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Effects of Land-use Change on Nutrient Discharges from the Patuxent River Watershed

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ABSTRACT: We developed an empirical model integrating nonpoint source (NPS) runoff, point sources (PS), and reservoir management to predict watershed discharges of water, sediment, organic carbon, silicate, nitrogen, and phosphorus to the Patuxent River in Maryland. We estimated NPS discharges with linear models fit to measurements of weekly flow and 10 material concentrations from 22 study watersheds. The independent variables were the proportions of cropland and developed land, physiographic province (Coastal Plain or Piedmont), and time (week). All but one of the NPS models explained between 62% and 83% of the variability among concentration or flow measurements. Geographic factors (land cover and physiographic province) accounted for the explained variability in largely dissolved material concentrations (nitrate [NO_3], silicate [Si], and total nitrogen [TN]), but the explained variability in flow and particulates (sediment and forms of phosphorus) was more strongly related to temporal variability or its interactions with land cover and province. Average concentrations of all materials increased with cropland proportion and also with developed land (except Si), but changes in cropland produced larger concentration shifts than equivalent changes in developed land proportion. Among land cover transitions, conversions between cropland and forest-grassland cause the greatest changes in material discharges, cropland and developed land conversions are intermediate, and developed land and forest-grassland conversions have the weakest effects. Changing land cover has stronger effects on NO_3 and TN in the Piedmont than in the Coastal Plain, but for all other materials, the effects of land-use change are greater in the Coastal Plain. We predicted the changes in nutrient load to the estuary under several alternate land cover configurations, including a state planning scenario that extrapolates current patterns of population growth and land development to the year 2020. In that scenario, declines in NPS discharges from reducing cropland are balanced by NPS discharge increases from developing an area almost six times larger than the lost cropland. When PS discharges are included, there are net increases in total water, total phosphorus, and TN discharges.

Introduction

Human activities increase discharges of water and materials from watersheds to aquatic systems (Correll 1987; Turner and Rabalais 1991; Carpenter et al. 1998). Elevated inputs of materials—such as sediment, nitrogen, phosphorus, and organic carbon—foster a host of problems in freshwater and estuarine systems throughout the world (Nixon 1995; Rabalais et al. 2001). In the Chesapeake Bay estuary, eutrophication has contributed to excessive phytoplankton production, hypoxia, the decline of submerged aquatic vegetation, and other environmental problems (Orth and Moore 1983; Officer et al. 1984; Jordan et al. 1991a,b; Boesch et al. 2001).

The Patuxent River, a tributary estuary of Chesapeake Bay in Maryland, is a well-studied system that has been used as a model system for testing environmental study methods and management strategies (Boynton et al. 1995). In the 1960s and 1970s, the rising population of the upper watershed increased wastewater discharges to the river. Public outcry over the resulting pollution and ecological degradation of the Patuxent estuary led to agreements to regulate development and to remove nutrients from wastewater (D'Elia et al. 2003). The Chesapeake Bay agreements have provided further impetus for reductions in nutrient discharges (Boesch et al. 2001). Large reductions in wastewater nutrient discharges have been achieved, but have not produced dramatic improvements in water quality in the Patuxent estuary, suggesting a need to also reduce nonpoint source (NPS) nutrient discharges (D'Elia et al. 2003; Lung and Bai 2003). Continued development of the watershed seems inevitable (Maryland Office of Planning [MOP] 1993, 1995; Tassone et al. 1998; Bockstael and Irwin 2003). Managing to maintain or improve estuarine water quality demands clear understanding of nutrient sources and quantitative predictions of how increasing

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population and changing land use will affect nutrient loads.

We have studied the factors controlling water, sediment, and nutrient discharges to Chesapeake Bay for many years (Correll 1987; Jordan et al. 1993; Correll and Weller 1997; Jordan et al. 1997a,b,c; Correll et al. 1999b,c,d,e). Our participation in the COASTES project (Complexity and Stressors in Coastal Ecosystems) has extended our research to the Patuxent Basin. The COASTES team has used the Patuxent as a model system to investigate how ecological complexity modifies the responses of estuaries to multiple stressors (Breitburg et al. 2003). We monitored the discharges of water and nutrients to the estuary for 2 yr to quantify the current sources of nutrients to the estuary (Jordan et al. 2003). We also developed models to predict watershed discharges under alternate watershed conditions, as described in this paper. Other COASTES scientists have used our estimated watershed discharges to drive a set of linked estuarine models, which are analyzed to explore how changes in watershed nutrient loadings affect estuarine water quality, estuarine biota, and the economic values of fish and shellfish (see citations in Breitburg et al. 2003).

This paper presents the formulation and application of a Patuxent watershed nutrient discharge model. We predict NPS nutrient loadings using statistical models fit to our 2 yr of stream monitoring data, and then we use monitoring data to account for point source (PS) discharges and water management effects. We evaluate the performance of the full model in representing observed water and nutrient discharges, then we apply it to predict water and nutrient discharges for alternate watershed scenarios, including some purely hypothetical scenarios and a more realistic planning scenario for the year 2020 developed by the Maryland government (Tassone et al. 1998; MOP 2000; D. M. Weller personal communication). The strengths and limitations of this approach are discussed, and our efforts are compared to other watershed models that have been applied in the Patuxent Basin. We also discuss some issues in evaluating model performance and quantifying land cover for nutrient discharge modeling.

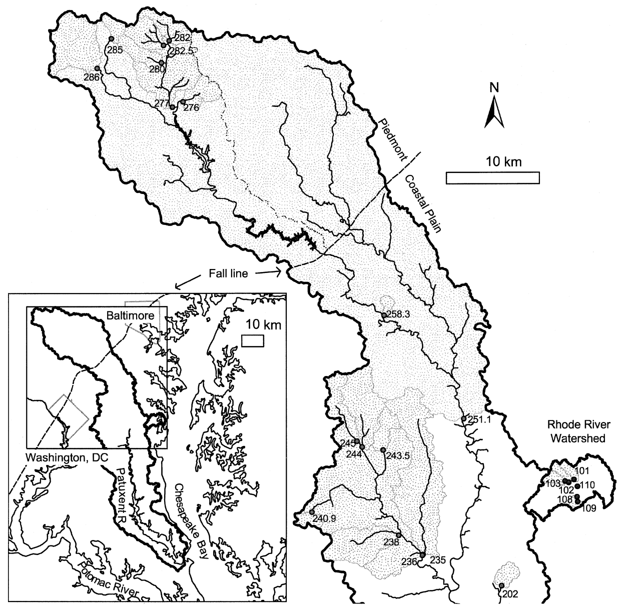

Fig. 1. The Patuxent River watershed and estuary. The inset shows the entire Patuxent drainage basin relative to the Chesapeake Bay and the cities of Baltimore, Maryland, and Washington, D.C. The upper part of the basin is enlarged to show automated sampling stations (dots) in the Patuxent drainage and in the adjacent Rhode River drainage. Subwatersheds draining to the sampling stations are outlined in gray and darkly stippled. Station 251.1 monitored discharges from the upper 40% of the Patuxent watershed. Its basin is lightly stippled. The dashed line in both the inset and enlargement is the fall line boundary between the Piedmont and Coastal Plain physiographic provinces. The dotted and dashed line above the fall line separates the Piedmont portion of the Patuxent drainage into two parts: a western portion draining through two water supply reservoirs and an eastern portion lacking reservoirs.

Methods

Watershed Data

The 2,300-km^2 Patuxent watershed is located in Maryland near the cities of Washington, D.C., and Baltimore, Maryland (Fig. 1). The watershed drains to a 137-km^2 subestuary of Chesapeake Bay (Boynton et al. 1995; Hagy et al. 2000). The northwestern 28% of the watershed is in the Piedmont physiographic province and the remainder is in the Coastal Plain (Langland et al. 1995). For 55% of the Piedmont area, drainage passes through one or both of two reservoirs maintained for flood control and drinking water supply. According to one land cover data set, the watershed is 49% forest, 10% cropland, 12% developed land, and 28% grassland (Environmental Protection Agency–Environmental Monitoring and Assessment Program [EPA–EMAP] 1994). In 1990, 491,000 people lived in the watershed (up 90% from 262,000 in 1970), mostly concentrated in the northern part of the watershed in the urbanizing areas near Washington and Baltimore (Lizgarra 1999).

We measured discharges from 17 watersheds in the Patuxent River drainage basin and 6 additional watersheds in the adjacent Rhode River basin. Fifteen of the watersheds are in the Coastal Plain physiographic province and 7 are in the Piedmont province. One station on the main branch of the Patuxent at the head of the estuary (251.1) sampled discharge from 40% of the entire Patuxent, including land from both provinces, 2 reservoirs, and 7 major municipal wastewater treatment plants (Fig. 1, Table 1). At each site, we established an automated station, which monitored stream depth continuously and controlled the compositing of volume-integrated water samples. Such samples accurately quantify both dissolved and suspended materials, including those transported episodically during storm flows (Jordan et al. 1986, 2003). The composited water samples were collected weekly and analyzed for total suspended sediment (TSS), total organic carbon (OC), dissolved silicate (Si), forms of nitrogen (nitrate, NO_3, total Kjeldahl nitrogen, TKN, and ammonium, NH_4), and forms of phosphorus (total phosphorus, TP, and phosphate, PO_4). Analyses for OC, TKN, NH_4, TP, and PO_4 yielded the totals of dissolved and particulate forms. Organic phosphorus (OP) was calculated by subtracting PO_4 from TP and organic nitrogen (ON) by subtracting NH_4 from TKN. Jordan et al. (2003) provide more complete information and references on our methods of flow measurement, water sampling, and chemical analysis. We operated the 23 stream samplers from July 27, 1997, through August 4, 1999, to obtain 105 weeks of data. We grouped weeks 1–52 as water year 1 and weeks 53–105 as water year 2. Annual precipitation was 122 cm in year 1 and 71 cm in year 2 (Jordan et al. 2003). Compared to a 160-yr precipitation record, (mean precipitation = 108 ± 21.8 cm, Correll et al. 1999a), year 1 was a wet year while year 2 was a drought year.

We developed geographic descriptions of the study watersheds and the rest of Patuxent basin. Using a geographic information system, we digitized the station locations and the boundaries of study watersheds and modeled watershed sections from U.S. Geological Survey 7.5 minute topographic maps. Existing digital maps provided information on land cover (EPA–EMAP 1994) and physiographic provinces (Langland et al. 1995). Twelve reported land cover categories were aggregated to 7 categories as follows: cropland, grassland, herbaceous wetland, developed land (combining high and low intensity developed), forest (combining deciduous, evergreen, and mixed forest and deciduous wooded wetland), bare (combining soil and rock), and water. We intersected the watershed boundaries with the digital maps to quantify land cover and physiographic province for subwatersheds (Table 1). The Washington Suburban Sanitary Commission provided data on water discharge and drinking water withdrawal from the water supply reservoirs (Wright and Wold personal communication). The Maryland Department of the Environment provided the locations of point source discharges (Table 2) and monthly data on volume and material concentrations for each source (Papuli and Liang personal communication).

Statistical Nonpoint Source Models

We developed linear statistical models to predict NPS water flow and material concentrations from independent variables representing watershed geography and time. We represented watershed geography with physiographic province (a classification variable: Piedmont or Coastal Plain) and with the fractions of cropland and developed land in each watershed. The fractions of grassland or forest were not included as independent variables. For all the study watersheds, the fractions of cropland, developed land, forest, and grassland sum to essentially 1, so including too many categories would lead to invalid models (see multicollinearity, SAS Institute, Inc. 1999). Factor analysis (principal components with varimax rotation, Harman 1976; SAS Institute, Inc. 1999) of the land cover data for the 23 study watersheds showed that the land cover data were well-represented by two factors. The first factor correlated strongly with cropland, grassland, and forest ($r = 0.78$, 0.94, and -0.84, respectively) but only weakly with developed land ($r = 0.11$). Factor 2 correlated strongly with developed land ($r = 0.99$) and weakly ($r < 0.55$) with the other three land covers. Our previous work has found that the fractions of cropland and developed land are the most useful predictors of nutrient concentrations, and that the addition of more land cover fractions does not typically enhance the predictions (Jordan et al. 1997a,b,c, 2000). Croplands receive most of the anthropogenic nutrients introduced into agricultural systems (Jordan and Weller 1996; Castro et al. 2001). For all of these reasons, we chose cropland and developed land to represent the 2 axes of significant variation in land cover among the study watersheds.

In fitting the statistical models for material concentrations, data from 22 study watersheds were used. The large watershed (251.1) that had discharges strongly altered by reservoir management and PS inputs was excluded. The model for water flow also excluded the Rhode River watersheds and completely forested watershed 258.3, which all had unrepresentatively low annual water discharges, possibly because of their small sizes (Jordan et al. 1997a, 2003). In the nutrient models, we excluded the watershed 282 NH_4 data, which were anomalously high because of cattle waste in a grazing area near the sampling station (Jordan et al. 2003). We also omitted data for watershed 240.9 during several weeks when a sewage leak caused very high nutrient levels (Jordan et al. 2003).

The models were fit with the GLM (General Lin-

TABLE 1. Area, physiographic province (Langland et al. 1995), and land cover (EPA-EMAP 1994) for study watersheds and modeled sections of the Patuxent River drainage. Area was calculated using watershed boundaries traced from U.S. Geological Survey 7.5′ topographic maps. The fraction of a section not in the Piedmont is in the Coastal Plain physiographic province. Three minor land cover categories (wetlands, bare land, and water) are not included here.

Subwatershed	Area (km^2) Total	Area (km^2) Land Only	Province Percent in Piedmont	Land Cover Percentages Developed Land	Cropland	Grassland	Forest
Rhode River study watersheds							
101	2.26	2.26	0	4.8	10.1	33.2	52.0
102	1.94	1.94	0	5.7	8.5	29.4	56.4
103	2.47	2.47	0	2.0	4.4	23.0	70.6
108	1.50	1.50	0	6.6	14.5	27.7	51.3
109	0.17	0.17	0	0.0	14.9	44.9	40.2
110	0.06	0.06	0	0.0	0.0	0.0	100.0
Patuxent Coastal Plain study watersheds							
202	4.82	4.82	0	1.1	30.6	40.8	27.5
235	233.75	233.28	0	23.0	6.9	32.7	37.2
236	60.83	60.75	0	15.5	13.8	26.3	44.3
238	23.21	23.21	0	10.8	11.9	44.4	32.8
240.9	3.99	3.99	0	70.1	0.0	26.4	3.5
243.5	7.43	7.25	0	16.3	6.8	48.1	28.8
244	24.22	24.20	0	44.0	0.0	22.4	33.6
245	15.28	15.28	0	62.9	0.0	12.4	24.7
258.3	2.14	2.14	0	3.1	0.5	1.6	94.8
Patuxent Piedmont study watersheds							
276	9.11	9.11	100	3.3	15.2	50.5	31.1
277	58.37	58.28	100	1.6	16.9	46.6	34.9
280	7.94	7.91	100	0.0	19.8	41.9	38.4
282	10.06	10.06	100	0.1	23.3	53.6	23.0
282.5	10.55	10.52	100	5.8	16.7	49.2	28.3
285	4.54	4.54	100	0.0	20.5	56.5	23.0
286	27.78	27.78	100	2.6	11.9	34.6	50.9
Patuxent Mainstem study watershed							
251.1*	908.35	901.17	70	19.0	7.8	29.4	43.8
Modeled Patuxent sections							
Piedmont Reservoir*	347.61	341.40	100	4.2	10.9	39.1	45.8
Piedmont no reservoir*	286.48	285.71	100	22.5	7.9	33.2	36.4
Piedmont*	634.09	627.11	100	12.5	9.5	36.4	41.5
Coastal plain in 151.1*	274.27	274.07	0	33.9	3.9	13.2	49.0
251.1 + 235*	1142.10	1134.45	55	19.8	7.6	30.0	42.4
Coastal plain*	1660.48	1633.80	0	11.8	10.1	24.7	52.3
Whole watershed*	2294.57	2260.91	28	12.0	9.9	28.0	49.3
Watersheds of 19 estuarine segments (see Fig. 2)							
1*	937.89	930.68	68	18.9	8.2	29.3	43.5
3*	20.31	20.18	0	6.9	14.9	31.7	44.9
5*	43.85	43.67	0	3.4	14.5	34.6	47.1
7*	37.52	37.41	0	1.0	19.7	35.6	43.5
9*	19.77	19.74	0	2.9	11.8	36.1	46.2
11*	304.21	303.38	0	19.7	6.7	31.5	41.5
13*	120.90	119.90	0	2.9	14.8	33.4	48.1
15	19.13	18.44	0	4.0	21.5	22.8	48.3
17	98.00	97.74	0	2.5	14.4	33.5	48.6
19*	31.74	31.44	0	0.9	15.1	33.5	46.6
21	72.33	71.98	0	1.7	9.6	31.1	53.8
23	18.64	18.32	0	0.8	17.6	26.9	52.9
25	167.05	163.44	0	3.3	9.5	23.9	62.1
27	86.84	84.75	0	8.4	18.0	14.2	58.3
29	95.42	91.94	0	1.8	13.9	19.4	63.7
31	33.81	32.81	0	2.6	13.1	13.7	68.6
33	90.96	86.13	0	1.3	7.2	20.8	69.6
35	53.98	50.20	0	4.2	8.2	23.4	63.7
37	42.24	38.76	0	13.6	0.5	12.8	71.2

* Sections containing point source discharges (see Table 2).

TABLE 2. Numbers of major and minor point sources and total volume of point source discharge in study watersheds and modeled sections of the Patuxent River drainage discharges (Papuli and Liang personal communication). Watershed sections from Table 1 lacking point sources are omitted.

Subwatershed	Major	Minor	Discharge 10^6 m^3 yr^{-1}
Patuxent mainstem study watershed			
251.1	7	6	47.0
Modeled Patuxent subwatersheds			
Piedmont reservoir		1	0.001
Piedmont no reservoir		1	0.3
Piedmont		2	0.3
Coastal plain in 251.1	7	4	46.7
251.1 + 235	7	4	47.0
Coastal plain	8	15	70.9
Whole watershed	8	17	71.2
Watersheds of 19 estuarine segments (see Fig. 2)			
1	7	6	47.0
3		1	0.0001
5		1	0.006
7		1	0.1
9		3	0.5
11	1	1	23.4
13		3	0.1
19		1	0.02

ear Models) procedure of the Statistical Analysis System (SAS Institute, Inc. 1999) in two stages. For material concentrations, the first stage involved examination of a full model, including all independent variables and their interactions, entered in the order: crop, developed, province, crop × province, week, crop × week, developed × week, crop × province × week. In the second stage, variables or interactions that were not statistically significant (Type I test, $p > 0.05$) were eliminated to yield a set of reduced models. The same two stages were used for modeling water flow, but the order of entering variables in the full model was week, developed, crop, province, crop × province, developed × week, crop × week, province × week, crop × province × week. The possible interaction developed × province was not considered in the full models for flow or concentrations because the proportion of developed land in the Piedmont study watersheds only varied from 0% to 6% (Table 1). This was not a wide enough range to permit resolving differences in the effects of development between the two provinces.

By including the classification variable week and its interactions with geographic variables, the models were allowed to accommodate temporal variability on a variety of scales without defining the mechanisms driving that variability. In essence, including week and its interactions in a linear model fits a separate model relating flow or concentration to the geographic variables in each of the 105 study weeks. Interannual, seasonal, and week-to-week variations were then represented by the separate model parameters fit to the observed data in each week. The effects of episodic events, such as storms, are accommodated to the extent that the effects are common across many of the study watersheds. Isolated storms affecting only one or two watersheds cannot be accommodated. Such events increase the noise or variability that cannot be explained.

Landscape Discharge Model

Reduced statistical models were used to predict NPS flow and material concentrations for 23 watershed sections comprising the entire Patuxent basin. The sections were subwatersheds of the 19 estuarine segments (Fig. 2, Table 1). The watershed of segment 1 was subdivided into 4 sections: Piedmont draining to reservoirs, Piedmont with no reservoir, Coastal Plain above the sampling station (251.1, Fig. 1), and a small (30 km^2) residual section below the monitoring station but upstream from the lower boundary of estuarine segment 1. The watershed of segment 11 was divided into a larger (234 km^2) section upstream of monitoring station 235 and a smaller (70 km^2) section downstream from the station (Table 1). These subdivisions ensured that each section included only one physiographic province, isolated the effects of the two large reservoirs into one section, and enabled the model to make predictions that could be compared to the measurements of watersheds 235 and 251.1.

When the fractions of cropland and developed land in a watershed section are both low, the models for some materials can predict small negative concentrations. To eliminate such physically unrealistic predictions, we tested non-linear formulations that cannot predict negative numbers. The resulting models were even more unrealistic: they predicted concentrations orders of magnitude too large when the fractions of cropland or developed land were large. Ultimately, we used linear models and applied a minimum criterion to prevent unrealistically low predictions. In each week, we identified the minimum values of flow and material concentrations observed among our sampled watersheds for that week, and then we set predictions below those minima equal to the observed minima. In imposing these limits, we assumed that the lowest observed values represent realistic lower bounds for flow and concentrations across all the watersheds.

To combine the NPS predictions with data on water withdrawals and PS contributions, we multiplied each section's NPS water discharge per hectare by its area to estimate total NPS water dis-

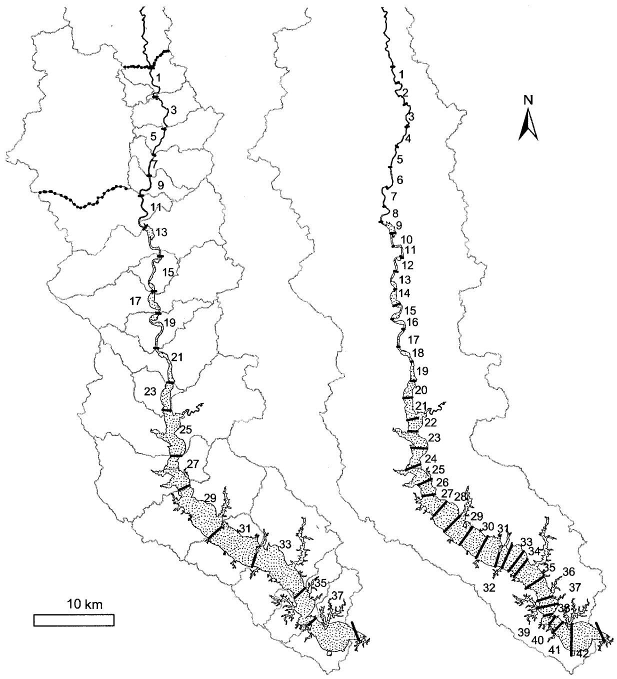

Fig. 2. Estuary segmentations used in estuarine circulation models. Left: 19-segment version. The solid black lines are the boundaries of the estuarine segments, and the gray lines are the boundaries of the subwatersheds draining to those segments. The dotted lines separate portions of the watersheds of segments 1 and 11 that are adjacent to the estuary and downstream from monitoring stations 251.1 and 235, respectively. Right: 42-segment version. Simulated discharges for 19 segments were apportioned to 42 segments using the following list of fractions based on estuary surface areas (see text). Numbers for the 19-segment scheme are in plain text and numbers for the 42-segment scheme are in italics: 1 *1* 0.985, *2* 0.015; 3 *2* 0.362, *3* 0.638; 5 *3* 0.023, *4* 0.760, *5* 0.218; 7 *5* 0.724, *6* 0.276; 9 *6* 0.662, *7* 0.338; 11 *7* 0.343, *8* 0.509, *9* 0.148; 13 *9* 0.387, *10* 0.344, *11* 0.269; 15 *11* 0.083, *12* 0.464, *13* 0.453; 17 *14* 0.655, *15* 0.345; 19 *15* 0.298, *16* 0.364, *17* 0.338; 21 *18* 0.519, *19* 0.481; 23 *20* 0.600, *21* 0.400; 25 *21* 0.187, *22* 0.290, *23* 0.391, *24* 0.132; 27 *24* 0.272, *25* 0.600, *26* 0.128; 29 *26* 0.179, *27* 0.272, *28* 0.353, *29* 0.196; 31 *29* 0.286, *30* 0.175, *31* 0.539; 33 *32* 0.247, *33* 0.294, *34* 0.090, *35* 0.243, *36* 0.127; 35 *36* 0.154, *37* 0.282, *38* 0.167, *39* 0.258, *40* 0.138; 37 *40* 0.113, *41* 0.338, *42* 0.549.

charge per week. For the section containing the water supply reservoirs (Fig. 1), the flow model could not accurately predict weekly water discharges as modified by water withdrawal and reservoir management, so instead the actual measured discharges (Wright and Wold) were used, which integrated the complex effects of evaporation, reservoir storage, water withdrawal, and water releases on discharge at the lower dam. For each watershed section, we multiplied the water discharge and material concentrations to estimate NPS material discharges. Fluxes of water and materials from all PS discharging to streams within a section were added (Table 2) to get the weekly total discharges due to land runoff and PS. PS data were available for flow, TSS, NO_3, NH_4, TKN, PO_4, and TP; and we calculated OP, ON, and total nitrogen (TN) from those data. PS data were not available for OC and Si, so our analysis accounts only for NPS of OC and Si.

After completion of the NPS and PS calculations, we added the discharges from the four sections of the watershed of estuarine segment 1 and the two sections of the segment 11 watershed were added to assemble predictions for discharges from the mapped watersheds of 19 segments (Table 1, Fig. 2) of the estuary model (Lung 1992). Later versions of the estuary model (Lung and Bai 2003) require watershed inputs for a more detailed 42-segment scheme (Fig. 2). We could not meaningfully map the watersheds of the smaller segments, so we instead apportioned predicted discharges for the 19 segments into the 42 segments based on the fraction of estuary surface in each original segment that fell into each segment of the new scheme (Fig. 2). Weekly material fluxes were divided by water discharge to recover the average material concentrations for each segment and week. We supplied weekly results for all 42 segments to the estuarine modelers (Lung and Bai 2003), but we aggregated results for concise presentation in this paper by summing weekly predicted discharges to estimate annual fluxes, 2-yr average fluxes, and flow-weighted average concentrations for larger sections of the watershed (Table 1).

Effects of Watershed Changes

Three analyses of the model were used to explore the effects of land cover change on material discharge. First, we constructed graphs illustrating how the proportions of cropland and developed land affect water discharge and material concentrations. Hypothetical Piedmont or Coastal Plain subwatersheds were modeled that varied from 0% to 100% cropland and from 0% to 100% developed land. We used the fitted NPS models to estimate weekly water flows and nutrient concentrations for the hypothetical subwatersheds, and then aggregated by year to get total water flows and volume weighted average concentrations for years 1 and 2 of the simulation. The resulting graphs illustrate the modeled effects of land cover, physiographic province, and wet or dry years.

The second analysis modeled how changing land cover from base conditions (Table 1) for a 10-km^2 area would change water and material fluxes from three functionally different parts of the watershed. By using cropland and developed land as independent variables, we lumped the remaining land covers into a third category of other land: primarily forest and grassland (Table 1). All 6 possible transitions of 10 km^2 were modeled among the three land cover categories for three watershed sections:

the Piedmont draining to the reservoirs, the Piedmont not draining to reservoirs, and the Coastal Plain (Table 1). We summarized all the results graphically, and tabulated the results for the land use transitions representing ongoing development of the watershed.

The third analysis simulated the effects on watershed discharges of several specific scenarios of change in land cover and point source discharges. For each scenario, we modified the land cover and/or point source discharges for the 23 watershed sections comprising the entire basin, ran the model, and aggregated the predicted discharges to 19 estuarine segments as described above. To concisely summarize the scenarios, predicted discharges were summed across all watershed sections and weeks to estimate the annual discharges to the estuary for each scenario, and then compared to totals from modeled current conditions.

Three of the scenarios were hypothetical ones, in which changes were applied uniformly across the entire Patuxent watershed. We implemented the land cover changes by adding or removing an equal amount of land from the forest-grassland cover category. Land development also increases PS loadings. It was assumed that development would not change the chemical composition of PS discharges, but would change discharge volume in the same proportion as the change in developed land. If we doubled developed land, we also doubled the volume of point source discharge. It was also assumed that none of the scenarios would change rates of water release from the Piedmont water supply reservoir. For scenarios that involved changes in both cropland and developed land, we ran separate simulations for each component of the overall scenario to help reveal the separate effect of each change. For example, in the half cropland and half developed land scenario, we simulated the effect of halving only the proportion of cropland, the effect of halving only developed land, the combined effects of both land cover changes, the effect of halving PS volumes, and the combined effects of all three changes.

A fourth scenario used realistic, spatially explicit predictions of future land cover estimated by the Maryland Department of Planning (MDP) using their growth simulation model (MOP 2000). MDP provided estimates of 1997 land use and projected land use for the year 2020 (MOP 2000; D. M. Weller personal communication). The projections were based on current zoning and land use policies and expected future population. The MDP data for both 1997 and 2020 used an MDP land use classification (MOP 1991; Weller and Edwards 2001) different from the land cover data that we used in our model (EPA–EMAP 1994), and estimates of the base fractions of cropland and developed land from Maryland Department of Planning and EPA–EMAP differ significantly (see Discussion). To apply our model to the 2020 projections, we had to develop relationships to translate the MDP projections into EPA–EMAP units. We applied stepwise multiple regression (SAS Institute, Inc. 1999) to province and MDP land use data for 211 Patuxent subwatersheds examined in an earlier analysis (Liu et al. 2000). These analyses yielded equations for converting MDP land use to EPA–EMAP land cover units. We converted both 1997 and 2020 MDP land data into EPA–EMAP units, then subtracted the 1997 from the 2020 estimates to get the predicted changes land cover fractions, which were added to the base EPA–EMAP land cover fractions (Table 1) to derive 2020 EMAP land cover fractions for use in this landscape discharge model.

We could not obtain official state of Maryland predictions for expected PS discharges in 2020, so we assumed that PS volume would increase in the same proportion as the increase in developed land while PS material concentrations remain constant. All of the major PS are currently located in the watersheds of segments 1 and 11 of the estuary model (Table 1, Fig. 2), so we used the ratio of 2020 developed land to base condition developed land in those two segments to represent the increase in PS discharges from the base condition to 2020.

Results

Statistical Nonpoint Source Models

The full statistical models for flow and material concentrations revealed which factors and interactions had significant effects on NPS discharges from the study watersheds (Tables 3 and 4). The reduced statistical models included only those significant factors, with the exceptions explained in the table footnotes. For each material, we calculated the total variability explained by the reduced model and the proportions of variability attributed to geographic and temporal factors and their interactions. The fitting procedure produced predictive NPS models for all materials except NH_4, and the reduced models explained more than 60% of the total variability among stations and weeks. The water flow model had the highest explanatory value ($r^2 = 0.87$), and the temporal variable (week) accounted for most of the variability explained (Table 3). The concentrations of two materials transported in solution, NO_3 and Si, were well-represented ($r^2 \geq 0.77$) by relatively simple models (Table 4), and most of the explained variability was attributed to geographic differences among water-

TABLE 3. Statistical models for weekly nonpoint source water discharge. The full model includes all factors and interactions. The numbers are the incremental percentages of variance explained by each single term when entered in the order listed. Statistically significant terms are flagged as *** $p < 0.0001$, ** $p < 0.01$. The reduced model includes terms significant in the full model, except as footnoted. Percentages of variance explained by the reduced model are given for week, all included geographic factors together, and all included interactions between week and geographic factors. the bottom row gives recalculated r^2 values after setting unrealistically low model predictions to the minimum values measured among the study watersheds (see text).

Factor	Variance Explained (%)
Full model	
Week	72.3***
Developed land	1.0***
Cropland	0.2***[1]
Province	0.1**
Cropland × province	0.5***[1]
Developed land × week	7.4***
Cropland × week	0.5
Province × week	6.6***
Cropland × Province × week	1.9***[1]
Total r^2 (% explained)	90.4
Reduced model	
Week	72.3
Geography	1.1
Interactions	13.8
Total r^2 (% explained)	87.1
Reduced model with weekly observed minimum	
Total r^2 (% explained)	87.2

[1] These terms omitted from final model because they produced clearly unreasonable differences in the effects of cropland between the Piedmont and Coastal Plain.

sheds. TN followed a similar pattern, probably because NO_3 is the dominant component of TN (Jordan et al. 2003). Significant proportions of PO_4, OP, TP, ON, and OC are transported while bound to particles (Jordan et al. 2003). Models for these materials attributed the most variability to temporal effects modified by geographic differences among watersheds, as represented by the land cover × week and province × week interactions. Relatively little variability in the particulate constituents was attributed to the simple temporal factor week, and even less variability to direct geographic effects (Table 4). Geographic differences, temporal effects, and their interactions were all not very useful in explaining NH_4 concentration, which had the poorest of all the models ($r^2 = 0.18$). Fortunately, NH_4 is a minor component of TN (Jordan et al. 2003), so the difficulty in modeling NH_4 concentration is less important for predicting TN discharge. The minimum observed concentration criterion, which we imposed to eliminate unreasonably low estimates, did not disrupt the predictive abilities of the models, rather the minimum limits increased overall r^2 values for most materials (Tables 3 and 4).

Evaluation of the Landscape Discharge Model

The landscape discharge model did a good job of representing the water discharges and nutrient concentrations observed during base conditions of the 2-yr study period. Example scatter plots of model results for the study watersheds aggregated to the annual scale (Fig. 3) show the strong relationships between the actual measurements and the model predictions. The plots also show how well the model predicts flow and concentration at station 251.1, which was not used in fitting the NPS flow and concentration models due to the PS and drinking water withdrawal in that watershed. However, the full landscape discharge model accounts for the effects of PS and reservoir management, and the station 251.1 data fall well within the clouds of points representing other stations (Fig. 3). Figure 3 also illustrates some differences among materials in the responses to weather. Data for flow are separated into two disjoint clusters of points representing the large difference in stream flow between the wet and dry years. In contrast, the N concentrations for most stations are quite similar in the wet and dry years, showing relatively little effect of weather. P is intermediate, showing generally higher concentrations in wet years, but with some overlap across all the stations between wet year and dry year data.

Although the model accounts for much of the variability among study watersheds at both the weekly (Tables 3 and 4) and annual (Fig. 3) time scales, model predictions for individual stations do vary from measured data (Fig. 3). Two study watersheds, 235 and 251.1, are particularly important since together they monitor about half of the watershed area of the Patuxent basin (Table 1). Model predictions of flow for these two watersheds were quite close to observed values in both years of the study (Fig. 3, Table 5). In both years, the model predicted well N concentrations for 251.1, but overestimated N concentrations at 235. P and sediment concentrations were harder to predict, as evidenced by lower percentages of variance explained (Table 4). At station 251.1, concentrations of these materials were overpredicted in the wet year (year 1), and underestimated in the dry year (Table 5). At station 235, these concentrations were underestimated in both years. However, the N and P scatter plots show that the differences between predicted and observed concentrations for 235 and 251.1 are quite small relative to the clear relationships between predictions and observations and to the scatter of individual stations around the overall relationships (Fig. 3).

TABLE 4. Statistical models for weekly nonpoint source material concentrations. The full models include all factors and interactions. The numbers are the percentages of variance explained by each single term when entered in the order listed. Statistically significant terms are flagged as *** $p < 0.0001$, † $p < 0.01$, ‡ $p < 0.05$. The reduced models include terms significant in the full model, except as footnoted. Percentages of variance explained by the reduced model are given for week, all included geographic factors together, and all included interactions between week and geographic factors.

Factor	TSS	PO_4	OP	TP	NH_4	ON	NO_3	TN	OC	Si
Full models										
Cropland	1.0*	1.6*	1.1*	2.0*	0.1[1]	0.3†	34.1*	28.6*	0.0[2]	10.4*
Developed land	0.6*	0.5*	0.7*	0.9*	3.3*	1.4*	0.2[3]	0.9*	0.9*	1.1*
Province	0.7*	4.3*	1.1*	3.7*	1.6*	0.7*	35.4*	23.6*	2.0*	54.1*
Cropland × province	0.0[2]	0.0[2]	0.0[2]	0.0[2]	0.2	0.2†	8.6*	9.7*	0.1[2]	2.0*
Week	11.5*	7.7*	7.1*	8.2*	13.3*	11.8*	2.4*	3.1*	8.8*	3.9*
Cropland × week	17.2*	18.6*	21.9*	18.4*	5.4	16.9*	1.0	3.4*	19.4*	0.5
Developed land × week	7.8*	13.9*	5.9*	9.8*	5.9	9.9*	0.3	2.3†	7.9*	2.0
Province × week	11.8*	14.4*	17.5*	14.0*	5.4	12.6*	2.2*	3.3*	15.1*	3.0*[4]
Cropland × Province × Week	6.9*	8.9*	5.2*	6.9*	1.2	8.5*	1.0	2.5†	5.9*	0.3
Total r^2	57.5	69.9	60.4	63.8	36.3	62.5	85.2	77.3	60.1	77.3
Reduced models										
Geography	2.3	6.4	2.9	6.6	4.9	2.7	78.4	62.8	2.9	67.7
Week	11.5	7.7	7.1	8.2	13.3	11.8	2.4	3.1	8.9	3.9
Interactions	43.7	55.8	50.5	49.0	0.0	48.0	2.6	11.4	48.3	0.0
Total r^2	57.5	69.9	60.4	63.8	18.2	62.5	83.4	77.3	60.1	71.6
Reduced model with weekly observed minimum										
Total r^2	61.8	74.6	68.0	69.6	18.3	67.3	83.4	78.1	66.2	71.7

[1] Cropland included in the reduced model because it is significant if entered after developed land.

[2] Nonsignificant terms automatically incorporated in the reduced model when the significant interaction of crop × province × week is included.

[3] Developed land included in the reduced NO_3 model for consistency with the TN model.

[4] Omitted. Became nonsignificant after cropland × week and developed land × week terms dropped.

We can also evaluate the consistency of the model by comparing alternate calculations of TN and TP. We can predict TN concentration two different ways: by directly fitting models with TN as the dependent variable and by adding predictions from separate models for NO_3, NH_4, and ON. Similarly, TP can be predicted directly or calculated by adding OP and PO_4. Among the 22 watersheds used to fit the NPS models, the sum of the modeled N or P components agreed with the directly modeled TN or TP within 2% relative error. For the two large watersheds, 235 and 251.1, the two estimates of TN agreed within 7% and the two P estimates differed by only 5%.

Table 5 also provides two estimates of the volume and composition of total discharge to the estuary under base conditions in 1997–1999. The modeled estimate uses model results for the entire watershed. The measured estimate uses the actual measured discharges from watersheds 251.1 and 235 (half the total watershed area), and relies on model results only for the unmonitored lower half of the watershed. The modeled estimates for the entire basin (Table 5) provide the base condition results to which results from alternate scenarios are compared. The base condition combines the EPA–EMAP 1991 land cover (EPA–EMAP 1994), NPS predictions based on measured watershed discharges for July 1997–August 1999, and PS discharges and reservoir management data for the same period.

Effects of Watershed Changes

The effects of land cover on stream flow and material concentrations are evident among simulations in which cropland and developed land proportions were each varied from 0% to 100% (Fig. 4). The graphs illustrate how the modeled effects of land cover differ between physiographic provinces and between wet and dry years. Although the NPS statistical models are linear (Tables 3 and 4), some of the simulated graphs are curved (Fig. 4). This occurs because the minimum criterion applied to eliminate unreasonably low concentrations introduces some nonlinearity at low fractions of cropland or developed land, or in the case of Si, at high fractions of developed land.

The different constituents showed some similar responses to changes in land cover. Modeled annual water flows increased with increases in developed land, but did not change with the fraction of cropland. All annual average material concentrations increased with increases in either cropland or developed land, except for Si concentration, which increased with the fraction of cropland but decreased with increasing developed land. For all material concentrations, an increase in the fraction of cropland generally produced a greater change in concentration than an equivalent change in the fraction of developed land. The axes in Fig. 4 provide a simple indicator of this pattern; for all materials except water, the axis range for the cropland relationship is larger than for the relationship of concentration to developed land. Within these broad general patterns, the effects of physiographic province, temporal variation, and their interaction varied among materials. Geographic variables provided most of the explanatory power in the nonpoint models for NO_3, TN, and Si (Tables 3 and 4). These models showed clear differences in the effects of cropland or developed land between provinces, but not much difference between wet and dry years. The patterns for NH_4 were even simpler. The NO_3 and Si models show a difference in the slopes of the land cover effects, while the NH_4 models had only a difference in level between provinces.

For the other materials (TSS, TP, PO_4, OP, ON, and OC) much of the variability explained in the NPS models was attributed to interactions between temporal and geographic factors (Tables 3 and 4), producing more complex patterns in Fig. 4. For TSS, TP, PO_4, OP, and TN, the effects of increasing cropland on nutrient concentration showed the same slope for both Coastal Plain and Piedmont in the wet year, but different and shallower slopes in the dry year. The effects of cropland in increasing nutrient concentrations were much stronger and more consistent between provinces in the wet year than in the dry year. Also in the wet year, the TSS, OP, and TN versus cropland curves for the two provinces had the same levels as well as the same slopes, so the province curves were almost identical. ON and OC had the most complex patterns in the concentration versus cropland plots; they had different slopes and levels for all the combinations of province and year. For most materials, the interactions of land cover proportion with physiographic province and year are more complex for developed land proportion than for cropland. One reason is that the minimum adjustment operates more frequently across the simulations varying developed land proportion, as evidenced by the greater nonlinearities in the curves graphed for the developed proportion simulations (Fig. 4).

Our separate analysis of 10-km² land transitions focuses on the effects of small changes from the

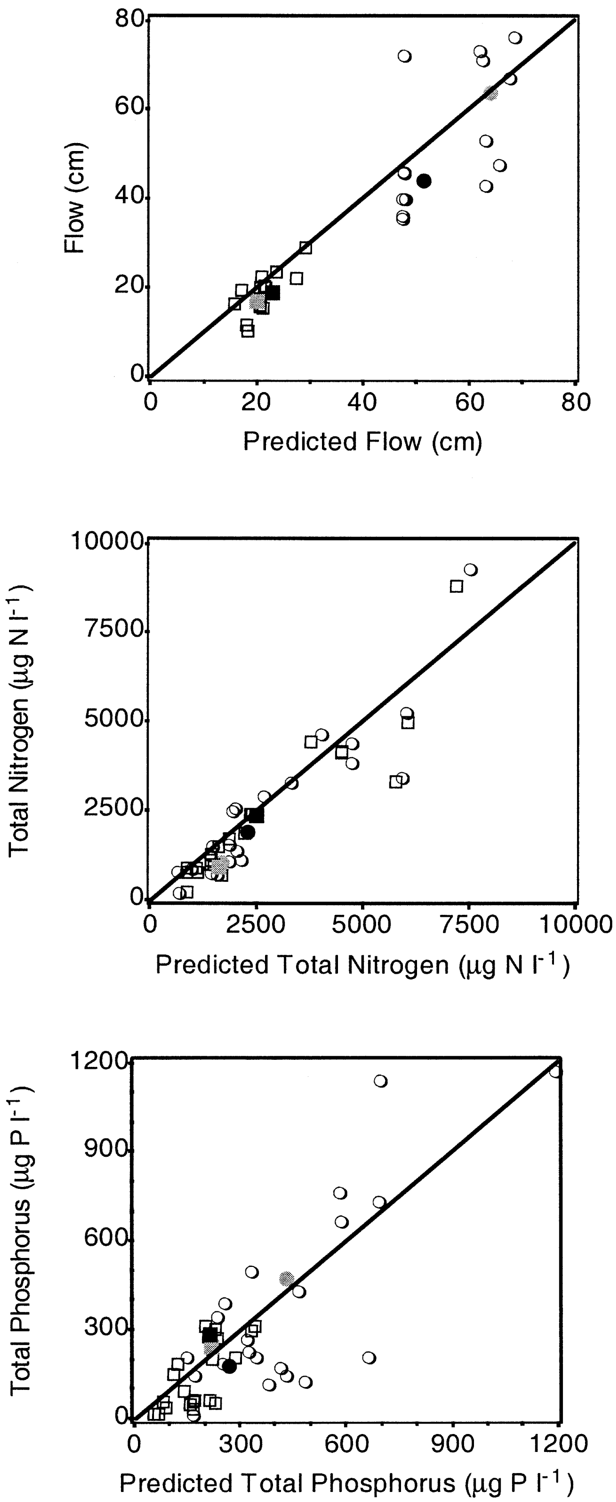

Fig. 3. Measured and simulated annual flows, TN concentrations, and TP concentrations for study watersheds. Weekly simulation results were aggregated to volume-weighted annual averages for the wet (circles) and dry (squares) years (years 1 and 2, respectively). Data from two stations are highlighted: station 235 (filled gray symbols) and station 251.1 (filled black symbols). Results for 251.1 include the effects of point sources and water management, but the 22 other stations lack significant point sources or water withdrawals so their data represent NPS discharges only. Points along the diagonal 1:1 line indicate perfect agreement between predictions and measurements. r^2 values for flow, TN, and TP are 0.84, 0.78, and 0.83, respectively.

TABLE 5. Measured and simulated material discharges and concentrations for the two-year watershed study. Modeled results are predictions of the landscape discharge model. Measured data for 251.1 and 235 come from monitoring stations sampling those two watersheds. The measured data for the entire watershed actually use measured data only for the half of the Patuxent drainage sampled by stations 235 and 251.1 (Table 1) and simulated results for the unmonitored half of the Patuxent basin. The modeled results for the entire watershed are the base condition results to which alternate watershed scenario results were compared (Table 4).

	Year	Flow cm	Concentrations (N and P in μg l^{-1}; TSS, OC, and Si in mg l^{-1}) TSS	TP	PO_4	OP	Tn	ON	NH_4	NO_3	OC	Si	Flow 10^6 m^3	Fluxes in Mg yr^{-1} TSS	TP	PO_4	OP	TN	ON	NH_4	NO_3	OC	Si
Watershed 251.1																						
Modeled	1	49.2	101	235	112	133	2,026	700	130	1,109	6.39	3.43	447	45,148	105	50	59	905	313	58	495	2,855	1,533
	2	20.6	29	180	108	73	2,239	686	169	1,551	4.14	2.52	187	5,396	34	20	14	418	128	32	290	774	471
Measured	1	44.3	45	180	81	99	1,920	656	129	1,135	5.87	3.45	403	17,923	72	32	40	773	264	52	457	2,363	1,391
	2	19.2	76	288	156	132	2,341	844	157	1,349	7.46	3.66	175	13,279	50	27	23	409	147	27	235	1,301	640
Watershed 235																						
Modeled	1	61.6	112	384	209	176	1,380	672	114	581	10.08	6.52	144	16,157	55	30	25	199	97	16	84	1,451	939
	2	17.7	47	180	93	88	1,260	637	126	505	7.38	6.24	41	1,938	7	4	4	52	26	5	21	306	259
Measured	1	64.2	215	475	266	209	1,092	636	82	374	9.00	5.40	150	32,230	71	40	31	164	95	12	56	1,350	811
	2	17.2	62	248	143	105	930	543	99	288	6.46	5.04	40	2,495	10	6	4	37	22	4	12	259	203
Entire Patuxent drainage																						
Modeled	1	56.9	124	412	231	185	1,766	690	115	883	8.70	6.73	1,306	161,278	538	301	241	2,306	901	150	1,153	11,358	8,794
	2	18.1	27	205	134	71	2,010	587	142	1,368	4.66	5.25	416	11,231	85	56	30	837	244	59	569	1,938	2,185
Measured	1	55.3	118	411	231	180	1,687	671	110	857	8.49	6.72	1,268	150,126	521	293	228	2,139	851	140	1,078	10,764	8,523
	2	17.5	49	259	161	98	2,017	643	133	1,256	6.01	5.70	403	19,671	104	65	40	812	259	54	506	2,419	2,297

base land cover proportions on material discharge. It is important to examine changes from the current condition because of the nonlinearity introduced by the weekly minimum adjustment, which makes the change in flow or concentration from a given land cover change depend on the initial land cover proportions (Fig. 4). The results of the simulations (Fig. 5, Table 6) show the effects of land cover transition, watershed section, and wet versus dry years on NPS discharges of water and 10 materials. Some general patterns emerge. Among land cover transitions, conversions between cropland and forest-grassland cause the greatest changes in discharge of all materials (except water flow and Si) regardless of place or year. Converting forest-grassland to cropland causes the largest increases in discharges, and the reverse transition causes the greatest decreases. Conversions between cropland and developed land have the next strongest effect on most material discharges and the strongest effect on Si. Changing cropland to developed land increases water flow, but reduces discharges of all other materials. Converting developed land to cropland would do the opposite. Transfers between developed land and forest-grassland have the lowest effect on discharges, but the effects are still important. Developing forest-grassland raises flow and discharges of all materials, except Si, which declines.

There are also general differences between the two physiographic provinces. The effects of changing land cover on NO_3 and TN discharges are greater in the Piedmont than in the Coastal Plain; for all other materials, except flow, the effects of land use change are greater in the Coastal Plain. Differences between the two Piedmont areas (with and without reservoirs) are less consistent. Differences in the response to land cover change can arise from the effects of the reservoirs and from differences in the base condition land cover proportions between the two Piedmont areas. For many materials, such as TN, Piedmont with reservoirs shows a smaller response to land cover change than Piedmont without reservoirs because of the removal of material-laden water from the reservoirs. For other materials, such as OC, the effects of initial land cover predominate so that some transitions show a greater change in the Piedmont with reservoirs.

The importance of flow regime is evident in comparing results for wet and dry years. Although flow was much lower in the dry year, the flow change from converting to or from developed land was greater in the dry year than in the wet year. For all other materials, the land cover changes induced larger changes in discharges in the wet year than in the dry year. The effect of year was much

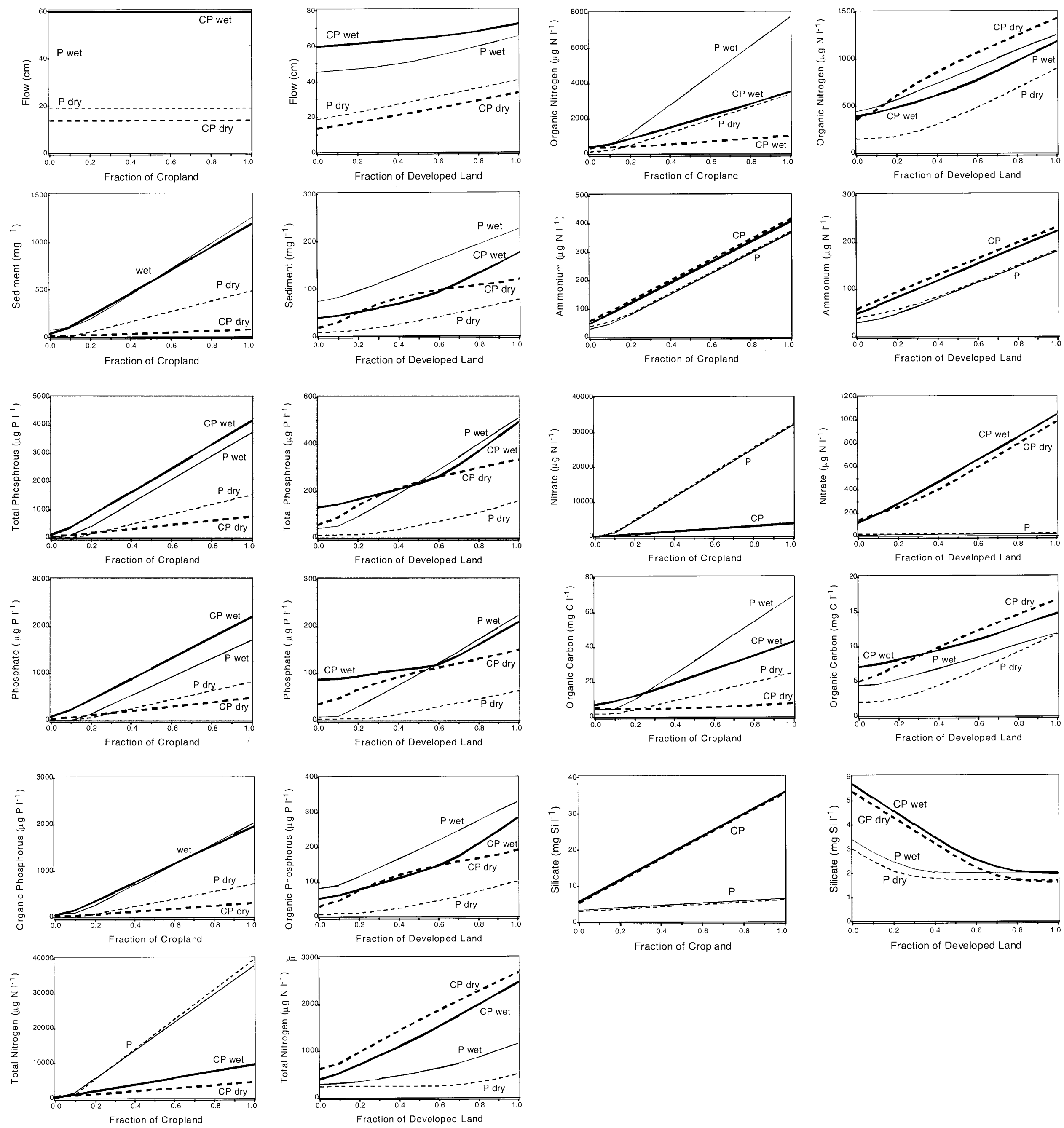

Fig. 4. Modeled effects of the fractions of cropland and developed land on NPS water discharge and material concentrations. Separate curves are shown for the Coastal Plain (CP, thick lines) and Piedmont (P, thin lines) provinces in year 1 (wet, solid lines) and year 2 (dry, dashed lines). Some of the relationships appear curved because of the operation of the minimum concentration criterion at lower fractions of cropland or developed land (see text).

stronger for TSS and forms of P than for OC, Si, and the forms of N; that is, the ratio of the discharge change in the wet year to the discharge change in the dry year is greater for TSS and P.

Simulations of specific alternate watershed scenarios show striking differences in nutrient delivery to the estuary (Table 7). When cropland was doubled from 10% to 20% of the landscape, water discharge was unaffected but discharges of all other materials went up. Discharges of TSS, TN, NO_3, and all forms of P increased by 70% or more. Increases in NH_4, ON, OC, and Si discharges were

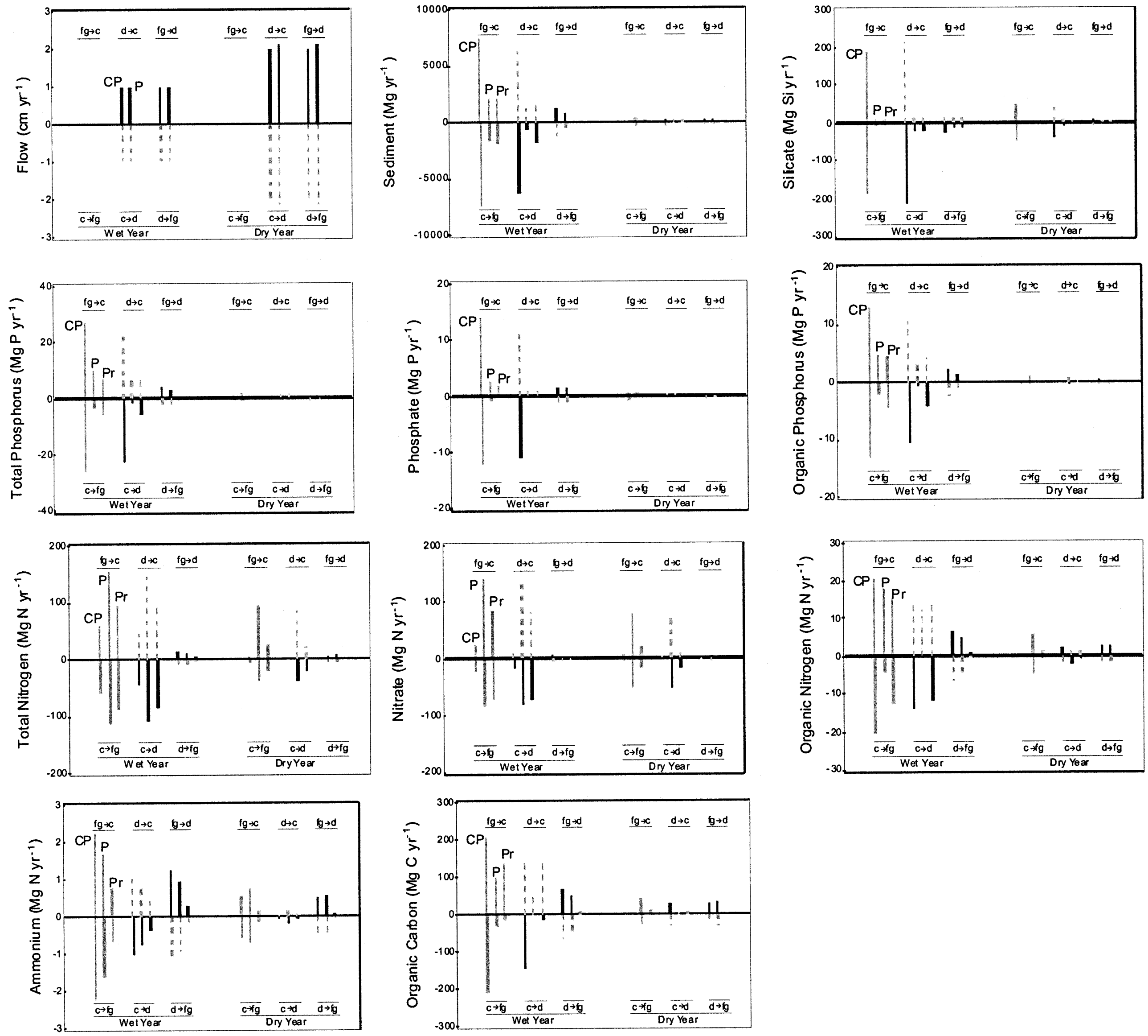

Fig. 5. Changes in NPS material discharges from 10-km^2 land cover transitions in three parts of the Patuxent drainage. We simulated the changes in NPS discharges from converting a 10 km^2 of land from one land cover to another. Each panel presents results for one material. The left hand side of a panel gives results for year one, a wet year. The right hand side shows results for year 2, an unusually dry year. On each side of a panel, there are 3 groups of bars representing three pairs of land cover transitions. The leftmost set of bars in each year represents the effect of converting forest-grassland to cropland (fg→c, above zero) and cropland to forest-grassland (c→fg, below zero). The middle set shows converting developed land to cropland (d→c, above zero), or the reverse (c→d, below zero). The rightmost set of bars shows converting forest-grassland to developed land (fg→d, above zero) or the reverse (d→fg, below zero). Likely future transitions (cropland or forest-grassland to developed land) representing ongoing development (Tassone et al. 1998; Bockstael and Irwin 2003; D'Elia et al. 2003) are shown in black (and summarized in Table 6), possible but unlikely transitions (exchanges between cropland and forest-grassland) are shown in gray, and very unlikely transitions (developed land to cropland or forest-grassland) are presented as dashed bars. These possibilities represent a return to historical watershed conditions (U.S. Geological Survey 1999). Within each subset of three bars, the leftmost bar shows Coastal Plain results (CP), the middle bar is for the Piedmont without reservoirs (P), and the rightmost is for Piedmont with reservoirs (Pr).

more moderate but still important (20–40%). The effects of increasing cropland were less pronounced in the dry year than in the wet year. Atomic N:P ratios fell from current conditions during the wet year, but were higher than current conditions in the dry year.

Doubling developed land from 12% to 24% of the watershed increased NPS water discharge by

TABLE 6. Changes in nonpoint source discharges resulting from developing a 10-km^2 area of either cropland or forest-grassland. Results are shown for three parts of the Patuxent drainage: Coastal Plain, Piedmont with reservoir, and Piedmont without reservoir.

	Year	Change in Flow (cm)	Change in material discharge (Mg yr^{-1})									
			TSS	TP	PO_4	OP	TN	ON	NH_4	NO_3	OC	Si
From forest-grassland												
Piedmont with reservoir	1	0.00	154	0.51	0.24	0.34	4.31	1.07	0.31	2.22	−2.38	−13.99
	2	0.00	21	0.03	0.01	0.02	1.19	0.19	0.06	0.60	4.09	−3.14
Piedmont no reservoir	1	0.99	916	3.00	1.35	1.59	9.84	4.90	0.94	4.64	50.41	−13.87
	2	2.12	227	0.52	0.23	0.32	6.19	2.77	0.56	4.34	34.37	−2.98
Coastal Plain	1	1.00	1,269	3.94	1.50	2.44	15.27	6.44	1.21	6.37	67.09	−25.51
	2	1.99	246	0.90	0.44	0.46	5.51	2.72	0.53	2.54	29.91	7.06
From cropland												
Piedmont with reservoir	1	0.00	−1,818	−5.60	−0.17	−4.06	−83.94	−11.90	−0.36	−71.43	−17.84	−22.27
	2	0.00	−56	−0.08	−0.02	−0.10	−19.80	−0.58	−0.07	−18.46	−1.68	−4.99
Piedmont no reservoir	1	0.99	−707	−1.34	0.46	−0.74	−107.78	0.25	−0.77	−81.07	13.37	−22.51
	2	2.12	−95	−0.35	−0.15	−0.24	−38.31	−2.22	−0.20	−50.16	0.66	−6.54
Coastal Plain	1	1.00	−6,257	−22.49	−11.17	−10.66	−44.70	−14.00	−1.02	−17.80	−142.38	−212.08
	2	1.99	307	−0.15	−0.29	0.14	−0.41	2.29	−0.05	−3.68	31.69	−41.19

5% and also increased NPS discharges of all materials (except Si) between 13% and 27%. The base land cover of the entire watershed is 9.9% cropland and 12.0% developed land (Table 1). Doubling developed land then changes a larger land area than doubling cropland; the effect of doubling developed land on NPS material discharges was less because material concentrations rise less steeply with the proportion of developed land than with the proportion of cropland (Fig. 4). Si discharges declined with increasing developed land because Si concentrations are inversely related to the proportion of developed land (Fig. 4). Doubling PS discharges would increase water flow by another 8% and add additional N and P. When both developed land and PS are doubled, increases in PS contributions would be less than the increases in NPS contributions for OP, TP, ON, and NH_4, but greater than NPS increases for NO_3 and PO_4. Even when the NPS and PS components of doubling developed land are combined, the total increase in discharge of all forms of N and P (except NH_4) was less than for doubling cropland. Doubling developed land did not change N : P ratios of NPS discharges, but raised the N : P ratio by 12% when PS increases were included. The percentage increases in both NPS and PS discharges from doubling developed land were greater in the dry year than in the wet year.

The third scenario of halving cropland, developed land, and PS flow produced dramatic improvements in water quality. Halving cropland from 9.9% to 5% of the watershed did not change water flow, but reduced NPS fluxes of all materials. TSS, TP, and TN fluxes declined to about 70% of current levels. Halving developed land from 12.0% to 6% reduced water discharge to 98% of current levels, and reduced discharges of all materials, except Si, which increased slightly. TSS, TP, and TN fluxes all declined to about 90% of current levels, a smaller decrease than achieved by halving cropland. Halving PS discharge decreased water discharge by 4% and decreased discharges of all forms of N and P. Combining all three effects gave a total flow decrease to 94% of current conditions while reducing TSS, TN, and TP fluxes to 50–60% of current levels. NO_3 discharges declined to 45% of current levels. The atomic N : P ratio was increased by halving cropland and decreased by halving PS. When all three manipulations were combined, there was a net decline in the ratio to 95% of its current value.

The year 2020 projections show increased discharges of water and all materials (except Si). In this scenario, cropland declines from 9.9% to 7.7% while developed land increases from 12.0% to 23.3% and the volume of PS discharge rises by a

TABLE 7. Changes in water and material discharges from the entire Patuxent watershed under alternate watershed scenarios. Annual scenario predictions are expressed as ratios to the same year of base condition of modeled discharges for the two-year period of watershed sampling (Table 5).

		Ratios to Modeled Base Conditions											
Scenario	Year	Flow	TSS	TP	PO_4	OP	TN	ON	NH_4	NO_3	OC	Si	Atomic N:P Ratio
Double cropland	1	1.00	1.85	1.91	1.80	2.01	1.76	1.49	1.29	1.93	1.40	1.35	0.92
	2	1.00	1.24	1.32	1.29	1.37	1.50	1.14	1.20	1.62	1.08	1.36	1.14
Double developed land	1	1.02	1.20	1.18	1.12	1.25	1.17	1.19	1.21	1.14	1.16	0.93	0.99
	2	1.12	1.65	1.27	1.19	1.43	1.23	1.37	1.29	1.16	1.55	0.99	0.96
Double PS flow	1	1.06	1.00	1.06	1.09	1.02	1.18	1.09	1.17	1.27	1.00	1.00	1.12
	2	1.16	1.02	1.40	1.48	1.23	1.51	1.31	1.33	1.58	1.00	1.00	1.08
Double developed and PS	1	1.08	1.20	1.24	1.21	1.27	1.35	1.28	1.38	1.42	1.16	0.93	1.09
	2	1.29	1.66	1.67	1.67	1.65	1.74	1.68	1.62	1.75	1.55	0.99	1.04
Half cropland	1	1.00	0.64	0.63	0.68	0.60	0.68	0.82	0.86	0.65	0.87	0.82	1.08
	2	1.00	0.98	0.90	0.90	0.89	0.87	0.96	0.91	0.77	0.99	0.82	0.97
Half developed land	1	0.99	0.92	0.93	0.96	0.91	0.93	0.93	0.90	0.93	0.94	1.04	0.99
	2	0.94	0.69	0.88	0.92	0.81	0.91	0.85	0.89	0.94	0.79	1.00	1.03
Half cropland and developed land	1	0.99	0.58	0.58	0.64	0.53	0.62	0.76	0.76	0.59	0.82	0.86	1.06
	2	0.94	0.66	0.78	0.83	0.71	0.80	0.82	0.80	0.73	0.79	0.83	1.02
Half PS flow	1	0.97	1.00	0.97	0.96	0.99	0.91	0.96	0.91	0.86	1.00	1.00	0.94
	2	0.92	0.99	0.80	0.76	0.89	0.74	0.85	0.83	0.71	1.00	1.00	0.93
Half cropland, developed land, and PS flow	1	0.96	0.58	0.55	0.60	0.52	0.52	0.71	0.68	0.46	0.82	0.86	0.95
	2	0.86	0.65	0.59	0.59	0.59	0.54	0.66	0.63	0.44	0.79	0.83	0.92
Year 2020 scenario, cropland down	1	1.00	0.87	0.87	0.90	0.85	0.84	0.93	0.95	0.80	0.96	0.94	0.97
	2	1.00	0.99	0.96	0.96	0.96	0.91	0.98	0.96	0.85	0.99	0.94	0.94
Year 2020 scenario, developed land up	1	1.01	1.15	1.14	1.09	1.19	1.13	1.14	1.17	1.12	1.12	0.94	1.00
	2	1.09	1.47	1.20	1.15	1.31	1.16	1.25	1.20	1.12	1.37	1.02	0.96
Year 2020 scenario cropland down and developed land up	1	1.01	1.01	0.99	0.97	1.02	0.97	1.06	1.11	0.90	1.06	0.88	0.98
	2	1.09	1.48	1.16	1.10	1.27	1.04	1.23	1.16	0.94	1.35	0.95	0.90
Year 2020, PS volume up	1	1.04	1.00	1.04	1.06	1.01	1.13	1.06	1.12	1.20	1.00	1.00	1.09
	2	1.12	1.01	1.28	1.35	1.17	1.37	1.22	1.24	1.42	1.00	1.00	1.06
Year 2020 scenario, cropland down, developed land up, PS volume up	1	1.05	1.01	1.03	1.03	1.03	1.10	1.12	1.24	1.10	1.06	0.88	1.07
	2	1.21	1.50	1.44	1.45	1.43	1.41	1.45	1.39	1.36	1.35	0.95	0.98

factor of 1.72 (Table 8). Taken separately, the decline in cropland reduces material discharges while the increase in developed land raises flow and material discharges (except for Si). When the two land cover transitions are combined, the effects on NPS discharges of TSS, TN, and TP cancel out: TN and TP discharges in 2020 discharges are within 1% of current values while TSS discharge rises 4%. The decrease in material discharges due to reducing cropland offsets the increases in NPS discharges from developing an area 5.85 times larger than the lost cropland. When PS increases are also included, the total increases from adding developed land outweigh the decreases from removing cropland, and there are net increases of 9% in flow, 8% in TP discharge, and 18% in TN discharge.

TABLE 8. Base condition (MOP 1991; EPA-EMAP 1994) and year 2020 land cover percentages for the entire Patuxent basin in EPA-EMAP and MOP units. Year 2020 land cover percentages from a growth simulation model (MOP 2000) were translated from MDP units into EMAP units using multiple regression equations as described in the text. % EMAP cropland = 12.23 − 0.31 × % MDP cropland − 0.11 × % MDP developed − 0.13 × % MDP forest − 0.06 × % Piedmont province ($r^2 = 0.59$, $p < 0.0001$). % EMAP developed land = 2.95 − 0.13 × % MDP cropland + 0.72 × % MDP developed ($r^2 = 0.73$, $p < 0.0001$).

	MDP Units		EMAP Units	
Land Cover	Base	2020	Base	2020
Cropland	22.5	17.5	9.9	7.9
Developed land	24.6	38.7	12.0	23.3

There were also differences in the effects of the 2020 projections between the wet and dry years. The decline in discharges from reducing cropland was stronger in the wet year than in the dry year. In contrast, increasing developed land raised both NPS and PS material discharges more in the dry year than in the wet (Table 7). Under 2020 conditions, wet year water flow, TSS, TN, and TP discharges would increase by 5%, 1%, 3%, and 10%, respectively, over current conditions in a wet year. In a dry year, flow, TSS, TN, and TP discharges would increase by much higher amounts of 21%, 50%, 44%, and 41%, respectively.

Discussion

Nutrient Sources and Effects of Watershed Changes

A major objective of our study was to quantify the effects of land cover on NPS discharges in order to predict the effects of land cover change. Our previous research has documented strong effects of land cover, particularly cropland, on N discharges (Jordan et al. 1997a,b; Liu et al. 2000). We also observed that the N discharges increase more strongly with cropland proportion in the Piedmont than in the Coastal Plain (Jordan et al. 1997c). Our Patuxent research (this paper; Jordan et al. 2003) confirms those results for a different set of watersheds and extends the models to include significant effects of developed land (Tables 3 and 4). Unlike some previous studies (Jordan et al. 1997a,b; Liu et al. 2000), the Patuxent research also documents significant effects of land cover on P concentrations in watershed discharges (Table 4, Fig. 4, and Jordan et al. 2003). The patterns of significant explanatory factors (Table 4) show the greater importance of temporal factors relative to geographic ones in explaining concentrations of particulate materials like TSS and forms of P. This reflects the importance of episodic storm events in transporting particulate materials (Jordan et al. 1997a,b; Correll et al. 1999e), but the effects of storms were modified by geographic differences among watersheds (Table 4). In contrast, concentrations of dissolved materials; like NO_3, TN, and Si; were less temporally variable, and the variations were more closely related to geography than to differences among weeks (Fig. 3, Table 4).

Croplands are the dominant NPS of nutrients in the Patuxent watershed, even though they comprise only 10% of the basin area (Jordan et al. 2003). For most materials, concentration responds more strongly to the percentage of cropland than to the percentage of developed land (Fig. 4); conversions of cropland to other land uses change nutrient loads more than land cover conversions not involving cropland (Table 6, Fig. 5); and nutrient declines from losses of small cropland areas can equal the nutrient increases from developing much larger areas (Table 7). Our findings suggest that careful management of crop systems remains critical to managing overall watershed discharges, despite the low and declining percentage of croplands in the watershed.

PS discharges are also an important nutrient source. During the first, relatively wet year of our study, PS supplied 5% of the water, 22% of the N, and 7% of the P delivered to the estuary (Jordan et al. 2003). In the second, drier year, PS were more important, supplying 14% of the water, 46% of the N, and 34% of the P. PS were formerly the largest sources of N and P, but improved treatment methods have reduced nutrient concentrations in wastewater discharges and NPS discharges are now dominant (Boynton et al. 1995; Sprague et al. 2000; D'Elia et al. 2003). However, the volumes of discharge from the largest treatment plants in the watershed are still increasing (Sprague et al. 2000) and will continue to do so as the watershed's population increases (D'Elia et al. 2003). Managing the volume and composition of PS discharges will remain critical to future nutrient discharges. For example, in our analysis of the year 2020 scenario (Table 7), declines in NPS nutrients from a lower proportion of cropland nearly offset increases in NPS nutrients from greater development. Including the increased point sources that would accompany more development tipped the balance toward higher future nutrient loads.

Scenario Analysis

Our scenario simulations quantified the possible shifts of nutrient discharges with changing watershed conditions (Table 7). Scenarios with increased cropland are relevant to earlier watershed conditions when agriculture was more prominent (U.S. Geological Survey 1999; D'Elia et al. 2003). Scenarios with more developed land are relevant to possible future conditions if development continues (Tassone et al. 1998; MOP 2000; Bockstael and Irwin 2003). Manipulations of cropland had greater effects than changing equivalent areas of developed land (Figs. 4 and 5, Tables 6 and 7). We also observed important differences between wet and dry years in the responses to land cover change (Figs. 3, 4, and 5, Table 7). For example, doubling cropland changes nutrient discharges more in the wet year than in the dry year (Table 7). In contrast, doubling developed land produced greater changes relative to base conditions under dry year conditions. In the double developed land and PS scenario, PS had more effect on the net increase in nutrient discharges under dry conditions than under wet ones. Similar patterns in the effects of increased development in dry and wet years were also evident in the year 2020 simulation. We expect increased PS discharges to have more effect in dry years than in wet years, because NPS discharges decline strongly with lowered rainfall while PS discharges remain relatively constant. NPS discharges contributed more to the total increases in 2020 dry year discharges than did PS (Table 7, see year 2 results for year 2020 developed land up and year 2020 point sources up). The observed differences between wet and dry years illustrate the importance of considering different weather conditions in predicting the effects of watershed changes on material discharges. Models based on average flow conditions only may miss important effects.

Strengths and Limitations

This model represents a parsimonious, empirical approach to simulating landscape nutrient discharges and their responses to watershed changes. At broad, landscape scales, simpler modeling approaches often work better (Meentemeyer and Box 1987; Turner 1989). Rather than relying on large numbers of mechanistic parameters that must be estimated from the literature or other data sources, this model was statistically fit to an extensive data set of measured watershed discharges. These models captured much of the temporal and geographic variability inherent in those measurements. Our statistical approach also produces quantitative measures of model adequacy (Tables 3, 4). No adjustments were made to the model to optimize predictions for any single calibration watershed, preferring instead to preserve the generality and statistical rigor of the fitting approach. A particular set of sections of the Patuxent watershed was analyzed (Table 1), but different or smaller subwatersheds could be used for other analyses demanding higher spatial resolution. This model was developed with data from the Patuxent and Rhode River watershed, but could probably be safely applied to other areas in the Coastal Plain and Piedmont regions of Maryland, where weather patterns and nutrient discharges are similar to these observations in the Patuxent basin (Jordan et al. 1997a,b,c, 2003). The general modeling approach could also be applied in other basins where many watersheds with contrasting land use patterns have been simultaneously monitored.

This approach does have some limitations. By modeling temporal variability as described here, the actual weather regime during the study period and its effects on flow and material concentrations are embedded in the model parameters. The models cannot simulate the effects of alternate weather conditions that were not observed during the study, such as greater rainfall, higher temperatures, or different distributions of rainfall within a year. The model can effectively represent how changes in land cover would alter water discharge and nutrient concentrations under the weather regime that was observed. Because the study included one wet year and one dry year, predictions can be contrasted for the two years to infer how this kind of weather variation would interact with changing land cover.

This NPS model considers two sources of geographic variation among watersheds: physiographic province and land cover, represented by cropland and developed land. Other NPS models include more land cover types, but our analyses showed that only two significant axes of land cover variation could be included in the statistical models relating concentrations to land cover among the study watersheds. Other factors, such as the density of septic systems (Nizeyimana et al. 1996; Wernick et al. 1998) and soil properties (Kellogg et al. 1992; Natural Resources Conservation Service 1995) can also influence NPS discharges. This approach could incorporate these factors if suitable geographic data were available to include in the statistical model. We continue to seek good data on other possible independent variables and to test whether they can enhance the predictive power of statistical models.

This model does not explicitly represent the effects of land management practices. In projecting to alternate scenarios, it is assumed that agricultural and developed lands keep the same management practices and associated nutrient discharge characteristics as the watersheds that were monitored. Modeled nutrient discharges could be adjusted with a posteriori estimates of how changes in land management, including implementation of best management practices, would alter NPS discharges. The current model could also be analyzed to assess what levels of reductions in PS fluxes or NPS discharges from cropland and developed land could be consistent with desired nutrient load targets.

This model also lacks mechanisms to represent losses of nutrients within the stream network. Large amounts of inorganic N can be removed in short transits of headwater stream channels (Peterson et al. 2000). Headwater removal is implicitly included in our empirical model because the monitoring stations sample discharges from headwater or higher order streams. N can also be removed in larger stream reaches. Initial analyses of the SPARROW model (Smith et al. 1997) indicated 51–55% P retention and 55–61% N retention in stream reaches with N and P levels similar to those of Patuxent streams. A later SPARROW analysis (Alexander et al. 2001) reported 37% average in-stream N retention in the Chesapeake drainage, but negligible N retention in stream networks showing few reaches in the RF1 digital stream map (DeWald et al. 1985). A Chesapeake-specific SPARROW version (Preston and Brakebill 1999) estimated in-stream removal of 70% the N and 94% of the P generated in the upper Patuxent watershed (essentially our watershed 251.1, Sprague et al. 2000). The Chesapeake Bay Program watershed model (Bicknell et al. 1997; Linker et al. 1999) estimates high N retention (60–80%) within the stream network of the entire Chesapeake drainage (Alexander et al. 2001), while the RivR-N model estimates 42–76% N removal in the streams of four Chesapeake tributaries (Seitzinger et al. 2002). In contrast, the SWAT watershed model (Srinivasan et al. 1993) predicted much lower in-stream N loses of 5–14% across 34 drainage basins, roughly ⅕ the predictions of SPARROW for the same basins (Alexander et al. 2001).

If in-stream retention in higher-order streams does remove a large fraction of the N and P entering the Patuxent stream network, then this study's model should grossly overestimate N and P losses from larger Patuxent subwatersheds because it does not account for nutrient removal in large streams. However, predictions of TN and TP discharges for our two largest measured basins (235 and 251.1) are quite consistent with relationships largely based on measurements of much smaller basins (Fig. 3). This result suggests that omitting processing in higher order streams may not introduce large errors for the Patuxent watershed, and argues against large fractions of in-stream retention upstream of the Patuxent estuary. These findings also illustrate the difficulty of using watershed discharge data to resolve among different hypothesized rates of in-stream removal.

Comparison to Other Models

A variety of discharge models have been developed for the Patuxent watershed. These models differ in spatial, temporal, and mechanistic detail, and in the degree of calibration to measured watershed discharges. The Patuxent is represented by three watershed segments in the Chesapeake Bay Program (CBP) applications of the HSPF model (Bicknell et al. 1997; Linker et al. 1999). A Patuxent-specific version of HSPF offering more spatial detail (39 segments) and greater local calibration (9 Patuxent stations) was also developed (Aqua Terra et al. unpublished data), but work was suspended before the model was thoroughly analyzed and applied. The Patuxent Landscape Model (PLM) is another model that incorporates more mechanistic detail on ecosystem processes and higher spatial resolution, using raster-based modeling to divide the Patuxent into thousands of grid cells (Voinov et al. 1999; Costanza et al. 2002). Like HSPF, PLM operates on a fine timescale (daily or finer) and includes hundreds of mechanistic parameters that are estimated indirectly then adjusted in model calibrations to actual watershed discharge data. The MDP has developed a Nonpoint Source Assessment and Accounting System (MOP 1993, 1995; Tassone et al. 1998), which predicts annual nutrient losses for over 100 Patuxent subwatersheds using loading coefficients (e.g., Beaulac and Reckhow 1982) modified by algorithms representing nutrient management alternatives. The U.S. Geological Survey SPARROW model fits statistical relationships relating annual stream load measurements to nutrient inputs (fertilizer application, PS, atmospheric deposition, and others) and modeled transport factors. The model includes considerable spatial detail represented by the individual reaches of a stream map and associated land areas. SPARROW models fit for both the entire United States and for the Chesapeake Bay only have been used to draw inferences about nutrient inputs to Chesapeake Bay (Smith et al. 1997; Preston and Brakebill 1999; Alexander et al. 2000, 2001).

TABLE 9. Patuxent watershed TN and TP discharges predicted by four watershed models: the Chesapeake Bay Program (CBP) watershed model (Bicknell et al. 1997; Linker et al. 1999), the Maryland Department of the Environment Patuxent watershed model (Aqua Terra et al. unpublished report), the Maryland Department of Planning (MDP) Nonpoint Source Assessment and Accounting System (MOP 1993, 1995; Tassone et al. 1998; Weller personal communication), and the SERC model (this paper; Jordan et al. 2003). The last two columns give the fraction of TN and TP discharge estimated to originate from croplands (where available).

		Nutrient Discharge ($Mg\ yr^{-1}$)		Percentage from Cropland	
Model	Year	TP	TN	TN	TP
SERC	1997–1998	538	2,306		
	1998–1999	85	837		
	Avg	311	1,571	56	79
CBP 2000	Avg	136	1,853	14	31
MDP 1990	Avg	140	1,456	48	62
MDP 2010	Avg	114	1,367	25	39
SERC 2020	1	554	2,536		
	2	123	1,180		
Aqua Terra	1986	177	1,828		
	1987	183	2,041		
	1988	167	1,880		
	1989	307	3,537		
	1990	187	2,580		
	Avg	204	2,373		

It is difficult to compare results of the various Patuxent models using published reports because the reports differ in the nutrient constituents, geographic areas, and time periods analyzed. However, estimates could be assembled from four models of average TN and TP discharge for the entire watershed (Table 9). The differences in TN and TP fluxes among the models seem relatively small compared to the variability among years observed for the models reporting predictions for more than 1 yr (Table 9). Load estimates were not reported for the Patuxent Landscape model, but average N concentration at Bowie for 1997 was predicted to be 11 mg N l^{-1} (Costanza et al. 2002), well above observed average N concentrations of 2–3 mg N l^{-1} (Table 5 and Sprague et al. 2000). The Smithsonian Environmental Research Center (SERC), CBP, and MDP models differ more in their attribution of sources and sinks of nutrients than in their average output estimates. For example, this model attributed 56% of the N load to croplands, while the CBP model attributes only 14% to agriculture, and the MDP model 48% (Table 9). For P, the

TABLE 10. Coefficients of determination (r^2) for three dependent variables: concentration (mg l^{-1} or μg l^{-1}), yield (m^3 ha^{-1} or kg ha^{-1}), and total watershed flux (10^6 m^3 or Mg). We calculated r^2 by relating measurements from the study watersheds to predictions of the final weekly statistical models (Tables 3 and 4). Both measurements and model results were averaged to the annual scale before calculating r^2

	Percent Variance Explained		
Material	Concentration	Yield	Flux
Flow	—	84	99.5
TSS	60	76	99.3
TP	75	88	99.1
PO_4	73	84	99.4
OP	73	87	97.4
TN	83	70	95.1
ON	71	83	97.0
NH_4	50	72	97.0
NO_3	86	67	87.7
OC	72	84	98.1
Si	85	84	97.8

percentages are 79%, 31%, and 62% for SERC, CBP, and MDP, respectively. Available models also differ in the amount of nutrients attributed to instream removal processes (see above). Such differences in attributing land sources and aquatic sinks of nutrients merit further study. The models are being used to guide potentially disruptive and costly nutrient management decisions, and the attributions are critical for identifying effective and acceptable management strategies. The wide variety of models available for the Patuxent watershed offers a valuable opportunity to further compare the strengths and implications of different modeling approaches.

Evaluating Model Fit

To evaluate performance, modelers often report coefficients of determination (r^2), which estimate the amount of variation explained by the model. For watershed nutrient models, the predicted variables in such calculations may be material concentrations (this paper, Jordan et al. 1997a,b, 2003), yield of nutrient in mass per unit area (e.g., Jones et al. 2001), or total flux of nutrient discharged from the entire watershed area (Smith et al. 1997; Linker et al. 1999; Preston and Brakebill 1999). However, coefficients of determination based on concentration, yield, and total flux can suggest very different assessments of model quality. R^2 values for discharge predictions were calculated from this model represented as concentrations, yields, and total watershed fluxes (Table 10).

For 7 of 10 materials considered, r^2 values for predictions of yield were higher than for predictions of concentration, and the models explained 11–22% more of the variability in yield than of the variability in concentration (Table 10). For three materials (TN, NO_3, and Si), r^2 was less for yield than for concentration. Nutrient yield is typically calculated as water flow per unit area (water yield) multiplied with nutrient concentration, so nutrient yield confounds the variability in concentration with variability in water flow. In extreme cases, examination of nutrient yield may suggest that a nutrient has been well modeled, when in fact all the apparent explained variability is actually the variability in water yield and the nutrient model is really no more explanatory than a water yield model. In our results, particulate materials whose concentrations rise with increasing flow, such as sediment or forms of P, showed enhancement of r^2 in estimating yield relative to estimating concentration. In contrast, the yield r^2 was less than the concentration r^2 for NO_3, which is largely transported in subsurface flow and is diluted during high flow periods (Jordan et al. 1997c). For NO_3, opposing variations in flow and concentration seem to cancel, so that r^2 is lower for nutrient yield than for concentration, while joint variations in water yield and the concentrations of particulates, lead to higher r^2 for yield than for concentration. NH_4 showed largest enhancement of r^2 for yield relative to concentration. In this case, the concentration model ($r^2 = 0.50$) was the poorest of 10 materials examined (Table 3), but the ability to predict flux/area was enhanced ($r^2 = 0.72$) by the relatively higher predictability of water yield ($r^2 = 0.9$, Table 2). If we evaluated model performance for NH_4 yield rather than NH_4 concentration, our success in predicting NH_4 yield would mask our relatively poor modeling of factors controlling NH_4 dynamics.

The interpretation of model quality for predictions of total watershed flux is further confounded. Large watersheds discharge more water and materials than small watersheds. This trivial pattern further enhances total flux r^2 values relative to yield r^2 values for all materials considered (Table 10), but the higher r^2 values clearly do not represent increased understanding of nutrient dynamics. The same patterns are observed with other measures of fit or even in visually comparing plots of measurements against predictions for concentration, yield, or total flux.

Nutrient models should be compared using their abilities to predict nutrient concentrations. The success in representing nutrient dynamics can then be examined separately from the ability to model water flow and from the trivial effects of watershed size.

Importance of Land Cover Data

The quality of land cover data presents an especially important limitation for this model and for other analyses or models predicting nutrient dis-

TABLE 11. Land cover for the Patuxent basin from four different land cover data sets developed by government agencies (MOP 1991; C-CAP 1992; EPA-EMAP 1994; Vogelman et al. 1998a,b; U.S. Geological Survey 2001). Minor categories are omitted.

	Land Cover Percentages			
Source	Developed Land	Cropland	Grassland	Forest
EPA-EMAP	12	10	28	49
C-CAP	12	13	21	50
U.S. Geological Survey	12	10	25	49
MOP	26	23	4	42

charge from watershed geography. Various agencies have classified land cover from aerial photography or from Landsat satellite images, and these efforts have achieved different levels of spatial resolution and categorical accuracy. For the Patuxent watershed, four sources of land cover information (Table 11) were examined. Three were derived from Landsat scenes taken between 1986 and 1993 (C-CAP 1992; EPA–EMAP 1994; Vogelmann et al. 1998a,b; U.S. Geological Survey 2001), while one was derived from 1990 aerial photography (MOP 1991) that was updated to 1997 using newer satellite imagery, property ownership information, and transportation maps (Weller and Edwards 2001). Estimates of forest proportion are quite similar among the land cover data sets, especially among the three derived from satellite images (Table 11). The three Landsat-based land covers also agree closely on the percentage of developed land, while the Maryland Department of Planning data set includes a much more generous definition of developed land. The land covers disagree widely in their estimates of cropland proportion (Table 11), and the originators of some of these data have acknowledged that the categorical accuracy in resolving cropland from grassland is especially poor (EPA–EMAP 1994). The confusion between these two categories is particularly limiting in efforts to analyze or model nutrient dischargers because croplands are major sources of nutrient release (Jordan and Weller 1996; Jordan et al. 1997a,b,c, 2003; Liu et al. 2000). In our previous studies, laborious ground observations were used to correctly resolve croplands from grasslands (Jordan et al. 1997a,b,c); however, such data could not be collected for this analysis.

For our Patuxent analyses, we chose the EPA–EMAP data set from the available land covers (Table 11) because it gave the best estimates of cropland proportions in comparisons to ground observations of subwatersheds in the Rhode River basin (Liu et al. 2000; Weller et al. 1996, Weller unpublished data). At the level of individual pixels or landscape patches, the EMAP land cover data do not resolve cropland from grassland with a high degree of classification accuracy (EPA–EMAP 1994; Weller et al. 1996; Weller unpublished data). When land cover data are aggregated to larger spatial units, such as whole watersheds or counties, the proportion of cropland estimated by the EMAP land cover strongly correlates with true proportion of cropland from agricultural census (Bureau of the Census 1990) or ground verified land use data (Weller et al. 1996; Weller unpublished data). Although the EPA–EMAP seemed the best of the available land covers, anomalous nutrient discharges were observed for some smaller Patuxent subwatersheds that may be due to land cover inaccuracies (Jordan et al. 2003).

The differences among land covers (Table 11) also required a development of relationships for translating among the land cover units of two data sets. Our models were developed for the EPA–EMAP land cover, but one scenario of interest involved predicting watershed discharges in the year 2020 using expected future land cover estimated by the Maryland Department of Planning in their land cover units. Our translation method developed relationships between EPA–EMAP and Maryland Department of Planning land covers that could be applied to convert the future predicted land cover from Maryland Department of Planning units to the EMAP units used in our model. Given the disparities among land covers (Table 7), caution is needed in analyses predicting nutrient discharges from simulation models, statistical relationships, or even simple land use loading factors (Beaulac and Reckhow 1982; Frink 1991). None of these methods should be extrapolated to new watersheds without a careful examination of how available land cover data may differ from the land cover for which models or relationships were calibrated. In many cases, some kind of translation between land cover units may be needed. The disparities among land covers and the need for translations also highlight a more general need for improved land cover classification methods that are more categorically accurate, and for formal analyses of the effects of land cover uncertainty on predictions of watershed discharges.

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