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MODELING NITROGEN TRANSPORT IN THE IPSWICH RIVER BASIN, MASSACHUSETTS, USING A HYDROLOGICAL SIMULATION PROGRAM IN FORTRAN (HSPF)[1]

Solange Filoso, Joseph Vallino, Charles Hopkinson, Edward Rastetter, and Luc Claessens[2]

ABSTRACT: Increased riverine nitrogen (N) fluxes have been strongly correlated with land use changes and are now one of the largest pollution problems in the coastal region of the United States. In the present study, the Hydrological Simulation Program-FORTRAN (HSPF) is used to simulate transport of N in the Ipswich River basin in Massachusetts and to evaluate the effect of future land use scenarios on the water quality of the river. Model results show that under a land use change scenario constructed with restrictions from environmental protection laws, where 44 percent of the forest in the basin was converted to urban land, stream nitrate concentrations increased by about 30 percent of the present values. When an extreme land use scenario was used, and 100 percent of the forest was converted to urban land, concentrations doubled in comparison to present values. Model simulations also showed that present stream nitrate concentrations might be four times greater than they were prior to urbanization. While pervious lands with high density residential land use generated runoff with the highest N concentrations in HSPF simulations, the results suggested that denitrification in the riparian zone and wetlands coupled with the hydrology of the basin are likely to control the magnitude of nitrate loads to the aquatic system. The simulation results showed that HSPF can predict the general patterns of inorganic N concentrations in the Ipswich River and tributaries. Nevertheless, HSPF has some difficulty simulating the extreme variability of the observed data throughout the main stem and tributaries, probably because of limitations in the representation of wetlands and riparian zones in the model, where N processes such as denitrification seem to play a major role in controlling the transport of N from the terrestrial system to the river reaches.
(KEY TERMS: nitrogen transport; land use change; watershed management; water quality; hydrochemical model; HSPF.)

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INTRODUCTION

Worldwide, increasing fluxes of nitrogen (N) in streams and rivers have been associated with rising human population densities, land use changes, and agricultural practices in watersheds (Cole *et al.,* 1993; Howarth *et al.,* 1996; Galloway, 1998). Depending on the physical and biotic characteristics of the watershed, and on the climatological conditions, large amounts of biologically available N can be transported in rivers and into lakes, estuaries, or coastal waters causing ecological impacts such as eutrophication, decreases in species diversity, and changes in community structure (Turner and Rabalais, 1991; Vitousek *et al.,* 1997; Howarth *et al.,* 2000).

Because of the complexity of factors involved in water quality problems, especially related to N biogeochemistry, watershed simulation models have been widely used as an effective tool to determine the key hydrological and biogeochemical processes controlling sediment and nutrient transport in rivers so that alternative land use or management scenarios can be evaluated. Conceptually, such models describe water and associated sediment and nutrient fluxes from the land surface and soil profile to rivers and then down the river drainage network (Krisanova *et al.,* 1999).

One of the most difficult challenges regarding the simulation of N flow in watersheds is the uncertainty with respect to processes that govern the N cycle in terrestrial and aquatic systems, such as fixation, mineralization, nitrification, denitrification and uptake by primary producers. According to watershed scale

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[2]Respectively, Postdoctoral Scientist, Assistant Scientist, Senior Scientist, and Associate Scientist, Marine Biological Laboratory, Marine Biological Laboratory, 7 MBL Street, Woods Hole, Massachusetts 02543 (current address/Filoso: Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, New York 14853); and Doctoral Candidate, Department of Geography, University of California-Santa Barbara, Ellison Hall 3611, Santa Barbara, California 93106-4060 (E-Mail/Filoso: sfw6@cornell.edu).

mass balance studies in the eastern U.S., riverine N export accounts for only 20 to 30 percent of the total inputs to terrestrial systems, while the remaining 70 to 80 percent is not well quantified (Boyer *et al.,* 2002). These uncertainties are aggravated by continuous land use changes that lead to modification of hydrological and nutrient flowpaths as well as N storages in the ecosystems. Field data and observations are essential to improving the efficiency, accuracy, and prognostic capability of hydrochemical models (Vallino, 2000), which in turn can help to determine and quantify key processes governing the N cycle in watersheds.

In this paper, a comprehensive watershed scale water quality simulation model, the Hydrological Simulation Program-FORTRAN (HSPF), is used to simulate the processing and transport of N in the Ipswich River watershed in northeastern Massachusetts. This watershed is representative of many coastal regions of the temperate zone where increasing urbanization is altering the ecosystem. Nitrogen processing parameters are calibrated by comparing model output to observations in both first-order headwater streams and along the main stem of the Ipswich River. Once calibrated, the effects of predicted future land use changes scenarios on N concentrations in the Ipswich River and, ultimately, the flux to Plum Island Sound are evaluated. The specific objectives are to determine the extent to which the conversion of forest to urban land alters riverine N fluxes and quantify changes given different levels of deforestation.

The HSPF model was selected because it is well documented, adequately represents complex urbanized river basins, and the modeling framework is amendable to evaluating land use changes. Moreover, it has been applied recently by the U.S. Geological Survey (USGS) to model the hydrology of the Ipswich River basin (Zariello and Ries, 2000) and to help in the development of watershed management programs in the state of Massachusetts.

METHODS

Study Area

The 404 km^2 Ipswich River watershed in the Boston Metropolitan area is located 50 km north of the City of Boston (Figure 1). The human population is approximately 130,000 with most people located in the southern portion of the watershed. Land use in the basin has changed considerably over the past several hundred years, and since 1960 conversion of forest to residential plots has become the dominant land use change. In 1991, the basin was about 32 percent urban/suburban, 6 percent agriculture, 19 percent water and wetland, and 43 percent forest (MassGIS). Although almost a quarter of the Ipswich watershed has been set aside for land conservation, projections of urbanization suggest that by 2101 less than 40 percent of unprotected forest will remain (Pontius and Schneider, 2001).

The average discharge of the Ipswich River is about 656x10^3 m^3/day of which about 175x10^3 m^3/day are used seasonally as public water supplies. These supplies provide water to 330,000 people, of which about 220,000 reside outside of the basin. Consequently, only about 10 to 20 percent of the water withdrawn from the basin returns to it as wastewater.

Water Quality Observations

Data on nitrate and ammonium concentrations in the main stem and tributaries of the Ipswich River were obtained from monthly samples collected between 1999 and 2001 (Williams *et al.,* 2004a). During this period, annual average concentrations of nitrate and ammonium along the main stem and at the confluences of major tributaries ranged from 5 to 25 micromolar (µM), and 1 to 4 µM, respectively (Figures 2a and 2b). Nitrate concentrations were highest in upstream tributaries and in the middle of the main stem (Figure 2a), whereas ammonium concentrations increased markedly from the upper reaches until about kilometer 43, decreasing gradually thereafter (Figure 2b). During the same period, nitrate concentrations in 43 first-order streams sampled by Williams *et al.* (2004b) ranged from undetectable levels to about 120 µM (Figure 3). Nitrate concentrations in first-order streams increased significantly ($p < 0.01$) with the increasing percentage of urban plus agricultural land in their subcatchments (Figure 3).

Model Description

HSPF is a comprehensive model that simulates hydrologic and biogeochemical processes in watersheds with pervious and impervious land surfaces, and in streams and well mixed impoundments (Bicknell *et al.,* 1997). The model can simulate urban and agricultural land use, surface and subsurface processes, runoff, sediment export, and the fate and transport of nutrients, pesticides, and other water quality constituents. The model is commonly used to assess the effects of land use changes, flow diversions, and point or nonpoint source treatment alternatives on

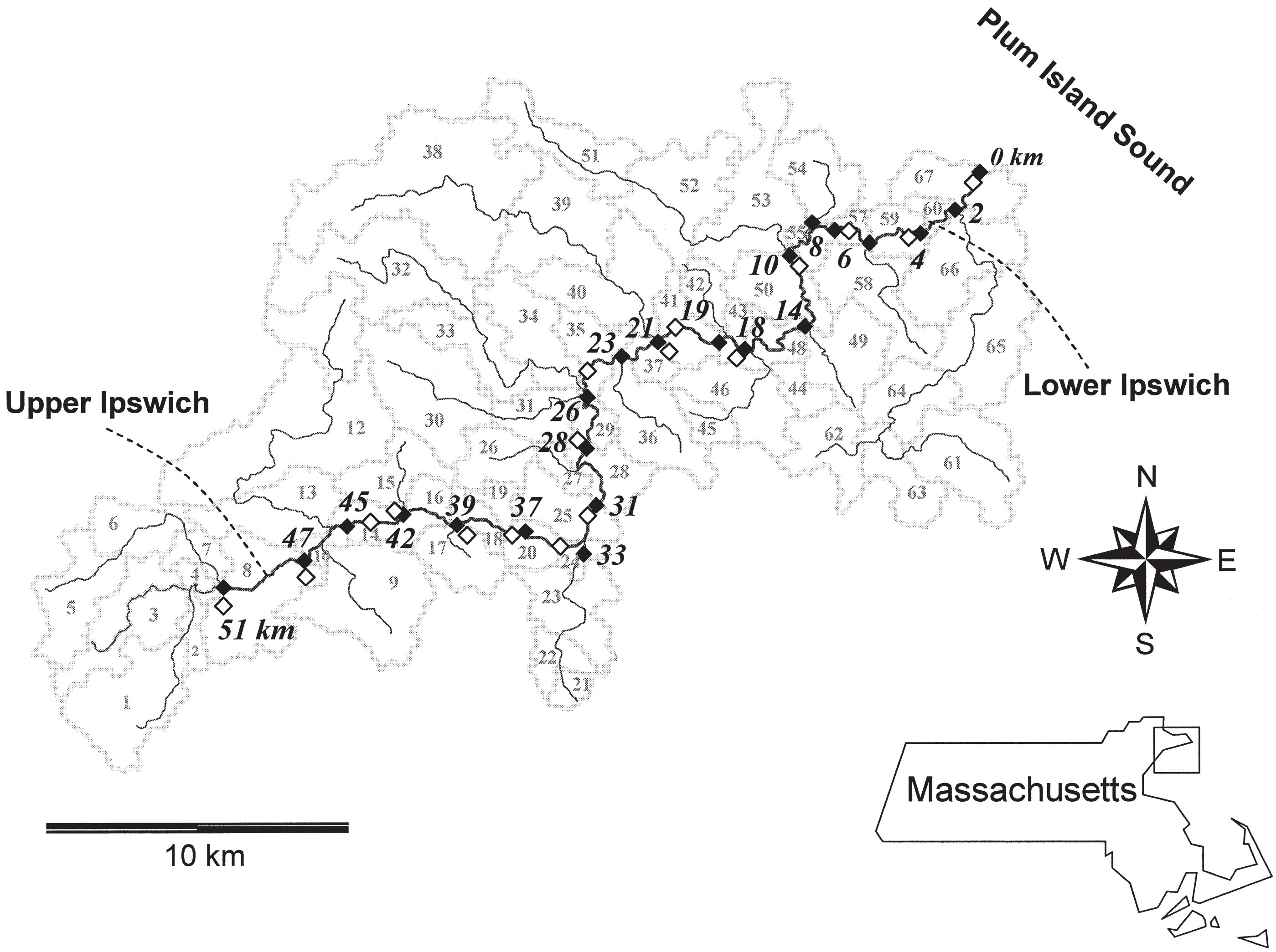


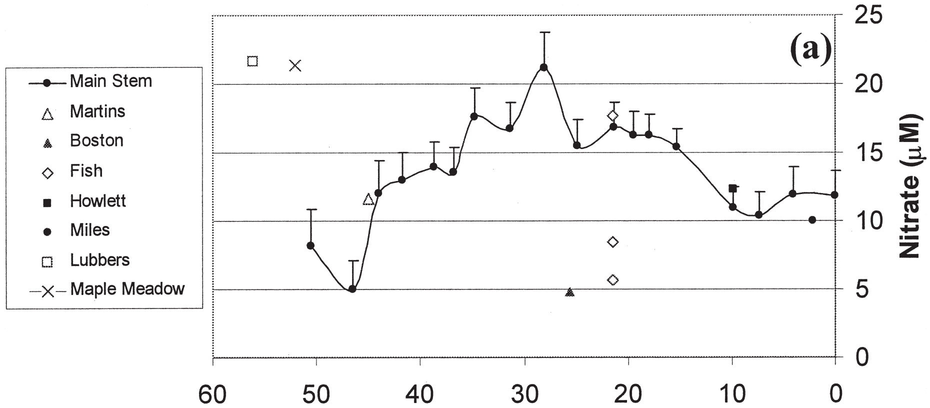
Figure 1. Map of the Ipswich River Basin, Northeastern Massachusetts, Divided Into 67 Subbasins or Hydrological Response Units (HRUs). The sampling sites where actual samples were collected and the nodes for which simulated data were generated are designated with solid (◆) and open (◊) diamonds, respectively. The sampling sites and simulation nodes were distributed along the main channel from the mouth (0 km) to the upper most reach (51 km). Numbers in italics indicate site distances (in kilometers) from the mouth of the river.

the hydrology and water quality of watersheds. The strength of the model lies in its ability to continuously simulate the comprehensive range of hydrological and associated water quality processes in watersheds with complex land use (Zarriello and Ries, 2000).

Structurally, HSPF is divided into three blocks that simulate processes occurring in: (1) pervious land; (2) impervious land; and (3) streams, lakes, and reservoirs. For N, there is a module that simulates the behavior of nitrate, ammonium and organic N in four soil layers of the pervious land, and another module that simulates N in its various forms in the stream reaches.

Transformations of N in pervious lands include plant uptake of inorganic forms, fixation, return to soil from plant tissues, immobilization, mineralization, nitrification, denitrification, adsorption/desorption of ammonium, and partitioning of organic N into dissolved and particulate forms, either as labile or refractory species (Figure 4). The N transformations are simulated individually in each of the four soil layers. Nitrogen that collects on impervious lands is advected to the aquatic system without any transformation.

After nitrogen is transformed in the soil layers of pervious land or advected from impervious land, it is transported to the aquatic system, where it undergoes further processing and transport in stream reaches. Several different routines are used to simulate inorganic N in the reaches. These include advection of



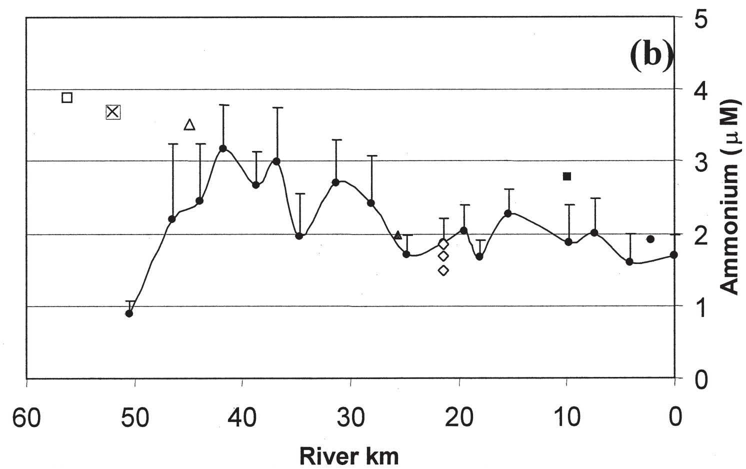


Figure 2. Average Monthly Nitrate and Ammonium Concentrations of Water Samples Collected Along the Ipswich River and Tributaries Between March 1999 and December 2000.

nitrate, nitrite, and ammonium, release of inorganic species from the benthos to the overlying waters, nitrification and denitrification processes, adsorption and desorption of ammonium, ionization and volatilization of ammonia, and mineralization (Figure 5). Additional sinks and sources of N are simulated for plankton and benthic populations and associated reactions. In all three modules, biochemical reactions are modeled with either first-order or Michaelis-Menten kinetics.

Model Implementation

The HSPF version 12 beta was used for all simulations. The subdivision of the watershed into subcatchments by HSPF is based on a Digital Elevation Model of the area with a certain threshold, followed by the segmentation of the land surface (Figure 6). Segmentation into pervious (PERLNDs) and impervious (IMPLNDs) lands in HSPF is based on topographical features, land use and land cover, soil type, surficial geology, or any other factor considered important to the hydrology of the watershed. For the Ipswich River watershed, Zariello and Ries (2000) defined land segments, or hydrological response units (HRUs) on the basis of land use characteristics, surface geology, and residential development densities.

The land use categories considered important in the watershed were: forest, open land, low density residential, high density residential, and commercial. These land use types were further classified according to soil permeability and storage characteristics – sand and gravel, till and bedrock, and alluvial deposits. Residential land cover types were further divided into areas on public water supply and on-site septic systems. Impervious land was divided into residential and commercial segments. Overall, 15 classes of pervious land and two of impervious land were created (Table 1).

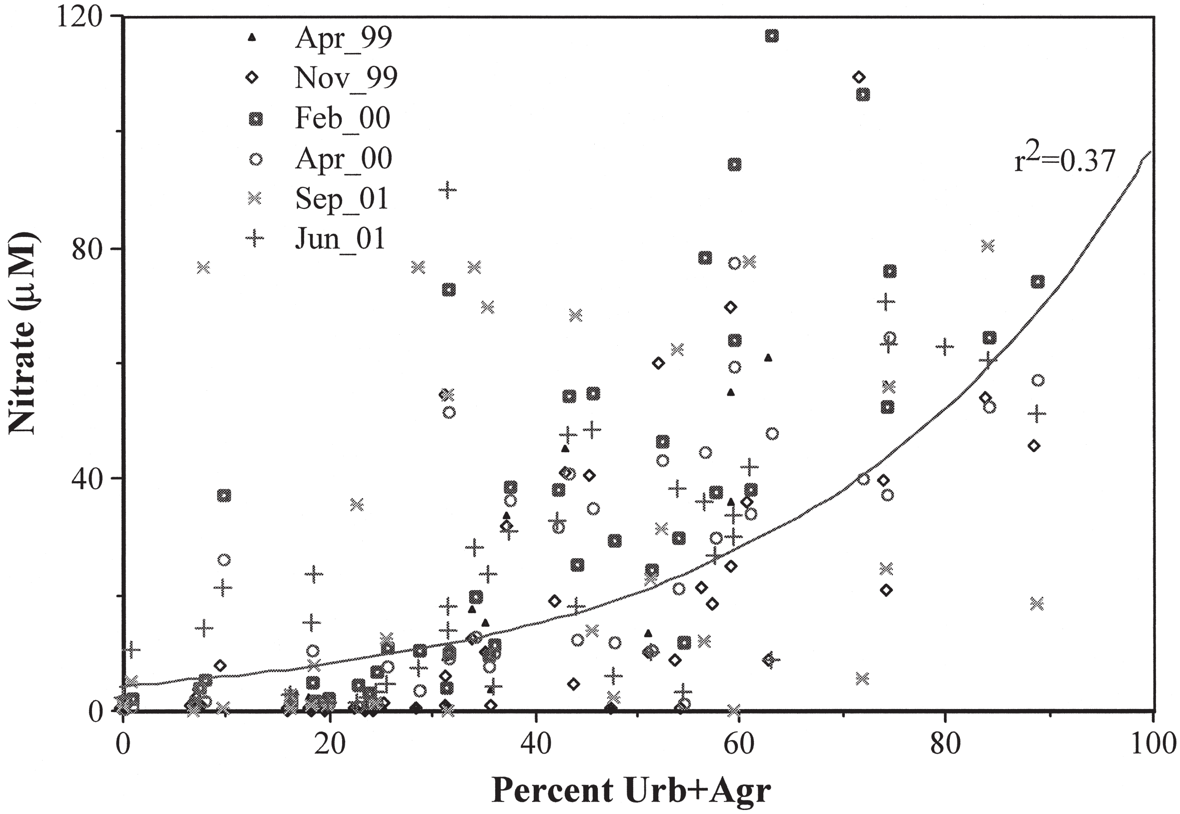


Figure 3. Percentage of Combined Urban Land Plus Agricultural Land Use Versus Nitrate Concentrations in the Catchments of 43 Headwater Streams Throughout the Ipswich River Basin (from Williams *et al.,* 2004b).

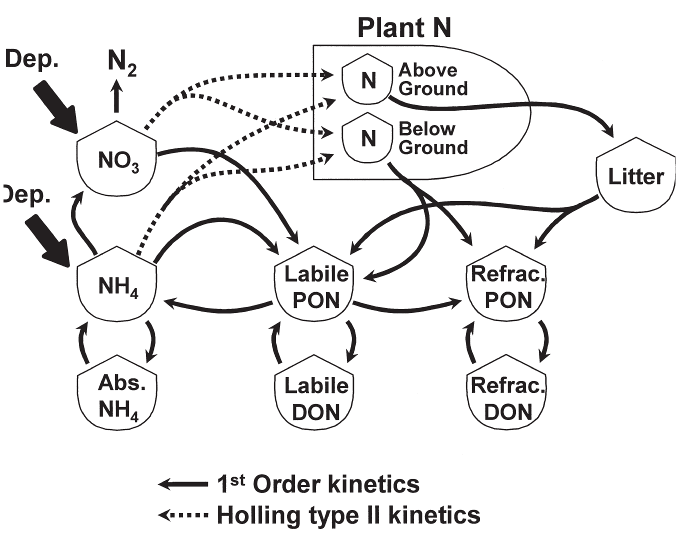


Figure 4. Schematic Representation of Nitrogen Processes Modeled by HSPF in Pervious Lands (PERLND). The processes are modeled for each individual soil layer.

The Ipswich River watershed was segmented into 67 subcatchments, each with one reach (Figure 1), according to hydrology, water use, and habitats (Zariello and Ries, 2000). Additional "virtual" reaches were added to most subcatchments during the hydrology calibration process by USGS to account for water storage in the wetlands of the watershed. All the pervious and impervious land HRUs in the catchment were assumed to drain into virtual wetland reaches before draining into the channel reaches (RCHRES). Several nodes were selected along the main channel to correspond to water quality sampling sites so that simulated results could be compared to observed data (Figure 1).

The model was run for a two-year period (March 1999 to December 2000) in hourly time steps with meteorological data on precipitation, air temperature, dew point temperature, solar radiation, and wind speed. These input data were obtained from the National Climatic Data Center (NCDC) and spanned from January 1961 to December 2000.

Other input data for the model include atmospheric deposition loads, septic system loads, and fertilizer application rates (Table 2). It was assumed that all of these N sources were introduced to the watershed through the surface and upper layers of the soil, and on the water surface. Atmospheric deposition data included monthly wet deposition obtained from field measurements conducted during the model simulation period, and dry deposition assumed to be equivalent to wet deposition. Human waste or septic system loads were calculated on the basis of the average number of households per area in high density and low density residential land use types of the Ipswich basin (Zariello and Ries, 2000). It was assumed that each household produced an annual load of 15 kg N, or 5 kg/yr per capita (Howarth *et al.,* 1996), and that 40 percent of this load is lost in septic systems of conventional design (Valiela *et al.,* 1997). The total septic system load was adjusted to exclude the waste treated in sewage plants.

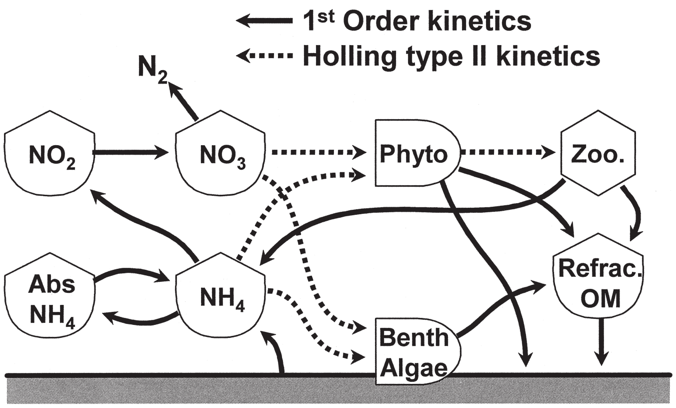


Figure 5. Schematic Representation of Nitrogen Processes Modeled by HSPF in Streams (RCHRES) and "Virtual Reaches."

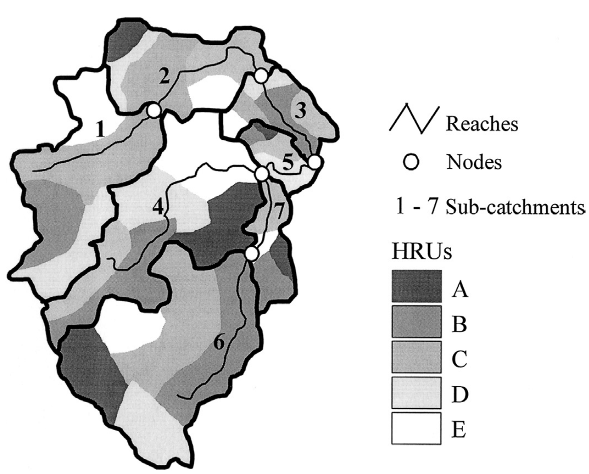


Figure 6. Representation of a Watershed Divided Into Seven Subcatchments in HSPF. Each subcatchment is composed of several Hydrological Response Units (HRUs).

Application of fertilizer was restricted to residential areas because agricultural land in the basin is negligible and mainly pasture. A low intensity application rate was also assumed: 14 kg N/ha/yr in 34 percent of the households (Valiela *et al.,* 1997; Williams *et al.,* 2004a). Fertilizer application occurs during the May to August growing season.

TABLE 1. Hydrologic Response Units (HRUs) Used to Represent the Ipswich River Basin (adapted from Zariello and Ries (2000).

HRU	Surficial Geology	Land Use
PERLND 1	Sand and Gravel	Forest
PERLND 2	Sand and Gravel	Open
PERLND 3	Sand and Gravel	Low Density Residential*
PERLND 4	Sand and Gravel	Low Density Residential*
PERLND 5	Sand and Gravel	High Density Residential
PERLND 6	Sand and Gravel	High Density Residential*
PERLND 7	Sand and Gravel	Commercial
PERLND 8	Till	Forest
PERLND 9	Till	Open
PERLND 10	Till	Low Density Residential*
PERLND 11	Till	Low Density Residential*
PERLND 12	Till	High Density Residential
PERLND 13	Till	High Density Residential*
PERLND 14	Alluvial	Forest
PERLND 15	Alluvial	Open
IMPLND 1		Impervious residential
IMPLND 2		Impervious commercial

*Represent areas with on-site septic systems.

While surface and ground water withdrawals can affect tributary and mainstem flow in the summer (Zariello and Ries, 2000), these flows were not modeled because of lack of available data for the simulation period of the present study and because water withdrawals are now restricted during the low water periods.

Land Use Change Scenarios

To model changes in N inputs to the watershed caused by the conversions of forest or agricultural land to urban or commercial area requires precise information on the location of such modifications. The spatial and temporal pattern of deforestation and urbanization was based on scenarios constructed by Pontius and Schneider (2001), where they compared land use changes restricted or unrestricted by environmental protection laws. The laws included the Wetlands Protection Act, Rivers Protection Act, floodways, wellhead protection buffers, zoning, and minimum lot size. The likelihood that any particular forest or open area would be converted into residential and/or commercial land was based on factors such as proximity to roads, rivers, and existing residential areas.

TABLE 2. Balance of Actual Nitrogen Inputs and HSPF Simulated Outputs for Each Type of PERLND of the Ipswich River Basin.

HRU	Inputs (kg/ha/yr)				Outputs	Retention
	Atmospheric Deposition	Septic System	Fertilizer	∑ Inputs	(kg/ha/yr	(percent)
PERLND 1	8.6	0	0	8.6	0.01	100
PERLND 2	8.6	0	0	8.6	1.60	81
PERLND 3	8.6	29	14	51.6	4.20	92
PERLND 4	8.6	29	14	51.6	6.20	88
PERLND 5	8.6	0	14	22.6	1.60	93
PERLND 6	8.6	63	14	85.6	13.3	72
PERLND 7	8.6	0	0	8.6	6.20	30
PERLND 8	8.6	0	0	8.6	0.14	98
PERLND 9	8.6	0	0	8.6	3.00	70
PERLND 10	8.6	29	14	51.6	4.40	91
PERLND 11	8.6	29	14	51.6	5.20	90
PERLND 12	8.6	0	14	22.6	2.10	91
PERLND 13	8.6	63	14	85.6	11.4	74
PERLND 14	8.6	0	0	8.6	0.06	99
PERLND 15	8.6	0	0	8.6	1.30	85

The first future scenario simulated is based on Pontius and Schneider (2001), where they predicted that 44 percent of the nonalluvial forest is converted to urban land between 1991 and 2101. The implementation of this scenario for each of the 67 subcatchments was achieved by reducing the area of nonalluvial forests and open land HRUs (PERLNDs 1, 2, 8, and 9) (Table 1) in the present land use scenario to 56 percent of their current size. The area subtracted was then added to the subcatchments as urban residential and commercial land based on the fraction that each particular urban HRU occupied in the subcatchment. For instance, if a Sand and Gravel high density residential HRU (e.g., PERLND 5) occupied 10 percent of a subcatchment, then 10 percent of the area deforested in the subcatchment would become PERLND 5. In another example, if a Till low density residential HRU (PERLND 10) occupied 15 percent of the subcatchment, then 15 percent of the area deforested would become PERLND 10, and so forth.

In the second land use change scenario, an extreme situation was used, where no legal constraints were applied, and the forest and open areas with nonalluvial surficial geology were completely converted into residential and commercial lands. Again, the forest areas removed were added to the subcatchments as urban residential and commercial PERLNDs and IMPRLNDs, as described above.

A scenario where all of the urban, commercial, and open lands were replaced by forest was also evaluated. In this scenario, all of the area of nonforest land was converted to forest area, according to the respective surface geology. This scenario represents a pristine watershed prior to colonial settlement.

Model Calibration

The model was calibrated for N processing and transport in the Ipswich River by comparing model results with observed data of N concentrations in streams. Calibration focused on N dynamics since the hydrology component was previously calibrated by the USGS (Zariello and Ries, 2000). Although the simulations did not include water withdrawals from ground water (Zariello and Ries, 2000), the simulated hydrology for the period beyond the USGS calibration period agreed well with observations because water withdrawals in the Ipswich basin have been restricted (Figure 7).

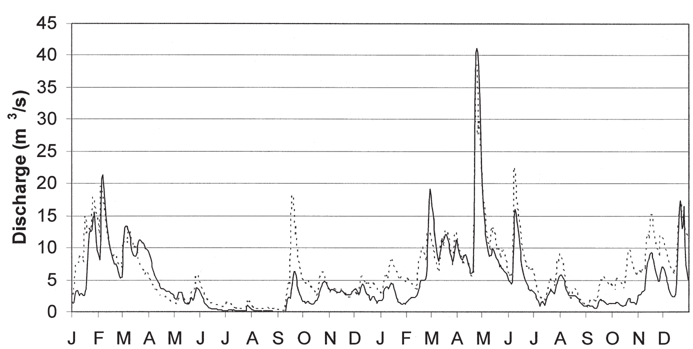


Figure 7. Observed (solid line) and Simulated Hydrographs (dashed line) of the Ipswich River for the Study Period, at the Downriver USGS Gauging Station (i.e., Ipswich).

The calibration process involved adjustments of parameter values for N transformations in the pervious land module for each land cover type. Parameters governing PERLNDs were first adjusted within acceptable ranges based on literature data if available and on a database containing parameter values from HSPF tests in different regions of the U.S. (HSPF-Parm; Table 3), and then calibrated by comparing nitrate and ammonium loads generated by HSPF for the PERLNDs to first-order stream data.

TABLE 3. Important Nitrogen Parameters in the Calibration of HSPF for the Ipswich River Basin.

Description	Parameter	Description	Unit	Variable	Initial Value	Calibrated Value	Module
			NIT-FSTPM Table				
N first-order reaction rate parameters for soil layers surface, upper, lower, ground water)	KDSAM	Reaction rate for ammonium desorption	per day	Forest	0, 0, 0, 0	0, 0, 0, 0	PERLND
				Open	0, 0, 0, 0	0, 0, 0, 0	
				Low residential	0, 0, 0, 0	0, 0, 0, 0	
				High residential	0, 0, 0, 0	0, 0, 0, 0	
	KADAM	Reaction rate for ammonium adsorption		Forest	0, 0, 0, 0	1 to 2, 1, 0.5, 0.5	
				Open	0, 0, 0, 0	1, 1, 0.5, 0.5	
				Low residential	0, 0, 0, 0	1, 1, 0.5, 0.5	
				High residential	0, 0, 0, 0	1, 1, 0.5, 0.5	
	KIMNI	Reaction rate for nitrate immobilization		Forest	0, 0, 0, 0	0.5, 3.3, 1.2, 0	
				Open	0, 0, 0, 0	0.5, 0.1, 0.0, 0	
				Low residential	0, 0, 0, 0	0.5, 0.1, 0.0, 0	
				High residential	0, 0, 0, 0	0.5, 0.1, 0.0, 0	
	KAM	Reaction rate for organic N ammonification		Forest	2e-3, 2e-4, 1e-4, 1e-4	1e-5, 1e-4, 1e-4, 1e-3	
				Open	0, 0, 0, 0	0, 0, 0, 0	
				Low residential	0, 0, 0, 0	0, 0, 0, 0	
				High residential	0, 0, 0, 0	0, 0, 0, 0	
	KDNI	Reaction rate for denitrification of nitrate		Forest	0, 0, 0, 0.03	0, 0, 0, 0.04	
				Open	0, 0, 0, 0.02	0, 0, 0, 0.01	
				Low residential	0, 0, 0, 0.02	0, 0, 0, 0.03	
				High residential	0, 0, 0, 0.02	0, 0, 0, 0.1	
	KNI	Reaction rate for nitrification		Forest	10, 10, 3, 0.5	2, 1, 1, 0.5	
				Open	10, 5, 3, 0.5	2, 1, 1, 0.5	
				Low residential	10, 5, 3, 0.5	5, 5, 3, 0.5	
				High residential	10, 5, 3, 0.5	5, 3, 2, 0.5	
	KIMAM	Reaction rate for ammonium immobilization		Forest	5, 2, 0.2, 0	2, 2, 0.5, 0	
				Open	5, 2, 0.2, 0	2, 2, 0.2 to 0.5, 0	
				Low residential	5, 2, 0.2, 0	0.1, 0.1, 0, 0	
				High residential	5, 2, 0.2, 0	0.1, 0.1, 0, 0	
			NIT-ORGPM Table				
Organic N transformation parameters for soil layers (surface, upper lower, ground water)	KLON	Particulate/ soluble partitioning coefficient for labile organic N	per day	Forest	9000 (all soil layers)	8500 (all soil layers)	PERLND
				Open	9000 (all soil layers)	8500 (all soil layers)	
				Low residential	9000 (all soil layers)	8500 (all soil layers)	
				High residential	9000 (all soil layers)	8500 (all soil layers)	
	KRON	Particulate/		Forest	33000 (all soil layers)	30000 (all soil layers)	
				Open	33000 (all soil layers)	30000 (all soil layers)	
				Low residential	33000 (all soil layers)	30000 (all soil layers)	
				High residential	33000 (all soil layers)	30000 (all soil layers)	
	KONLR	First-order conversion rate of labile to refractory particulate organic N		Forest	1e-4 (all soil layers)	1e-4, 1e-4, 1e-3, 0.01	
				Open	5e-6 (all soil layers)	1e-5, 1e-5, 1e-4, 1e-3	
				Low-residential	5e-6 (all soil layers)	1e-5, 1e-5, 1e-4, 1e-3	
				High-residential	5e-6 (all soil layers)	1e-5, 1e-5, 1e-4, 1e-3	

TABLE 3 (cont'd). Important Nitrogen Parameters in the Calibration of HSPF for the Ipswich River Basin.

Description	Parameter	Description	Unit	Variable	Initial Value	Calibrated Value	Module
				NIT-ORGPM Table (cont'd.)			
	THNLR	Temperature correction coefficient		Forest	1.07 (all soil layers)	1.07 (all soil layers)	PERLND
				Open	1.07 (all soil layers)	1.07 (all soil layers)	
				Low residential	1.07 (all soil layers)	1.07 (all soil layers)	
				High residential	1.07 (all soil layers)	1.07 (all soil layers)	
				MON-NITUPT Table			
Monthly plant uptake parameters for nitrogen (nonforest)			per day	**Surface Layer**			**PERLND**
				Jan, Feb, Mar,	0.02, 0.02, 0.04,	0.00, 0.00, 0.50,	
				Apr, May, Jun,	0.06, 0.06, 0.06,	0.50, 0.50, 0.40,	
				Jul, Aug, Sep,	0.06, 0.06, 0.06,	0.50, 0.50, 0.25,	
				Oct, Nov, Dec	0.06. 0.02, 0.02	0.15. 0.15, 0.00	
				Upper Layer			
				Jan, Feb, Mar,	0.04, 0.04, 0.04,	0.00, 0.00, 0.50,	
				Apr, May, Jun,	0.06, 0.08, 0.08,	0.55, 0.45, 0.45,	
				Jul, Aug, Sep,	0.08, 0.08, 0.08,	0.55, 0.40, 0.25,	
				Oct, Nov, Dec	0.08. 0.06, 0.04	0.10. 0.10, 0.00	
				Lower Layer			
				Jan, Feb, Mar,	0.04, 0.04, 0.04,	0.00, 0.00, 0.00,	
				Apr, May, Jun,	0.06, 0.08, 0.08,	0.05, 0.10, 0.15,	
				Jul, Aug, Sep,	0.08, 0.08, 0.08,	0.15, 0.10, 0.10,	
				Oct, Nov, Dec	0.08. 0.06, 0.04	0.00. 0.00, 0.00	
				NIT-UPIMCSAT Table			
Half saturation kinetic parameter for for Michaelis-Menten type kinetics for soil layers (surface, upper, lower, ground water)	CSUNI	Nitrate half saturation constant for uptake	μg/l	Forest (S&G)	50 (all soil layers)	50, 70, 70, 50	PERLND
				Forest (Till)	50 (all soil layers)	70, 80, 80, 50	
				Forest (Fine Dep.)	50 (all soil layers)	70, 80, 80, 50	
	CSUAM	Ammonia half saturation constant for uptake		Forest (S&G)	5, 10, 20, 10	10, 10, 10, 20	
				Forest (Till)	5, 10, 20, 10	10, 20, 20, 20	
				Forest (Fine Dep.)	5, 10, 20, 10	10, 20, 20, 20	
	CSINI	Nitrate half saturation constant for immobilization		Forest (S&G)	10, 10, 10, 10	5, 5, 5, 10	
				Forest (Till)	10, 10, 10, 10	5, 10, 10, 10	
				Forest (Fine Dep.)	10, 10, 10, 10	5, 10, 10, 10	
	CSIAM	Ammonia half saturation constant for immobilization		Forest (S&G)	2 (all soil layers)	2, 2, 2, 2	
				Forest (Till)	2 (all soil layers)	3, 3, 3, 2	
				Forest (Fine Dep.	2 (all soil layers	3, 3, 3, 2)	
				MON-NITUPNI Table			
Monthly nitrate uptake maximum rates when using saturation kinetics method			mg/l/d	**Surface Layer**			**PERLND**
				Jan, Feb, Mar,	15, 20, 20	40, 30, 80	
				Apr, May, Jun,	30, 35, 45,	80, 80, 70	
				Jul, Aug, Sep,	45, 45, 45,	70, 70, 65	
				Oct, Nov, Dec	40, 35, 30	50, 45, 30	
				Upper Layer			
				Jan, Feb, Mar,	10, 15, 15	40, 30, 80	
				Apr, May, Jun,	20, 25, 30,	80, 80, 70	
				Jul, Aug, Sep,	30, 30, 30,	70, 70, 65	
				Oct, Nov, Dec	30, 25, 20	50, 45, 30	
				Lower Layer			
				Jan, Feb, Mar,	0.6, 0.7, 0.7,	35, 35, 75,	
				Apr, May, Jun,	0.9, 1.0, 1.0,	75, 75, 60,	
				Jul, Aug, Sep,	1.0, 1.0, 1.0,	55, 50, 45,	
				Oct, Nov, Dec	1.0, 1.0, 0.8	40, 30, 25	

TABLE 3 (cont'd). Important Nitrogen Parameters in the Calibration of HSPF for the Ipswich River Basin.

Description	Parameter	Description	Unit	Variable	Initial Value	Calibrated Value	Module
				MON-NITUPAM Table			
Monthly ammonium uptake maximum rates when using saturation kinetics method			mg/l/d	**Surface Layer**			PERLND
				Jan, Feb, Mar,	5, 7.5, 7.5,	5, 5, 15,	
				Apr, May, Jun,	10, 12, 15,	10, 25, 30,	
				Jul, Aug, Sep,	15, 15, 15,	30, 30, 30,	
				Oct, Nov, Dec	15, 12, 10	25, 5, 5	
				Upper Layer			
				Jan, Feb, Mar,	10, 10, 12	5, 5, 25,	
				Apr, May, Jun,	15, 15, 15	26, 26, 26,	
				Jul, Aug, Sep,	15, 25, 25	30, 35, 30,	
				Oct, Nov, Dec	20, 15, 10	20, 5, 4	
				Lower Layer			
				Jan, Feb, Mar,	0.5, 0.5, 0.6,	0.0, 0.0, 0.7,	
				Apr, May, Jun,	0.7, 0.8, 0.8,	0.8, 0.8, 0.8,	
				Jul, Aug, Sep,	0.8, 0.8, 0.8,	0.8, 0.9, 0.9,	
				Oct, Nov, Dec	0.7, 0.6, 0.5	0.8, 0.4, 0.0	
				MON-NITIMNI Table			
Monthly nitrate immobilization rates when using saturation kinetics method			mg/l/d	**Surface Layer**			PERLND
				Jan, Feb, Mar,	0.05, 0.05, 0.05,	0.3, 0.3, 1.5,	
				Apr, May, Jun,	0.10, 0.10, 0.10,	3.0, 3.0, 3.0,	
				Jul, Aug, Sep,	0.15, 0.15, 0.10,	3.0, 3.0, 2.0,	
				Oct, Nov, Dec	0.10, 0.10, 0.05	0.5, 0.2, 0.3	
				Upper Layer			
				Jan, Feb, Mar,	0.05, 0.05, 0.05,	0.3, 0.3, 1.5,	
				Apr, May, Jun,	0.10, 0.10, 0.10,	3.0, 3.0, 3.0,	
				Jul, Aug, Sep,	0.15, 0.15, 0.10	3.0, 3.0, 2.0,	
				Oct, Nov, Dec	0.10, 0.10, 0.05	0.5, 0.2, 0.3	
				Lower Layer			
				Jan, Feb, Mar,	0.02, 0.02, 0.02,	0.00, 0.00, 0.05,	
				Apr, May, Jun,	0.04, 0.04, 0.05,	0.05, 0.05, 0.05,	
				Jul, Aug, Sep,	0.05, 0.05, 0.05,	0.05, 0.05, 0.10,	
				Oct, Nov, Dec	0.04, 0.04, 0.02	0.10, 0.00, 0.00	
				Ground Water			
				Jan, Feb, Mar,	0.05, 0.05, 0.05,	0.00, 0.00, 0.10,	
				Apr, May, Jun,	0.10, 0.10,0.10,	0.10, 0.10, 0.10,	
				Jul, Aug, Sep,	0.15, 0.15, 0.10,	0.10, 0.10, 0.10,	
				Oct, Nov, Dec	0.10, 0.10, 0.05	0.10, 0.00, 0.00	
				MON-NITIMAM Table			
Monthly ammonium immobilization rates when using saturation kinetics method			mg/l/d	**Surface Layer**			PERLND
				Jan, Feb, Mar,	0.10, 0.10, 0.10,	0.0, 0.0, 0.2,	
				Apr, May, Jun,	0.10, 0.10, 0.20,	0.2, 0.3, 0.3,	
				Jul, Aug, Sep,	0.10, 0.10, 0.10,	0.5, 0.5, 0.4,	
				Oct, Nov, Dec	0.10, 0.10, 0.10	0.3, 0.0, 0.0	
				Upper Layer			
				Jan, Feb, Mar,	0.10, 0.10, 0.10,	0.0, 0.0, 0.2,	
				Apr, May, Jun,	0.10, 0.10, 0.10,	0.2, 0.3, 0.3,	
				Jul, Aug, Sep,	0.10, 0.10, 0.10,	0.5, 0.5, 0.4,	
				Oct, Nov, Dec	0.10, 0.10, 0.10	0.3, 0.0, 0.0	
				Lower Layer			
				Jan, Feb, Mar,	0.01, 0.01, 0.01,	0.00, 0.00, 0.02,	
				Apr, May, Jun,	0.01, 0.02, 0.02,	0.02, 0.02, 0.02,	
				Jul, Aug, Sep,	0.02, 0.02, 0.02,	0.02, 0.02, 0.02,	
				Oct, Nov, Dec	0.01, 0.01, 0.01	0.02, 0.00, 0.00	
				Ground Water			
				Jan, Feb, Mar,	0.05, 0.05, 0.05	0.00, 0.00, 0.10,	
				Apr, May, Jun,	0.05, 0.05, 0.05	0.10, 0.10, 0.10,	
				Jul, Aug, Sep,	0.10, 0.10, 0.10	0.10, 0.10, 0.10,	
				Oct, Nov, Dec	0.05, 0.05, 0.05	0.10, 0.00, 0.00	

TABLE 3 (cont'd). Important Nitrogen Parameters in the Calibration of HSPF for the Ipswich River Basin.

Description	Parameter	Description	Unit	Variable	Initial Value	Calibrated Value	Module
				NUT-NITDENIT Table			
Nitrification and denitrification parameters for reaches and virtual reaches	KTAM20	Nitrification rates of ammonia	per hr	**Reaches**	0.006 to 0.6	0.08 to 0.8	REACHES
				Virtual reaches	0.006 to 0.6	0.05 to 0.6	
	KTN0220	Nitrification rates of ammonia and nitrite	per hr	**Reaches**	0.001 to 0.1	0.05 to 0.5	
				Virtual reaches	0.001 to 0.1	0.01 to 0.6	
	TCNIT	Temperature correction coefficients for nitrification	none	**Reaches**	1.03 to 1.07	1.04 to 1.07	
				Virtual reaches	1.03 to 1.07	1.07 to 1.15	
	KNO320	Nitrate denitrification rate at 20 degrees C	per hr	**Reaches**	0.001 to 0.6	0.20 to 0.82	
				Virtual reaches	0.001 to 0.6	0.001 to 0.1	
	TCDEN	Temperature correction coefficients for denitrification	none	**Reaches**	1.02 to 1.04	1.07 to 1.09	
				Virtual reaches	1.02 to 1.04	1.08 to 1.15	
	DENOXT	Dissolved oxygen concentration threshold for denitrification	mg/l	**Reaches**	1.5 to 10	5 to 10	
				Virtual reaches	1.5 to 10	5 to 20	
			mg/l	Reaches			

Note: Initial values were obtained from HSPFparm and calibrated values were obtained by optimization.

For the forested and nonforested land segments, plant uptake of N was simulated by the methods of saturation and first-order kinetics, respectively. Initial conditions of N in the soil layers were adjusted by running the model for a period of 35 years prior to the onset of the present simulation. The soil N concentrations at the end of the 35-year simulation were then used as initial conditions and the 35-year simulation was repeated. This iterative procedure was performed until soil N values were stable over a 35-year period.

Nitrogen processing parameters were first set according to values from HSPFParm that were determined for the Choptank, Patuxent, and Susquehanna Rivers (Table 3). The parameters representing processes such as soil denitrification and plant and soil storages were also adjusted to be roughly proportional to values estimated by Van Breemen *et al.* (2002) for northeastern U.S. watersheds. Subsequently, all parameters were adjusted based on field data of nitrate and ammonium concentrations from 43 headwater streams sampled to assess the relationship between water quality and land use in the Ipswich River watershed (Williams *et al.,* 2004b). Although an abstraction, it was assumed that solute concentrations in headwater streams reflected processes occurring in PERLNDs and, therefore, the concentration in water leaving the terrestrial systems. Still, the extent to which the model replicates reality regarding the magnitude of N retention and losses in the PERLNDs versus the transitional zone between the terrestrial and aquatic systems is a matter for discussion.

All N first-order kinetic parameters were important to the calibration process, especially those representing denitrification, nitrate immobilization, and organic N ammonification (Table 3). Another sensitive parameter was that related to the conversion rate of labile organic matter into refractory organic N. Because of the lack of published values for this type of conversion rate, multiple runs of the model were performed varying the rates within two orders of magnitude of values presented in HSPFparm (Table 3) until the closest agreement between predicted and measured values of N concentrations was achieved.

The parameters related to half-saturation rates for forested pervious lands did not affect the simulation results as much as the parameters related to nonforest lands (Table 3) probably because of the lower contribution of forests to dissolved N fluxes to the aquatic system. According to the observed data from Williams *et al.* (2004b), headwater streams of subcatchments with 80 to 100 percent forest cover had low nitrate concentrations (between 1 and 5 mM), whereas those with less than 80 percent forest had concentrations up to 120 mM (Figure 3). Nitrate in the water leaving the PERLNDs in the calibrated model had similar trends, with higher concentrations associated with predominantly urban land covers (Figure 8).

Parameters of N immobilization, uptake by plants and return to soil in the PERLNDs were allowed to vary throughout the year in the calibration process to account for the seasonality observed in the New England region (Table 3). However, none of the monthly parameters seemed to affect the calibration with respect to monthly variation of instream N concentrations as much as the parameters that represent N transformations in the virtual and stream reaches (Table 3).

During comparison of observed and simulated instream nitrate and ammonium concentration data for 1999 and 2000, the parameters that most affected model output were those related to nitrification and denitrification processes in the virtual reaches (NUT-NITDENIT block). These parameters not only controlled temporal variation of N concentrations in the Ipswich River, but also the spatial variation in the mainstem and tributaries. The denitrification rates used in the calibration were somewhat arbitrary because the Ipswich wetlands are represented in the model only to account for water storage in the hydrological calibration and do not have the proper dimensions in terms of area and depth of the real wetlands. Therefore, denitrification rates were calibrated in relative terms to account for about 50 to 80 percent of the N losses that occur between the terrestrial system and the river reaches, so simulated and observed concentrations would match.

Calibration was performed by comparing the concentration values from 34 nodes selected throughout the main channel, tributaries, and small streams with observed data from 30 water quality monitoring locations, 22 of them located in the main channel (Figure 1) and eight in smaller creeks and tributaries.

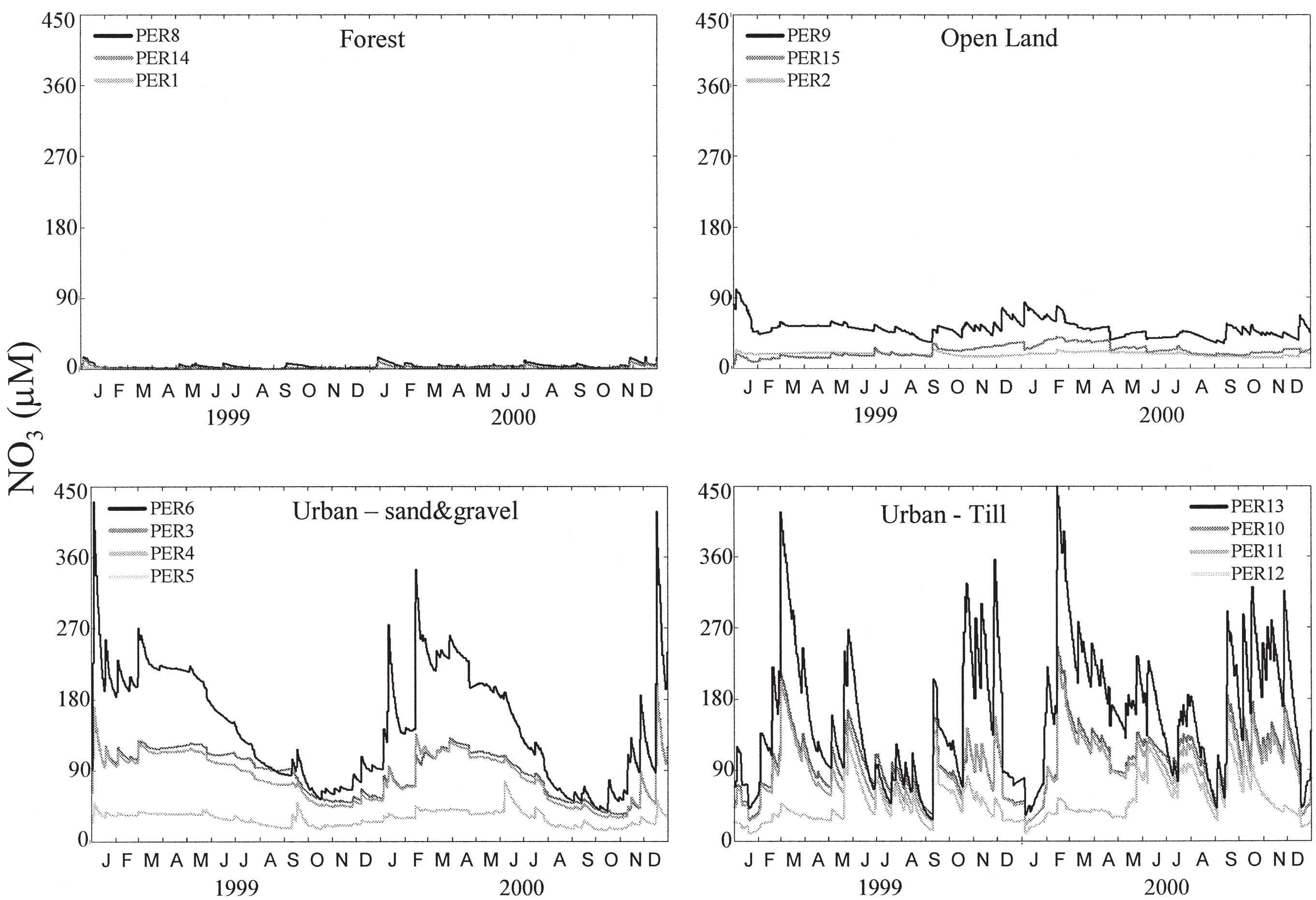


Figure 8. HSPF Simulated Runoff From Pervious Lands on Sand and Gravel, Till, and Alluvial Soils, Covered by Forest, Open Land, Low Density and High Density Residential Areas With and Without Septic Systems (Table 1).

ANALYSIS OF SIMULATION RESULTS AND DISCUSSION

Present Land Use Conditions

Concentrations of nitrate and ammonium simulated by HSPF for the Ipswich River matched the general trend of the observed data (Figures 9 and 10), but predictions for any particular sampling event in the main stem had substantial errors, as show by the high percent Root Mean Square Errors (Table 4). On two simulation dates, the model consistently underestimated nitrate and ammonium concentrations. The largest underestimations for nitrate were for June 27, 1999 (r^2 = 0.06, Table 4) in the beginning of the low water period (Figure 9), and again for January 29, 2000 (r^2 = 0.59), when freezing temperatures contributed to snowpack accumulation. For ammonium, underestimations were larger for January 29, 2000 (Figure 10: r^2 = 0.001, Table 4), than for other months. On average, ammonium concentrations were predicted poorly by the model while nitrate concentrations were predicted well (r^2 > 0.35) for most sampling events (Table 4).

During extremely low water and snowpack accumulation periods, the observed high nitrate and ammonium concentrations in the upper Ipswich River reaches may have been caused by a reduction in the amount of recharge water from precipitation that could mix with base flow and dilute the effluent water from septic systems. However, because of limitations in the model, inputs from septic system loads were forced to enter the watershed in the upper soil layer or subsurface of the pervious land, probably causing simulated base flow derived from ground water to have low concentrations of N and, accordingly, reduced amounts of N loading to streams. Base flow, defined as precipitation water that percolates downward to the water table and then flows into the

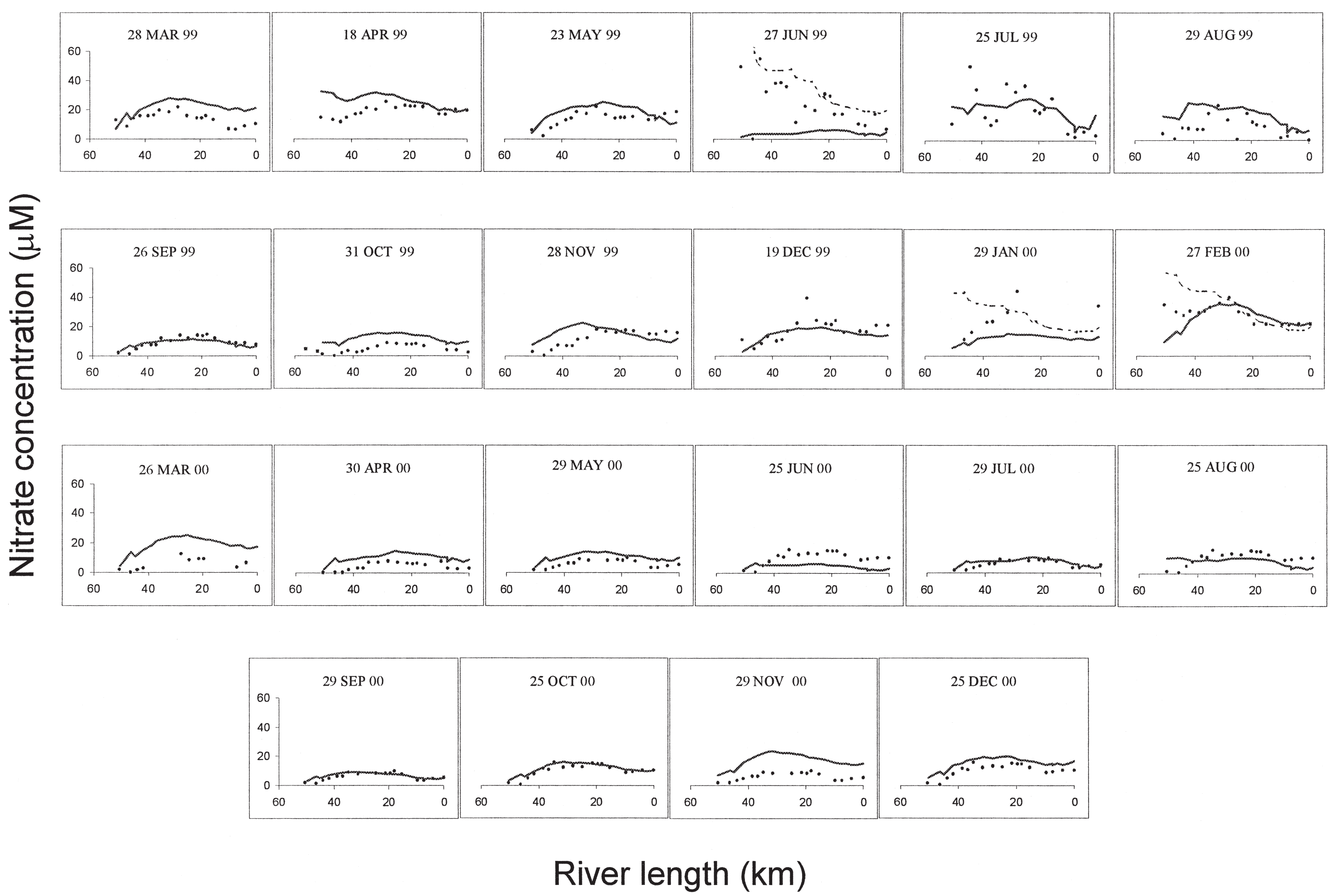


Figure 9. Monthly Nitrate Concentrations in the Ipswich River, Validated for 1999 to 2000. Observed (◆) and Simulated Concentrations (—) are Indicated for Each Month of the Validation Period. The results of the second calibration for the months of June 1999 and February 2000 using lower denitrification rates in the "virtual reaches" are indicated only for the specific months (-·-).

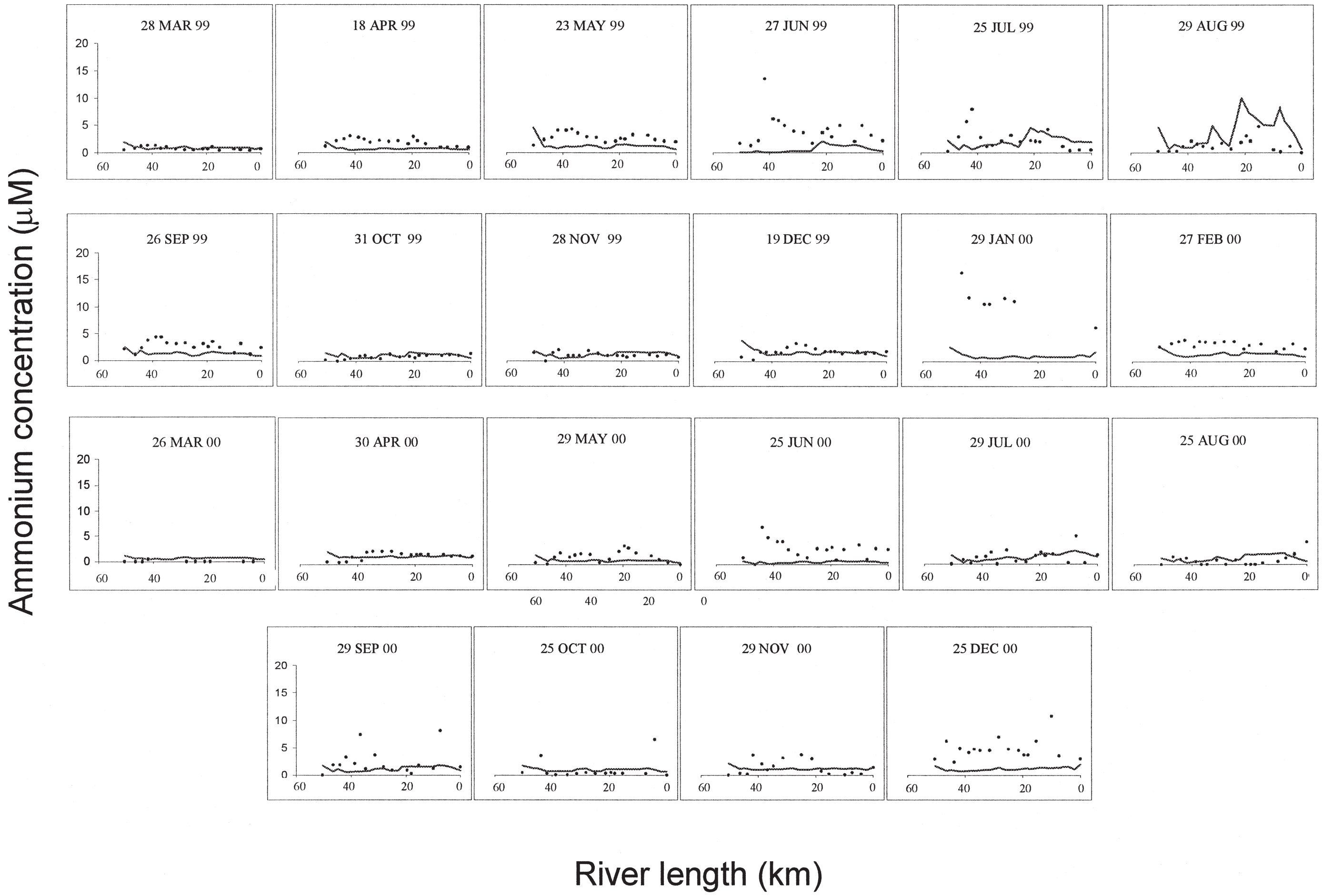


Figure 10. Monthly Ammonium Concentrations in the Ipswich River, Validated for 1999 to 2000. Observed (◆) and simulated concentrations (—) are indicated for each month of the validation period.

stream as ground water seepage (Linsley *et al.,* 1982), is the main source of water to the Ipswich River during dry months, whereas in wet months interflow becomes a major component of the runoff, especially in pervious land on till and bedrock (Zariello and Ries, 2000). Interflow is defined as the water that infiltrates the soil surface and moves laterally through the upper soil layers until it enters a stream channel (Linsley *et al.,* 1982).

Another reason for the high observed nitrate concentrations in the upper reaches in comparison to the simulated values during low water and snow accumulation periods could be that the model is not simulating high loads of nitrate from residential pervious and impervious lands that might be occasionally transported directly to the river (e.g., storm drains) without being denitrified or assimilated between the upland and aquatic system. Riparian zones and wetlands are known to effectively buffer N transport to the aquatic environment, given suitable conditions such as water saturation, and nitrate and carbon availability (Haycock *et al.,* 1993; Hill *et al.,* 2000). Under normal hydrological conditions in the Ipswich basin, much of the upland nitrate load is probably reduced by denitrification or assimilation during the transport of water through anoxic sediments, wetlands, riparian vegetation, and in small headwater streams, but during low flow periods these N processing zones may be bypassed. According to Hill *et al.* (2000), denitrification may not effectively remove nitrate from ground water transported at depth through permeable riparian sediments unless interaction occurs with localized supplies of organic matter. In the Ipswich basin, the active zones that can effectively remove nitrate may be above the nitrate rich water flowpath during low water months.

Although vegetation uptake retains N in the summer in temperate regions, denitrification during this period may be at a minimum because soil moisture is low in regions of adequate organic carbon availability (Pinay *et al.,* 1993), and hydrological routing of water occurs under the active layer of the riparian zone. In winter months, hydrological routing of water over the riparian zone or wetland soil surface are likely to

TABLE 4. Model Performance Statistics for All the Dates for Which Data Were Simulated and Compared With Observed Data From the Ipswich River.

Date	RMSE (percent)		r^2		Slope		Intercept	
	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4
MAR99	101	60	0.19	0.19	0.43	-0.16	1.55	9.9
APR99	69	62	0.01	0.08	-0.03	-0.05	2.50	0.72
MAY99	114	57	0.62	0.01	0.78	0.01	7.30	0.99
JUN99	78	80	0.06	0.13	-0.01	-0.01	4.24	0.21
JUL99	104	161	0.58	0.14	0.36	-0.12	1.00	1.41
AUG99	238	351	0.42	0.18	0.77	0.56	8.10	0.57
SEP99	145	52	0.72	0.11	0.43	0.09	5.12	0.92
OCT99	233	120	0.43	0.03	-0.87	0.14	8.06	0.69
NOV99	124	160	0.21	0.05	-0.45	-0.22	20.0	2.25
DEC99	46	163	0.56	0.02	0.25	-0.07	10.0	1.56
JAN00	43	58	0.59	0.01	0.21	-0.01	6.60	0.76
FEB00	15	57	0.35	0.03	0.69	-0.05	6.43	1.33
MAR00	253	10	0.72	0.50	1.26	-0.40	13.0	0.69
APR00	199	66	0.51	016	1.03	0.11	16.0	1.24
MAY00	130	101	0.35	0.30	0.47	0.09	8.15	0.54
JUN00	130	79	0.15	0.10	0.13	0.02	2.36	0.20
JUL00	62	326	0.36	0.14	0.31	0.26	5.59	0.40
AUG00	97	289	0.03	0.02	0.09	0.05	4.72	0.60
SEP00	59	129	0.08	0.02	-0.13	-0.02	9.37	0.86
OCT00	50	367	0.61	0.09	0.50	0.04	5.84	0.84
NOV00	23	237	0.54	0.22	0.57	-0.05	7.89	1.17
DEC00	144	73	0.66	0.04	0.53	0.01	5.22	0.92

reduce the retentiveness of nitrate between terrestrial and aquatic systems because of a combination of low soil temperatures and high flow velocities, which decrease the contact period of the water with the soil (Haycock *et al.,* 1993).

In the model, because all the water transported from the land segments was assumed to drain into the "virtual reaches" representing wetlands before flowing into stream reaches, denitrification in the interface occurred regardless of spatial and temporal changes in hydrology and nitrate-rich water flowpaths. When simulations were run using reduced denitrification rates (1 percent of the previous values) for all the virtual reaches of the upper Ipswich River and streams (i.e., Subcatchments 1 to 22), and the remaining reaches (by 50 percent), the fit between observed and predicted nitrate concentration values improved significantly for June 1999 and February 2000 (Figure 9, dashed line).

Rates of denitrification were reduced more in the upper portion of the basin because they had to be higher during the calibration process to match observed concentration values. High denitrification rates in this region likely reflect natural rates for this portion of the basin, where a combination of conditions are favorable for denitrification. For instance, the upper region of the basin lies on highly urbanized lowland areas overlying fluvial sand and gravel, where base flow contributes the majority of the total runoff (Zariello and Ries, 2000), and, therefore, nitrate is more likely to have contact with the sediments and undergo denitrification. Moreover, lower runoff, slower stream currents, and frequent impoundments in this lowland region might enhance denitrification even further. An inverse relationship between denitrification losses and basin runoff or stream order has been observed for the Mississippi basin (Alexander *et al.,* 2000; Donner *et al.,* 2002).

It was not possible to further improve the fit between observed and simulated data for January most likely because of the manner in which septic loads are represented in HSPF. Septic system inputs enter the system in the surface layer, while in reality they enter the deepest layer. Consequently, septic-system N loads in the model are retained in the snowpack in January and transported to the aquatic system only when snowmelt occurs. Because septic system loads are the dominant source of N to the terrestrial system of the Ipswich River watershed (Williams *et al.,* 2004a), the accumulation of these inputs during freezing conditions considerably reduces N flux to virtual reaches and streams during these periods. Therefore, model adjustments that incorporate new loading mechanisms to handle septic system inputs are needed.

According to the calibration settings, between 98 and 100 percent of the N inputs into the forest HRUs were retained in the landscape, while the urban HRUs retained 72 to 93 percent (Table 2). Although the retention rates were relatively high for urban landscapes, especially considering that denitrification losses from septic systems have been previously subtracted from the inputs, simulated concentrations in the runoff leaving the urban HRUs were high in relation to concentrations in first-order stream draining subcatchments with greater than 80 percent urban land cover. Therefore, significant denitrification losses had to be simulated in the virtual reaches and small-order streams in order for observed and simulated nitrate concentrations in the main steam to match, suggesting that large amounts of nitrate transported from pervious and impervious lands to streams are assimilated and lost in the riparian interface between the terrestrial and aquatic systems, and/or in the extreme headwater of small order streams.

High N retention rates in forested catchments can be justified by the fact that temperate forests are commonly N limited (Magill *et al.,* 2000). For urban areas, N losses or retention are attributed to processes such as ammonia volatilization, ammonium sorption and denitrification, enhanced by anaerobic conditions and high availability of dissolved organic carbon of the septic system plumes themselves (Robertson and Blowes, 1995). Losses through denitrification in the virtual reaches are representative of natural processes observed for riparian zones and wetlands, especially when large loads of N from highly urbanized watersheds are transported to the aquatic system (Haycock *et al.,* 1993). Nitrogen processing and denitrification losses can be also high in headwater streams (Alexander *et al.,* 2000). However, experiments conducted by Williams *et al.* (2004a) in discrete first-order streams of the Ipswich River showed that rates of nitrate loss and retention are less than 0.1 µmole $N/m^2/h$, suggesting that losses of nitrate occur at the terrestrial/riparian interface and in wetlands of first-order streams, as opposed to the stream channels themselves. In contrast to nitrate, experiments with ammonium showed relatively high assimilation rates in first-order streams of the Ipswich River. The experimental results agreed with the model simulations when relatively large amounts of ammonium are nitrified and/or assimilated in the first-order reaches of the watershed.

The magnitude of N losses simulated by the model in the virtual and river reaches of the Ipswich River watershed is illustrated in a simple input/output budget constructed for two contrasting subcatchments of the basin, which are 25 and 65 percent forested (Figure 11). Regardless of land use, over 70 percent of the total N inputs is retained on land before reaching the aquatic system. In the virtual reaches, over 90 percent of the remaining inputs is lost or retained (Figure 11). Only in the stream reaches are there differences in the percent losses and/or assimilation, with another 33 percent lost in the urban stream (Reach 3) but about 1 percent in the stream draining the predominantly forested catchment (Reach 54). Therefore, only a small fraction (< 10 percent) of the N inputs from atmospheric deposition, fertilizer, and septic system loads reaches the Ipswich River and tributaries, while the majority is retained in the terrestrial system and riparian/wetland zone (Figure 11).

Quantification of N losses in riparian zones or in first-order stream wetlands is experimentally difficult. The HSPF simulations provide estimates of the relative importance of processes occurring in the riparian/wetland interface, small order tributaries, and river main stem in maintaining the water quality in the Ipswich basin. Field research could help clarify the importance of various mechanisms controlling N retention in these zones. These results also show the need to preserve the integrity of these regions as the watershed continues to be developed.

Effects of Land Use Change

Simulation results show that when urbanization proceeds according to existing environmental regulations (Pontius and Schneider, 2001), with 44 percent of the forest converted to urban land in the next 100 years, changes in ammonium concentrations will be trivial (0.2 to 0.5 µM), while nitrate concentrations will increase 30 percent from the present values (Figures 12a and 12b). While substantial, this increase was probably small compared to changes that have occurred since colonization (Figure 12). Comparisons between present and pristine simulations suggest that the watershed has already been fairly degraded by urbanization. Simulations also suggest that complete deforestation will further degrade the system and nitrate concentrations will eventually increase by 100 percent of the present values, especially in the middle and lower reaches of the main stem (Figures 12c and 12d).

Simulated nitrate concentrations in the deforestation scenarios increased less in the upper reaches of the river because denitrification rates are higher for the virtual reaches of this region during calibration (to compensate for the high nitrate loadings generated by the model for the highly residential pervious lands). Moreover, the watershed area associated with the mid and lower reaches of the Ipswich is relatively less urbanized than that associated with the upper

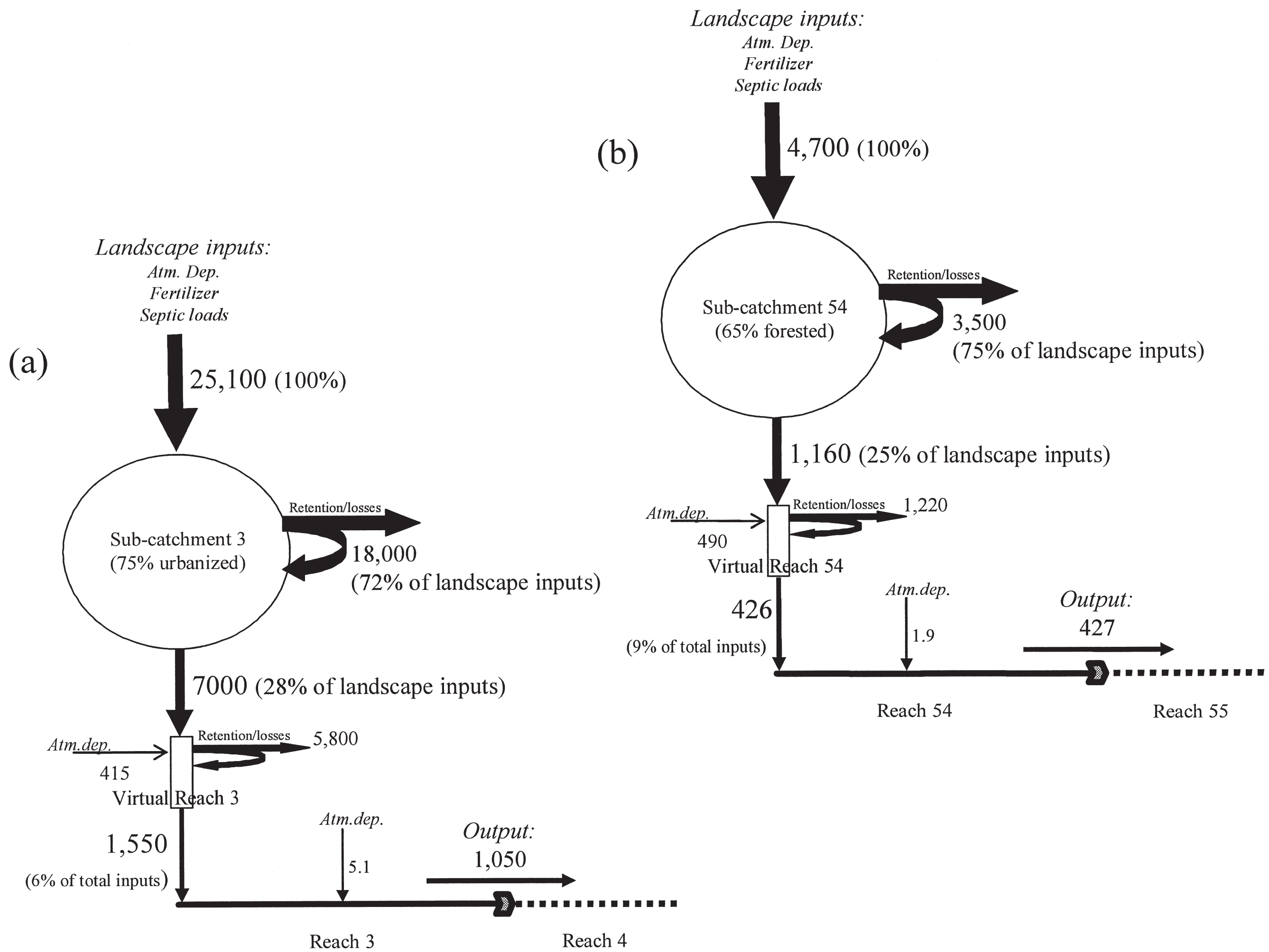


Figure 11. Nitrogen Budgets Based on Actual Inputs and Simulated Outputs for Two Subcatchments of the Ipswich River Watershed. (a) Subcatchment 3 is mainly urban, while (b) Subcatchment 54 is mainly forested.

reaches, so conversion of forest to urban cover would have a proportionally larger impact on nitrate concentrations in the river.

Another predicted effect of urbanization is increased temporal variation in nitrate concentrations both in small catchments and in the main stem (Figure 13). This variability probably reflects the erratic concentration patterns of highly urbanized subcatchments (e.g., RCH 3, Figure 13). However, the degree of variation in nitrate concentrations along a stream reach will depend on the dominant surface geology of the catchment (Figure 13). Concentration patterns in the deforestation scenario for REACH 38 [Figure 13(2a)], for instance, was not as erratic as those of REACH 3 probably because Subcatchment 38 lies on till and bedrock as opposed to sand and gravel in Subcatchment 3, and has different water flowpaths (Zariello and Ries, 2000).

CONCLUSIONS

Simulations using HSPF enabled estimation of the key mechanisms controlling N flux and fate in the Ipswich River watershed. The results suggest that although most of the N retention and losses occur in the terrestrial system (approximately 75 percent), assimilation and denitrification in the riparian and first-order wetlands are “hot spots” for N processing and losses, attenuating much of the anthropogenic N inputs into streams (further 90 percent reduction). The model also predicted that land use changes such as partial and total deforestation and subsequent urbanization of the basin will increase nitrate concentrations in streams. According to the simulations, nitrate concentrations in streams are presently four times as high as they were prior to the beginning of land use changes in the basin, and land use changes

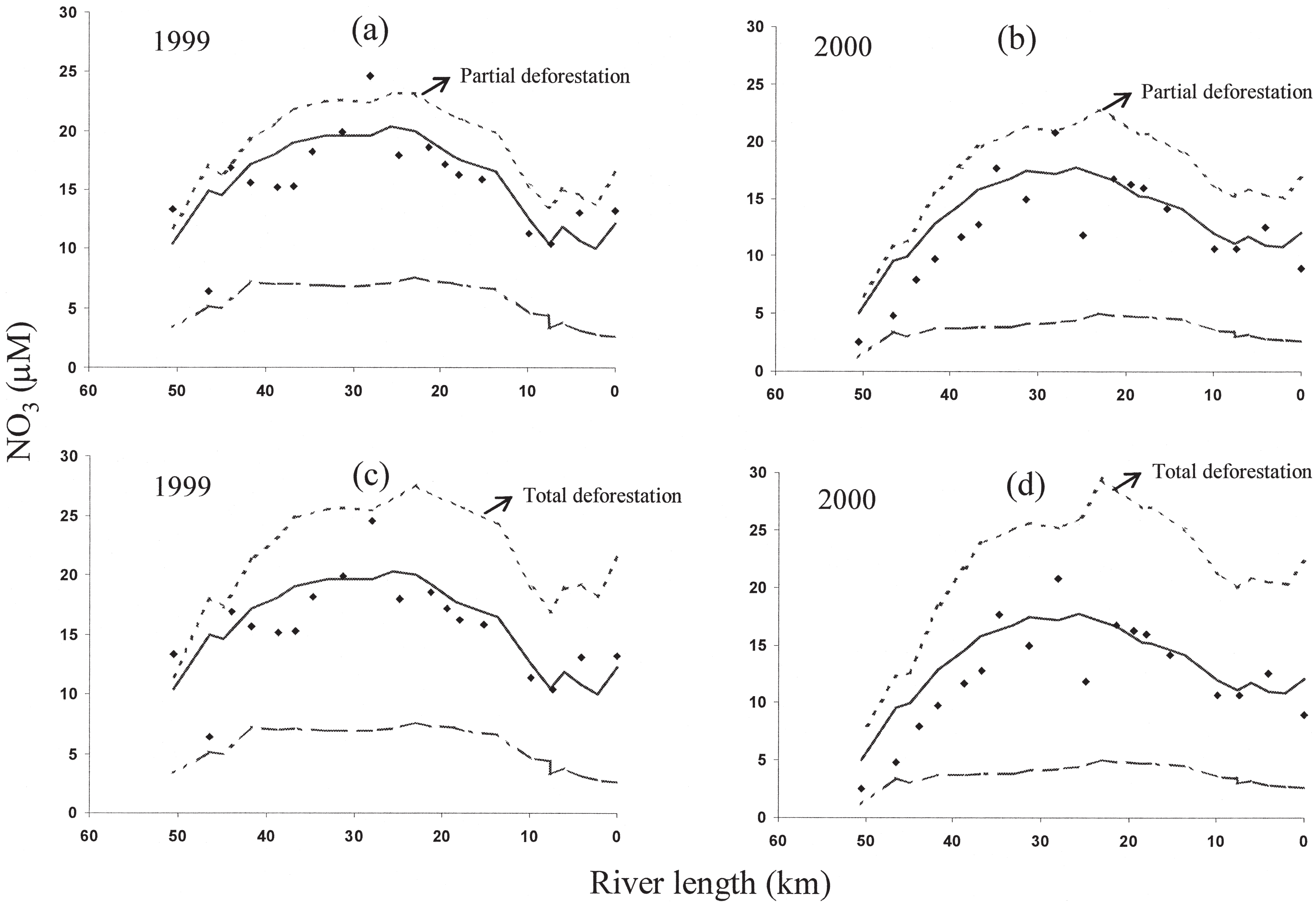


Figure 12. Observed (◆), Validated (—), and Predicted (- -) Annual Nitrate Concentration Averages for the Ipswich River in Future Scenarios of (a, b) Partial and (c, d) Total Deforestation. Concentrations simulated for a scenario of 100 percent forest cover are presented (-··-) as reference.

restricted by environmental laws will potentially result in an increase of about 30 percent of the present nitrate concentrations. If no restrictions are applied to land use changes and all the forest in the basin is converted into urban land, this increase can reach up to 100 percent of the present concentrations of dissolved inorganic nitrogen. Increases will be more pronounced in the middle and lower portions of the basin than in the already highly urbanized upper portion. Also, the portion of the Ipswich River draining bedrock and till uplands will have the highest nitrate concentration increases with urbanization.

The simulation results showed that HSPF can predict the general patterns of inorganic N concentrations in the Ipswich River and tributaries, although it has some difficulty simulating the extreme variability of the observed data. Because inaccuracies in the model predictions were related to the positioning of septic system inputs in the model, and to the disconnection of N processing simulated in wetlands and riparian zones to the hydrology of the basin, improvements in the model should focus on these two aspects. Understanding how the hydrology of the wetlands and riparian zones control denitrification rates and the loading of nitrate to the aquatic system may be crucial to the management of water quality and N concentrations of the basin. Model results provide a comprehensive assessment of the effects of land use changes on the water quality of the river and some insight to regional decision makers and stakeholders in developing and analyzing management scenarios for the Ipswich River basin.

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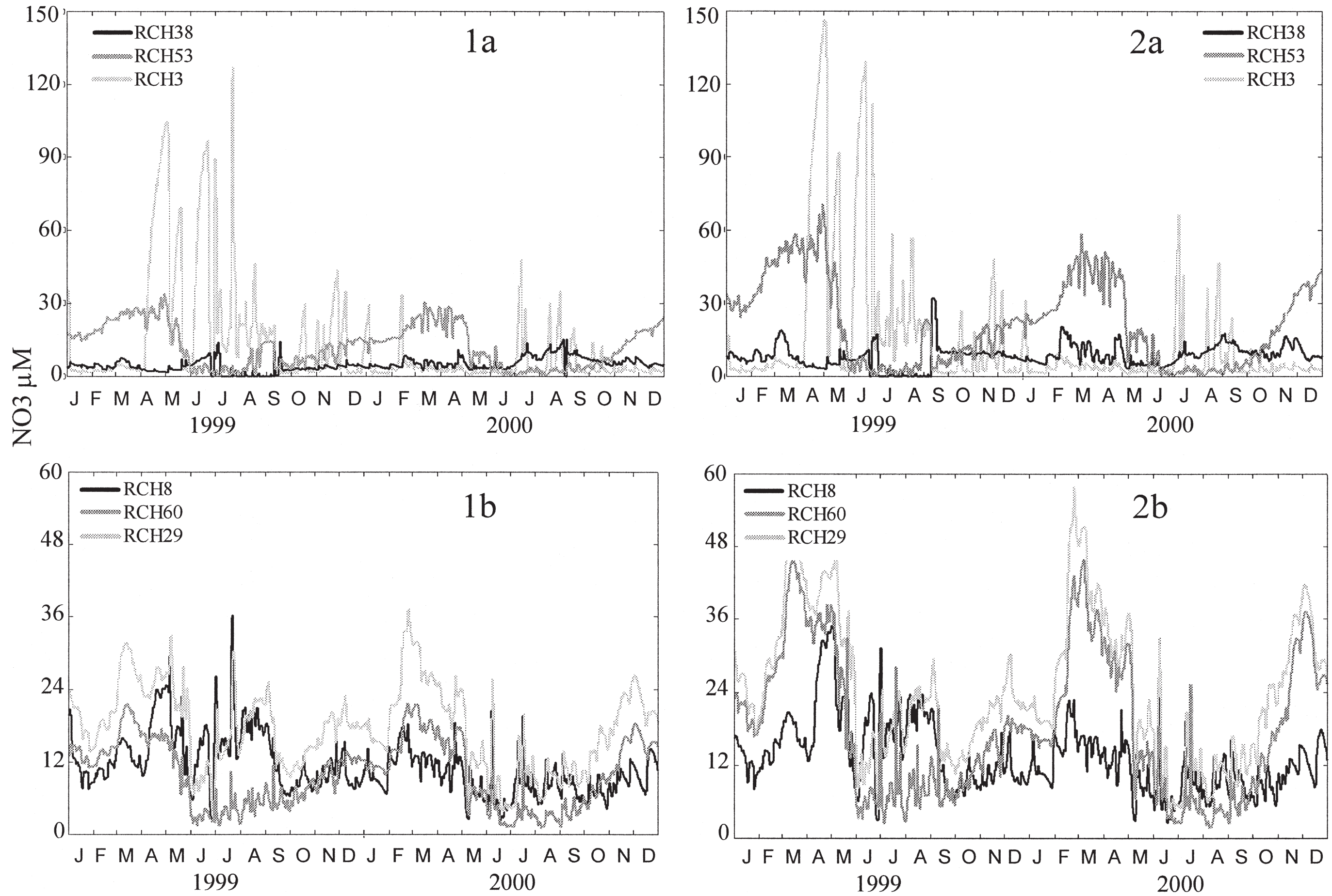

Figure 13. HSPF Simulated Nitrate Concentrations in (1) Present Land Use Scenario and (2) Total Deforestation of (a) Small Headwater Tributaries and (b) Main Stem of the Ipswich River.

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