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WATER RESOURCES AND THE REGIME OF WATER BODIES

Patuxent Landscape Model: 4. Model Application

A. Voinov, R. Costanza, T. Maxwell, and H. Vladich

Gund Institute for Ecological Economics, University of Vermont 590 Main Street, Burlington, VT 05405-0088
E-mail: alexey.voinov@uvm.edu

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Abstract—Using the LHEM/SME the Patuxent Landscape Model (PLM) was built to simulate fundamental ecological processes in the watershed scale driven by temporal (nutrient loadings, climatic conditions) and spatial (land use patterns) forcings. The model addresses the effects of both the magnitude and spatial patterns of land use change and agricultural practices on hydrology, plant productivity, and nutrient cycling in the landscape.

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INTRODUCTION

We analyzed 18 scenarios of past and alternative future land use patterns and policies, including: (1) historical land use in 1650, 1850, 1950, 1972, 1990 and 1997; (2) a “buildout” scenario based on fully developing all the land currently zoned for development; (3) four future development patterns based on an empirical economic land use conversion model; (4) agricultural “best management practices” which lower fertilizer application; (5) four “replacement” scenarios of land use change to analyze the relative contributions of agriculture and urban land uses; and (6) two “clustering” scenarios with significantly more and less clustered residential development than the current pattern. Results indicate the complex nature of the landscape response and the need for spatially explicit modeling.

Scenarios

The goal of the linked ecological economic model development was to test alternative scenarios of land use patterns and management. A wide range of future and historical scenarios may be explored using the calibrated model. We have developed scenarios based on the concerns of county, state and federal government agencies, local stakeholders and researchers. The following set of initial scenarios were considered:

A group of *historical scenarios* based on the USGS reconstruction [3] of land use in the Patuxent watershed:

(1) 1650—pre-development era. Most of the area forested, zero emissions.

(2) 1850—agro-development. Almost all the area under agricultural use, traditional fertilizers (marl, river mud, manure, etc.), low emissions.

(3) 1950—decline of agriculture, start of reforestation and fast urbanization.

(4) 1972—maximal reforestation, intensive agriculture, high emissions.

(5) *Baseline scenario.* We use 1990 as a baseline to compare the modeling results. The 1990–1991 climatic patterns and nutrient loadings were used.

(6) *1997 land use pattern.* This data set has just recently been released and we used it with the 1990–1991 forcings to estimate the effect of landuse change alone.

(7) *Buildout scenario.* With the existing zoning regulations, we assumed that all the possible development in the area occurred. This may be considered as the worst case scenario in terms of urbanization and it’s associated loadings.

(8) *Best Management Practices (BMP)*—1997 land use with lowered fertilizer application and crop rotation. These management practices were also assumed in the remaining scenarios.

A group of scenarios of change in land use over the 5 years following 1997 (i.e. for 2003) developed based on the *Economic Land Use Conversion (ELUC)* Model by N. Bockstael:

(9) Development as usual.

(10) Development with all projected sewer systems in place.

(11) Development with no new sewers but contiguous patches of forest 500 acres (202 ha) and more protected.

(12) Development with all sewers in place and contiguous forest protected.

A group of hypothetical scenarios to study *dramatic change* in land use patterns using the 1997 land use as the starting point. These scenarios are designed to show the total contribution of particular land use types to the current behavior of the system by completely removing them.

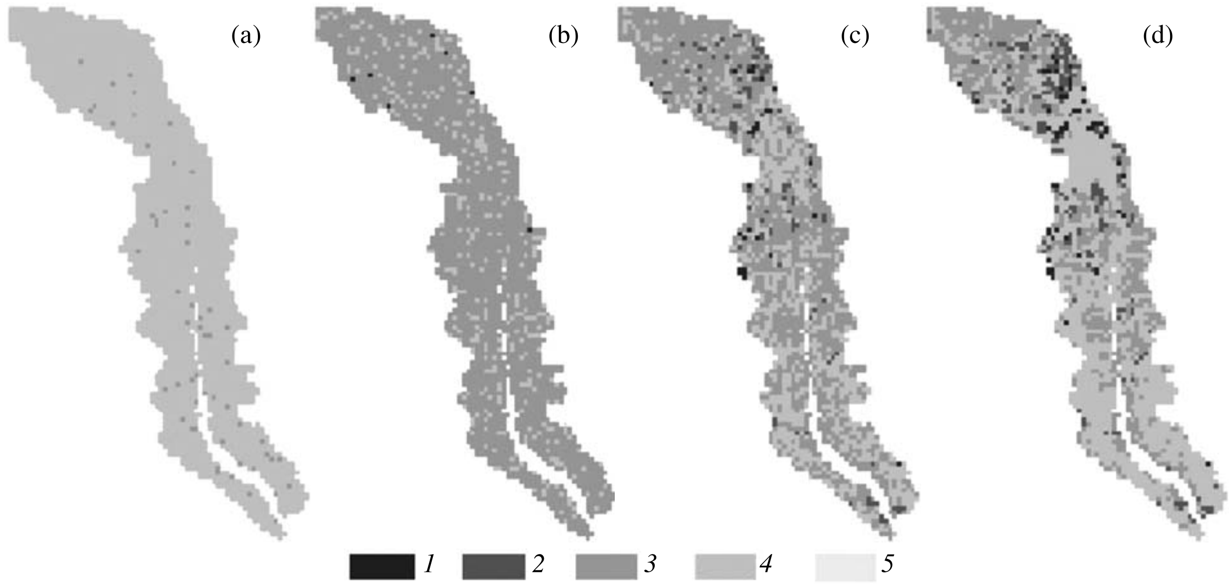

Fig. 1. Approximate reconstruction of Patuxent watershed development for 1650, 1850, 1953 and 1972, based on USGS estimates [3].

(13) Conversion of all currently agricultural land into residential.

(14) Conversion of all currently agricultural land into forested.

(15) Conversion of all currently residential land into forested.

(16) Conversion of all currently forested land into residential.

Another group of hypothetical scenarios to study the *effects of clustering*, again using the 1997 land use as the starting point:

(17) Residential clustering—conversion of all current low density residential land use into urban around 3 major centers.

(18) Residential sprawl—conversion of all current high density urban into residential randomly spread across the watershed.

The scenarios were driven by changes in the Landuse map, the Sewers map, patterns of fertilizer application, amounts of atmospheric deposition, and location and number of dwelling units. Since the model is spatially explicit and dynamic, it generates a huge amount of output for each scenario run. We can only present a brief summary here in the form of spatially and temporally averaged values for a few key indicators. Table 1 is a summary of some of the model output from the different scenarios looking at nitrogen concentration in the Patuxent River as an indicator of water quality, changes in the hydrologic flow and changes in the net primary productivity of the landscape. Some selected additional results of the scenario runs are described briefly below.

Historical Scenarios

In this group of scenarios we attempted to reconstruct the historical development of the Patuxent watershed, starting from the pre-European settlement conditions in 1650. The 1850, 1950 and 1972 maps (Fig. 1) were produced based on data from Buchanan et al. [3]. In 1650 the watershed was almost entirely forested, with very low atmospheric deposition of nitrogen, no fertilizers and no septic tank discharges. The rivers had very low nutrient concentrations. By 1850 the landscape had been dramatically modified by European settlers. Almost all the forests were cleared and replaced with agriculture (Table 1). However fertilizers used at the time were mostly organic (manure, river mud, green manure, vegetable matter, ashes), the atmospheric deposition of nutrients was still negligible, and the population was low, producing little septic tank load.

After 1850, agricultural land use began shrinking and forests began regrowing. By 1950 the area of forests had almost doubled. At the same time, rapid urbanization began, primarily along the Washington DC—Baltimore corridor. This affected the Patuxent watershed both directly (through changes in land use from agriculture and forests to residential and commercial uses) and indirectly (through increased auto use in the larger region and increased atmospheric inputs of nutrients). This process continued until the 1970s, when reforestation hit it’s maximum. Since then, continued urbanization of the area has been affecting both agricultural and forested areas at approximately the same rate. The atmospheric emissions and fertilizer applications were assumed to grow steadily from the low pre-industrial levels to modern load levels. The growing population in the residential sectors was contributing to growing discharges from septic tanks.

Table 1. Some results of scenario runs for the Patuxent Model. The historical scenarios (1650–1972) are a reconstruction based on estimates done by USGS. The "build-out" scenario was estimated based on the existing zoning maps and the average population densities for particular land use types. The buildout conditions represent the "worst case" scenario. The ELUC scenarios (LUB1-4) are based on the model by N. Bockstael. Other scenarios are described in the text. The table lists the land use distribution for each scenario, followed by the nitrogen inputs from the atmosphere, fertilizers, decomposition, and septic tanks. Next are the average, max and min Nitrogen in surface waters, and the max and min water levels in streams. W_{max} is the total of the 10% of the flow that is maximal over a one year period. This represents the peak flow. W_{min} is the total of the 50% of flow that is minimal over a one year period. This is an indicator of the baseflow. $N_{gw.c}$—is the average concentration on N in the ground water. Since ground water is a fairly slow variable in the model and the model had only 1 year of relaxation time in the experiments performed, this variable probably does not adapt fast enough to track the changes assumed under the different scenarios. Total NPP (kg/m^2/yr) presents the average across the whole watershed of plant productivity. It reflects the approximate proportion of forested and agricultural land use types, which have a larger NPP than residential land uses. See text for additional details

Scenario	BLand use types, number of cells				Ixnput of N, kg/ha/year				N concentrations in surface waters, mg/l			Water level in watercources, m/year		$N_{gw.c}$, mg/l	NPP, kg/m^2/yr
	forest	resid	urban	agro	atmos	fertil	decomp	septic	average	maximum	minimum mg/l	W_{max}	W_{min}		
1	2386	0	0	56	3.00	0.00	162.00	0.00	3.14	11.97	0.05	101.059	34.557	0.023	2.185
2	348	7	0	2087	5.00	106.00	63.00	0.00	7.17	46.61	0.22	147.979	22.227	0.25	0.333
3	911	111	28	1391	96.00	110.00	99.00	7.00	11.79	42.34	0.70	128.076	18.976	0.284	1.119
4	1252	223	83	884	86.00	145.00	119.00	7.00	13.68	60.63	0.76	126.974	19.947	0.281	1.720
5	1315	311	92	724	86.00	101.00	113.00	13.00	10.18	40.42	1.09	138.486	18.473	0.265	1.654
6	1195	460	115	672	91.00	94.00	105.00	18.00	11.09	55.73	0.34	147.909	18.312	0.289	1.569
7	312	729	216	1185	96.00	155.00	61.00	21.00	12.89	83.03	2.42	174.890	11.066	0.447	0.558
8	1195	460	115	672	80.00	41.00	103.00	18.00	5.68	16.41	0.06	148.154	16.736	0.23	1.523
9	1129	575	134	604	86.00	73.00	98.00	8.00	8.05	39.71	0.11	150.524	17.623	0.266	1.494
10	1147	538	134	623	86.00	76.00	100.00	11.00	7.89	29.95	0.07	148.353	16.575	0.269	1.512
11	1129	577	134	602	86.00	73.00	99.00	24.00	7.89	29.73	0.10	148.479	16.750	0.289	1.500
12	1133	564	135	610	86.00	74.00	100.00	12.00	8.05	29.83	0.07	148.444	16.633	0.271	1.501
13	1195	1132	115	0	86.00	0.00	96.00	39.00	5.62	15.13	0.11	169.960	17.586	0.292	1.702
14	1867	460	115	0	86.00	0.00	134.00	18.00	4.89	12.32	0.06	138.622	21.590	0.142	2.258
15	1655	0	115	672	86.00	82.00	130.00	7.00	7.58	23.50	0.10	120.771	20.276	0.18	1.950
16	0	1655	115	672	86.00	82.00	36.00	54.00	9.27	39.40	1.89	183.565	9.586	0.497	0.437
17	1528	0	276	638	86.00	78.00	121.00	17.00	7.64	25.32	0.09	166.724	17.484	0.216	1.792
18	1127	652	0	663	86.00	78.00	83.00	27.00	8.48	25.43	0.11	140.467	17.506	0.349	1.222

1990 vs. 1997 vs. Buildout

Comparison between the 1990 and 1997 model output shows that there was a considerable decline in the numbers of forested and agricultural cells, which was due to the increase in residential and urban areas. Accordingly, fertilizers contributed less to the total nitrogen load for the watershed, whereas the amount of nitrogen from septic tanks increased (Table 1). These load totals also demonstrate the relative importance of different sources of nitrogen on the watershed. Under existing agricultural practices the role of fertilizers remains fairly high. Atmospheric deposition contributes unexpectedly high proportions of the nitrogen load. The role of septic tanks may seem minor, however it should be remembered that the fate of septic nitrogen is quite different from the pathways of fertilizer and atmospheric nitrogen. Under existing design of septic drainage fields, the septic discharge is channeled directly to groundwater storage almost entirely avoiding the root zone and nutrient uptake by terrestrial plants.

From 1990 to 1997 most of the land use change in the model occurred by replacing forested with residential land use types. As a result we do not observe any substantial decrease in water quality in the Patuxent River (Table 1). The changes in hydrologic parameters that are associated with the substitution of residential areas for forested and agricultural ones result in somewhat more variability in the flow pattern, however this difference is not very large. Apparently during this time period the residential land use is still less damaging than the agricultural one and the loss in environmental quality that is associated with a transfer from forested to residential conditions is compensated by a net gain in a similar transfer from agricultural to residential use.

These trends are reversed when we move on to the buildout (BO) conditions in the model. At some point a threshold is passed after which most of the development occurs due to deforestation and the effect of residential and urban use becomes quite detrimental for the water quality and quantity in the watershed. The baseflow (represented by the 50% minimal flow values) decreases to almost half of the pre-development 1650 conditions, the peak flows become very high because of the overall increase of impervious surfaces. Accordingly the nitrogen content in the river water grows quite considerably.

Best Management Practices (BMPs)

The next scenario attempts to mimic the possible effects of BMPs. Government concerns are primarily aimed at nutrient reduction through non-point source control and growth management (MOP 1993) [28] and have the broader goal of improving the groundwater, river and estuarine water quality for drinking water and habitat uses. Non-point source control methods under study include: stream buffers, adoption of agricultural and urban Best Management Practices (BMPs), and forest and wetland conservation. Urban BMPs or stormwater management, involve both new development and retrofitting older developments. Growth management includes programs to cluster development, protect sensitive areas, and carefully plan sewer extensions. Clustered development has been proposed and promoted in Maryland as a method to reduce nonpoint sources and preserve undeveloped land.

At this time we have limited our consideration of BMPs to reduction of fertilizer application. Crop rotation has been assumed previously as a standard farming practice in the area. In addition to that we assessed the potential for nutrient reduction in the Patuxent from reductions achieved by farmers in the basin who have adopted farm nutrient management plans. The Maryland Nutrient Management Program (NMP) enlists farmers who are willing to create and implement nutrient management plans which use a variety of techniques to lower application rates including: nutrient crediting with and without soil testing, setting realistic yield goals, and manure testing and storage. The biggest gains for farms without animal operations tended to come from adjusting yield goals (Patricia Steinhilber, Coordinator of the NMP, pers comm., 1996). From this information, we created an expected nutrient reduction of 10–15%, which is the typical reduction for farms in the NMP (Tom Simpson, MDA, pers. comm., 1996). Another major source of fertilizer application reduction is accounting for atmospheric deposition in calculations of nutrient requirements. This has been promoted by some of the recent recommendations issued by MDA. As a result we get quite a considerable change in fertilizer loading and reduction of agricultural land use in the watershed becomes no longer beneficial for water quality in the river (Table 2).

ECONOMIC LAND USE CONVERSION (ELUC) MODEL SCENARIOS

This group of scenarios distributes 28,000 projected new dwelling units (using 1997 conditions as a base) within the area of the 7 counties that include the Patuxent watershed under certain assumptions about the location of sewers and forest preservation strategies. Most of the change occurs in the upper Patuxent portion of the watershed. As seen from Table 2 the resulting changes in land use distributions were not as dramatic as during the 1990–1997 period. Correspondingly the changes in water quality in the river were quite subtle. Our indicators show less than a 1% change relative to the 1997 conditions. However, it is noteworthy that in these scenarios contrary to the previous period most of the land use change is from agricultural to residential habitats. The reduction of agricultural loadings turns out to be more important than the increase in septic tank discharges. Because of the high primary productivity of agricultural land use relative to residential, we also observe a decline in average NPP. Apparently these

Table 2. PLM Data. Unless otherwise noted, spatial and temporal resolution refer to the source data. Data source information is given in the reference in brackets after the table

Model Inputs	Resolution		Source
	spatial resolution (# sites)	temporal resolution/time step	
Physical parameters			
precipitation and temp	7 station	50 yrs/daily	EARTHINFO [9]
wind speed, humidity	2 station	5 yrs/daily	EARTHINFO [9]
Forest			
tree growth dynamics	Species leve	1/yr	NE TWIGS FVS [5, 34]
nutrient dynamics	E US/20	1/yr	[14]
Wetlands			
nutrient retention rates	Pax R/6 sites	One time	CEES [43], JHU [17]
stock values	225 locations	7 to 10/year	CBP [32]
population dynamics	Mesocosms	Beweekly	MEERC [22]
Agriculture (BMP Parameters)			
fertilizer applications	State	Annual	Extension [2, 8]
nutrient reduction/retention rates	State/by county	Annual	CBP/UM Extension [31], MOP [28]
population dynamics	1 point	4000 yrs/1 d	Model database EPIC [42]
soil interactions	0.1 km^2	Daily	Model database WEPP [24]
Urban			
% impervious surface	Land use/type	None	MOP [25], SCS [33]
nutrients in runoff	Land use/soil	None	NURP US EPA [30]
point source nitrogen	All NPDES	10 yrs/monthly	MDE
urban BMP efficiencies	Counties	Event	MOP [28]
GIS coverages			
land use	200 m; 30 m	1984–1994/5×	MOP [20], NOAA [36], EPA [40]
river network	200 m	None	U.S. Census Bureau [35]
soils	200 m	None	MOP, STATSGO [29]
elevation	3 arcsec	None	DEM USGS [37]
watershed boundary	200 m	None	Based on elevation
estuarine bathimetry	200 m	None	NOAA/NOS [27]
roads and towns	Vector	None	U.S. Census Bureau [35]
groundwater (initial)	200 m	1985	USGS[13], elev., river
streamflow	13 station	1979–1995/daily	USGS[38]
surface water quality	13 station	10 years/beweekly	CBP[11], ACB[16]
groundwater levels	16 station	5 yrs/monthly	USGS[13]
groundwater quality	105 station	1973–1990 1×/well	MDE[41], USGS[23]
NDGI (Green index)	1250 m	1993/monthly	USGS[15]
forest dynamics	187 sites	10 yrs/10 yrs	FIA [12]
tree ring data	11 sites	175 yrs/1 y	NOAA[26], IEE
agricultural census data	State & county	50 yrs/5 yrs	USDA [10], USBS [4.7], DHMH [19]
urban development	3 arcsec	1792–1992/13×	BWRC [5]

changes do not bring us to the threshold conditions after which the residential trends of development become especially damaging to the environmental conditions.

HYPOTHETICAL SCENARIOS

In the next group of scenarios we considered some more drastic changes in land use patterns. None of these are realistic, but they allow one to estimate the relative contributions of major land use types to the current behavior of the system. They were also essential to evaluate the overall robustness of the model and estimate the ranges of change that the model could accommodate. For example by comparing Scenarios (14) and (15) one can see that agricultural land uses currently play a larger role in the nutrient load received by the river than residential land uses, even under the BMPs. We get a considerable gain in water quality by transferring all the agricultural land into residential. Contrary to expectations, cluster development (Scenario 17) did not turn out to be any better for river water quality than residential sprawl (18). Because of larger impervious areas associated with urban land use, the peak runoff dramatically increased in this scenario. This in turn increased the amount of nutrients washed off the catchment area. Cluster development would be beneficial only if it is accompanied by effective sewage and storm water management that will reduce runoff and provide sufficient retention volumes to channel water off the surface into the ground water storage. It should be noted however that in our definition of these scenarios we have only modified the land use maps in terms of the limited number of aggregated categories that we are distinguishing. The changes in the infrastructure (roads, communications, sewers, etc.) that should be associated with the cluster vs. sprawl development have not yet been taken into account.

Conversion of all currently forested areas into residential (Scenario 16) was almost as bad as the Build Out scenario (7). However the crop rotation assumed in (16) decreased the amounts of fertilizers applied somewhat and resulted in lower overall nitrogen concentrations. The septic load in this case was so large because the transition to residential land use was assumed to occur without the construction of sewage treatment plants. In the Build Out scenario most of the residential and urban dwellings were created in areas served by existing or projected sewers.

SUMMARY OF SCENARIO RESULTS

One major result of the analysis performed thus far is that the model behaves well and produces plausible output under significant variations in forcing functions and land use patterns. It can therefore be instrumental for analysis and comparisons of very diverse environmental conditions that can be formulated as scenarios of change and further studied and refined as additional data and information are obtained. The real power of the model comes from its ability to link spatial hydrology, nutrients, plant dynamics and economic behavior via land use change. The economic sub-model incorporates zoning, land use regulations, and sewer and septic tank distribution to provide an integrated method for examining human response to regulatory change. The projections from the economic model of land use change based on proposed scenarios shows the probable distribution of new development across the landscape so that the spatial ecological aspects can be evaluated in the ecological model. The model allows fairly site specific effects to be examined as well as regional impacts so that both local water quality and Chesapeake Bay inputs can be considered.

The scenario analyses also demonstrated that the Patuxent watershed system is complex and its behavior is counterintuitive in many cases. For example, in the entirely forested watershed of 1650 the flow was very well buffered showing very moderated peaks and fairly high baseflow. The agricultural development that followed in the next century actually decreased both the peak flow and the baseflow, contrary to what one would expect, even though the decrease in the baseflow was much more significant than the decrease in the peaks. Apparently evapotranspiration rates for the kinds of crops currently included in the model were high enough to keep the peaks down. Comparing the effects of various land use change scenarios on the water quality in the river (Fig. 2) similarly shows that the connection between the nutrient loading to the watershed and the nutrient concentration in the river is complex and difficult to anticipate or generalize. This merely confirms the need for a complex, spatially explicit simulation model of the type we have developed here.

Nevertheless, a few general patterns emerge from analysis of the scenario results, including:

As previously observed [2], the effects of temporarily distributed loadings are less pronounced than event-based ones. For example, fertilizer applications that occur once or twice a year increase the average nutrient content and especially the maximum nutrient concentration quite significantly, whereas the effect of atmospheric deposition is much more obscure. The difference in atmospheric loading between Scenarios (1) and (3) is almost 2 orders of magnitude, yet the nutrient response is only 5–6 times higher, even though loadings from other sources also increase. Similarly the effect of septic loadings that are occurring constantly is not so large. The average N concentration is well correlated ($r = 0.87$) with the total amount of nutrients loaded. The effect of fertilizers is most pronounced among the individual factors ($r = 0.82$), while the effect of other sources is much less (septic $r = 0.02$; decomposition $r = 0.40$; atmosphere $r = 0.71$). The fertilizer application rate determines the maximum nutrient concentrations ($r = 0.76$), with the total nutrient input also playing an important role ($r = 0.55$). Even the groundwater concentration of nutrients is related to fertilizer appli-

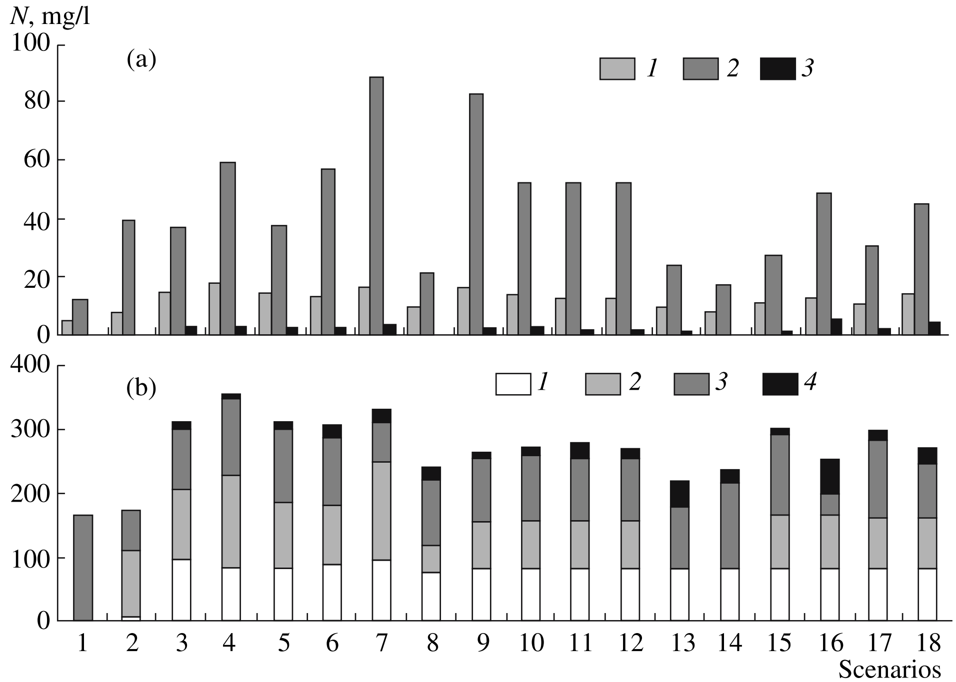

Fig. 2. Nitrogen loading and concentration of nitrogen in the Patuxent river under different scenarios of land use.

cations ($r = 0.64$), however in this case the septic loadings are more important ($r = 0.68$), even a more important one than the total N loading ($r = 0.52$).

The hydrologic response is quite strongly driven by the land use patterns. The peak flow (max 10% of flow) is determined by the degree of urbanization ($r = 0.61$). The baseflow (min 50% of flow) is very much related to the number of forested cells ($r = 0.78$), but in both cases there are obviously other factors involved.

We used the net primary productivity (NPP), excluding agriculture and urban areas, as an indicator of ecosystem health and ecosystem services. The NPP is primarily provided by forested areas in the watershed. Different land use patterns result in quite significant variations in NPP, both in the temporal (Fig. 3) and in the spatial domains. The predevelopment 1650 conditions produce the largest NPP, under Build Out conditions NPP is the lowest. Interestingly, there are certain areas that currently produce higher NPP than in 1650. This is because of increased nutrient availability due to atmospheric deposition and fertilizer applications in adjacent agricultural areas.

CONCLUSIONS

Linked ecological economic models like the PLM are potentially important tools for addressing issues of land use change at the regional watershed scale. The model integrates our current understanding of ecological and economic processes at the site and landscape scales to give estimates of the effects of spatially explicit land use or land management changes. The model also highlights areas where knowledge is lacking and where further research should be targeted. Specifically, the PLM model represents advances in the following areas:

The model links topography, hydrology, nutrient dynamics, and vegetation dynamics at a fairly high temporal (1 day) and spatial (200 m) resolution with land use patterns and the longer term dynamics of land use change. As far as we know, it is the most advanced model of its type for application at the regional watershed scale.

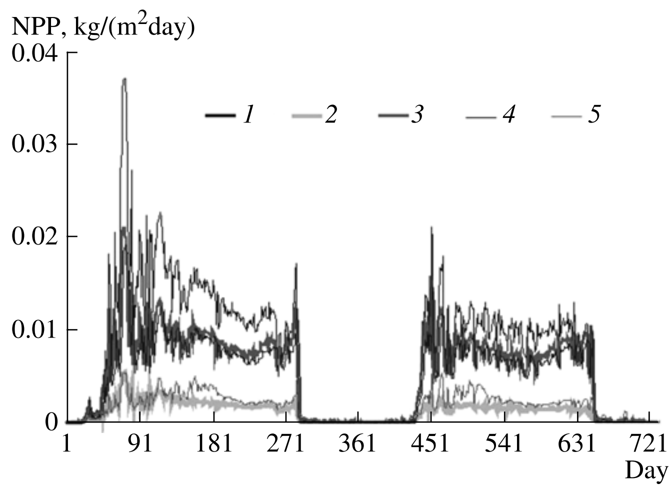

Fig. 3. Variations in dynamics of NPP under various scenarios.

The model allows the impacts of the spatial pattern of land use on a large range of ecological indicators to be explicitly assessed, providing decision makers and the public with information about the consequences of specific land use patterns.

The model has been extensively calibrated over several time and space scales, a difficult and often ignored operation for models at this scale and complexity. New methods based on multi-criteria decision models were developed for this purpose.

The model operates at several scales simultaneously, including the site (or unit model) scale and the landscape scale, which integrates all the unit models.

The model is process-based, with processes changing in dominance over time. This allows better understanding of the underlying phenomenon occurring on landscapes and therefore more detailed predictions of the possible results of changing land uses and policies.

While the model is formulated deterministically, extensive sensitivity analysis, allows us to understand its complex dynamics without resorting to multiple stochastic replications. In the full spatial mode, when cells change from one land use type to another, a bifurcation threshold is simulated, and all the parameters in the cell change to those of the new land use type.

The high data requirements and computational complexities for this type of model mean that development and implementation are relatively slow and expensive. However, for many of the questions being asked this complexity is necessary. We have tried to find a balance between a simple, general model, which minimizes complexity and one that provides enough process-oriented, spatially and temporally explicit information to be useful for management purposes.

Spatial data is becoming increasingly available for these types of analyses and our modeling framework is able to effectively use this data to model and manage the landscape. One can also use the model to estimate the value of specific data collection investments for a particular model, watershed, and set of goals.

Because of the high complexity and large uncertainties in parameters and processes, any numerical estimates generated are intended to be used with caution. The high data requirements and computational complexities impede model development and implementation.

The goal of a given study ultimately justifies the application of a certain modeling approach. In the case of large watersheds with complex and diverse ecosystem dynamics and extensive data requirements, the model inevitably needs fine tuning to the peculiarities of local ecological processes and the specifics of available information. With models of such computational burden we want to avoid all possible redundancies. Therefore, the approach based on modeling systems and constructors that offer the flexibility of building models from existing functional blocks, libraries of modules, functions and processes [21, 39], seems to be more appropriate for watershed modeling.

The Modular Modeling Language that we use offers the promise that models of varying degrees of detail can be archived, and made available for interchange during new model development. Then, for implementing a model for a particular area, modules can be selected based on the relative importance of local processes and high detail can be used where needed and otherwise avoided. The flexibility of rescaling the model spatially, temporally and structurally, allows us to build a hierarchical array of models varying in their resolution and complexity to suit the needs of particular studies and challenges, from local up to global ones. With each aggregation level and scheme chosen, we can view the output within the framework of other hierarchical levels and keep track of what we gain and what we lose.

"SMART GROWTH"

The PLM model can be used to analyze the impacts of specific development and/or regulatory policies. A couple of our current scenarios deal directly with these issues. For example, the policy sometimes referred to as "smart growth" has achieved some currency, and has been advocated by several states, including Wisconsin and Maryland. "Smart" in this context is usually taken to mean "clustered" rather than "sprawled" development of new residential and commercial activities on the landscape. Scenarios 17 (residential clustering) and 18 (residential sprawl) look at the effects of a hypothetical clustering or sprawling of the existing residential land uses. The clustering scenario converts all current low density residential land uses in the watershed to urban around three major centers, leaving everything else the same as the base case scenario. The sprawl scenario converts all current high density urban into residential, randomly spread around the watershed. Table 2 shows some of the characteristics and impacts of these scenarios.

Compared to the 1997 baseline, the clustered scenario had 276 km^2 of urban, compared to 92 km^2, and 0 km^2 of residential compared to 311 km^2, while the sprawled scenario had 652 km^2 of residential and 0 km^2 of urban. Forest and agricultural areas and nutrient inputs were adjusted accordingly. For example, the clustered scenario had an average of 17 kg/ha/yr of N input from septic tanks, compared to 18 kg/ha/yr for the base case and 27 kg/ha/yr for the sprawled scenario. The sprawled scenario also had average fertilizer N input (101 kg/ha/yr) larger than both the clustered scenario (89 kg/ha/yr) and the base case scenario (100 kg/ha/yr) due to additional inputs from more lawns.

The clustered scenario is better in terms of N in streams, with lower values of the average (10.5 mg/l) and W_{max} (30.06 mg/l) than the base case (12.37 and 56.00 mg/l respectively) and about the same value for

W_{min} (1.33 and 1.37 mg/l). The sprawled scenario is much worse with 13.5, 45.14, and 3.55 mg/l, respectively. The clustered scenario is a bit ambiguous in terms of hydrology compared to the base case, with higher W_{max} and W_{min}. This is due to the increased storm water runoff from urban areas, vs. dispersed residential. This effect could be ameliorated with adequate urban storm water management—which was not assumed to be present in the current scenario run. The sprawled scenario had a lower W_{max} and about the same W_{min} compared to the base case, due to the replacement of agricultural land with low density urban. Ground water *N* was lower in the clustered and higher in the sprawled scenario than the base case. Finally, NPP was significantly higher in the clustered scenario (1.868 kg/m^2/yr) than the base case (1.627 kg/m^2/yr) and lower in the sprawled scenario (1.271 kg/m^2/yr). Higher NPP correlates with a higher production of ecosystem services (see above) and a higher quality of life.

MODELING AND DECISION MAKING

Humans interact with the model in two distinct, but complementary ways. First, stakeholders were involved in developing the model and can use the model to address policy and management issues. In this mode human decision-making is outside the model, but interacts with the model iteratively. The model is affected by decisions stakeholders make via changes the modelers make in response to the stakeholder's input, and new scenarios that are run in response to their requests.

In the second mode, human decision-making is internalized in the model. Only a few models have attempted to fully integrate ecological systems dynamics and endogenous human decision making (cf. [6]), and none of these have been spatially explicit. In this mode, one tries to model the human agent's responses to the changing conditions in each cell, and the changes in built, human, and social capital. So far in the PLM, modeling of human decision-making has been limited to the economic land use conversion model discussed earlier. We are currently adding local socioeconomic dynamics to the unit model to further internalize human decision-making.

These two modes are complementary because observing how people make decisions interacting with the version of the model that does not include human decision-making can help us understand and calibrate the version of the model that does include human decision-making internally.

We have been quite successful so far in using the model in mode one at several scales. Most land use policy decisions in Maryland are made at the county level, and we have been interacting with several counties (in particular Calvert County) using the model to address land use policy decisions. For example, we performed a detailed case study of the Hunting Creek subwatershed for the Calvert County Planning Commission to address questions of land use impacts on stream water quality (see http://giee.uvm.edu/PLM for details) [44]. At the federal level, EPA and other environmental management agencies, are, as we said at the beginning of this article, getting much more involved in watershed and landscape level analysis and policy making. For these agencies it is not so much the specific results for the Patuxent watershed that are of most interest, but the general technique and the general results that may be applicable to all watersheds. The landscape modeling techniques we have developed are certainly applicable to any watershed, and many of the scenarios we reported in this paper are relevant to some of the general policy questions that EPA and other environmental management agencies are addressing. These include the impacts of buildout (scenario 7), agricultural best management practices (scenario 8), the overall impacts of agriculture (scenario 14) and residential development (scenario 15), and the effects of sprawl and clustering (scenarios 17 and 18, see above). Models like the PLM are essential tools to improve our ability to make informed regulatory policy decisions at the watershed and landscape scales.

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