DEVELOPMENT AND TESTING OF WATERSHED-SCALE MODELS FOR POORLY DRAINED SOILS

G. P. Fernandez, G. M. Chescheir, R. W. Skaggs, D. M. Amatya

ABSTRACT. *Two watershed-scale hydrology and water quality models were used to evaluate the cumulative impacts of land use and management practices on downstream hydrology and nitrogen loading of poorly drained watersheds. Field-scale hydrology and nutrient dynamics are predicted by DRAINMOD in both models. In the first model (DRAINMOD-DUFLOW), field-scale predictions are coupled to the canal/stream routing and in-stream water quality model DUFLOW, which handles flow routing and nutrient transport and transformation in the drainage canal/stream network. In the second model (DRAINMOD-W), DRAINMOD was integrated with a new one-dimensional canal and water quality model. The hydrology and hydraulic routing components of the models were tested using data from a 2950 ha drained managed forest watershed in the coastal plain of eastern North Carolina. Both models simulated the hydrology and nitrate-nitrogen (NO_3-N) loading of the watershed acceptably. Simulated outflows and NO_3-N loads at the outlet of the watershed were in good agreement with the temporal trend for five years of observed data. Over a five-year period, total outflow was within 1% of the measured value. Similarly, NO_3-N load predictions were within 1% of the measured load. Predictions of the two models were not statistically different at the 5% level of significance.*

Keywords. *DRAINMOD, DUFLOW, Subsurface drainage, Water quality, Watershed-scale model.*

Water quality problems in coastal rivers and estuaries in the U.S. have been the source of great concern in recent years. These concerns, including nuisance algal blooms, hypoxia, and other conditions related to fish mortality and health, are at least partially due to excessive nutrient loading. A large portion of these nutrients comes from agricultural and forested lands. While nutrients are delivered to estuaries from an entire river basin, watersheds in the lower coastal plain likely contribute a larger proportion of the nutrient load because of their close proximity to estuaries.

Water and nutrient management practices such as controlled drainage have been used to reduce nutrient and sediment loading to receiving waters while maintaining or improving the productivity of the lands in the coastal plains (Gilliam et al., 1979; Skaggs and Gilliam, 1981; Evans et al., 1991; Gilliam et al., 1997; Amatya et al., 1998). Models have been developed to reliably predict the effects of agricultural management practices on nutrients and sediment transport at the field edge (Skaggs, 1982; Breve et al., 1997; Skaggs and Chescheir, 1999; Youssef, 2003). While management practices are applied at the field scale, water quality and environmental impacts of concern usually occur further downstream in the receiving lakes, reservoirs, or estuaries. As drainage water moves through a network of ditches, canals, and natural streams, in-stream processes may have substantial impact on nutrient and sediment transport. Models are needed to reliably predict the effects of field-scale land and water management on nutrient and sediment transport at the watershed scale considering potential in-stream processes.

Simulation models are often used to assess alternative land use and management practices on productivity of agricultural and forest lands and on water quality. Distributed, physically based simulation models integrate various interactions of factors affecting watershed hydrology and water quality. Several watershed-scale models have been developed, e.g., HSPF (Johansen et al., 1984), AGNPS (Young et al., 1987), QUAL2E, (EPA, 1987), SWRRB (Arnold et al., 1990), SWAT (Arnold et al., 1998), and BASINS (EPA, 2000). However, the application of these models is limited for shallow water table soils, and these lands constitute an extremely important part of the U.S. cropland (Skaggs, 1999) with large acreage in the southeastern coastal plains (Pavelis, 1987). The primary limitation of most models is the inability to characterize the hydrology of shallow water table soils, where surface and subsurface flows are very dependent on water table depth. Most models do not simulate water table depth and, therefore, cannot accurately predict discharge or the proportion of surface runoff and subsurface drainage. Surface runoff and subsurface drainage are the primary pathways of nutrient transport from coastal plain watersheds.

Few models have been developed to effectively simulate the hydrology in watersheds with mostly poorly drained, shallow water table soils. Northcott et al. (2001) applied a cell-based DRAINMOD-N with surface runoff routing to

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model subsurface drain flow and nitrate-nitrogen (NO_3-N) load in fields with irregular tile drainage systems in east central Illinois. However, this model does not include detailed in-stream transport and process modules.

This article documents two approaches for development and application of integrated, physically based, watershed-scale hydrology and water quality models to poorly drained watersheds. In each approach, field hydrology was predicted by DRAINMOD (Skaggs, 1978, 1999). In the first approach, in-stream hydraulics and NO_3-N transport were predicted using DUFLOW (Aalderink et al., 1995). In the second approach, DRAINMOD was integrated with a new one-dimensional canal and water quality model. The two modeling approaches were tested and compared based on the ability to predict discharge and NO_3-Nloads on a 2950 ha, forested watershed in the coastal plain of eastern North Carolina.

Model Description

Drainmod-Duflow

An integrated watershed-scale hydrology and water quality model was developed by linking field hydrology and nutrient submodels with a canal/stream routing and in-stream water quality model. The following section describes the field hydrology, stream hydraulics, and water quality submodels of the integrated system.

DRAINMOD is a field-scale, water management simulation model developed by Skaggs (1978, 1999). DRAINMOD characterizes the responses of the soil water regime to various surface and subsurface water management practices. It predicts the response of the water table and soil moisture to precipitation and evapotranspiration, considering surface and subsurface drainage under various water table control or sub-irrigation practices. The model is generally used to simulate the performance of drainage and related water table management systems over a long period of climatological data. DRAINMOD has been well tested in numerous field experiments on a wide range of soils, crops, and climatological conditions (e.g., Skaggs et al., 1981; Skaggs, 1982; Chang et al., 1983; Gayle et al., 1985; Rogers, 1985; Fouss et al., 1987; Susanto et al., 1987; McMahon et al., 1988; Broadhead and Skaggs, 1989; Wright et al., 1992; Cox et al., 1994). The current version of the model includes routines for salinity (Kandil et al., 1992), nitrogen (Breve et al., 1997), crop yield (Hardjoamidjojo and Skaggs, 1982), and soil temperature predictions (Luo et al., 2000). A new nitrogen version was developed by Youssef (2003) but has not been tested for forested conditions.

DUFLOW is a hydrodynamic and water quality model that includes canal hydraulics and water quality transport and transformation within the canal systems (Aalderink et al., 1995). The model can handle looped networks, simulates various control structures (e.g., weirs, culverts, siphons, etc.), and has options for management and operation of structures in the canal network. The hydraulic routing component of DUFLOW predicts canal water levels and discharges at various points in the network by solving the St. Venant equations of continuity and momentum using the four-point implicit Priessmann scheme solved with a Newton-Raphson method. External and internal boundary conditions are solved within the Priessmann scheme. DUFLOW allows three options in considering flow inertia. The user can choose to consider the Froude term (inertia fully accounted for), eliminate the Froude term (zero-inertia) or use the Froude-term effect not to exceed frictional-resistance effects (damped). For large, slow-flowing canals, the Froude term has minimal impact, but it can be significant in higher velocity canals.

The water quality component is a solution to a one-dimensional advective-dispersive mass transport equation. There is flexibility in the specification of the kinetic processes and the relationships of the modeled water quality parameters in DUFLOW. The in-stream water quality constituent dynamics component can be user supplied. This feature of DUFLOW is attractive because it allows the exploration of various alternatives when defining the in-stream nutrient transport and transformation calculations based on the availability of data to support parameter specification. The DUFLOW model was examined by the ASCE Task Committee on Irrigation Canal System Hydraulic Modeling (Clemmens and Holly, 1993), and this committee suggested that mass conservation was attained within the model and the model can handle mild unsteadiness. However, large or frequent perturbations causing unsteady flows or large time and space increments may cause the model to give poor predictions.

Model Linkage

The framework for linking DRAINMOD and DUFLOW was designed as a dynamic interaction of field hydrology and stream routing. The field hydrology model (DRAINMOD) was dynamically linked to the stream routing component on an hourly basis. Predicted hourly canal water levels in the drainage network at the field outlets served as control for the field hydrology. At the field outlets, canal water levels were estimated based on conditions at the end of the previous day. Using these estimates, DRAINMOD simulated field hydrology, and predicted hourly outflows were used as inflows to the stream routing model. Hourly canal water levels predicted by the routing model were then compared with the assumed canal water levels at the beginning of the hour within the field model. The model iterated until the difference between the predicted and assumed canal water levels were within a specified tolerance limit.

Outputs of field hydrology and hydraulic routing are aggregated to the desired time step to drive the water quality component of the linked model. Water quality simulation is a two-step process in which watershed hydrology and hydraulic routing are simulated first, followed by in-stream process simulation. This framework is consistent with the modeling framework of DUFLOW. The current application of the linked model does not consider detailed mechanistic nutrient dynamics at the field scale. Edge-of-field load estimates were obtained from a regression equation of the relationship between measured load and flow. The regression equations were developed using the measured data from five fields in the watershed. The transport of nutrients from the field edge was modeled with the advective-dispersion simulation in DUFLOW. Nutrient transformations along the drainage canals were simulated with a lumped parameter model where in-stream nitrogen transformation was described by an exponential decay function. The model is based on a gross assumption that complex in-stream processes can be adequately described by a lumped parameter model. Fernandez et al. (2002) showed that a lumped parameter water quality model could be used to adequately describe in-stream NO_3-N changes.

DRAINMOD-W

The linkage between DRAINMOD and DUFLOW was a "black box" with the two models operating sequentially but with dynamic interaction. DRAINMOD-W was developed to simplify the interaction between field hydrology and stream hydraulics. The basic assumption in this new model that was different from DRAINMOD-DUFLOW was that the hourly interactions can be approximated on a daily basis. We assumed that transient conditions during the day would not significantly affect the accuracy of predictions of drainage volumes at the watershed outlet and, in turn, still reasonably predict NO_3-N loads. While this approximation may not be appropriate during large events and rapidly fluctuating flows, it was assumed that this approach may be used to predict drainage volumes and NO_3-N losses in the slow-moving canals and streams of the coastal plains.

In DRAINMOD-W, stream conditions at the end of a previous day serve as initial and boundary conditions for predicting daily hydrology for the next day. Future modifications will shorten the time step such that predicted stream conditions from the previous hour are used. This will be consistent with DRAINMOD, which is based on a 1 h time step. The daily approximations discussed above allowed computational times to be reduced by three times, compared to DRAINMOD-DUFLOW. For example, a one-year simulation with DRAINMOD-W runs in 15 min, compared to 45 min with DRAINMOD-DUFLOW, on a 900 MHz Pentium III computer. The following sections describe model details.

Hydraulics

The canal routing submodel was based on the solution to the one-dimensional, nonlinear partial differential equations governing unsteady flow in open channels for which the dependent variables are the flow rate and water-surface elevation (fig. 1). The partial differential equations were discretized and replaced by the appropriate finite-difference equations according to a weighted, four-point implicit scheme with user-specified temporal and spatial weighting factors. Flexibility in specifying the weighting factors allows the user to vary the implicit-solution technique from a box-centered scheme to a fully forward scheme.

Using water surface elevation and canal discharge as dependent variables, the continuity and momentum equations were written as (Liggett and Cunge, 1975):

$$B\frac{\partial Z}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial(\alpha Qv)}{\partial x}+gA\frac{\partial Z}{\partial x}+\frac{g\,|\,Q\,|\,Q}{C^2AR}=0 \tag{2}$$

where x and t are space and time coordinates, $Z(x,t)$ is the water surface elevation, $v(x,t)$ is the average cross-sectional velocity, $Q(x,t)$ is the discharge, $R(x,t)$ is the hydraulic radius of the cross-section, $A(x,t)$ is the cross-sectional area of flow, $B(x,t)$ is the cross-sectional flow width, g is the gravitational acceleration, C is Chezy's resistance coefficient, and α is a correction factor for non-uniformity of the velocity distribution in the advection term.

With a finite-difference approximation according to a four-point implicit scheme, the partial differential equations may be transformed to the following (Liggett and Cunge, 1975):

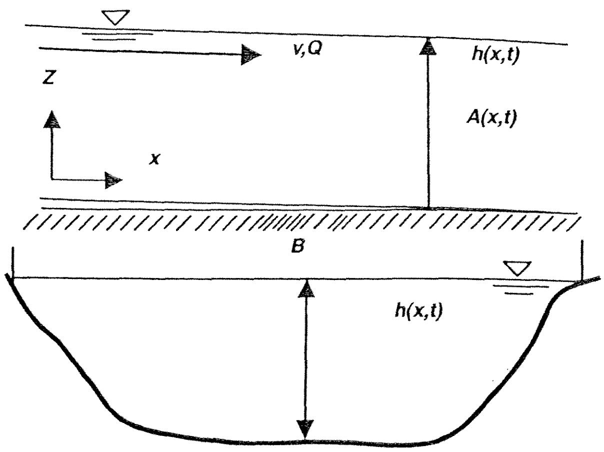

Figure 1. Coordinate system and notation.

$$B\left[\frac{Z_{i+1}^{j+1}+Z_i^{j+1}}{2\Delta t}-\frac{Z_{i+1}^{j}+Z_i^{j}}{2\Delta t}\right]$$

$$+\theta\left[\frac{Q_{i+1}^{j+1}-Q_i^{j+1}}{\Delta x}\right]+(1-\theta)\left[\frac{Q_{i+1}^{j}-Q_i^{j}}{\Delta x}\right]=0 \tag{3}$$

for the continuity equation and:

$$\frac{1}{g\tilde{A}}\left[\frac{Q_{i+1}^{j+1}+Q_i^{j+1}}{2\Delta t}-\frac{Q_{i+1}^{j}+Q_i^{j}}{2\Delta t}\right]$$

$$+\frac{2\alpha Q}{g\tilde{A}^2}\left[\theta\frac{Q_{i+1}^{j+1}-Q_i^{j+1}}{\Delta x}+(1-\theta)\frac{Q_{i+1}^{j}-Q_i^{j}}{\Delta x}\right]$$

$$-\frac{\alpha Q^2}{g\tilde{A}^3}\left[\frac{\tilde{A}_{i+1}^{j+1}-\tilde{A}_i^{j+1}}{\Delta x}\right]+\theta\left[\frac{Z_{i+1}^{j+1}-Z_i^{j+1}}{\Delta x}\right]$$

$$+(1-\theta)\left[\frac{Z_{i+1}^{j}-Z_i^{j}}{\Delta x}\right]$$

$$+\frac{|\tilde{Q}|}{2C^2}\left[\frac{Q_{i+1}^{j+1}+Q_i^{j+1}}{2}+\frac{Q_{i+1}^{j}+Q_i^{j}}{2}\right]=0 \tag{4}$$

for the momentum equation. The variables in non-derivative form were approximated by:

$$f(I)\approx\theta\frac{f_{i+1}^{j+1}-f_i^{j+1}}{2}+(1-\theta)\frac{f_{i+1}^{j}-f_i^{j}}{2} \tag{5}$$

where θ is a weighting factor indicating the time between the t^j and t^{j+1} timelines at which the spatial derivatives are evaluated. After some algebraic simplifications, the flow equations can be written as:

$$aQ_{i+1}^{j+1}+bZ_{i+1}^{j+1}+cQ_i^{j+1}+dZ_i^{j+1}=e \tag{6a}$$

$$a'Q_{i+1}^{j+1}+b'Z_{i+1}^{j+1}+c'Q_i^{j+1}+d'Z_i^{j+1}=e' \tag{6b}$$

for the momentum and continuity equations respectively, where a, b, c, d, e and a', b', c', d', e' are functions of Q and Z at the previous and current time steps. Combining equations 6a and 6b, the discharge (Q) at both ends of a canal segment can be expressed as a function of Z, the water surface elevations at both ends:

$$Q_i^{j+1} = \alpha Z_i^{j+1} + \beta Z_{i+1}^{j+1} \tag{7a}$$

$$Q_{i+1}^{j+1} = \alpha' Z_i^{j+1} + \beta' Z_{i+1}^{j+1} \tag{7b}$$

The model considered the discharges at segment ends as functions of the water surface elevation. Using external and internal boundary conditions and initial conditions, a matrix solution may be obtained directly from the set of flow equations written for all segments in the network. Conditions at the physical boundaries may be specified as canal water levels, discharges, or a relation between these parameters. The continuity equation was written for each node in the network, considering compatibility in canal water levels at the node points where two segments join. The equation set thus reduces to M equations in M unknowns, where M is the number of node points (including the external boundary nodes). In matrix form, the equation set can be expressed as:

$$[A]\{Z\} = \{f\} \tag{8}$$

where $[A]$ is the coefficient matrix, $\{Z\}$ is the vector of unknown water surface elevation at the node points, and $\{f\}$ is a vector of known constants. The equation was solved by an iterative technique similar to the DUFLOW model (Aalderlink et al., 1995).

Water Quality

The water quality submodel of DRAINMOD-W was based on a one-dimensional transport equation. The concentration of a constituent in a one-dimensional segment as a function of space and time may be written as (Zheng and Bennett, 2002):

$$\frac{\partial C}{\partial t} + \frac{\partial UC}{\partial x} - \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) = \frac{dC}{dt} \tag{9}$$

where C is the constituent concentration, Q is flow, D is the dispersion coefficient, x and t are space and time coordinates, and dC/dt is the in-stream process term. The solution technique follows that of the method used in the flow computation. In the flow computations, the discharges at segment ends were expressed as functions of the water surface elevations at both ends. In this case, the transports (T) at segment ends were expressed as functions of the concentrations at both ends. The transport (T) was defined as:

$$T = UC - D\frac{\partial C}{\partial x} \tag{10a}$$

$$\frac{\partial C}{\partial t} + \frac{\partial T}{\partial x} - P = 0 \tag{10b}$$

where T is the mass transport representing the quantity of constituent passing a cross-section per unit time. Using a mass balance over the nodes of the network resulted in a set of linear equations that can be written with the constituent concentrations as dependent variables.

To characterize the in-stream processes, a first-order decay equation was assumed and may be written as:

$$\frac{dC}{dt} = -kC \tag{11}$$

The decay coefficient (k) is formulated as a function of the depth of water in the canal and a mass transfer coefficient ($k = \rho/d$, where ρ is the mass transfer coefficient and d is the depth of water; Appelboom, 2004). In the current model, the in-stream process module is fixed using the simple equation above. Future enhancements will include a user-specified in-stream process module that will be linked to the model at run-time. This feature will allow the exploration of various alternatives to defining the in-stream nutrient processes, depending on the level of detail used in representing the nutrient dynamics in the drainage canals and the availability of data to support parameter specification.

DRAINMOD-W includes a field hydrology model specific to poorly drained watersheds. The model is flexible, however, as it can be used to route flows and constituents from upland watersheds, provided the user specifies the time series of inflows and outflows and the nutrient loads or concentrations at node points in the network. An upland-type field hydrology can also be integrated into the model, where the integrated model would be applicable to watersheds that may consist of upland, transitional, and lowland areas.

Model Integration

The basic framework for integration assumes that water surface elevation in the main canals at the beginning of the day serves as the control for the field hydrology simulation for the day. Effects of transient conditions in the outlet canal or stream during the day on the field hydrology were not considered. Water losses from the field are predicted by DRAINMOD. The losses were routed to the field outlet using an instantaneous unit hydrograph (SCS method) modified for flatland conditions. Using the stream conditions of the previous day, the field drainage entered the stream network depending on the stream levels. Field drainage may be controlled or conventional drainage. This is in contrast to DRAINMOD-DUFLOW, where hourly iteration between field hydrology and stream dynamics was considered.

Testing the Models

Methods

The watershed modeling approaches were compared using predicted discharge and NO_3-N load to measured discharge and NO_3-N load at an eastern North Carolina watershed. The models were compared on a 2950 ha drained forested watershed located in Plymouth, N.C., in the lower coastal plain (S4 in fig. 2). The watershed is in the Weyerhaeuser Company's Parker Tract in Washington County. The S4 watershed is a subwatershed of a larger, intensively instrumented, 10,000 ha, mixed land-use watershed. The watershed consists of both organic (primarily Belhaven and Pungo series) and mineral (Portsmouth and Cape Fear series) soils. Approximately 60% of the watershed is Belhaven Muck (loamy, dysic, thermic Terric Haplosaprists). The surface layer of this soil is typically black organic muck that is highly decomposed sapric material. Mineral soils dominate the western side of the S4 watershed including

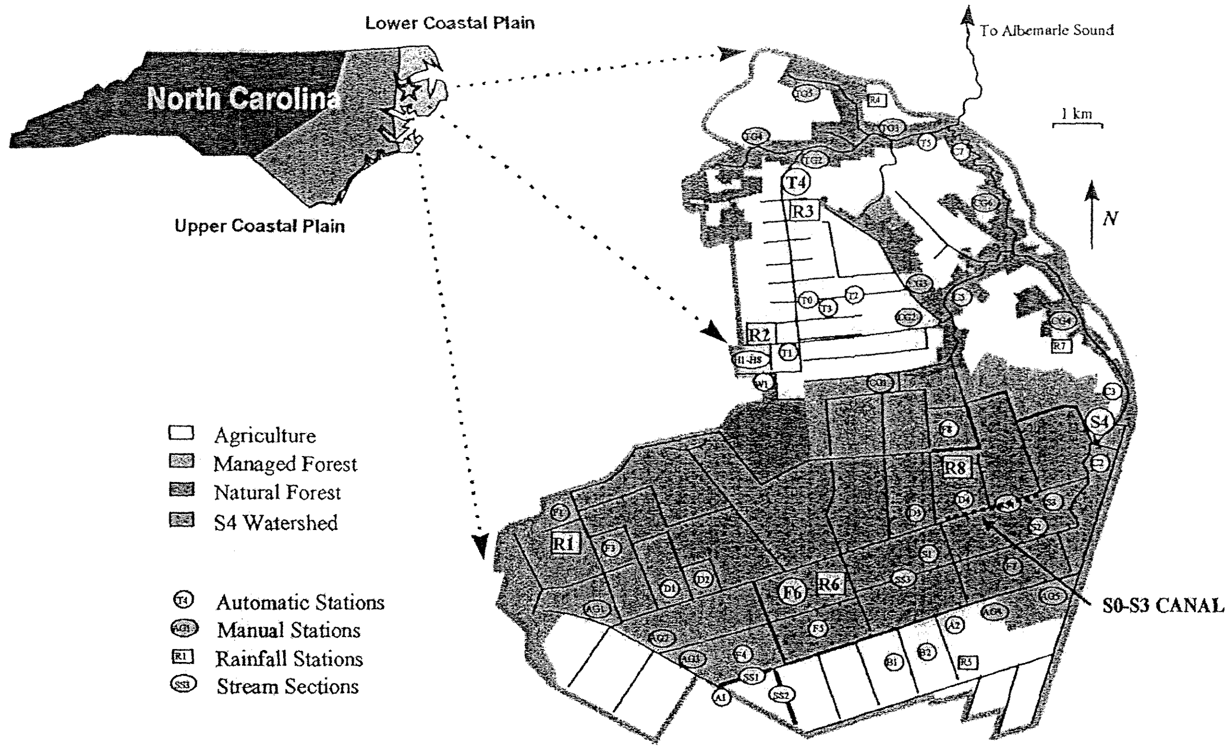

Figure 2. Diagram of the study area near Plymouth, N.C.

Cape Fear loam (fine, mixed, semiactive, thermic Typic Umbraquults), Portsmouth fine sandy loam (fine-loamy over sandy or sandy skeletal, mixed, semiactive, thermic Typic Umbraquults), Wasda muck (fine-loamy, mixed semiactive, acid, thermic Histic Humaquepts), and Arapaho fine sandy loam (coarse loamy, mixed, semiactive, nonacid, thermic Typic Humaquepts) (SCS, 1981). The primary land use in the watershed is loblolly pine (*Pinus taeda*) with stand ages ranging from 1 to over 30 years. Second growth, mixed hardwood stands with ages up to 99 years are also present.

The drainage system is typical of the Coastal Plain. The watershed is artificially drained by a network of field ditches, generally 0.6 to 1.2 m deep, spaced approximately 80 to 100 m apart, which empty into collector canals that are 1.8 to 2.5 m deep and spaced approximately 800 m apart. The collectors empty into main canals approximately 1.8 to 3.0 m deep and spaced about 1600 m apart.

Rainfall was measured using recording raingauges at three sites on the watershed (fig. 2). Additional meteorological data were recorded at a weather station located at R6. Canal water levels were continuously monitored at nine gauging stations. These are located at five field drainage outlets (F3, F4, F5, F6, F7), three on main canals (S1, S2, S3), and one at the outlet of the watershed (S4) (fig. 2). Water levels were recorded upstream and downstream of 120° V-notch weirs at the gauging stations for flow computations. Flow at the outlet of the watershed was measured through a riser structure with dual 120° V-notch weirs. A velocity meter was also installed at the outlet structure. When the weir was submerged, continuously recorded measurements using the velocity meter were used to determine flow rates. A more detailed description of the network of monitoring stations for both flow and water quality sampling for this watershed was presented by Shelby (2002).

Flow Simulation

The watershed was divided into 27 fields, with the drainage channel network discretized into 53 segments consisting of 45 canal reaches and 9 weir control structures (fig. 3). Division of the watersheds into modeling units (fields) assumes homogeneity with respect to soils, surface cover, and management practice within fields. Areas of the delineated fields ranged from 42 to 205 ha, with an average of 109 ha. Stream lengths, dimensions of canal and weir control structures, and field and canal bed elevations were obtained from field surveys. Table 1 shows the typical ditch and canal dimensions and spacing. Watershed outflow was modeled by using the field outflows predicted by DRAINMOD as inflows into the network at designated node points. DRAINMOD predicts surface and subsurface drainage from each field. These drainage flows were routed to the field outlets using an instantaneous unit hydrograph with an hourly time step.

Rainfall inputs were obtained from three raingauges and were assigned to each field based on a "nearest neighbor" analysis to account for spatial variability of rainfall over the watershed. The rainfall record for the five-year period of simulation indicated a slight decreasing trend from R8 (near the outlet of the watershed) to R1 (western edge of the watershed, fig. 2). Potential evapotranspiration inputs to the model were estimated with the Penman-Monteith method (Monteith, 1965) using meteorological data from the R6 weather station augmented with data from a weather station located at the Tidewater Research Station (4.5 km north). Since soil water properties were not measured for all the

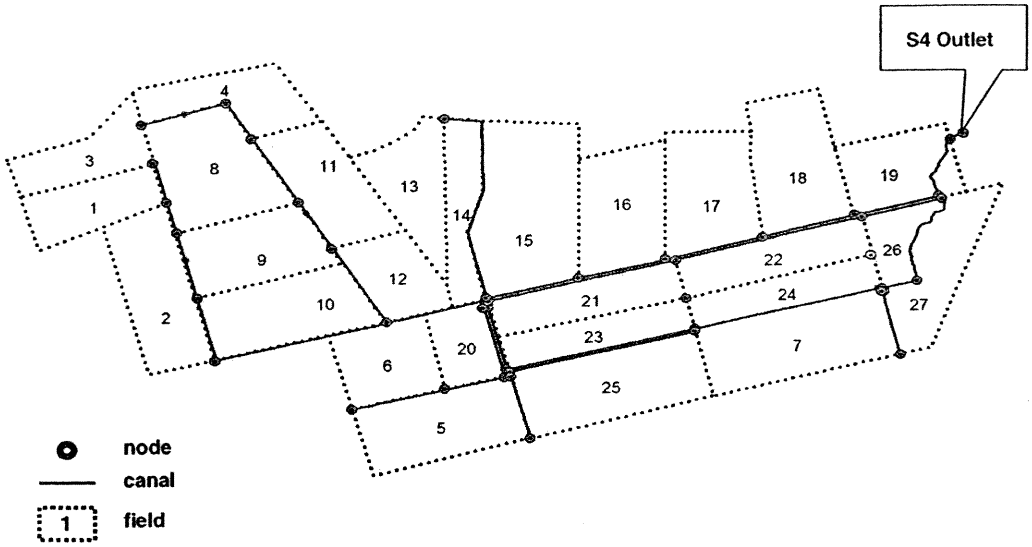

Figure 3. Schematic diagram of the field/canal/node network of the S4 watershed (not to scale).

fields in the study area, properties of the dominant soil series in each field were obtained from measurements from field 3 (mineral soil) and field 6 (organic soil) (Diggs, 2004) and from published values as reported in Skaggs and Nassahzadeh-Tabrizi (1986).

The watershed models were calibrated using approximately two years (1996-1997) of observed flow and validated using three years (1998-2000) of observed flow. Calibration involved adjusting saturated hydraulic conductivity and surface storage on a field-by-field basis.

Nitrate-Nitrogen Load Simulation

Measured and predicted NO_3-N loads at the watershed outlet (S4) were compared over the five-year period where NO_3-N loads were calibrated and validated, as described for flow simulation. DRAINMOD-N algorithms and inputs for predicting nitrogen and carbon dynamics have not yet been fully developed and tested for forested soils, so NO_3-N concentrations and loads at the field outlets were not simulated with a physically based model. Instead, NO_3-N loads were simulated using a multiple regression equation that relates predicted daily loads to daily flows and loads of the previous day. Regression equations were developed using measured NO_3-N loads from five fields in and around the watershed. Predicted flows from the hydrologic model were used to predict NO_3-N loads from each field during the calibration and validation periods. The regression relationships developed are specific to this watershed, and other relationships would be needed to estimate NO_3-N loads at the field edge in other watersheds with different characteristics.

Table 1. Characteristics of lateral, collector ditches, and drainage canals.

Parameters	Lateral Ditch	Collector	Main Canal
Ditch spacing (m)	100 to 200	800	--
Bottom width (m)	0.50 to 0.70	1.20 to 1.80	2.00 to 2.50
Ditch depth (m)	0.70 to 1.00	1.80 to 2.50	2.00 to 3.00
Side slope	0.8:1	0.6:1	0.5:1
Bottom slope	0.0001	0.0001	0.0001
Manning's n	--	0.035	0.04 to 0.05

The decay coefficient used in the lumped parameter in-stream module was modified or adjusted so that measured NO_3-N loads at the outlet matched predicted NO_3-N loads during the calibration period. Thus, the decay coefficient was a calibration parameter in this study. Decay coefficients reported by Appelboom (2004), based on detailed experiments along the SS1 canal (fig. 2), ranged from $k = 0.07$/d to 0.16/d. These values correspond to a mass transfer coefficient of $\rho = 0.064$ m/d for depths of 0.4 to 0.9 m. Calibration in this study resulted in an effective $k = 0.12$/d, which is in the range of values obtained experimentally by Appelboom (2004).

Statistical Measures

The adequacy of the models to predict the daily and monthly flows and NO_3-N loads at the outlet of the watershed was determined using a number of different statistical measures in the literature. The most common measure is the coefficient of determination (r^2) or alternatively the correlation coefficient (r) (Legates and McCabe, 1999). The coefficient of determination is obtained from the regression of the predicted values versus the observed values. Another criterion is the Nash-Sutcliffe coefficient of efficiency E (Nash and Sutcliffe, 1970), which is defined as:

$$E = 1.0 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{12}$$

where O_i are the measured values, P_i are the model predictions, and $\overline{O}$ is the average of measured values. The coefficient of efficiency defined above ranges from $-\infty$ to 1, where 1 is perfect model prediction. The coefficient of efficiency expresses the fraction of the error variance relative to the variance of the measured values. For values of $E \geq 0.75$, simulation results are considered to be good (Van Liew et al., 2003). For values between 0.36 and 0.75, the simulation results are considered satisfactory (Motovilov et al., 1999).

The mean absolute error (MAE) and the deviation of the predicted value expressed as percent of the measured value (PE) are also reported in this article:

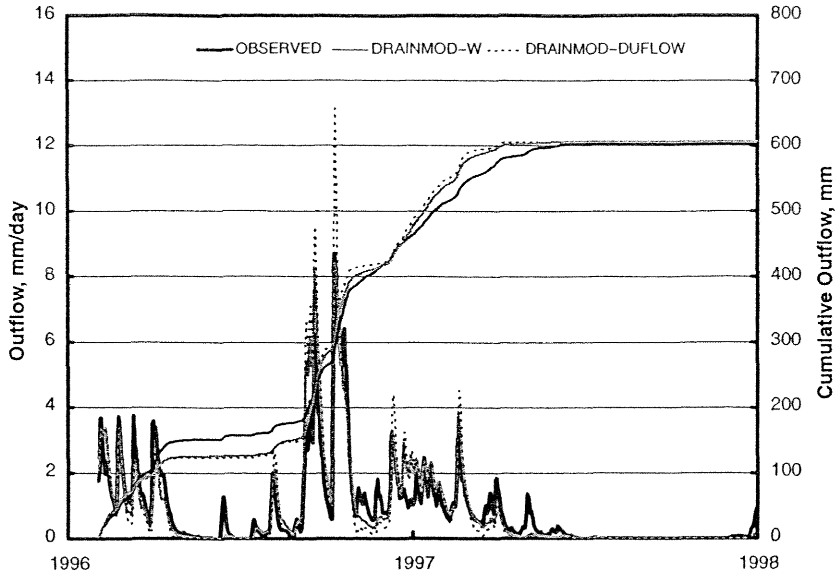

Figure 4. Measured and predicted daily and cumulative daily outflow at the outlet of the S4 watershed for the calibration period (1996-1997).

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} \left| P_i - O_i \right| \tag{13a}$$

$$\mathrm{PE} = \frac{P_i - O_i}{O_i} \times 100 \tag{13b}$$

Results and Discussion

Watershed Outflow

The temporal trend and magnitude of outflows predicted using each approach at the S4 outlet were in close agreement with observed daily flows for the calibration period (fig. 4). However, hydrograph peaks were generally overpredicted, especially during large flow events. Overall, peak flow rates predicted by DRAINMOD-DUFLOW were slightly greater than those predicted by DRAINMOD-W. The greatest outflow rates are usually predicted when there is a large amount of surface runoff. This was the case during periods of overprediction when water records indicate that the water table was at the surface in fields F7 and F8 during the large events. The overpredictions may have been due to the fact that effects of culverts in the network were not considered in the application of either modeling approach. The culverts would have restricted flow during large flow events when predicted flow rates exceeded the capacity of the culverts. These restrictions would have reduced flow rates upstream of the measuring point at S4 and thus attenuated peak flow rates at S4. During the large events, predicted stages at the outlet were high with rapid recession, a result of the model simulating unrestricted flow along the canals. Another possibility is that during large events, the weir at S4 was submerged and measured flow may also have been underestimated.

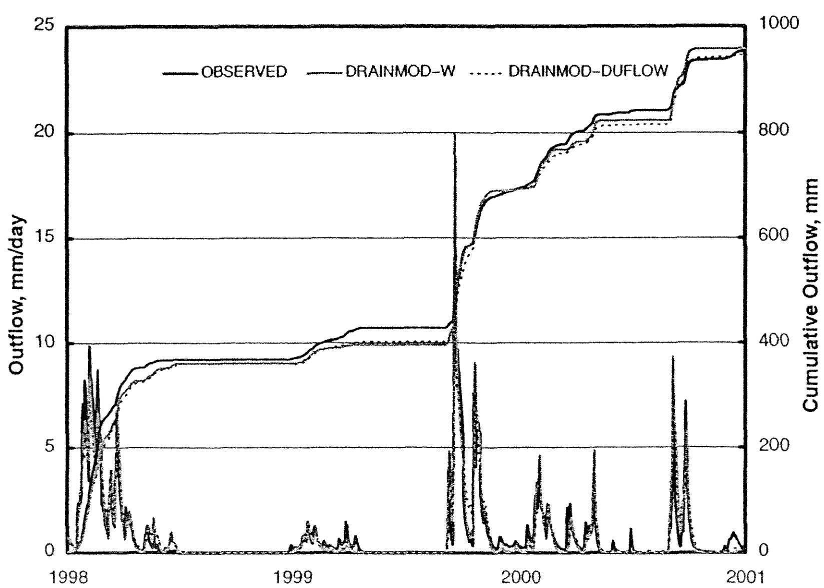

Figure 5. Measured and predicted daily and cumulative daily outflow at the outlet of the S4 watershed for the validation period (1998-2000).

Table 2. Summary of measured and predicted seasonal outflows at the outlet of the S4 watershed.

		Rainfall (mm)	Measured Outflow (mm)	Predicted Outflow (mm)		Deviation (mm)	
				DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W
1996[a]	Feb.-March	211	114.2	97.2	100.3	−17.0	−13.9
	April-June	208	43.5	26.3	26.0	−17.2	−17.5
	July-Sept.	541	105.5	165.3	153.1	59.8	47.6
	Oct.-Dec.	341	200.8	198.1	197.2	−2.7	−3.6
1997	Jan.-March	220	114.4	116.9	122.0	2.4	7.5
	April-June	208	24.0	2.8	8.0	−21.2	−16.0
	July-Sept.	280	0.1	0.0	0.2	−0.1	0.1
	Oct.-Dec.	249	5.5	1.4	0.4	−4.1	−5.1
1998	Jan.-March	426	326.9	305.8	295.3	−21.1	−31.5
	April-June	354	41.8	54.8	63.3	13.0	21.5
	July-Sept.	217	0.0	0.2	1.1	0.2	1.1
	Oct.-Dec.	278	1.5	0.04	0.02	−1.5	−1.5
1999	Jan.-March	217	49.5	33.1	38.5	−16.4	−11.0
	April-June	280	9.0	1.8	4.2	−7.2	−4.8
	July-Sept.	630	146.0	174.4	138.1	28.5	−7.9
	Oct.-Dec.	255	119.9	122.0	152.0	2.1	32.1
2000	Jan.-March	243	104.8	87.8	80.0	−17.1	−24.9
	April-June	346	39.6	42.3	41.2	2.7	1.6
	July-Sept.	507	86.7	122.2	109.9	35.5	23.2
	Oct.-Dec.	125	28.3	13.4	22.5	−14.9	−5.8

[a] 1996 measured flow data from February to December.

For the validation period (1998-2000), the timing and magnitude of the flow events were also accurately simulated using either approach (fig. 5). Similar to the calibration period, the hydrograph peaks were overpredicted during large events, and DRAINMOD-W predicted somewhat greater peak flows than DRAINMOD-DUFLOW. As was the case in the calibration period, the overprediction during large flow events probably resulted from the effects of the culverts detaining flow or from potential underestimates in measured flow when the weir was submerged. For the three-year period, errors in predicted cumulative outflow were 0.4% and −0.8% for DRAINMOD-DUFLOW and DRAINMOD-W, respectively. A summary of measured and predicted seasonal outflows during calibration and validation is presented in tables 2 and 3.

The two modeling approaches predicted similar outflows during the study period (fig. 6). Predictions of the two models were in close agreement with each other and with the observed monthly flows. Overall, the cumulative predicted outflow from the two modeling approaches was within ±1% of the measured outflow for the five-year period (table 3). The small differences in the cumulative flows predicted by the two models were expected (fig. 6) because DRAINMOD was used to predict field outflow in both modeling approaches.

On an annual basis, both modeling approaches overpredicted outflows for 1996 and 1999 and underpredicted for 1997 and 1998 (table 3). The largest percentage errors occurred for 1997, but 1997 was a very dry year with the least annual outflow over the five-year period. In 2000, the approaches differed in their predictions; DRAINMOD-W underpredicted annual outflow, and DRAINMOD-DUFLOW overpredicted annual outflow.

Table 4 summarizes the statistics of the comparisons between the predicted and measured outflows for each modeling approach. The Nash-Sutcliffe coefficients for monthly values are greater than 0.8 for each approach, suggesting that the modeling approaches were "good" on a monthly basis. The Nash-Sutcliffe coefficients for daily comparisons were slightly less but still within the acceptable range. Similarly, the Pearson correlation coefficients are greater than 0.90, indicating significant association between the predicted and measured daily and monthly outflows.

Table 3. Summary of measured and predicted annual outflows at the outlet of the S4 watershed.

Period	Rainfall (mm)	Measured Outflow (mm)	Predicted Outflow (mm)		Prediction Error (%)		Mean Absolute Daily Error (mm)	
			DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W
1996[a]	1301	464	487	477	4.9	2.8	0.6	0.5
1997	957	144	121	131	−15.9	−9.0	0.2	0.1
1998	1275	370	361	360	−2.4	−2.7	0.3	0.3
1999	1382	324	331	333	2.2	2.8	0.4	0.3
2000	1220	259	266	254	2.7	−1.9	0.4	0.3
1996-97	2258	608	608	607	<0.1	−0.1	0.4	0.3
1998-00	3877	954	958	946	0.4	−0.8	0.4	0.3
1996-00	6136	1562	1566	1553	0.3	−0.6	0.4	0.3

[a] 1996 data from February to December.

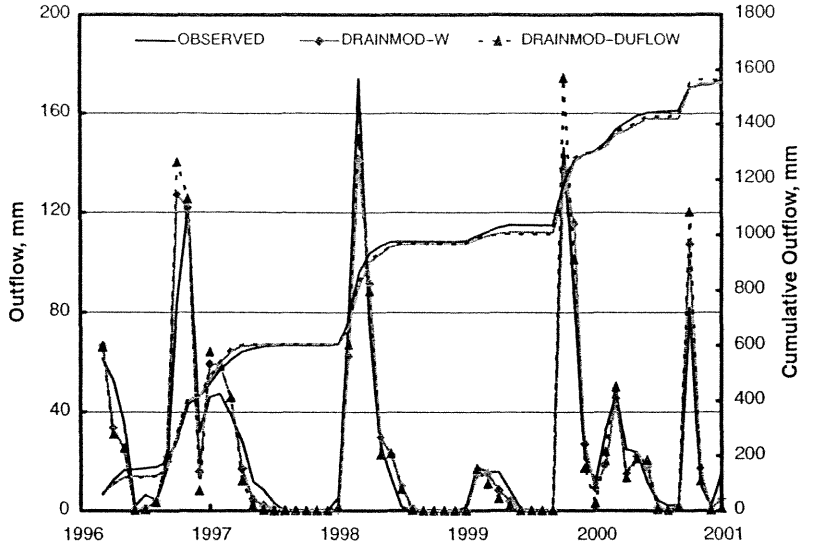

Figure 6. Measured and predicted monthly and cumulative monthly outflow at the outlet of the S4 watershed for 1996-2000.

Table 4. Summary of statistics of goodness of fit for watershed outflows.

		Calibration (1996-1997)		Prediction (1998-2000)	
		DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W
Daily	Observed daily mean (mm)	0.868	0.868	0.870	0.870
	Predicted daily mean (mm)	0.868	0.867	0.874	0.863
	Average deviation (mm)	<0.001	−0.001	0.004	−0.007
	Percentage error	<−0.1%	−0.1%	0.4%	−0.8%
	Nash-Sutcliffe coefficient	0.679	0.834	0.807	0.873
	Pearson correlation coefficient	0.910	0.933	0.914	0.935
Monthly	Observed monthly mean (mm)	26.43	26.43	26.50	26.50
	Predicted monthly mean (mm)	26.43	26.40	26.61	26.28
	Average deviation (mm)	<−0.01	−0.03	0.11	−0.22
	Percentage error	<−0.1%	−0.1%	0.4%	−0.8%
	Nash-Sutcliffe coefficient	0.760	0.852	0.923	0.929
	Pearson correlation coefficient	0.934	0.953	0.969	0.964

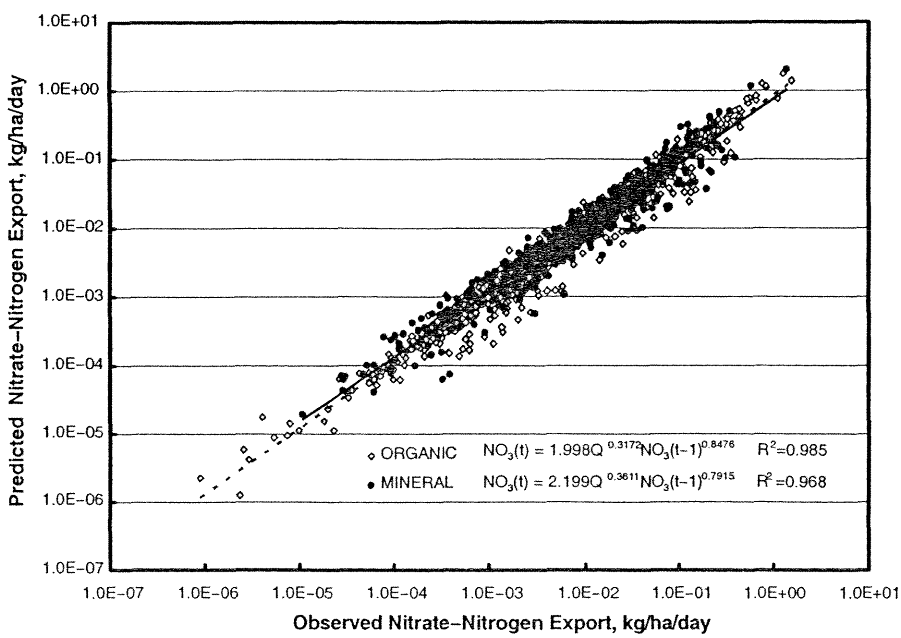

Figure 7. Measured and predicted daily nitrate-nitrogen load at the field edge for 1996-1997.

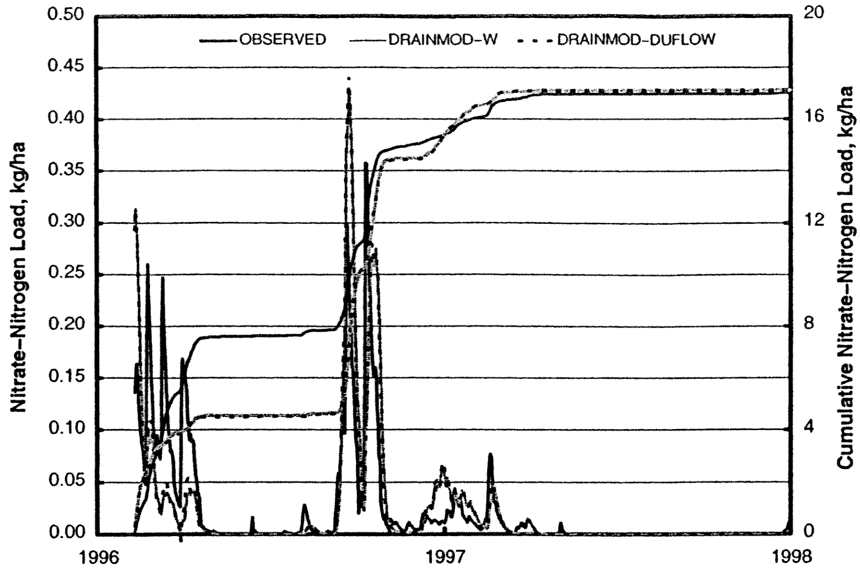

Figure 8. Measured and predicted daily and cumulative daily nitrate–nitrogen load at the outlet of the S4 watershed for the calibration period (1996–1997).

NITRATE-NITROGEN LOAD

Nitrate-nitrogen export was estimated using the following regression models:

For mineral soils:

$$\log NO_3\text{–}N_{(t)} =$$

$$2.199 + 0.3611 \log Q_{(t)} + 0.7915 \log NO_3\text{-}N_{(t-1)} \quad (14a)$$

For organic soils:

$$\log NO_3\text{-}N_{(t)} =$$

$$1.998 + 0.3172 \log Q_{(t)} + 0.8476 \log NO_3\text{-}N_{(t-1)} \quad (14b)$$

where $NO_3\text{-}N_{(t)}$ is the NO_3-N load (kg/ha) at day t, $Q_{(t)}$ is the mean daily flow (m^3/sec) at day t, and $NO_3\text{-}N_{(t-1)}$ is the NO_3-N load (kg/ha) at day t–1. Figure 7 shows the comparison of the predicted and measured daily NO_3-N loads during the calibration period.

Figures 8 to 10 show the daily, monthly, and cumulative observed and predicted NO_3-N loads over the study period. During the calibration period, NO_3-N loads predicted by DRAINMOD-DUFLOW and DRAINMOD-W were less than 0.5% overpredicted on average. This overprediction likely resulted from the regression models, because the regression models overpredicted daily NO_3-N loads by 6% during the calibration period. However, these discrepancies are relatively small given the uncertainties in the modeling approaches and even the observed load. Nitrate-nitrogen concentrations were generally high after large storm events and particularly after an extended dry period. Mineralization

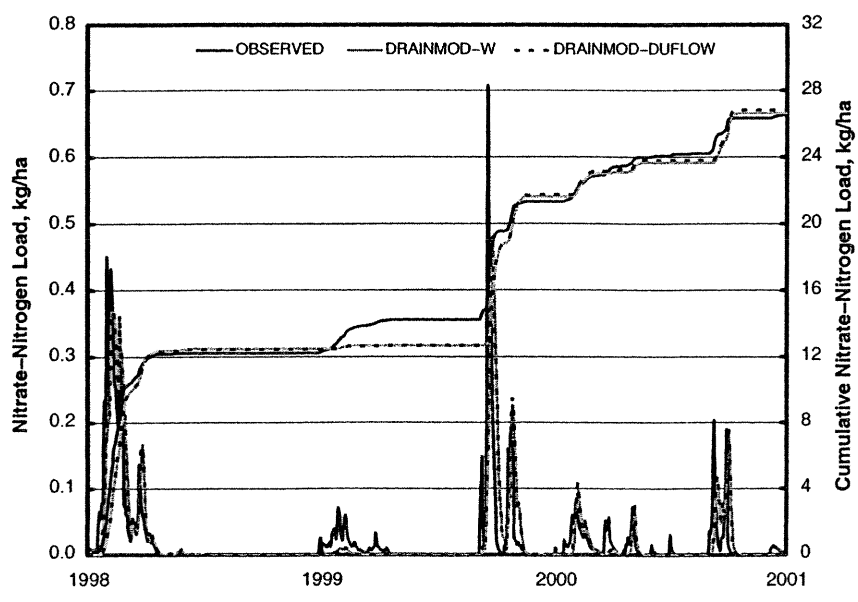

Figure 9. Measured and predicted daily and cumulative daily nitrate-nitrogen load at the outlet of the S4 watershed for the validation period (1998-2000).

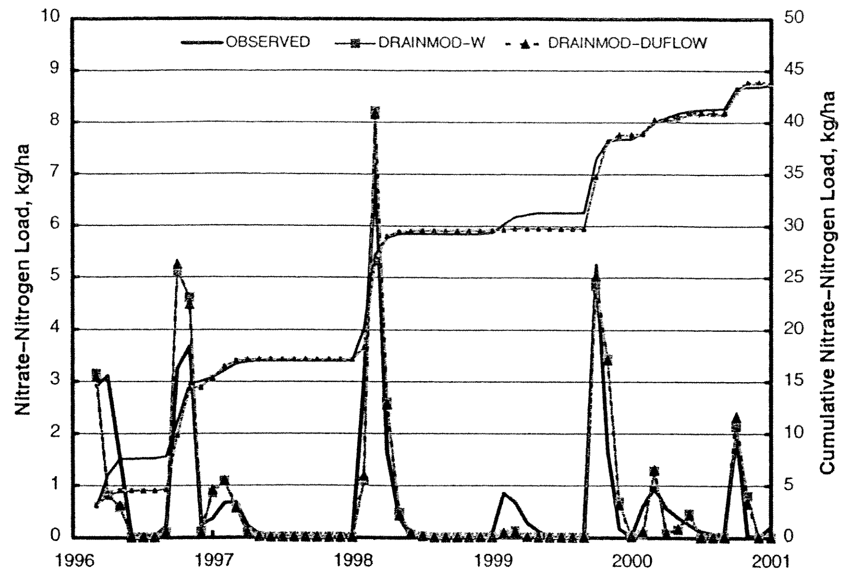

Figure 10. Measured and predicted monthly and cumulative monthly nitrate-nitrogen load at the outlet of the S4 watershed for 1996-2000.

in the organic soils in the S4 watershed during the dry periods increases NO_3-N in the soil, which readily flushes out of the system during the rainfall events (Diggs, 2004). This mechanism was not considered in the regression model for estimating the field loads.

Similar to the calibration period, the two modeling approaches overpredicted the cumulative NO_3-N load during the validation period, where DRAINMOD-DUFLOW and DRAINMOD-W predictions were 1% and 0.3% greater on average than the measured loads, respectively. The regression model used to predict daily NO_3-N loads overestimated loads by a much as 15% during the validation period. In addition, peak outflow rates were generally overpredicted from 1998 to 2000 and may contribute to the slight increase in overpredictions.

Sensitivity analysis indicated that a 1% increase in the decay coefficient resulted in a 0.1% decrease in nitrate loads at the outlet. However, a 1% increase in export concentrations would translate into a 1% increase in outlet load. Given that the cumulative flows were well predicted, the relatively small differences in NO_3-N loads were likely because of errors in predicted NO_3-N concentrations and export from each field by the regression models. However, the lumping of all in-stream process influencing NO_3-N concentrations and transport in the decay coefficient cannot be ignored.

Tables 5 and 6 show the seasonal and annual NO_3-N load predictions. The cumulative predicted NO_3-N load was

Table 5. Summary of measured and predicted seasonal load at the outlet of the S4 watershed.

				Predicted (kg/ha)		Deviation (kg/ha)	
		Rainfall (mm)	Measured (kg/ha)	DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W
1996	Feb.-March	211	6.031	3.901	3.978	−2.130	−2.053
	April-June	208	1.600	0.617	0.578	−0.982	−1.022
	July-Sept.	541	3.473	5.354	5.233	1.880	1.760
	Oct.-Dec.	341	4.278	5.505	5.576	1.227	1.298
1997	Jan.-March	220	1.544	1.737	1.728	0.194	0.184
	April-June	208	0.079	0.011	0.016	−0.069	−0.064
	July-Sept.	280	0.000	0.000	0.000	0.000	0.000
	Oct.-Dec.	249	0.057	0.000	0.000	−0.057	−0.057
1998	Jan.-March	426	11.805	11.910	11.910	0.105	0.106
	April-June	354	0.394	0.530	0.566	0.136	0.172
	July-Sept.	217	0.000	0.000	0.002	0.000	0.002
	Oct.-Dec.	278	0.098	0.000	0.000	−0.098	−0.098
1999	Jan.-March	217	1.800	0.197	0.189	−1.603	−1.611
	April-June	280	0.126	0.002	0.003	−0.124	−0.123
	July-Sept.	630	5.251	5.044	4.854	−0.208	−0.398
	Oct.-Dec.	255	1.847	4.042	4.141	2.194	2.294
2000	Jan.-March	243	2.099	1.496	1.414	−0.603	−0.685
	April-June	346	0.731	0.600	0.585	−0.131	−0.146
	July-Sept.	507	2.121	2.328	2.145	0.208	0.024
	Oct.-Dec.	125	0.252	0.652	0.809	0.401	0.557
Average			2.179	2.196	2.186	0.017	0.007

Table 6. Summary of measured and predicted annual nitrate-nitrogen loads at the outlet of the S4 watershed.

	Measured (kg/ha)	Predicted (kg/ha)		Prediction Error (%)		Mean Absolute Daily Error (kg/ha)	
		DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W
1996	15.382	15.377	15.365	<–0.1	–0.1	0.0331	0.0340
1997	1.680	1.748	1.744	4.2	3.8	0.0029	0.0031
1998	12.297	12.440	12.478	1.2	1.5	0.0143	0.0153
1999	9.024	9.285	9.187	2.9	1.8	0.0233	0.0251
2000	5.203	5.076	4.953	–2.4	–4.8	0.0135	0.0143
1996-97	17.062	17.125	17.109	0.4	0.3	0.0172	0.0177
1998-00	26.524	26.801	26.618	1.0	0.3	0.0170	0.0182
1996-00	43.586	43.926	43.727	0.8	0.3	0.0171	0.0180

within 1% of the measured load over the five-year period. The prediction errors of each modeling approach were within ±5% of the observed annual NO_3-N load. The greatest overprediction was in 1997, where both approaches overpredicted the loads by approximately 4%. The 4% difference was relatively small when considering the magnitude of the measured export (1.7 kg/ha). For both models, the mean absolute error over the five-year period was less than 19 g NO_3-N/ha.

Table 7 summarizes statistics for the comparisons between the predicted and measured NO_3-N loads of each modeling approach. The Nash-Sutcliffe coefficients were greater than 0.36 for daily and monthly calibration and validation, indicating a satisfactory fit (Motovilov et al., 1999). The Nash-Sutcliffe coefficients for monthly validation were greater than 0.85, indicating a good fit. Pearson correlation coefficients for the daily comparisons (>0.7) were less than that for the monthly comparisons (>0.87), likely because the correlation coefficient is sensitive to over- or underprediction outliers in daily comparisons (Legates and McCabe, 1999). In general, the statistics indicated satisfactory fit between the predicted daily and monthly NO_3-N loads for each modeling approach. Statistically, no significant differences in the predictions of the two modeling approaches were observed.

Summary and Conclusions

This article described the framework of linking and integrating DRAINMOD with DUFLOW (DRAINMOD-DUFLOW) and with a fully integrated one-dimensional canal routing and NO_3-N transport model (DRAINMOD-W). The two modeling approaches were applied on a 2950 ha drained forested watershed in eastern North Carolina. Each approach accurately described the hydrology of the watershed over a five-year period (1996-2000) with a prediction error with 1% and a mean daily error less than 0.5 mm. Although the hydrograph peaks were slightly overpredicted during the large flow events, cumulative drainage volumes were accurately predicted by the two approaches. The overprediction of the peaks can be attributed to several factors: (1) the current versions of the models do not consider the restricting effects of culverts on the flows in the main canals during large events when flow rates may have exceeded the capacity of the culverts, (2) the weir at the outlet was often submerged during the large events, which may have resulted in errors in flow measurements, (3) errors may have occurred in model parameterization, such as the extrapolation of soil parameter measurements to different fields, and (4) errors may have occurred in the spatial distribution of rainfall and potential evapotranspiration estimates.

Predicted daily and monthly NO_3-N loads were also in good agreement with measured NO_3-N loads over the five-year period. The prediction error was less than 1% and should be considered excellent given the complexity of the water quality processes and the uncertainty in estimating the field NO_3-N concentrations and loads. In addition to errors in the predicted field exports, the decay coefficient represents a lumped parameter used to determine NO_3-N transport and transformation. These modeling approaches do not fully consider the complexity and temporal and spatial variability of in-stream processes, but both approaches provided similar predictions. Overall, measured NO_3-N loads were closely correlated with flow, demonstrating the need for accurate prediction of field and watershed hydrology.

Table 7. Summary of statistics of goodness of fit for watershed nitrate-nitrogen load.

		Calibration (1996-1997)		Validation (1998-2000)	
		DRAINMOD -DUFLOW	DRAINMOD -W	DRAINMOD -DUFLOW	DRAINMOD -W
Daily	Observed daily mean load (kg/ha)	0.0247	0.0247	0.0242	0.0242
	Predicted daily mean load (kg/ha)	0.0248	0.0247	0.0244	0.0242
	Average deviation (kg/ha)	0.0001	<0.0001	0.0002	<0.0001
	Percentage error	0.4%	0.3%	1.0%	0.3%
	Nash-Sutcliffe coefficient	0.395	0.363	0.536	0.457
	Pearson correlation coefficient	0.761	0.743	0.769	0.729
Monthly	Observed monthly mean load (kg/ha)	0.742	0.742	0.737	0.737
	Predicted monthly mean load (kg/ha)	0.745	0.744	0.745	0.739
	Average deviation (kg/ha)	0.003	0.002	0.008	0.002
	Percentage error	0.4%	0.3%	1.0%	0.3%
	Nash-Sutcliffe coefficient	0.656	0.664	0.870	0.857
	Pearson correlation coefficient	0.870	0.878	0.952	0.940

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