Modelling Watersheds as Spatial Object Hierarchies: Structure and Dynamics

EEOS 627 Environmental Modeling with Raster GIS
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Overview

The Baltimore Ecosystem Study (BES) is a long term ecological research (LTER) project funded by the National Science Foundation (NSF) and the Environmental Protection Agency (EPA) in an effort to learn how an urban area works as an ecological system.

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Jacquie

Baltimore Ecosystem Study

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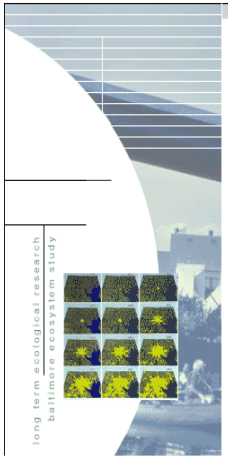

What is the Baltimore Ecosystem Study?

When people think of ecology, they usually imagine studies out in the country. The next thing they think of is studies involving the relationship of plants and animals to one another. They also imagine studies that show how organisms relate to the physical environment -- air, water, and soil. People and cities usually don't come to mind when ecology is mentioned.

But ecologists now realize that it is important to understand cities and suburbs, because about three quarters of the people in the United States live in metropolitan areas. More people are also moving to cities throughout the world. So ecologists want to know how organisms and environments in and around cities are affected by the buildings and paved surfaces, the things that people do, and the new environments that cities create. To do that ecologists have to work with other researchers who understand people. That means more than just knowing how many people there are in an area. Understanding the urban environment requires that we understand how people are interact as groups and organizations that make decisions. What people do and build in and around cities affect the environment and the plants and animals for many miles around

What is the Long Term Ecological Research Network?

The Baltimore Ecosystem Study is one of 24 research programs established by the National Science Foundation to study ecological systems over long time periods. Ecological processes often take long times to occur, and so scientists must collect and use data that span long time periods. The projects that make up the Long-Term Ecological Research Network span different kinds of sites of interest to ecologists and decision makers. There are sites in the Arctic, in Antarctica, in moist coniferous forests, deciduous forest, coastal areas, grasslands and deserts. BES represents the particularly dynamic and patchy ecosystem type found in and around cities, and enhances ecological understanding by including an ecosystem type rarely studied by ecologists.

LTER

http://www.lternet.edu

The Baltimore Ecosystem Study is a long-term ecological research project. It is funded by the National Science Foundation and the Environmental Protection Agency to learn how an urban area works as an ecological sytstem. We want to know the ecological interactions in the whole range of habitats -- from the center city of Baltimore, out into the surrounding rural areas. We are conducting research on the soil, the plants and animals on land and in the streams, the water quality, and condition of the air in and around Baltimore. For that information to make sense, we are also studying how families, associations, organizations and political bodies make decisions that affect ecological processes. In other words, we are treating the whole collection of urban, suburban and rural areas as an ecological system that includes people and their activities. This is a really unusual approach to ecology because it combines with social sciences, physical sciences, and education to understand a big metropolitan area as an ecological system. Saying that an urban area is a system just means that we are concerned with the interactions between wild and domestic organisms, people and their organizations, and the natural and built environment all affect one another. It is these relationships that determine the quality of the environment we experience in the places where we live, work and relax.

The research project is long-term, because conditions in the past affect the urban environment we experience now, and we also need to be able to say what environmental effects the things we are doing now in and around our cities will affect the environment in the future. This information can help people, including individuals, families, organizations and government agencies, to make decisions that have the environmental effects that they want. We will try to keep people informed through this publication, through meetings and workshops, through school and community interactions, and through the web. We're young, and growing rapidly. We look forward to keeping in touch with you.

Signed in online

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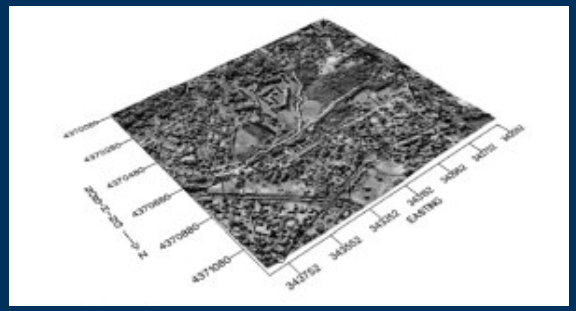
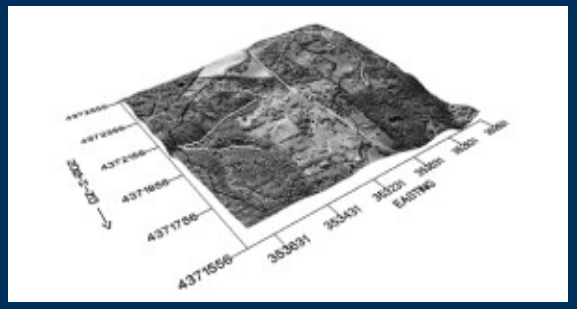
The Gwynns Falls Watershed

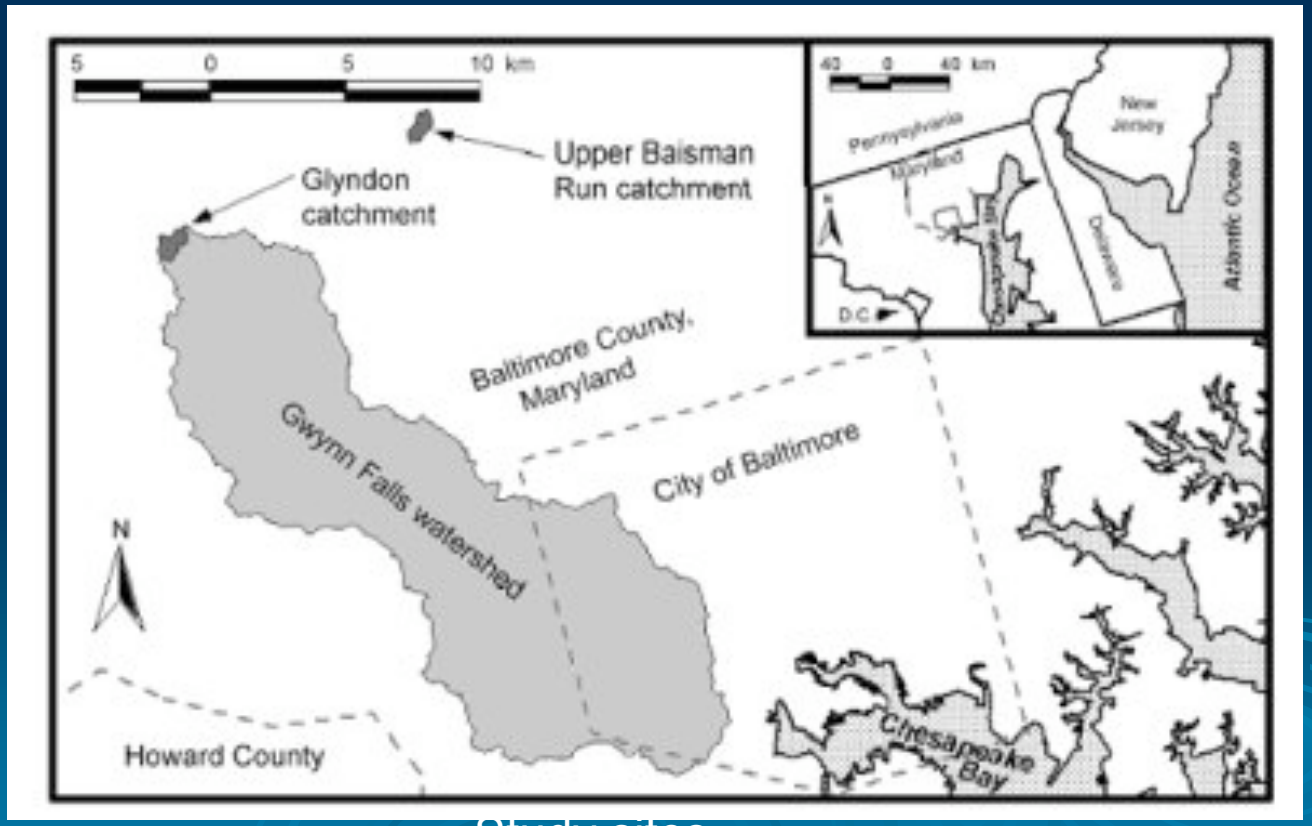
- 76°30', 39°15'
- It is approximately 17,150 hectares
- The watershed lies in Baltimore City and Baltimore County, Maryland and drains into the Chesapeake Bay
- It contains 16 sub-watersheds, which range in size from 465 hectares to 1,855 hectares



Glyndon Catchment



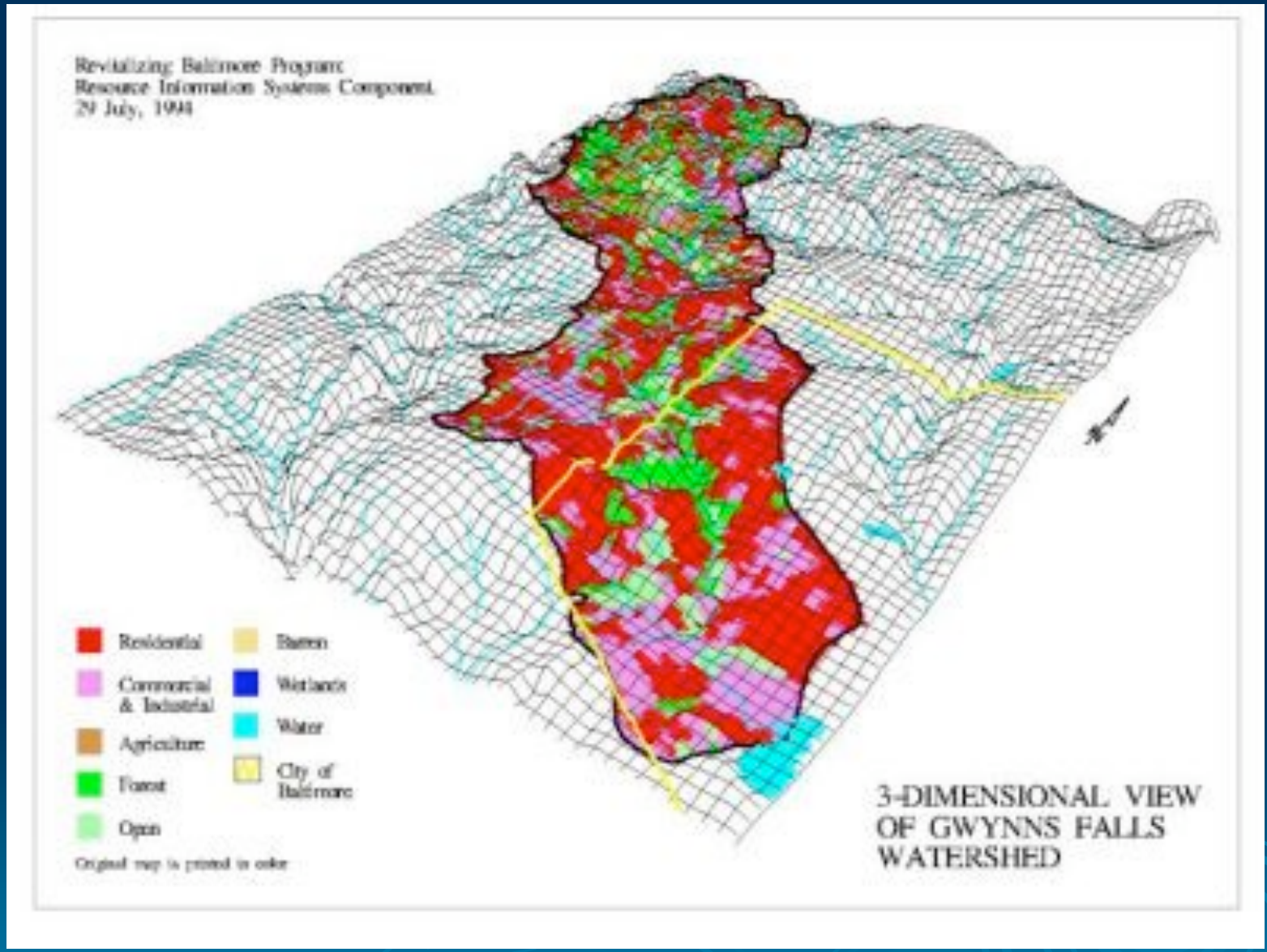
Upper Baisman Run Catchment



Study sites

Model Design

- The watershed as a landscape object hierarchy
- Classes link to identifiable landforms and surface cover which are organized and addressed around the stream network
- Simulating the watershed from small instrumented catchments to that of a large regional basin through a simplified landscape to determine the generation, transport and fate of non-point source pollutants in surface water systems



This is a patch pattern superimposed on a land feature model

Model Design

- Meteorological variables are accepted from multiple sources including point and spatially distributed observations
- Some of the variables are:
  - Temperature
  - Humidity
  - Precipitation
  - Insolation
  - Wind Speed and direction

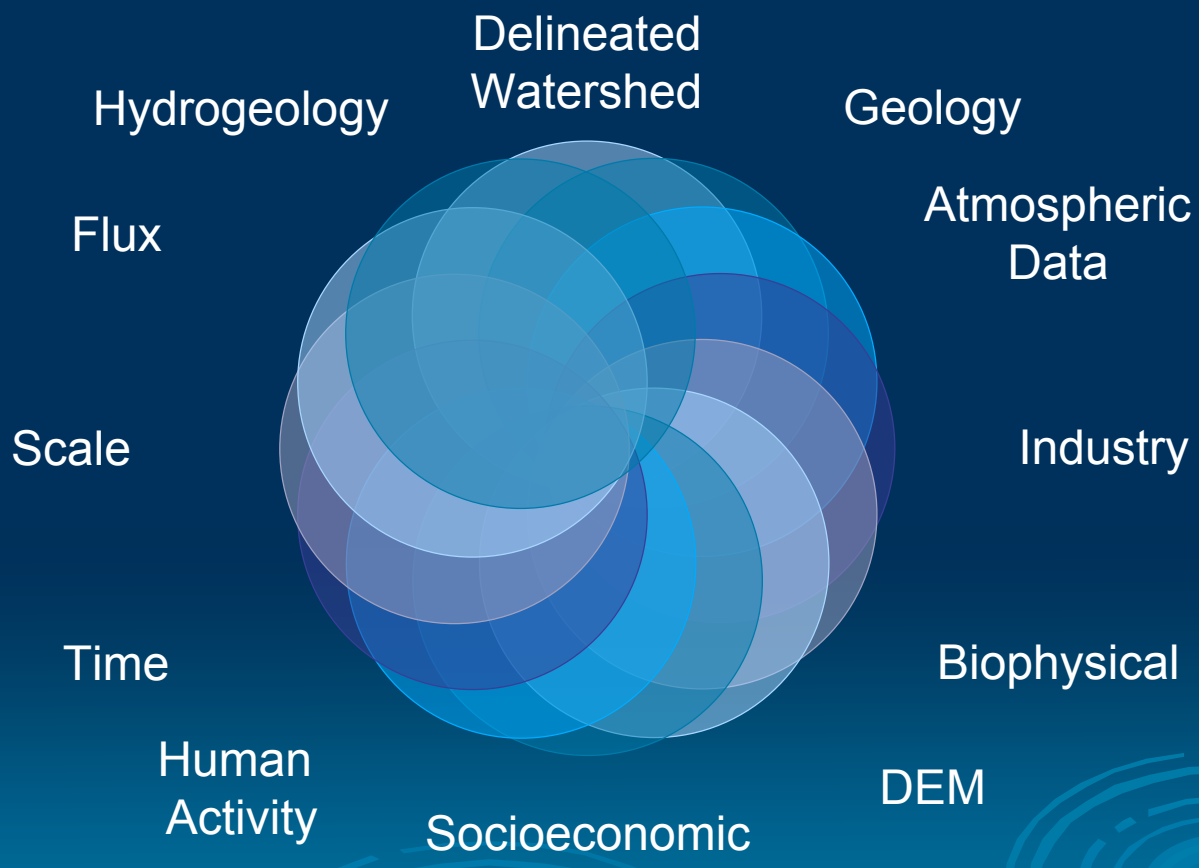
Model Design

- Human interaction is represented by estimating flux, changes in landcover as well as modifications to the drainage network and flowpaths
- Atmospheric layer dynamics
- Groundwater models
- Biophysical and socioeconomic processes as part of the extended model

Conceptual Model Design

- Two sets of surface process models developed over a decade are spatially structured within the watersheds geomorphology
  - Ecosystems
  - Hydrogeology

Spatial Model Components

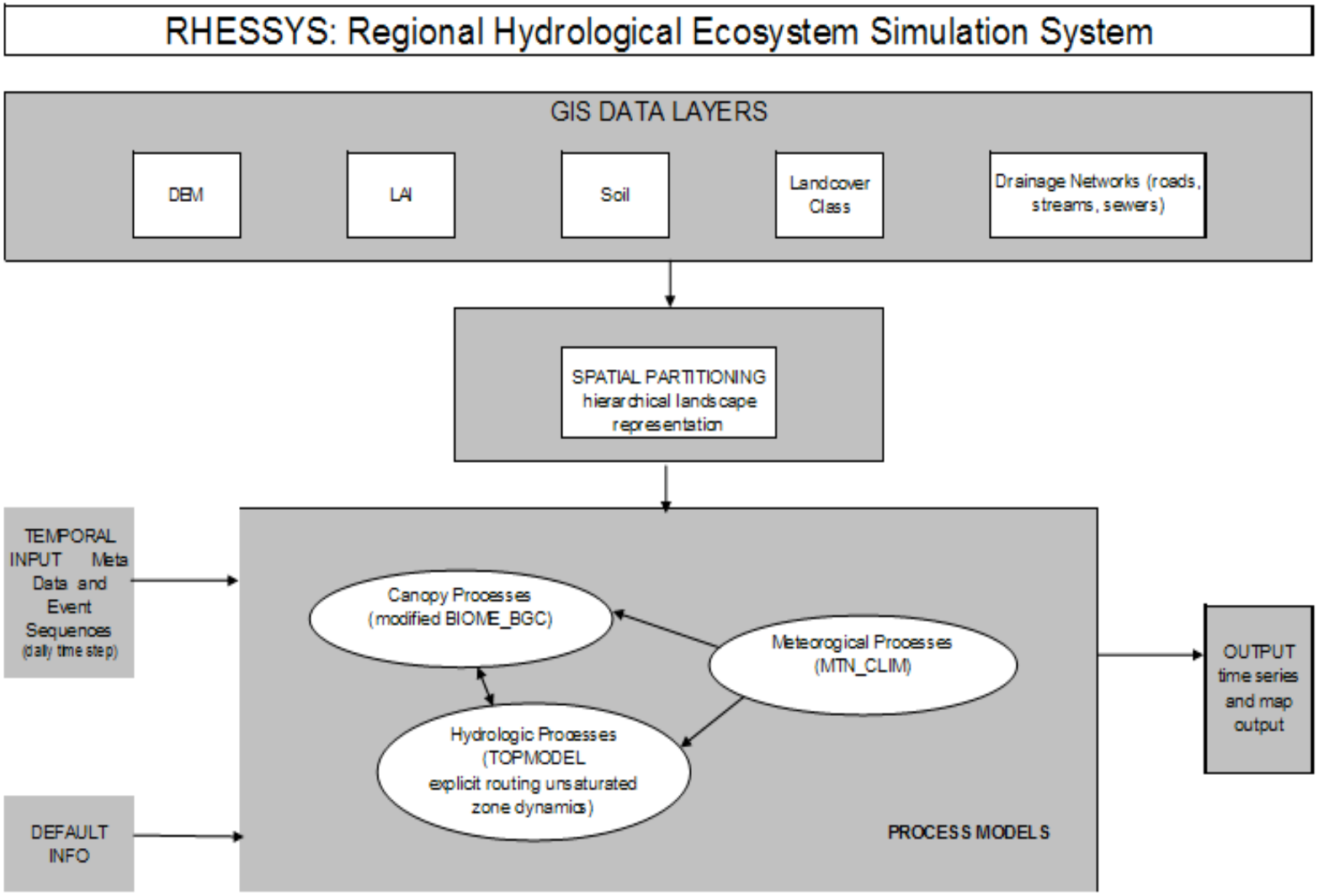


Model Design

- One dimensional estimates of terrestrial water, carbon and nutrient cycling
- Export of water, carbon and nutrients in drainage water typically follows lateral surface or subsurface flowpaths
- Flowpaths can be altered by the hydrologic cycle, ranging in scale from 10's to 100's of meters in length and often mimicking that of the hillslope or length of the divide to the stream network

Model Design

- Other studies indicate that nitrogen that leaches beneath the root zone can be removed through uptake (denitrification)
- Small riparian zones can be catalysts for significant sinks
- This data underscores the importance of potential changes in hydrogeology when incorporating vegetation near flowpaths


RHESSYS: Regional Hydrological Ecosystem Simulation System
GIS DATA LAYERS
DEM
LAI
Soil
Landcover Class
Drainage Networks (roads, streams, sewers)
SPATIAL PARTITIONING hierarchical landscape representation
TEMPORAL INPUT Meta Data and Event Sequences (daily time step)
DEFAULT INFO
Canopy Processes (modified BIOME_BGC)
Meteorological Processes (MTN_CLIM)
Hydrologic Processes (TOPMODEL explicit routing unsaturated zone dynamics)
PROCESS MODELS
OUTPUT time series and map output

RHESSys

- A method of representing the landscapes spatial structure concentrating on the hillslope level and the interaction at and below the surface level
- A spatial data simulation system that solves soil, canopy, water, carbon and nutrient budgets over a set of surface patches defined in a set of hydrologic flow fields within a watershed
- Simulations are driven by meteorological inputs and execution instructions that control the temporal events in a Temporal Event Control or TEC file

Time steps

- Time steps are designed to operate over a hierarchy of scales utilizing spatial data sets and remote sensed data to represent a 3-D landscape

Landscape

- Watershed c-> hillslope c-> climate zone c-> patch c-> canopy zone
- A spatial data model which represents elements within the landscape as the watershed instead of raster or vector data
- Land surface classes characterize geographically defined components including landforms and vegetation
- At the patch level, class objects correspond to a GIS component for spatial analysis

World Data

- World class defines both spatial and temporal data within the watersheds dynamics
- It identifies links to the meteorological, soils, vegetation and other land cover
- It contains a set of basin class objects to define individual and contiguous watersheds

Basin Data

- The basin class defines the watershed above a given output location
- It contains a stream network and drainage areas
- Streamflow routing is defined for this class indicating the runoff accumulation from hillslopes
- Basins are also the aggregate units for ecosystem and hydrologic processes
- Variables are computed at the sub-basin level

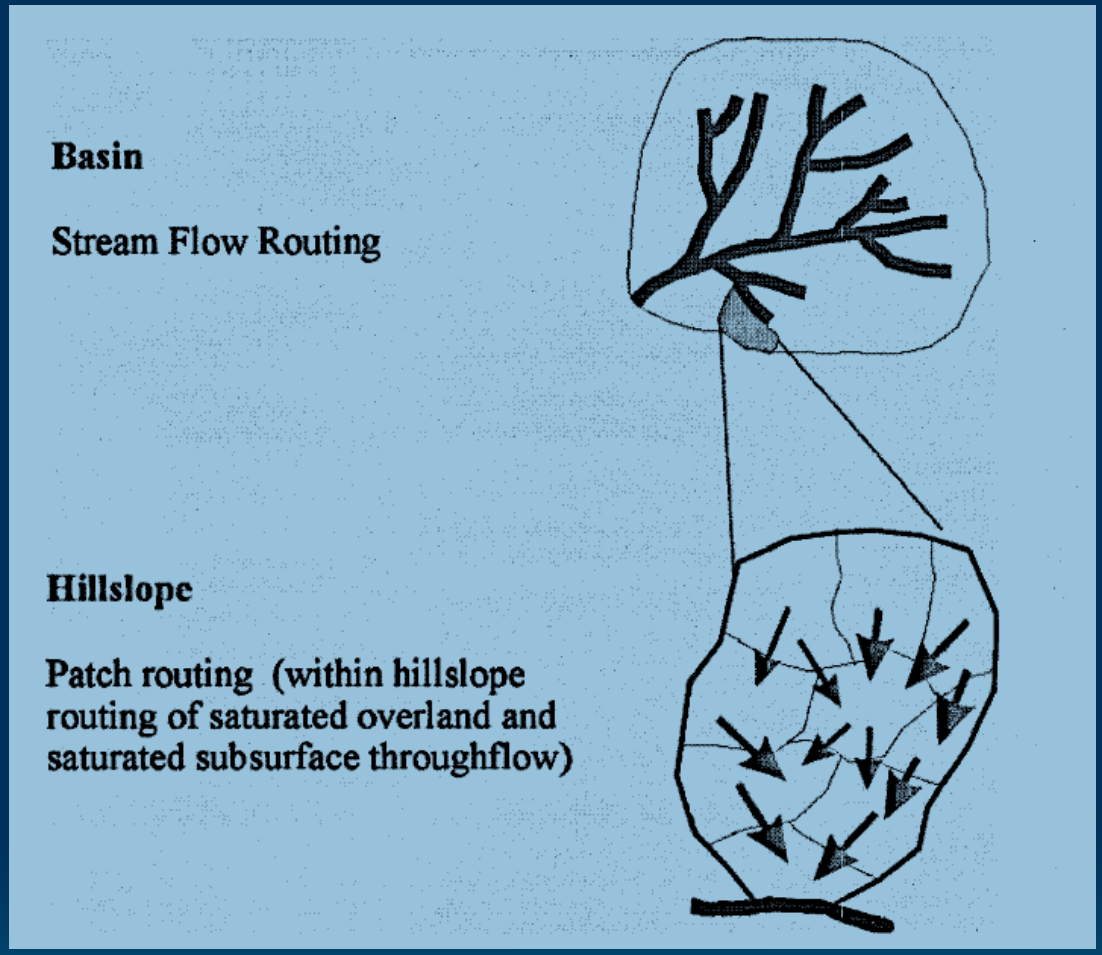


Figure 2 Containment hierarchy of landscape objects within RHESSys from the basin to patch level (strata are contained within patches). Stream routing is defined at the basin level, overland and subsurface flow routing at the hillslope level, and 1-D soil-canopy-atmosphere exchange and transformation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

Hillslope Data

- Hillslope defines the area that drains into a specific link in the stream network
- A hillslope can be derived by GIS tools
- Each hillslope is comprised of a set of contained patches
- Lateral redistribution of soil moisture between patches and base flow are defined here
- Flow fields can be solved for each hillslope

Zone Class

- Zones are areas that have similar climates and meteorological variables such as: Radiation, precipitation, vapor pressure and temperature in conjunction with altitude, slope and aspect
- A zone contains one or more patches that is linked to time series climate data derived from observation stations or models
- They are contained within hillslopes and therefore obtain slope and aspect as defined during that process

Patch Class

- The highest spatial resolution
- Patches can be defined as grid cells and include polygons defined to represent the variation in land cover, soil conditions and topography within the hillslope
- Flow patch information can be accumulated into total runoff or through the stream network
- Roads are integral in flow routing causing significant changes to the surface and subsurface flowpaths

Patch Class

- Patch themes vary and can be overlaid, the shape of a patch should allow the flowline to enter and exit once
- Soil moisture which is driven by infiltration, exfiltration, saturation zone recharge and runoff occur at this level
- Soil water are updated in the patch through the estimation of vertical flux through the unsaturated zone and recharge via lateral flux

Human Activity

- This includes, irrigation, fertilization
- Redirection of storm water (sinks)
- Socioeconomic data
- Aging infrastructure of water and sewer lines

Canopy Stratum Class

- Canopy stratum inherits spatial partitioning from their parent patch
- They define multiple vertical layers and corresponds to a overstory or understory within the canopy structure
- Litter is included as a separate stratum layer (height of zero)
- Layers may be sorted by height and the total fraction of the layers must equal one

Canopy Stratum Class

- Canopy biological and physiological processes are defined within the class
- For example, stomatal, photosynthesis , transpiration and respiration are modeled at the canopy stratum
- Soil water uptake, litter fall, decomosition and mineralization are processes that exchange mass with the parent patch

Stratum Class

- Within the urban watershed, manmade impervious surfaces must be expressed statistically as scales will vary immensely
  - Parking lots, and roads verses walkways
  - Single family home verses large structures
  - These variables are key to runoff in urban patch enviroments

RHESSys Object Hierarchy

Default Collection	Functional	Data Factory	Output Objects	Output Files
World Defaults	World Processes	World linked list		
Basin Defaults	Basin Processes	Basin linked list Basin data	Basin Output	Basin Output files
Hillslope Defaults	Hillslope Processes	Hillslope linked list Hillslope data	Hillslope Output	Hillslope Output files
Zone Defaults	Zone Processes	Zone linked list Zone data	Zone Output	Zone Output files
Patch Defaults	Patch Processes	Patch linked list Patch data	Patch Output	Patch Output files
Stratum Defaults	Stratum Processes	Stratum linked list Stratum data	Stratum Output	Stratum Output files

GIS Interfaces

- Originally written in the GRASS, using a raster environment by defining and manipulating information within the regions
- Spatial processing automated statistical summaries and computation of hillslope, basin, patch and strata attributes through which the world file was created for export
- Independent execution of command lines linking data input and output then reimported to GRASS for additional analysis and reporting

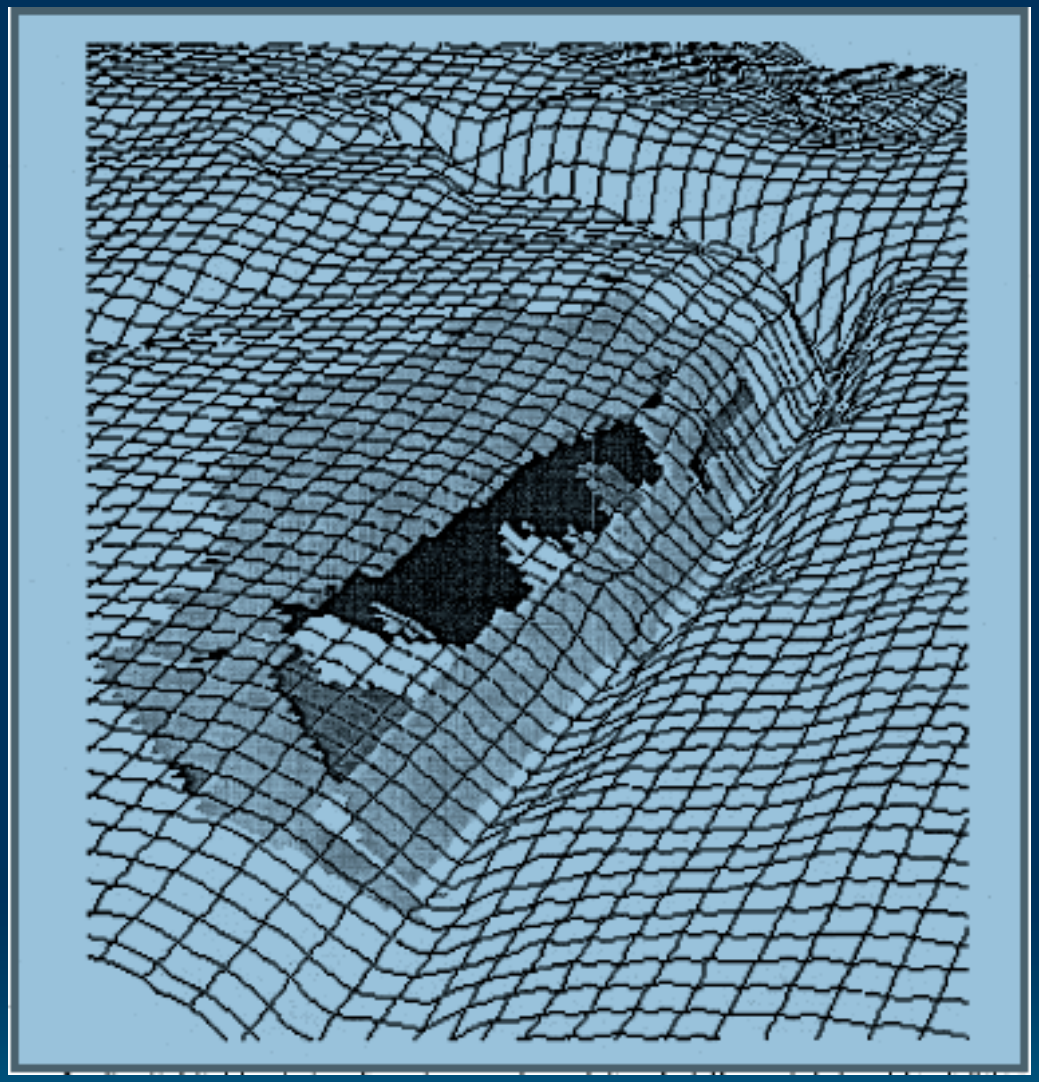
ARCView Interface

- “Using Avenue script for ArcView, RAIMEnt (RHESSys ArcView Integration and Modeling Environment) provides enhanced functionality and a tighter coupling of the GIS/modeling environment” (Tenenbaum 1998)
- RAIMEnt reproduces the GRASS structured functions as well as all other steps to establish the model, execute the simulation and visualize the product

Additional ArcView Features

- Model tracking and documentation that stores information on the set of GIS layers, meteorological data and other controls used in specific simulations
- Automated reinforcement of spatial data assumptions
- Dialog boxes to facilitate data layer decisions and model setup

- Visual spatial data output, mapped back to specific class partitions and time steps
- Facilities to operate and incorporate external code results through linked libraries, thereby extending spatial analytical capabilities beyond those of ArcView
- Easier distribution among users
- Object level information is stored in tables linked to class shapefiles
- The user does not work directly with the World File that is created upon model execution

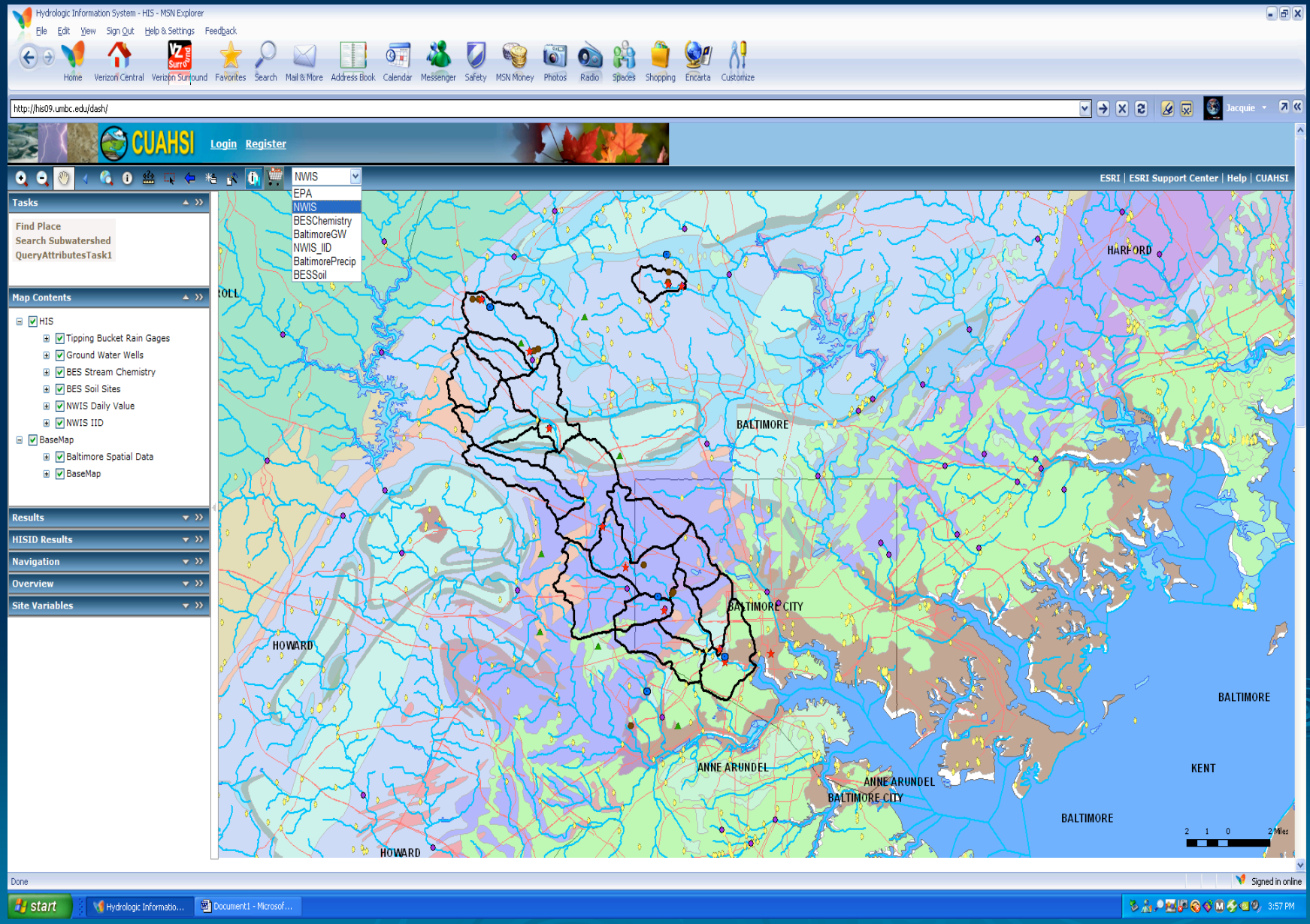


Spatial fields of standing stem carbon defined at the patch level for hillslope 1 with grey values ranging from ~1.4 kg.C.m^{-2} to ~ 1.7 kg.C.m^{-2}. Differences are largely accounted for by variations in soil moisture, with steep midslope area being better drained and typically experiencing greater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

Conclusion

- Implemented a spatially distributed hydroecological model as an object oriented containment hierarchy
- Processes were defined for specific landscape classes that correspond to the scale at which they occur
- Produced a system that integrates different processes in space and time that represents human interaction within the watershed's hillslope down to the catchment level

- Further exploration is desired incorporating census data and better defining socioeconomic indices at the patch level to determine how significantly the population influences nutrient and water budgets
- The key component of this system is embedding the 1-D ecosystem model within the multiple strata and patches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Sources

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