DIVISION OF WATER QUALITY
DWQ

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North Carolina Department of Environment and Natural Resources

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May 31, 2007

MEMORANDUM

To: Aquifer Protection Section Central Office
Aquifer Protection Section Regional Supervisors
Construction Grants and Loans Section
Interested Parties

From: Ted L. Bush, Jr., Chief
Aquifer Protection Section

Subject: Performance and Analysis of Aquifer Slug Tests and Pumping Tests Policy

In response to the need for consistent evaluation of land based utilization and disposal sites as well as other subsurface investigations, the Aquifer Protection Section has adopted the subject policy dated May 31, 2007, to be utilized by both consultants preparing applications and Division review staff. The subject policy reflects recent changes in the non-discharge rules with the adoption of Subchapter 02T. This policy provides additional detail to the requirements in Subchapter 02T. In addition this policy will assist with the preparation and review of other subsurface investigations needed for reports submitted for Division review.

All permit applications and other site reports shall be reviewed in accordance with the attached document for any application received on or after August 1, 2007. For any application received prior to that time, staff should review the application for adherence to the policy and discuss with the applicant and/or their consultants to encourage consistency with the policy.

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Performance and Analysis of Aquifer Slug Tests and Pumping Tests Policy

May 31, 2007

Table of Contents

Introduction

A determination of hydraulic conductivity, transmissivity, and/or specific yield is required under several different types of permit applications and subsurface investigations associated with groundwater contamination incidents. This policy provides guidance regarding the methods used to determine these parameters for projects under the Division of Water Quality’s (Division) regulatory purview. .

(1) Purpose of policy

The purpose of this policy is to: (a) provide guidance to investigators in selecting and applying an appropriate method (slug test or pumping test) for assessing an aquifer’s hydraulic characteristics; (b) alert investigators to the most common oversights associated with performing and analyzing these test methods; and (c) provide a guidance to regulators to use in evaluating the adequacy of test results submitted by investigators.

(2) Basis for technical approach

This policy is based on methods and techniques that are generally accepted by educators and consultants. These include the following sources:

The Bouwer and Rice Slug Test – An Update, by Herman Bouwer, Ground Water Journal, May – June 1989.

Groundwater and Wells, 2nd Edition, by Fletcher G. Driscoll, Johnson Division, St. Paul, MN, 1986.

Analysis and Evaluation of Pumping Test Data, 2nd Edition, by G. P. Kruseman and N. A. de Ridder, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 1990.

(3) The purpose of aquifer testing

Aquifer testing is performed to: a) estimate the hydraulic conductivity, transmissivity, and specific yield of an unconfined aquifer or storativity of a confined aquifer, to b) quantify the vertical leakage from one aquifer into another and/or c) to assess the effects of boundaries such as surface water boundaries or low permeability features such as intrusive dikes. Aquifer testing results help provide the basis for: hydrogeologic conceptual models; estimation of sustainable groundwater withdrawal rates; capture zone analyses; and estimation of groundwater contaminant migration rates. Vertical leakage is assessed by pumping one aquifer and observing the concurrent hydraulic response of the other aquifer. The Division may require the applicant to quantify the items mentioned above in situations where there is potential to (a) harm groundwater users, (b) degrade the existing quality of the groundwater in question, based on its current classification (see 15A NCAC 02L.0200), or (c) degrade surface water quality.

(4) The method chosen by the investigator

The method used to ascertain representative values of hydraulic conductivity, transmissivity, specific yield, and other aquifer parameters should be chosen based on site-specific conditions and the intended application of the information.

Slug tests actually test the formation immediately adjacent to the well which, in the vast majority of cases, will not be representative of the entire aquifer, and should only be used in those situations where a high degree of numerical and volumetrically representative accuracy is not needed. The analyses of slug tests usually produce approximate values of hydraulic conductivity, and do not produce values of storage coefficients. Since slug tests only provide hydraulic conductivity estimates for a very small portion of the formation of interest, where practical, multiple slug tests should be carried out in different representative wells in order to determine a range of estimated hydraulic conductivities. ***Slug tests should never be exclusively relied upon when designing a groundwater recovery system, or in any other situation where a more reliable estimate of the effects of long-term pumping (including the establishment of a hydraulic zone of capture) is required.***

Pumping tests performed on aquifers produce values of hydraulic conductivity, transmissivity, storativity or specific yield that are far more accurate and volumetrically representative of the aquifer. These tests typically stress the aquifer and draw water from a distance, furnishing information that defines and demonstrates the aquifer's ability to store and transmit water. Pumping tests should have two or more observation wells to allow the collection of data that is not affected by hydraulic losses near the pumping well, and to allow for a more accurate determination of aquifer characteristics.

Section I: Slug Tests

In general, the Division considers "Slug out" tests to be more representative of actual aquifer conditions. However, "Slug in" tests are acceptable in cases where the well screen and sand pack interval are fully submerged. "Slug out" tests create a dewatering of the saturated zone and are acceptable to the Division for obtaining ***rough estimates*** of hydraulic conductivity. The rapidly changing level of the water in the well, and the time at which each level occurred during the performance of the test, must be measured accurately. This is best performed with a transducer/datalogger arrangement, which can be programmed to record the time and water level data at appropriate intervals. Formations that have high hydraulic conductivities may exceed the limitations of the method and, in the case of most traditional methods of analysis, will produce analytical results that can only be said to be above a certain value. However, there are several more recently developed methods of analysis that have been developed to better handle high-conductivity scenarios. In high conductivity situations, more accurate values of aquifer parameters can be obtained by performing a pumping test.

(1) Basic Testing Requirements:

(a) Before beginning the test

Select a well-constructed, well-maintained monitor well for the test. Although 2-inch diameter wells are most often used, wells having larger diameters may also be used. The age of the well, the depth of the well, borehole diameter, the length of the well screen and sand/gravel filter pack, the size of the screen slots, the size of the sand/gravel filter material surrounding the well screen, the method(s) used to develop the well and its results, and the drilling method used to install the well should all be known to the investigator. Verify that a good hydraulic connection exists between the well's interior and the aquifer formation by removing a few bailers full of water from the well and measuring the amount of time required for the water level to return to static. If the water level does not return to static within a reasonable amount of time with respect to the expected hydraulic conductivity of the material screened, a good hydraulic connection may not exist, and the well should be redeveloped prior to conducting the slug test. All new wells used to perform slug test must be properly developed. The integrity of older wells should also be evaluated to ensure it has not been compromised. Well screens can become clogged by silt or bacteria over time, and this could affect the accuracy of the test.

(b) Frequency of Water Level Measurements

A pre-test static water level should be determined initially. The water level should be measured (along with the elapsed time) as often as possible during the first two minutes of the test. If a transducer/datalogger arrangement is used, the apparatus may be programmed to measure the water level at very frequent intervals for the first two minutes, and at less frequent intervals thereafter (logarithmic time sampling). If the measurements are taken by hand using an electric tape, the measurements should be taken as frequently as possible during the first two minutes of the test; then at intervals of ten seconds for the third and fourth minutes; and at intervals of thirty seconds from the fifth minute until the conclusion of the test (10 minutes of elapsed time or 95% water level recovery, whichever occurs first).

(c) Accuracy of Water Level Measurements

Water level measurements must be accurate to within one eighth of an inch or one hundredth of a foot.

(d) Duration of the Slug Test

The slug test should be performed for no less than ten minutes, or until such time as the water level in the test well recovers 95% of its original pre-test level, whichever occurs first.

(2) Method of Analysis:

The data from the slug test should be analyzed by applying an appropriate and recognized method of slug test analysis such as the Bouwer and Rice method. It should be understood that the value of aquifer hydraulic conductivity produced by the analysis of the test represents an estimate that may vary by as much as a full order of magnitude from the true value. Knowledge of the saturated aquifer thickness needs to be incorporated into the analytical methodology, because uncertainty about the aquifer thickness will lead to additional error. A slug test should never be used as the sole determinant of an aquifer's hydraulic conductivity or transmissivity in situations where an accurate estimate of these parameters is required, such as in the design of a "closed-loop" system. Contact the Division to determine if the use of slug tests only is appropriate for a particular investigation or evaluation. Slug tests on multiple monitor wells may be used to estimate the variability of these parameters across a site.

Section II: Pumping Tests

Aquifer pumping tests involve the pumping of a well at a constant, sustained rate, or by maintaining a constant pumping discharge rate in order to hydraulically stress an aquifer and study its behavior under such conditions. Vertical leakage between aquifers can be assessed by pumping from one aquifer and observing the concurrent hydraulic response of the other aquifer. Pumping tests are best performed on a fully penetrating, fully developed well with water-level measurements frequently taken at the pumping well and at two or more observation wells. The observation wells should be situated on different sides of the pumping well and at different distances from it. Further information regarding the appropriate number and spacing of observation wells for different aquifer settings in references such as Kruseman and deRitter (1990) and Driscoll (1989).

(1) Basic Testing Requirements:

(a) Before beginning the test

The aquifer test(s) should be well planned from the start. The locations and depths of the pumping well and observation wells should be based on a conceptual model of the site hydrogeology and the hydrostratagraphic units to be tested. For example, if the aquifer formation has a potential to exhibit horizontal anisotropy, the observation wells should be placed such that they measure water-level response at positions parallel and perpendicular to the direction of suspected highest horizontal hydraulic conductivity with respect to the pumping well. If the underlying leakage to a semi-confined aquifer is to be measured, then observation wells should be placed and sealed into the deeper aquifer to test the response of the semi-confined aquifer. Additional information with regard to placement of pumping and observation wells for various hydrogeologic conditions can be found in Kruseman and deRitter (1990) and Driscoll (1989).

Properly disposing of the pumped water from the aquifer test is an important consideration of aquifer test planning. If the ground water to be pumped is contaminated above the appropriate groundwater standards, then in most cases the pumped water must be treated and disposed of properly after securing the appropriate permit. If the groundwater to be pumped is not contaminated above the groundwater standards, then the pumped water should be piped at least 250 feet away and hydraulically downgradient from the pumping well, or greater if there is a likelihood of the recharging water affecting the aquifer test results. Alternatively, and particularly when high discharge rates are planned, an evaluation of the expected cone of influence at the anticipated conclusion of the test should be made, and the discharge distance adjusted to be beyond the radius of the maximum cone of influence.

The age of the pumping well, the depth of the well, borehole diameter, the length of the well screen and sand/gravel filter pack, subsurface soils, the size of the screen slots, the size of the sand/gravel filter material surrounding the well screen, the method(s) used to develop the well and its results, and the drilling method used to install the well should all be known to the investigator. Verify that a good hydraulic connection exists between the well's interior and the aquifer formation by removing a few bailers full of water from the well and measuring the amount of time required for the water level to return to static. If the water level does not return to static within a reasonable amount of time with respect to the expected hydraulic conductivity of the material screened, a good hydraulic connection may not exist, and the well should be redeveloped prior to conducting the pumping test. Well screens can become clogged by silt or bacteria over time, and this could affect the accuracy of the test. It is essential that the pumping well and all observation wells be properly developed before beginning the pumping test.

More observation wells are recommended for those aquifers that have heterogeneous geologic and hydraulic characteristics. One of the wells (a "background" well) should be situated beyond the hydraulic influence of the pumping well and should serve to measure natural changes in the water level of the aquifer, which may take place during the pumping test.

Periodic water level measurements should be taken in the pumping well and in the observation wells over a 24 hour period before the test begins in order to document ongoing recharge, discharge, or atmospheric or tidal fluctuations affecting the aquifer.

(b) Frequency of Water Level Measurements and Pumping Rate Measurements

Static water levels should be collected from all wells initially, and immediately prior to the test. Water level measurements within the pumping well should be taken initially and then at least every ten seconds for the first minute; every twenty seconds from two minutes to five minutes; every thirty seconds from five minutes to ten minutes; every minute from ten minutes to twenty minutes; every five minutes from twenty minutes to an hour; and every fifteen minutes thereafter. Water level measurements in observation wells should be taken initially and then at intervals determined by factors such as the type of aquifer (confined or unconfined) being tested, the distance from the observation well to the pumping well, the pumping rate, and the results of the "pre-test" (see below). Further information regarding water level measurements can be found in references such as Kruseman and deRitter (1990) and Driscoll (1989). The flow rate should be monitored continuously at the beginning of the test and the pump speed or orifice opening adjusted so as to keep the flowrate constant for a constant discharge rate pumping test. The pump will tend to slow down as it is forced to work harder, lifting the water from increasingly deeper levels as the test progresses and the water level in the pumping well falls.

(c) Accuracy of Water Level Measurements

Water level measurements must be accurate to within one eighth of an inch or one hundredth of a foot. Water level measurements taken inside the pumping well should be protected from false readings caused by cascading water and other forms of turbulence.

(d) Maintaining a Constant Pumping Rate

The test well should be "pre-tested" prior to the actual test (this can be a formal step-drawdown test or a more informal method) in order to verify the ability of the well to furnish water, the ability of the pump to operate and to deliver the water, and the appropriateness of the intended pumping rate. A pump should never be set to deliver its maximum pumping rate at the beginning of a test, as the pumping rate will usually decrease as the water level within the well falls and the pump is forced to raise the water a greater vertical distance. A pump or its discharge line should be set to deliver up to 2/3 of the system capacity at the beginning of a test, and this can be done by either initially decreasing the running speed (RPM), or by partially closing off the discharge line with an in-line valve. In order to maintain a constant discharge rate, the pump's running speed will have to be increased, or the discharge control valve opened, as the water level in the well falls. The rate of discharge, as indicated by an orifice weir or in-line flow meter, will have to be watched carefully during the first several minutes of the test, and the flow control valve or pump speed may have to be adjusted almost continuously during this time in order to maintain a constant discharge rate.

(e) Verification of the Pumping Rate

Regardless of the type of apparatus used to measure the rate of pumping, the pumping rate should be periodically verified by another method of measurement. The three most common methods of flow measurement are an in-line flow meter, an orifice weir, and the use of a calibrated bucket and stopwatch.

(f) Duration of the Pumping Test

As a general rule, as a test proceeds, the hydraulic stress on the aquifer increases as a progressively greater volume of the aquifer contributes to the well. The longer a test is performed, the more representative the data will be. The “industry standard” for the duration of a pumping test is 24 hours, and longer tests may be advisable for certain situations, such as the testing of low-conductivity formations or gathering information for the design of pump-and-treat groundwater remediation systems. Shorter duration tests may be allowed for more transmissive aquifers; however, the Aquifer Protection Section Central Office at (919) 733-3221 should be contacted first for prior approval. Recovery measurements which begin after the pump is turned off may be taken at the pumping well and the observation wells to provide additional data for analysis and comparison. These recovery measurements should be collected using the same type of scheme for frequency of measurements described above, using the pump shutoff time as the initial time.

(g) Other information

If there is concern about the existing groundwater quality and/or contamination, then groundwater samples should be collected during the pump test. Any questions regarding this should be directed to the Aquifer Protection Section Central Office at (919) 733-3221.

Other information that has been found to be useful in the analysis and interpretation of pumping tests includes barometric pressure readings (essential if non-vented transducer cables are used), the temperature of the discharged water, the air temperature and general weather conditions during the test, and any natural or man-made events that could impact the accuracy of the pumping test. These events include changes in the pumping rate of a nearby pumping well; rainstorms; the passage of storm fronts; snowmelt events; abrupt changes in air temperature; wind conditions; earthquakes; tidal events; and changes in aquifer loadings (vehicle or railcar displacement). Careful notes should be taken during the test that record the exact time at which any unusual phenomenon occurs.

(2) Method of Analysis:

Before the water level data from the pumping well and observation wells is analyzed, the data should be corrected for the influence of factors such as: barometric pressure fluctuations when testing confined or semi-confined aquifers; local aquifer loadings from railroad cars, etc.; tidal influences in aquifers hydraulically connected to or otherwise influenced by ocean tides; partial aquifer penetration of observation wells; turbulent hydraulic losses at or near the pumping well (“well efficiency” losses); the hydraulic effects of recharge boundaries or barrier boundaries; and aquifer recharge from recent precipitation or surface application events. Pre-test water level measurements taken in the pumping well and observation wells can be examined to assess the potential influence of these factors.

In many cases, it is usually helpful to plot the drawdown contours in map-view at various times throughout the test duration. These types of plots may help correctly interpret boundary effects and anisotropic effects.

The pumping test analysis should be based on a recognized and appropriate method that is appropriate and valid for the site conditions. It is not acceptable to find the best fit to a set of field data and conclude, based on this fit alone, that the aquifer system actually is the model used in the analysis. Other field data from boring logs, geological mapping, and location of boundaries needs to be consistent with the analysis model chosen. Further information regarding the applicability of methods of pumping test analysis can be found in references such as Kruseman and deRitter (1990).

Section III: Reporting Aquifer Test Results

Scaled maps showing the locations of all wells involved in the test should be provided. The maps should be clear and legible, with each of the pumping well and each of the observation wells being clearly labeled and identified. Any other locations where data was gathered during the test (water supply wells, streams, etc.) should be included and labeled on the maps. Cross-sections are considered to be very helpful. All aquifer test data and analyses should be clearly documented, including appropriate aquifer response graphs. It may be appropriate to provide map-view groundwater drawdown contours at various times of an aquifer pumping test. All analysis methods should be clearly documented. If commercially available computer software is used in the analyses, then complete printout sheets of the data, the analyses, and a list of all analytical assumptions (aquifer type, extent, etc.) should be provided. The Aquifer Protection Section may request that large data sets (spreadsheets) be provided in electronic form.

The construction details for the pumping well and all observation wells used during the test should also be submitted. The aquifer test data should be included in the report. The data should be comprehensive in that it include the identity of the well being monitored, the static water level in the well, the water level measurements along with the (elapsed) time of each measurement, and the unit of measurement used. Concurrent confirmatory pumping rate discharge readings, taken at appropriate intervals, should also be included, as should be time(s) of any adjustments made to the rate of discharge. Any corrections made to the water level data should be noted, along with the reason(s) for those corrections. Post-test water level recovery data, when taken, should also be included.

References

Bouwer, Herman, *The Bouwer and Rice Slug Test – An Update*, Ground Water Magazine, May-June 1989.

Driscoll, Fletcher G., *Groundwater and Wells,* 2nd Edition, Johnson Division, St. Paul, MN, 1986.

Kruseman, G. P. and de Ridder, N. A., *Analysis and Evaluation of Pumping Test Data*, 2nd Edition, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 1990.

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