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Patuxent landscape model: integrated ecological economic modeling of a watershed

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Abstract

The Patuxent Landscape Model (PLM) is designed to simulate fundamental ecological processes on the watershed scale, in interaction with an economic component that predicts the land use patterns. The paper focuses on the ecological component of the PLM and describes how the spatial and structural rescaling can be instrumental for calibration of complex spatially distributed models. The PLM is based on a modified General Ecosystem Model (GEM) that is replicated across a grid of cells that compose the rasterized landscape. Different habitats and land use types translate into different parameter sets to be fed into GEM. Cells are linked by horizontal fluxes of material and information, driven mostly by the hydrologic flows. This approach provides additional flexibility in scaling up and down over a range of spatial resolutions and is essential to track the land use change patterns generated by the economic component. Structural modularity is another important feature that is implemented in the general purpose software packages (Spatial Modeling Environment and Collaborative Modeling Environment), that the PLM employs.

Keywords: Landscape modeling; Scaling; Dynamic spatial modeling; Land use change

Software availability

Program title:	CME (Collaborative Modelling Environment)
Developer:	Ferdinando Villa
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Telephone:	(410) 326 7446
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E-mail:	villa@cbl.umces.edu
Year first available:	1997
Hardware required:	UNIX workstation or Linux PC
Software required:	TCL/Tk, OpenGL or Mesa, HDF
Program language:	C++, TCL/Tk.
Program size:	~ 1 Mb source archive; binary size depends on platform
Availability and cost:	free to educational and non-profit institutions.

Program title:	SME (Spatial Modelling Environment)
Developer:	Thomas Maxwell
Contact address:	University of Maryland Institute for Ecological Economics, P.O. Box 38, Solomons, MD 20688
Telephone:	(410) 326 7388
Fax:	(410) 326 7354
E-mail:	maxwell@cbl.umces.edu
Year first available:	1997
Hardware required:	UNIX workstation or Linux PC
Software required:	C++ compiler; optional extensions—TCL/Tk, HDF, MPI, Postgres
Program language:	C++, Java

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PII: S1364-8152(98)00092-9

Program size:	~ 1 Mb source archive; binary size depends on platform
Availability and cost:	free to educational and non-profit institutions.

1. Introduction

Large drainage basins are composed of multiple smaller catchments. Each of these catchments contains a heterogeneous collection of land uses which vary in composition and spatial pattern (structure) and thus differ in functions such as nutrient retention. Two problems arise from this heterogeneity that present major challenges to both research and management. First, variation in structure and function inevitably prevents true replication in intensive field studies that attempt to relate landscape function to landscape structure. Second, variation among land uses within watersheds makes it difficult to directly extrapolate among spatial scales. Even though drainage basins can be broken down hierarchically into smaller catchments based on topography, "scaling up" from intensive catchment studies is not a linear additive process because of differences among catchments and interactions between adjacent land uses. Management of water quality over large drainage basins must address both problems with innovative methods synthesizing data from intensive experimental studies on a few watersheds, then extrapolating important generalizations to larger drainages using modeling techniques.

The Patuxent Landscape Model (PLM) was designed to serve as a tool in a systematic analysis of the interactions among physical and biological dynamics of the Patuxent watershed (Maryland, USA), conditioned on socioeconomic behavior in the region. A companion socioeconomic model of the region's land use dynamics was developed to link with the PLM and provide a means of capturing the feedbacks between ecological and economic systems (Fig. 1). By coupling the two models and exchanging information and data between them, the socioeconomic and ecological dynamics can be incorporated. Whereas in most ecosystem models the socioeconomic development is fed into the model in the form of scenarios or forcing functions, a coupled model can explore dynamic feedbacks, adjusting the socioeconomic change in response to the ecological perturbations.

To run the ecological and economic modules in concert, we need to account for specifics of both modules in their design and make assumptions about how the information will be exchanged. In particular, the spatial representation of both should be matched such that land use or land cover transformations in one module can be communicated to the other one directly inside the model. In this case it would be difficult to employ the approach based on spatial aggregation to larger units, called elementary landscapes, elementary watersheds, elementary areas of pollution or hillslopes (Beven and Kirkby, 1979; Krysanova et al., 1989; Band et al., 1991; Sasowsky and Gardner, 1991), which are considered homogeneous and form the basis for the hydrologic flow network. In these models the boundaries between spatial units are fixed and cannot be modified during the course of the simulation. A more mechanistic approach seems to be better suited when the landscape is aggregated as a grid of relatively small homogeneous cells and process-based simulations are run for each cell with relatively simple rules for material fluxing among nearest neighbors (Sklar et al., 1985; Burke et al., 1990; Costanza et al., 1990; Engel et al., 1993; Maxwell and Costanza, 1995). This fairly straightforward approach requires extensive spatial data sets and high computational capabilities in terms of both storage and speed. However it provides for quasi-continuous modifications of the landscape, where habitat boundaries may change in response to socioeconomic transformations.

The economic module of the PLM was presented elsewhere (Bockstael, 1996; Bell and Bockstael, 1997; Bockstael and Bell, 1997; Geoghegan et al., 1997). In this paper we focus on describing the construction of the ecological module, paying special attention to those aspects of the model that were stipulated by the integrated fashion of the entire research effort. We first outline the overall model design in terms of its spatial, temporal and structural organization. Then we look at the single-cell (unit) ecological model and focus on some of the recent modifications of the General Ecosystem Model (GEM) necessary for the Patuxent application. Next we consider the spatial implementation of the model and discuss some aspects relating to scale and resolution. We conclude with a review of the results and potential applications of the model.

2. Model structure

The PLM may be considered as an outgrowth of the approach first developed in the Coastal Ecosystem Landscape Spatial Simulation (CELSS) model (Sklar et al., 1985; Costanza et al., 1990), and later applied to a series of wetland areas, the Everglades clearly being the most sophisticated example (Fitz et al., 1998; Fitz and Sklar, 1998). The modeled landscape is partitioned into a spatial grid of square unit cells. The model is hierarchical in structure, incorporating the ecosystem-level unit model that is replicated in each of the unit cells representing the landscape (Fig. 2). With this approach, the model builds on the format of a raster-based geographic information system (GIS), which is used to store all the spatially referenced data included in the model. Thus, the

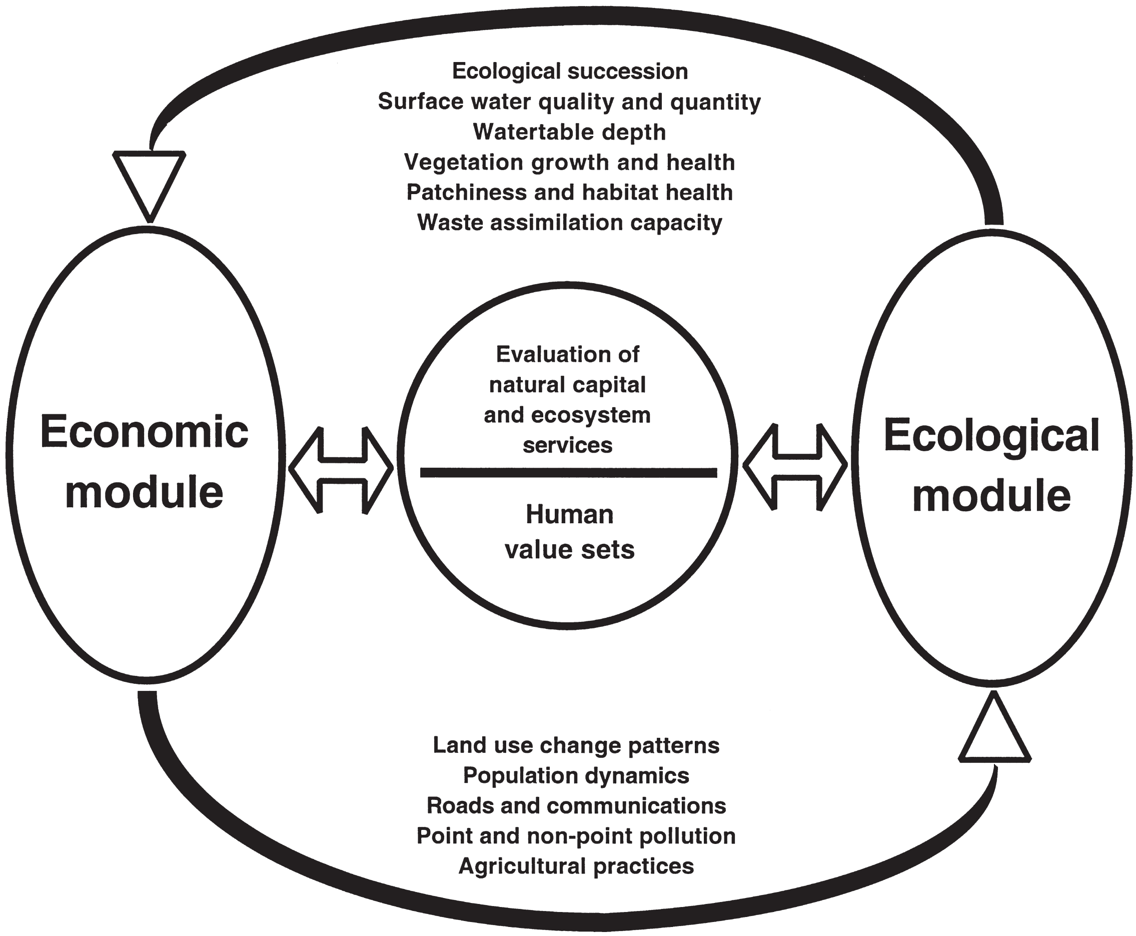


Fig. 1. Relationships and linkages between the economic and ecological subsystems. The ecological and the economic modules provide essential feedbacks that are instrumental to create a realistic system of values and to learn to measure these values.

model can be considered an extension of the analytical function of a GIS, adding dynamics and knowledge of ecological processes to the static snapshots stored in a GIS.

Although the same unit model runs in each cell, individual models are parameterized according to habitat type and georeferenced information for a particular cell. The habitat-dependent information is stored in a parameter database which includes initial conditions, rate parameters, stoichiometric ratios, etc. The habitat type and other location-dependent characteristics are referenced through links to GIS files. In this sense, the PLM is one of several site specific ecological models that are process-based and are designed to apply to a range of habitats. Some other models within this category are CENTURY (Parton et al., 1988), TEM (Vorosmarty et al., 1989), and BIOME-BGC (Running and Coughlan, 1988). All these models can be adapted to a particular site through parameterization of initial stocks and flux rates among various ecosystem components. These models vary in complexity and capabilities, which makes one model more suitable for certain applications than others. As a rule of thumb, more complex models will resolve issues in more detail, but are more difficult and time-consuming to calibrate and run (Maxwell and Costanza, 1994). The unit model in the PLM aims for an intermediate level of complexity so that it is flexible enough to be applied to a range of ecosystems but is not so cumbersome that it requires a supercomputer.

The unit models in each cell exchange matter and information across space. The horizontal fluxes that join the unit models together are defined by surface and subsurface hydrology. Alternative horizontal fluxes could be movement of air, animals, and energy such as fire and tidal waves although at this stage the PLM fluxes only water and entrained material. The spatial hydrology module calculates the amount of water fluxed over the surface and in the saturated sediment. The fluxes are driven by cell-to-cell head differences of surface water and saturated sediment water, respectively. Water fluxes between cells carry dissolved and suspended material. At each time step, first the unit model updates the stocks within each cell due to vertical fluxing and then cells communicate to flux matter horizontally, simulating

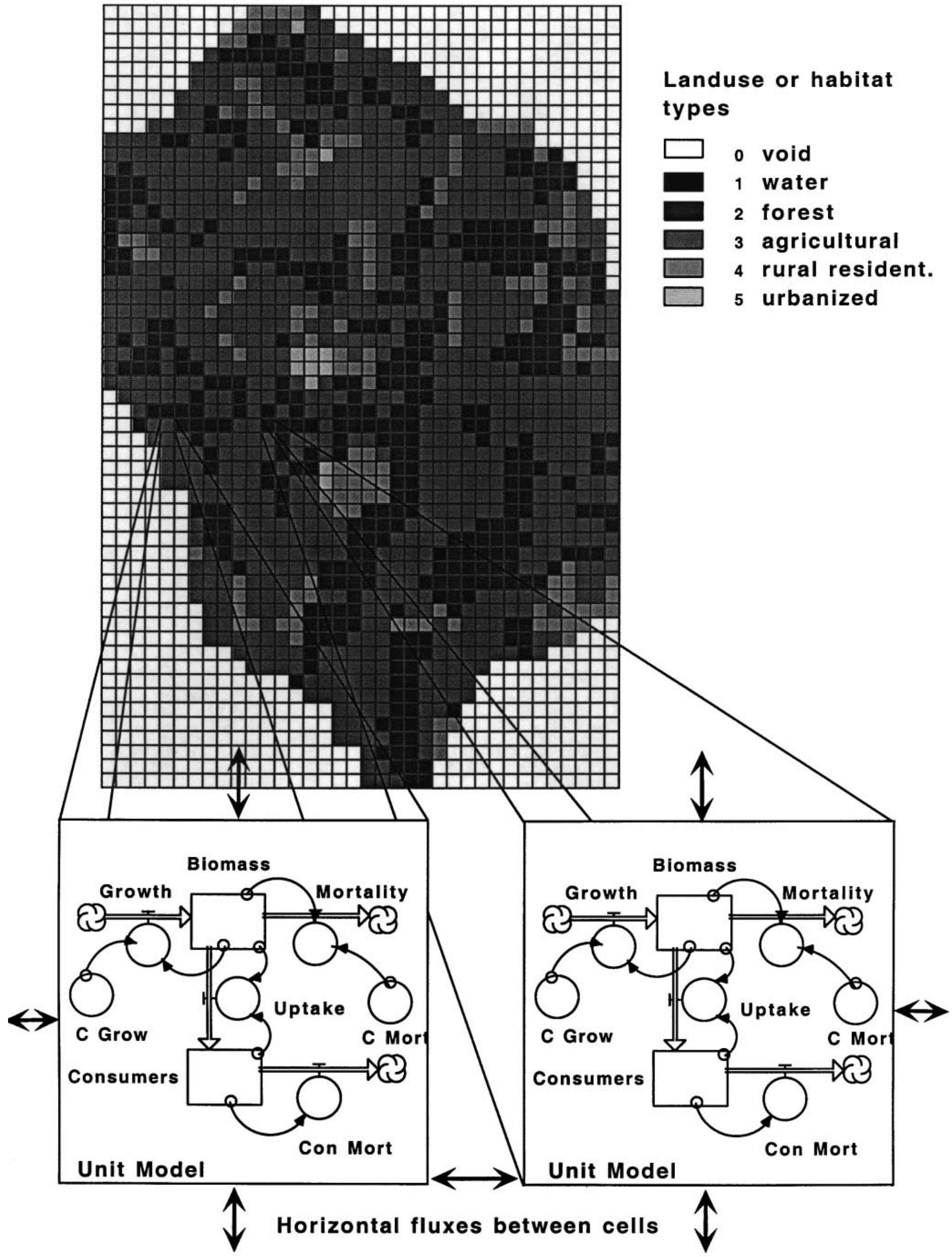


Fig. 2. Spatial organization of the Patuxent watershed model. The unit model is replicated in each of the cells on the study area. Different habitat types are characterized by different parameters in the unit model. Hydrological fluxes connect the unit models horizontally.

flows and determining ecological conditions across the landscape.

Fig. 3 presents how the various modeled events are distributed in time when simulated in the PLM. The model employs a time step of 1 day, so that most of the ecological variables are updated daily. However certain processes can be run at longer or shorter time steps. For example some spatial hydrologic functions may need an hourly time step, whereas certain external forcing functions are updated on a monthly or yearly basis.

This explicit spatial and flexible temporal design of the PLM ecological module is instrumental for a linkage with a companion economic model that predicts the probability of land use change within the seven counties of the Patuxent watershed (Bockstael, 1996). The economic model allows human decisions to be modeled as a function of both economic and ecological spatial variables. Based on empirically estimated parameters, spatially heterogeneous probabilities of land conversion are modeled as functions of predicted land values in residen-

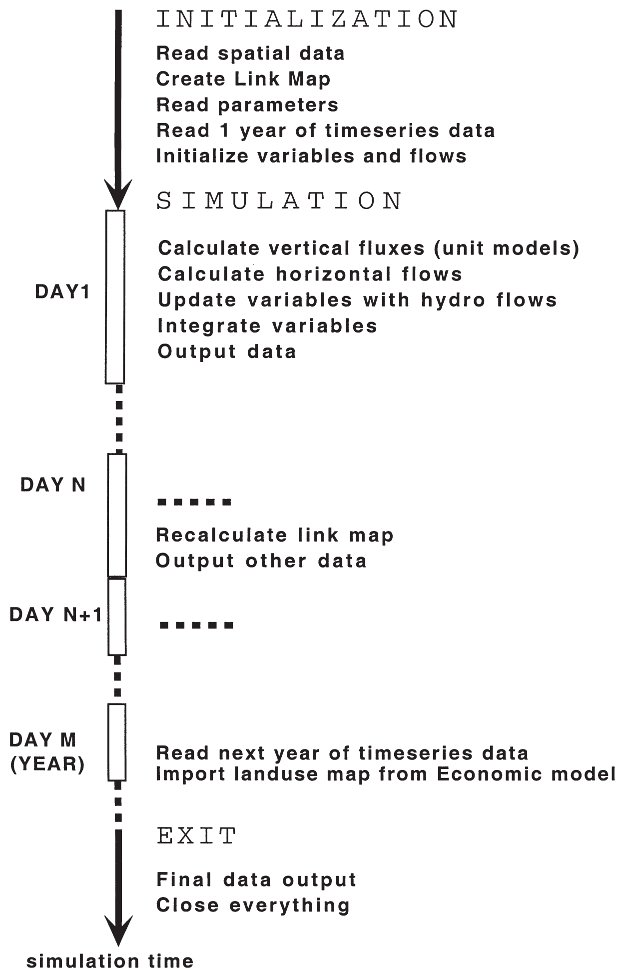


Fig. 3. Temporal course of events in PLM. SME offers certain flexibility in scheduling simulation events. Individual time steps can be assigned to different modules.

tial and alternative uses, and costs of conversion. Land value predictions are modeled as functions of local and regional characteristics. The predictive model of land use conversion generates the relative likelihood of conversion of cells, and thus the spatial pattern of greatest development pressure. To predict the absolute amount of new residential development, the probabilistic land use conversion model is further combined with models of regional growth pressure. As a result a new landuse map is generated and fed into the ecological model on a yearly basis.

3. Unit model

The General Ecosystem Model or GEM (Fitz et al., 1996) was used as the initial unit model in developing the PLM. However, since GEM was developed and calibrated mostly for wetland ecosystems, certain modifications were made in order to provide for a smooth transfer to the predominantly dry, terrestrial habitats of the Patuxent watershed.

The GEM unit model is structured according to a modular concept, which is enforced by the semantics of the development tools used (Maxwell and Costanza, 1997). Different modules (or sectors) can be designed independently and linked together in a piecewise fashion. This process facilitates the reuse of modules and a cleaner subdivision of the development effort. Different sectors in the GEM represent hydrology, nutrient movement and cycling, terrestrial and estuarine primary productivity, and aggregated consumer dynamics (Fig. 4). The hydrology sector of the unit model is fundamental to modeled processes since it links the climatic forcing functions to chemical and biotic processes, and allows feedbacks between sectors. Phosphorus and nitrogen are cycled through plant uptake and organic matter decomposition, with the latter simulated in the sector that describes the sediment/soil dynamics. The sector for macrophytes includes growth response to various environmental constraints (including water and nutrient availability), changes in leaf canopy structure (influencing water transpiration), mortality, and other basic plant dynamics. Feedbacks among the biological, chemical and physical model components structure habitat and influence ecosystem response to changing conditions.

In what follows, we give a brief account of the modifications that GEM underwent in the PLM implementation, referring the reader to (Fitz et al., 1996) for further details on GEM.

3.1. Hydrology

The traditional scheme of vertical water movement (Novotny and Olem, 1994), also implemented in GEM, assumes that water is fluxed along the following pathway: rainfall – > surface water – > water in the unsaturated layer – > water in the saturated zone. Snow is yet another storage that is important to mimic, the delayed response caused by certain climatic conditions. In each of the stages some portions of water are diverted due to physical (evaporation, runoff) and biological (transpiration) processes, but in the vertical dimension the flow is controlled by the exchange between these 4 major phases. Taking into account the temporal (1 day) and spatial (200 m, 1 km) resolution of the PLM formalization and of the available input data, we can simplify this model.

At a daily time step assumed in GEM and PLM, the model cannot attempt to mimic the behavior of shorter term events such as the fast dynamics of a wetting front, when rain water infiltrates into soil and then travels through the unsaturated zone towards the saturated groundwater. During a rapid rainfall event, surface water may accumulate in pools and litterfall but in a catchment

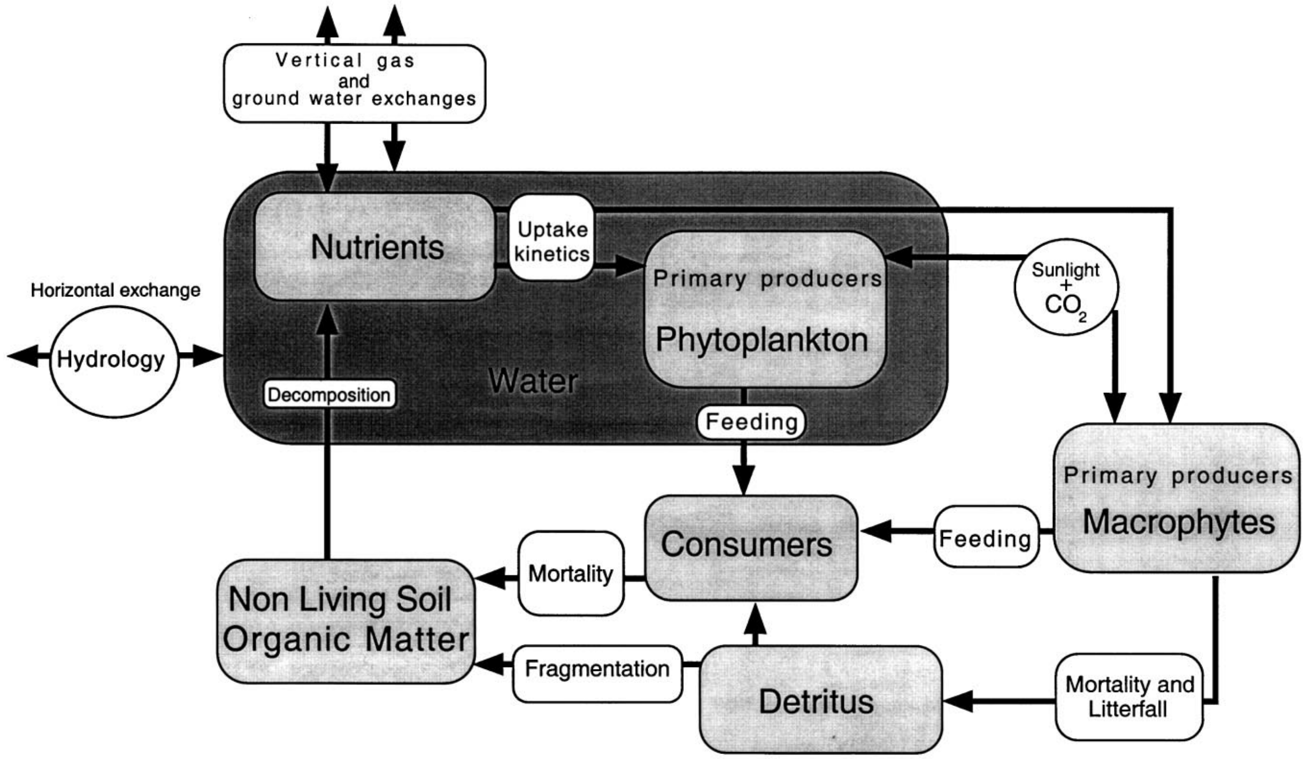


Fig. 4. GEM conceptual diagram.

such as the Patuxent watershed, over the period of a day, most of this water will either infiltrate, evaporate, or be removed by horizontal runoff. Infiltration rates based on soil type within the Patuxent watershed range from 0.15 to 6.2 m/day (Maryland Department of State Planning, 1973), potentially accommodating all but the most intense rainfall events in vegetated areas. The intensity of rainfall events can strongly influence runoff generation, but climatic data are rarely available for shorter than daily time steps. Also, if the model is intended to be run over large areas for many years, the diel rainfall data become inappropriate and difficult to project for scenario runs. Therefore, a certain amount of detail must be forfeited to facilitate regional model implementation.

With these limitations in mind, we have simplified the unit hydrologic model as follows (Fig. 5):

- We assume that, rainfall infiltrates immediately to the unsaturated layer and only accumulates as surface water if the unsaturated layer becomes saturated or if the daily infiltration rate is exceeded. Ice and snow may still accumulate.
- Surface water may be present in cells as rivers, creeks and ponds. Surface water is removed by horizontal runoff or evaporation.
- Within the day time step, surface water flux will also account for the shallow subsurface fluxes that rapidly bring the water distributed over the landscape into the micro channels and eventually to the river. Thus, the surface water transport takes into account the shallow subsurface flow that may occur during rainfall, allowing the model to account for the significantly different nutrient transport capabilities between shallow and deep subsurface flow.

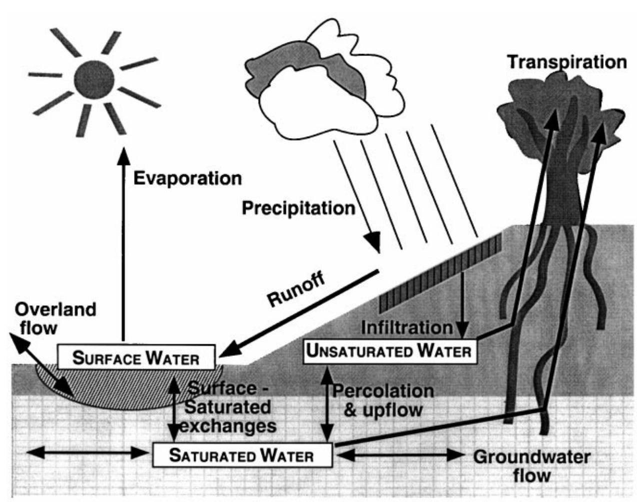


Fig. 5. Hydrologic sector of modified GEM. The main state variables represent water in streams, rivers, creeks (Surface Water), in the unsaturated soil layer (Unsaturated Water) and in the saturated groundwater storage (Saturated Water).

Conceptually this is close to the slow and quick flow separation (Jakeman and Hornberger, 1993; Post and Jakeman, 1996) assumed in empirical models of runoff. In this case the surface water variable accounts for the quick runoff, while the saturated storage performs as the slow runoff, defining the baseflow rate between rainfall events.

3.2. Nutrients

The GEM nutrients sector was changed to better match the aggregated hydrologic module (Fig. 6). As in GEM, the nutrients considered in the PLM are nitrogen and phosphorus. Various nitrogen forms, NO_2^-, NO_3^- and NH_4^+ are aggregated into one variable representing all forms of nitrogen that are directly available for plant uptake. Available inorganic phosphorus is simulated as orthophosphate. The distinction appears in conceptualizing nutrients on the surface, since in the PLM they are no longer associated with surface water and therefore need not be in the dissolved form. On the contrary, since most of the time most of the cells have no surface water, *n_SF* ($n = N$ or P) represents the dry deposition of nitrogen or phosphorus on the surface. Over dry periods *n_SF* continues to accumulate with incoming fluxes from air deposition or mineralization of organic material. When rainfall occurs, a certain proportion of the accumulated *n_SF* becomes dissolved and therefore is made available for horizontal fluxing and infiltration.

Further modification of the nutrient dynamics was required to accommodate the aggregation of surface and shallow subsurface flows in the hydrologic sector. In the PLM a proportion of nitrogen and phosphorus stored in the upper soil layer is made available for fast horizontal fluxing along with nutrients on the land surface. We have assumed this layer to be 10 cm thick, following a similar formalization in the CNS model (Haith et al., 1984), where this upper soil layer was also assumed to be exposed to direct surface runoff.

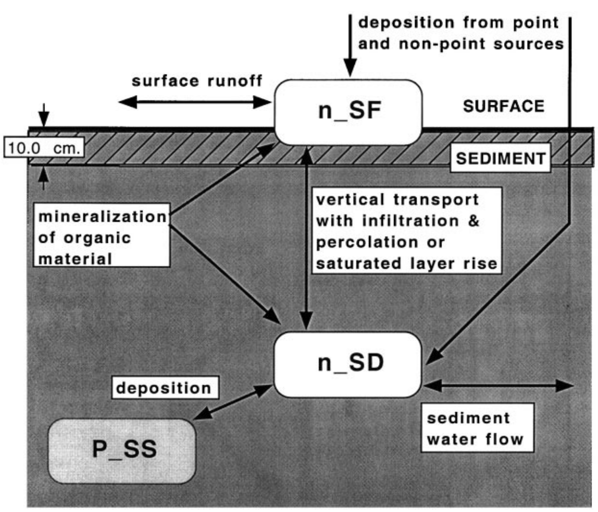


Fig. 6. Nutrients sector of modified GEM. *n_SF* and *n_SD* represent total available phosphorus (P) or nitrogen (N) on the surface and in the sediment, respectively. *P_SS* is the sorbed phosphorus of the sediment that is immobilized and deposited.

In addition to *n_SF* (mineral *N* or *P* on the surface), and *n_SD* (mineral *N* or *P* in the sediment), the phosphorus cycle features another variable *P_SS*, which is the phosphorus deposited in the sediment in particulate form, no longer available for plants uptake, and effectively removed from the phosphorus cycle. The dissolved PO_4 at higher concentrations becomes absorbed by the organic material and metal ions in the soil. Therefore the rate of sorption is also controlled by the amount of organic material in the soil, which in this case mostly consists of soil microorganisms (microbes). At lower concentrations of soluble PO_4 in the sediment, *P_SS* becomes available again and returns back into the cycle.

3.3. Macrophytes

The GEM macrophyte sector was updated to allow the model to better distinguish different plant communities. We added dynamics in carbon to nutrient ratios that are important to woody and perennial plant communities (Vitousek et al., 1988) and introduced important differences between evergreen and deciduous plant communities. Additional fluxes were added to allow for human intervention through fertilizing, planting and harvesting of crops and trees. The newly revised macrophyte sector can now simulate the nutrient storage of a forest ecosystem in multiple year simulations and allow scenarios for Best Management Practices (BMP's) in agriculture and urban lawns.

As in GEM, macrophytes are represented by two state variables for photosynthetic and non-photosynthetic plant matter. The carbon to nutrient ratios (C:N:P ratios) for both state variables link to different steps in the nutrient cycles. The C:N:P ratio in the photosynthetic part is instrumental in controlling uptake and the resulting accumulation of organic nitrogen and phosphorous. The C:N:P ratio in the non-photosynthetic biomass is used to estimate the rates of decomposition and the extent of nutrient mineralization. The GEM strategy to account for the organic nutrient pool as a fixed portion of both stock variables, assumed static C:N:P ratios for woody and photosynthetic biomass. Yet C:N:P ratios tend to increase as woody biomass low in nutrient content accumulates in aging forests. Our new strategy still assigns fixed C:N:P ratios to the photosynthetic biomass, but relates changes in the non-photosynthetic biomass C:N:P ratios to changes in woody biomass, bringing estimated nutrient storages closer to measured values.

Some concepts were redefined in the new model to represent a greater variety of habitats. The terms evergreen and deciduous are broadly interpreted to encompass not only trees but other plant communities. Most of the agricultural crops and annual herbs are considered deciduous, while wetlands, grasslands and lawns are considered evergreen. The main difference between the deciduous and non-deciduous plant communities is that a fall hormonal trigger mechanism causes the deciduous plants to shed the photosynthetic part of the plant, while recovering some of the biomass for the non-photosynthetic tissues. No recovery of biomass occurs from leaf mortality. It is during this fall period when seeds and tubers are formed and photosynthetic products are stored in tree root systems. In the spring deciduous plants experience accelerated growth in addition to a seasonal growth also experienced in the evergreen community.

Allocation of photosynthetic products to leafy or woody tissues is controlled by the maximum in the ratio of photosynthetic to non-photosynthetic materials (*Max_ph:nph*). An accelerated spring growth, simulating sap flow in trees and seed germination, was introduced for the deciduous portion of the plant community. Labile carbon stored in non-photosynthetic tissues (roots, stems and branches) are translocated to produce photosynthetic tissue (leaves) in an attempt to reach a community-specific *Max_ph:nph*. Translocation from the non-photosynthetic tissue to the photosynthetic tissue comes to a halt when all labile carbon is used from storage, or the *Max_ph:nph* ratio is reached, or hormonal activity ceases. New photosynthetic products are created in the leaves, under the various environmental restrictions similar to GEM. These newly available products can be allocated to additional leaf growth if *Max_ph:nph* is not yet reached, or can be translocated back to the non-photosynthetic parts for growth of woody matter or storage. Growth in woody matter offsets the photosynthetic to non-photosynthetic ratio from *Max_ph:nph* and allows for additional growth in leafy material.

4. Spatial implementation

Once the local ecological processes were described, we needed to decide on the algorithms that put the local dynamics within a spatial context. For watersheds in general and for the Patuxent in particular, hydrologic fluxes seem to be the most important mechanism linking the cells together and delivering the suspended and dissolved matter across the landscape.

The importance of hydrologic transport has been long recognized and considerable effort has been put into creating adequate models for various landscapes (Beven and Kirkby, 1979; Beasley and Huggins, 1980; Grayson et al., 1992). Nevertheless there are no off-the-shelf universal models that can be easily adapted for a wide range of applications. As a part of a more complicated modeling structure, the hydrologic module is required to be simple enough to run within the framework of the integrated physical-ecological model yet sufficiently detailed to incorporate locally-important processes. As a result, some hydrologic details need to be sacrificed to make the whole task more feasible, and these details may differ from one application to another, depending upon the size of the study area, the physical characteristics of the slope and surface, and the goals and priorities of the modeling effort.

To simplify hydrologic calculations, we merge process based and quasi-empirical algorithms (Voinov et al., 1998). First, given the cell size within the model (200 m or 1 km), every cell is assumed to have a stream or depression where surface water can accumulate. Therefore the whole area becomes a linked network of channels, where each cell contains a channel reach which discharges into a single adjacent channel reach along the elevation gradient. An algorithm generates the channel network from a link map which connects each cell with its one downstream neighbor chosen from the eight possible nearest neighbors.

Second, since most of the landscape is characterized by an elevation gradient, the flow is assumed to be unidirectional, fluxing water downstream. In the simplified algorithm, a portion of water is taken out of a cell and added to the next one linked to it downstream (Fig. 7A). To comply with the Courant condition (Chow et al., 1988), this operation is reiterated many (10–20) times a day, effectively generating a smaller time step to allow faster riverflow. The number of iterations needed for the hydrologic module is calibrated so that the water flow rates match gauge data.

This procedure was further simplified by allowing the water to flow through more than one cell over one iteration (Fig. 7B) and then generalized by assuming a variable number cells in the downstream link (Fig. 7C), as a function of the amount of water in the donor cell. This was adopted to allow for a faster flow when more water is available on the surface (Voinov et al., 1999). It increased flexibility in describing individual hydrographs and in generalizing them over longer time periods and over larger watershed areas.

For groundwater movement we used a linear Darcy approximation, that moves water among adjacent cells in proportion to a conductivity coefficient and the head difference. The groundwater movement provides the slow water flow that generates the river baseflow. Surface water runoff is the major determinant of the peak flow observed.

5. Software development

The sophisticated structure of PLM is supported by several general-purpose software packages, that have been developed and refined to meet the needs of PLM. Fig. 8 presents the interaction between the software modules and the data involved. The modules shown in gray are the ones that the user needs to interface with.

The unit model is developed using the off-the-shelf application STELLA (HPS, 1995), that has been widely

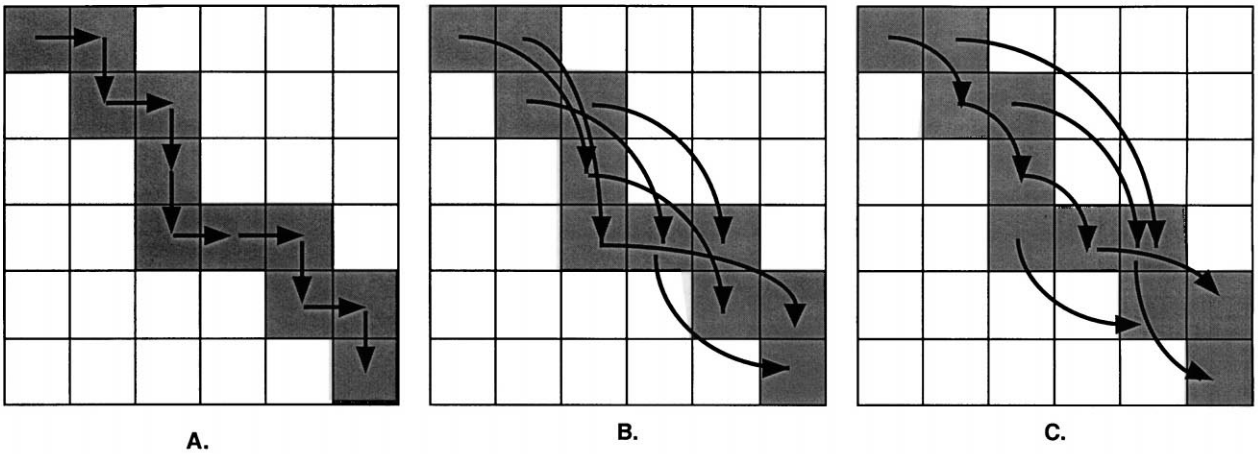


Fig. 7. Algorithms of spatial hydrologic fluxing in the model. A. fixed linking to the next cell downstream. Hydrologic fluxing is reiterated *n* times over the same link map. B. fixed linking over *n* cells downstream. Instead of *n* iterations of fluxing, the water is moved directly to the *n*-th cell downstream. C. dynamic linking. The length of the link path is determined as a function of the stage in a cell.

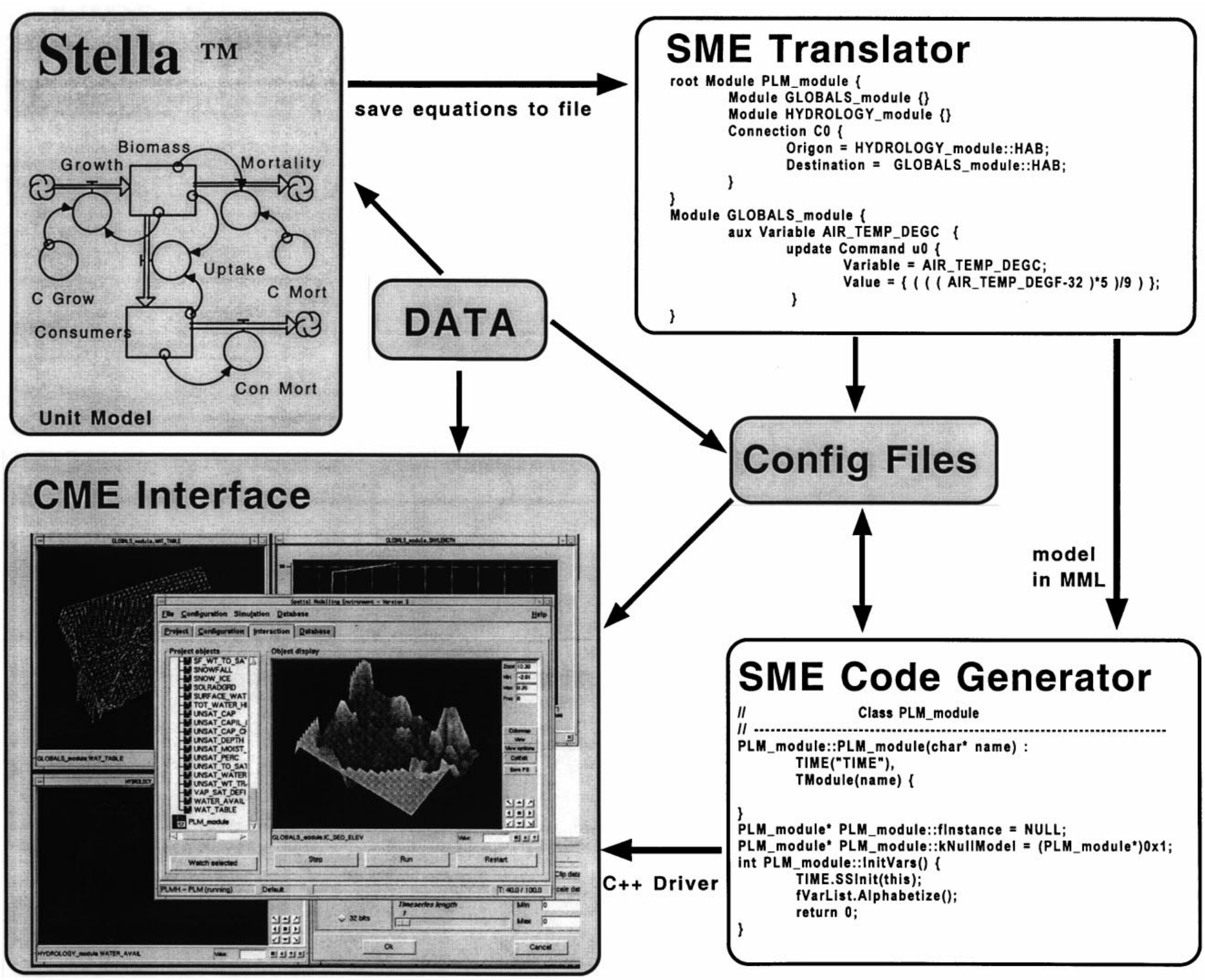


Fig. 8. Software used in PLM. The gray areas show the front-end packages that the user needs to interact with while developing and running the model.

used for dynamic simulation modeling and allows simple icon-based model building and preliminary analysis. Using STELLA as a front end also greatly simplifies the communication of the model structure to the stakeholders and decision makers (Costanza and Ruth, 1998). The Spatial Modeling Environment (SME) (Maxwell and Costanza, 1994; Maxwell, 1995; Maxwell and Costanza, 1995) links icon-based modeling environments with distributed computing resources.

The model equations generated from STELLA are exported to the SME through a program which translates the STELLA file into the Modular Modeling Language (MML) (Maxwell and Costanza, 1997). This language provides the semantic structures needed to facilitate archiving and reuse of modules by other researchers in the future. MML-specified model components can be combined hierarchically and are converted by the Code Generator into a C++ object hierarchy within the SME. The C++ objects are then compiled and linked with SME libraries to generate a stand-alone simulation driver.

The SME driver is a simulation environment which runs the spatial simulation on a number of possible parallel or serial computers. It is implemented as a set of distributed C++ objects which exchange data among themselves using network-based multiprocessing. A spatial simulation running within the SME driver is structured as a set of independent modules, each with a potentially unique spatio-temporal representation, defined by a data structure called a Frame. The Frame specifies the topology of the module and is implemented as a set of Points (cells) with (inter-cellular) links, as well as algorithms for transferring/translating data to/from other Frames. Examples of Frames used in PLM include two-dimensional grids (spatial coverages such as soil maps, landuse maps, etc.), graphs and networks (e.g., for rivers and streams), and Point sets (e.g., for running unit models for a single aggregated set of conditions rather than across a heterogeneous space). With this method, simulations involving modules with disparate spatio-temporal scales can be executed transparently, since the implementation of each module's Frame allows incoming data to be remapped to fit its topology, and remaps outgoing data into a universal format.

Unsophisticated users do not need to understand all the details of SME as long as they are running the front-end package, which is the SME user interface, implemented as a module in the Collaborative Modelling Environment (CME) (Villa, 1997a). CME allows users to define projects, simulation models, input/output configurations, and simulation runs with different calibration data. All of these objects are stored in the database for sharing by collaborating individuals or groups.

6. Calibration and testing

Much of the time involved in developing spatial process-based models is devoted to calibration and testing of the model behavior against known historical or other data (Costanza et al., 1990). Calibrating and running a model of this level of complexity and resolution requires a multi-stage approach. We performed the calibration and testing at several time and space scales (Fig. 9). Taking advantage of the model modularity, these tests were carried out for various parts of the model as well as for the whole model. Initial unit model calibrations were handled in STELLA, then the fine tuning was performed using the Model Performance Index (MPI) (Villa, 1997b; Villa et al., 1999). At the same time certain modules were put into the spatial context and calibration of the spatial model was carried out. The data against which we test and calibrate the model have been summarized by Wainger et al. (1999) and can be also found on our web page at http://iee.umces.edu/PLM. In what follows we mostly illustrate this multi-tier calibration procedure with some of the results obtained for the hydrologic module of the model.

First a "ball-park" calibration was performed for the unit model hydrology. The unit model simulates the head of SURFACE WATER, SNOW/ICE, water in the unsaturated layer (UNSAT WATER), and water in the saturated sediment (SAT WATER) (Fig. 10). The latter two variables represent the actual amount of water in the saturated and unsaturated layers, as if it was completely "squeezed" out of the sediment and then its head measured. To calculate the real depth of the water table, the amount of saturated water is multiplied by the soil porosity. At this stage it was important to reproduce the qualitative picture of water dynamics in a cell, making sure that there are no long-term trends and that the stages remain within certain limits over several years of model runs.

The results were quite sensitive to the horizontal flow rates of surface and ground water (Fig. 11), which could be only parameterized rather than calculated in the unit model. Fairly small changes in values of these parameters ($< 5\%$) produced visible variations in the state variables, hiding the variability due to changes in the other parameters responsible for local vertical dynamics (infiltration, evapotranspiration, etc.). Therefore more detailed calibration of the hydrologic model in the local scale did not make much sense. Besides there was no reliable local data to compare the unit model output to.

For a spatial implementation, we chose two scales at which to run the model—a 200 m and 1 km cell resolution. The 200 m resolution is more appropriate for capturing some of the ecological processes associated with landuse change but is too detailed and requires too much computer processor time to perform the numerous model runs required for calibration and scenario evaluation.

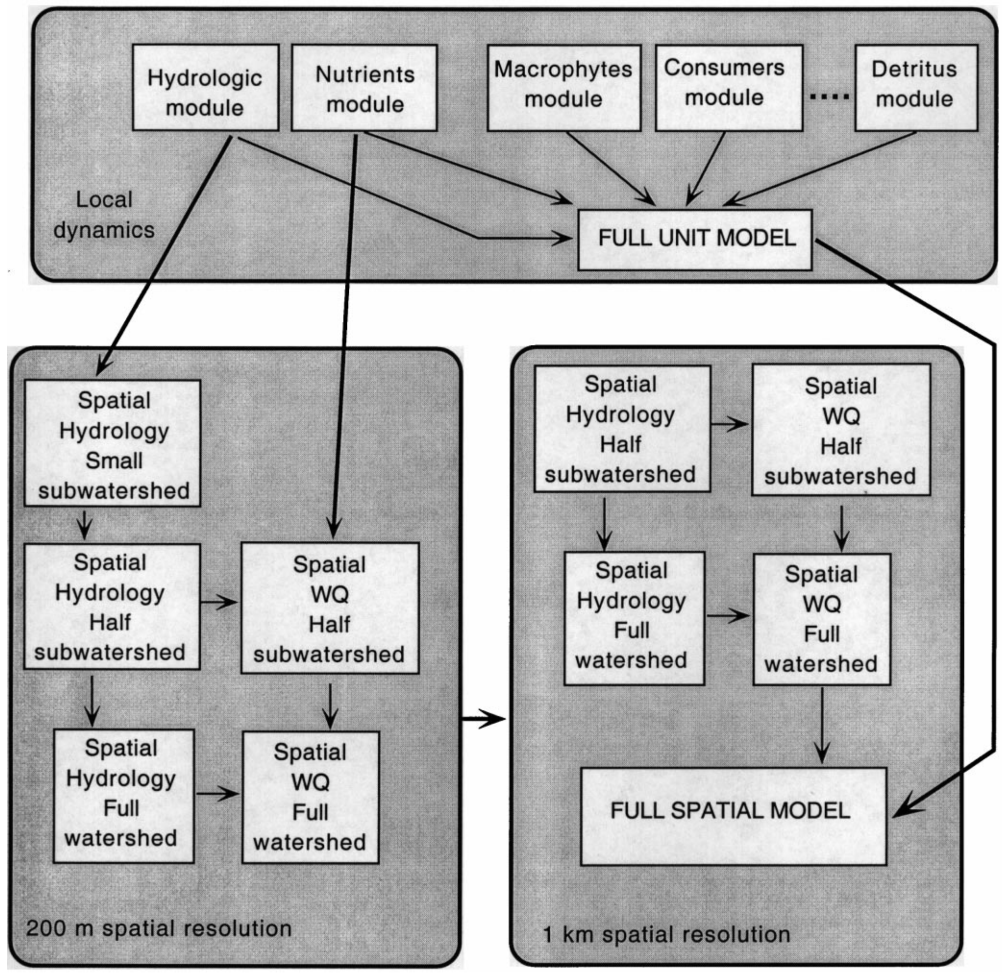


Fig. 9. Multi-tier calibration process for a complex spatial model. Different modules are calibrated independently at a variety of spatial scales and resolutions.

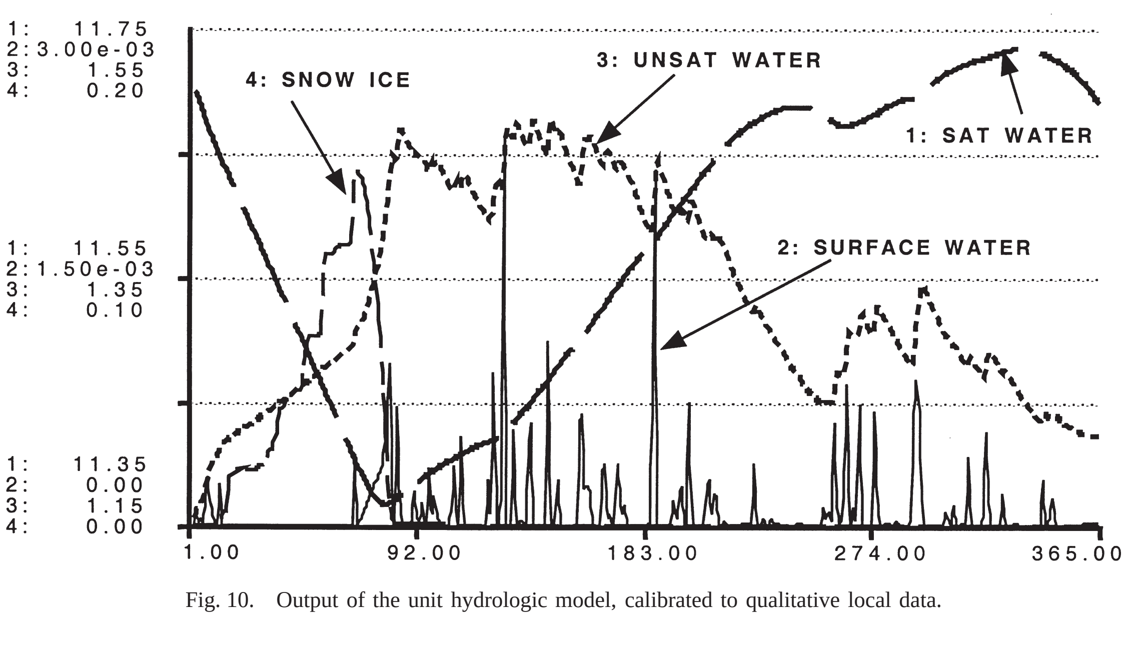


Fig. 10. Output of the unit hydrologic model, calibrated to qualitative local data.

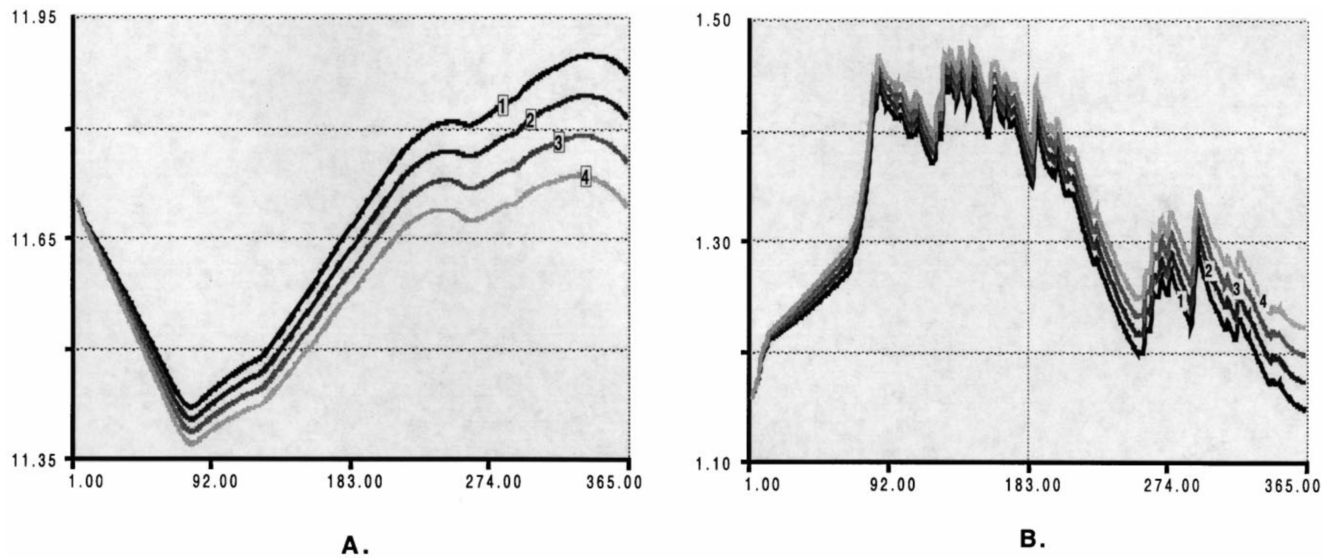


Fig. 11. Sensitivity tests for water in saturated (A.) and unsaturated storage (B.). High sensitivity to horizontal groundwater flow rate demonstrates the importance of spatial hydrologic processes for the adequate model performance in the local scale. (1—flow rate = 0.0027 m/day; 2—0.0028; 3—0.0029; 4—0.003.)

The 1 km resolution reduced the total number of model cells in the watershed from 58,905 to 2352 cells.

We also identified a hierarchy of subwatersheds for calibration at different spatial extents. The Patuxent watershed has been divided into a set of nested subwatersheds to perform analysis at three scales (Fig. 12). A small (23 km^2) subwatershed of Cattail creek in the northern part of the Patuxent basin was used as a starting point. The next larger watershed was the upper non-tidal half of the Patuxent watershed that drained to the USGS gage at Bowie (940 km^2). Ultimately we examined the whole Patuxent watershed (2352 km^2). The number of total model cells grew from 566 cells initially, to 23,484 cells for the half watershed, and then to 58,905 cells for the entire study area at the 200 m resolution.

A set of experiments was staged with the small Cattail creek subwatershed to test the sensitivity of the surface water flux. Three crucial parameters controlled surface flow in the model: infiltration rate, horizontal conductivity and number of iterations per time step in the hydrologic model. Riverflow peak height was strongly controlled by the infiltration rate. The conductivity determined river levels between storms and the number of iterations or the linkage length modified the width of the storm peaks.

Surface water flow was calibrated against the 13 USGS gaging stations in the area that have data concurrent with the climatic data series (1980–90). The model results for the Cattail subwatershed were in fairly good agreement with the gauge data (Fig. 13). The model parameters were adjusted over a time period of one year, and then they were fixed for the second year run. Since the initial conditions were roughly approximated it took several months for the model to adjust. In comparing the

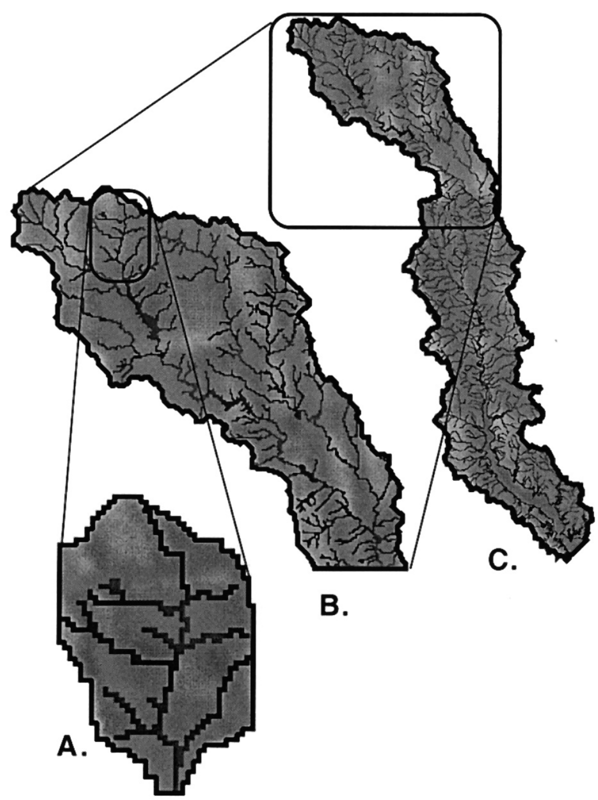


Fig. 12. Spatial hierarchy of subwatersheds adopted in the PLM. A. small Cattail Creek subwatershed; B. upper part of the watershed draining at Nr. Bowie USGS gaging station; C. the full Patuxent River watershed.

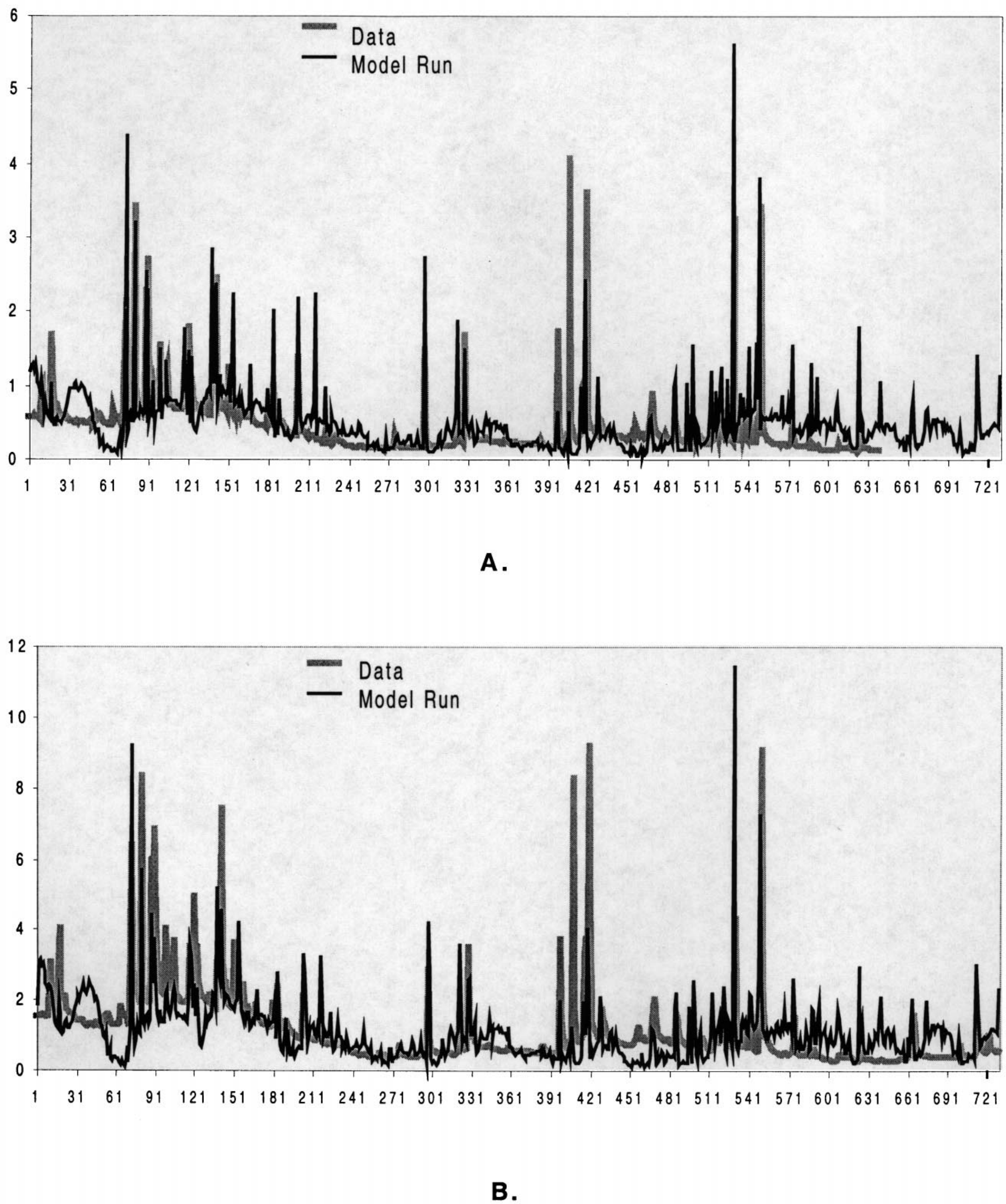


Fig. 13. Calibration (first 365 days) and verification (second 365 days) of the spatial hydrologic module based on the 1980–81 data for two gaging stations on Cattail Creek. A. Nr. Cooksville station; B. Nr. Glenwood station.

results to the data it should be noted that we were not greatly concerned about simulation of individual hydrographs or rainfall events. Rather we were trying to reproduce the overall water flow patterns and total volumes fluxed in the area over the time period of a year and more. Some of the flow statistics for the model calibration over a time period of five years are presented in Table 1.

Table 1
Model verification statistics for the Cattail subwatershed and the Half subwatershed draining at Bowie

	Cattail Data	Model	% error	Bowie Data	Model	% error
Total Flow	2510.41	2527.58	0.68	36617.43	37978.78	3.6
max 10%	930.2	925.79	−0.48	12497.58	16546.70	27.9
min 50%	587.3	596.25	1.50	7917.98	6582.62	−18.4
Total 1986	326.16	282.24	−15.56	4752.94	4352.84	−8.8
Total 1987	472.83	469.25	−0.76	6446.08	7041.22	8.8
Total 1988	482.01	414.22	−16.37	6751.99	5841.62	−14.5
Total 1989	660.62	748.29	11.72	10507.98	11881.88	12.3
Total 1990	568.78	611.31	6.96	8158.45	8861.23	8.3

The calibration for the small subwatershed did not hold as well for the half-watershed area, when the same model was applied. For the gaging station used to calibrate Cattail Creek, the error was quite small, however for downstream gaging stations on the Patuxent River the error was considerably higher. We failed to capture the peak flows in the model.

The number of iterations (effective time step) was adjusted to increase the accuracy of the fit for the larger watershed. Sensitivity analysis performed for the Cattail subwatershed indicated that this parameter could be optimized at 15 iterations. In the larger watershed a better fit was obtained by increasing the number of iterations. At this scale we were moving water further and therefore needed to increase water movement by increasing the number of iterations to better simulate the short-term high peaks. In this case, the variable linkage length approach became crucial and significantly improved the model performance. The simulation results after these adjustments are presented in Fig. 14. The results still were not as good as for the Cattail subwatershed (Table 1), however the total volumes and average flow patterns matched well enough. This model behavior illustrates that different scales present new emergent behavior of the system, and that rescaling is always a delicate process that cannot be done mechanically until there is a greater understanding of the processes involved. Unless adaptation to changing scale is embedded into the model structure (e.g. the self-adjusting linkage length), running the model at varying scales will require recalibration to account for additional data and function that potentially appears in the larger scales.

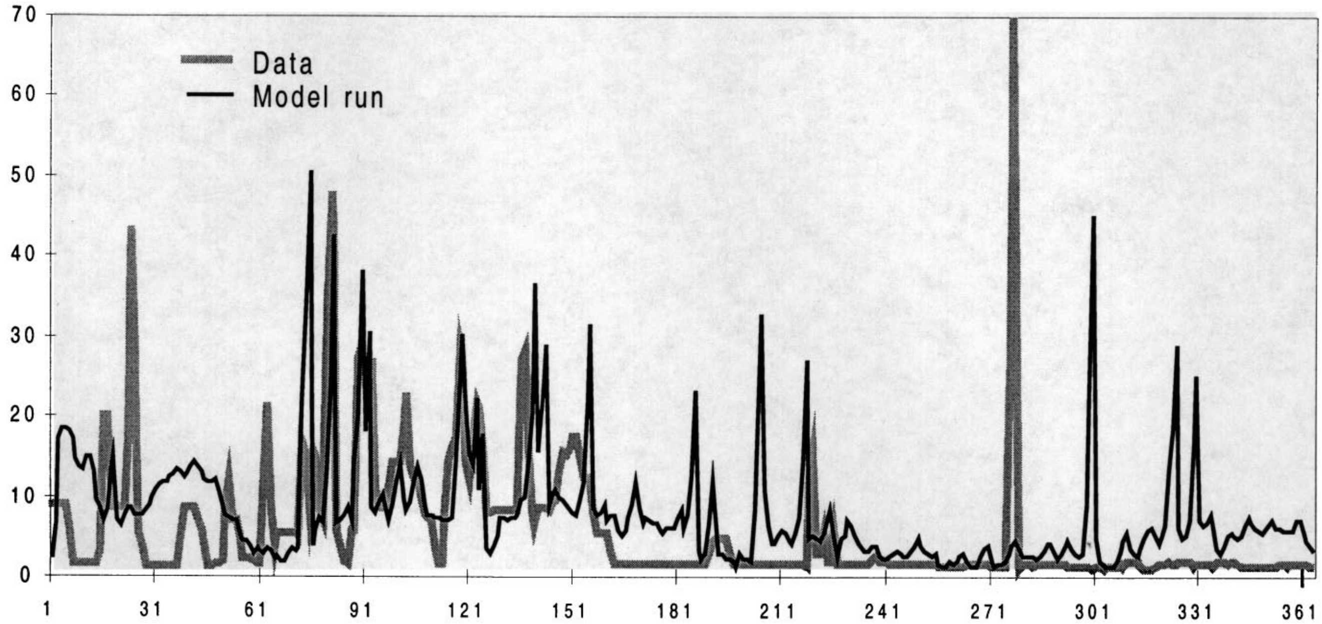
Of the many possible sources for changes in performance, it is likely that the spatial or temporal representation of climatic data is an important factor. In the PLM the spatial rainfall and other data were interpolated from daily records of 7 stations distributed over the study area. The smaller Cattail hydrology was driven by one climatic station whereas the half-watershed model incorporated data from 3 stations. The lack of data on the true variability of the meteorological data in space and time hinders the model's ability to accurately represent short term or localized response in river flow. However, the general hydrologic trends seemed to be well captured by the model.

The other model component that was significantly altered by spatial dynamics, was the nutrients module, especially in its part that represented the fate of nitrogen available for plants uptake. Unlike nitrogen, phosphorus is more easily absorbed and is less available for horizontal transport in terrestrial ecosystems, whereas nitrogen is more easily dissolved and is closely related to hydrologic fluxes. Therefore another submodel was considered that in addition to hydrology, contained the nitrogen module. This was the model that we referred to as the Water Quality (WQ) submodel (Fig. 9), and which was calibrated at the same scales and resolutions as the hydrologic model alone. Unfortunately the data available for dissolved nitrogen were limited to observations of NO_3 content in the estuarine part of the Patuxent river. The northern-most point in that data set was close enough to be extrapolated to the outlet point of the study area in the half watershed scale. The calibration was performed for this station and then for the full watershed.

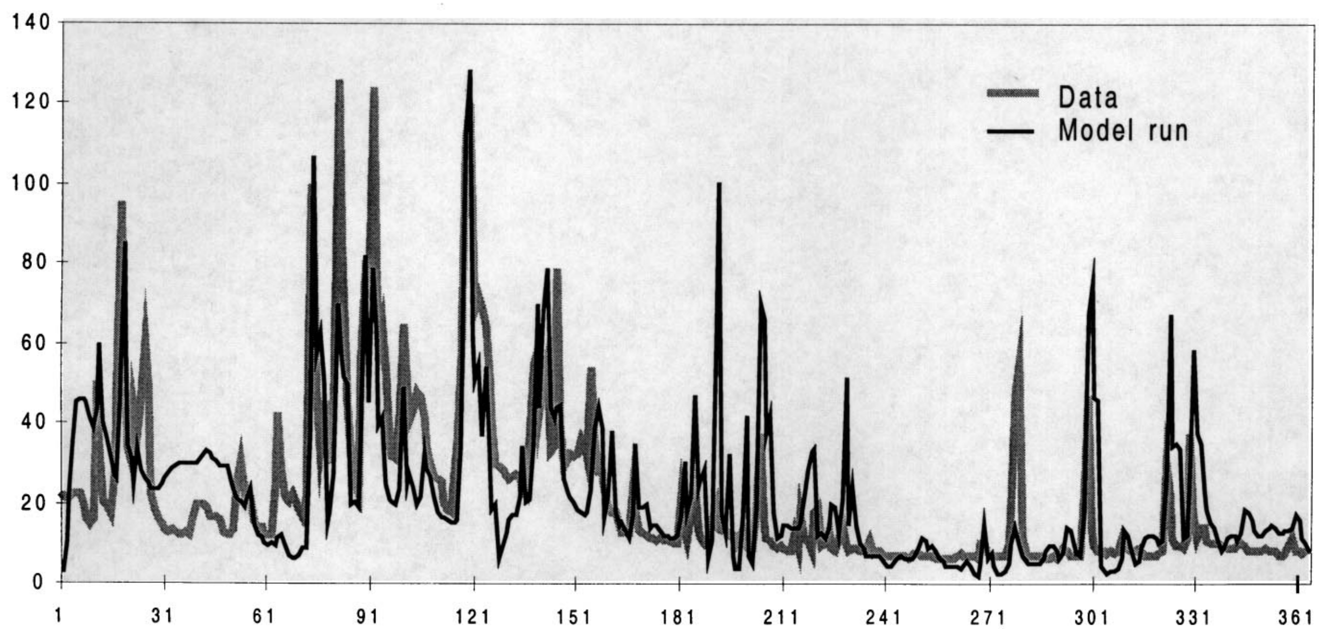
Spatial dynamic output is best represented as color animation, therefore we refer the reader to our Internet page at http://iee.umces.edu/PLM, which further describes the model and gives a better idea of its performance.

7. Full ecological model

The multi-tier calibration approach assumes that modules can be calibrated independently, at least to a certain extent. The hydrologic module was much more dependent on the spatial implementation than the full ecological unit model, that presented local dynamics within particular habitat types. Therefore while most of the hydrologic calibrations had to be carried out spatially, the ecological unit model could be rigorously studied and calibrated for the local conditions within the spatially homogeneous cell. The calibration presented here simulates a 10-year time period using a constant weather



A.



B.

Fig. 14. Verification for the spatial hydrologic module based on the 1980–81 data for two gaging stations in the upper subwatershed. A. Nr. Laurel station. This station is located immediately after a reservoir, which operation schedule is not accounted for in the model. This explains the flat baseflow rate measured at summer, as well as the high flow on Day 275 caused by opening the tainter gate in the Dam; B. Nr. Bowie station.

regime from 1986 for each year. Field monitoring at 12 forested sites located within the Eastern United States (Johnson and Lindberg, 1992) provided mean flux rates and organic matter nutrient contents for input and calibration. Biomass and species composition for the Patuxent area were derived through the Forest Inventory and Analysis Database (FIA) (Hansen et al., 1997). The forest association was oak-hickory with 0.6% coniferous trees and the rest of the parameters were queried from the database for this association. The consumer sector was made inactive in anticipation of stronger supporting data currently being developed.

The calibration was run for three different stages in forest development. At the first or young stage the forest biomass was set at 10% of the maximum attainable biomass which is based on the 75th percentile value for oak-hickory in the FIA. The second stage (intermediate) was set at 50% of the maximum biomass, while the third stage (old) was set at 90% of the maximum biomass. Ten year averages of inorganic phosphate concentrations (PO^{4-}), dissolved inorganic nitrate concentrations (DIN), net primary production (NPP) (Table 2), detrital matter and non-living soil organic matter (NLOM) (Fig. 15) are compared to similar values available through the FIA Database for the Patuxent watershed, or literature on temperate forests.

Similar unit calibration procedures were performed for the other habitat types on the watershed. The PLM currently distinguishes between 5 land use types: 1) open water and wetlands, 2) agricultural land, 3) forests, 4) urbanized land (which includes commercial, high density residential and industrial land), 5) low density and medium density residential land. After calibrating the unit model for the 5 "habitat" types, we could start running and recalibrating the model spatially for the whole area and for all the processes included.

The full spatially explicit ecological model, including the full unit model and the spatial hydrologic model as described above, was run for several years using historical climate inputs for calibration purposes. Two methods were used to compare the model performance to the available data. On the one hand, certain modeled variables, or indices that aggregate model variables, were compared to point time series data. In this case spatial dynamics were integrated into time-series data. On the other hand, we were generating raw spatial data (map coverages), that could be compared to data, when available.

Several time-series data sets such as streamflow, nutrient concentration in the streams, and historical tree-ring data for the region, were available to calibrate longer-term runs of the model with these data sets. Model output was compared to field data by visually inspecting superimposed graphs and comparing annual mean and total values.

Comparison of raw spatial data is a much more difficult and less studied procedure. Data are scarce and rarely match the spatial extent and resolution required by the model. One of the few spatial data sets that are available for comparison with model output is the data derived from Advanced Very High Resolution Radiometer (AVHRR) satellite data, the Normalized Difference Vegetation Index (NDVI) or "greenness" index. It was used to calibrate the full model's predictions of net primary production (NPP) and leaf area index (LAI) for intra-annual effects. We created an index from the NDVI data in order to compare the magnitude of NDVI change to the magnitude of NPP and change between cells in time and space. This was useful for qualitative spatial calibrations. Quantitative correlation between NDVI and biomass growth parameters such as LAI or NPP is yet to be agreed upon, especially for terrestrial, hardwood communities (Fassnacht et al., 1997). Visual comparison showed fairly good agreement between the model output and the data currently available. NDVI data for at least a 5-year period, from 1990–1995, will be used for further model verification. Among others, example output for plant primary production and total photosynthetic biomass from the model can be seen on our Web Page (http://iee.umces.edu/PLM). It shows the typical pattern of seasonal growth in the region.

The model development has now reached the stage when we can start running and analyzing various scenarios. An example of one such experiment is presented in Fig. 16, where we have compared the simulated flow from Cattail Creek area under the land use patterns that existed in 1990 with the flow that the same landscape generated if it was completely forested (the pre-colonization conditions). As it could be anticipated the forested watershed produced more baseflow and lower flow peaks.

Table 2
10-year averages for three forest model variables compared to literature values

	NPP ($kg \cdot M^{-2} \cdot Y^{-1}$)		PO^{4-} (μg/l)		DIN (μg/l)	
Model output	Mean	SD	Mean	SD	Mean	SD
Young	0.039	0.006	0.017	0.004	4.1	5.5
Intermediate	0.29	0.014	0.025	0.019	2.7	2.6
Old	0.497	0.014	0.031	0.027	4.2	3.5
All forest ages	0.27	0.190	0.024	0.02	3.7	4.1
Reference data						
All forest ages	0.14[a]	0.67	0.185[b]	0.165	5[c]	5

[a]Derived through the FIA Database for the Patuxent watershed.
[b]Midpoint and maximum deviation reported by Stevenson (1986) for sandy soils.
[c]Midpoint and maximum deviation reported by Aber (1992) for deciduous forests.

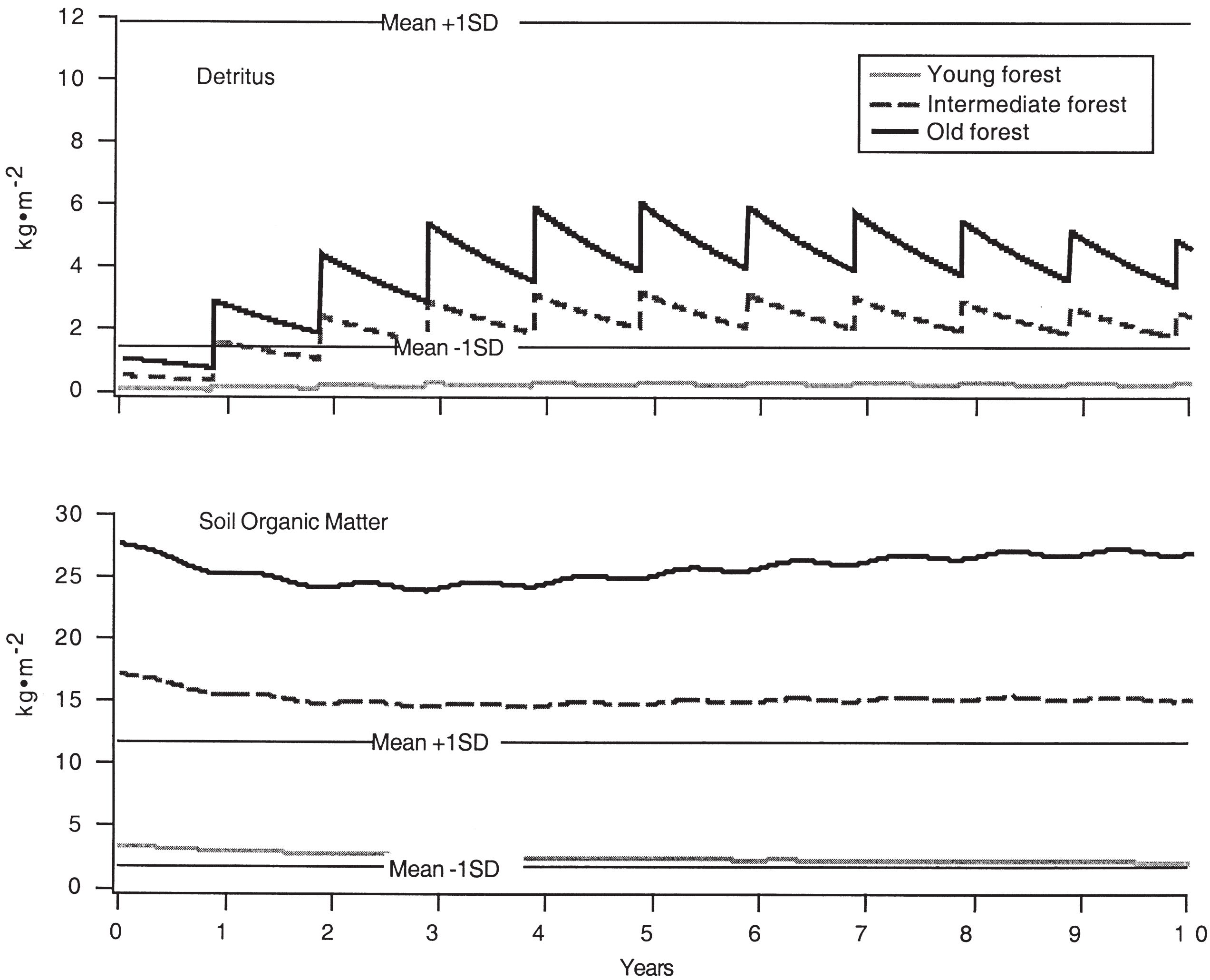


Fig. 15. Example of calibration results for the full unit model. Comparison of detritus and soil organic matter dynamics with 10-year mean values found in literature.

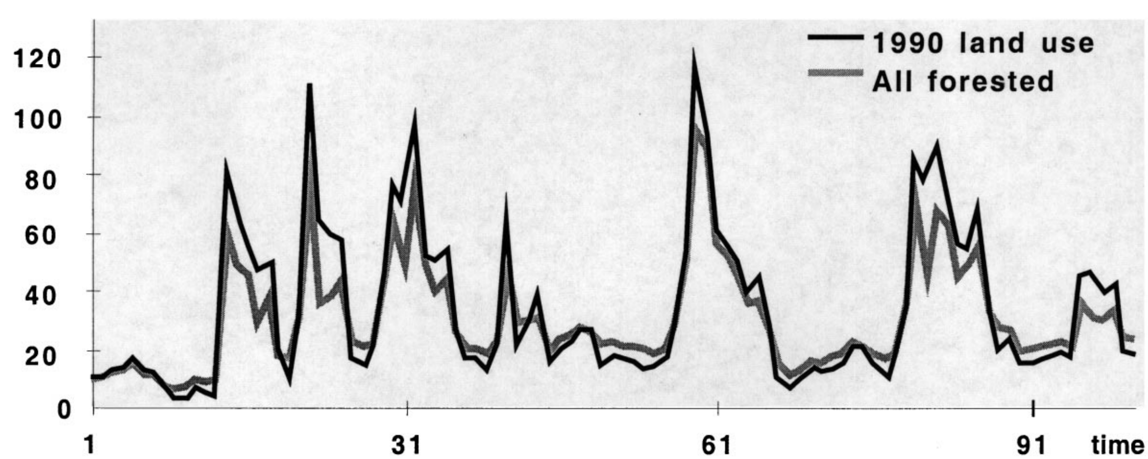


Fig. 16. An example of a scenario run with the PLM. Simulation of waterflow from Cattail subwatershed under 1990 land use patterns and for the all forested landscape.

8. Conclusions

The linked ecological economic model is a potentially important tool for addressing issues of land use change. Because of the high complexity and large uncertainties in parameters and processes, any numerical estimates are intended to be used with caution; nevertheless, the model can offer useful information to those currently addressing degradation of ecological systems in the Patuxent basin. Most important, the model integrates our current understanding of ecological and economic processes to give the best available estimates of the effects of land use or land management change. The model also highlights areas where knowledge is lacking and where further research could be targeted for the most impact.

The high data requirements and computational complexities slow model development and implementation, but PLM tries to find a balance between the simple and general by minimizing complexity while providing 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 take advantage of spatial and dynamic data in its relatively raw form without being forced to use complex spatial or temporal aggregation schemes. System dynamics strongly influences ecosystem processes, with processes changing in dominance over time; our ecological analyses will be inadequate unless we incorporate them. We will continue to trim model components where possible based on sensitivity analyses while maintaining the GEM's generality and the PLM's explicitness.

Our experience with GEM implementation indicates that general models should be applied with caution. While they may be extremely useful for cross ecosystem comparisons and intercalibrations (Fitz et al., 1996), general models may become redundant or inadequate in particular applications. 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 (Voinov and Akhremenkov, 1990; Maxwell and Costanza, 1997), 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 both spatially, temporally and structurally, allows us to build an 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.

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