a new well may intercept ground water which had been flowing to a pre-existing well. This may cause greater drawdowns around the older well with resulting interference in more distant pumping wells, stream depletion, or movement of low-quality ground water.

III. FINAL HYDROGEOLOGIC REPORT TO ACCOMPANY WATER-SUPPLY DIVERSION APPLICATION

Much information is needed to properly evaluate a water-supply diversion application. An outline of all applicable items is shown in table 4 (page 17).

Some of the required information can be found in published reports. For areas with existing wells, additional information may be available through the Bureau of Water Allocation's files. Undoubtedly, some of the information will have to be generated by the applicant through a site-specific study. All of the data gathered by the applicant should be available to BWA for review; most of this will need to be submitted as part of the final hydrogeologic report.

Based on the available information, BWA can either approve, conditionally approve, or disapprove the application. BWA can also require tests to be conducted or more information to be submitted.

A discussion of the items that should be included in the final hydrogeologic report follows.

III.A. Proposed Diversion Volume
The applicant must state and justify the requested diversion volume in terms of the total yearly volume, average yearly pumping rate, maximum monthly pumpage volume, and maximum instantaneous pumping rate. The applicant must submit a general pumping schedule for the proposed well which includes an estimate of total pumpage for each month of the year. This is intended to identify wells with seasonal variation in pumpage and to ascertain if the proposed pumping schedule is consistent with the aquifer's assessed capabilities.

The application should also include an analysis of existing use, projected growth, production/consumption ratio, water-quality limitations, available interconnections, and other pertinent data in order to justify the allocation.

III.B. General Site Data
The applicant must accurately show, on a 7.5-minute U.S. Geological Survey topographic quadrangle map, the site of the proposed water-supply well. Detailed site maps pinpointing the proposed production and observation wells must also be submitted at a minimum scale of 1:6,000. All roads, pumping wells, relevant property lines, streams, wetlands, pollution sites and environmentally sensitive areas within 5 miles of the site must also be shown. Other areas which may affect or be affected by the proposed diversion should also be shown. More than one map may be required to show all necessary data at an appropriate scale.

Other pertinent information should include average local precipitation, land use, proposed development near the well location, and tidal variations, if applicable. In some cases the Bureau of Water Allocation may require average precipitation by month. Any reasonable factor which could affect the quality and quantity of water pumped from the proposed well should be discussed.

III.C. Existing Hydrogeologic Data

Many hydrogeologic factors govern ground-water occurrence, flow, and quality at a site. It is beyond the applicant's scope to conduct a field investigation of all factors. However, many state, federal and private reports cover regional hydrogeology throughout New Jersey. Additionally, logs from wells drilled at or near the site can provide valuable information. The applicant should conduct a literature search for information concerning the site and the adjacent region.

. . . III.C.1. Hydrogeologic setting

The applicant must describe the hydrogeology of the project area, including aquifer and confining unit(s) thicknesses, areal extent, outcrop areas, and relationships to other aquifers. A brief description of the hydrogeologic setting is appropriate. This description should include a discussion of the expected recharge area of the water that would supply the requested diversion.

. . . III.C.2. Aquifer properties

The applicant should submit a summary of known values for aquifer hydraulic conductivity, transmissivity, storage coefficient, thickness, and any other relevant aquifer characteristics. If nearby aquifer tests have been conducted, results from these would be a valuable supplement. A comparison between previously known values and those derived from the new test(s) is valuable.

A map of the regional ground-water flow pattern is required. This helps identify recharge and discharge areas, hydraulic heads in the various aquifers, and geologic controls on ground-water flow. The applicant should also submit an interpretation of ground-water-flow patterns based on data collected during the test period. Regional maps may be constructed from a combination of field data, well-record data, and sound hydrogeologic assumptions.

. . . III.C.3. Confining-unit properties

Confining units overlying and underlying the aquifer can exert a profound effect on the aquifer. Impermeable units can prevent local recharge or discharge (perhaps inducing recharge or discharge in more distant areas), prevent vertical migration of pollutants or saltwater, and have other effects. Leaky, semipermeable units may allow limited vertical flow. The thickness, vertical hydraulic conductivity, and areal extent of the confining units are of great importance. All available information relevant to the confining units in the vicinity of the proposed diversion site should be submitted.

. . . III.C.4. Data on other formations

Other formations in the stratigraphic column may affect the aquifer being pumped. For this reason information on the hydraulic characteristics, areal extent, water levels, nearby pumpage, known leakage, and other relevant factors in these neighboring formations is required. Of special interest are data bearing on the potential for hydraulic interconnections between water-bearing units.

. . . III.C.5. Water-quality data

The chemistry of the ground water at the site may have an effect on the suitability of the water for domestic or industrial purposes. The applicant must note whether any quality data are available. This includes any raw-water data collected for the Bureau of Safe Drinking Water for a proposed public water-supply well.

. . . III.C.6. Other pertinent data

Any other information the applicant feels would be useful in characterizing the aquifer and predicting the effect of the proposed diversion is required. All references used in preparing the application must be properly cited so as to allow for further research.

III.D. Nearby Pumpage

Public-supply and major pumping wells yielding more than 100,000 gallons per day within 5 miles of the proposed diversion must be identified, regardless of the aquifer tapped. The pump capacity is required for each major well cited. Assistance can be provided by the Bureau of Water Allocation.

All domestic wells within a 1-mile radius of the proposed well should be identified. If a major subdivision (50 homes or more) with individual wells lies between 1 and 3 miles from the site, simply locating the subdivision and giving the total number of wells and average well depth is acceptable. BWA has well records and well permits available for public review. An appointment is necessary in order to view BWA's records.

III.E. Well and Pump Information

The applicant must present data on planned construction of the production well. This includes total depth, screen and casing specifications, and any other pertinent data.

Technical specifications of the permanent pump, along with the pump's performance curve and proposed installation depth, are required. If these data are not available

Table 4. Items required in the final hydrogeologic report.

1. Proposed diversion
   - -total yearly pumpage
   - -maximum monthly pumpage
   - -proposed pumpage schedule

2. Site data
   - -roads, property lines, buildings
   - -nearby environmentally sensitive areas
   - -nearby surface-water bodies, streams, and wetlands
   - -nearby pollution sites
   - -maps at appropriate scales (U.S.G.S. 1:24,000 quadrangle scale map, site map at 1:6,000 or larger)
   - -other pertinent information

3. Hydrogeologic data
   - -thickness, areal extent, and recharge areas of aquifer
   - -thickness and areal extent of any confining units
   - -thickness, areal extent, and recharge areas of any other aquifers at the site
   - -hydrogeologic parameters of all aquifers pertaining to the diversion
   - -hydrogeologic parameters of all confining units pertaining to the diversion
   - -discussion of generalized flow path in aquifer
   - -recharge/discharge estimates
   - -any pertinent water-quality data
   - -other pertinent information

4. Nearby pumpage
   - -domestic wells within 1 mile
   - -all allocation permits within 5 miles (with pumping rates)
   - -all public-supply wells within 5 miles (with pumping rates)

5. Pumping and observation-well information
   - -casing diameter, type, and depth
   - -screen length, depth, and slot size
   - -gravel pack specifications
   - -well development method(s)
   - -prior tested (efficiency, specific capacity)
   - -size, installation depth, and rating curve of final pump
   - -other pertinent information

6. Test description
   - -type of test(s)
   - -field procedures used
   - -changes from pretest proposal

7. Test data
   - -all measurements made during background period
   - -all measurements made during test period
   - -all measurements made during recovery period

8. Test analyses
   - -analysis method(s) used and appropriateness
   - -calculated values
   - -consistency of calculated values with previous values
   - -discussion of any data or analysis anomalies
   - -estimated accuracy of results

9. Regional effects
   - -other ground- and surface-water users
   - -saltwater intrusion sites
   - -environmentally sensitive areas
   - -dependable yield of the aquifer
   - -regional ground-water model
   - -surface water, streams, wetlands

10. Other regulatory considerations
    - -ground-water pollution
    - -ground-water impact areas
    - -water-supply critical areas
    - -environmentally sensitive areas
    - -other relevant considerations

at the time of application, they should be submitted when available. If pump performance is being submitted to the Bureau of Safe Drinking Water, then it need not be also submitted as part of this report.

If the well has been pumped previously, its performance history is needed, including pumping rates and drawdowns from any previous aquifer tests. If the well has been geophysically logged by downhole methods, or by a TV log, the log is also required.

Any other factor which might affect the performance of the well and/or pump, such as age and redevelopment techniques, should be identified.

III.F. Test Procedures

The report must specify the procedures used during testing of the proposed production well. This includes a description of measurement devices, locations and schedules of measurements, variations in discharge, and all other relevant procedures.

Any changes from the planned test procedures must be noted, highlighted, and explained in the final report.

III.G. Test Data

All data taken during the test must be reported. These include water levels at all monitoring points, pumping rates, barometric pressure, streamflow volumes, precipitation, and all other relevant data. It is recommended that these data be added to the report in an appendix. It would be helpful if the applicant would submit the information additionally in the form of a file (or files) on a computer data disk.

III.H. Test Analyses

All analyses of the test data must be reported. In addition to reporting the final values, the applicant must supply worksheets or graphs showing the calculations. If computer software was used in interpretation, it must be identified, along with representative printouts of calculation techniques.

III.I. Radius of Influence

The radius of influence of a pumping well defines an area that experiences an effect attributable to that pumping well. This concept is easy to state but is in practice difficult to quantify. BWA considers the radius of influence to be that area which experiences one foot or more of ground-water drawdown when water levels have completely stabilized in response to the proposed allocation's maximum demand.

In a water-bearing unit which meets *all* theoretical conditions of an ideal confined aquifer, the radius of influence extends an infinite distance from the pumping well. The aquifer receives no recharge and a pumping well will eventually influence all parts of the aquifer.

In a strict sense, no water-bearing unit in New Jersey meets all of the requirements of an ideal confined aquifer. All aquifers have a source of recharge, perhaps an outcrop area many miles away, or slow leakage from an adjacent unit. However, if the recharge is sufficiently slow or far away, then the aquifer will appear to be confined for a test of the duration required by BWA.

Radius-of-influence calculations are not the only indicator of those areas subject to adverse effects. BWA reserves the right to establish areas of significant impact outside a calculated radius of influence.

Five methods for calculating the radius of influence are presented here. There may be others just as acceptable; no single method is appropriate in all situations. In making an estimate of the radius of influence of a pumping well it is important to determine whether water levels have completely stabilized. This may not happen during a 72-hour aquifer test. If it doesn't, then water levels should be projected to stable levels.

The first method, perhaps the most popular, is the Jacob distance-drawdown method for multiple observation wells in a confined aquifer. On a semilog graph, drawdown in each well at a specified time is plotted on the linear scale while distance is shown on the logarithmic scale. A line drawn through the drawdown data can be extended to show the distance at which drawdown is zero. This distance is then interpreted to be the radius of influence. One problem with this method is that the line drawn depends upon the time at which the measurements were taken and the rate at which the well was pumped. The radius of influence thus could be different for different times and pumping rates; there is no unique radius of influence. Additionally, this methodology is based upon a confined-aquifer analysis technique and does not explicitly allow for any recharge.

The second method predicts the distance from a pumping well at which a specified drawdown (1 foot, for example) will occur after a specified period of time (1 year, for example), assuming no recharge takes place. This method uses values of transmissivity and storage derived from hydrogeologic tests. The assumption is then made that, in the real world, the aquifer receives recharge. Thus this calculation results in a conservative estimate of that area actually affected by pumping. This calculation, like the Jacob graphic solution, is highly dependent upon the drawdown and time chosen.

The third determines, by an appropriate method, the average yearly ground-water recharge in the area of the well. The radius of influence is then assumed to be that distance from the pumping well which encompasses enough area to provide sufficient ground-water recharge to offset pumpage. This method makes no allowance for input from ground-water flow or the changes in the area of influence of the well in years of higher or lower ground-water recharge.

The fourth method calculates the area the pumping well would dewater in one year if there were no recharge at all. The assumption is then made that over the course of a year there would probably be enough recharge to balance the ground-water pumpage and the calculated distance is therefore a conservative estimate.

A fifth method for calculating the radius of influence, and perhaps the most useful when done correctly, is to construct a numerical model of ground-water flow in the aquifer. By accurately modeling the aquifer, leakage and recharge, boundaries and other hydrogeological features, a complete estimation can be made of the possible impact of a proposed diversion under steady-state conditions.

Radius-of-influence calculations are highly dependent upon the professional judgment of the person doing the calculations. It is advisable to calculate this value several different ways and to compare the results.

III.J. Regional Impacts

The applicant must investigate regional impacts of the requested diversion. The following section addresses some possible impacts which should be considered.

. . . III.J.1. Previous ground-water users

Any diversion may cause additional drawdown at nearby pumping centers. This well interference may be significant, depending on the hydrogeology of the area, volume of ground water involved, and distance to other pumping wells. Regulations require that existing ground-water users be free of adverse effects from new allocations. It is the responsibility of the applicant to show to what degree the new diversion will affect other ground-water users. Any process which lessens the ground-water yield of previously approved diversions may be viewed by BWA as adequate cause for denial of an application. The determination of adverse impact on other ground-water users may be made even in the absence of objections from other users.

. . . III.J.2. Saltwater intrusion

Some areas of the state are experiencing ground-water quality changes associated with saltwater intrusion. Pumpage near areas with water of elevated chloride concentrations may accelerate this degradation of water quality. Diversion applications near such areas must address the possibility of inducing saltwater into the proposed pumping well, or into other pumping wells. Saltwater intrusion may come from the ocean or from connate water already in or near an aquifer. The water may move laterally from a recharge area under the ocean, leak upward from an underlying formation (upconing), or leak down from an overlying formation containing saltwater. All of these possibilities should be considered.

. . . III.J.3. Environmental impacts

The applicant must show that the proposed diversion will not adversely affect the natural environment. The applicant must analyze the effect of the diversion on nearby surface waters and on their ecology.

. . . III.J.4. Dependable yield

The total amount of water withdrawn from an aquifer should not exceed the "dependable yield" of the aquifer (N.J.A.C. 7:19-6 *et seq.*). Many definitions have been offered for dependable yield. No one definition is suitable in all cases. Instead of dependable yield it may be better to use the term 'acceptable yield.' This is the yield which will not result in unacceptable effects on other ground-water and surface-water users and the environment.

An aquifer supplies water to wells by taking it from one or more of three sources. First, the aquifer could take in more water from its recharge zones. Second, the aquifer could allow less water to exit in discharge zones. Third, the water could be removed from storage in the aquifer by lowering water levels. All three of these sources could be adversely impacted by a diversion.

Calculating the acceptability of the proposed diversion is a three-step process. First, it requires estimating the effects of the withdrawal on water levels, recharge, and discharge. Next it requires estimating the effects of the changes on other ground-water users, stream flow, wetlands, polluted ground water, and any other point of concern. Third, the impacts upon each of the items defined in the second step must determined to be acceptable or unacceptable by the Bureau of Water Allocation.

The Water Allocation Permit procedures, as outlined in NJAC 7:19-1,2,3 *et seq.*, detail what is required by the

Bureau of Water Allocation and outlines the decision making process.

. . . III.J.5. Regional ground-water models

Ground-water models may be used to determine the regional impacts of a proposed diversion. The accurate development and appropriate use of a ground-water model requires an understanding of the geologic framework, hydrology, and hydraulic properties of the aquifer system. Many considerations must be taken into account when building a model. One important point is that the area the model covers affects the preciseness of results. In general, the larger the area covered, the less detail the model provides about any one particular point.

BWA does not routinely require using ground-water models for water-allocation permit applications. However, models may be employed by BWA or the applicant in specific, complex cases. If ground-water modeling is proposed, then it must be discussed in detail in the report to allow a thorough review by BWA.

III.K. Other Regulatory Considerations

The process of locating, testing, and gaining approval of a major water-supply well will be affected by a great number of regulatory programs. It is the responsibility of the applicant to identify and meet all regulatory requirements. The following discussion of programs is not exhaustive, but serves as a starting point. A thorough diversion application will identify all areas of concern and address them.

. . . III.K.1. Ground-water pollution

Any pumping near a ground-water pollution site which could cause movement of contaminated ground water, or cause interference with a remedial action scheme, is of great concern. Applicants should note the location of any nearby ground-water contamination sites. The Ground-Water Quality Management Element maintains an inventory of such sites. The applicant must evaluate the potential of contamination of the ground water to be produced by the well.

Ground-Water Impact Areas have been designated in some localities of widespread ground-water pollution. Additional restrictions or constraints may be placed on wells drilled in these areas. BWA maintains a list of these areas.

. . . III.K.2. Water-Supply Critical Areas

The Water-Supply Critical Area program restricts ground-water pumpage in several counties and aquifers in New Jersey. This program allows new pumping from the designated aquifers only after an extensive review of the water-supply needs and the potential impacts of the pumping. The Water Supply Element maintains maps delineating current Critical Areas and can provide explanations of any pumpage restrictions (N.J.A.C. 7:19-6).

. . . III.K.3. Environmentally sensitive areas

The application should investigate environmentally sensitive areas and estimate the impact of enhanced pumping on these areas. NJDEPE, along with regional planning commissions, maintains special regulations for certain environmentally sensitive areas in the state. NJDEPE maintains a distinct set of water-quality standards for the New Jersey Pinelands, where land use is regulated by the Pinelands Commission. Any ground-water withdrawals that could affect the Pinelands are reviewed by the Pinelands Commission in addition to the regular DEPE review. Within NJDEPE, the Division of Fish and Game may review an application to determine if the requested ground-water diversion will affect streamflow critical to wildlife.

. . . III.K.4. Bureau of Safe Drinking Water

The Bureau of Safe Drinking Water (BSDW) is responsible for protecting public-supply wells (N.J.A.C.7:10-11.1 and 12.1). Contacting BSDW at the beginning of the process of applying for such a well, and becoming familiar with its requirements, may prevent misunderstandings and delays later in the approval process.

. . . III.K.5. Local regulations

County and/or municipal regulations may affect the drilling of a well and conducting of an aquifer test. Possible areas of concern include the need for additional well permits, construction of access roads, sediment control, test requirements, and so on. The applicant should investigate what local regulations apply by contacting the county or local health department, engineering or planning department, and/or Soil Conservation District.

IV. ORGANIZATIONAL AND REGULATORY INFORMATION

The New Jersey Department of Environmental Protection and Energy, Water Supply Element, Bureau of Water Allocation is the office directly concerned with the issuance of permits for ground-water withdrawals. However, a series of other organizations may be involved during the process of obtaining an allocation permit. The following list is intended to be a guide to the State's regulatory organization. It is, however, not comprehensive.

The publication "Easy Access" is the offices directory for the New Jersey DEPE. It is very helpful when navigating through the sometimes bewildering array of Bureaus, Elements, Divisions and Programs. A copy of this report (which is referred to as 'Easy Access') can be obtained from:

Division of Financial Management and General Services
Department of Environmental Protection & Energy
CN 402
Trenton, NJ 08625 (609) 292-1553

IV.A. Organizational Structure

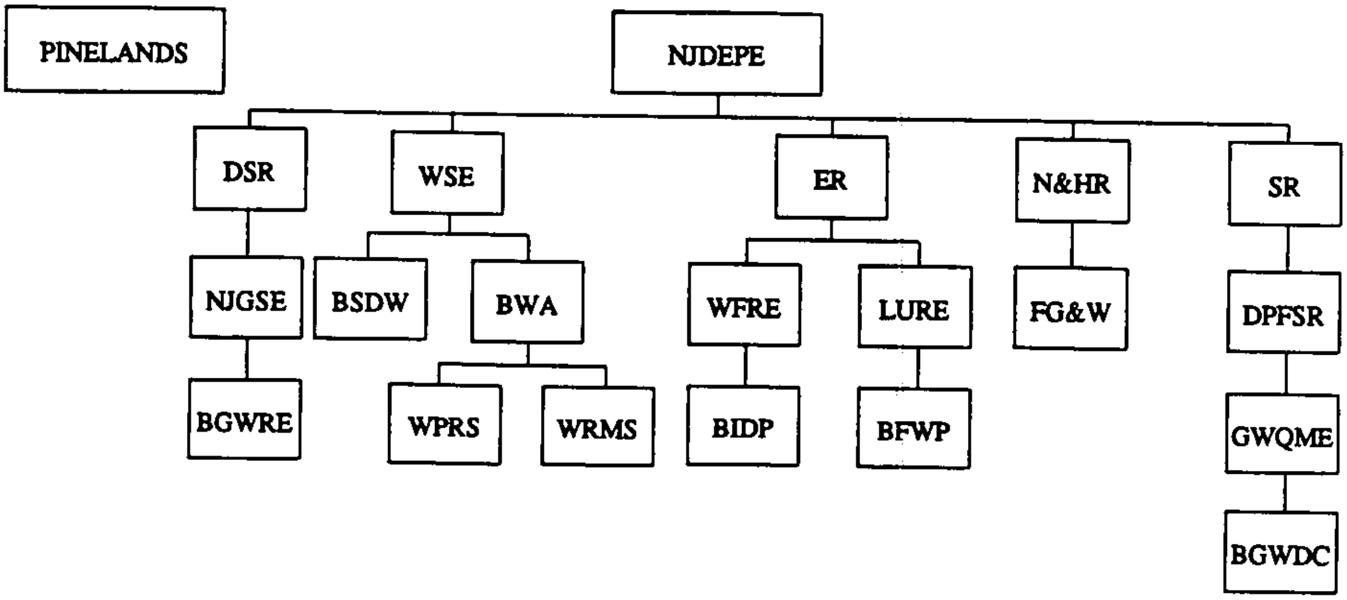
The New Jersey Department of Environmental Protection and Energy (NJDEPE or DEPE) is divided into several Divisions and Programs. These in turn are subdivided. Figure 3 (page 24) is an organizational chart of some of the DEPE bureaus an applicant for a ground-water allocation is likely to encounter.

Occasionally the Department reorganizes. The divisional breakdown listed here, as well as the telephone numbers, were current in March 1992.

IV.B. Regulatory Authorization

A wide range of regulations has been promulgated giving the NJDEPE authority over environmental matters. A partial listing is given in table 5. The applicant must ascertain which programs are relevant to his or her specific situation. A staff member of one program may not be able to, nor should be expected to, give guidance concerning a different program.

State Organizations



ABBREVIATION	BUREAU/ORGANIZATION	PHONE*
BFWP	Bureau of Freshwater Wetlands Permits	633-6563
BGWDC	Bureau of Ground-Water Discharge Control	292-0424
BGWRE	Bureau of Ground-Water Resources Evaluation	984-6587
BIDP	Bureau of Industrial Discharge Permits	292-4860
BSDW	Bureau of Safe Drinking Water	292-5550
BWA	Bureau of Water Allocation	292-2957
DPFSR	Division of Publicly Funded Site Remediation	292-9120
DSR	Division of Science and Research	984-6070
ER	Environmental Regulation	292-2795
FG&W	Division of Fish, Game & Wildlife	292-2965
GWQME	Ground-Water Quality Management Element	292-5262
LURE	Land Use Regulation Element	984-3444
NJDEPE	New Jersey Deparment of Environmental Protection & Energy	292-3131
NJGSE	New Jersey Geological Survey Element	292-1185
N&HR	Natural and Historical Resources	292-3541
Pinelands	Pinelands Commission	894-9344
SR	Site Remediation	292-9120
WFRE	Wastewater Facilities Regulation Element	292-4543
WPRS	Well Permit and Regulation Section	984-6831
WRMS	Water Resources Management Section	292-2957
WSE	Water Supply Element	292-7219

* All phone numbers current as of March 1992 and in area code 609.

Figure 3. Partial organizational chart of state agencies.

Table 5. Programs and regulations applicable to aquifer testing and water-supply wells.

Bureau of Water Allocation programs:	
PROGRAM	**REGULATIONS**
Water Allocation permits	N.J.A.C. 7:19-1,2,3 *et seq.*
Water Allocation general management regulations	N.J.A.C. 7:19-6
Sealing of abandoned wells	N.J.A.C. 7:9-9
Agricultural water use certifications	N.J.A.C. 7:20A-1,2

Bureau of Safe Drinking Water Programs:	
PROGRAM	**REGULATIONS**
Physical connection permits	N.J.A.C. 7:10-1 *et seq.*
Standards for the construction of public non-community and non-public water systems	N.J.A.C. 7:10-12.1 *et seq.*
Standards for the construction of public community water systems	N.J.A.C. 7:10-11.1 *et seq.*
Surface-water quality standards	N.J.A.C. 7:9-4.15
Ground-water quality standards	N.J.A.C. 7:9-6

Wastewater Facilities Regulation Element programs:	
PROGRAM	**REGULATIONS**
New Jersey Pollution Discharge Elimination System	N.J.A.C. 7:14A-1.1 *et seq.*
Discharge permits	N.J.A.C. 7:14A-1.1 *et seq.*

Land Use Regulation Element programs:	
PROGRAM	**REGULATIONS**
Freshwater wetlands	N.J.A.C. 7:7A-1 *et seq.*

Pinelands Commission programs:	
PROGRAM	**REGULATIONS**
Pinelands Management Act	N.J.A.C. 7:50-4,5,6

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Ordering information (current as of July 1991)

N.J. Geological Survey publications may be ordered from:

Maps and Publications Sales Office
Bureau of Revenue
CN-417
Trenton, NJ 08625
phone: (609) 777-1038

U.S. Geological Survey publications may be ordered from:

USGS Books and Reports Section
Box 25425
Denver, CO 80225
phone: (303) 236-7476

APPENDIX
AQUIFER-TEST-ANALYSIS PROCEDURES

Based on hydrogeologic and test conditions, water levels can respond to an aquifer test in a variety of ways. Understanding the physical system must precede data analysis to prevent the use of an inappropriate technique. The following sections discuss the types of aquifers, aquifer tests, and some of the assumptions required by the analysis techniques.

TYPES OF AQUIFERS

An aquifer is a saturated hydrogeologic unit able to yield significant quantities of water to a well or spring. Aquifers are commonly classified as unconfined, confined, or semiconfined. This classification is based on the hydrogeologic properties of the units overlying and underlying the aquifer and the water level in the aquifer in relation to the top of the aquifer. Water levels in the three different types of aquifers respond differently to pumping.

Additionally, aquifers are classified by lithologic characteristics. Features such as degree of consolidation, amount of fracturing, and type of porosity are used to convey information about a unit's hydrogeologic properties. On this basis, aquifers are broadly classified as unconsolidated aquifer types or bedrock aquifer types.

Confined Aquifers

A confined aquifer is overlain and underlain by relatively impermeable units through which ground-water flow is nonexistent or negligible. All voids in the aquifer are filled with water at a pressure greater than atmospheric. The potentiometric head in the confined aquifer is at a level higher than the top of the aquifer.

During aquifer and multiple-well tests, the potentiometric head in the confined aquifer remains above the top of the aquifer; no dewatering of the aquifer occurs. Recharge to the aquifer from overlying or underlying units is minimal. All water produced by the well comes from water moving laterally in the aquifer towards pumping centers.

Unconfined Aquifers

An unconfined aquifer is bounded above by the water table, not an impermeable unit. The potentiometric head in the aquifer is at the elevation of the water table.

During an aquifer or multiple-well test, the water level falls in response to pumping. Declines in water-level release water from storage. This water, along with water already moving laterally through the aquifer, is the source of water which is discharged from a pumping well.

If, during the course of an aquifer test in an unconfined aquifer, the water-table elevation changes by less than 5 percent of the saturated thickness, the data may be suitable for analysis by a confined-aquifer method. This decision is at the discretion of the hydrogeologist analyzing the data. Otherwise, the change in saturated thickness of the aquifer caused by drawdown during the test must be accounted for in the analysis of the data.

Semiconfined Aquifers

A semiconfined aquifer is similar to a confined one except that the overlying and/or underlying units are not impermeable; a limited volume of ground water flows through them into the aquifer. All voids in the aquifer are filled with water which is at a pressure greater than atmospheric. The potentiometric head in the aquifer is above the top of the aquifer.

During an aquifer or multiple-well test, the potentiometric head remains above the top of the semiconfined aquifer; no dewatering occurs. Recharge from overlying or underlying units depends upon the drawdown in the semiconfined aquifer and the permeability of the confining units. Water produced by the well comes either from water moving laterally in the aquifer towards pumping centers or from leakage from the underlying and/or overlying units.

A semiconfined aquifer can be recognized in at least three ways. (1) Lithologic information on the confining units may indicate that the units are not fully confining and may allow some leakage. (2) Water levels in the presumed semiconfining units or the layers directly overlying or underlying them may change during the aquifer test. If the water level in a semiconfining unit changes by 5 percent or more of its thickness, and this change can be attributed to pumping from the underlying aquifer, then this layer is presumed to be contributing water to the underlying aquifer. In such cases a methodology applicable to semiconfined aquifers must be used when analyzing all test data. (3) The observed drawdown data may match theoretical type curves. If the data fit a theoretical semiconfined-aquifer type curve and not the confined-aquifer type curve, then the aquifer probably is semiconfined.

As a general principle, it is always advisable to attempt to fit observed data to both confined and semiconfined type curves. This lessens the probability of neglecting any vertical leakage.

Unconsolidated Aquifers
Unconsolidated aquifers are generally gravel and sand deposits interbedded with relatively minor amounts of silt and clay. The materials may be compacted somewhat, but lithification due to cementation is minor or absent. The deposits retain much of their original intergranular porosity. Overall permeability of an unconsolidated aquifer can be strongly influenced by any continuous silt or clay layers in the deposit.

Consolidated Aquifers
In a consolidated aquifer, the grains are cemented or compacted into a firm and cohesive mass. Consolidated aquifers are also called bedrock aquifers. Consolidated aquifers can be made up of igneous, metamorphic, or sedimentary rock.

Secondary porosity is generally the prime mechanism for ground-water movement in consolidated aquifers, though primary porosity may be present in some clastic sedimentary rocks. The porosity of consolidated aquifers tends to be much lower than that of unconsolidated aquifers. Joints and other fractures are the most common source of secondary porosity. In carbonate rock aquifers, chemical dissolution is another source of porosity. The distribution and orientation of the secondary-porosity structures can be the dominant factors in controlling the hydrogeologic characteristics of the aquifer. The most common phenomena observed during aquifer tests are anisotropy and complex responses in storage behavior.

TYPES OF AQUIFER TESTS

Steady and Unsteady Aquifer Tests
Aquifer tests are divided into two types, steady state and unsteady state, based on observed drawdown in the pumping well or in an observation well.

In a steady-state test, water levels do not change with time; they have reached a stable level which balances pumpage with water flowing to the pumping well. Commonly, data from steady-state tests are used in a distance-drawdown analysis method, which requires data from more than one observation well.

An unsteady-state test utilizes drawdown data gathered during the fall of water levels immediately following the start of the pump. Usually the data are plotted one well at a time, with observed drawdown plotted against elapsed time. The tests are said to be unsteady-state tests because the water levels have not reached equilibrium. In an unsteady-state test the changing water levels from one well are analyzed to yield aquifer properties.

The question of exactly when water levels in a well reach a steady (or equilibrium) state is often debated. If the aquifer being tested is a true confined aquifer, then it will theoretically never reach equilibrium. Certainly, when the rate of drawdown has slowed to inches per day the water level could be considered to be close to steady state.

No specific rate of decline is established here to define stabilization. A judgment that stabilization has been reached is a decision based on the slope of the time/drawdown plot(s). An often-used standard is an average decline in water level in an observation well of 1 to 1.5 inches per hour. The Bureau of Safe Drinking Water considers stabilization to have occurred if drawdown has been less than 6 inches over a six hour period. By testing equilibrium versus nonequilibrium solutions on the data, the applicant can determine if the correct assessment has been made.

Good references for the theory, design, and analysis of aquifer tests are Bentall (1963a, 1963b), Ferris and others (1962), Kruseman and others (1990), Lohman (1972), Reed (1980), and Stallman (1971).

Testing of Bedrock Aquifers
The theory underlying the aquifer tests mentioned above assumes that the aquifer is homogeneous and, usually, isotropic. This is frequently not the case for fractured-bedrock aquifers. An additional limiting factor is that most analytic methods are best suited for unconsolidated aquifers which have well defined overlying and underlying boundaries. In a consolidated formation of unknown depth, the effective aquifer thickness can be open to question.

Because of these limiting factors, the analytical techniques developed for confined, unconfined and semiconfined conditions are most accurately applied to unconsolidated aquifers. A separate set of solutions has been developed for fractured bedrock aquifers.

Choice of Testing Methodology
No rigid guidelines are established here to indicate which specific technique to use in each situation; often more than one method is available. Tables 6, 7, and 8 (pages 31, 32, 33) list analytical techniques that are appropriate under various hydrogeologic conditions. Each technique is applicable under specific sets of assumptions. The applicant should attempt to satisfy the assumptions associated with the analytical technique before applying it in the aquifer-test evaluation.

Assumptions and Common Violations
All methods of analyzing aquifer test data require some assumptions as to the hydrogeologic nature of the aquifer and the nature of the test. The assumptions are rarely entirely satisfied.

Basic Assumptions
The first aquifer-test-analysis methods developed were applicable to a specific type of aquifer. This aquifer is assumed to be:

- confined;
- homogeneous (all parts of the aquifer are exactly the same as all other parts);
- isotropic (the hydrogeologic properties of the aquifer are constant regardless of the direction of ground-water flow);
- areally infinite (has no boundaries) and of uniform thickness;
- all monitoring and observation wells fully penetrate the aquifer and are fully screened;
- the pumping rate is constant throughout the test;
- storage of water is negligible;
- water removed from storage is discharged immediately once the head declines, and;
- prior to pumping the potentiometric surface is horizontal.

Subsequent work has addressed the following common violations of these basic assumptions:

Partially-Penetrating Wells
If the pumping well fully penetrates the confined aquifer, then ground-water flow towards the pumping well is horizontal. For the purposes of these guidelines, a well is considered to fully penetrate the aquifer if it is screened through 80 percent or more of the aquifer's saturated thickness. If it is screened through a smaller percentage, vertical flow in the aquifer may affect water levels in nearby observation wells. If the pumping well does not meet the criteria for a fully penetrating well, then the aquifer-test-analysis method used should be appropriate to a partially-penetrating well situation.

In general, the closest observation well should be at a distance of 1.5 times the saturated thickness of the aquifer from a partially-penetrating pumping well to avoid problems associated with vertical water flow near the well screen.

Variable Discharge Rate
One assumption often violated is that there is no variation of the pumping rate during the aquifer test. A constant pumping rate is very hard to achieve. For the purpose of these guidelines, if the pumpage does not vary by more than 10 percent during the test it can be considered to be at a constant rate.

To hold the pumping-rate variation to a minimum it is recommended that the pump work against a partially closed discharge valve. This valve can be progressively opened to maintain a constant discharge rate as the pump output falls off due to the extra lift required as the water level drops. A valve also permits varying the output to reduce the effects of mechanical, atmospheric or electrical variations.

If the pumping rate does vary significantly, a suitable methodology must be used to analyze the data. For a confined aquifer, where the saturated thickness does not change, the principle of superposition can be used to account for variations in pumpage rates. For more detail see Eden and Hazel (1973) and Jacob (1946).

The step test is a special case of the variable-discharge-rate aquifer test. This test is performed in order to analyze the efficiency of the well at different pumping rates. For more detail see Brereton (1979), Clark (1979), Labadie and Helweg (1975), Lennox (1966), Nahm (1980), Rorabaugh (1953), Sheahan (1971), and Sternberg (1968).

Delayed Yield
In an unconfined aquifer, water is discharged from aquifer storage as the water level declines. This change in storage may not occur instantaneously, but is prolonged by the time required to drain openings above the saturated zone. Delayed yield is the process that yields water to the pumping well after the water level has declined, before steady state has been reached.

Delayed yield of water may flatten out the drawdown curve and simulate a steady-state condition. However, once delayed yield is over, water levels may drop again until a steady state is achieved.

Delayed yield should be considered and accounted for in all unconfined-aquifer tests. This may require extending the length of the test, sometimes to many days. If lengthening the test is not practical, the long-term effects of delayed yield should be evaluated by an alternate method in order to assess long-term drawdown.

Aquifer Boundaries

If an aquifer test is conducted near a boundary of an aquifer, that boundary may affect observed water levels. A no-flow boundary (one which contributes no ground-water flow) increases drawdown. Such boundaries can be detected in the time/drawdown data as a sudden water-level decline in one or more observation wells.

A constant head boundary (such as a perennial stream) may contribute significant recharge to the aquifer, lessening drawdown. Such a boundary is usually evidenced in the time/drawdown data by sudden stabilization of water levels.

Boundaries such as these may be accounted for in the analysis by the use of image wells and the principle of superposition. The details are covered in many basic ground-water texts.

Anisotropic Aquifers

An aquifer whose hydrogeologic properties vary in different directions is said to be anisotropic. In rock aquifers which trend in a preferential direction, for instance, anisotropy may be an extremely important factor governing ground-water flow. Such flow can be accounted for if the principle directions of anisotropy are known. Anisotropy may be identified on the basis of geologic evidence or predominant drawdown directions. If anisotropy affects water levels during an aquifer test, calculated aquifer properties may be inaccurate for the aquifer as a whole, but may be useful to describe effects in a specific direction.

Multiple-Well Tests

In a confined aquifer the principle of superposition can be used to analyze the effect of several wells pumping simultaneously. Theoretically, the total drawdown is the simple sum of the drawdown caused by each individual pumping well.

In an unconfined aquifer this principle cannot be used. More complex methods, such as those based on a computer model, may be required.

The strength of a multiple-well test is that it measures actual drawdowns under anticipated everyday operating conditions. The usual goal of a multiple-well test is not to estimate aquifer properties, but to predict drawdowns at important points (at other wells, streams, or wetlands, for example) at key times. Thus, analysis of these tests is often a matter of plotting drawdowns and analyzing actual effects, rather than engaging in a formal mathematical treatment.

Fractured-Rock aquifers

In a fractured rock aquifer, the aquifer matrix is largely impermeable. Instead, fractures and other structural features in the rock provide the major conduits for movement of fluids.

Typically, analytic techniques focus on a dominant characteristic or feature of the aquifer, such as a long, well-developed fracture zone, with boundaries or other aquifer properties idealized and assigned constant values. Some approaches conceptualize fractures as important for movement of ground water, but relatively insignificant as reservoirs of ground-water storage. These methods assume the bulk of ground-water storage comes from the aquifer matrix. Other approaches consider ground-water storage in both the fractures and in the aquifer matrix.

Table 8 (page 33) highlights methodologies that address specific features of fractured-rock aquifers, such as anisotropy, effects of storage release, and contrasts in transmissivities of the bulk aquifer matrix and fractures. Originally developed for analysis of granular aquifers, the anisotropy methodologies listed in table 8 have practical application in fractured-rock settings where the test conditions do not seriously compromise the boundary conditions specified in the conventional analysis of transmissivity and storativity.

The other methodologies listed in table 8 are analytical techniques directed at phenomena customarily observed in fractured-rock aquifers. The double-porosity models address the relative roles of fractures and the aquifer matrix (or "block") as sources of ground-water storage. The release of water from these sources results in a time-drawdown response which appears similar to the delayed-yield response of unconfined aquifers. The single-fracture models focus on interaction of the aquifer matrix and a fracture penetrated by a production well. For wells located on a fracture or fracture system, the early time-drawdown data often exhibit a diagnostic half-slope (0.5) on a log-log plot.

There are excellent overviews of these analytic methods and examples of their application in Sauveplane (1984) and Houlden (1984).

In some cases fractured rock aquifers may be analyzed as unconfined aquifers because they exhibit similar time/drawdown characteristics. During the early part of a test the fractures contribute water to the well. During the midsection part, pores and smaller fractures are dewatered, leading to the appearance of delayed yield. During the late part of the test water comes to the well from fractures farther away.

Much work has been done trying to systematize the analysis of fractured-rock aquifer tests. As examples, see Boulton and Streltsova (1977, 1978), Gringarten (1982), Gringarten and Witherspoon (1972), Hantush (1966), Houlden (1984), Jenkins and Prentice (1982), Neuman and others (1984), Papadopulos (1965), Sauveplane (1984), and Way and McKee (1982).

Solution-Channeled Limestone and Dolomite Aquifers
Fractured, solution-channeled limestone and dolomite rocks may pose specific hydrogeological conditions. Weathered carbonate rocks normally contain cavernous zones developed as a result of chemical dissolution along joints, bedding planes, and other planar surfaces. Solution mechanisms in carbonate rocks favor the development of larger openings at the expense of smaller ones. Thus, some of the analytical methods that focus on long, well developed fractures may be particularly applicable to solution-channeled aquifers. The block-and-fissure model used to describe fractured rock aquifers may be particularly useful in carbonate aquifers where solution-channel development is significant.

Carbonate rocks can be highly anisotropic and nonhomogeneous on a localized scale, but may behave more homogeneously on a regional scale. In many cases solution-channeled aquifers behave like fractured-rock aquifers and can be analyzed as such. In general, methods that recognize water table and/or leaky artesian conditions may be extremely useful in analyzing aquifer tests in fractured and solution-channeled carbonate-rock aquifers.

Table 6. Types of aquifer-test analyses for 'uncomplicated' situations (modified from Kruseman and DeRidder, 1979, who describe and reference all of the methodologies).

Assumptions: Aquifer is homogeneous, isotropic, areally infinite, and of uniform thickness. Pumping and observation wells fully penetrate and screen the aquifer. Prior to pumping the piezometric surface is horizontal. Discharge rate is constant and storage in the well can be neglected. Water removed from storage is discharged instantaneously with decline of head.

AQUIFER TYPE	TYPE OF SOLUTION	NAME OF SOLUTION	METHOD OF SOLUTION
confined	steady-state	Thiem	calculation
	unsteady-state	Theis	curve fitting
		Chow	nomogram
		Jacob	straight line
		Theis recovery	straignt line
semiconfined	steady-state	DeGlee	curve fitting
		Hantush Jacob	straight line
		Ernst modification of Thiem method	calculation
	unsteady-state	Walton	curve fitting
		Hantush I	inflection point
		Hantush II	inflection point
		Hantush III	curve fitting
unconfined with delayed yield	unsteady-state	Boulton	curve fitting
semiunconfined with delayed yield	unsteady-state	Boulton	curve fitting
unconfined	steady-state	Thiem-Dupuit	calculation
	unsteady-state	Thiem*	calculation
		Theis*	
		Chow*	
		Jacob*	

* Solutions for the confined, unsteady-state case can be applied to the unconfined, unsteady-state case only if the drawdown is modified by an appropriate factor. See Kruseman and DeRidder, 1979, for more detail.

Table 7. Types of aquifer-test analyses for 'complicated' situations (modified from Kruseman and De Ridder, 1979, who describe and reference all of the methodologies).

Assumptions: Aquifer is homogeneous, isotropic, areally infinite, and of uniform thickness. Pumping and observation wells fully penetrate and screen the aquifer. Prior to pumping the piezometric surface is horizontal. Discharge rate is constant and storage in the well can be neglected. Water removed from storage is discharged instantaneously with decline of head.

Modified assumption	Aquifer type	Type of solution	Name of solution	Method of solution
aquifer crossed by one or more fully penetrating recharge or barrier boundries	confined or unconfined	steady-state	Dietz	calculation
		unsteady-state	Stallam	curve fitting
			Hantush	straight line image
aquifer homogeneous, anisotropic and of uniform thickness	confined or unconfined	unsteady-state	Hantush	calculation
			Hantush - Thomas	calculation
	semiconfined	unsteady-state	Hantush	calculation
aquifer homogeneous and isotropic but thickness varies exponentially	confined	unsteady-state	Hantush	curve fitting
prior to pumping the potentiometric surface slopes	unconfined	steady-state	culmination	calculation point
		unsteady-state	Hantush	curve fitting
discharge rate variable	confined or unconfined	unsteady-state	Cooper-Jacob	straight line
			Aron-Scott	straight line
			Sternberg	straight line
			Sternberg recovery	straight line
partially penetrating pumping well	confined	steady-state	Huisman correction I and II	calculation
			Jacob correction	calculation
	semiconfined	steady-state	Huisman correction I and II	calculation
	unconfined	steady-state	Hantush correction	calculation
	confined	unsteady-state	Hantush modification of Theis	curve fitting
			Hantush modification of Jacob	straight line
two-layered aquifer with semipervious dividing layer	semiconfined	steady-state	Huisman-Kemperman	nomograph and curve fitting
			Bruggeman	straight line

Table 8. Analytic solutions for tests in fractured rock and karst settings.

Conventional methods addressing anisotropy:
The following methodologies were developed to determine anisotropy in a horizontal aquifer. For application in fractured rock aquifers, it is assumed that aquifer's behavior approximates that of a porous medium. Standard methodologies and their applicable assumptions are used to obtain values of transmissivity and storage, from which anisotropy is calculated.

Aquifer type(s)	Phenomenon modeled	Method of solution	Reference	Minimum number of wells for calculations
confined, homogeneous	2-D anisotropy	curve fitting or straight line with calculation	Papadopulos (1964)	four
leaky and nonleaky, homogeneous	2-D anisotropy	curve fitting or straight line with calculation	Hantush (1966)	four
leaky and nonleaky, homogeneous	2-D anisotropy	curve fitting or straight line with calculation	Neuman and others (1984)	three
homogeneous and heterogeneous, horizontal and vertical anisotropy, partial penetration	3-D anisotropy	curve fitting with calculation	Way and McKee (1982)	four

Special methods addressing phenomena of fractured rock and karst aquifers:
The double porosity models focus upon the release of ground-water storage from the fracture system and the aquifer matrix; transmissivity is assumed constant and the bulk of ground-water storage is in the aquifer matrix. The single-fracture models focus upon the interaction of the aquifer matrix and a fracture penetrated by a production well; the fracture functions as a highly transmissive extension of the well but, ideally, does not contain storage; all storage is derived from the aquifer matrix.

Aquifer type(s)	Phenomenon modeled	Method of solution	Reference	Remarks
confined, homogeneous, isotropic	double porosity block and fissure storage	curve fitting	Boulton and Streltsova (1977)	Fractured rock or karst aquifers.
unconfined, homogeneous, isotropic	double porosity block and fissure storage	curve fitting	Boulton and Streltsova (1978)	Fractured rock or karst aquifers.
confined, matrix is homogeneous and isotropic; fracture and aquifer system strongly anisotropic	pumping well penetrates vertical fracture or horizontal fracture.	curve fitting	Gringarten and Witherspoon (1972); Gringarten (1982)	Analysis for pumping well data only.
confined, matrix is homogeneous and isotropic; fracture and aquifer system strongly anisotropic	pumping well penetrates vertical fracture	straight line	Jenkins and Prentice (1982)	Analysis for hydraulic diffusivity (T/S), estimate of storativity (S) from other methods needed to solve for transmissivity (T).

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