DRAINWAT−BASED METHODS FOR ESTIMATING NITROGEN TRANSPORT IN POORLY DRAINED WATERSHEDS

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

ABSTRACT. *Methods are needed to quantify effects of land use and management practices on nutrient and sediment loads at the watershed scale. Two methods were used to apply a DRAINMOD−based watershed−scale model (DRAINWAT) to estimate total nitrogen (N) transport from a poorly drained, forested watershed. In both methods, in−stream retention or losses of N were calculated with a lumped−parameter model, which assumes that N concentration decreases exponentially with residence (or travel) time in the canals. In the first method, daily field outflows predicted by DRAINWAT were multiplied by average N concentrations to calculate daily loads at the field edge. Travel time from the field edge to the watershed outlet was computed for each field for each day based on daily velocities predicted by DRAINWAT for each section of the canal−stream network. The second lumped−parameter method was similar but used predicted annual outflow to obtain annual load at the field edge. The load was transported to the watershed outlet, and the in−stream N loss was determined by using a constant average velocity (obtained by long−term DRAINWAT simulations), independent of season, for the entire canal−stream network. The methods were applied on a 2,950 ha coastal forested watershed near Plymouth, North Carolina, to evaluate daily, monthly, and annual export of nitrogen for a five−year (1996−2000) period. Except for some late spring and hurricane events, predicted daily flows were in good agreement with measured results for all five years (Nash−Sutcliffe coefficient, E = 0.71 to 0.85). Estimates of monthly total N load were in much better agreement (E = 0.76) with measured data than were the daily estimates (E = 0.19). Annual nitrogen load was predicted within 17% of the measured value, on average, and there was no difference (α = 0.05) between measured and estimated monthly and annual loads. The estimates of annual N loads using travel time with a daily velocity yielded better results than with the constant average velocity. The estimated delivery ratio (load at the outlet/load at the field edge) for total N was shown to vary widely among individual fields depending on their location in the watershed and distance from the outlet. Both of the methods investigated can potentially be used with GIS in predicting impacts of land management practices on total N loads from poorly drained watersheds.*

Keywords. *Decay rate, Delivery ratio, DRAINMOD, Lumped−parameter model, Outflows, Poorly drained soils.*

A number of studies have focused on the development and application of models for predicting effects of land use and management practices on sediment and nutrient loads on poorly drained lands (de Wit, 2001; Skaggs and Chescheir, 1999; Arnold et al., 1998; Breve et al., 1997; Johnes, 1996; Heatwole et al., 1987). While these methods have been shown to be reliable for predicting loads at the field edge, water quality concerns are usually focused at the mouth of the watershed, or in receiving waters, which may be several miles downstream. A major challenge to planners and regulators is to determine the cumulative effects of management practices and land use changes on nutrient loads to these receiving waters. For example, de Wit (2001) stated that the flow regime is a major factor affecting nitrogen (N) and phosphorus (P) losses in the river network. Therefore, success in modeling the cumulative effects, including drainage water quality and pollutant loads, is highly dependent on successfully predicting the hydrology and hydraulics at a watershed scale.

In recent years, hydrologic and water quality models to describe cumulative effects of pollutant loads on a watershed scale have been developed and applied for various purposes (Santhi et al., 2001; de Wit, 2001; Worrall and Burt, 1999; Styczen and Storm, 1993; Heatwole et al., 1987). However, only a limited number of models can accurately describe the hydrology of relatively flat, poorly drained fields and the in−stream hydraulics of canals and streams that may be affected by backwater conditions due to low−gradient outlets.

DRAINMOD (Skaggs, 1978) is a widely used hydrology model for predicting effects of drainage design and management practices on drainage outflows from shallow water table soils. Fernandez et al. (1997, 2004) linked DRAINMOD with the Dutch hydraulic model DUFLOW (Aalderink et al., 1995) to develop a process−based watershed−scale hydrologic and water quality model for coastal watersheds. Although such process−based models are generally considered to be more accurate and reliable than simpler models,

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they are less likely to be used in operational situations due to the large number of inputs and the time required for application. In cases when only planning−level information is needed, simpler, lumped−parameter water quality models may be preferred. Skaggs et al. (2003) outlined a range of possible alternatives for combining DRAINMOD with flow routing and in−stream transport submodels to develop watershed−scale lumped−parameter hydrology and water quality models of varying degrees of complexity.

A Geographic Information Systems (GIS) based lumped−parameter water quality model using DRAINMOD for field hydrology was recently developed and tested (Fernandez et al., 2002). The model uses first−order kinetics for in−stream nutrient fate and transport. The first−order kinetics assumption means that the decrease in N loads as drainage water moves from the field edge to the watershed outlet is exponentially dependent on time in transit and can be described with a single attenuation coefficient. The coefficient was determined from field studies of the in−stream processes (Birgand, 2000) and by model calibration. Travel time was obtained from long−term simulations using DRAINMOD−DUFLOW. The authors showed that predicted loads at the watershed outlet were most sensitive to predictions of flows and concentrations at the field scale. Although model predictions were not extremely sensitive to the decay rate, the uncertainty in its estimate affected the overall uncertainty of model predictions.

In the research reported in this article, the watershed−scale model DRAINWAT (Amatya et al., 1997), which is an extension of the DRAINMOD−based flow routing model FLD&STRM (Konyha and Skaggs, 1992), was used to simulate field hydrology and channel hydraulics. The model has been successfully tested for predicting outflow rates in lower coastal plain watersheds with varying sizes and land uses (Konyha and Skaggs, 1992; Amatya et al., 1997, 1998).

The main objective of this study was to evaluate two methods for estimating annual total nitrogen (N) load at the outlet of a 2 950 ha forested watershed in the North Carolina coastal plain. The first method used daily DRAINWAT outputs for flow rates from the fields and velocities in the drainage canals to determine travel time and predict daily, monthly, and annual total nitrogen loads. The second method used only annual predictions of outflows and assumed a constant average velocity in the drainage network to predict the annual nitrogen load.

METHODS

SITE DESCRIPTION

The study watershed is a part of a 10,000 ha lower coastal plain watershed study site located in Washington County in eastern North Carolina (fig. 1). The 2,950 hectare watershed (S4) drains mainly managed pine forest stands and some second−growth mixed pine and hardwood stands to an outlet at Kendrick's Creek 11 km upstream from the Albemarle Sound. The primary drainage system is a network of field ditches and canals, which divide the watershed into a mosaic of regularly shaped fields and blocks of fields. Field ditches provide both surface and subsurface drainage to a network of collector and main canals, leading to the watershed outlet at S4. This outlet is equipped with a dual 120° V−notch weir, where stage measurements are conducted for estimating flow rates.

Soils consist of mineral soils (Portsmouth, Cape Fear, and Wasda series) located in the northern part and organic soils (Belhaven and Pungo series) in the southern part of the watershed (SCS, 1981). Rainfall was measured with a recording rain gauge (R6) near the center of the watershed. An automatic weather station located adjacent to R6 was

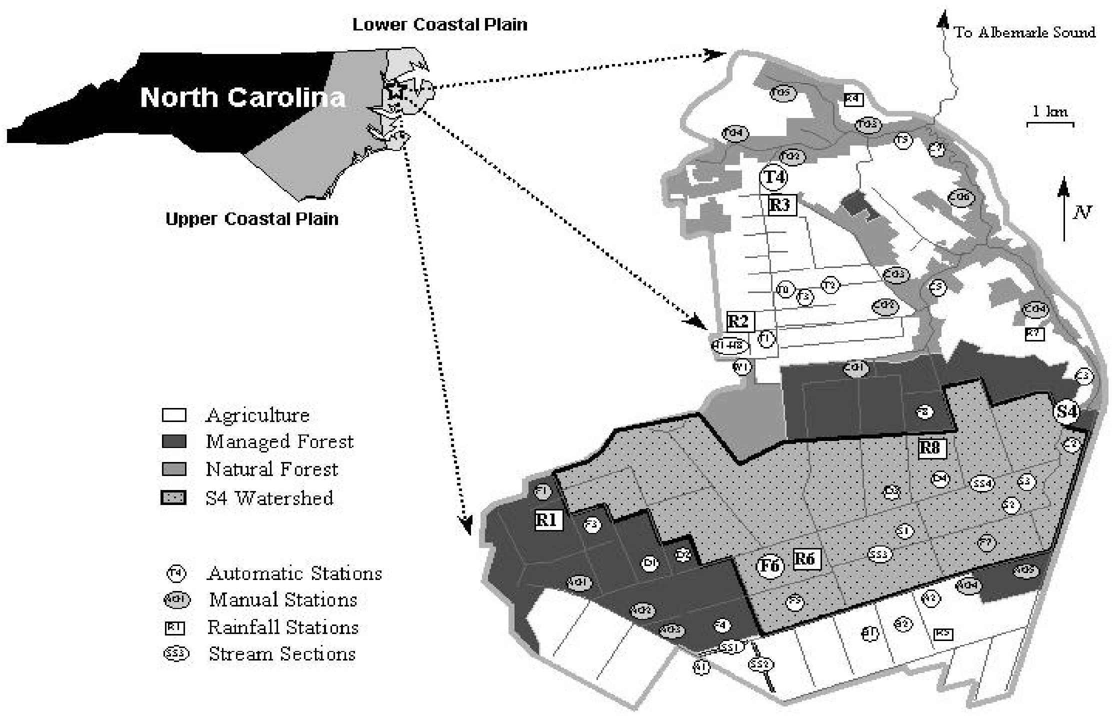

Figure 1. Location of 2,950 ha forested watershed (S4) in 10,000 ha watershed−scale study site in the lower coastal plain near Plymouth in eastern North Carolina.

used to collect data for estimating daily potential evapotranspiration (PET) using the Penman−Monteith method for pine forest (Amatya et al., 2003). Field hydrologic parameters were stored in a GIS database. Both upstream and downstream stage elevations for computing flow rates were continuously monitored, and flow−weighted water quality samples were collected continuously at the outlet of selected fields and in−stream locations, including the S4 outlet. A detailed description of the watershed, its instrumentation, and the monitoring procedures are described elsewhere (Chescheir et al., 1998; Shelby, 2002).

DRAINWAT

The watershed−scale hydrologic model DRAINWAT is based on DRAINMOD (Skaggs, 1978), which is a widely used field−scale agricultural water management model to predict effects of soil, crop, and water management practices on the hydrology of poorly drained lands. DRAINWAT uses DRAINMOD and its forestry version DRAINLOB (McCarthy et al., 1992) modules for predicting daily field hydrology. Predicted total daily flows are routed to the field outlet using the SCS unit hydrograph method. Flows from each field outlet are further routed downstream to the watershed outlet through the canal−stream network reaches using numerical solutions of one−dimensional St. Venant equations. Daily average velocities and their associated flow depths and rates are calculated at each individual node of interest on the canal−stream network. Details of the model and modeling procedure are described elsewhere (Konyha and Skaggs, 1992; Amatya et al., 1997).

In−Stream Processes

The net effect of the physical, chemical, and biological processes on N loss as drainage water flows through the network of canals to the outlet was considered by a simple lumped−parameter exponential decay function of the travel time (i.e., the residence time of the water as it travels from the field edge to the outlet). The method further assumes that dispersion of the constituent concentration along the canals and ditches is negligible (i.e., slug flow) and that there are no sources or sinks of N, other than that represented by natural decay (Loucks et al., 1981). Assuming a steady−state condition, N concentration (C_x) at any point in a canal−stream network may be written in the terms of the initial concentration (C_o) at the upstream location (field edge) (Loucks et al., 1981) as:

$$C_x = C_o\, e^{-kT} \qquad (1)$$

where k is the N decay rate coefficient, and T is the travel time.

The equation uses only two variables (concentration at the field edge and travel time) for each field, and one input parameter (decay constant, k) to estimate nutrient concentration in the water draining from each field and arriving at the watershed outlet. This method for determining the effects of in−stream processes on the N load may be applied either as a part of the hydrology/hydraulics model (DRAINWAT) or as a separate algorithm with DRAINWAT outputs serving as inputs to determine loads at the outlet. In this case, the experimental decay and load calculations were done in a separate algorithm or submodel (fig. 2).

Exponential decay concepts for N and P transformation or losses during transport have been used in other studies (Wagner et al., 1996; Heatwole et al., 1987). It is recognized that this method of quantifying in−stream changes is approximate, but it is easy to apply and has been used successfully in those studies. The relationship for exponential decay of concentration was assumed to be equally valid for nutrient load, which is a product of the concentration and flow rate, as was shown by Trepel and Palmeri (2002). Therefore, the nutrient load delivered from field i to the watershed outlet (L_i) is defined as:

$$L_i = L_{io}\, e^{(-k^*T_i)} \text{ (mass/area)} \qquad (2)$$

where L_{io} is the nutrient load at the edge of field i, k is the decay rate coefficient, and T_i is the time required for the nutrient to be transported from the edge of field i to the watershed outlet. Thus, the load delivered after attenuation from each field to the watershed outlet (L_i) is not the same as the load at the field edge (L_{io}), as shown above. The total cumulative annual load (L) of a nutrient at the watershed outlet is then defined as the sum of the loads delivered from each individual field:

$$L = \Sigma(L_i) \text{ (mass/area)} \qquad (3)$$

Delivery Ratio (DR)

The delivery ratio (DR_i) is defined as the ratio of the load (L_i) delivered at the outlet from field i to the load at the field edge (L_{io}):

$$DR_i = L_i / L_{io} \qquad (4)$$

Thus, combining equations 2 and 4:

$$DR_i = e^{(-k^*T_i)} \qquad (5)$$

where the delivery ratio is the fraction of the nutrient load delivered from the field edge to the watershed outlet. Equation 5 implies that loss in the canal−stream network increases with increasing distance or travel time (retention time) from the field edge to the outlet, and as such the distribution of the sources within the basin is taken into account (de Wit, 2001). This concept was successfully applied by Fernandez et al. (2002) to predict the total N load for a two−year period (1996−1997) using travel time predicted by DRAINMOD−DUFLOW on the same watershed. In this study, methods using DRAINWAT with two different approaches for estimating DR were tested for a longer period of data (1996−2000). One of these methods is very simple and can even be implemented in a spreadsheet environment, as was shown by Amatya et al. (2001).

Nutrient load at a field edge (L_{io}) is often estimated as the product of an “export coefficient” (kg/ha) and the field area (ha). The export coefficient is based on soil type, land and water management practices, crop, and fertilization. Tables of export coefficients would generally be prepared for a specific location (state, county), which would implicitly incorporate effects of weather and climate on the values. Export coefficients can be estimated from published data (Chescheir et al., 2003; Johnes, 1996; Evans et al., 1993; Frink, 1991; Beaulac and Reckhow, 1983). The load at the field edge may also be obtained by direct measurements, as was done here, or from process−based models such as DRAINMOD−N (Breve et al., 1997). Alternatively, the value can be estimated as a product of outflow measured or

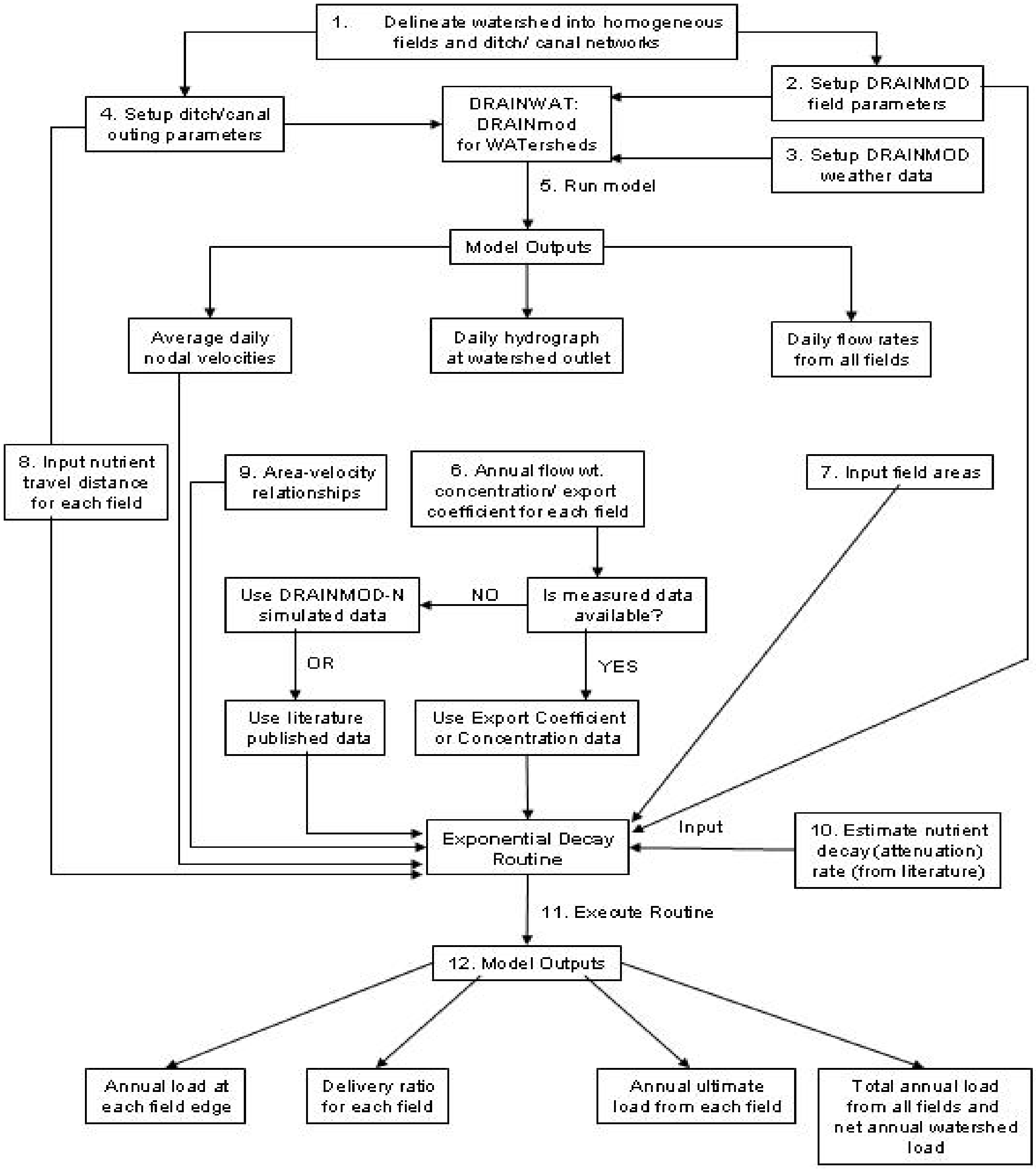

Figure 2. Schematic of watershed load estimate procedures using DRAINWAT outputs.

simulated using DRAINMOD (see procedures below) and export concentration (e.g., average nutrient concentration obtained by direct measurements or published data). In other cases, loading functions developed for specific land management practices may be used (Haith and Shoemaker, 1987; RTI, 1995).

Nutrient Decay Rate Coefficient (k)

The nutrient decay rate coefficient (k) is used to approximate the cumulative effects of several complex in−stream processes (nitrification, denitrification, sedimentation, and plant uptake and release). Hence, it is a fairly uncertain parameter with large variability. The values of k may vary with light, temperature, season, and location in the canal, with values increasing as flows become more infrequent or decrease in magnitude. Birgand (2000) showed that most of the nitrate retention in a North Carolina canal draining agricultural lands was due to denitrification. Because denitrification rates increase with temperature, k would be smaller for wet, cold seasons than for dry, hot seasons. The rates may also vary with the form of nitrogen in the drainage water. Field effective values for the k coefficient may shift with management practice and/or land use as the form of N at the field edge changes from labile to more recalcitrant forms of N, or vice versa. Reaction constants for different stages of nitrogen transformations are reported by Bowie et al. (1985). For example, the decay rate (k) as a result of denitrification was reported between 0.01 and 0.20 day^{-1}. Alexander et al. (2000) published values of in−stream loss rates of total N (0.05 to 0.45 day^{-1}) as a decreasing function of mean stream water depth. Heatwole et al. (1987) reported N uptake rate values of 0.000025 m^{-1} and 0.000038 m^{-1} in units with respect to distance for Florida canals and natural streams, respectively. Assuming an average water flow velocity of 0.03 m sec^{-1} (2592 m day^{-1}) for a canal network, these uptake rates would be equivalent to a range in k of 0.07 to 0.1 day^{-1}.

Travel Time (T_i)

Travel time (T_i) is the time required for the nutrient leaving the field edge to arrive at the watershed outlet and is calculated as:

$$T_i = L/V \text{ (day)} \tag{6}$$

where L is distance (m) traveled by the nutrient from the field edge to the watershed outlet, and V is the average velocity (m/day) of water as it moves through the canal−stream network. The average velocity, and hence the travel time, varies from event to event and may be estimated as a function of season and location in the watershed.

The procedures for estimating nutrient load from a watershed using DRAINWAT outputs for hydrology/hydraulics with the above equations for nutrient transport are presented in figure 2.

Application of DRAINWAT

DRAINWAT was applied to the 2,950 ha S4 watershed for a five−year period (1996−2000). For modeling purposes, S4 was divided into 27 fields (fig. 3), each having assumed uniform soils and vegetation management practices and separated by a collector ditch or a main canal. The areas of the fields varied from 42 ha to 205 ha (average of 109 ha) and were obtained from the GIS database (Amatya et al., 2003). Soil hydraulic properties used as input to the DRAINMOD module are presented in table 1. A rooting depth of 30 to 45 cm and a surface storage parameter of 7.5 cm was used for most of the bedded pine forests.

The main ditch−canal network in the watershed was delineated along with the location of outlets draining each individual field in the network, as shown in figure 3. Travel distance from the field outlet to the watershed outlet along the ditch−canal network was measured for each of the fields using available maps. The characteristics of the ditch and canal−stream network in the watershed are given in table 2.

Rainfall data collected for the five−year period (1996−2000) at gauge R6 in the middle of the watershed were used as the primary input in DRAINMOD. Daily PET estimated using the Penman−Monteith method (Amatya et

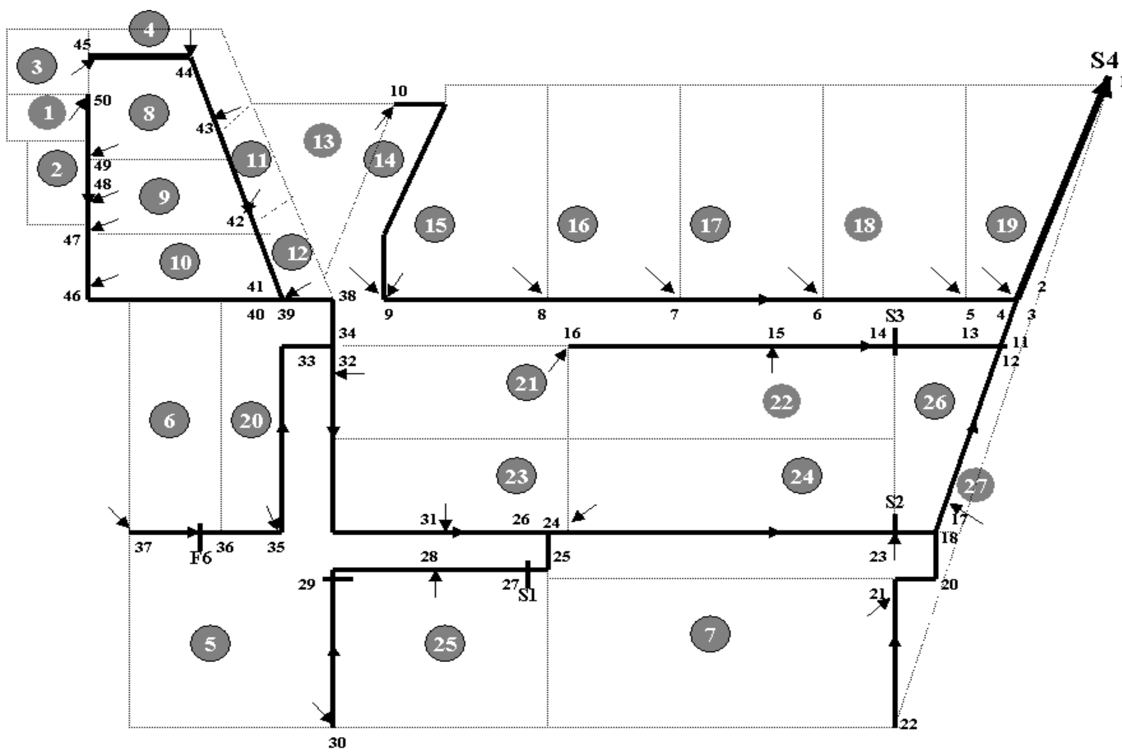

Figure 3. Delineation of individual fields (dotted lines and circled numbers) and ditch−canal network (solid bold lines) showing field outlets (node numbers with arrows) draining fields in 2,950 ha watershed S4. Short cross lines intersecting the canal lines represent weir locations.

Table 1. Main soil hydraulic properties of forested watershed S4.

Soil Parameter	Soil Type: Belhaven	Cape Fear	Pungo	Portsmouth	Wasda
Depth to impermeable layer (cm)	270	300	250	240	200
Hydraulic conductivity (cm/h) (depth range, cm)	20 (0 to 30)	15 (0 to 100)	10 (0 to 30)	50 (0 to 30)	20 (0 to 30)
	1 (30 to 80)	45 (100 to 300)	1.7 (30 to 150)	10 (30 to 50)	0.4 (30 to 80)
	0.01 (80 to 270)	−−	5.0 (150 to 250)	10 (50 to 240)	1 (80 to 200)
Saturated water content in root zone (cm^3/cm^3)	0.73	0.48	0.69	0.37	0.76
Water content at wilting point (cm^3/cm^3)	0.45	0.22	0.40	0.13	0.45

Table 2. Characteristics of lateral and collector ditches and drainage canals.

Parameters	Lateral Ditch	Collector Ditch	Drainage 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	0.025	0.035	0.04 to 0.05

al., 2003) with daily weather data from a station near gauge R6 (fig. 1) was input into the model. Annual rainfall and PET for the watershed is presented in table 3 for the five−year study period. Detailed description of the model parameterization including a one−year (1996) calibration (Amatya et al., 1998) and testing for prediction of hydrology including its internal consistency for the 1996−1998 period was presented by Amatya et al. (1999). The internal consistency of a model implies its ability to predict not only the flows at the watershed outlet but also the flows, soil moisture, and other variables within the fields and in−stream locations.

Model−simulated outputs for five years of daily outflows at the watershed outlet were compared to measured data to test the performance of the hydrologic model using the Nash−Sutcliffe coefficient of efficiency (Amatya et al., 1997). Predicted daily outflows from each field and daily average velocity at each node in the canal network were saved in output files. A separate exponential decay routine was developed to compute daily total nitrogen (N) load arriving at the outlet from each field using equations 2 through 6 as shown below. Predicted daily field outflows and daily average velocities at nodes along the flow path were inputs to this routine (fig. 2).

Daily total N load at each of the field outlets was calculated as a product of the predicted daily outflow and an average total N concentration in the outflow. Total N concentration was obtained as a sum of measured NO_3−N and TKN concentrations for all grab and flow−proportional composite samples measured periodically for the five−year period (1996−2000) in outflows from eleven experimental forested fields (F1, F3, F4, F5, F6, F7, F8, D1, D2, D3, and D4) within and in the vicinity of watershed S4 (fig. 1). Data were sorted for fields with mineral (F1, F3, and D2; 101 samples) and organic (F4, F5, F6, F7, F8, D1, D3, and D4; 332 samples) soils for only the first three−year period (1996−1998). Values obtained by averaging the maximum and minimum observed concentrations were then used to estimate an average total N concentration for the mineral and organic soils (table 3).

These values (7.9 mg L^{-1} for organic soil and 2.6 mg L^{-1} for the mineral soil) were assumed to be constant for the five−year period (1996−2000) and were assigned to each of the 27 fields as inputs to the model, depending on the soil category constituting the majority of the field area. This provided an opportunity to test the validity of this estimate of concentration in computing the annual total N loads for all five years. The average proportion of TKN was about 50% and 60% of measured total N concentration in organic and mineral soils, respectively. A lower value of 1.0 mg L^{-1} was used for a wetland (field 27) based on previously measured unpublished data.

Most of the values reported in the literature for the nitrogen decay rate (k) as a result of denitrification vary between 0.01 and 0.20 day^{-1} (Bowie et al., 1985). In the absence of measured data, a constant decay rate (k) value of 0.05 day^{-1}, similar to the one used by Fernandez et al. (2002) and suggested by Heatwole et al. (1987) for South Florida canals, was used in this application. The decay rate value for the channels in this watershed was assumed to be similar to those of Florida canals because of similarity in gradient and humid coastal location. Higher values of 0.1 day^{-1} for natural processes (Heatwole et al., 1987) and 0.12 for a surface flow wetland (Trepel and Palmeri, 2002) have been suggested. The value used herein also falls within the in−stream loss rate range of total N recently compiled by Alexander et al. (2000) for streams of Chesapeake Bay.

The travel path was identified using the nodes from each field edge to the watershed outlet. Distance between nodes of each reach in the flow path was measured from maps and input into the routine for calculating load at the outlet. Daily travel time for each field was computed by summing the travel times of each reach (in the flow path to the outlet) obtained by dividing the reach distance by the average daily velocity between the nodes of the reach. A daily delivery ratio (DR) was then computed using the travel time (T_i) and decay rate (k) in equation 5 for each field. The N load delivered from each field to the watershed outlet (L_i) was obtained by multiplying N load (L_{io}) at the field edge with DR in equation 2. The total annual load was calculated as the sum of N loads arriving from all fields at the watershed outlet for all days of the year (eq. 3). The annual watershed total N load without the effects of in−stream transport was also computed for comparison.

The second approach was a much simpler, easier to apply, but more approximate method. Total N was estimated using a spreadsheet in which DRAINWAT−predicted total annual outflow from each field was multiplied by the average total N concentration (in the first approach) to obtain total N load at the field edge. Exponential decay (eq. 1) was again assumed, but a simpler method was used to determine travel

Table 3. Measured annual rainfall, outflow, total N concentrations in field outflows, and predicted outflows. PET was estimated using the Penman−Monteith method with daily weather data.

Years	Measured Rainfall (mm)	Estimated PET (mm)	Measured Outflow (mm)	Predicted Outflow (mm)	Prediction Error in Outflow (%)	Range of Total N in Outflow Concentration from: Organic Soil (mg L^{-1})	Mineral Soil (mg L^{-1})
1996	1410	968	458	403	−11.8	0.5 to 15.3	0.1 to 5.1
1997	959	999	144	128	−11.1	0.6 to 7.1	0.2 to 3.4
1998	1276	1042	280	294	5.0	0.6 to 11.6	0.5 to 4.6
1999	1381	1075	266	270	1.5	−−	−−
2000	1220	1033	276	217	−15.2	−−	−−

time. Total distance from the field edge to the watershed outlet for each field was input into the spreadsheet. Travel time for each field was estimated using a single value of average velocity throughout the network, assuming it independent of season and location. The average velocity was obtained from DRAINWAT simulations for the watershed network for an eight−year period (1990−1997) (Amatya et al., 2003). This period covered six previous years (1990−1995) independent of the study period of 1996−2000. Weather data for the earlier years were obtained from the nearby Tidewater Research Station. Daily values of predicted velocities from 11 locations in the drainage network were averaged for the eight−year period to obtain a constant average velocity. Travel time for each field was then obtained by dividing the distance from the field edge to the outlet by this average velocity.

Daily, monthly (computed as sum of daily), and annual total N loads computed by these approaches were compared with measured data using graphical plots and statistical evaluations. Statistical evaluations included comparison of observed and predicted mean values, regression parameters (slope, intercept, and coefficient of determination (R^2)), Nash−Sutcliffe coefficient (E), and absolute error. These parameters, especially E, are frequently used for evaluating the performance of hydrologic and water quality models (Van Liew and Garbrecht, 2003; Santhi et al., 2001; Amatya et al., 1997; Refsgaard, 1997; Ambroise et al., 1995).

Results and Discussion

Measured and DRAINWAT−predicted daily and cumulative drainage outflows for watershed S4 are presented in figure 4 for each of the five years (1996−2000). Generally, model−predicted outflow from storm events was in close agreement with measured data. Exceptions were some winter events in 1999 and a few summer events. The model also did a good job in predicting the time distribution of outflows. Total cumulative outflow at the end of the five−year period (not shown) was underpredicted by 90 mm, which was only 6.5% of the total measured outflow of 1404 mm. Part of this was due to underprediction in April through July of 1996, which may have been due to errors in ET or spatial variability in rainfall, the effect of which was sustained through the entire five years. Peak flow rates were overpredicted during large hurricanes and summer tropical events of 1996 and 1999 (fig. 4). The weir outlet was submerged during those events, so some of the difference between predicted and measured results may have been due to measurement error. When considered on a year−by−year basis, the average absolute daily deviation in daily flows varied from 0.14 mm in 1997 to 0.41 mm in 1999. The Nash−Sutcliffe coefficient of agreement between measured and predicted daily data ranged from 0.71 to 0.84, with 0.75 for the calibration period, and is considered satisfactory based on other studies (Santhi et al., 2001; Amatya et al., 1997; Refsgaard, 1997). The predicted mean daily flow for the five−year period was not statistically different ($\alpha = 0.05$) from the measured data.

Predicted annual outflows were underpredicted by as much as by 15% in 2000 and overpredicted by less than 5% in 1998 and 1999 (table 3). The model's predictions on a monthly basis were judged to be acceptable based on calculated average absolute monthly deviation of 8 mm and the Nash−Sutcliffe coefficient of 0.85 for the 59−month period of data. These values were similar to those obtained by Fernandez et al. (2002) using DRAINMOD−DUFLOW for a two−year period on this watershed. These calculated errors in the outflows were considered acceptable for predicting the N export. Details of testing of DRAINWAT for

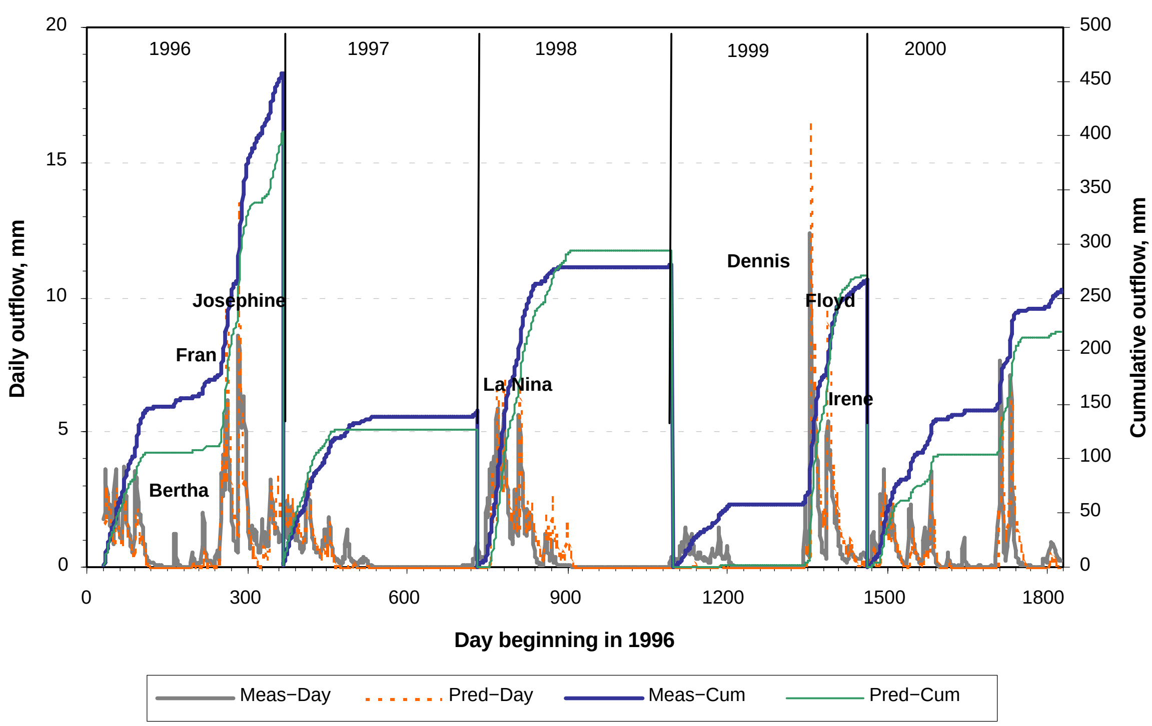

Figure 4. Measured and predicted daily and cumulative outflows for watershed S4. Tropical storms and hurricanes are identified by name (Fran, Dennis, Floyd, etc.).

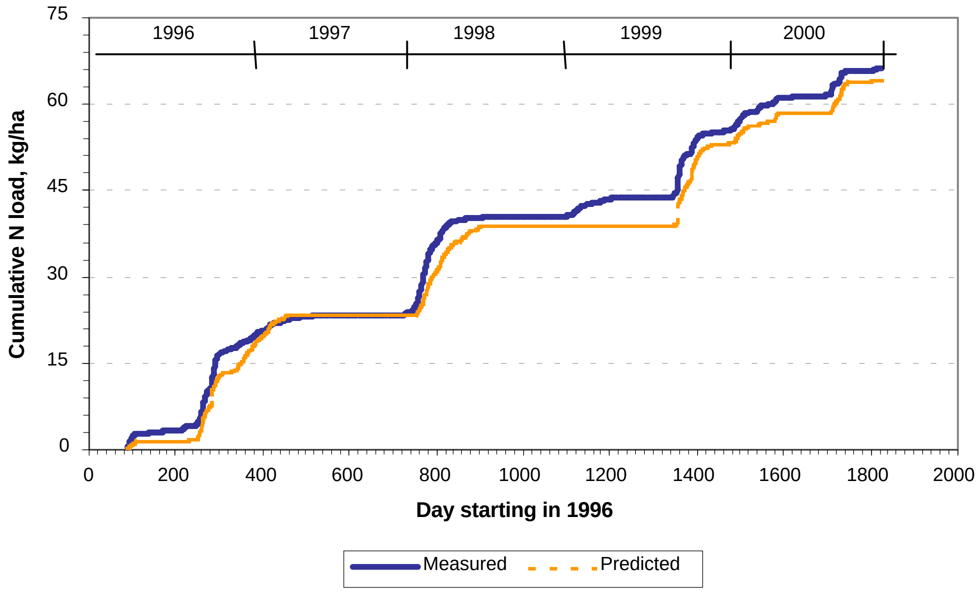

Figure 5. Measured and estimated daily cumulative total N load for watershed S4.

multi−year and multi−site hydrology are described in a companion article that will soon be submitted for publication.

Approach 1: Estimates Based on Daily Average Velocities

Estimated cumulative N loads at the outlet of S4, computed using daily average velocity to determine travel times, were compared with measured values (fig. 5). The accuracy of the estimated nitrogen load, which is determined as the sum of the estimated loads delivered to the outlet from all fields, primarily depends on how well the model predicts the daily drainage outflows for the individual fields, and on the estimated or assumed N concentrations at the field edge (Fernandez et al., 2002). The estimated daily loads tended to agree with measured loads, except for early 1996 and early 1999, when daily loads were underestimated. Although on a five−year total basis, the estimated load of 64 kg/ha was only 3.2% lower than the measured total of 66 kg/ha (fig. 5), the estimated daily distributions of N load were not in close agreement with measured daily loads. This was shown by the regression statistics (slope = 0.61; R^2 = 0.60) and by the lower Nash−Sutcliffe coefficient of only 0.19 computed for the five−year data. Furthermore, the mean of the estimated daily load of total N over the five−year period (0.038 kg/ha) was found to be different (α = 0.05) from the measured value of 0.041 kg/ha.

On a monthly or seasonal basis, however, the estimates were in much better agreement with measured values than on a daily basis, as shown by the statistics in table 4. This method performed well in predicting monthly losses in all years, except for 1997. Although R^2 was high for 1997, the E statistic was very low, indicating a large bias in estimates. This was evident from the slope of 1.79, which resulted because the loads were overestimated for the periods with flow in 1997. Loads were overestimated because the measured N concentration was actually lower than the 7.9 mg L^{-1} assumed (table 3). Flows for that period were somewhat underpredicted. Note that hydrology was calibrated for the year 1996 only, and a constant average concentration measured between 1996 and 1998 was used for all five years. Both the slope (0.81) and R^2 (0.77) parameters for the entire five−year period were higher than those calculated for the daily estimates. The Nash−Sutcliffe coefficient increased from 0.19 for daily estimates to 0.76 for the monthly. The five−year estimated monthly mean of 1.15 kg/ha was not statistically different (α = 0.05) from the observed mean of 1.26 kg/ha, indicating that the method's estimates of total N loads are acceptable on a monthly time scale.

The estimated annual N loads for each of the five years are compared with measured values in table 5. Except for 1997, estimated annual N loads were within 16% of measured values for all years. Although annual outflow in 1997 was underpredicted by 11% (table 3), the estimated load was 38% higher than measured due to an overestimated N concentra− tion. Errors in estimates for 1999 and 2000, for which

Table 4. Computed statistics for five−year monthly measured and estimated total N loads for watershed S4.

Year	Average Monthly Load: Measured (kg/ha)	Average Monthly Load: Predicted (kg/ha)	Mean Monthly Measured (kg/ha)	Regression Parameters: Intercept (kg/ha)	Regression Parameters: Slope	Regression Parameters: R^2	Nash− Sutcliffe Coefficient (E)
1996	2.42	1.91	0.85	−0.07	0.82	0.81	0.76
1997	0.40	0.55	0.31	−0.16	1.79	0.94	0.10
1998	1.40	1.29	0.75	0.38	0.65	0.78	0.75
1999	1.23	1.18	0.69	0.00	0.96	0.78	0.73
2000	0.92	0.93	0.29	−0.06	1.08	0.89	0.85
All years	1.26	1.15	0.59	0.14	0.81	0.77	0.76

Table 5. Measured and predicted five−year annual total N loads for watershed S4. Loads in 1996 are only for 11 months starting in February.

Year	Measured Load (kg/ha)	Predicted Load: Daily Average[a] (kg/ha)	Predicted Load: Annual Velocity[b] (kg/ha)	Predicted Load: Florida k'[c] (kg/ha)	Absolute Prediction Error: Daily Average[a] (%)	Absolute Prediction Error: Annual Velocity[b] (%)	Absolute Prediction Error: Florida k'[c] (%)	Predicted Load without DR[d], kg/ha (%)
1996	26.6	21.0	20.0	19.3	21.1	24.8	27.4	23.7 (5.9)
1997	4.8	6.6	6.4	6.2	37.9	33.7	29.3	7.1 (7.0)
1998	16.8	15.5	14.8	14.3	7.8	12.1	14.9	16.5 (6.1)
1999	14.8	14.1	13.4	13.0	4.4	9.3	12.2	14.9 (5.4)
2000	11.0	11.2	10.8	10.5	1.6	1.5	4.6	12.1 (7.4)
Average	14.8	13.7	13.1	12.7	14.6	16.3	17.7	14.9 (7.4)

[a] Daily velocity predicted by DRAINWAT used to determine travel time.
[b] Constant annual velocity of 0.03 m sec^{-1} used to determine travel time and in−stream loss of N in the spreadsheet.
[c] Florida *k* in the spreadsheet.
[d] Predicted load without delivery ratio, and percent retention in parentheses.

measured concentration data were not used, were only 7.8% and 4.4%, respectively. Average annual errors in estimates for the five−year period with and without 1997 were 13.7% and 7.5%, respectively. There was no statistical difference (α = 0.05) between the five−year means of measured data (14.8 kg/ha) and the estimated value of 13.7 kg/ha.

In summary, estimated N loads based on travel times obtained by using daily velocities predicted by DRAINWAT were in good agreement with measured data. Secondly, on a monthly and annual basis, but not on a daily basis, the estimate of a constant total N concentration, based on three−year measured data from selected fields, and its assignment to other fields depending on soil category, gave reasonable results on average. The year 1997, with relatively lower rainfall, was an exception, and the N load was overpredicted for that year. Thirdly, the decay rate (*k*) of 0.05 day^{-1}, which was selected based on values reported in the literature (Fernandez et al., 2002; Alexander et al., 2000; Bowie et al., 1985), produced results in good agreement with measured monthly and annual loads for this study.

Approach 2: Predictions Based on a Constant Average Velocity

In the second approach, a constant average canal velocity of 0.03 m sec^{-1} (standard deviation = 0.05 m sec^{-1}) was determined from an eight−year (1990−1997) DRAINWAT simulation of the site (Amatya et al., 2003) and used in a spreadsheet analysis to determine N loads. The travel time for nutrient transport was thus assumed to be independent of seasonal flow and dependent only on the location as a function of distance from the field edge to the outlet (fig. 3). The annual total N load computed by this approach is also shown in table 5. Results show that the estimate of annual N load using a single average annual velocity was consistently lower than that obtained with approach 1, in which a daily average velocity was used to compute travel time and in−stream losses. Although the errors with approach 2 were larger on average, the estimated total N load was within 5% of the results obtained with approach 1. Statistical analysis using a t−test indicated no difference (α = 0.05) between the means of annual measured (14.8 kg/ha) and estimated total N load (13.1 kg/ha) by this approach (table 5).

Results for approach 2 indicate a possibility of using a single attenuation coefficient as a function of only distance from the field edge to the watershed outlet to estimate delivery ratio (DR) of the annual total N load. Heatwole et al. (1987) used a similar approach by defining rate coefficients for nitrogen and phosphorus uptake as a function of distance from the field edge to the outlet. They reported a value of k = 0.000025 m^{-1} for N uptake rates for South Florida canals. This value is close to the value we used in approach 2. A *k* value of 0.05 day^{-1} and an average velocity of 0.03 m sec^{-1} may be converted to a distance−based *k* of 0.000019 m^{-1}, as compared to the 0.000025 m^{-1} value reported by Heatwole et al. (1987). Had we used the results of Heatwole et al. (1987) along with the DRAINWAT−predicted constant average velocity of 0.03 m sec^{-1} to estimate *k*, we would have obtained a value of k = 0.066 day^{-1}, as compared to k = 0.05 day^{-1} that was used. The effect of using this *k* value (0.066 day^{-1}) to calculate the annual N loads is shown in table 5 under Florida k'. As expected, results were in good agreement with estimates using k = 0.05 day^{-1} in approach 2. Average estimation errors were only 3% greater (17.7%) on average than with approach 1 (table 5). Further, a t−test (α = 0.05) showed that the mean annual load estimated by this approach, with the *k* value obtained from the Florida studies (Heatwole et al., 1987), was not different from the measured load. Results of this analysis showed that N loads predicted with approach 1 were in closer agreement with measured values than approach 2. However, the use of a constant attenuation coefficient should be interpreted cautiously. Nitrogen transport and fate is a complex process and should not be assumed to be simply a function of distance from the sources (Alexander et al., 2000).

The effect of in−stream processes on the annual N load was evaluated by comparing estimated N loads with and without a delivery ratio (table 4). Results showed that in−stream attenuation reduced the estimated N load by only 5% to 7%, on average, for this watershed. The magnitude of the in−stream losses is consistent with findings of Fernandez et al. (2002) and Birgand (2000). The reader may question the need to use models such as DRAINWAT to consider relatively small differences in predicted loads. However, this small percentage is partly due to the relatively small size of the watershed. In−stream processes may result in substantially larger N losses for larger watersheds where travel distances are larger and residence times are greater (de Wit, 2001). In addition to the average effects of in−stream processes on loads, it is important to understand the spatial and temporal distribution of N load discharged by various fields and their proportional contribution to the N load of the total watershed. This requires a distributed hydrologic model, like DRAINWAT, that has been tested for internal consistency (Amatya et al., 1999) to predict flow rates, which in turn affect the travel times and loads.

Table 6. Annual distribution of delivery ratios (DR) computed by approach 1 for selected fields (1, 19, 21, and 27) shown in figure 3. Distances from field outlet to the watershed outlet (S4) for fields 1, 19, 21, and 27 are 12.6, 0.35, 3.5, and 0.73 km, respectively.

Year	Wet Period (November to April)				Dry Period (May to October)				Annual			
	1	19	21	27	1	19	21	27	1	19	21	27
1996	0.89	1.00	0.91	1.00	0.92	1.00	0.94	1.00	0.91	1.00	0.93	1.00
1997	0.88	0.99	0.93	0.99	−−	0.93	0.71	0.99	0.88	0.99	0.93	1.00
1998	0.90	1.00	0.94	1.00	0.84	0.99	0.92	0.99	0.90	1.00	0.93	1.00
1999	−−	0.96	0.92	0.99	0.93	1.00	0.94	1.00	0.93	0.99	0.94	1.00
2000	0.88	0.99	0.91	0.99	0.91	0.99	0.93	1.00	0.90	0.99	0.92	1.00

Analysis of predicted total N loads from individual fields revealed that, depending on the location of the field in the watershed (fig. 3), the delivery ratio (DR) varied from 0.71 for a field located upstream in a relatively dry year (1997) to 1.0 for a field near the outlet. Lower DR values were generally obtained for fields 1 and 21, located farther away from the outlet (table 6 and fig. 3), as expected.

For any given field, the DR value indicates the fraction of N load entering the canal at the field edge that is transported to the watershed outlet. Thus, to have maximum impact on reducing pollutant loads at the watershed outlet, best management practices (BMPs) should be targeted at the fields with the largest potential N loads and the largest DR values, assuming soils and land uses are similar. The spatial distribution of predicted field loads, DRs, and the respective loads arriving at the watershed outlet can be effectively displayed using GIS interface modules (Fernandez et al., 2002). The DR value, which is dependent on travel time and hence the velocity of flow, varied spatially, seasonally, and from year to year, as expected (table 6). For this reason, the DRAINWAT method that accounts for the spatial and temporal variation of velocity as affected by both location and season (approach 1) was more accurate than the spreadsheet−based method (approach 2).

The spreadsheet−based method, in this study, used DRAINWAT−predicted annual outflows with average concentration to derive annual load at each field edge. Alternatively, annual outflows estimated by other relevant methods and export coefficients (annual load per unit area) based on a specific land use and management practice can also be used to estimate the load at the field edge by this method.

Summary and Conclusions

A DRAINMOD−based watershed−scale hydrologic model (DRAINWAT) was applied in conjunction with a lumped−parameter first−order exponential decay algorithm to evaluate total nitrogen (N) loads at the watershed outlet for a five−year period (1996−2000). Model predictions of both daily and annual outflows at the outlet of the 2,950 ha lower coastal plain watershed for all years were in good agreement with measured values. Some discrepancies in flow predictions in late spring and summer were attributed to errors in modeling ET and/or rainfall distribution. Other discrepancies resulted from errors in flow measurements during large hurricane events. Predicted daily outflows and velocities were used with measured average N concentrations at the field edge and an exponential decay model to estimate daily N loads at the watershed outlet. The Nash−Sutcliffe coefficient (E) and statistical tests showed that this method did a much better job in estimating monthly and annual total N loads than daily loads for the five−year period. The average annual estimation error of 14% in total N load was also considered acceptable, given the complexity of the hydrologic model and the uncertainty in estimated field−level N concentrations and in−stream decay rate. It was thus shown that the DRAINWAT model can provide the drainage outflows and velocities needed to implement a lumped−parameter nutrient decay model for in−stream transport to estimate monthly and annual N transport on poorly drained coastal watersheds.

Results of this study also indicated that annual watershed losses of N due to in−stream processes can be estimated based on a constant average velocity and exponential decay with a single attenuation coefficient using a spreadsheet. Constant average velocity was determined from long−term DRAINWAT simulations. As expected, this approach was less accurate than the use of daily DRAINWAT simulations of stream velocity, travel time, and N losses, and results should be cautiously applied. However, the spreadsheet approach may be useful as a planning level tool for estimating watershed loads. On a watershed scale, the effect of annual in−stream loss of total N was only about 7%, indicating that the routing/attenuation method has a lesser effect on the watershed load than did the estimated annual field loads. However, on a field−by−field basis, the predicted delivery ratio (DR) for total N varied from 0.71 to 1.0, depending on the location of the field in the watershed. The range of DR would likely be greater for larger watersheds. Research is underway to develop and test various methods, including uncertainty analysis, for determining N transport on multiple poorly drained watersheds.

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