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APPLICATION OF WATERSHED SCALE MODELS TO PREDICT NITROGEN LOADING FROM COASTAL PLAIN WATERSHEDS

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ABSTRACT

DRAINMOD-based watershed models have been developed and tested using data collected from an intensively instrumented research site on Kendricks Creek watershed near Plymouth. NC. These models were applied to simulate the hydrology and nitrate nitrogen (NO_3-N) loading from two other watersheds in the Coastal Plain of North Carolina, the 11600 ha Chicod Creek watershed and the 8300 ha Upper Broad Creek watershed. GIS databases were compiled that include the existing land use/land cover, hydrography, soils series, digital elevation models, and digital orthophoto quarter quadrangles for each watershed. The resulting databases were used as input for process-based models (DRAINMOD-DUFLOW) that predicted the hydrology of the watersheds in their existing state of land use and management practices. These simulations characterized the hydraulics and hydrology of the watersheds, and generated inputs to a simpler GIS-based lumped parameter model that predict NO_3-N loads at the outlets of the watersheds. The GIS-based lumped parameter models were then used to make long-term (30-35 year) simulations of the watersheds in their current states of land use and management practices. Predicted mean annual NO_3-N load delivered at the watershed outlets and the delivery ratios of NO_3-N from each field that arrived at the watershed outlets are analyzed and compared for the three watersheds.

KEYWORDS: Drainage, BMP, Nitrogen, Watershed, DRAINMOD, Water Quality

Introduction

The impacts of excessive nitrogen (N) loading to streams in a watershed occur in the receiving waters (lakes, major rivers, or estuaries) at the outlet of the watershed. The non-point sources of N are usually well distributed among the many fields or blocks within the watershed. Likewise, the management practices that can be implemented to reduce N loading are distributed on a field by field basis throughout the watershed. In order to quantify the impacts of land use and management practices on the N loading at the watershed outlet, simulation models are needed that can both predict the N loading at the edge of individual fields and predict the fate of N as it moves through the stream network to the watershed outlet. Various distributed parameter models exist for predicting the N loading at the outlet of watersheds (e.g. HSPF, Johansen et al., 1984; AGNPS, Young et al., 1984; SWAT, Arnold et al., 1998). While these models are useful for upland conditions, the curve number methods used to quantify runoff volume in these models is not applicable for the high water table soils that exist in lower coastal plain areas. Accurately quantifying the runoff volume is essential to predicting N loading from a watershed. Since water table depth greatly affects runoff volume from high water table soils, a watershed model that simulates water table depth for each field would be more applicable for predicting N loading from lower coastal plain watersheds.

DRAINMOD-based hydrology and water quality models have been developed to predict N loading at the outlets of coastal plain watersheds (Skaggs et al., 2003; Fernandez et al. 2004; Amatya et al., 2004). Since these models simulate water table depth and runoff volume from individual fields distributed throughout a watershed, they can account for management practices and land use changes that occur on the field scale and predict the cumulative impact of these changes on N loading at the watershed outlet. The DRAINMOD-based models have accurately predicted drainage volume and NO_3-N load at the outlet of a well instrumented and documented watershed near Plymouth, NC (Skaggs et al., 2003, Fernandez et al. 2004, Amatya et al., 2004). This paper will present a study using these models to predict NO_3-N loading from three coastal plain watersheds in North Carolina and compare the predicted loads based on watershed characteristics. This study utilized the current database of land-use, topography, stream network, soil, and weather data readily available to consultants, and State and Federal agencies who would eventually use the models.

PROCEDURES

Three watersheds in eastern North Carolina are used in this simulation study (Figure 1). The Kendricks Creek watershed is located near Plymouth, NC and drains to the Albemarle Sound. The Chicod Creek watershed is located near Greenville, NC and drains to the Tar River. The Upper Broad Creek watershed is located near New Bern, NC and drains directly to the Neuse River estuary. Data collection at these watersheds has varied in intensity depending on the objectives of the individual research projects.

Kendricks Creek

The models used in this study were developed and tested with data from the 10000 ha watershed that drains to Kendricks Creek. Data collected from this watershed was much more intensive than those collected at the other watersheds. Flow measurements were recorded and drainage waters sampled for water quality analyses at 54 stations within the watershed. These stations were located at the outlet of the watershed, at the outlet of sub-watersheds, on main drainage canals, and at the outlet of agricultural and forested fields. Water table depth was recorded continuously at 28 locations and precipitation at 8 sites on the watershed. A detailed description of the watershed is given by Chescheir et al. (1998). A six-year data set has been collected on the site and measurements continue.

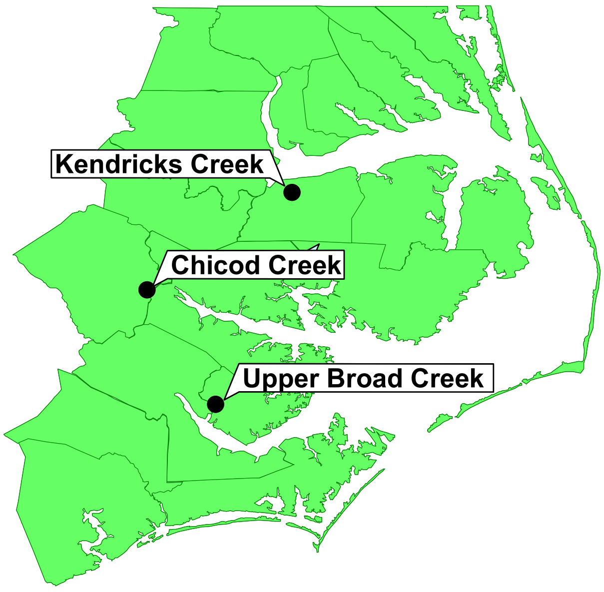


Figure 1. Location of study watersheds

A 8100 ha sub-watershed within the 10000 ha study watershed was simulated for this study. Land use on the sub-watershed consists of cropland (35%), managed forest (59%), unmanaged forested wetlands and riparian areas (6%) (Table 1). The watershed is relatively flat (surface elevations 3 to 6 m above mean sea level) and the soils are mostly poorly drained and very poorly drained mineral and organic series. The primary drainage system on both agricultural and managed forest lands is a network of ditches and canals which divide the watershed into a mosaic of regularly shaped fields and blocks of fields. Field ditches, spaced 80 to 100 m apart and 0.6 to 1.5 m deep, provide both surface and subsurface drainage. They drain to a network of collector and main canals which lead to the watershed outlet.

Chicod Creek

The Chicod Creek watershed is 11400 ha in area and drains a combination of agricultural (50%), managed forest (26%) and natural forest lands (24%) (Table 1). A drainage improvement project was implemented in 1972, which involved channelization and maintenance on 25 km of streams and canals. The watershed is not as flat as the Kendricks Creek watershed with surface elevations 4 to 16 m above mean sea level. The soils are all mineral soils ranging from poorly drained to moderately well drained. The primary drainage system on both agricultural and managed forest lands is a network of ditches and canals draining to a dendritic pattern of channelized streams which divide the watershed into mostly irregularly shaped fields and blocks of fields. Flow rates have been recorded at the outlet of the watershed from a gaging station operated by the United States Geological Survey (USGS) in cooperation with the North Carolina Department of Environment and Natural Resources (NCDENR) since 1992. Daily nutrient monitoring was conducted for a full year from February 1993 to February 1994 and again from February 1997 to February 1998 by NCDENR.

Table 1. Characteristics of the Watersheds Simulated in this Study.

	Kendricks Creek	Chicod Creek	Upper Broad Creek
Area, ha	8100	11600	8300
Max Channel Elevation, m	5	15	8
Min Channel Elevation, m	1	3	2
Max Channel Length, m	23600	16800	12100
Avg Channel Slope, m/km	0.17	0.71	0.50
Land Use			
Agriculture	35%	50%	32%
Manage Forest	59%	26%	56%
Natural Forest	6%	24%	12%
Mean Annual Rainfall, cm	130	126	139
Mean Annual Outflow, cm	39	41	46
Mean Annual ET, cm	91	85	93
Mean Annual Load, kg/ha	4.5	5.6	3.6
Min Delivery Ratio	48%	67%	68%

Upper Broad Creek

The Upper Broad Creek watershed is 8300 ha in area and drains a combination of agricultural (32%), managed forest (56%) and natural forest lands (12%) (Table 1). The topography is between that of the Chicod Creek watershed and the Kendricks Creek watershed with surface elevations 3 to 9 m above mean sea level. The soils are all mineral soils ranging from very poorly drained to moderately well drained. The primary drainage system on both agricultural and managed forest lands is a network of ditches and canals draining to a dendritic pattern of natural streams which divide the watershed into mostly irregularly shaped fields and blocks of fields. Flow rates and nutrient concentrations have not been intensively measured on this watershed. Biweekly water quality grab samples have been collected starting in September 2002.

Data Collection

The models used in this study require input data for soil properties, land use and management practices, stream network configuration and dimensions, and weather data. Many of these data are available in GIS formats, which have become the standard input for distributed parameter models. These data, however, need to be verified in the field since some errors may exist.

For the Chicod Creek and Upper Broad Creek watersheds, the overall data collection procedure involved making an initial collection of the existing GIS databases, verifying the data during field trips to the watersheds, correcting the data if needed, and preparing the data for model input. Initial data collection utilized the current GIS database of land-use, topography, stream network, and soil data readily available to State and Federal agencies. The land use and land cover data (LULC) were collected by USGS and compiled into 1:250,000 quadrangle tiles. Topography data were 1:24,000 digital elevation models (DEM) compiled and made available through USGS. Stream network or hydrography data were in the form of 1:24,000 digital line graphs compiled and made available through USGS. Soils data were obtained from the Soil Survey Geographic (SSURGO) data base compiled and made available through NRCS-USDA. Digital road maps were obtained from the North Carolina Department of Transportation. We also obtained 1998 color infrared digital orthophoto quarter quadrangles (DOQQ) that were compiled and made available by USGS and the North Carolina Center for Geographic Information & Analysis (NCCGIA).

All of the GIS databases were converted to formats readable by ArcView GIS 3.2. The data were transformed to the same projection (NC State Plane 1983/meters) if needed. Overlay maps of hydrography, roads, and DOQQ were printed for use during field trips to the watersheds. The purposes of the field trips were to verify the watershed boundaries, to verify the stream network and to collect information on local management practices. On the initial trips, we met with the NRCS District Conservationists. For the Chicod Creek watershed, we also met the manager of the local drainage district and obtained a copy of the "as built" plans for the original drainage project and the current management plan. On tours of the watersheds, the District Conservationists corrected our first estimates of the watershed boundaries. Subsequent trips were made to verify some land-uses and watershed boundaries.

Input data for the Kendricks Creek watershed were collected before the color infrared DOQQs were available. Field boundaries, stream hydrography, and roads were digitized from printed 1991 DOQQs available on Washington County Property Maps. The digitized data were verified with additional 1994 air photos and ground truthing. Soils data were obtained from the Soil Survey Geographic (SSURGO) data base. Tours of the watershed with NRCS District Conservationists were conducted to verify the watershed boundaries, the stream network and to collect information on local management practices.

Preparation of Model Inputs

The stream network was discretized using the information available on the DOQQs and in the case of the Chicod Creek watershed, the "as built" plans for the original drainage project. The discretized network was generally consistent with the USGS hydrography data; however, some details of the hydrography data were not consistent with our field observations. Inconsistencies were resolved through field observations and the assistance of major land holders in the watersheds.

The watersheds were discretized into fields according to general land uses (agriculture, managed forest, natural forest, and shrubland) as determined from the DOQQs and the LULC coverage. Another factor considered in field decretization was the stream network. That is, the fields were delineated such that each field drained to an appropriate stream node. Average field size for the Chicod Creek watershed was 161 ha and ranged from 39 to 357 ha. For the Upper Broad Creek watershed, average field size was 188 ha and range from 86 to 351 ha, while for the Kendricks Creek watershed average field size was 163 ha and ranged from 58 to 248 ha.

The fields were overlaid with the SSURGO soil database to determine what soil series was most representative of each field. The number of soil series and the detail of their distribution shown in the soil maps was far greater than could be reasonably treated in the model; therefore, the soils series observed on the watershed were lumped into representative soil types. The soil type that covered the greatest area in a field was chosen to represent the entire field. After the distribution of the soil types, the percent coverage of each soil type in the discretized fields did not match the percent coverage determined by the SSURGO soil map of the watershed. The differences were reconciled by changing the assigned soil types of some fields to the soil type that represented the second greatest area.

Soil input data required by the DRAINMOD model were available from past research for the representative soil types. For the Chicod Creek and Upper Broad creek watersheds, detailed information about the field drainage design and the current conditions of the drains was not known. DRAINMOD simulations were used to determine drain spacings for each soil that produced reasonable yields (80% relative yield for corn), but subsurface drainage intensity was less than optimum. Therefore the drainage designs used for the watershed simulations resulted in conditions that were on average a little wetter than optimum which was most likely the average conditions for the agricultural lands in the watersheds. For the Kendricks Creek watershed, drainage design was know for the fields and the observed spacings and depths were used in the simulations.

Hourly rainfall and daily maximum and minimum temperature data were available from the National Climate Center. Weather data from Plymouth, NC were used for the Kendricks Creek simulations while data from Greenville, NC and New Bern, NC were used for the Chicod Creek and Upper Broad Creek, respectively, The temperature data were used to calculate potential evapotranspiration by the Thornthwaite method with monthly correction factors for eastern North Carolina (Amatya et al., 1995) .

Model Description

Two watershed scale models were used for this study, DRAINMOD/DUFLOW (Fernandez et al., 2004) and DRAINMOD-GIS (Fernandez et al., 2003). Both models divide a watershed into individual fields, each of which is simulated using the water management model DRAINMOD (Skaggs, 1999). The outflow from each field is then routed through the stream network to the watershed outlet. The differences between the models are in the complexity of the routing procedures and the routines for predicting NO_3-N loading at the watershed outlet.

DRAINMOD/DUFLOW is the more complex model using the Dutch model DUFLOW (Aalderlink et al., 1995) to simulate stream hydraulics and NO_3-N transport and transformations. For stream routing, DUFLOW predicts water levels and discharges in the stream network by solving the St. Venant equations of continuity and momentum. The NO_3-N component is a solution of the advective-dispersive mass transport equations. Various process models for NO_3-N transformations can be used; however, N transport and transformations were not simulated by DUFLOW for this study.

The routing component of the DRAINMOD-GIS model is a spatially distributed canal routing model using a unit-impulse-response function based on a solution to the diffusion wave equation for routing (a simplification of the St Venant equations neglecting inertial terms). The solution is represented as a first-passage-time distribution in terms of velocity and dispersion coefficient. The first-passage-time distribution of travel time in the flow path to the watershed outlet is determined by convolving the response functions of the elements along the path (Olivera and Maidment, 1999). The loss of NO_3-N as it moves along the flow path is characterized by a first order exponential decay model.

The simplifications in the DRAINMOD-GIS model allow its integration into a GIS. The simplifications also produce a more stable model that can readily be used for long-term (30 - 35 year) simulations of complex watersheds. The DRAINMOD/DUFLOW model, however, was still used to provide velocities for the stream sections. The use of the two models for this study, therefore, proceeded as follows. The DRAINMOD/DUFLOW model was used to simulate the hydrology and hydraulics of the watershed for a six year period. These simulations produced average velocities for each stream section for each month of the year. The monthly average velocities were flow weighted averages over the six year simulation period. These monthly average velocities were then used in DRAINMOD-GIS simulations of the watersheds for the periods when flow data was measured. Simulated outflows compared well to the measured outflows at the Kendricks Creek and Chicod Creek watersheds. No calibration was needed for the hydrology and hydraulics simulations.

The nitrogen load at the edge of each field was calculated by multiplying daily surface and subsurface flow volumes by export concentrations for surface and subsurface flow respectively. The export concentrations NO_3-N were estimated from those reported by Deal et al.(1986) for different soils. The mass of NO_3-N delivered to the watershed outlet from each field was determined by using the time of travel along the flow path in the first order exponential decay equation. The decay constant was assumed to be 0.2 day^{-1}. Total NO_3-N load at the watershed outlet was the sum of the delivered loads from all of the fields.

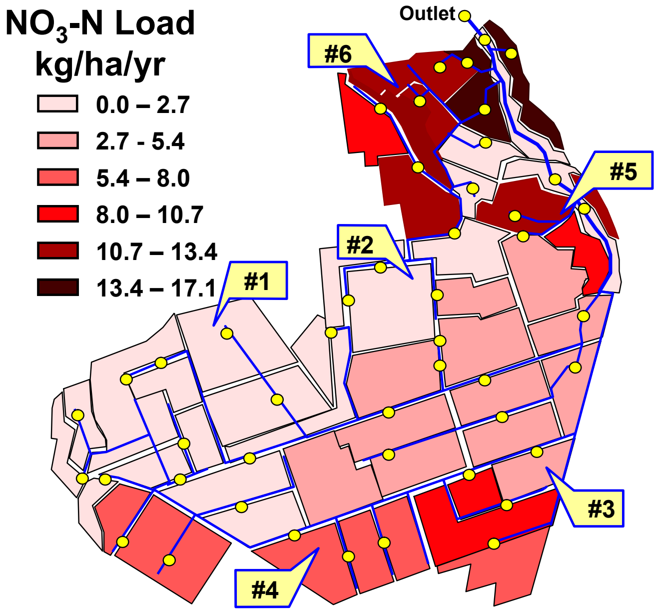
The DRAINMOD-GIS model was used to simulate the outflow and nitrate loads for a 30 year period from 1960 through 1989 for Chicod Creek and for Kendricks Creek. The simulation period for Upper Broad Creek was 35 years (1955-1989). The mean and distribution of the annual NO_3-N loads at the watershed outlet over the period were predicted by the simulation. The simulation also predicted the mean and distribution of the NO_3-N load delivered from each field to the watershed outlet as well as the mean delivery ratio (NO_3-N load from the field delivered to the watershed outlet/ NO_3-N load export at the field edge) for each field.

RESULTS AND DISCUSSION

Results from long term simulations using distributed parameter watershed scale models can produce information that is very useful for watershed managers. In addition to predicting the mean annual NO_3-N load at the watershed outlet, these simulations predict the load that is delivered to the outlet from each field in the watershed (Figure 2). The simulations also predict the range and distribution of annual loads at the watershed outlet and the delivered loads from each field in response to annual weather patterns (Figure 3). The average annual delivery ratio for each field is also predicted by these simulations (Figure 4). Delivery ratio (DR) is defined for a given field as the ratio of the load of a constituent arriving at the watershed outlet from that field to the load entering the canal at the field edge. DR varies from 0 to 1 and is an expression of the in-stream attenuation of the constituent considered. Such plots can be used to target the application of management practices or changes in land use.

Kendricks Creek

Predicted mean annual NO_3-N load delivered at the outlet of the Kendricks Creek watershed for the 30 year DRAINMOD-GIS simulation was 4.5 kg/ha. Predicted mean annual NO_3-N load delivered from individual fields varied depending on land use, soil type and location of the field in the watershed (Figure 2). For instance, annual NO_3-N load delivered from an agricultural field (F# 6) located near the outlet was 13 kg/ha, while the delivered load from an agricultural field (F# 4) located farther from the outlet was 7.6 kg/ha. Delivered load from the forested fields was lower with 1.8 kg/ha for a field near the outlet and 1.1 kg/ha for a field located farther from the outlet.



F#6

Figure 2. Distribution of annual NO_3-N loads delivered from the fields to the outlet.

Figure 3. Ranking by percent of 30 year simulation of annual NO_3-N loads delivered from selected fields in response to annual weather patterns. Distribution of annual NO_3-N loads at the watershed outlet is also shown.

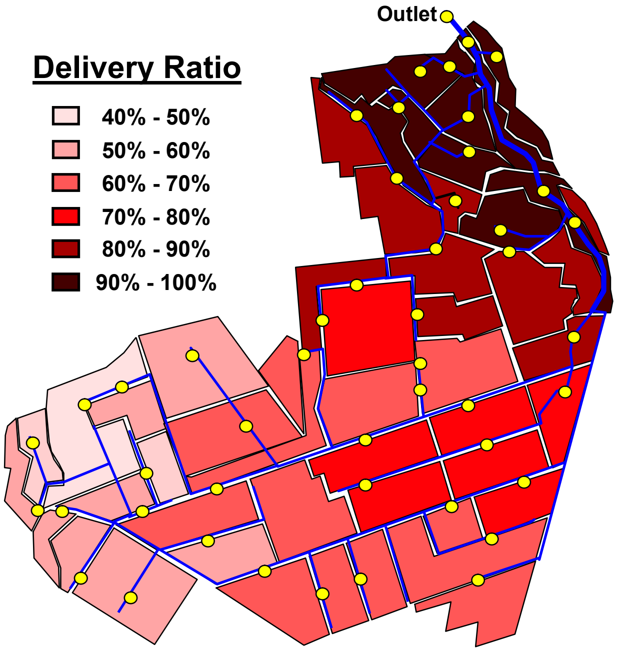


Figure 4. Distribution of the delivery ratios of NO_3-N loads delivered from the fields to the outlet

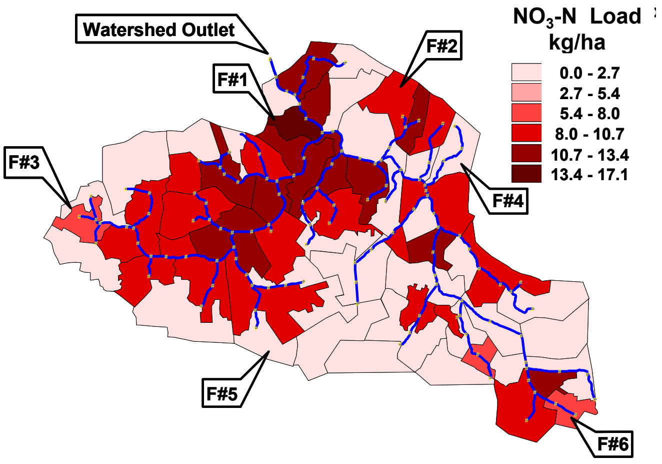
Predicted annual NO_3-N load delivered at the outlet of the Kendricks Creek watershed varied from year to year depending on rainfall patterns (Figure 3). Annual NO_3-N loads ranged from 1.3 kg/ha during a dry year (rainfall = 1020 mm) to 7.5 kg/ha during a wet year (rainfall = 1597 mm). Predicted annual NO_3-N load delivered from individual fields also varied with annual rainfall. The annual delivered load ranged from 4.5 to 22.1 kg/ha for Field F#6, from 1.4 to 14.5 kg/ha for Field F#4, and from 0.3 to 3.4 kg/ha for Field F#3.

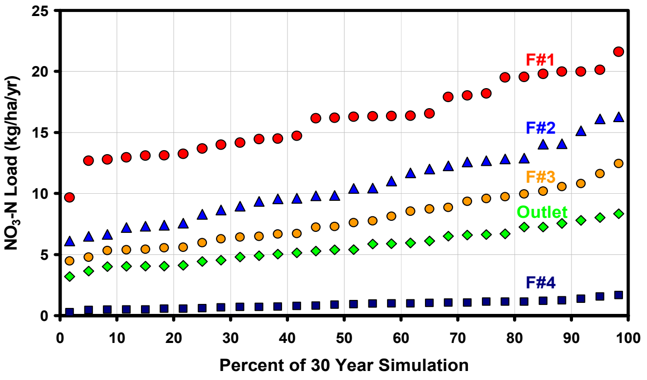
For the Kendricks Creek watershed, DR generally decreased as the distance of a field from the watershed outlet increased (Figure 4). The lowest value for DR was 48% for a field located in the northwestern part of the

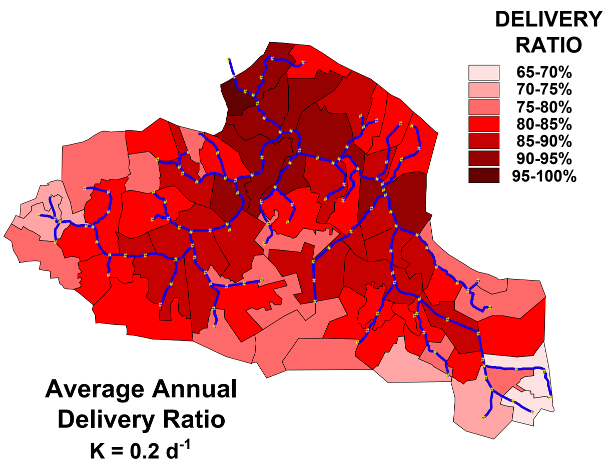
Chicod Creek

The predicted mean annual NO_3-N load delivered at the outlet of the Chicod Creek watershed for the 30 year DRAINMOD-GIS simulation was 5.6 kg/ha. As with the Kendricks Creek watershed, predicted mean annual NO_3-N load delivered from individual fields varied depending on land use, soil type and location of the field in the watershed (Figure 5). Annual NO_3-N load delivered from an agricultural field (F# 1) located near the outlet was 16.1 kg/ha, while the delivered load from agricultural field (F# 3) located farther from the outlet was 7.8 kg/ha. Delivered load from the forested fields was lower with 1.0 kg/ha for a field near the outlet and 0.8 kg/ha for a field located farther from the outlet.

Predicted annual NO_3-N load delivered at the outlet of the Chicod Creek watershed varied from year to year depending on rainfall patterns (Figure 6). Annual NO_3-N loads ranged from 3.2 kg/ha during a dry year (rainfall = 990 mm) to 8.3 kg/ha during a wet year (rainfall = 1490 mm). Predicted annual NO_3-N load delivered from individual fields also varied with annual rainfall. The annual delivered load ranged from 9.8 to 22.1 kg/ha for Field F#1, from 5.9 to 16.2 kg/ha for Field F#2, and from 0.2 to 2.3 kg/ha for Field F#4.







As with the Kendricks Creek watershed, DR for field in the Chicod Creek watershed generally decreased as the distance from the watershed outlet increased (Figure 7). The lowest value for DR was 67% for a field located in the southeast corner of the watershed.

Upper Broad Creek

Figure 6. Ranking by percent of 30 year simulation of annual NO_3-N loads delivered from

The predicted mean annual NO_3-N load delivered at the outlet of the Upper Broad Creek watershed for the 35 year DRAINMOD-GIS simulation was 3.6 kg/ha. Predicted mean annual NO_3-N load delivered from individual fields varied depending on land use, soil type and location of the field in the watershed (Figure 8). Annual NO_3-N load delivered from an agricultural field (F# 1) located near the outlet was 16.2 kg/ha, while the delivered load from agricultural field (F#3) located farther from the outlet was 8.5 kg/ha. Delivered load from the forested fields was lower with 1.5 kg/ha for a field near the outlet and 0.8 kg/ha for a field located farther from the outlet.

Figure 7. Distribution of the delivery ratios of NO_3-N loads delivered from the fields to the outlet

Predicted annual NO_3-N load delivered at the outlet of the Upper Broad Creek watershed varied from year to year depending on rainfall patterns (Figure 9). Annual NO_3-N loads ranged from 1.8 kg/ha during a dry year (rainfall = 1157 mm) to 5.6 kg/ha during a wet year (rainfall = 1682 mm). Predicted annual NO_3-N load delivered from individual fields also varied with annual rainfall. The annual delivered load ranged from 8.3 to 24.5 kg/ha for Field F#1, from 4.6 to 12.6 kg/ha for Field F#3, and from 0.2 to 2.1 kg/ha for Field F#4.

As with the other watersheds, DR for field in the Upper Broad Creek watershed generally decreased as the distance from the watershed outlet increased (Figure 10). The lowest value for DR was 68% for a field located in the northern part of the watershed.

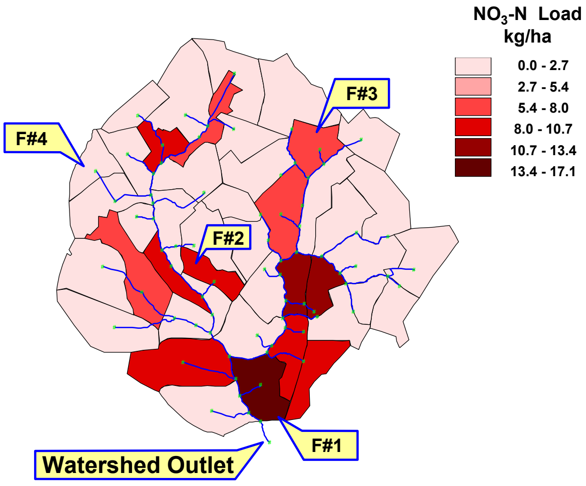


Figure 8. Distribution of annual NO_3-N loads delivered from the fields to the outlet.

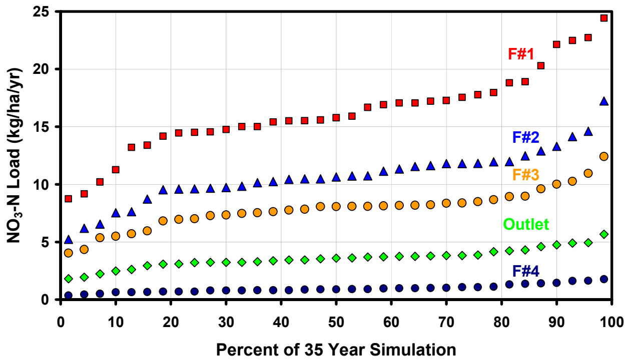


Figure 9. Ranking by percent of 30 year simulation of annual NO_3-N loads delivered from selected fields in response to annual weather patterns. Distribution of annual NO_3-N loads at the watershed outlet is also shown.

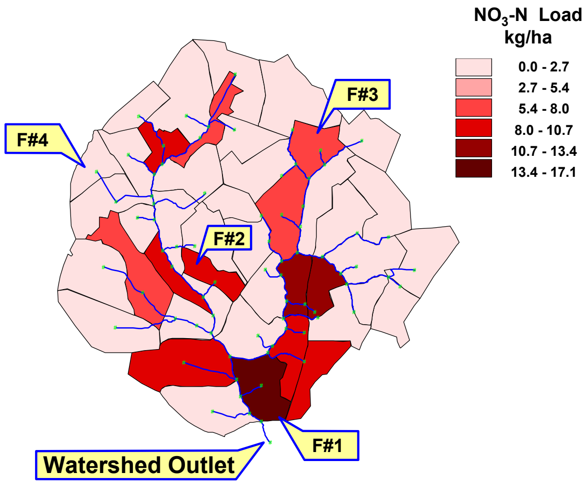


Figure 10. Distribution of the delivery ratios of NO_3-N loads delivered from the fields to the outlet

Comparison of Watersheds

A variety of factors affect the cumulative NO_3-N load at the outlet of Coastal Plain watersheds. The factors can be divided into those that impact the loads at the field edge and those that affect the fate of NO_3-N as it moves through the stream network. Loads at the field edge are affected by land use, soil type, and management practice. Factors affecting the fate of NO_3-N as it moves through the stream network are stream length, stream slope, channel dimensions, and decay rates.

The predicted mean annual NO_3-N load delivered at the outlet of the watersheds were different for each watershed. The highest NO_3-N load was from the Chicod Creek watershed while the lowest NO_3-N load was from the Upper Broad Creek watershed (Table 1). Higher loads from the Chicod Creek watershed was due to the higher percentage of the watershed having agricultural land use (50% compared to 35% for Kendricks Creek and 32% for Upper Broad Creek). Upper Broad Creek watershed, with the lowest percentage of land in agriculture land use, had the lowest predicted mean annual NO_3-N load delivered at the outlet. For these watersheds, land use is the factor that has the greatest impact on the mean annual NO_3-N load delivered at the outlet. The large impact of land use, a factor affecting NO_3-N loads at the field edge, makes the impact of other factors more difficult to determine when only analyzing the delivered NO_3-N load at the watershed outlet.

The impacts of the factors that affect the fate of NO_3-N as it moves through the stream network are better determined by analyzing the predicted delivery ratios (DR) for the fields in the watersheds. Fields on the Kendricks Creek watershed had the lowest DR compared to fields on the other watersheds. While the total area of the Kendricks Creek watershed was less than the other watersheds, the drainage pattern was such that most of the outflow drained to a single channel. This channel made a circuitous route to the watershed outlet, starting at the western edge of the watershed and traveling south, east, and north before ending at the northeast corner of the watershed. The maximum channel length was 23600 m compared to 16800 m for Chicod Creek and 12100 m for Upper Broad Creek; therefore, maximum channel length affected DR in this study. Note that the drainage patterns of the Chicod Creek and Upper Broad Creek watersheds have two main channels that make relatively direct routes to the watershed outlets.

The other factor affecting DR was average channel slope. The average slope of the Kendricks Creek watershed, which had the lowest DR, was less than the average channel slope for the other watersheds. Indications of the impact of channel slope are observed by comparing the other two watersheds. While the maximum channel length of the Upper Broad Creek watershed was less than that of the Chicod Creek watershed, the minimum DR of both watersheds was nearly the same. The channel slope of the Broad Creek watershed (0.50 m/km) was less than the slope of Chicod Creek (0.71 m/km). The factors affecting DR in this study were factors that also affected the travel time of the water through the canal and stream network, since the decay constant was assumed to be the same for all of the watersheds. Greater distance of travel and lower velocities resulting from lower slopes increased travel times and decreased DR.

Plots showing the distribution of DR can be used to target the application of management practices or changes in land use. For example, the results for Kendricks Creek (Figure 3) show that the application of practices to reduce NO_3-N losses near the mouth of the watershed, where the delivery ratios are 0.9 to 1.0, would be about twice as effective as application of the same practices on similar fields near the head of the watershed where the DR values are less than 0.5. Simulations that produce these plots are also valuable since they can predict the annual NO_3-N load delivered at the outlet of the watersheds and the distribution of these loads in response to annual weather patterns. The models presented here will also be valuable when they are used in sensitivity analyses to quantify the impacts of factors such as management practices, soil type, channel length, and slope on the NO_3-N load delivered to watershed outlets.

CONCLUSIONS

DRAINMOD-based watershed models were used to predict NO_3-N load delivered to the outlets of three coastal plain watersheds in North Carolina: the 8100 ha Kendricks Creek watershed, the 11600 ha Chicod Creek watershed, and the 8300 ha Upper Broad Creek watershed. The models also predicted the delivery ratios (DR) of NO_3-N load from each field that arrived at the watershed outlet. Predicted mean annual NO_3-N load delivered at the outlet of the watersheds were 4.5 kg/ha for Kendricks Creek, 5.6 kg/ha for Chicod Creek and 3.6 kg/ha for Upper Broad Creek. The minimum DR predicted for fields on each watershed were 48%, 67%, and 68%, respectively. The higher percentage of agricultural land use on the Chicod Creek watershed (50% compared to 35% for Kendricks Creek and 32% for Upper Broad Creek) was the primary factor causing the highest NO_3-N load delivered to the outlet. The greater channel length and lower channel slope were the primary factors causing lower DR on the Kendricks Creek watershed. The models presented here will be valuable for determining the impact of land use and management practices in a watershed on NO_3-N loading at the watershed outlet.

Acknowledgements

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