TECHNICAL ADVISORY
FOR PREPARING AN AQUIFER TEST PLAN
AS PART OF A
VIRGINIA GROUND WATER WITHDRAWAL PERMIT APPLICATION

This Aquifer Test Plan Technical Advisory is meant to be a thought provoking document that provides advice to permit writers when establishing the requirements in an Aquifer Test Plan (ATP), and to applicants or their consultants when developing proposed ATPs for testing in support of a Ground Water Withdrawal Permit. ATPs must be designed for the specific location and proposed withdrawal that is being considered. The ATP is intended to be a stand-alone reference document taken to the field to guide staff during the test.

When an aquifer test is required for technical evaluation of a groundwater withdrawal application, an ATP is submitted to the Virginia Department of Environmental Quality (DEQ) for review, prior to commencement of the test. The review process is intended to ensure that the field activities proposed support DEQ's information requirements and will provide the information necessary to complete a technical evaluation of withdrawal impacts. Comments on the draft plan are provided by DEQ to both the permit applicant and the author of the plan.

An ATP will be reviewed jointly by the Regional Office (RO) and Central Office. This process will be aided by the submission, at least 30 days prior to the test, of the original ATP and one copy to the RO. ATP comments should be used by the applicant as an advisory; it is ultimately the responsibility of the applicant to provide test data that is adequate to develop a technical evaluation of impacts to support permitting requirements.

"The purpose of design is to improve the probability that a test will yield acceptably accurate values of the hydraulic coefficients." (Stallman, 1971, p. 6) These hydraulic coefficients will in turn help adequately define the vertical and horizontal impacts of the proposed withdrawal on the hydrogeologic system. A plan is only as good as its implementation. It is highly recommended that DEQ staff be present at some point during the test. They are not there to direct the test in any way, but to observe, learn, and lend a hand when requested.

This Technical Advisory outlines the suggested content of an ATP and provides information regarding important aspects of plan development and implementation. It is intended to assist the applicant with preparation and implementation of an aquifer test; however, it remains the applicant's responsibility to provide the DEQ with satisfactory test results. Documents which may be of further assistance are listed in the references section of this document.

Preparing for the Development of an Aquifer Test Plan

— Part of preparing an ATP includes research on the surrounding area. Communications with DEQ, USGS geologists, and research of technical publications, focused on Virginia's Coastal Plain, are important to develop an understanding of the site geology. The utilization of any existing wells should consider the construction (including gravel packing of annular space) with respect to the local geology. Any well construction activities should include a planning conference with DEQ.

— It is prudent to visit the site where an aquifer test will be conducted, prior to writing an ATP. A scouting visit can help identify planning considerations like; nearby domestic wells that may interfere with field testing, access problems (both site permission and well access ports), possible recharge/discharge boundaries, etc.

— In addition to visiting the testing site, it may be necessary to research the presence of nearby wells at DEQ, VDH Office of Drinking Water and the local health department (or even a door-to-door survey). A site visit can often help determine if these types of searches are needed. Information on nearby wells can be critical for the background monitoring phase of an aquifer test.

— Long-term background monitoring, prior to plan development can identify local interferences prior to field testing activities. This kind of information can then be used to develop specific plans for controlling (or minimizing the effects) of known interferences. Without this information, the plan must be written to include contingencies for interferences identified in the background data collected immediately prior to the start of the test. During the background monitoring period, the on-off times and the discharge rates should be recorded for any nearby wells (identified through record searches and site reconnaissance) in use. Any other local activities that may affect the test should be documented during the background monitoring period.

— Variations in water levels during background monitoring are a good indication of variations that may occur during an aquifer test. After monitoring is complete, the data should be analyzed to identify any interference (e.g. tides, other pumping wells). The goal of any aquifer test is to control all variables that would affect site water levels, so that the impacts of the pumping well are the only effects occurring during the test. If interferences can not be eliminated (e.g. tidal fluctuations), often the timing of the test can be altered to minimize these interferences. In all cases the maximum effort should be made to eliminate interference as these variations can render aquifer test data useless.

An Aquifer Test Plan Should Include/Address:

— A conceptual narrative summary of the proposed test setup that includes production and observation well locations and construction, proposed pumping rate, background monitoring, length of test, discharge location, methods of measuring drawdown and discharge, and any other applicable information.

— A plan to supply water to the system (if necessary), during the test, should be included in the ATP. This plan to supply water to the system should have no other facility wells pumping!

— The results of data source (VDH, DEQ, etc.) searches and field reconnaissance to identify any wells in the vicinity of the test wells along with their construction, if known, and an evaluation of whether or not their pumping may affect water levels at the test site should be included in the ATP. The evaluation should consider pumping rate and proximity of nearby wells.

— All applicable Virginia Department of Health (VDH) requirements should be considered when preparing the ATP and concurrence with those portions of the ATP pertaining to their requirements should be obtained from the VDH prior to implementing the ATP. In the case of modifications to waterworks during performance of the aquifer test, concurrence should be obtained from the VDH that the planned modifications would not adversely impact the water supply.

Well Construction and Placement of Observation Well

— The number and placement of observation wells will be dependent on the hydrogeologic properties at the test site. In tests where only one observation well is to be used, this well is often 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 from it. However, high pumping rate tests may include additional observation wells as much as several thousand feet away. Selection of observation well locations should incorporate predictive simulations performed using published estimates of aquifer properties, the proposed test pumping rate, and the proposed test length in order to estimate the drawdown that may occur in the observation wells during the test. The predictive simulations can be conducted using, for example, two-dimensional analytical solutions such as Theis or Hantush. Based on the predictive simulations, adjustments to the proposed pumping rate or length of test may need to be considered to insure that sufficient drawdown in the observation wells is achieved. The simulation method employed and the results of the simulations should be included in the ATP.

— Observation wells and production wells must be gravel packed and the casings grouted to prevent leakance between aquifers. Gravel pack should be terminated close to the top of well screens and should not extend above the top of the target aquifer.

— Wells that are hydraulically connected to more than one aquifer are not appropriate as either the primary pumping or observation well(s) for an aquifer test.

— In the case that a production well is screened in more than one aquifer, characterization of all affected aquifers is required. That is, there should be one pumping and one monitoring well for each screened aquifer, and each pumping and monitoring well should be screened in only one aquifer.

— A schematic drawing showing the proposed test system setup should be provided in the Aquifer Test Plan. The drawing should show: locations of all wells, their construction including screened intervals, gravel pack, the receptor for the discharge water, and all water level and discharge measuring devices. If the drawing is not to scale, all distances between wells, all depths, etc. should be noted. Each well should be labeled with its name and DEQ well number.

— A well location map must be included showing the locations of the test wells, the discharge location and any intermediate discharge water holding tanks, ponds, etc. at the test site. This map should show local cross streets and be of sufficient detail to drive to the test site. Each well should be labeled with its name and DEQ well number.

— During drilling of the boreholes for the wells, cuttings must be circulated and collected every 10 feet. A set of ground samples should be collected and placed in a well-drained area (not on plastic). A driller's log shall be prepared from the cuttings. Large withdrawals or those in critical areas should develop geologist's logs from the cuttings. DEQ should be notified twoweeks in advance prior to drilling.

— Geophysical logs (16"/64" Normal, Single Point, Self Potential, and Natural Gamma) shall be performed in the production well or observation well borehole. The scale for the geophysical logs shall be 20 feet per inch.

— The driller/geologist log, as applicable, and a GW-2 form shall be submitted to the DEQ within 30 days of completion of the wells. The final geophysical log shall also be submitted at this time. The DEQ numbers assigned to the wells shall be included on each page of all submissions.

<u>Well Completion/Development</u>

— It should be determined that the test pump intake is set at a depth that is above the top of the aquifer from which the production well is to draw water. This not only simulates withdrawal conditions during production but allows the well capacity for the required pump setting to be evaluated. The top of the aquifer shall be determined from review of all available logs, with concurrence from the DEQ.

— Whenever possible, an electric motor driven pump is preferred to a gasoline or diesel driven pump/generator in order to lessen the possibility of variations in flow rate. If a gasoline or diesel driven pump/generator must be used, its speed should be restricted to one-half to two-thirds of its maximum RPM so that it will run within its most steady range.

— The method of well development should be included in the plan. The wells shall be developed at a minimum by pumping. Preferable development is by surging and pumping.

— The reaction of all observation wells to changing water levels should be tested by injecting or removing a known volume of water from each well and measuring the subsequent change of water level. Any wells that appear to have poor response should be either redeveloped or replaced. The results of these "slug" tests including an electronic version of the data should be included in the aquifer test report.

— Before an aquifer test can begin, the recovery period, after completion of any pre-test pumping, must be at least as long as the pre-test pumping period and water levels should recover to 95% or one-foot, which ever is less, of pre-pumping water levels. Water level measurements in the pumping well should be taken prior to any pre-testing and during recovery from pre-testing, to document the achievement of static conditions after the completion of pre-testing.

<u>Aquifer Test Background Monitoring</u>

— The results and analysis of any long-term background monitoring completed prior to developing the plan must be reported. Contingencies for controlling or minimizing any identified interferences must be included in the plan.

— A description of the background monitoring activities that will be performed immediately prior to the pumping phase of the test is required in the ATP. A background monitoring period is necessary (1) to establish baseline (or static) water-level conditions prior to beginning the aquifer test and (2) to identify water level interferences if long-term monitoring was not conducted prior to developing the ATP. During the background monitoring period, the on-off times and the discharge rates should be recorded for any nearby wells (identified through record searches and site reconnaissance) in use. Any other local activities that may affect the test should be documented during the background monitoring period. Planned background monitoring activities should be included in the ATP and the results of background monitoring should be included in the aquifer test report.

— *Duration of Background monitoring immediately prior to test pumping phase*
Interference is the primary reason for rejecting the results of an aquifer test. Whenever possible, applicants and their consultants should conduct long-term background monitoring prior to developing an Aquifer Test Plan (see section "Preparing for the Development of an Aquifer Test Plan"). Whether or not this "planning phase" monitoring has been completed directly affects the plan for background monitoring immediately preceding the test pumping phase. Long term monitoring will allow for the permitee to identify and anticipate interferences during both the background and pumping phases.

When long-term monitoring was done in advance of ATP development:

- Interference(s) identified during long term monitoring and a plan to minimize or control the specific interference(s) should be addressed in the ATP, and implemented during the aquifer test and background monitoring.
- The length of time to monitor background immediately prior to the test pumping phase should be of sufficient duration to achieve static water level with consideration to anticipated interferences (but no less than 24 hrs).

When no long term monitoring has occurred:

- The length of monitoring should be of sufficient length to identify interference(s) and insure a static water level is achieved before beginning the pumping phase of the test. The period proposed must be long enough to capture changes in water levels with tidal periodicity and pumping interference that may change over a 24-hour period or relative to the day of week (i.e. business or household operations). Therefore a minimum of 72 hours immediately prior to pumping is recommended. The data must then be analyzed with DEQ concurrence.
- A field-analysis method for identification of interference(s) should be addressed in the ATP. This evaluation should include planning for obtaining DEQ concurrence regarding the background data review results.
- Contingency plans for different types of interferences should be discussed in the ATP these interference(s) may include, but are not limited to
    1. Nearby Pumping
    2. Tides

— The period of time for background monitoring immediately preceding the pumping phase should be sufficient to ensure that all static water levels are not fluctuating. Water level measurements should be taken at a maximum of 15 minute intervals, but one minute intervals are recommended if data storage limits permit. After monitoring is complete, background data should be analyzed to determine any interference (e.g. tides). The water level prior to the aquifer test should not change more than four inches during the six hours immediately preceding the aquifer test. In addition, the water level should not change by more than one inch during the two hours immediately preceding the aquifer test. If additional variation is observed, the test should not commence until the cause of the variation can be identified and mitigated.

— A plan to address any background interference should be made. Background monitoring data collected immediately prior to the pumping phase of the test should be inspected carefully, **prior to initiating the pumping phase**, for any signs of interference. Data should be plotted at an appropriate scale with regard to water level to maximize the spread of data points along the Y-axis (assuming data is plotted X-axis = time and Y-axis = water level). The data plot should only show a time period sufficiently after pumping has ceased when water levels are changing slowly to best inspect for tides. If tidal influences are detected in the plot or if influences due to tides are unclear, the raw background data and a plot should be sent to DEQ Regional Office staff for assessment prior to starting the aquifer test. Staff will make a recommendation regarding timing the beginning of the test to coincide with the time of smallest water level change in the tidal cycle (1.5 hours prior to an anticipated high or low tide). This will minimize the tidal influence on the aquifer test data. It should be noted that aquifer tides most likely will not coincide with water body tides, and therefore low and high tide arrival should be estimated based on aquifer tidal data.

— Reference datum, for all water level measurements, should be clearly specified and should remain constant from background monitoring through recovery.

Aquifer Test Pumping Period

— During the aquifer test, the production well should be pumped at the maximum rate expected during normal operations. In all cases, the withdrawal rate should be sufficient to adequately define a drawdown curve from the test's time-drawdown data.

— Discharge flow rate shall be recorded in gallons per minute at least once every 10 minutes during the first hour of the test and at least every 60 minutes thereafter. The flow rate should not vary by more than plus or minus 5 percent. Flow shall be measured either with an automated data recorder or manually monitored. Flow rate readings shall be submitted with the test results. Test results submitted with significant pumpage variations or insufficient flow rate recordings may be rejected.

— Adjustments to flow rate should be controlled by a valve in the discharge line rather than by controlling power to the pump.

— Whenever continuous pumping is interrupted longer than 1 minute, the test will be suspended for a period of time so that water levels reach 95% of pre-aquifer test pumping levels and at least as long as the elapsed pumping time before pumping is resumed. However, if the data is adequate enough to define the shape of the drawdown curve, the test can be suspended and recovery should be monitored.

- Water levels in the pumping well and observation well shall be measured to 0.01 foot (one one-hundredth of a foot).

- Barometric pressure, collected on site, should be measured at the same frequency as water levels (specify inches of mercury or feet of water).

- 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 recorded occasionally as a check on the automatic system. The frequency at which water levels are recorded should correspond with the schedule listed below.

Time Since Pumping Began or Ceased	Time Between Measurements
0 - 2 minutes	10 seconds
2 - 5 minutes	30 seconds
5 - 15 minutes	1 minute
15 minutes - 1 hour	5 minutes
1 - 2 hours	10 minutes
2 - 8 hours	30 minutes
8 - 24 hours	1 hour
24 hours - end	2 hours

- During the test, each time interval reading for each well should be manually plotted to observe the progress of the test and to determine when the test can be concluded. The test should continue until the data are adequate to define the shape of the type curve sufficiently so that acceptably accurate values of the hydraulic coefficients can be determined. Any irregularities in the plots should be noted and reported to the DEQ as soon as possible but prior to dismantling the test equipment. Any irregularities should also be discussed in the test report.

Aquifer Test Recovery Period

- Post-testing recovery data should be recorded from all wells and with the same frequency as pumping data. An adequate recovery portion of the test is usually as long as the pumping period or as long as it takes for water levels to recover to 95 percent of pre-aquifer test pumping levels in the pumping well but not less than 8 hours. In the case of tidal influences, at a minimum, 24 hours of recovery should be monitored. As the presence or absence of a foot check valve in the pumping well will affect observed recovery, its status should be noted on the data sheets. A check valve is necessary to obtain good recovery data.

- As was the case during the pumping period, recovery data should be manually plotted, for each time interval reading, to observe the progress of the test and to determine when the test can be concluded. The recovery period should continue until the data are adequate to define the shape of the type curve sufficiently so that acceptably accurate values of the hydraulic coefficients can be determined.

Aquifer Test Report

— An original and one copy of an aquifer test report must be submitted that contains at a minimum:

- ♦ An introduction that describes the project, its location, and hydrogeologic setting
- ♦ Aquifer test setup description, including schematic drawing, and well location map
- ♦ Driller/geologist logs, completed GW-2 form for each well constructed, and geophysical logs
- ♦ Notes of any anomalies during background or test.
- ♦ Description and results of background monitoring
- ♦ Description and results of pre-testing
- ♦ Documentation of return to static water levels after pre-testing
- ♦ Results of aquifer test, including copies of field plots with explanations of any irregularities in the plots, tables of water level measurements for all wells, and table of discharge flow rates. Water level data must also be submitted in electronic format.
- ♦ Raw data from all background monitoring activities and from the determination of "static" through the pumping and recovery portions of the test. Reference datum should be clearly specified and should remain constant from background monitoring through recovery.
- ♦ Barometric pressure collected during monitoring.
- ♦ Discharge measurement data.

It is suggested that the report also include data analysis to determine hydraulic properties of the aquifer. All calculations should clearly show the data used for input, the equations used and the results achieved. Any assumptions made as part of the analysis should be noted in the calculation section. This is especially important if the data were corrected to account for conditions discovered during background monitoring. The calculations should reference the appropriate tables and graphs used for a particular calculation.

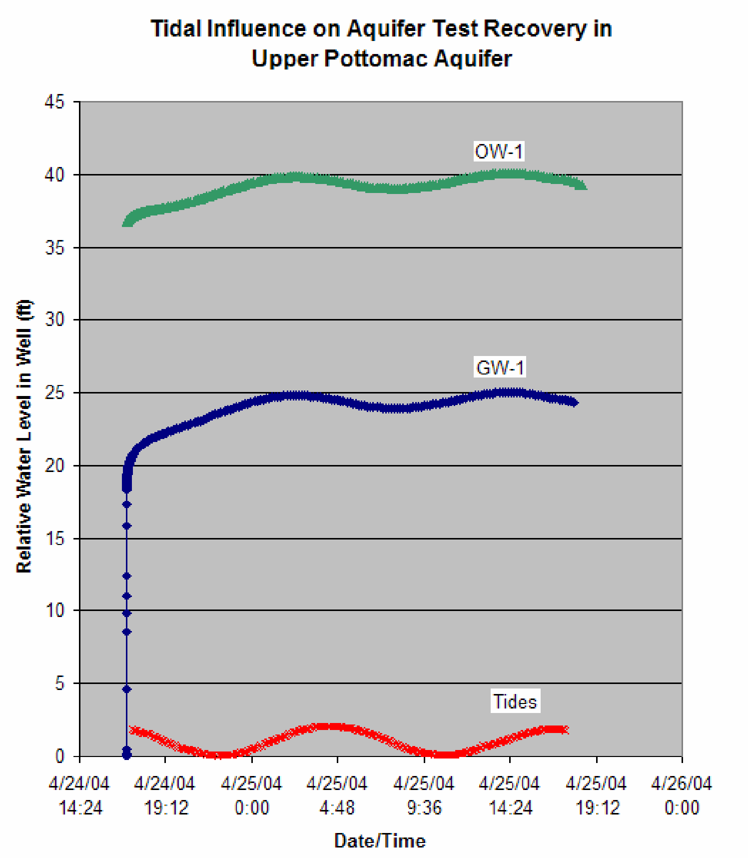
Appendix

Definitions:

Static Water Level (SWL) – The level of water usually measured right before pumping begins. It is important that SWL is steady prior to aquifer test initiation. If water levels are varying prior and during an aquifer test, data may not be characteristic of any Type Curve, therefore making it difficult to analyze aquifer properties. For aquifer tests conducted in support of a DEQ Ground Water Withdrawal Permit, a "static" water level will be achieved when water levels do not change more than four inches during the six hours immediately preceding the aquifer test and no more than one inch during the two hours immediately preceding the pumping phase of the test.

Factors affecting SWL:

1. *Tides* – Aquifers located within close proximity of tidal bodies are subject to short-term fluctuations of head, due to tides. The amplitude of fluctuation diminishes from its maximum at the coast to zero at some distance inland, determined by the aquifer characteristics. Additionally, a phase shift occurs. That is, the time at which high or low tide as seen in an observation well will not necessarily synch with the high or low tide seen in the tidal body. The figure below shows an aquifer's response to both aquifer test recovery and tides, combined. As you can see the phases are out of synch between the observed surface water tide and the tidal response in the wells.



Note: This is an illustration of tidal effects during an aquifer test. This graph shows that tides at the tidal reference station do not necessarily correspond directly in time with the tides seen at the well. It is imperative that tides are observed in wells for multiple days, so as to be able to predict the onset of high or low tide in wells.

Tidal influences can be minimized by timing the beginning of an aquifer test pumping period to one and one-half hours prior to high tide or low tide, as anticipated at the monitoring well. This will allow for the beginning of the aquifer test to coincide with a period of tidal influence that is minimal.

2. *Barometric Pressure* – Changes due to atmospheric pressure can be observed in the pumping and observation wells. When barometric pressure decreases, water levels in a well will rise, and when barometric pressure increases, water levels in a well will fall.

3. *Background Pumping* – Wells pumping in proximity to the aquifer test can substantially affect drawdown levels during the aquifer test. All background pumping should be terminated during the aquifer test.

Transmissivity (T) – The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is the product of the hydraulic conductivity K and the saturated thickness of the aquifer D. Transmissivity has dimensions of $Length^3/(Time \times Length)$, usually expressed in ft^2/d or m^2/d.

Storativity (S) – The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of the specific storage and aquifer thickness. Storativity is a dimensionless quantity, also called storage coefficient.

Leakage Factor (L) – A measure for the spatial distribution of leakage through a confining unit into an aquifer and vice versa. Large values of L indicate a low leakage rate through the confining unit and small values of L indicate a high leakage rate through the confining unit. The leakage factor has dimensions of length.

Barometric Efficiency - Kruseman and de Ridder state, "From the changes in atmospheric pressure observed during a test, and the known relationship between Δp and Δh, the water-level changes due to changes in atmospheric pressure alone (Δh_p) can be calculated for the test period for the well. Subsequently, the actual drawdown during the test can be corrected for the water-level changes due to atmospheric pressure." To do this one first needs to determine the wells Barometric Efficiency (BE), by using the equation $BE = \gamma\, \Delta h / \Delta p$ where γ is the specific weight of water. Kruseman and de Ridder state that BE usually ranges between 0.2 and 0.75. Once a BE is determined for the well, one can use the relationship for BE to determine a change in head due to a change in barometric pressure.

Type Curves

When evaluating aquifer tests, using the Theis or Hantush Type Curves, the following **basic assumptions** apply to both type curves:

1. The aquifer is has a confining layer on top.
2. Aquifers are horizontal and have infinite horizontal extent.
3. Aquifer is homogeneous and isotropic.
4. The pumping well and the observation wells are fully penetrating.
5. The pumping well is 100% efficient and has an infinitesimal diameter.
6. Darcy's law holds.
7. The aquifer water levels are horizontal prior to pumping.

8. Water levels are static prior to the start of pumping.
9. Water level changes are due to the effect pumping well alone.
10. Flow to the well is radial and horizontal.

Theis Type Curve

The solution to the two-dimensional groundwater flow equation for a confined homogeneous aquifer given by Theis (1935) is known as the Theis equation and is

$$d = \frac{Q}{4\pi T} W(u)$$
$$d = h_0 - h$$
$$u = \frac{r^2 S}{4Tt}$$

d	is the drawdown in the confined in ft or m
h_0	is the water level at time t in the confined aquifer in ft or m
h	is the initial water level in the confined aquifer in ft or m
Q	is the pumping rate in either ft^3/day or m^3/day
T	is the transmissivity of the confined aquifer in ft^2/day or m^2/day
$W(u)$	is the well function
S	is the storativity for the confined aquifer and is dimensionless
r	is the radial distance from the pumping well to the observation well in ft or m
t	is the time since pumping began in days

Additional assumptions for the Theis Type beyond the basic assumptions include:
1. The aquifer is confined at the top and the bottom
2. The aquifer has no source of recharge.
3. The aquifer is compressible, and water is released instantaneously from storage.
4. The well is pumped at a constant rate.

Hantush Type Curve (1954)

The solution to the two-dimensional groundwater flow equation for a **leaky confined aquifer** given by Hantush and Jacob (1954) is known as the Hantush-Jacob formula and is

$$d = \frac{Q}{4\pi T} W(u, r/B)$$
$$d = h_0 - h$$
$$u = \frac{r^2 S}{4Tt}$$
$$B = (Tb'/K')^{1/2}$$

where

d	is the drawdown in the confined in ft or m
h_0	is the water level at time t in the confined aquifer in ft or m
h	is the initial water level in the confined aquifer in ft or m

Q	is the pumping rate in either ft^3/day or m^3/day
T	is the transmissivity of the confined aquifer in ft^2/day or m^2/day
$W(u, r/B)$	is the well function
r	is the radial distance from the pumping well to the observation well in ft or m
B	is the leakage factor in ft or m
S	is the storativity for the confined aquifer and is dimensionless
t	is the time since pumping began in days
b'	is the thickness of the confining unit in ft or m
K'	is the hydraulic conductivity of the confining unit in ft/day or m/day

Additional assumptions for the Hantush-Jacob Type Curve beyond the basic assumptions include:

1. The confining unit is overlain by an unconfined aquifer.
2. The water table in the overlain unconfined aquifer does not fall during pumping of the aquifer.
3. Groundwater flow in the confining unit is vertical.
4. The aquifer is compressible, and water is released instantaneously from storage.
5. The confining unit is incompressible, and no water is released from storage during pumping of the aquifer.

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