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Response of a Watershed Model to Varying Spatial Landscape Characteristics

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Abstract. Using a spatially-explicit deterministic model of hydrology and soil nitrogen dynamics in a small watershed in upstate New York, we investigate the effect of varying the spatial distribution of land use on processes within the watershed. Multiple landscapes having specific properties are generated, and the effects on runoff of water, runoff loss of nitrogen, and other soil nitrogen processes are observed over a period of two years. We illustrate techniques of visualization for comparing total magnitude and spatial and temporal distributions of these variables. The ultimate goal of our approach is to develop a methodology for use in comparative studies of land use modification at the landscape scale.

INTRODUCTION

Because nitrogen can be seen both as a pollutant and a nutrient, understanding the nitrogen dynamics of watersheds is crucial to both surface and groundwater quality management, to effective agricultural management, and to the advancement of our understanding of other terrestrial and aquatic ecological processes. With the explosive growth of computer resources over the last few decades, mathematical modeling of nitrogen at the watershed scale has advanced from empirical loading models, to process-based lumped-parameter models, to spatially explicit models. While the first two categories of model permit the estimation of annual or seasonal loading rates, and the construction of average mass balances of some watersheds, they fail for complex watersheds in which flows are generated primarily in small "source areas". They also do not allow examination of the impacts of the position of

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nitrogen sources in the watershed, and the effects of correlations between sources and topography and soil properties which affect nitrogen transport and transformations. Even some of the most successful watershed models which incorporate spatial information do so by aggregating topographic or soil data (e.g., Beven and Kirkby, 1979) or by using monthly or greater time steps (e.g., Bartell and Brenkert, 1990), thereby losing the detail of the spatial interactions and the response to individual rainfall events.

Under what circumstances should these details matter? If we are considering alternative strategies for managing a watershed in which we must decide the location of nitrogen sources (e.g. cornfields) it may be of interest to know whether location strongly affects nitrogen load from the watershed. A related question is whether an existing mosaic of land use in a watershed represents the smallest environmental impact in terms of surface or groundwater loading, or if alternative mosaics could be more desirable.

Below, we report some preliminary results of our analysis of a small upstate New York watershed which incorporates data describing the spatial distribution of topography, land use, and soils. We discuss the effects of changing land use characteristics on soil water and nitrogen spatial distributions and losses from the watershed in runoff.

METHODS

Model Descriptions

Hydrology

For this study, we simulate the hydrology and nitrogen dynamics of a 15.3 ha watershed in upstate New York on a daily time step for two years, beginning in April, 1991. We use a GIS-based hydrology model originally developed by Zollweg and Steenhuis (Zollweg, 1994) and adapted for our application (Kuo et al., 1996) to drive a spatially explicit soil nitrogen model. Hydrology is driven by local daily precipitation and pan evaporation data

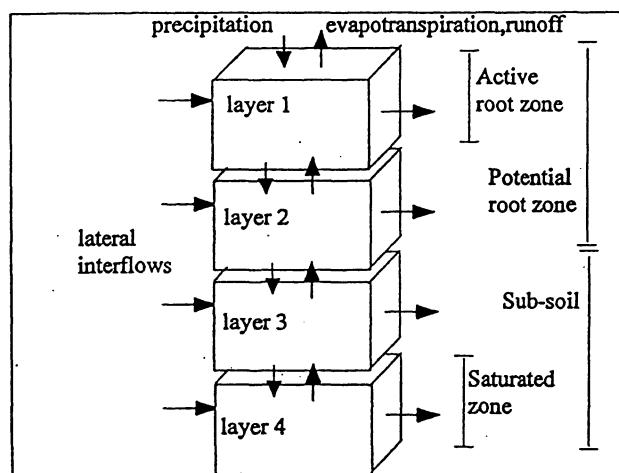


Figure 1. Schematic of hydrology model

obtained from the Northeast Regional Climate Center at Cornell. The hydrology model describes the watershed as a collection of 1531 100 m² cells which are divided into 4 layers (figure 1).

The top layer represents the active root zone the bottom boundary of which varies in depth through the growing season. Layer 2 is the zone between this depth and the maximum depth of the root zone. Layer 3 represents the unsaturated zone below the potential root zone, and is bounded below by the water table. Layer 4, the saturated zone, is bounded below by impervious bedrock, the depth to which depends on local soil type.

Water enters the top layer of each cell through rainfall and snowmelt. Lateral exchange of water between a cell and its eight neighbors is determined by the product of local hydraulic conductivity and elevational gradient. Vertical exchanges are governed by mass balance between layers, given the impervious bottom boundary condition of the bottom layer. Water in excess of saturation is lost from the top layer as surface runoff. Water is also lost from the active root zone by evapotranspiration.

Nitrogen

The nitrogen model (figure 2) includes exchanges between three components in each cell: organic N, ammonia, and nitrate. Nitrogen is added to the watershed in the form of dry deposition (daily) and wet deposition (episodically with rain) of nitrate and ammonium, and through fertilizer applications of nitrate on agricultural lands. In the simulations discussed here, a 100 kg/ha application of nitrate to crop land occurs on May 31 of each year. Exchanges between the N pools are mediated by microbial activity which depends on temperature and soil moisture content.

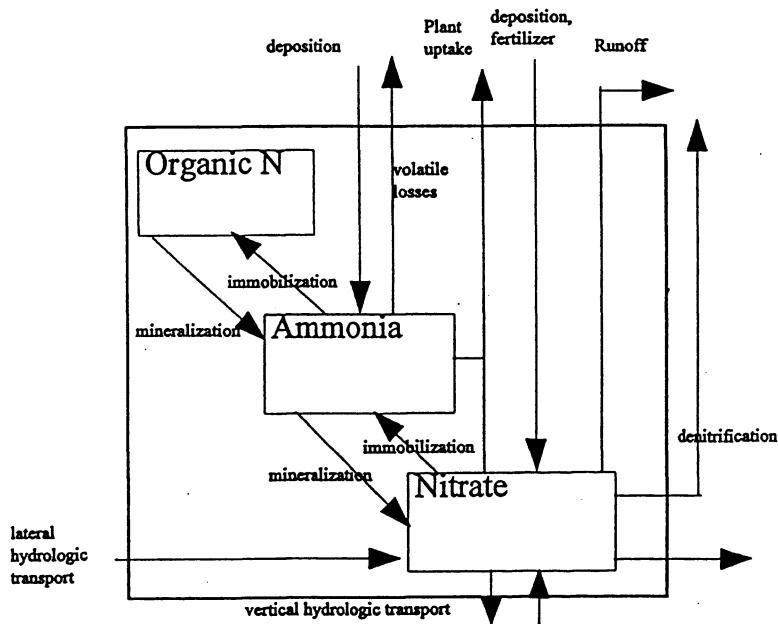


Figure 2 . Schematic of nitrogen model

Organic nitrogen may be mineralized to ammonia, which in turn may be nitrified or lost to the atmosphere through volatilization. Nitrate is lost to the atmosphere by denitrification under wet soil conditions. Nitrate is assumed to be the only mobile component of nitrogen. It moves in dissolved form with water within the watershed, and is lost from the watershed in runoff water. Both ammonium and nitrate are taken up by plants following a demand schedule determined by the land use category of the particular cell.

Landscape

Land use data characterizing the watershed were determined from 1991 aerial photographs (1:24,000; figure 3a); digital elevation data were digitized from contours of USGS 1:24,000 topographic maps (figure 3c); soil maps (1:20,000) from the Tompkins County soil survey (figure 3d) (Poiani et al. , submitted).

We consider three alternative land use mosaics for the watershed: existing land use ("original"), 100% active cropland ("agricultural") and a "synthetic landscape" generated using a conditionally independent hierarchical model (Searle, et al., 1992) ("random"). The existing land use mosaic includes five categories: active agriculture (43%), forest (41%), wetland (9%), inactive agriculture (4%), and low density residential (3%) (figure 3a). The agricultural mosaic was included to examine the limiting case in which a nitrogen fertilizer is applied to the entire landscape. Detailed description of the synthetic landscape generator is beyond the scope of this paper, but is provided in McCulloch et al. (1995). Briefly, the land use categories are modelled as a function of slope, and are generated using a spatially autoregressive correlation structure to induce a high correlation between land uses in adjacent cells. Synthetic landscapes are useful for assessing variation and for "filling in" landscapes which may undergo change. The example realization of the synthetic landscape model considered here resulted in the following distribution of land uses: active agriculture (54%), forest (22%), wetland (6%), inactive agriculture (1%), and low density residential (18%) (figure 3b).

RESULTS AND DISCUSSION

Hydrology and nitrogen were simulated for two years beginning April 1. Here, we compare the water and nitrate conditions in the landscape at the time of the fertilizer application to cropland in the second year, after any effects associated with the initial condition (saturated soil water content; constant N concentrations) have dissipated, and again just prior to the start of the next growing season.

Maps of the total soil moisture content for the "original" mosaic are shown in figure 3e and 3f. We show the results from this case only because those corresponding to the other mosaics are nearly indistinguishable from this one. The figures indicate that by the end of May in the second year of the simulation, and persisting through and after the growing season, the watershed

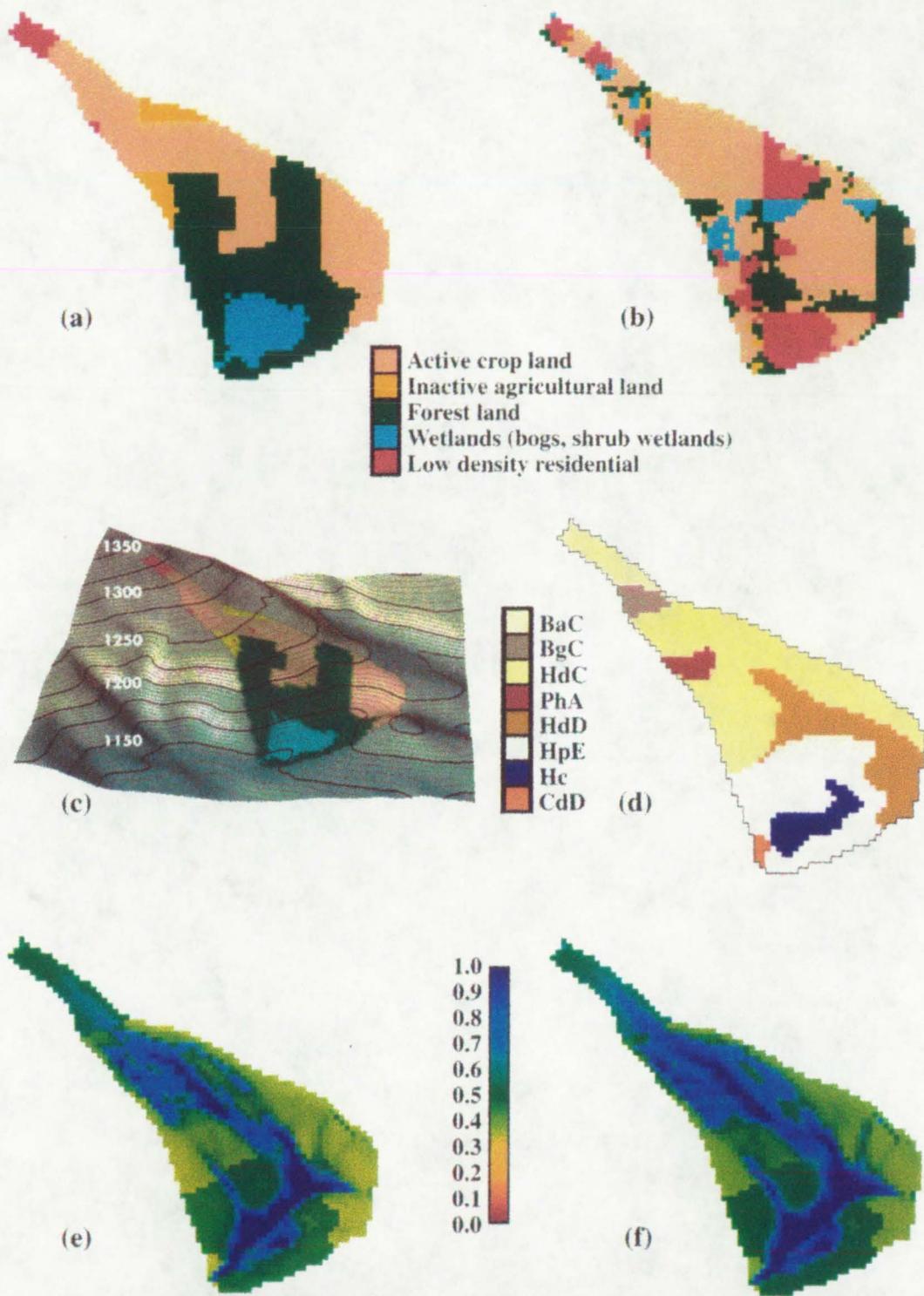


Figure 3 (a) Original land use map, (b) "random" land use map, (c) elevation map with original land use map superimposed and 5' elevation contour lines, (d) soil map, (e) moisture saturation index at time of second fertilizer application, (f) saturation index 276 days later

has established a distinctive pattern of high moisture content along a central drainage which curves to the lower left where the outlet is located. Even during the driest periods of the simulation, this central feature exists, expanding and contracting following rainfall and snowmelt events.

The average nitrate concentration in the root zone corresponding to the same dates for each of the land use mosaics are shown in figures 4a and 4b, along with cumulative runoff losses of nitrate. For all three landscape mosaics, the pattern of nitrate concentration follows the distribution of crop land immediately following fertilizer application, as expected, because the rate of nitrate applied is at least an order of magnitude greater than that from typical atmospheric deposition. However, about nine months after application, the pattern shows the effect of water content in the root zone. In particular, the wet areas that occupy the center of the map and curve to the lower left appear to be largely depleted of nitrate. This may be due to a combination of denitrification and runoff losses, both of which occur at their highest rates under saturated conditions. We believe the transitional pattern from a land use dominated mode immediately following a large application of nitrogen to a soil/topography based pattern as hydrological processes proceed is a general feature of mixed use watersheds.

Not surprisingly, cumulative runoff losses exhibit a sharp increase immediately following fertilizer application on all landscapes, with a gradually increasing trend thereafter. The highest losses occur from the "agricultural" mosaic. The "random" mosaic generates nitrate losses intermediate between the "agricultural" and the "original" mosaic.

Of some interest is the relatively high loss of nitrogen in runoff from the synthetic landscape. High losses are also observed in two alternative realizations of the synthetic landscape not shown here. Expressed per area of crop land, the losses from the synthetic landscapes are near or above those generated from the "agricultural" mosaic. One interpretation of this result is that a more sophisticated landscape generation algorithm should take persistent features of soil moisture (or its governing variables: topography, porosity and hydraulic conductivity) into account. It seems unlikely that the factors which have selected the location of cropland in a landscape reduce the runoff losses of nitrogen, but further work with synthetic landscapes may shed light on this issue.

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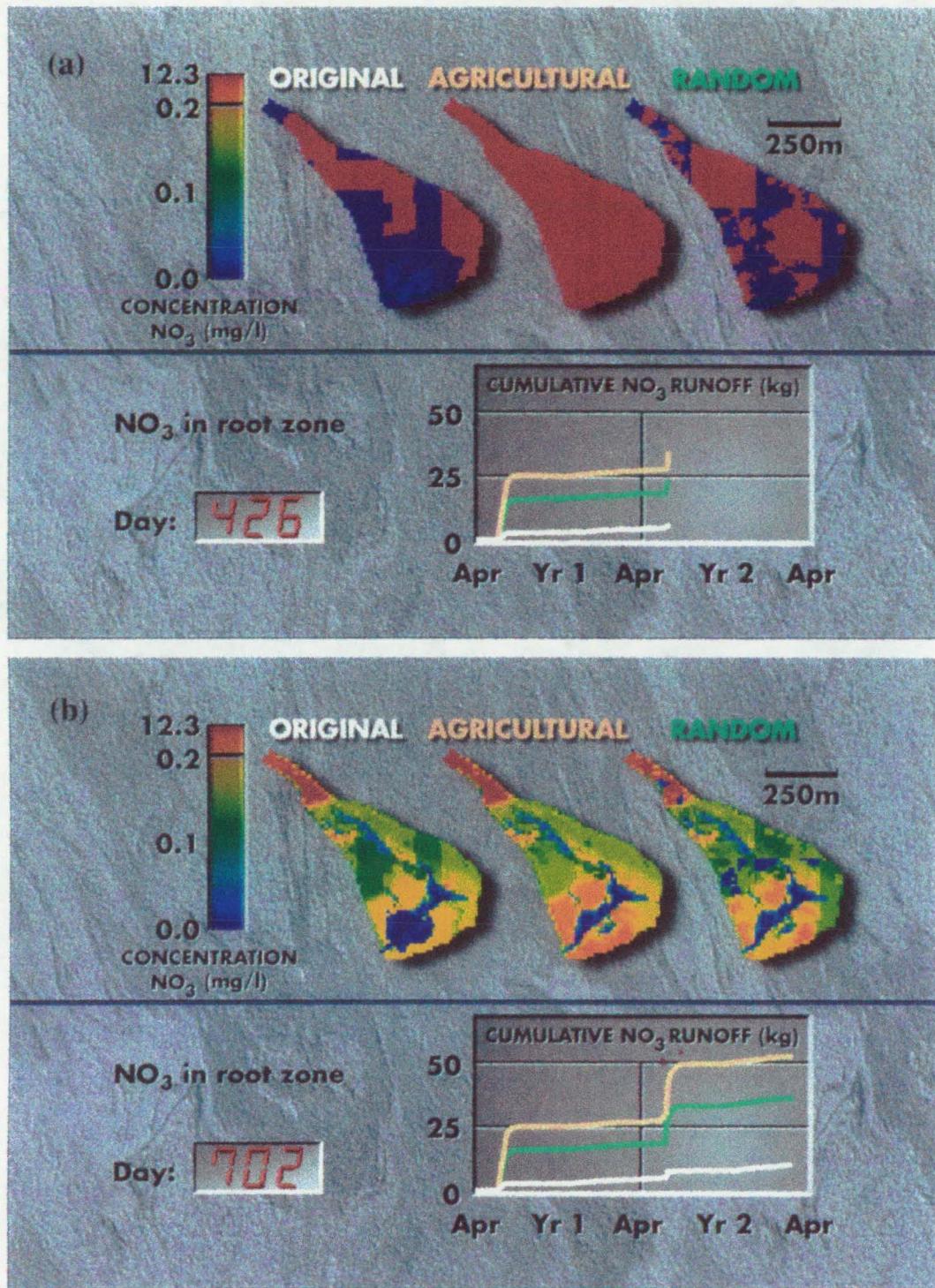


Figure 4 (a) Distribution of nitrate nitrogen in the root zone on the date of the second fertilizer application (day 426) and corresponding cumulative nitrate losses in runoff for the three land use mosaics; (b) same variables 276 days later.

BIOGRAPHICAL SKETCHES

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