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Research Article

Modelling Watersheds as Spatial Object Hierarchies: Structure and Dynamics

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Abstract

The generation, transport and fate of non-point source pollutants in surface water systems is recognized as a major threat to water supplies, aquatic and coastal ecosystems. The transformation and movement of water, carbon and nutrients through watersheds integrates a set of ecosystem processes along hydrologic flowpaths. Human individual and institutional interactions with these processes involve direct addition or abstraction of these substances, or the alteration of land cover and drainage systems. In natural and developed catchments, these processes often vary at granularities ranging from below the level of a hillslope, up through regional watersheds. This suggests the need for the development of hierarchical analysis tools that can address the integration of a set of biophysical, biogeochemical and socioeconomic processes over a spectrum of scales. We describe and illustrate the use of a watershed model implemented as a spatial object hierarchy, representing successively contained landform classes associated with class specific processes as member functions. The model has been linked in a range of looser and tighter couplings with GRASS and ArcView, supplemented by specific terrain analytical functions. We illustrate the data and model system for an instrumented catchment monitored as part of the Baltimore Ecosystem Study (BES), a Long Term Ecological Research (LTER) site centering on integrated carbon, water and nutrient cycling.

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1 Introduction and Context

Watersheds are discrete, nested geomorphic systems representing the convergence of a set of tributaries and subcatchment areas, delimited by a complementary set of drainage divides. These systems also represent the convergence and interaction between the geophysical media of the atmosphere, earth surface ecosystems, landforms and soil, and subsurface geologic units. The exchange of energy and mass between these different media occurs on time scales ranging from seconds to millenia, and mutually adjusts the states and dynamics of each. Watersheds can be defined at spatial scales ranging from hectares through millions of square kilometers.

Human individual and institutional activity directly and indirectly interacts with watershed mass and energy budgets either by direct addition or abstraction of water, nutrients and other material, or by altering the composition of the surface and reengineering drainage lines and flowpaths. Problems such as water quality clearly involve the interactions of biophysical and socioeconomic processes along with multiple media (e.g. Novotny and Olem 1993). Consequently, land policy and management strategies have begun to adopt a multi-media approach in which the interactions of human and biophysical systems are considered within delimited watersheds.

Both geophysical and human societal activities are represented over a length of time and space scales. Surface and shallow subsurface flow fields are typically delimited at the scale of hillslopes (divide to stream or drain), and interact with parcel or patch scale ecosystem processes and land management. Deeper groundwater systems may be defined over significantly larger length and time scales, interacting with human activities over similarly larger scales. A major challenge for spatially distributed environmental models is the difficulty of representing the landscape at a granularity that can address the significant scales of interaction between geophysical and socioeconomic processes, and the scales at which planning and management occur. This suggests the development of spatial analytical and modeling tools that explicitly account for the range of scales encountered, and the distributed form, function and interactions between the natural and built environment. Given the complexity of watersheds as natural systems and their strong interactions with socioeconomic activities and human health, a comprehensive model treatment would benefit from a modular and hierarchical framework in which different components and subsystems can be separately defined.

In this paper we describe a spatial object-oriented (OO) framework to model watershed systems, with a focus on computing the spatial and temporal distribution of watershed hydrological and ecosystem flux. Landscape object classes are defined as a formal, spatial hierarchy in which conceptual classes successively contain additional classes ranging from full watersheds down through subcatchments, hillslopes and individual surface patches. We focus on the development of landscape object classes required to represent watershed form, the distribution and dynamics of flow fields characterizing surface and shallow subsurface processes, and interaction with individual and institutional activity. The system is implemented in C++ under both UNIX and WINDOWS and currently interfaces with GRASS and ArcView.

2 Background and Design Specifications

2.1 Design Specifications

Specific goals and design criteria for the watershed system we describe include:

1. a formal representation of the watershed as a landscape object hierarchy in which classes correspond to identifiable landforms and surface cover organized and addressed around the stream network;
2. the ability to scale the simulations from small, instrumented experimental catchments to large regional watersheds using progressively simplified and generalized landscape and process representation within the component hierarchy;
3. the ability to accept forcing variables (e.g. meteorological fields) from multiple sources including point or spatially distributed observations, and model (e.g. atmospheric) output;
4. the representation of human interactions by estimating flux (addition and abstraction of water, carbon and nutrients) and the effects of altered surface cover and drainage flowpaths;
5. the ability to couple with models representing atmospheric boundary layer dynamics, as well as groundwater models.

Additional feedbacks between the set of biogeophysical processes and socioeconomic processes are envisioned as an extension of the model described here, and are a major focus of the Baltimore Ecosystem Study (BES).

2.2 Conceptual Model Development

The system we describe has grown out of the synthesis of two sets of surface process model paradigms from the ecosystems and hydrological disciplines, but spatially structure within a watershed geomorphology framework. A set of ecologically-based models have been developed over the past decade to estimate terrestrial water, carbon and nutrient (WCN) cycling in one dimension at plot to global scales. These include Pnet (Aber et al. 1997), Century (Parton et al. 1988), BIOME-BGC (Running and Coughlan 1988, Running and Hunt 1993), CASA (Potter et al. 1993) and others. However, within watershed systems, export of WCN in drainage waters typically must follow lateral surface or subsurface flowpaths along which nutrients and carbon concentrations can be significantly altered by the combined impacts of ecosystem uptake and transformation processes. These flowpaths have length scales typically ranging in the 10s to 100s of meters characterizing the size of typical hillslopes, or the length from a drainage divide to the nearest stream channel. A number of studies have demonstrated that a significant proportion of nitrogen leaching beneath the rooting zone may be removed along these pathways by uptake or denitrification, with a large part of this sink in small riparian zones (Jordan et al. 1997, Gilliam and Skaggs 1988, Lowrance 1992). These observations emphasize the significance of hydrogeological conditions and the pattern of vegetation patches along hydrological flowpaths. The relative magnitude of surface/subsurface flowpaths varies with hydrogeological conditions, geomorphic structure as expressed by hillslope form and catchment wetness. Some of these flowpaths consistently bypass riparian areas, while others may form bypass mechanisms at high flow. The set of 1-dimensional ecosystem models do not effectively incorporate the problem of lateral divergence and flowpath source and sink effects. Riparian areas are typically very narrow zones with length scales measured in meters, and are well below the resolution of moderate to coarse satellite and terrain data (e.g. >100m). The routing techniques must either operate at resolutions that can capture the small length scales involved, or offer techniques of estimating flowpath effects at subgrid resolution.

Many operational hydrologic models, such as HSPF (Bicknell et al. 1997, Imhoff 1999), have begun to address these problems in order to predict non-point nutrient sources. Modules are being incorporated that account for evapotranspiration, root uptake and denitrification. However, this class of model is typically conceptually lumped, are driven by land use specific parameters, and do not represent terrestrial flowpath networks or the temporal dynamics of surface ecosystems. In most cases land use classes are also conceptually treated in a (1-D) plot paradigm, without routing by lateral flow. The granularity of the planning and development process, which is at the streetscape to subdivision level within which land cover and drainage systems are defined, is not well resolved by specifying land use category alone.

More recent, distributed models, including DHSVM (Wigmosta et al. 1994), RHESSys (Band et al. 1993, Nemani et al. 1993, Mackay and Band 1997), TAPES (Grayson et al. 1992), the PLM (Voinov et al. 1999) and TOPOG (Vertessy et al. 1996) explicitly account for surface and shallow subsurface flowpath effects on soil water divergence. RHESSys and TOPOG have also incorporated carbon and nitrogen cycling and transport, adapting algorithms from BIOME-BGC, Century and other models, and therefore link local ecosystem dynamics with a routing scheme that can simulate the dynamics paths and transformations that occur at the hillslope level. The PLM (Voinov et al. 1999) also incorporates carbon and nitrogen budgets, in this case solved over extensive raster domains.

2.3 Modelling System Description

RHESSys (Band et al. 1993, Nemani et al. 1993, Mackay and Band 1997, Tague and Band 1998) is a spatial data and simulation system that solves coupled soil/canopy water, carbon and nutrient budgets over a set of surface patches which are defined in a set of hillslope hydrologic flow fields within a watershed (Figures 1 and 2). GIS operations are used to process spatial data describing the terrain, soil and canopy properties into a hierarchically nested set of landform elements. The simulations are driven by meteorological inputs and a set of model execution instructions controlling temporal events included in the Temporal Event Control (TEC) file. The process modules operate at a mix of subdiurnal to daily time steps that have been designed to operate over a hierarchy of scales using available remote sensing and spatial data sets to represent 3-D landscape structure. RHESSys was originally constructed by integrating FOREST-BGC (Running and Coughlan 1988) with TOPMODEL (Beven and Kirkby 1979), and has been extended to incorporate more comprehensive ecosystem and hydrologic modules. RHESSys is best described as a method of representing the spatial structure of the landscape, with a paradigm focussed at the hillslope (or valley side) level, with most of the dynamics occurring at this level and below. The watershed is then viewed as a population of hillslopes organized around the stream network. Characteristics of each of the component landform objects are estimated from a combination of remote sensing, digital terrain analysis and GIS analysis of soil, land cover and meteorological information. Key processes that contribute to an understanding of water, carbon and nutrient cycling and transport and require representation within the object oriented model include:

1. in situ land surface water and energy cycles, including
   (a) net radiation, latent and sensible heat flux partitioning,
   (b) interception, infiltration, runoff generation, root water uptake and vertical soil water flux;
2. land surface carbon and nutrient cycling, including photosynthetic fixation, respiration, litterfall and decomposition, atmospheric deposition, nitrification, denitrification, microbial immobilization, root uptake, canopy allocation and leaching processes;
3. overland and shallow subsurface lateral flux of water, sediment, carbon and nutrients through terrestrial ecosystems, including all significant sink, source and transformation processes along flowpaths.
4. direct and indirect interactions with human society, including direct application and abstraction of WCN, alteration of land cover and flowpaths.

Note that at the present time, item 4 is prescribed in the model. We are currently developing statistical functions relating land management (e.g. irrigation, fertilization)

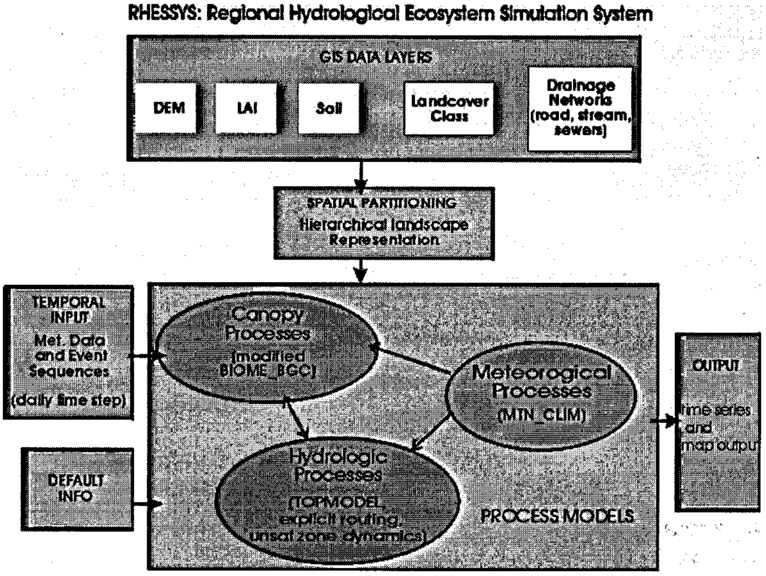

Figure 1 Structure of RHESSys consisting of a GIS capable of organizing the spatial information required to instantiate the landscape object hierarchy, and a spatially distributed object-oriented simulation model that operates on daily to sub-diurnal time steps to compute water, carbon and nutrient budgets. Temporal events are prescribed prior to simulation through the TEC file, and can include simple controls on data output, or redefinition of object attributes due to disturbance, land use change, or data assimilation from satellites (e.g. phenology).

with local socioeconomic variables defined at the parcel (patch) and larger scales. Surface cover and drainage infrastructure, including road and storm sewer networks, are similarly prescribed, but can be easily altered to investigate different development scenarios. At the present time the hydrologic models only include surface and shallow subsurface flow. Longer time scales processes associated with deeper groundwater need to be incorporated by coupling with a groundwater model.

All hydroecological processes incorporated in RHESSys exist as member functions associated with a specific landscape object class and included in a function library. It is beyond the scope of this paper to describe the large number of hydroecological processes incorporated, but a description can be found in Band et al. (1993, 2000), Tague and Band (2000), Mackay and Band (1997), Lammers et al. (1997) and Fernandes (1999). Previous versions of the model have been used in a set of different biomes in North America to investigate WCN dynamics in watersheds ranging in size from 10 hectares (Creed and Band 1998) to 63,000 km^2 (South Platte, Baron et al. 1998) at resolutions ranging from 5m to 1km. At the latter resolution, hillslopes are not resolved and subgrid processes need to be implicitly represented (Lammers et al. 1997).

3. Class Definitions and Containment Hierarchies

3.1 Landscape Representation

RHESSys characterizes a watershed as an object containment hierarchy of

Watershed *c*-> hillslope *c*->climate zone *c*->patch *c*->canopy strata

where *c*-> denotes spatial containment (Figure 2). In this sense, we employ a spatial data model that directly represents landscape elements following a conceptual model of the watershed, rather than a standard cartographic model (e.g. raster or point-line-area). The spatial partitioning and attribute computation of the landscape elements are typically carried out using available GIS systems (e.g. GRASS, ArcView), but are then spatially and topologically defined and structured as a class object hierarchy. At a higher level of abstraction, the land surface classes represent geographically defined components including landforms and vegetation canopies (with the exception of the *climate zone*) which act as containers for system state variables. Each instantiated class object down to the patch level corresponds to a GIS component for spatial analysis or visualization of state or flux variables computed for any time step. Strata are contained within patches, but are not explicitly located, allowing mixed canopy and land cover conditions. Each class of the spatial hierarchy is associated with different processes modeled by the simulation system. Thus, each level of the hierarchy is defined as a particular class with specific state variables, parameters and functions appropriate for that class definition (Table 1).

As the system is designed to interface and share state and flux variables with a set of linked models (e.g. atmospheric, groundwater, socioeconomic) and visualization methods, we have separated data storage and process representations. While a more 'natural' structure of the system is gained with the object hierarchy, the scattered nature of the state variables among many objects can degrade numerical operations. Our current approach maintains a central location for state variables, facilitating both numerics within the current model and the access of fields for visualization or by other interacting models.

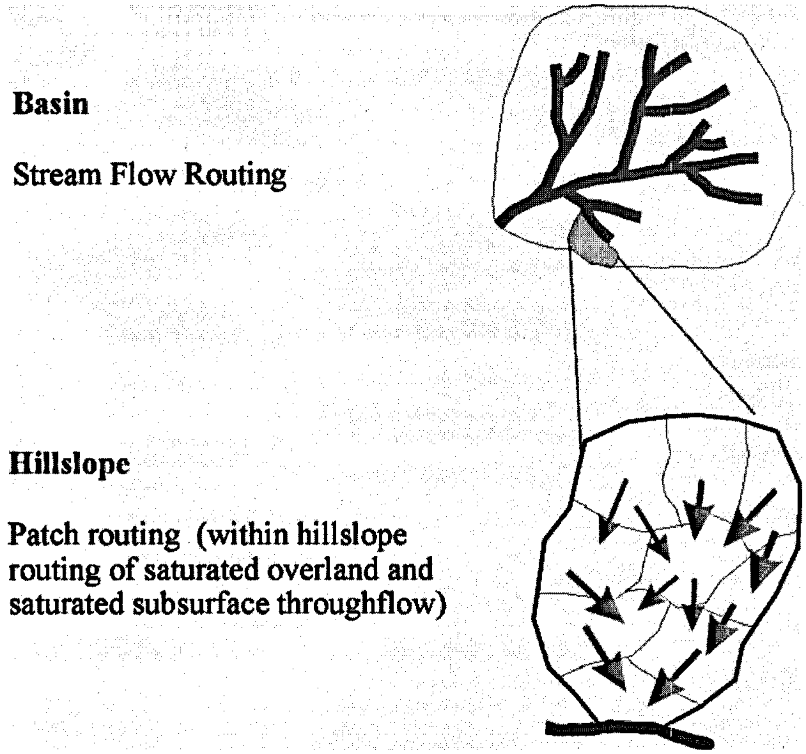

Figure 2 Containment hierarchy of landscape objects within RHESSys from the basin to patch level (strata are contained within patches). Stream routing is defined at the basin level, overland and subsurface flow routing at the hillslope level, and 1-D soil-canopy-atmosphere exchange and transformation of water, carbon and nutrients at the patch and strata level.

3.2 World Definition

The *world* class defines the full domain (spatial and temporal) within which watershed dynamics will be addressed, and identifies links to the set of inputs describing meteorological data, and information on the types of soils, vegetation and other land cover in the region. It contains a set of *basin* class objects that define separate or contiguous watersheds.

3.3 Basin Definition

The *basin* class defines the watershed area above a specified outlet. It contains a stream network and associated drainage areas (Figure 2). The stream network, in turn is defined as a tree graph containing interior and exterior edges (stream links) following the terminology of Shreve (1967). Streamflow routing is defined for this class, accumulating runoff production from contained *hillslopes*. *Basins* also serve as aggregating units for ecosystem and hydrologic processes and state variables computed at the sub-basin level.

Table 1 RHESSys object connectivity and hierarchy. For multiple basins, hillslopes, zones, patches and strata, each would have its own functional object, data object (attached to the appropriate linked list) and default data object. The number of output objects is based on the number of variables chosen in the output choice file. The number of output files is based on the entries in the TEC file, which controls the scheduling of temporal events including changes in land cover (e.g. harvest, fire) as well as model run logistics.

Default collection	Functional	DataFactory	Output objects	Output files
World defaults	World processes	World linked list World data		
Basin defaults	Basin processes	Basin linked list Basin data	BasinOutput	Basin output files
Hillslope defaults	Hillslope processes	Hillslope linked list Hillslope data	HillslopeOutput	Hillslope output files
Zone defaults	Zone processes	Zone linked list Zone data	ZoneOutput	Zone output files
Patch defaults	Patch processes	Patch linked list Patch data	PatchOutput	Patch output files
Stratum defaults	Stratum processes	Stratum linked list Stratum data	stratumOutput	Stratum output files

3.4 Hillslope Class

Hillslopes define areas which drain to a common side of a stream link. *Hillslopes* can be derived either by available GIS tools (e.g. *r.watershed* in GRASS) or other terrain partitioning software as described in Band (1989), Lammers and Band (1990) and others. Each *hillslope* is composed of a set of contained *patches*. By definition, each *hillslope* drains into a stream link, which is shared with the *hillslope* object draining into the opposite side of the link. Lateral redistribution of soil moisture between *patches* and base flow are defined at the *hillslope* level. Lateral water redistribution can be handled by two methods (Plate 1, see plate section):

1. use of TOPMODEL (Beven and Kirkby 1979) in which the patches are defined as spatially discontiguous pixels sharing a similar topographic-soils index, and
2. an explicit inter-patch routing method, generalized from the approach of Wigmosta et al. (1994) to allow variable patch shape and size (Tague and Band 1998). In this case, the flow topology between patches is determined as a function of local gradients and shared *patch* boundary lengths.

As *hillslopes* are bounded by a set of drainage divides and a stream reach, they are independent of each other (flow does not cross divides or streams). Thus, flow fields can be solved separately for each *hillslope*. Given the limited number of contained *patches*, the *hillslope* level is a good candidate for parallelization. Like basins, *hillslopes* can be used to aggregate processes or stores contained in lower parts of the hierarchy.

3.5 Zone Class

Zones denote areas of similar climate and define meteorological variables including radiation, precipitation, vapor pressure and temperature as well as functions that extrapolate base station meteorological information to local landscape conditions (e.g. altitude, slope, aspect effects). Each *zone* contains one or more patches and is linked to a set of input climate time series which may be derived from observations (base meteorological stations) or models. The *zone* class will generate climate data that may not be available from a base station (i.e. zones contain member functions to estimate radiation flux and vapor pressure from daily temperature range). Numerous strategies exist to partition areas of similar climate. In hilly or mountainous areas, elevation bands within hillslopes, for example, are likely to have uniform microclimates as discussed in Lammers et al. (1997). As *zones* are contained within *hillslopes* they can inherit slope and aspect defined by the *hillslope* partitioning algorithms. In areas without significant relief, the distribution of base stations (using for example Thiessen polygons) or atmospheric model grids, intersected with hillslopes, can also be used to define *zone* partitioning.

3.6 *Patch Class*

Patches represent the highest resolution spatial unit. *Patches* can be defined as grid cells (as special cases) but include a more general set of polygons defined to optimally represent variation in surface cover, topographic and soil conditions within the *hillslope*. An advantage of the irregular polygons is the ability to adapt shape and size to accommodate varying spatial gradients in important variables. This is especially important for representation of narrow riparian regions surrounding streams and hillslope hollows which may be significantly smaller than a standard grid resolution (e.g. <30m–100m). A disadvantage is the potential difficulty of altering *patch* pattern within a simulation time domain, in which case a high resolution regular grid with fixed structure may be preferred.

Roads and streams are special instances of *patches* that would also not be well represented with a raster data model. Although a stream link is not wholly contained within a *hillslope*, it does act as an absorbing boundary for (two) *hillslopes*, and is included as such in the *patch* flow routing topology. The flow absorbed into the stream patches can then be simply accumulated to gain total runoff production, or dynamically routed through the stream network. Roads also have an areal cover and are integral parts of the flow routing system, often causing significant changes in surface and subsurface water flowpaths. *Patches* can be an overlay of a few different themes, such as wetness index, vegetation cover and, when explicit routing is used, the stream and road networks. We are currently working to improve the *patch* construction methods as there are a number of constraints that should be observed to preserve an unambiguous routing sequence. Patch shape should be convex such that a flowline enters and leaves a *patch* once. One method we are exploring is to adapt the terrain partitioning methods included in TOPOG and TAPES which can satisfy the geometric and topologic constraints discussed above and simplify the routing scheme.

Note that depending on the type of routing that is chosen, *patch* classes are defined in different ways. However, with the exception of the manner in which saturated zone soil water is redistributed over the hillslopes, the two forms of *patch* instantiation (TOPMODEL index intervals or explicitly defined) are functionally identical. Unsaturated and saturated soil moisture dynamics are computed at the *patch*. The *patch* partition must group together areas of similar soil moisture since soil moisture driven processes such as infiltration, exfiltration, saturation zone recharge and runoff production occur at this level. Soil water balances are updated in the *patch* by a set of functions that estimate vertical flux of water through the unsaturated layer and the net recharge due to lateral flux.

Finally, human activity would be defined at the *patch* level by specifying local rates of irrigation, fertilization or abstraction of water. We are currently exploring the development of simple statistical tools to use socioeconomic data at the *patch* level to estimate lawn fertilization rates as part of the BES. Advertent or inadvertent redirection of water by storm and sanitary sewers would also be processed at this level. At present, unplanned infiltration and input (I/I) of water into sanitary sewer lines is a large problem in aging infrastructure. We do not specify precise locations of sewer lines within a *patch*, but specify the presence and densities of these features which can act as sources of effluent or as drains, depending on hydrological conditions. The presence of storm drains within a *patch* can also be specified as a sink and redirection of runoff to patches other than those defined immediately downslope. The alteration of the drainage sequence by roads and storm sewers provides an important drainage bypass effect that changes the progressive accumulation of runoff and shallow throughflow downslope (Tague and Band 2000).

3.7 Canopy Stratum Class

Canopy *strata* fully inherit their spatial partitioning from their parent *patches*. Unlike other levels, however, canopy *strata* define multiple vertical layers. Each *stratum* corresponds to a different layer such as overstory or understory in the canopy structure. The litter layer is also included as a separate *stratum* layer. A height state variable associated with each layer defines its processing relative to the other layers. Incoming radiation, precipitation and wind velocity are attenuated through successive multiple layers sorted by height (litter layers are given a height of zero). There can also be multiple *strata* at the same height. In this case, an associated cover fraction of less than one must be associated with each *stratum* at the same height. The total cover fraction at any height must equal one. Multiple *strata* at the same height are assumed to be well mixed in regard to radiation and precipitation interception.

All canopy physiological and biogeochemical processes are defined within this class. Processes such as stomatal physiology, photosynthesis, transpiration, respiration and allocation are modeled at the canopy *stratum* level. Soil water uptake, litter fall, decomposition and mineralization are processes that exchange mass with the parent *patch* object. These processes have time scales ranging from subdiurnal to decadal and longer. Therefore, the model can follow processes up through long term canopy development and growth, as well as change in soil nutrient and organic matter content.

Within urbanizing watersheds, the *stratum* class is generalized to include non-vegetated built layers such as building rooftops and pavement. Typically, the distribution of impervious surfaces must also be expressed statistically as length scales can be very short (e.g. walkways). This variable is a key control on runoff production from urban *patches*.

4 GIS Input and Structure of Landscape Description in RHESSys

4.1 Interface Design

The full state of the system, including object state variables, model parameters and information regarding valid time domains for the initial state and simulation, is contained within a single file. The *worldfile* describes the full hierarchy at a given instance of time and can be generated:

1. from spatial data within a GIS environment with a specific interface program, or
2. during a model simulation at any given time step.

This latter procedure is used to generate a full system description, giving the ability to stop and start the simulation at any specific time, allowing storage of a complete simulation state which can then be used for initial conditions. This is an important feature as some of the long time scale processes such as canopy development and nutrient cycling may occur over decades, requiring long initialization times to avoid transient conditions arising from incomplete or unbalanced initial conditions. The user can also specify an alternate *worldfile* specifying an alteration in system state, simulating development, forest fires or other disturbances or land cover changes within the GIS environment. These types of temporal events, including changes in land cover/harvest are communicated through the Temporal Event Control (TEC) file (Figure 1). The TEC file also controls the scheduling of periodic events such as fertilization, or simple system functions such as enabling and stopping output of specific variables at specific times.

Within the *worldfile* and internally within the RHESSys simulation (Table 1) each level of the spatial hierarchy has associated with it the following items:

1. *Identifier*: Each object instance of a class is assigned a unique ID derived from the GIS partition layer.
2. *State Variables*: State variables are initialized at the start of the simulation and are temporally updated as the simulation runs (e.g. soil moisture at the patch level). Within RHESSys, state variables are stored in the DataFactory to facilitate access by other applications (models, visualizers) and to improve numerical processing.
3. *A link to default variables*: Defaults remain constant throughout the simulation and are usually associated with a standard class for that level of the spatial hierarchy (i.e. *patch* defaults may be defined for different soil types – gravel, clay etc, pore size index is one of the default variables included in that class).
4. *A link to a climate station*: The *zone* level is associated with a link to a particular base climate station which contains meteorological time series that can be derived from actual stations or from atmospheric models. This structure supports a one-to-many mapping of input climate base stations to landscape objects and allows input base climate data (prior to topographic correction) to vary spatially. The climate station contains climate time series input and information about the climate base station (or atmospheric model grid cell).

When the routing sub-model is used, it is necessary to explicitly describe the connectivity between individual patches within a hillslope. A description of this hierarchy is given in a *flow table*, which is input into RHESSys. The *flow table* is created from terrain analytic functions operating on the defined set of *patches* and describes the flow network topology.

4.2 GRASS Interface

Our initial GIS interface with RHESSys was written into the GRASS environment. This constituted a fairly loose coupling of the GIS/modeling environment as it required all spatial processing to be accomplished in a raster environment by defining and then manipulating information within connected component regions. The spatial processing automated the statistical summarization and functional computation of *basin, hillslope, patch* and *strata* attributes for creation of the *worldfile* for export to the simulation model. The model is then independently executed using command line options that specify the modeling environment, link a set of input data files, and define output files. Any of the model internal state variables can be defined for output at any specified space and time frequency. Model output would then need to be reimported to GRASS or another package (e.g. SPlus) for further analysis and visualization.

4.3 ArcView Interface

More recently, we have developed an enhanced utility using Avenue script for ArcView. RAIMEnt (RHESSys Arc-view Integration and Modeling Environment) provides enhanced functionality and a tighter coupling of the GIS/modeling environment (Tenenbaum 1998). RAIMEnt reproduces the functions previously structured with GRASS, along with all other procedural steps required to set up the model environment, execute the simulation and visualize results. Additional features include:

1. a model tracking and documentation facility which stores information on the set of GIS data layers, meteorological files and other model control information used in specific simulations,
2. automated enforcement of spatial data assumptions (e.g. exhaustive partitioning of parent objects by descendent objects),
3. dialog boxes to facilitate the choice of data layers and model setup,
4. visualization of spatial data output, mapped back to specified class partitions at different time steps,
5. facilities to operate and incorporate the results of external code through linked libraries, significantly extending spatial analytic capabilities beyond what is embedded in ArcView.

RAIMEnt provides both a more tightly coupled GIS/modelling environment as all functionality is presented through the common ArcView interface, and a GIS/modeling software package that is much more easily distributed to a range of users. All object level information can be stored and manipulated in ArcView tables linked directly to class shapefiles. The user never works directly with the *worldfile* that is automatically produced at the time of model execution which is launched from ArcView, or could be directly read back into ArcView tables. The hydroecological modeling still requires expertise in judging the quality and uncertainty embedded in input data sets, the limits of model assumptions and interpretation of model outputs and uncertainty, but the technical barriers of specific model set up, operation and visualization are greatly eased.

4.4 *Model and Spatial Data Handling Illustration*

A simple illustration of the modeling system is presented in Plate 2 and Figures 3 and 4. The hillslope and patch partitioning of a small watershed in Baltimore County is presented in Plate 2. This catchment is 40 hectares in area and is used as a control forested catchment within the Baltimore Ecosystem Study (BES). In this illustration, we show the use of the modeling and spatial data system to generate time series of basin nitrate concentrations in streamflow (Figure 3), as well as the spatial distribution of long term ecosystem adjustment at the patch level (for hillslope 1, Plate 2), in this case the accumulation of stem carbon (Figure 4). Both of these processes, occurring over very different time scales, are partially dependent on soil water patterns as controls of carbon and nitrogen cycling. The large increase in nitrate export from the catchment during the summer appears to be a result of a change in the coupling of uplands through the riparian patches as shallow subsurface throughflow decreases through the summer, and a transformation of the lower slope patches from nitrate sinks to sources as the riparian zone saturation levels decline. In this case, nitrate export from the catchment can only be understood by explicit consideration of the interaction between upslope, midslope and riparian patches, an interaction that would be lost with a spatially lumped approach. Over longer time scales, the greater drainage of the steeper midslope region results in greater soil water limitations, reducing net primary production which results in lower standing stem carbon. Note that these simulated patterns can be tested with plot scale measurements which we are currently carrying out.

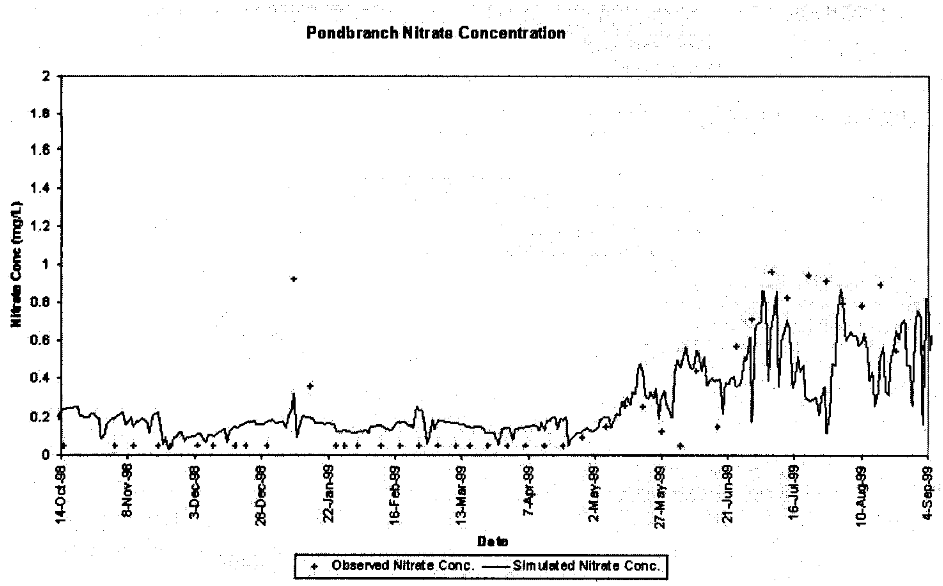

Figure 3 Time series of nitrate concentrations in streamwater exported from Pond Branch. During the dormant season nitrate levels are largely below the detection limits, and rise significantly during the (drier) growing season when a number of the patches appear to switch from nitrate sinks to sources.

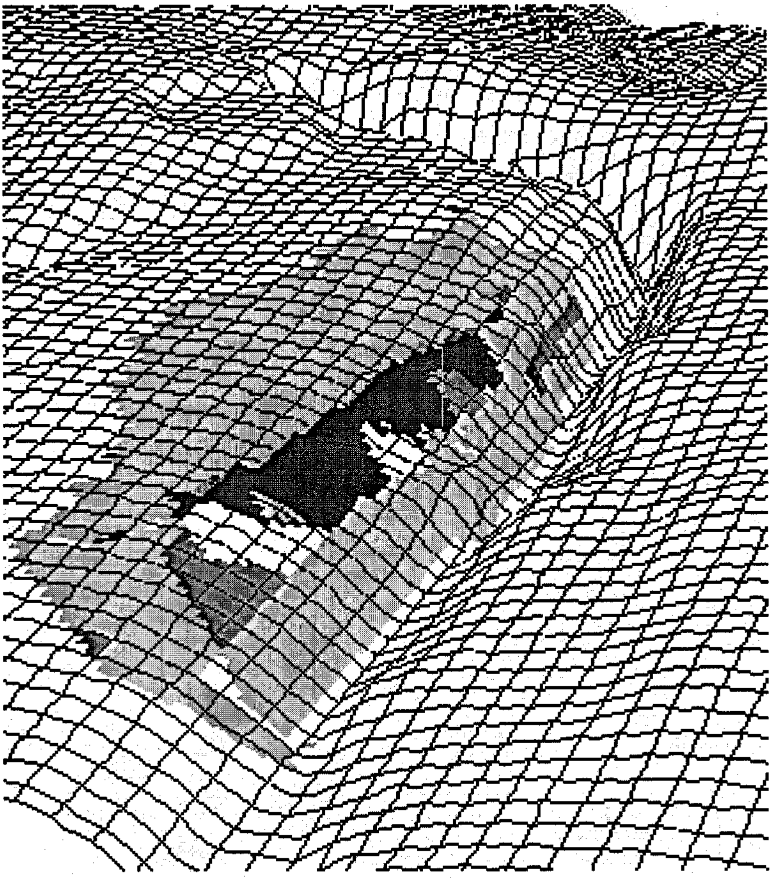

Figure 4 Spatial fields of standing stem carbon defined at the patch level for hillslope 1 (Plate 2) with grey values ranging from ~1.4 $kg.C.m^{-2}$ to ~1.7 $kg.C.m^{-2}$. Differences are largely accounted for by variations in soil moisture, with the steep midslope area being better drained and typically experiencing greater soil water limitations through the summer growing season.

4 Conclusions

We have implemented a spatially distributed hydroecological model as an object oriented containment hierarchy. Processes are defined as member functions for specific landscape classes, corresponding to the scales at which they occur within watersheds. This produces a system that mixes processes occurring over a wide range of space and time scales, and which achieves sufficient granularity to represent and test the effects of field scale variation and human interaction with the landscape at the hillslope to small catchment level. For urbanizing regions, this corresponds to the scale at which developments (roads, drives, buildings) are designed. We are currently exploring the use of municipal or county parcel data sets in conjunction with census (block) and high resolution imagery to define socioeconomic indices at the patch level to aid in the estimation of human influenced nutrient and water budgets. At this level, specific activities or even land cover may not be explicitly mapped, but we need to statistically estimate expected values for such processes as fertilization rates or irrigation. The paradigm is based on the assumption that there is a finite resolution at which it is feasible to directly locate landscape components (the *patch*), but that heterogeneity in both state and flux variables below that level may still need to be expressed by aspatial distributions (*strata*). Different solution schemes are incorporated for the movement and transformation of water, carbon and nutrients depending on the amount of land surface information available, as well as the degree of spatial and process precision deemed appropriate.

A key attribute of the system is the embedding of a full, 1-dimensional ecosystem model, instantiated within multiple *patches* and *strata*, along explicitly defined hydrologic flow paths. While the system maintains a 'real-world' interpretability by defining and representing processes on spatially discrete, encapsulated landform classes, the flux of water and dissolved components needs to be solved over flow fields, in which case access to arrays of hydraulic potential values for defining gradients are required. Instead of having these models individually interrogate different land surface objects, spatially distributed state variables are consolidated in linked, spatially defined lists in the DataFactory. Likewise, other applications software, including animation and spatial statistical tools will be incorporated that can interface with the centralized data structures produced here. This has the effect of consolidating state variables that otherwise are scattered through different instantiated objects, with the goal of improving numerics and access by other applications.

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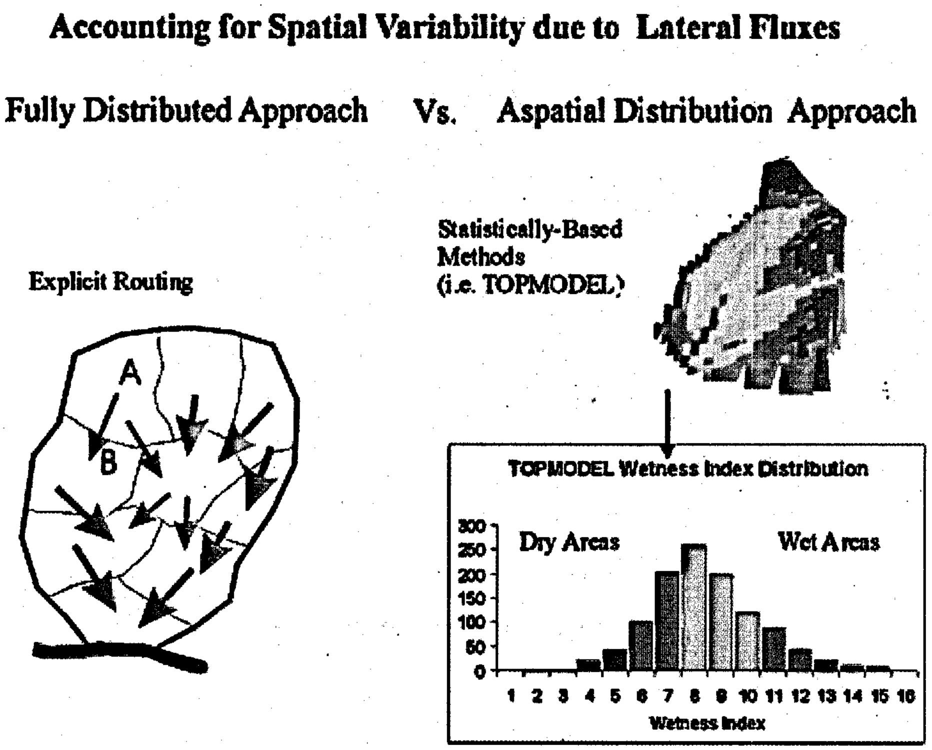
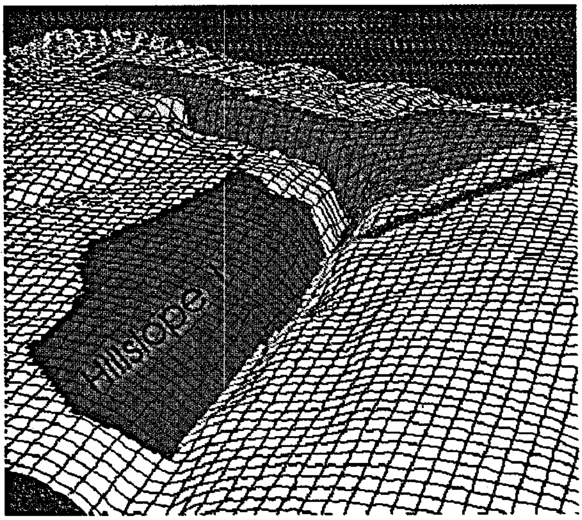


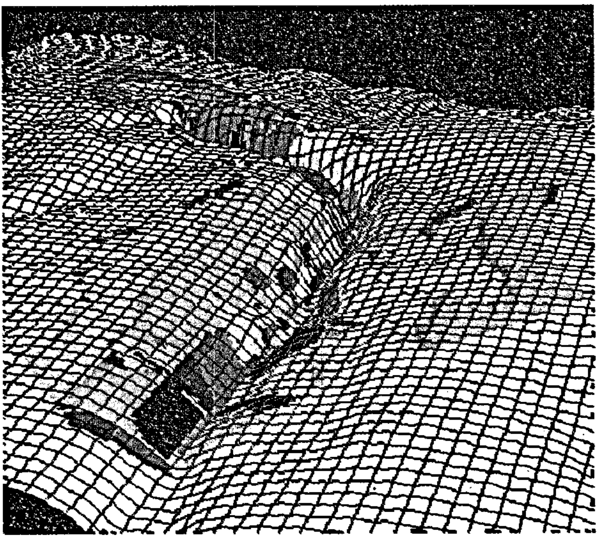
Plate 1 Two alternative soil water redistribution methods; one based on explicit routing through spatially defined patches, and the second based on the statistical approach of TOPMODEL

Plate 1 from L E Band, C L Tague, S E Brun, D E Tenenbaum, and R A Fernandes 'Modelling Watersheds as Spatial Object Hierarchies: Structure and Dynamics', pages 181–196

Pondbranch
Hillslopes
(hydrologic
sub-basins)



Patch
(similar soil
moisture
characteristics)



Hillslope and Patch Partitioning for Pondbranch Watershed

Plate 2 Illustration of the basin, hillslope and patch hierarchy for Pond Branch

Plate 2 from L E Band, C L Tague, S E Brun, D E Tenenbaum, and R A Fernandes 'Modelling Watersheds as Spatial Object Hierarchies: Structure and Dynamics', pages 181–196