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LUMPED PARAMETER MODELS FOR PREDICTING NITROGEN LOADING FROM LOWER COASTAL PLAIN WATERSHEDS

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ABSTRACT

In recent years physically based comprehensive distributed watershed scale hydrologic/water quality models have been developed and applied to evaluate cumulative effects of land and water management practices on receiving waters, Although these complex physically based models are capable of simulating the impacts of these changes in large watersheds, they are often prohibitive for regular applications because of excessive input data requirements and because of uncertainties in both the model processes and input data. This task is beyond practical reality for policy makers and managers who need to make decisions about multiple watersheds with limited rime and resources. Nevertheless, important decisions need to be made with regard to nutrient and water management practices at the field and watershed scales. Models are needed to make decisions that reflect our current understanding of the system yet require input parameters that can be readily determined with a minimum of uncertainty.

In this project, lumped parameter watershed scale water quality models of various levels of complexities for predicting nitrogen loading from lower coastal plain watersheds have been developed and tested. These watershed scale lumped parameter models, developed and tested herein, are based upon DRAINMOD, a field scale hydrologic water management model for poorly drained high water table conditions that has been successfully tested for varying geographical and climatological conditions. The watershed scale models have in-stream hydraulic and quality transport submodels linked to DRAINMOD. Models were simplified and a lumped parameter approach used lo describe in-stream water quality processes. The models were tested with both water quantity and quality (concentrations and loadings) of nitrogen collected over a three-year (1996-I 999) period on several subwatersheds across an intensively monitored 10,000 ha lower coastal plain watershed near Plymouth, North Carolina. Model testing involved only minimal calibration that used data available in the literature as input to the model. Given the complexity of the model and limited data, predictions of daily and annual outflows at the outlets of all the subwatersheds ranged from acceptable to excellent. The model performed better for a uniform managed forest than for an agricultural watershed, which was more heterogeneous with respect to soils, crops, and water management practices, The degree of accuracy of predictions of seasonal and annual loads of nitrogen varied widely depending upon the season and the level of complexity chosen in lumping the transport processes.

A spreadsheet-based export coefficient model, which used average annual velocity for estimating travel time in the delivery ratio, was as good as using a day-by-day velocity simulated by the complex watershed scale hydraulics model. A GE-based lumped parameter model was developed based on an export coefficient-delivery ratio (DR) concept, with the DR dependent on time of travel from field to the watershed outlet. The GIS model can be used to quantify the seasonal and annual nitrogen loads at the watershed outlet. Research is underway to include an uncertainty analysis component with this lumped parameter water quality model so that nitrogen loading predictions can be described as a probabilistic distribution.

SUMMARY AND CONCLUSIONS

This study was conducted on a 10,000 ha watershed near Plymouth in eastern North Carolina to develop lumped parameter water quality models for predicting nitrogen loading from coastal plain watersheds. The watershed was instrumented to measure cumulative effects of land use and management practices on loading of nutrients and sediment from lower coastal plain watersheds. Flow rates and drainage water quality measured at both the field scale and at the watershed scale were used for testing models developed to predict hydrology and nutrient transport. Hydro-meteorologic and water quality data collected over a near four-year (1996-99) period on the study watershed were summarized. Rainfall data from several rain gauges distributed across the watershed were used as model inputs. Daily weather data measured at two weather stations (one at forest site and another at the agricultural site) were used to estimate daily PET for grass and forest references. These data were also used as model inputs. Soil hydraulic properties for the model were based on literature published data for the soil series identified using SCS soil survey report.

It was hypothesized that the nitrogen loading to downstream receiving waters is mostly dependent on the hydrology (drainage outflows) as a result of storm events of different sizes and patterns. This means that the hydrology and flow routing part should be accurately predicted before testing water quality components of the model The lumped paramcrer models developed were based on a field scale hydrologic model, DRAINMOD, that has been successfully tested for predicting water table depths and outflow rates from poorly drained, high water table soils.

Two DRAINMOD based watershed scale distributed hydrologic/hydraulic models, DRAINMOD-DUFLOW and DRAINWAT were tested for their ability to predict drainage flow rates and cumulative flow volumes from subwatersheds ranging in size from 7 10 ha to 8 140 ha, and having multiple land uses. The predictions of daily drainage rates and total outflow using DRAINWAT were in excellent agreement with measured data for the subwatershed S4, which had fairly homogeneous soils and vegetation. The predictions were somewhat poorer for the agricultural subwatershed T4, which was more heterogeneous with respect to soils, crops, and water management practices. Predicted outflows and stages for two other subwatersheds, C2 and C5, were in reasonable agreement with observed data, but the agreement varied among storm events. The model was able to accurately predict both low flow events during dry periods as well as peak drainage rates during the summer tropical events that occurred on a large 8140 ha watershed with mixed land use. Some of the errors were attributed to weir submergence during large events caused by the hurricanes and to backwater conditions due co beaver dams. For most of the subwatersheds tested, the model gave reliable predictions of drainage outflows when general published soil property data were used as input. These results provide a basis for using these general soil property data in the watershed scale models. It was concluded that these hydrologic models can be used lo reliably predict outflow rates and volumes, and therefore, can bc linked with waler quality models to predict cumulative total nitrogen loading from the poorly drained coastal watersheds,

Models with different levels of complexity and input requirements wore evaluated in this study. However, models based on DRAINMOD (DRAINMOD-DUFLOW and DRAINWAT) were used to develop and test the comprehensive lumped parameter water quality models, Lumped parameter water quality transport and transformation models were derived based on the primary assumption that the rate of change in nitrogen concentration is directly proportional to the concentration (i.e. first order kinetics). This leads to the assumption that concentration in drainage water decays exponentially with time of travel in the canals and coastal streams. Field experiments were conducted to measure in-stream processes and. parametrise the in-stream model. The hydrologic models were linked internally or externally with the exponential decay equations to route the nutrients to the watershed outlet. Other methods based on. only DRAINMOD and/or simple rainfall-runoff models, including an export coefficient (average annual loading) approach that does not need field hydrology and concentration, were also identified for estimating nutrient export at the field edge. A constant decay parameter, that lumps all the transformation processes in the canal network, was assumed for all methods. Different methods of estimating travel time needed to compute a delivery ratio using the decay parameter were developed. GIS based and. simple spreadsheet based lumped parameter methods were tested for predicting nitrogen loads.

Most of the models considered were tested with data from a 2950 ha experimental forested subwatershed. 'Both DRAINMOD-DUFLOW and DRAINWAT based models with the exponential decay equation for nutrient transformation predicted annual nitrate loads within reasonable error. The GXS based approach was encouraging as a spatial analysis tool for prediction and assessment of annual N loads from lands with multiple land uses and management practices. Simple, easy to use, spreadsheet based export coefficient models were also analyzed. Results for the forested watershed S4 indicated that there was not much difference in annual loads estimated by using travel time on day-by-day basis using the DRAINMOD based model and the annual average travel time obtained from velocity-area relationships, where average velocity was obtained from long term model simulations. These results indicate that the net effect of in-stream processes on nitrogen loads can be reasonably estimated by these lumped parameter models which assume an exponential decay of concentration with time of travel.

The uncertainty associated with input parameters on the field hydrology, flow routing, and nutrient transformation/transport on nitrogen loading predicted by the lumped parameter models was discussed. An analysis of uncertainty of the results of the field scale model DRAINMOD-N showed that the predicted subsurface drainage was most sensitive to lateral saturated hydraulic conductivity than to eight other inputs. However, the results of the watershed scale model (DRAINMOD-DUFLOW) analysis, applied to the 2950 ha forested S4 subwatershed, showed that uncertainty of inputs for maximum surface storage and lateral hydraulic conductivity have much less impact on the uncertainty of predicted NO_3-N loads at the outlet, than they have on the same load at the field edge. The parameters most affecting predicted peak outflow rates and total outflow in watershed scale model FLD&STM/DRAINWAT were, in order of importance, time of concentration, channel bottom slope, soil hydraulic conductivity, and channel roughness. The simulated outflow was only moderately dependent on channel depth and width, rooting depths or drainable porosity.

A sensitivity analysis using the decay coefficient, average velocity, and the field loading in the lumped parameter models indicated that predicted nitrogen load at the watershed outlet is more sensitive to loading at the field edge (predicted drainage outflows and export concentrations) than to velocity and the decay coefficient, Although model predictions of N loads were shown to be relatively insensitive to the decay rate parameter, the uncertainty of the decay rate produced the widest confidence limits of all properties and parameters investigated, affecting the overall uncertainty of the model predictions. Analysis of the sensitivity of DRAINMOD-DUFLOW predictions to reaction coefficients showed that denitrification rate was more sensitive than either the mineralization rate or the dispersion coefficients.

The study concluded that a lumped parameter water quality model using a DRAINMOD based hydrologic model with an exponential decay equation for in-stream transformations can be used for evaluating the effects of land use and management practices on nitrogen loading at the outlets of the lower coastal plain watersheds, Preliminary results of application of these models demonstrated their potential as decision making tools.

RECOMMENDATIONS

1. Case studies should be conducted on the application of the watershed scale models developed in this research. Such studies on 10,000 to 50,000 ha watersheds in the lower coastal plain would allow evaluation of effects of land uses and management practices on nitrogen loads. They would also identify data gaps, effects of model parameter uncertainty on predicted nitrogen loads, and further research needs for application of this technology.

2. Models with different levels of complexity and input requirements were evaluated in this study. A GIS based system for organizing input data and visual display of the outputs of the different models should be developed, Such a modeling system could provide hierarchical methods of selecting the most reliable and appropriate model based on data availability and the objectives of analyses to be conducted.

3. DRAINMOD based hydrologic/hydraulic models should be tested with multiple years of flow data from multiple sites with different land uses and management practices for their ability to predict drainage flow rates with a minimal field calibration, This will allow evaluation for using both the published soil hydraulic properties as well as the effects of variation due to weather.

4. The models should also continue to be refined to accurately predict not only flow rates at the watershed outlets but other fluxes such as waler table depths and flow rates at in-stream locations to verify the internal consistency of the model. 'This would first provide increased accuracy of predicted nitrogen loading rates at the field scale, in which the fluxes are dependent upon the predicted field water table depths and flow rates at the field edge. Secondly, it would allow to accurately predict the velocity distribution in the canal network used in estimates of travel time component of delivery ratio of nitrogen.

5. Soil hydraulic properties used in calibration of the models tested herein need to be processed and linked in a GIS data base format such that DRAINMOD based GIS models can be easily used for processing input parameters. This will facilitate use of GXS models in spatial analysis of nutrient exports in the watershed,

6. Additional field experimental studies need to bc conducted to determine the nitrogen decay rates for in-stream processes in a range of canal/ditch system typical of the coastal plain. This should include a study of the variability of decay parameter on a seasonal basis.

7. Emphasis should be placed on accurately determining the field edge loads and their statistical distributions. More research is needed to establish a sound database for export concentrations or coefficients for lower coastal plain fields

with different land uses and management practices. Flow and water quality data collected at this study watershed and other sites need to be systematically processed and analyzed to (a) develop export coefficients (average annual field loads) specific co each land management practice, (b) to estimate annual exports using measured average annual concentration data with DRAINMOD predicted annual average outflows, and (c) to determine statistical distributions and their parameters for nitrogen components for conducting uncertainty analysis of predicted nitrogen loads at the watershed outlet.

8. Extensive field validation of DRAINMOD-N for both agricultural and forested fields is needed to provide a more reliable means of estimating export coefficients for N loading from the fields with different land uses and management practices.

9. As with hydrologic/hydraulic models, DRAINMOD based lumped parameter water quality models developed herein should also be tested with multiple site years of data to calibrate the decay parameter for different nitrogen components. Testing of these lumped parameter models is more challenging but necessary on agricultural lands with complex combinations of land uses and management practices, as they discharge larger nutrient loads to the receiving waters compared to the forested lands.

10. Further efforts including dye tracer study for measuring velocities and travel times are needed to develop and validate velocity-drainage area relationships for lower coastal plain watersheds. This will improve reliability of method for estimating travel times and delivery ratios used in GIS and spreadsheet based lumped parameter models.

11. Testing of the GIS based lumped parameter water quality models for watersheds with multiple land uses is needed, Spreadsheet based models should also be tested. These methods will be very useful tools for the planners and land managers to visualize and evaluate the effects of land management practices for making management decisions.

12. The next big step is to link the lumped parameter water quality models with an uncertainty analysis component. The research on linking DRAINMOD-DUFLOW based lumped water quality model with an uncertainty analysis component is already underway. Possibility of linking MS-EXCEL spreadsheet based model with a decision tool such as @RISK is being explored to conduct uncertainty analyses of nitrogen predictions using Monte Carlo simulations.