Michael F. Easley, Governor

William G. Ross Jr., Secretary
North Carolina Department of Environment and Natural Resources

Alan W. Klimek, P.E. Director
Division of Water Quality

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: Groundwater Modeling 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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Groundwater Modeling Policy

May 31, 2007

NCDENR Division of Water Quality – Aquifer Protection Section

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Introduction

The phrase "*predictive calculations or modeling*", or variations of this phrase, appears several times in the North Carolina Administrative Code Section 15A NCAC 02L and 15A NCAC 02T regulations. This Division of Water Quality (Division) policy provides guidance regarding this phrase as it pertains to these regulations, and is not intended as a stand alone step-by-step manual for conducting groundwater modeling.

(1) Purpose of policy

The dual purpose of this policy is to: (a) provide guidance to investigators in selecting and using appropriate groundwater models for both permitted sites and incident investigations; and (b) provide guidance for regulators to use in evaluating the adequacy of groundwater modeling results submitted by investigators.

(2) Basis of technical approach

This policy is based on the following guides published by the American Society for Testing and Materials (ASTM, available at www.astm.org):

D 5447-93	<u>Application of a Ground-Water Flow Model to a Site-Specific Problem</u>
D 5609-94	<u>Defining Boundary Conditions in Ground-Water Flow Modeling</u>
D 5610-94	<u>Defining Initial Conditions in Ground-Water Flow Modeling</u>
D 5611-94	<u>Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application</u>
D 5490-93	<u>Comparing Ground-Water Flow Model Simulations to Site-Specific Information</u>
E 978-92	<u>Evaluating Mathematical Models for the Environmental Fate of Chemicals</u>

and also on the following other sources:

"Groundwater Modeling Guidance", by Richard J. Mandle, Groundwater Modeling Program, Michigan Department of Environmental Quality, 2002.

"Groundwater Modeling for Hydrogeologic Characterization", by the California Environmental Protection Agency, July, 1995.

Ground-Water Modeling, by James W. Mercer and Charles R. Faust, National Water Well Association, 1981.

A Review of Field-Scale Physical Solute Transport Processes in Saturated and Unsaturated Porous Media, by L.W. Gelher, A. Mantoglou, C. Welty, and K.R. Rehfeldt, Electric Power Research Institute (EPRI) EA-4190, Palo Alto, CA., 1985.

Contaminant Hydrogeology, by C.W. Fetter, Macmillan Publishing Co., New York, 1993.

Groundwater Transport: Handbook of Mathematical Models, by I. Javandel, C. Doughty, and C.F. Tsang, American Geophysical Union Water Resources Monograph 10, Washington D.C., 1984.

Other references were also used in specific areas of the guidelines. See the complete list of references at the end of this document.

(3) Particular groundwater flow or transport model chosen by investigator

By its nature groundwater modeling must be site specific, and site characterization (as documented by the report documenting the hydrogeologic evaluation) must precede selection of an appropriate groundwater model. The Division requires that any model used on a Division-regulated project: (1) be thoroughly documented in readily accessible published format; (2) be peer-reviewed in the scientific literature [includes appropriate government publications and reviews published by or in cooperation with the International Ground Water Modeling Center]; and (3) be appropriate to the site under investigation, as determined by these guidelines. If there is uncertainty whether the use of a particular model will be accepted, contact the Aquifer Protection Section (Central Office) at (919) 733-3221.

(4) Types of predictive calculations or modeling

There are three types of predictive calculations or modeling described by the Division in these guidelines: (a) groundwater mounding calculations, (b) groundwater contaminant transport calculations where the groundwater standards are to be protected, and (c) groundwater contaminant transport calculations to surface water bodies where the surface water quality standards are to be protected. These three types of predictive calculations or modeling are performed for the following regulatory purposes:

(a) Groundwater mounding calculations

The permitted disposal and utilization systems in Subchapter 02T have a design criteria of maintaining a one-foot minimum vertical separation between the seasonal high water table and the ground surface. The intention of this regulation is to maintain a minimum of one foot of vertical separation between the applied waste (ground surface if applied on the ground) and the altered or mounded seasonal high groundwater table in order to facilitate soil remediation effects of the applied waste. The "altered or mounded" term is meant to signify the additive or compounded effects of the disposal activity onto the ambient seasonal high groundwater table. This mounding effect onto the seasonal high groundwater table is usually obtained via predictive calculations or modeling methods (often called groundwater mounding analysis). In addition, this analysis may be used to determine the effects of groundwater lowering or mounding on surface water bodies (e.g., wetlands, steams, etc.).

(b) Groundwater contaminant transport calculations applied to investigating and/or maintaining groundwater standards

It is the intention of Subchapter 02L and 02T regulations to maintain and protect the groundwater quality of the state. With this goal, the purpose of the predictive calculations or modeling is to document that the activity in question will not result in contravention of groundwater standards at a specified receptor or location, or at the assigned compliance boundary for a permitted facility. In the particular case regarding treatment and disposal of soil containing petroleum products, the purpose of the predictive calculations or modeling is to document that the disposal activity will not result in the contravention of groundwater standards, in addition to other environmental standards (e.g., surface water).

(c) Groundwater contaminant transport calculations applied to evaluating potential impact to surface waters

Because one of the intentions of the Subchapter 02T regulation is to not allow any violations of surface water standards, the Division may require that an evaluation be made to determine the potential impact of the waste disposal activity or release onto the surface waters. Predictive calculations or modeling methods may be required for the following facilities that have or propose a non-discharge disposal activity and there is reasonable concern that surface waters may be adversely impacted by the subject non-discharge waste disposal activity:

(i) any facility treating industrial waste,
(ii) any facility with a design flow of over 25,000 gpd, or
(iii) any facility utilizing a high-rate disposal system.

This evaluation would be conducted using a standard hydrogeologic investigation in combination with predictive calculations or modeling to determine the potential impact to surface waters. The evaluation would be mainly concerned with the potential impact of waste nutrients (nitrogen and phosphorus) onto the surface water body, but also could consider other surface water quality standards as described in 15A NCAC 02B .0200 at the direction of the Division. The evaluation would predict the resultant impact in terms of total pounds/day of contaminant to potentially discharge into the surface water body of concern. The Division may require this “groundwater to surface water” potential nutrient impact to be evaluated whenever surface waters or groundwater lowering ditches or drains are located inside the facility’s compliance boundary, or otherwise reasonably deemed to be “at risk” by the Division.

Section I: Groundwater Modeling Process

The groundwater modeling process involves the following steps:

(1) define study objectives
(2) develop an initial conceptual model and data collection plan
(3) collect required data
(4) refinement of conceptual model
(5) select a computer model
(6) construct a groundwater model
(7) calibrate groundwater flow and transport model
(8) use models for predictive simulations
(9) conduct sensitivity analysis of calibrated models and predictive simulations
(10) perform mass balance calculations
(11) performance monitoring and model refinement

In general, the groundwater modeling process is a direct outgrowth of the hydrogeologic investigation. Most of the data required by the groundwater modeling process should be acquired in the hydrogeologic investigation and documented. The overall purpose of the hydrogeologic investigation is to support a demonstration as to whether or not the groundwater standards can be met. These predictions are accomplished via predictive calculations or modeling.

(1) Define study objectives

In this critical first step, complete and detailed objectives of the modeling effort are specified. These objectives will dictate the level of detail and accuracy required in model simulation. These objectives should:

- Adequately address any regulatory requirements. These requirements will typically be:
  - ensuring that the groundwater standards will be maintained at the facility's compliance boundary or specific property location,
  - ensuring that the contaminant plume will not adversely affect a known or potential receptor,
  - estimating the flow and loading to surface water discharge areas;
  - estimating the zone of influence around an infiltration gallery to ensure a closed loop infiltration and recovery groundwater system (for infiltration galleries), or
  - ensuring that the one-foot water table separation rule can be maintained.
- Identify constituents and processes to be modeled and acceptable model assumptions to be made.
- Provide acceptable tolerances for model calibration.

The study objectives as defined above should be documented in writing. And a description should be provided with regards to how the model/predictive calculations will address the study objectives.

(2) Develop an initial conceptual model and data collection plan

A conceptual model of groundwater flow is an interpretation or working description of the characteristics and dynamics of the physical hydrogeologic system. This is also a critical step in the modeling process, for if the investigator incorrectly conceptualizes the hydrogeologic environment, then groundwater model results likewise will be incorrect and will produce invalid predictions. The purpose of the conceptual model is to document regional and site-specific hydrogeologic data into a set of assumptions and concepts that can be evaluated quantitatively with the numeric or analytic models used for analysis and prediction.. Consult the Division's *Hydrogeologic Investigation and Reporting Policy* for further guidance on developing a conceptual model and on performing a hydrogeologic investigation.

An initial conceptual model should be developed from available regional and local studies and information, and initial site visits before significant site-specific data collection efforts are undertaken. This step is necessary to assure that adequate types and quantities of data are collected to adequately define the conceptual model and to constrain the numerical model or calculation basis. The initial conceptual model generally undergoes refinement or modification as a result of the data collection process, and may be further modified as a result of sensitivity analyses with the quantitative model.

The conceptual model and quantitative models derived from it should adhere to the principle of parsimony. That is, the simplest model that adequately describes the operation of the hydrogeologic system for the expected analysis conditions is always preferred over more complex models.

For the Mountain and Piedmont regions of North Carolina, the conceptual model of the occurrence and movement of groundwater described by LeGrand is a good starting point. For coastal plain applications, the model described by Giese, et al provides an initial model framework.

The conceptual model should include a written description of the following:

(1) Topography and drainage
(2) Hydrostratigraphic units:
   a. Lateral and vertical boundaries
   b. Relationship to other units
   c. Hydraulic and transport properties within each unit
(3) Boundary and Initial Conditions for Flow and Transport
(4) Time Domain to be used for analyses (steady or transient)
(5) Sources and sinks for water to enter or leave the modeled system
   a. Recharge and evapotranspiration
   b. Wells and springs
   c. Connected surface water bodies
   d. Topographic and manmade drains

(3) Collect required data

Data should be collected in accordance with the procedures outlined in the Division's *Hydrogeologic Investigation and Reporting Policy* document.

An important component of the data collection process is the documentation of data variability, uncertainty, and deficiencies, and a compilation of the uncertainties recorded for each of the other components.

Groundwater models should not be used as a substitute for site-specific measurements of field data. Rather, the site-specific measurements should be used to constrain the modeling by providing data for model calibration, measurements of hydrostratigraphic unit geometries and properties, as well as sources and sinks to be modeled.

(4) Refinement of conceptual model

Analysis of collected field data may support the initially developed conceptual model. Or, the analysis can result in a refinement of the initially developed conceptual model.

At this stage the investigator should address the adequacy of the data collection effort. The collection of additional appropriate site data may be required in order to further refine/confirm the conceptual model.

(5) Select a computer model

A computer model is a set of one or more mathematical algorithms that simulate the characteristics of a physical hydrogeologic system. The computer model selected should be appropriate for the conceptual model developed. Modeling objectives should provide guidance on the complexity of model required. In general, the simplest model should be used that adequately matches the conceptual model. If the problem can be conceptualized in two dimensions, then a three-dimensional model is unnecessary. When selecting an appropriate groundwater model for a particular application, it is important to consider the amount and quality of data available. Do not use a complex, multi-dimensional groundwater model if there is not sufficient on-site data in addition to adequate knowledge of outer hydraulic boundaries, sources and sinks. However, there may be situations in which a fully developed three-dimensional numerical model is required, such as multi-aquifer groundwater flow/transport problems or multi-layer models incorporating multiple soil horizons (where such complex models result from complex conceptual models, and necessitate greater detailed hydrogeologic data collection).

When selecting a groundwater computer model, the user should consider the track record of the model. The Division's Aquifer Protection Section requires that any model used on a Division-regulated project: (1) be thoroughly documented in readily accessible published format; (2) be peer-reviewed in the scientific literature [includes appropriate government publications and reviews published by or in cooperation with the International Ground Water Modeling Center]; and (3) be appropriate to the site under investigation, as determined by this policy.

(6) Construct a groundwater model

Model construction is the process of transforming the conceptual model into mathematical form. For numerical models, this process usually involves translating the conceptual model into a discretized flow domain, identifying discrete periods of time for analysis or annually-averaged conditions, and compiling input parameters for the groundwater computer model, including initial and boundary conditions and hydraulic properties. For semi-analytical models, the process is similar, except no spatial discretizing is required. For analytical models, again no spatial discretizing is required, but care must be taken to ensure that the pre-set boundary conditions for a particular analytical solution adequately match the site in question, and that the assumed groundwater flow field is adequate for the site.

(a) <u>Flow sources and sinks</u>

Sources and sinks influence groundwater flow patterns, and their effects should be documented for inclusion in the selected model. Common sources and sinks that should be identified include: pumping or injection wells, precipitation and evapotranspiration (or net groundwater recharge described below), drains, leakage across confining layers, and flow to or from surface water bodies. Descriptions of sources and sinks should include rates and temporal (seasonal and otherwise) variability. Development of a water budget is usually helpful to quantify the contributions of sources and sinks.

Net groundwater recharge (or simply recharge) refers to the portion of precipitation that infiltrates the soil and enters into the surficial groundwater aquifer, and is a key parameter in all groundwater flow models. Recharge can be quantified in two general ways: by either performing stream hydrograph baseflow separation on a regional (basinwide or sub-basinwide) scale, or evaluating detailed site-specific soil infiltration/evapotranspiration and surface runoff estimates and performing a site-specific water balance to estimate recharge. Obtaining accurate estimates of recharge is difficult without extensive regional and/or site-specific evaluation, and usually published recharge estimates are used. With any groundwater flow model, there is always a direct correlation between net groundwater recharge and the aquifer bulk transmissivity, which is usually evident during the model calibration process (see Section I (7) Calibrate groundwater flow and transport model below) and easily seen by running sensitivity analyses. Therefore, selecting the appropriate net recharge is usually balanced with selecting the appropriate aquifer bulk transmissivity.

At times it can be advantageous to model total precipitation (P) into the groundwater flow model, and model evapotranspiration (Et) out of the model, with the net groundwater recharge (R) being estimated as $R = P - Et$. A benefit of this methodology is that seasonal changes in recharge (R) can be easily modeled using long-term averaged precipitation (P) and standard evapotranspiration (Et) models. When modeling recharge via the P – Et methodology, special care should be taken to check the model water balance output to ensure that the model calculated recharge ($R = P - Et$) is within an acceptable or reasonable range.

(b) Boundary conditions and extent of model

The physical size or extent of the model (length, width and depth of model) often has a large bearing on the flow sources and sinks that need to be included into the model in addition to the types of boundary conditions included in the model. In general, the groundwater flow and transport model should have as many physical boundaries (such as rivers, lakes, ocean) as possible in order to adequately simulate the regional groundwater flow conditions at the particular site of interest. These types of physical boundaries can generally be considered specified head, specified flux, or head-dependent flux boundaries. Other good physical boundaries to model would be ridge lines or hilltops, which can usually be considered no-flow boundaries for the surficial aquifer. However, these types of features may not be no-flow boundaries for deeper confined aquifers.

In general, model boundaries should be located far enough away to minimize their direct influence on the study area. To accomplish this and help lead the investigator toward using real surrounding physical boundaries in the model, the physical size (i.e., each horizontal dimension) of the model should be at least four (4) times larger than the largest dimension of the facility's land application system or other source of contamination. This general rule can also be applied to the area impacted by small point source contamination sources such as might be encountered in incident investigations. For example, if a proposed spray irrigation facility has a spray field that is 1000 feet by 500 feet, then in general the model should be at least 4000 feet in length and breadth, or may need to be larger if appropriate in order bring in a physical boundary, such as a neighboring river, into the model. Exceptions to this rule may be if a constant head boundary (river, stream, etc.) or other boundaries are close to the site being modeled. When in doubt as to how large to make the extent of the model, it should be made larger in order to take into account neighboring physical boundaries.

Caution should be exercised when modeling groundwater-lowering ditches, which should not be modeled as constant head boundaries. In general these features should be modeled as a head-dependent drain boundary, where the drain elevation is the elevation of the lowest topographical elevation in the ditch or drain pipe. In many situations, these drain elevations provide important controls on the configuration of the water table and the depth to water beneath land application units. Additionally, groundwater-lowering ditches may necessitate an investigation into the potential impact to surface waters.

(c) <u>Regional groundwater gradient</u>

It is important that the predictive groundwater model accurately reflect the regional groundwater gradient as measured in the field. Failure to do so will generally result in incorrect groundwater mounding calculations and incorrect groundwater contaminant transport calculations. It is important to realize that if the model boundary conditions are correctly established, and if the sources and sinks (which include groundwater recharge and leakage across confining layers) are modeled correctly, then the model-predicted regional groundwater gradients will reflect field-measured groundwater gradients. If the model-predicted groundwater gradients are too high or too low or in the wrong direction, then this generally indicates that the model boundary conditions are incorrect and/or the model sources and sinks are incorrect.

It is often the case that groundwater gradients vary seasonally, varying in magnitude and direction. This again is generally a result of seasonal changes in physical boundary conditions, such as changing river water level; and seasonal changes in sources and sinks, such as changing groundwater recharge and evapotranspiration rates from winter to summer. Whether or not the groundwater model needs to take into account these seasonal groundwater gradient changes depends on the problem being solved and the time-scale of the problem. For groundwater mounding problems, the worst-case scenario will be in the winter and early spring when the seasonal groundwater table is at its maximum elevation. For groundwater contaminant transport problems, generally the time-scale of interest is measured in years because of generally slow-moving groundwater. For time scales measured in years or decades of years, seasonal fluctuations of groundwater gradient tend to average out, and modeling yearly averaged gradients is appropriate.

(d) <u>Hydraulic properties</u>

Hydraulic properties include the transmissive and storage characteristics of the aquifer system, such as transmissivity, hydraulic conductivity, storativity, and specific yield. They also include the leakage coefficients of stream, lake and riverbeds. Field and laboratory measurements of these properties should be documented, compared to accepted ranges for the medium under investigation, and uncertainty associated with the property measurements estimated. An assessment of heterogeneity and anisotropy over the aquifer domain for each property should be made, particularly in the Piedmont and Mountain regions of the State. See the Division document entitled *Performance and Analysis of Aquifer Slug Tests and Pumping Tests Policy* for details related to conducting aquifer tests.

(e) Parameters used in transport models

Groundwater transport models require certain additional hydraulic and chemical parameters, these being effective porosity, longitudinal and transverse dispersion coefficients (or dispersivity), chemical retardation factor, and chemical biodegradation decay rate. See Appendix A for details on how to estimate these parameters.

(f) Groundwater to surface water models

If the conceptual model involves a groundwater discharge to a surface water body, then consideration needs to be given to how the surface water body will be modeled. Generally, the surface water body can either be modeled as a constant head boundary where the yearly-average surface water elevation is used as the constant head, or as a head-dependent boundary where the surface water elevation is allowed to vary dependent on groundwater baseflow and upstream conditions. The evaluation should predict the resultant contaminant impact in terms of total pounds/day of contaminant to potentially discharge into the surface water body of concern, once the groundwater contaminant plume has reached steady-state conditions. See Section I (7) Calibrate groundwater flow and transport model (below) for more details on transport analyses.

(g) Contaminant source concentration used in transport models

Groundwater transport models require a source concentration or mass flux to be designated for the source of the contaminant plume to be modeled. In some situations, uncertainty in the timing, magnitude, and mass of chemical sources may contribute the largest uncertainty in predictions using transport models. In the case of a groundwater remediation system being modeled, the measured groundwater contaminant concentration in the source area actually measured in the field may be used. These sources should be considered constant and continual unless it can be documented that virtually all of the source mass has been removed.

In the case of a land application system (spray irrigation of treated wastewater, for example), the correct source groundwater contaminant concentration to be used in a transport model may be difficult to determine because of the uncertainty of chemical removal/uptake in the cover crop and shallow soil horizons. There are two cases to consider:

- If the cover crop and shallow soils are deemed to have no removal capacity for a particular contaminant chemical of concern, then the treated wastewater effluent chemical concentration should be used as the source concentration of contaminant flux into the groundwater system.
- If the cover crop and shallow soils are deemed to have a certain removal capacity for the particular contaminant, then the Division will allow 50% removal of the Realistic Yield Expectation (R.Y.E., as documented by NRCS, NCSU, etc.) to be used in calculating the resultant contaminant

concentration assumed to leach into the groundwater system (see Appendix A for a detailed discussion).

(h) Data deficiencies and uncertainty

A final component of the conceptual model is the documentation of data deficiencies, a compilation of the uncertainties recorded for each of the other components, and an acknowledgment of any alternative conceptual models that could be developed from the available data. This last component of the conceptual model is an important step, for it forces the investigator to quantitatively address the adequacy of the data collection effort. If high uncertainty is associated with the conceptual model, then an elaborate and costly modeling effort may not be justified.

(7) Calibrate groundwater flow and transport model

A reliable groundwater flow model must be able to simulate the observed movement of groundwater and/or concentrations of contaminants. Typically, a groundwater flow model is calibrated by comparing model output, such as a water level or head and discharge to surface water, with actual measured values. When groundwater flow calibration is involved, the modeling results should include (1) an evaluation of the calibration process, and (2) the resultant calibrated groundwater/potentiometric surface(s) with posted head residuals at individual observation wells. Residual statistics should be evaluated and reported.

Model calibrations are normally conducted with the flow model in “steady-state” mode, where all the model parameters are fixed and do not vary with time. Typically, annual averaged groundwater levels are used or approximated. However, in certain situations it may be necessary for the investigator to also calibrate a transient (or dynamic) flow model. In this situation, the model output for various time steps is compared to the observed values, such as water levels that vary monthly, seasonally, or during the course of a pumping test.

In addition to model calibration using individual observation wells, the gradient (magnitude and direction) of the model-predicted groundwater table/potentiometric surfaces(s) should reflect the field-measured gradient across the modeled site. It is possible, for example, that part of the modeled potentiometric surface appears accurate, but another part of the potentiometric surface is obviously wrong, either in magnitude or direction. Using such a model to predict contaminant transport may lead to serious errors.

It is important to realize that even though good groundwater flow calibration may be achieved, this does not imply that the model is “correct” in its representation of the actual hydrogeologic processes of the modeled site. Often times the groundwater flow model calibration process leads to the investigator realizing more site/subsurface information is necessary to improve either (a) the overall model calibration, and/or (b) the overall model water budget. Once the investigator is satisfied with a particular model calibration, the overall model water budget should be checked to ensure that a reasonable groundwater recharge value is being used for the particular site being modeled. For example, a groundwater flow model being used for a particular site in the interior coastal plain may appear to calibrate well, but if the resultant water budget shows that the net groundwater recharge is 30 inches/year when a net groundwater recharge of about 10 – 12 inches/year is more generally accepted, then the overall model should be re-evaluated to determine the source of error. In this particular case, it may likely be determined that the overall aquifer transmissivity was set too high, which led the investigator to adjust the net groundwater recharge too high in order to maintain adequate calibration. It may also imply that the overall hydrogeologic framework is incorrect or not complete.

Numerical groundwater contaminant transport models require that the groundwater flow field first be evaluated. Therefore, a numerical transport model calibration is really a two-step process. In Step #1 the groundwater flow model is calibrated, and then the flow field calculated by the flow model is used in the contaminant transport model. Step #2 involves calibration of the groundwater transport model to historic data on contaminant concentrations and degradation rates. Groundwater transport model calibration will require a minimum of two discreet sampling events from an appropriate time interval from the site. However, calibrating a groundwater transport model using to too few sampling events, or between time intervals that are relatively short, can lead to serious errors in predictive calculations.

(8) Use models for predictive simulations

The main purpose of a modeling effort is to generate a representative groundwater flow and/or transport model that will make accurate predictions based on an altered environment. Predictive simulations may either be run when using a model in “steady-state” mode or in “transient” mode. In steady-state mode, all the model parameters are fixed and do not vary with time, whereas in transient mode certain parameters such as rainfall, evapotranspiration, pumping rates, etc., are varied seasonally (typically) to generate a seasonal groundwater table variation. Predictive simulations will generally be of two forms: (a) groundwater flow and mounding simulations, and/or (b) groundwater transport simulations.

(a) <u>Groundwater flow and mounding predictive simulations</u>

Typically, predictive groundwater flow models are run in steady-state mode, when dynamic equilibrium is achieved. Transient groundwater flow models are run when multiple time periods are simulated. If the flow model is being run to predict a groundwater mound height generated by some type of land application system (such as an infiltration gallery or spray irrigation system), then the model is typically run for 200 - 360 days, or whenever the groundwater mound height appears to stabilize (or 720 days, whichever comes first). However, the simulation period should be a year or less, as the seasonal groundwater table/mound fluctuation is typically cyclical.

(b) <u>Groundwater transport simulations</u>

Groundwater transport models are typically run with the flow model in steady-state mode using average annual conditions. Because the time span of groundwater contaminant travel is usually measured in years, over the span of multiple years the seasonal groundwater flow variations are generally averaged out, and thus performing transport models with a transient groundwater flow model is generally not required.

A transport model should be run until the contaminant plume has reached steady-state (or near steady-state) conditions. Assuming the source of the contaminant flux remains constant (or near constant), at some point in time the shape of the plume will reach a maximum size and the shape of the plume will remain relatively fixed for future times. For larger discharging land application systems, steady-state conditions may not be reached for decades, especially if deeper semi-confined aquifers are involved in the groundwater flow and transport process.

(9) Conduct sensitivity analysis of calibrated models and predictive simulations

Sensitivity analysis involves varying values for a property, such as hydraulic conductivity, and observing the effect on model calculated head or concentration values. Usually there is a certain amount of uncertainty with regard to the actual aquifer hydraulic conductivity or transmissivity values to be used in the model. Thus, sensitivity analysis is particularly helpful in quantifying the uncertainty associated with model-predicted future or altered site conditions. By varying the hydraulic conductivity or transmissivity, or other potentially sensitive parameters, over the range of potentially expected values, the range of resultant groundwater elevations or concentrations will be generated. The investigator can then determine expected head or concentration results with a range of uncertainty associated with it.

The sensitivity analysis should identify a range of values for each sensitive input parameter. Data collected from on-site testing will help constrain the range of values for sensitive parameters. On-site data should be used whenever possible in the model domain. For poorly constrained parameters, use the most conservative input value(s) that can reasonably be expected to occur for the particular model application. For example, if the groundwater model is used to predict mounding conditions in response to irrigation, and the sensitivity analysis indicates that the model is sensitive to changes in transmissivity values, the transmissivity value(s) used in the model must be those which, within a reasonable range for the given hydrogeologic conditions, would result in the highest mounding of water levels. If a groundwater contaminant transport model is being used to predict the maximum distance that a contaminant may be expected to travel, sensitive input values used must be those which, within a reasonable range for given hydrogeologic conditions and chemical properties, would result in the furthest distance traveled for the modeled constituent.

The results of the sensitivity analyses should include a table showing the sensitive parameters and their ranges, and figures showing the resulting variations in modeled parameters using the two value endpoints (highest and lowest value) for each sensitive parameter. Additional field characterization may be required to obtain data for model input parameters that are determined to be relatively sensitive.

(10) Perform mass balance calculations

Water and mass balance model outputs (or calculations) should be shown describing all flow and transport fluxes. All source and sink terms should be shown and the net results should balance within reasonable margins for error (less than 0.5%).

For model calibration, if net groundwater recharge (R) is being modeled as total precipitation (P) into the model minus evapotranspiration (Et) out of the model ($R = P - Et$), then the water balance output should show the total P into the model, and the total Et out of the model, and an evaluation of the net groundwater recharge (R) into the model should be made. For groundwater mounding model simulations, the water balance output should show the total additional flux of water added into the model above the net groundwater recharge (R).

For groundwater transport models where a particular contaminant is reaching a receptor such as a stream or a well, the mass balance should show the total mass of contaminant (as a function of time) reaching the receptor, the total mass removed from the model domain at the receptor, and the total contaminant mass introduced into the model domain at the source.

(11) Performance Monitoring and Model Refinement

Groundwater models can be useful tools to simulate hydrogeologic conditions and contaminant concentrations over time. Models are most useful when used as working “tools” that are refined and improved when more information on site hydrogeologic conditions becomes available. As more site data becomes available, the groundwater model should be checked against this data and the model may need to be refined in order to more accurately predict future conditions. Additional wells or monitoring points may be required during the performance-monitoring period if the performance monitoring data indicates an inadequate monitoring network.

When required, a Performance Monitoring Report should be submitted to the Division’s Aquifer Protection Section on an annual basis, or at a time interval agreed upon by the Section and the Responsible Party, which will contain the predicted model outputs compared with data obtained during the performance monitoring period. If there is a significant discrepancy between the predicted model output and the performance monitoring data, the groundwater model should be refined in order to more closely match actual field conditions.

Section II: Reporting Modeling Results

Results from groundwater modeling efforts must be adequately documented. Such documentation must provide regulators sufficient information to determine the adequacy of the model and supporting data, and validity of the modeling results. The major reporting elements shown below must be included in the model report submission. This format is a modified format taken from ASTM D 5447. The value of this format is that it standardizes criteria that should be considered in any modeling effort. The detail provided within the format should reflect the investment that has gone into the modeling effort.

The Division may request that groundwater computer model data inputs and outputs be provided in electronic form in order to allow staff to evaluate the model using the actual model.

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Appendix A

Dispersion, Chemical Retardation Factor, and Chemical Biodegradation Decay Rate Parameters used in Transport Models

Groundwater transport models typically require certain additional hydraulic properties and chemical properties, these being (a) longitudinal and transverse dispersion coefficients (or dispersivity), (b) chemical retardation factor, and (c) chemical biodegradation decay rate.

(a) Dispersion measures the natural spreading of a contaminant plume during migration. Site specific dispersion parameter values are difficult to measure without extensive field investigations, but fortunately researchers have developed methods of estimating them using simple formulas. The dispersion coefficient depends not only on the variability of the local hydraulic conductivity at the site, but also on the scale of the problem (i.e., the distance from the original plume site to the groundwater receptor or endpoint of travel). See Fetter (1993) or Gelhar (1985) for more discussions regarding these issues.

Longitudinal dispersion is a measure of the contaminant plume spreading in the direction (parallel) of groundwater flow. Transverse dispersion is a measure of the contaminant plume spreading perpendicular to the direction of groundwater flow. The longitudinal dispersion coefficient can be estimated as follows:

$$\mathbf{D_L = 0.1\ L\ v}$$

where:
- $\mathbf{D_L}$ = longitudinal dispersion coefficient in feet^2/day
- $\mathbf{L}$ = distance in feet from the original plume site to the groundwater receptor of interest or endpoint of travel
- $\mathbf{v}$ = average groundwater velocity in feet/day

The transverse dispersion coefficient ($\mathbf{D_T}$) can be estimated from the relation $\mathbf{D_L/D_T}$ = 6 to 20, depending on site conditions (Fetter, 1993), but a ratio of $\mathbf{D_L/D_T}$ of 10 is probably good for typical cases.

Often groundwater transport models will use the longitudinal and transverse dispersivity parameter instead of the longitudinal and transverse dispersion coefficient. The relationship between the two parameters is as follows:

$$\mathbf{D_L = \alpha_L v + D^*}$$
$$\mathbf{D_T = \alpha_T v + D^*}$$

where $\boldsymbol{\alpha_L}$ is longitudinal dispersivity in feet, $\boldsymbol{\alpha_T}$ is transverse dispersivity in feet, **v** is average groundwater velocity in feet/day, and $\mathbf{D^*}$ is effective diffusion coefficient, which is related to the diffusion due to concentration gradients. For typical groundwater transport problems, $\boldsymbol{\alpha_L}$ **v** and $\boldsymbol{\alpha_T}$ **v** are numerically much larger than $\mathbf{D^*}$, and thus $\mathbf{D^*}$ can often be ignored (See Fetter, 1993. However, in some transport problems **v** can be numerically very low, such as leakage through a liner problem, and $\mathbf{D^*}$ term will dominate, implying that the main dispersion mechanism is diffusion via concentration gradients.) In this case:

$$\mathbf{D_L / D_T} = \boldsymbol{\alpha_L / \alpha_T} = 10 \quad \text{(typically)}$$

(b) Chemical retardation factor (unitless number) is the measure of the relative migration velocity of the chemical (contamination) compared to water. For inorganic constituents (such as cations, anions, including NO_3, Cl) and fecal coliform, the retardation factor is normally set to 1. For organic chemicals, the retardation factor (**R**) should be based on the following formula:

$$\mathbf{R = 1 + \rho K_{oc} f_{oc} / n}$$

where:

- $\boldsymbol{\rho}$ = aquifer bulk density in g/cm^3, default = 1.8 g/cm^3
- $\mathbf{K_{oc}}$ = organic carbon-water partition coefficient in L/kg
- $\mathbf{f_{oc}}$ = aquifer organic carbon fraction (unitless), default = 0.001
- $\mathbf{n}$ = aquifer effective porosity (unitless)

The organic carbon-water partition coefficient ($\mathbf{K_{oc}}$) is readily available for most organic chemicals from various sources. Values other than the default values for aquifer bulk density ($\boldsymbol{\rho}$) and organic carbon fraction ($\mathbf{f_{oc}}$) should be documented.

(c) The chemical biodegradation decay rate measures the rate at which a contaminant is attenuated due to biological activity in the subsurface. Setting the decay rate to zero implies no biodegradation. Many groundwater transport models that allow biodegradation assume a first-order decay rate. Typically, these models will either require the decay rate in units of either 1/days or 1/years. Some models, however, may require the decay rate to be entered in terms of a half-life (or lifetime). The relationship between half-life ($\boldsymbol{\tau}$) and first-order decay (**k**) rate is:

$$\boldsymbol{\tau} = \mathbf{0.693 / k}$$

where if $\boldsymbol{\tau}$ is in days, then **k** is in 1/days, or if $\boldsymbol{\tau}$ is in years, then **k** is in 1/years, etc. If a non-zero biodegradation rate is used in a transport model, evidence needs to be presented to justify its use.

With regards to Nitrate (NO_3) transport and decay in groundwater, there is evidence that Nitrate may decay (NO_3 denitrifying in a riparian buffer zone, for example) via a zero-order decay rate (see Nelson et. al., 1995), or via Michaelis-Menton kinetics that leads to a first-order decay for smaller concentrations and a shifting to a zero-order decay for larger concentrations (see Maag et. al, 1997). In this special case of NO_3 denitrifying (and other contaminants that may be similar), special care should be taken when modeling NO_3 removal with solely a first-order decay model, as over-prediction of the NO_3 removal rate could potentially occur.

Appendix B

Example Calculation of Nitrate Source Concentration to be used in a Groundwater Transport Model for Land Application Systems Utilizing a Cover Crop

Groundwater transport models require a source concentration or mass flux to be designated for the source of the contaminant plume to be modeled.

If the cover crop and shallow soils are deemed to have a certain removal capacity for the particular contaminant, then the Division will allow 50% removal of the Realistic Yield Expectation (R.Y.E., as documented by NRCS, NCSU (see http://www.soil.ncsu.edu/nmp/ncnmwg/yields/), site specific yield records, etc.) to be used in calculating the resultant contaminant concentration assumed to leach into the groundwater system (see North Carolina Cooperative Extension Service, 1990).

> *Note: This 50% R.Y.E. limit with regards to the cover crop is only for the purposes of calculating a potential "conservative" resultant contaminant concentration assumed to leach into the groundwater system, and do not imply that the cover crop will not remove the full R.Y.E. However, studies have shown that certain chemicals of interest (nitrogen, for example) typically do not accumulate in the soil, and are readily leached downward through the cover crop root zone into the surficial groundwater aquifer, especially when the crop is not in its growing season. Therefore, this 50% rule is meant to be conservative in order to guard against potential contaminant impact to groundwaters and surface waters of the State.*

This calculation should be done according to the following example.

A certain municipal wastewater treatment plant uses spray irrigation to land apply its treated wastewater. The WWTP has a design flow of 50,000 GPD (0.05 MGD), and the investigator is concerned about meeting the NO_3 (nitrate) groundwater standard of 10 mg/l N at the compliance boundary. The WWTP sprays onto a 15 acre dedicated field where the cover crop is fescue grass on Goldsboro soils. The WWTP achieves the following average effluent limits with regard to nitrogen species:

[Ammonia-N]	=	8 mg/l
[NO_3-N + NO_2-N]	=	10 mg/l
[TKN]	=	15 mg/l

Total nitrogen in the wastewater effluent is thus [TKN] + [NO_3-N + NO_2-N] = 25 mg/l (ppm) N. The total pounds/year of N applied to the spray fields is:

Total pounds N/year applied = (25 ppm N) x (0.05 MGD) x (8.34 lbs/gallon) x (365 days/year)

= 3,805 lbs N/year

Calculate the Cover crop R.Y.E. Uptake:

According to the NC State University Realistic Yield Expectations (R.Y.E.) for Soils in North Carolina (see NCSU, 2000), fescue planted on Goldsboro soil series will yield 4.0 dry tons of hay/acre/year.

According to the NRCS Conservation Practice , Standard Nutrient Management Code 590 document (see NRCS, 1998), Nitrogen Fertilization Rate for fescue is 40 - 50 lbs N/ton hay (use 50 lbs N/ton hay).

Combining the above two figures, 15 acres of fescue will consume:

R.Y.E. = (4.0 dry tons/acre/year) x (50 lbs N/ton hay) x (15 acres)

= (200 lbs N/acre/year) x (15 acres)

= 3,000 lbs N/year

The Division will allow 50% uptake of the R.Y.E. for the purposes of calculating contaminant concentrations leaching to the underlying groundwater system:

50% of R.Y.E = 0.5 x (3,000 lbs N/year) = 1,500 lbs N/year

Resultant pounds N/year assumed to leach into groundwater system = 3,805 lbs N/year - 50% of R.Y.E.
= 3,805 lbs N/year - 1,500 lbs N/year
= 2,305 lbs N/year

Resultant chemical conc. of flux leaching into the groundwater system = 2,305 lbs/year / (0.05 MGD x 8.34 x 365)
= 15.1 mg/l N

which is assumed to all convert (oxidize) to NO_3-N by the time the contaminant is in the groundwater system.

Thus, for the purposes of building the groundwater flow and transport model, the investigator would apply 50,000 GPD onto the 15 acres at a concentration of 15.1 mg/l NO_3-N and assume that all the contaminant flux recharges into the groundwater system.

From the above analysis, it is clear that if the total nutrients in the effluent is less than or equal to 50% of R.Y.E., then all the effluent nutrient is assumed to be taken up by the cover crop, and there is no need to perform any groundwater contaminant transport analysis for the nutrients involved.