This is not a peer-reviewed article.
Pp. 442-452 in Total Maximum Daily Load (TMDL) Environmental Regulations–II
Proceedings of the 8-12 November 2003 Conference (Albuquerque, New Mexico USA),
Publication Date 8 November 2003.
ASAE Publication Number 701P1503, ed. A. Saleh.

WATERSHED MODELS FOR PREDICTING NITROGEN LOADS FROM ARTIFICIALLY DRAINED LANDS

R.W. Skaggs[1], G.M. Chescheir[1], G. Fernandez[1] and D.M. Amatya[2]

ABSTRACT

Non-point sources of pollutants originate at the field scale but water quality problems usually occur at the watershed or basin scale. This paper describes a series of models developed for poorly drained watersheds. The models use DRAINMOD to predict hydrology at the field scale and a range of methods to predict channel hydraulics and nitrogen transport. In-stream changes of N load are estimated with a lumped parameter exponential decay function. The models were tested using data from a 10,000 ha eastern NC watershed. The models can be used in TMDL development and implementation procedures to target application of field scale management practices to maximize reduction in nitrogen load at the watershed scale.

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

INTRODUCTION

Water quality problems caused by excessive nutrient and sediment loading to streams are usually most critical at the watershed or river basin scale. Non-point sources of pollutants originate at the field scale and are spatially distributed within the watershed. Likewise, management practices to reduce nutrient and sediment loading are distributed on a field-by-field basis throughout the watershed. Because of transport and in-stream processes, impacts of field scale practices on pollutant loading at the watershed scale are not linear. That is, the impact of applying management practices to a field within the watershed, on the nutrient and sediment load at the watershed outlet, depends not only on the effectiveness of the practices at the field scale, but also on the location of the field with respect to the watershed outlet. In order to quantify the impacts of land use and management practices on the nutrient and sediment loading at the watershed scale, methods are needed to both predict loading at the edge of individual fields and the fate of nutrients as they move through the stream network to the watershed outlet.

Poorly drained soils make up an important part of our cropland base. Over 40 million ha, or about 25% of our nation's cropland, requires improved drainage for agricultural production (Pavelis, 1987). When properly managed, these lands are among the world's most productive soils. A large percentage of these drained lands are in the Corn Belt and Great Lake States. They are also concentrated in the Mississippi River valley and in the Atlantic and Gulf coastal where the drainage systems may be either open ditches or subsurface drains. In addition to agriculture, plantation forestry is also practiced on these poorly drained soils.

Agricultural production on most of these lands requires improved drainage and the application of fertilizers, both of which increase the potential for nutrient loading to receiving streams and estuaries. Contribution of nutrients from drained lands is of increased importance because of the location of these lands with respect to nutrient sensitive waters. For example, large areas of hypoxia in the northern Gulf of Mexico have been related to excessive nitrogen (N) derived primarily from agricultural sources via the Mississippi River (Rabalais et al.1996). Some of the greatest losses of N to surface waters come from lands with subsurface drains (Gilliam et al., 1999). The evidence suggests that the hypoxia problems in the Gulf are the result, at least in part, of N losses from drained lands in the Midwest. In North Carolina, scientists studying the Neuse and Tar-Pamlico rivers and estuary systems have concluded that N is the limiting element controlling plant growth, algae blooms and associated water quality problems, with approximately 54% of the current N load derived from agriculture. In this case, methods to reduce nutrient contributions from poorly drained watersheds are critical because they are primarily located in the coastal plain in close proximity to the threatened estuaries.

The magnitude of nutrient losses at the field scale depends on the type and management of the drainage system, as well as, fertilization rates and soil and climatological factors. For example, subsurface drainage losses of N are increased when excessive N fertilizer is applied, or when crop yields are suppressed by drought or other unfavorable growing conditions (Randall et al., 1992; Randall, 1998). Management practices, including the use of controlled drainage (Gilliam et al., 1979; Evans et al., 1991), riparian buffers (Gilliam et al., 1997), and nutrient management, have been developed to reduce nutrient loading to receiving waters. A combination of these practices is now being required by many state regulatory agencies to reduce nutrient and sediment loads as a part of total maximum daily load (TMDL) development and implementation. Methods have been developed to predict effects of land use and management practices on sediment and nutrient loads from poorly drained lands (Skaggs et al., 1995b; Breve et al., 1997). While these methods have been shown to be reliable for predicting loads at the field edge (Breve et al., 1997b; Northcott et al., 2001), they can't be used directly to predict loads at the watershed scale.

Our recent research has focused on development of watershed scale models, which consider the effects of in-stream processes as the drainage water moves through drains, ditches, canals and streams. This work builds on the field scale research and models discussed above, and it has produced a 6-year database quantifying nutrient movement and fate in a 10,000 ha watershed. These data have been used to develop and test a suite of models for predicting effects of management practices and land uses, applied at the field scale, on nutrient loads at the watershed outlet. The models range from relatively simple spreadsheet approaches, which typically use export coefficient and delivery ratio concepts, to more complex physically based methods that calculate travel times and in-stream changes of nutrients. On one end of the spectrum, the simple methods are relatively easy to apply, but only make general estimates of the effects of field and in-stream processes. On the other end, the more complex methods consider, in more depth, the field and in-stream processes for characterizing effects of field scale practices and land uses on flows and loads at the watershed outlet, but they are more difficult to apply on a routine basis.

The objective of this paper is to present a summary of models developed in our program for predicting the effects of land uses and management practices on nitrogen loads from drained watersheds and to demonstrate their application for a watershed in the NC coastal plain.

MODELING DRAINED WATERSHEDS

A schematic of our experimental watershed is shown in Figure 1. Systems of parallel open ditches or subsurface drains are used to lower the water table and provide sufficient drainage for agriculture and forestry. Drainage water moves from the field drains through drainage canals or natural streams to the watershed outlet. Watershed scale hydrologic and water quality models were developed by combining DRAINMOD (Skaggs, 1999), which is used to describe field scale

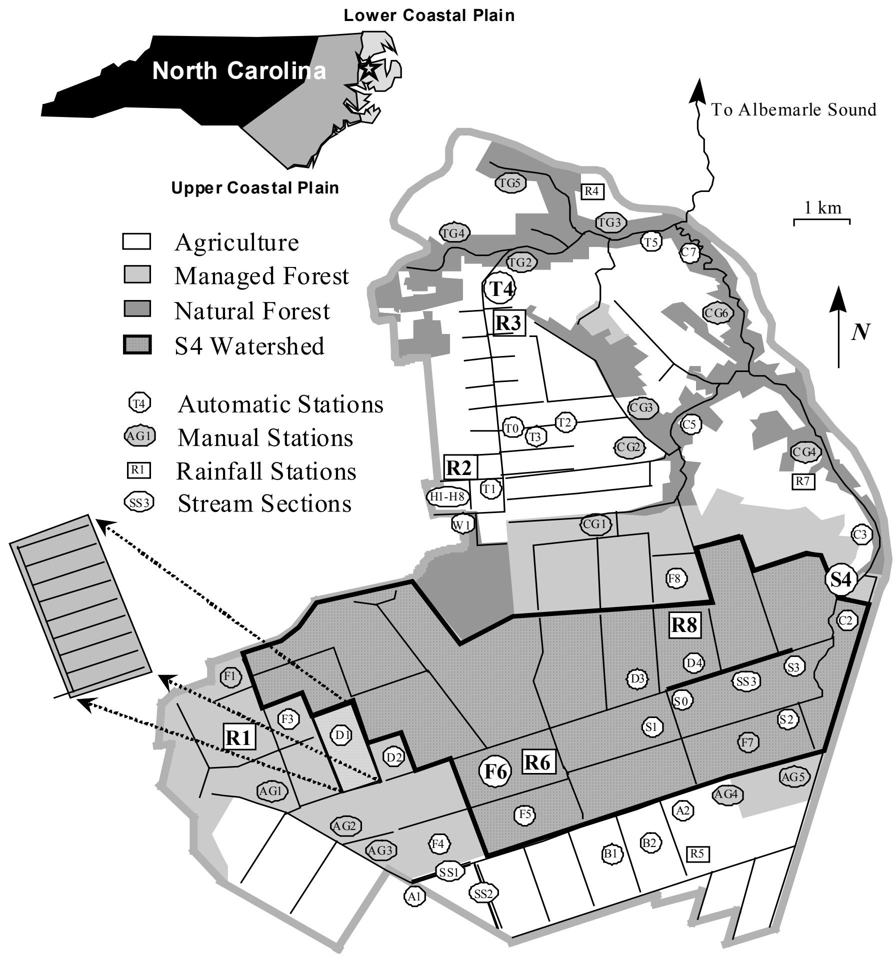

Figure 1. Schematic of the 10,000 ha study watershed near Plymouth in the NC coastal plain

processes, with various methods for describing flow and the transport and fate of constituents such as nitrogen, phosphorus and sediment as the drainage water moves through the canal/stream network. Except for the simplest, most approximate methods, the primary difference in the models described herein is in the sub-models used to describe flows in the canal/stream network and the changes in water quality that occur in route to the outlet. The models are listed in Table 1.

In general, a watershed is modeled as a set of independent sub-catchments draining into a network of channels (Fig. 1). Sub-catchments are large fields or sets of fields with uniform soil characteristics, crops and drainage systems. The canal/stream network is modeled as a combination of segments of constant cross-section with flow from the fields entering at the junctions or nodes.

DRAINMOD

Hydrology at the field scale is predicted in the models by DRAINMOD, which was developed to describe the performance of drainage and associated water management systems in soils with shallow water tables. DRAINMOD is based on water balances in the soil and at the soil surface. It uses functional methods to quantify infiltration, subsurface drainage, surface drainage, evapotranspiration (ET), seepage, freezing, thawing, snowmelt and seepage. The model predicts the water table depth and soil water contents above the water table, drainage rates and the other hydrologic components on a hour-by-hour, day-by-day basis for long periods of hydrologic record. Hydrologic predictions of the model have been tested and found to be reliable for a wide range of soil, crop and climatological conditions (Skaggs, 1999). The model includes algorithms to predict effects of excessive and deficit soil water conditions and planting date delays on crop yields. The

Table 1. Models developed to predict hydrology and nutrient transport in drained watersheds.

MOD NO	MODEL*	CHANNEL FLOW	FEED-BACK	TRANS-PORT	WATER QUAL.	UNCERT. ANALYS.	GIS	RUNTIME ONE-YR
1	DRAINWAT	ST.VENANT	YES HR	SLUG FLOW	EXP DECAY	NO	NO	
2	DM- DUFLOW	ST VENANT	YES HR	ADR	EXP DECAY		NO	9 MIN
3	DRAINMOD-W	ST VENANT	YES DAY	ADR	EXP DECAY		NO	3 MIN
4	DRAINMOD-GIS	SIMPLIFIED DIFFUSION	NO	SLUG FLOW	EXP DECAY		YES	1.5 MIN
5	WATGIS	N/A	N/A	SLUG FLOW	EXP DECAY	YES	YES	3 SEC
6	DRAINWAT-@RISK in SPREADSHEET	AVERAGE VELOCITY	NO	SLUG FLOW	EXP DECAY	YES	NO	

***All models use DRAINMOD to predict both surface and subsurface drainage rates at the field scale.**

current version of the model also includes options for predicting the movement of salt and effects of drainage on soil salinity. Breve et al. (1997a) incorporated approximate methods for computing a nitrogen balance in DRAINMOD, making it possible to predict effects of drainage design and management on nitrogen losses in drainage waters. Youssef (2003) developed more complete methods for describing the nitrogen cycle, which promise to greatly improve our ability to predict movement and fate of nitrogen in shallow water table soils.

Stream Routing

The "standard" method for predicting water levels (stage), velocities and flow rates in the drainage canal/stream network in our models is to solve the St. Venant equations for one-dimensional flow in open channels (Konyha and Skaggs, 1992). Although alternatives to improve the computational efficiency have been developed, this basic approach has been used in models 1-3 in Table 1. Predicted outflows for each field enter the canal at the field outlet. Depending on the size of the fields, surface runoff and subsurface drainage may be routed separately to the field outlet using the instantaneous unit hydrograph approach. Subsurface drainage rates depend on the water level in field ditches, which, in turn, depends on the stage at the field outlet. That is, there is interaction between the field drainage rates and the water level in the canal at the outlet. This interaction is termed "feedback" in Table 1. It is considered by using the predicted stage in the canal as the boundary condition in DRAINMOD. The boundary condition (stage in the outlet canal) is updated hourly for models 1 and 2, with iteration; it is updated daily for model 3.

Nutrient Transport

As nutrients move with the drainage water through the canal/stream system, concentrations are affected by advection, dispersion and in-stream reactions. Changes in concentrations may be considered by solving the differential equations describing the advective-diffusive-reactive processes (ADR equations) (Zheng and Bennett, 2002). Models 2 and 3 use this approach and include numerical solutions to the equations. The other models ignore dispersion and assume "slug" flow of the nutrients with drainage water.

In-Stream Changes

In-stream processes affecting the fate of nutrients in drainage channels are complex. They include physical, chemical and biological processes with interaction and feedback. While models have been developed that include quantification of N and P cycles, phytoplankton kinetics, and carbon and dissolved oxygen balances (e.g., WASP5 with EUTRO4, Ambrose et al., 1991), the large number and uncertainty of required input parameters limits their application. The models use a lumped parameter, first order decay assumption to approximate in-stream losses of various species of nitrogen as it is transported through the canal/stream network. The effect of those losses is to change the concentration of nitrogen as water moves down the stream, which may be expressed as,

$$\mathbf{C = C_0\, e^{-kt}} \qquad \mathbf{(1)}$$

where C_0 is the nitrogen concentration in a volume of water entering the canal at the field edge, C is the concentration associated with that volume at a position downstream, t is the residence time, or time of travel, of that volume of water, and k is the decay constant. Birgand (2000) found that the loss of nitrogen in canals of the lower coastal plain is closely associated with bottom sediment and proposed to describe the retention of nitrogen as a function of a mass transfer coefficient and the concentration of nitrogen in the water column. The constant, k , in the above equation is a function of the mass transfer coefficient and the depth of water in the canal.

Watershed Models

A brief description of the individual models is given below. The reader is referred to the references for details.

Model 1, *DRAINWAT* (Amatya et al.,1997, 2003) is based on FLD&STRM (Konyha and Skaggs, 1992) with modifications to consider forested conditions. Daily average stream velocities are used to calculate residence times and in-stream losses or retention of nitrogen are estimated with an exponential decay function built in a separate water quality module outside of DRAINWAT. Dispersion during nutrient transport in the stream is not considered.

Model 2, *DRAINMOD-DUFLOW* (Fernandez et al., 2003a) links DRAINMOD for field predictions with DUFLOW (Aalderink et al., 1995) to describe channel hydraulics and in-stream hydrodynamics. Flows from the field outlet are routed on an hourly time step to the watershed outlet. Routines in DUFLOW allow user specified models for predicting in-stream changes in water quality. A lumped parameter exponential decay function (Eq. 1) is used in our applications to predict loss of nitrogen as the water moves through the canal/stream system.

Model 3, *DRAINMOD-W*. (Fernandez et. al, 2001) This model is similar to model 2 in that it combines DRAINMOD with numerical solutions to the St.Venant equations for channel hydraulics and solves the ADR equations for transport of chemicals. The model uses a daily time step for updating channel water levels as a boundary condition in DRAINMOD. The model is structured such that other field scale models could be substituted for DRAINMOD so upland watersheds could be considered. A paper describing models 2 and 3 in detail and comparing their performance for a coastal plain watershed is currently in review.

Model 4, DRAINMOD-GIS (Fernandez et al., 2003b) uses a simplified canal routing model based on methods presented by Olivera and Maidment (1999). Stream/canal routing is simulated with a kernal function based on the first passage of time distribution to characterize the time of travel. Nutrient transport is assumed to be by convection without dispersion (slug flow) and in-stream losses of nitrogen are estimated with an exponential decay function. The model is integrated with a Geographical Information System (GIS) for both inputs and displaying outputs of the model. The model is easily adaptable for performing sensitivity and uncertainty analyses.

Model 5, WATGIS (Fernandez et al., 2002) is a GIS based, lumped parameter water quality model which uses spatially distributed delivery ratio (DR) parameters to account for nitrogen retention or loss along a drainage network. DR values are calculated from time of travel and an exponential decay model for in-stream processes. Models 2 or 3 above are used to develop relationships between travel time and daily flow depth, upstream drainage area and length of flow path from the field to the outlet. Once that relationship is developed this model can be used to predict effects of land use and management practices on nutrient load at the outlet. Run times are fast, results can be displayed on GIS and uncertainty analyses can be easily conducted.

Model 6, DRAINWAT-@RISKDRAINWAT-@RISK (Amatya et al., 2001) is a spreadsheet based model where predicted annual or seasonal field outflows simulated by DRAINWAT are used in @RISK decision tool system (Palisade Corporation, 1997), which is also embedded in a spreadsheet. Other inputs such as export concentrations for each field, distance from the field outlet to the watershed outlet, and in-stream decay rate may be entered in the spreadsheet for predicting the seasonal/annual nitrogen load delivered to the watershed outlet. The tools available in @RISK are used to evaluate effects of uncertainties of inputs such as decay rate and travel time on the loads using a probabilistic distribution obtained by Latin Hypercube sampling.

WATERSHED MEASUREMENTS AND MODEL TESTING

The models were developed and tested with data from a 10,000 ha eastern NC watershed (Figure 1). Land use on the watershed is typical of the region, consisting of cropland (36%), managed forest (52%), unmanaged forested wetlands and riparian areas (11%). The watershed is relatively flat (surface elevations 3 to 6 m above mean sea level) and the soils are mostly poorly drained and very poorly drained mineral and organic series. The primary drainage system on both agricultural and managed forest lands is a network of ditches and canals which divide the watershed into a mosaic of regularly shaped fields and blocks of fields. Field ditches, spaced 80 to 100 m apart and 0.6 to 1.5 m deep, provide both surface and subsurface drainage. They drain to a network of collector and main canals which lead to the watershed outlet. Some of the unmanaged forested lands do not have ditches and some of the agricultural lands have drain tile.

Flow measurements were recorded and drainage waters sampled for water quality analyses at 54 stations within the watershed. These stations were located at the outlet of the watershed, at the outlet of sub-watersheds, on main drainage canals, and at the outlet of agricultural and forested fields. Water table depth was recorded continuously at 28 locations and precipitation at 8 sites on the watershed. A detailed description of the watershed and is given by Chescheir et al. (1998). A six-year data set has been collected on the site and measurements continue.

Data from the watershed study were used to calibrate and test the models listed in Table 1. Details of the tests are given in the individual references listed with the model descriptions above. An example is given in Figure 2 for the DRAINMOD-DUFLOW model (from Fernandez et al., 2003). Measured and predicted daily and cumulative outflows at the outlet of the 3000 ha forested sub-watershed S4 (Figure 1) are plotted in the top graph for the 5-year period 1996-2000. Daily and cumulative NO_3-N loads are plotted in the bottom graph. The site was modeled as 27 fields, ranging in size from 46 to 205 ha, and 46 channel sections. Soil properties for the major soil types in the watershed were used as inputs (i.e., these inputs were not measured on a field by field basis). Site parameters such as ditch and canal dimensions, were determined from the GIS data base for the watershed. Hourly precipitation inputs to the model were obtained from three gauges on the watershed using the nearest neighbor approach for the individual fields. The model was calibrated with data for 1996-1997 by adjusting surface storage values for some of the fields and Manning's roughness values in the drainage canals. The calibration required was minimal and model did an excellent job in predicting the timing and magnitude of outflow events, as well as, the cumulative outflow over the 5-year period. The model failed to predict outflow for only a few small events in which flow was measured and very rarely predicted a flow event when none occurred. Good agreement between predicted and measured outflow results from accurate estimates of ET in the model, which used inputs for daily potential ET calculated by the Penman Montieth equation. Because DRAINMOD is used to describe the field hydrology in all of the models listed in Table 1, results similar to those given in Figure 2 could be expected on a

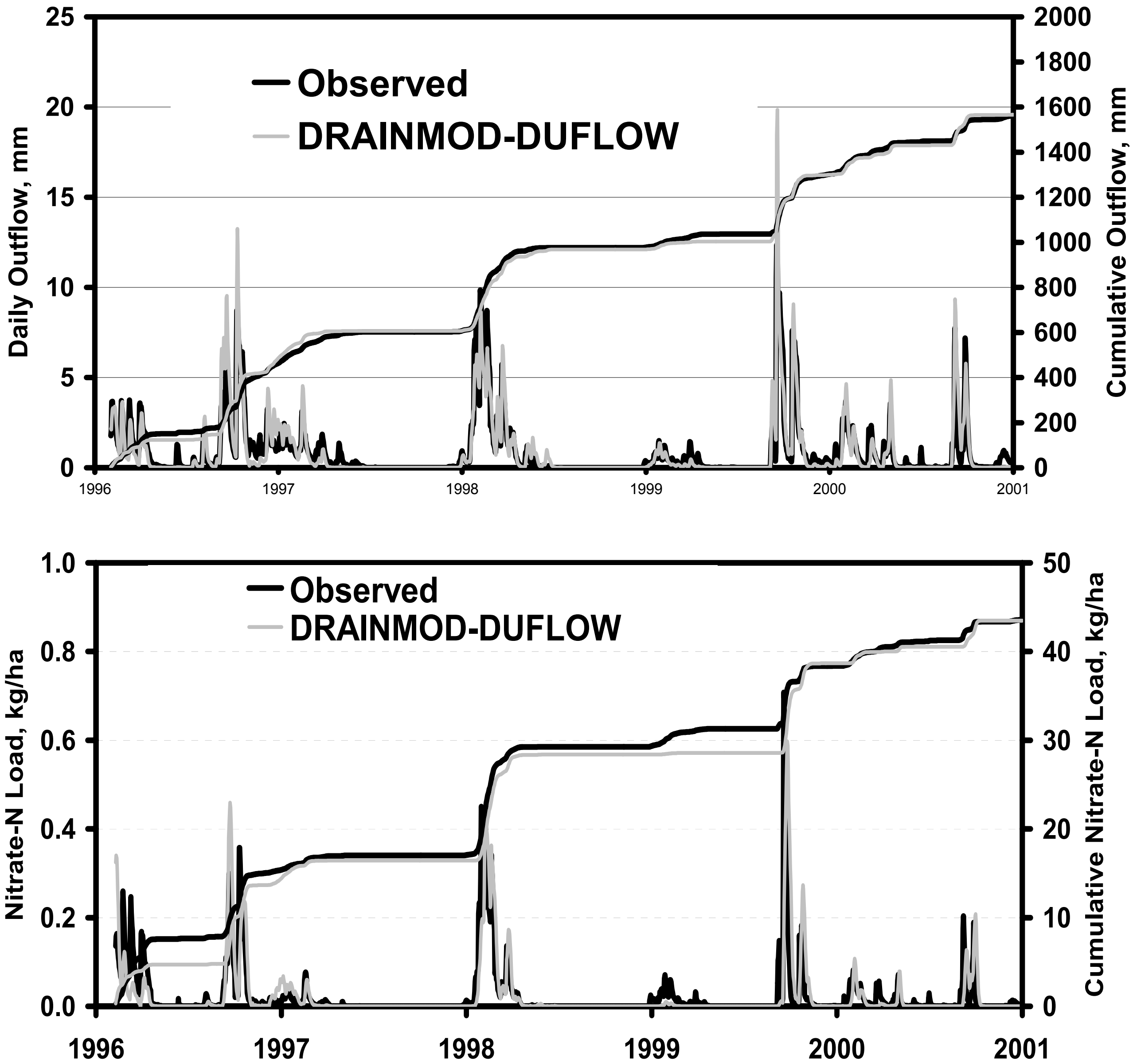

Figure 2. DRAINMOD-DUFLOW predicted and measured outflows (top) and nitrate nitrogen loads (bottom) for the forested watershed, S4 (after Fernandez et al., 2003).

monthly or annual basis. The different methods used for handling the channel dynamics will result in differences in predicted watershed outflows on a daily basis, but cumulative flows should be similar.

Predicted NO_3-N (nitrogen as nitrate) loads were also in good agreement with measured values as shown in Figure 2. In this case the model was calibrated by adjusting the exponential decay factor, k, in equation 1 to optimize agreement for the calibration period, 1996-1997. Field scale NO_3-N loads were determined with a regression equation developed with 1996-1997 data collected from 5 fields representing the major soil types and forest conditions on the S4 sub-watershed. The regression equation predicts field scale loads in terms of flow (predicted by DRAINMOD) and predicted load for the previous day (Fernandez et al., 2003). The model under-predicted NO_3-N load at the outlet of S4 substantially in some years and over-predicted it in others. Overall, the agreement shown in Figure 2 would be considered excellent for multiple years on a watershed scale. However, the need for field data, to develop the regression relationship for field scale loads, significantly reduces the utility of the model. DRAINMOD-N (Breve,1997a) does not describe the complete nitrogen cycle and has not been tested for the organic and high organic mineral soils of S4. DRAINMOD-NII (Youssef, 2003) should be capable of describing the nitrogen dynamics in these soils and is currently being tested on the site. This model will give us an independent method of predicting NO_3-N loads at the field outlets, increasing the applicability of the watershed models for evaluating effects of land uses and management practices on N loads.

EXAMPLE APPLICATION

An example product of the lumped parameter models described above is given in Figure 3 for the 8100 ha watershed draining to station C7 in figure 1. The C7 watershed includes the sub-watershed S4 as well as agricultural and forested lands to the South and North of S4. The DRAINMOD-GIS model was used to obtain results in Figure 3, which represent 30-year average values for delivery ratios for total N at the outlet of watershed C7. Simulations were initiated by running DRAINMOD for each field for a 30-year period of weather data. Nutrient concentrations at the field edge were based on five years of observed data for the various soils and land uses. DRAINMOD-GIS routs the flows through the drainage canal/stream network and calculates travel times. Loss of nitrogen along the flow path was determined by the lumped parameter exponential decay function (Eq.1). Application of the model in this way results in prediction of flow rates and loads on a day-by-day basis. Results can be summed to provide monthly, seasonal, or annual predictions. The average annual delivery ratio for each field is indicated by shading in Figure 3. The delivery ratio (DR) is defined for a given field as the ratio of the load of a constituent arriving at the watershed outlet from that field to the load entering the canal at the field edge. The DR concept is useful for both simple and complex models. It varies from 0 to 1 and is an expression of the in-stream attenuation of the constituent considered (in this case total N). Because the DR at any given time depends on flow rates and residence or travel times in the canals, it varies temporally as well as spatially. The values in Figure 3 are averages over a 30-year period. Results from each year can be used to conduct probability analyses for loads from individual field or from the watershed. The DR values plotted in Figure 3 demonstrate the value of the models being developed. Such plots can be used to target the application of management practices or changes in land use. For example, these results show that the application of practices to reduce total N losses near the mouth of the watershed, where the delivery ratios are 0.9 to 1.0, would be about twice as effective as application of the same practices on similar fields near the head of the watershed where the DR values are 0.4 to 0.5.

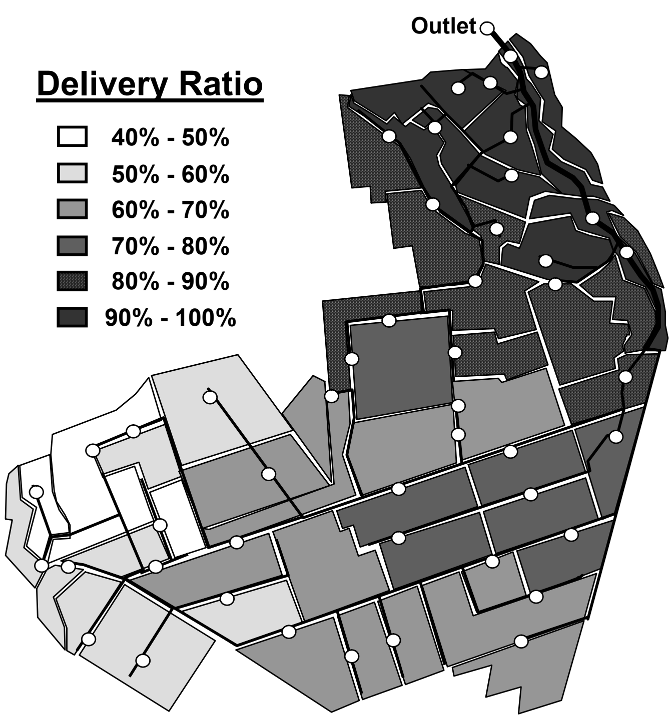

Figure 3. Average delivery ratios for total N based on 30-yr DRAINMOD-GIS simulations for watershed C7.

CONCLUSION

A suite of DRAINMOD-based models was developed to predict effects of management practices and land uses on nitrogen load at the watershed scale. The models, which use a lumped parameter approach to consider in-stream losses, can be used to target the application of management practices for maximum effect in reducing nitrogen loads from the watershed. These model will be valuable tools for development and implementation of TMDLs for watersheds that include poorly drained lands.

Acknowledgements:

The work reported in this paper was supported in part by grants from the USDA-NRI projects 98-35102-6493 and 99-35102-8571, by the U.S. EPA 319 Program, by the N.C. Water Resources Research Institute and by Weyerhaeuser Company. The contributions of Wilson Huntley, Charles Frick and Joe Bergman are gratefully acknowledged.

References

1. Aalderink, R.H., NJ Klaver, and R. Noorman. 1995. DUFLOW V2.0 Microcomputer package for the simulation of 1-D flow and water quality in a network of open channels", In Proc. Inter. Symp. On Water Quality Modeling, Orlando, FL, 416-425.
2. Amatya, D.M., G.M Chescheir, G.P Fernandez, RW Skaggs, and J.W. Gilliam.2003. Methods for estimating nitrogen transport in poorly drained watersheds, Trans ASAE, in review.
3. Amatya, D.M., G.M. Chescheir, G.P. Fernandez, R.W. Skaggs, and J.W. Gilliam. 2001. An Export Coefficient Based Water Quality Model Linked with @RISK Tool. In ASAE Paper 01-2213: 31-34, ASAE, St. Joseph,MI.
4. Amatya, D.M., Chescheir, G.M., Fernandez, G.P., Skaggs, R.W. 1999. Testing of a watershed scale hydrologic/water quality model for poorly drained soils. In K.W. King, ed., Proceedings of the Mini-Conference, Advances in Water Quality Modeling:33-39, St. Joseph, MI, ASAE
5. Amatya, D.M., R.W. Skaggs and J.D. Gregory. 1997. Evaluation of a Watershed Scale Forest Hydrologic Model. Journal of Agricultural Water Management, 32(1997):239-258.
6. Ambrose, R.B., T.A. Woll, J.L. Martin. 1991. WASP5.x, a hydrodynamic and water quality model: Model theory, user's manual and programmers' guide. *U.S. Environmental Protection Agency (EPA)*, Athens, GA.
7. Birgand. F. 2000. Quantification and Modeling of In-stream Processes in Agricultural Canals of the Lower Coastal Plains. Ph.D. Dissertation, Biological & Agricultural Engineering Department, North Carolina State University, Raleigh, NC.
8. Breve, M.A., R.W. Skaggs , J.E. Parsons and J.W. Gilliam. 1997a. DRAINMOD-N, a nitrogen model for artifically drained soils. Transactions of the ASAE 40(4):1067-1075.
9. Breve, M.A., R.W. Skaggs, J.W. Gilliam, J.E. Parsons, A.T. Mohammad, G.M. Chescheir, R.O. Evans. 1997b. Field Testing of DRAINMOD-N. Trans. Of the ASAE, 40(4):1077-1085.
10. Buchanan, T. J. 1964. Time of travel of soluble contaminants in streams. J. San. Eng. Div., ASCE:90:SA3, 1- 12
11. Chescheir, G.M., D.M. Amatya, G.P. Fernandez, R.W. Skaggs, and J.W. Gilliam. 1998. Monitoring and modeling the hydrology and water quality of a lower coastal plain watershed. Proc. of the 1998 WEF Conference, Denver, CO, May, 1998, pp:215-222.
12. Evans, R.O., J.W. Gilliam and R.W. Skaggs. 1991. Controlled drainage management guidelines for improving water quality. Publication no. AG-443. NC Coop. Ext. Ser. 16pp.
13. Fernandez, G.P., R.W.Skaggs , G.M. Chescheir, and D.M. Amatya. 2001. WATMOD: An integrated watershed scale hydrology and water quality model. ASAE P. 012082, St. Joe, MI.
14. Fernandez, G.P., R.W. Skaggs, G.M. Chescheir and D.M. Amatya. 2002. WATGIS: A GIS-Based Lumped Parameter Water Quality Model, *Transactions of ASAE.* Vol 45(3):593-600.

15. Fernandez, G.P., R.W.Skaggs , G.M. Chescheir, and D.M. Amatya. 2003a. Models for predicting hydrology and nitrogen losses from poorly drained watersheds. Trans ASAE, in review.

16. Fernandez, G.P., G.M. Chescheir, R.W. Skaggs and D.M. Amatya. 2003b. Applications of a DRAINMOD-based model to a lower coastal plains watershed. Presented at 2003 Internatioal Meeting, Las Vegas, NV, ASAE Paper No. 032167, St. Joseph, MI.

17. Gilliam, J. W., J. L. Baker and K. R. Reddy. 1999. Water Quality Effects of Drainage in Humid Regions. pp. 801-830. In R.W. Skaggs and J. Van Schilfgaarde (eds.) Agricultural Drainage. Agronomy Monograph No. 38. American Society of Agronomy. Madison, WI.

18. Gilliam, J.W., D.L. Osmond, and R.O. Evans. 1997. Selected Agricultural Best Management Practices to Control Nitrogen in the Neuse River Basin. North Carolina Agricultural Research Service Technical Bulletin 311, North Carolina State University, Raleigh, NC, 53 p.

19. Gilliam, J.W., R.W. Skaggs and S.B. Weed. 1979. Drainage control to diminish nitrate loss from agricultural fields. J. Environmental Quality 8:137-142.

20. Konyha, K.D. and R.W. Skaggs. (1992). A Coupled, field hydrology - open channel flow model: Theory. Trans. ASAE, 35(5): 1431-1440.

21. Northcott, W.J., R.A. Cooke, S.E. Walker, J.K. Mitchell, and M.C. Hirschi. 2001. Appl. of DRAINMOD-N to fields with irregular drainage patterns. Trans.ASAE, 44(2): 241-249.

22. Olivera, , F. and D. Maidment . 1999. GIS based spatially distributed model for runoff routing. Water Resources Research, 35:1155-1164.

23. Palisade Corporation. 1997. @RISK: Risk Analysis and Simulation Add-In for Microsoft Excel or Lotus 1-2-3, Windows Version. 31 Decker Road, Newfield, NY 14867.

24. Pavelis, G.A. 1987. Economic Survey of Farm Drainage. In G.A. Pavelis (ed.) Farm Drainage in the U.S.: History, Status and Prospects. USDA ERS, Misc. Publ. No.1455:110-136.

25. Rabalais, N.N., R.E. Turner, D Justic, Q. Dortch, J.W. Wiseman, Jr. and B.K. Sen Gupta. 1996. Nutrient changes in the Mississippi River.. Estuaries, Vol. 19(2B):385-407.

26. Randall, G.W. 1998. Implications of dry and wet cycles on nitrate loss to subsurface tile drainage. In: Drainage in the 21st Century: Food Production and the Environment Proc. Of the 7th Inter. Drainage Symposium, Mar 8-10, Orlando FL, ASAE, St. Joseph, MI 53-60.

27. Randall, G.W., G.L. Malzer and B.W. Anderson. 1992. Nitrate losses to tile drainage as affected by nitrogen fertilization of corn in a corn-soybean rotation. Agron. Abstracts, pg. 30.

28. Skaggs, R.W. 1999. Drainage Simulation Models. In: R.W. Skaggs and J.van Schilfgaarde (eds), Agr. Mono. 38, Agricultural Drainage, pp 469-536, Am. Soc.of Agr. Madison, WI.

29. Skaggs, R.W., M.A. Breve, and J.W. Gilliam. 1995. Predicting Effects of Water Table Management on Loss of Nitrogen from Poorly Drained Soils. Euro. J. Agr.: 4(94):1-11.

30. Amatya, D.M., G.M. Chescheir, G.P. Fernandez, R.W. Skaggs, and J.W. Gilliam. 2001. An Export Coefficient Based Water Quality Model Linked with @RISK Tool. In: ASAE Paper No. 01-2213, pp: 39-44.

31. Youssef, M.A. 2003. Modeling nitrogen transport and transformations in high water table soils. PhD Dissertation, N.C. State University, Raleigh, NC. 270p.

32. Zheng, C. and G.D. Bennett. 2002. Applied Contaminant Transport Modeling. Wiley Interscience. New York, NY.