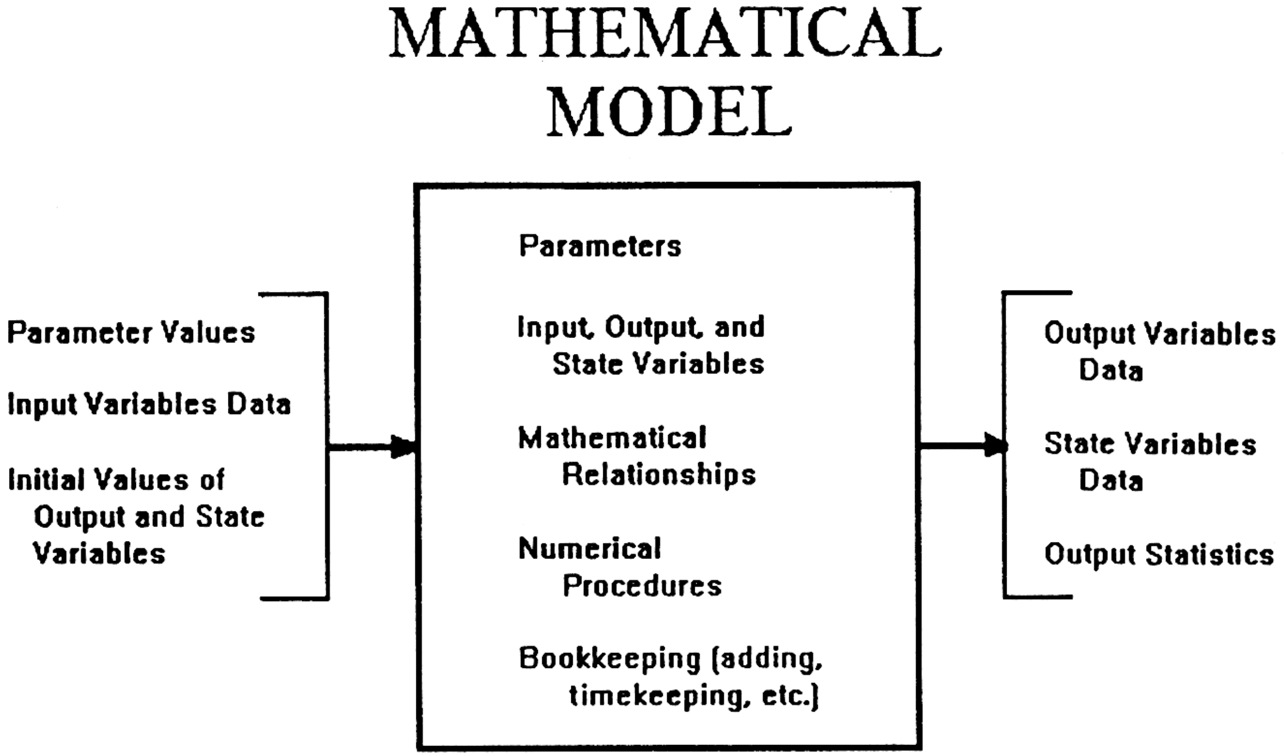
# Modelling Hydrological Processes

- In a typical hydrology course, you focus upon how hydrological processes work **in time**
  - i.e. Given this much water in such and such a store, if we add water via process X and remove water via process Y, how much water will remain in that store at time T
- This is a very useful way to look at things if you want to consider the state of a **particular store** or part of a catchment **in isolation**
- However, as our applications of hydrology get more **realistic**, we often want to consider what happens when we have **several stores**, and they can **interact** in **both time and space**

# Components of a Model



Nix, S.J. 1994. *Urban Stormwater Modeling and Simulation.* Lewis Publishers, U.S.A., p. 23.

Mathematical models have three basic components: The **input data**, the **algorithmic portion** that does the modeling, and **outputs** that describe the results

# Hydrological Modeling with GIS

- The discipline of **Geography** is equally interested (or perhaps more interested) in the change of phenomena (in ecosystems or other contexts) **in space**
- Thus, the approach you may have used in a hydrology course ignores some **key aspects** of hydrologic systems which are **popular with geographers**:
  - Processes work differently in **different locations**
  - We can better understand the underlying processes that make them function by describing them in terms of their **distribution in space (mapping)**
  - We can **subdivide** catchments **into smaller units** and study each in isolation to figure out how things are working
  - We can model the **interactions between the smaller units** to get at **the bigger picture**

# Lumped vs. Distributed Models

- We can distinguish between two types of models:
- **Lumped Models** – These are the sorts of models you likely would have focused on a hydrology course
  - They represent inputs and responses in terms of the **dimensions of time and whatever is being modeled** (issues of location and associated dimensions of length, area and volume are often absent)
  - **No account is taken of variation** within the entity being modeled:  It is **assumed to be homogenous and well-mixed**, i.e. Suppose we were running an evaporation model for a particular forest stand.  Even though there are likely various types of trees, canopy heights and densities, variations in soil etc. we model that forest stand using a single LAI and K, and with uniform soil characteristics etc.

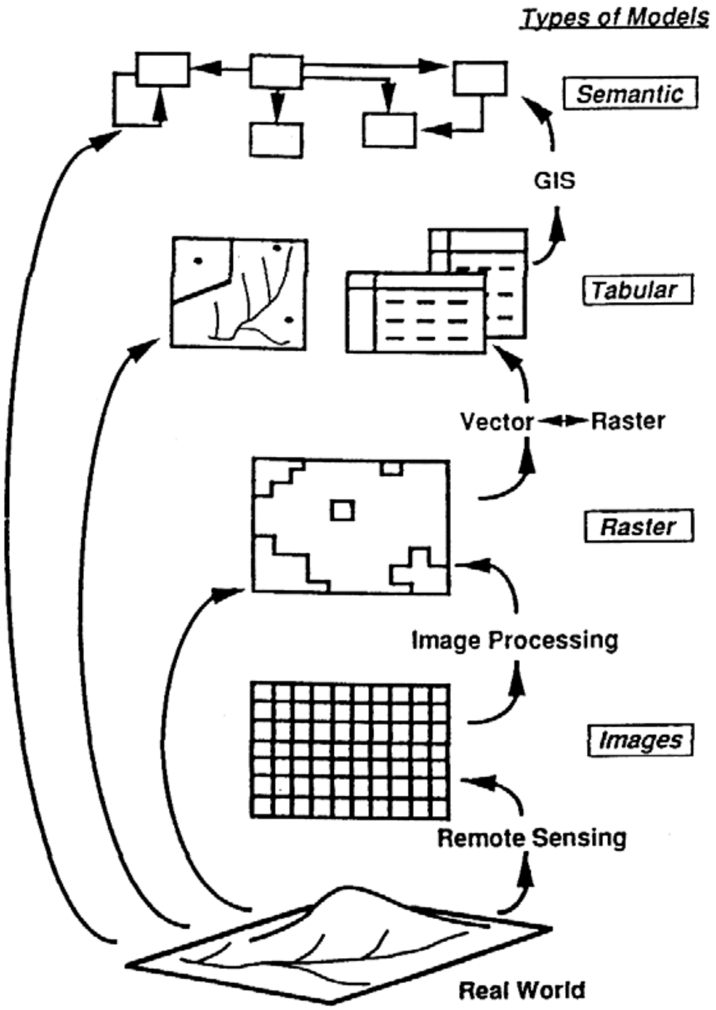
# Lumped vs. Distributed Models

- **Distributed Models** – These sorts of models take the variation of phenomena in space into account in their model structure
  - Both **inputs and responses have a spatial aspect** to them, i.e. **mapped information is required** as part of the input, and the output includes **spatial pattern** information
  - Distributed models are thus very useful when it comes to **representing and studying variation**. While the modeled sub-units still usually use the assumptions of homogeneity and being well-mixed, the units' size and shape are adjusted to make these **assumptions as reasonable as possible**, i.e. Perhaps the forest stand we are modeling consists of 2 or 3 distinctly different sub-units, each with distinct species, and canopy and soil characteristics. We could then model each of these **sub-units with its own parameters**.

# Catchment Representation in Distributed Models

- There are a tremendous number of **strategies** that can be used in **breaking up the world into sub-units**
- We can generalize that the goal is usually to **minimize variation with a sub-unit and maximize the variation between units**, but beyond that the possibilities are endless:
  - Tessellations can use **regular** (repeating) or **irregular** shapes
  - **Raster or vector** spatial data models can be used
  - The set of **model elements can be fixed** throughout a simulation, or **they can change as well** …
- The representation chosen usually reflects the particular **catchment and processes** being studied, and the **assumptions** made about their variation

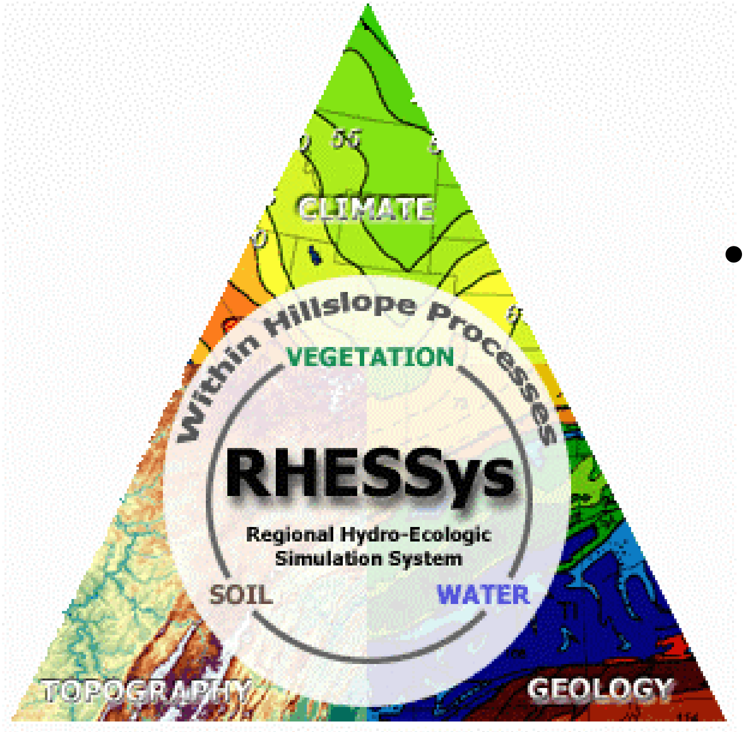
# Representing the Real World w/ Models



Maidment, D.R. 1993. GIS and Hydrologic Modeling. In Goodchild, M.F., B.O. Parks, and L.T. Steyeart (Eds.). *Environmental Modeling and GIS,* Oxford University Press, New York, p. 157.

- The figure to the left depicts a hierarchy for (spatial) models of **knowledge** about the real world
- This set of **spatial models** includes a few sorts of spatial representations that can be used in conjunction with RHESSys
- In the case of our lumped models, issues of location and spatial arrangement **have been unimportant**, so it was possible to skip directly from the Real World to a **semantic** model

# Regional HydroEcological Simulation System (RHESSys)

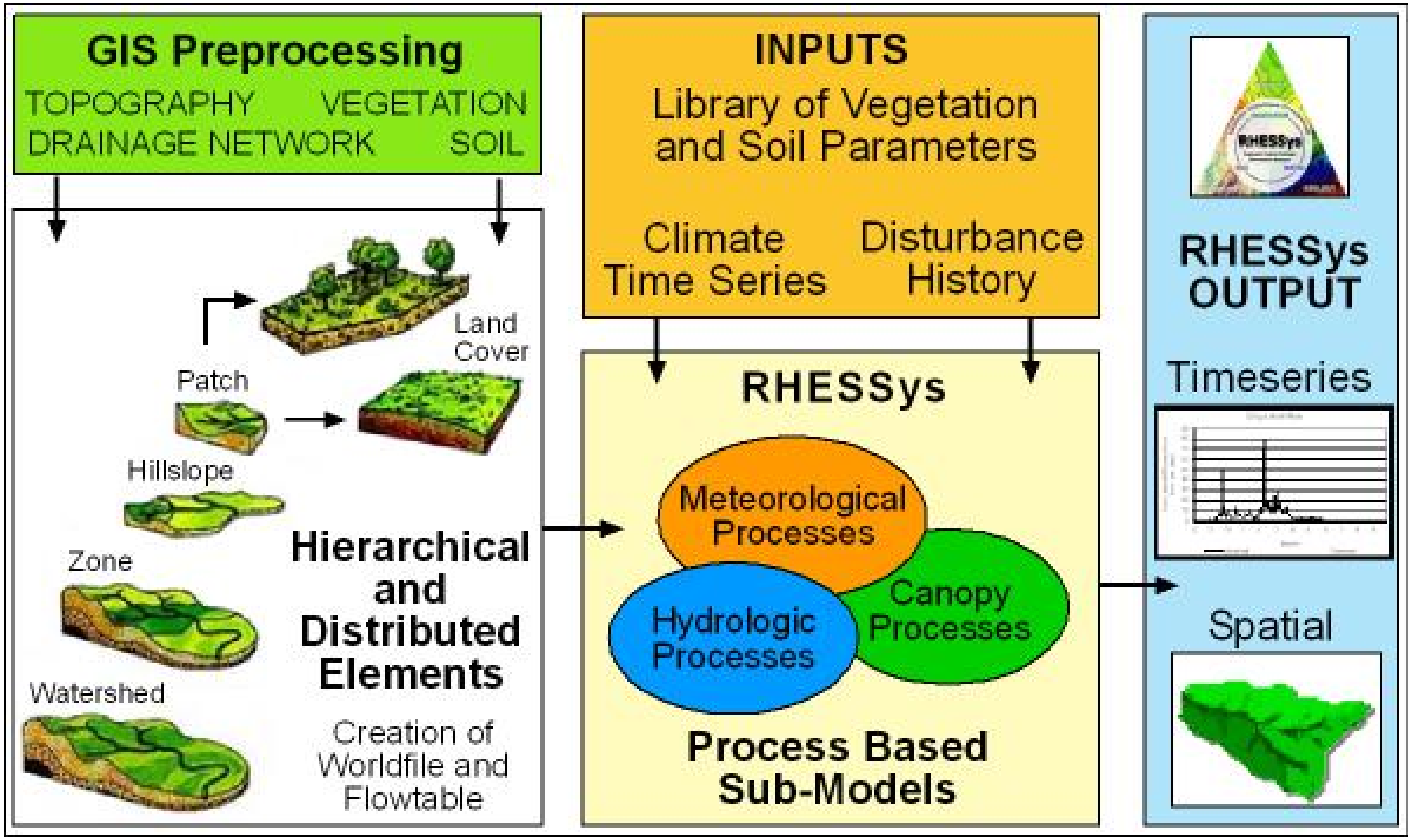


- The Regional HydroEcological Simulation System (RHESSys) is a GIS-based hydroecological modeling framework designed to simulate **water, carbon, and nutrient** fluxes
- By combining a set of **physically-based process models** and a methodology for **partitioning and parameterizing the landscape**, RHESSys is capable of modeling the spatial distribution and spatio-temporal interactions between different processes at the watershed scale

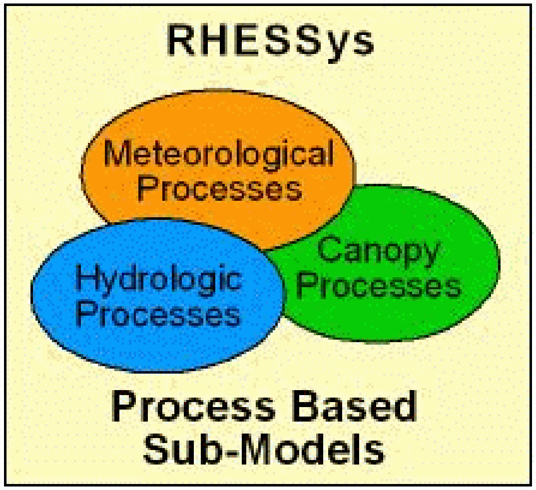
# How Does RHESSys Represent the Landscape?

- It models **processes** at spatial and temporal **scales** which efficiently and effectively represent **landscape heterogeneity:**
  - **Temporal** - Through **time step** iterations of processes in the model **execution** (some processes are computed daily, while others are computed hourly since the hourly variation makes a difference, and reaggregated to a daily time step)
  - **Spatial** - Through a **landscape representation** that enforces hierarchically contained object partitions, meaning that the entire watershed's extent is broken up into a set of basins, each basin is broken up into a set of zones, etc.
- Different processes are simulated using objects at **different levels in the hierarchy**

# Regional HydroEcological Simulation System (RHESSys)

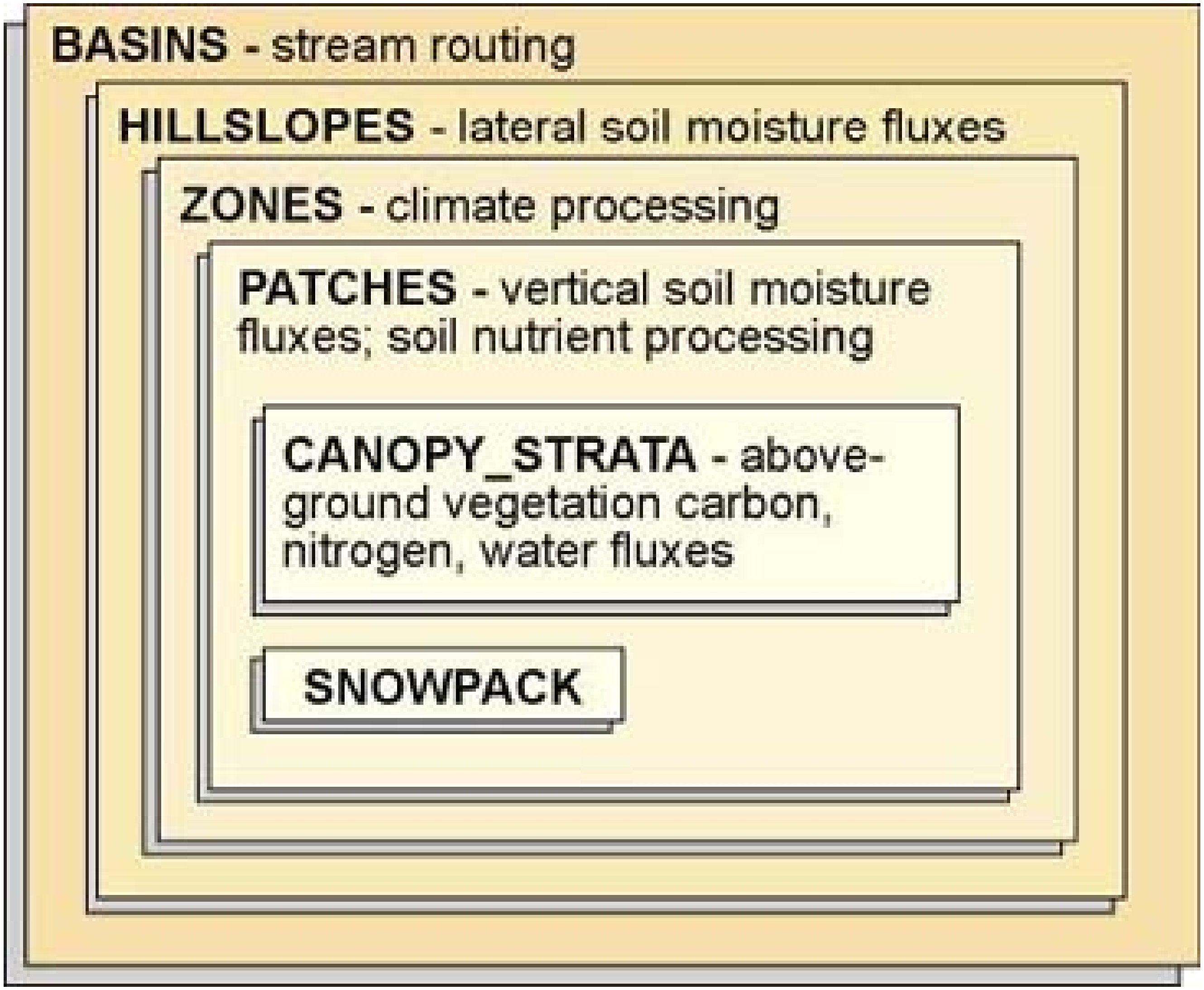


# RHESSys Process Based Sub-Models

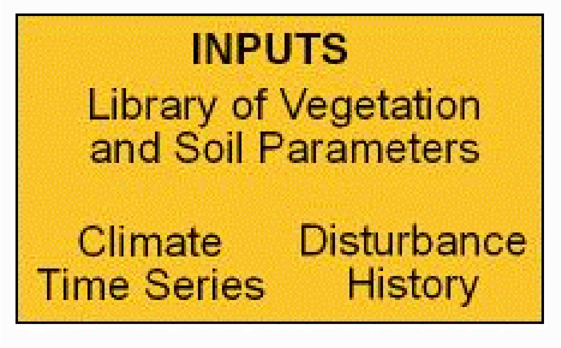


- Conceptually, the way RHESSys does its calculations is like any lumped model, simply applied in a **more complex** fashion:
- **State variables** keep track of the quantity of matter/energy of a particular sort in a particular object
- Matter and energy can move between particular stores within an object **OR** can move between objects (this is a **key difference**) according to the **process models** as applied at the appropriate level of the object hierarchy:
  - Meteorological processes use the **MT-CLIM** model operating in **Zones**
  - Hydrologic processes use either **TOPMODEL** or **DHSVM** in **Hillslopes** and **Patches**
  - Canopy processes use **BIOME-BGC** running at the **Stratum** level

# RHESSys Object Hierarchy



# RHESSys Inputs

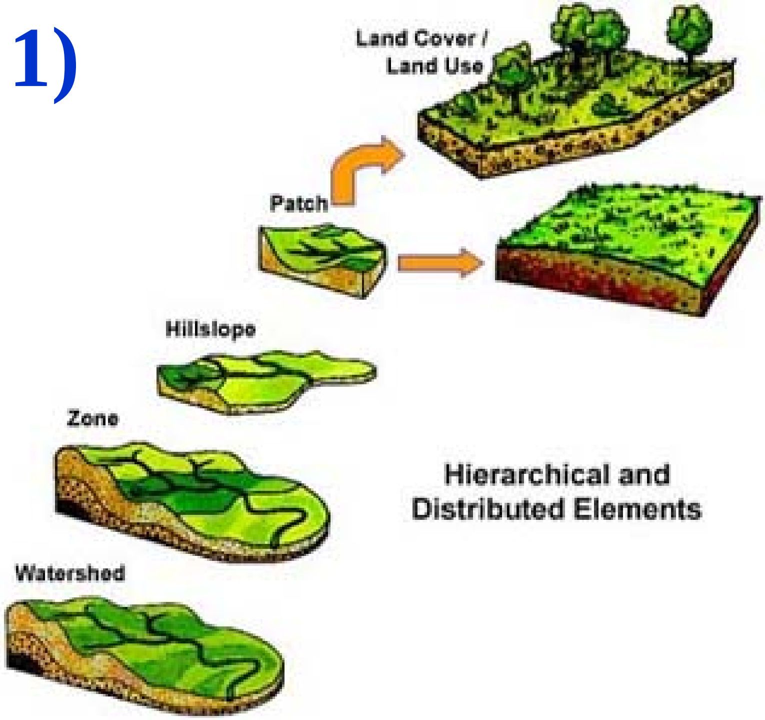


- RHESSys makes use of **a few kinds of input data** (other than the spatial description) to set up a model run:
- Values are drawn from a library of vegetation, soil, and land-use parameters to describe those characteristics of the landscape that **will not change through the model run**. These are called **default parameters**
- Also required is **time series information**, such as daily temperature and precipitation information
- One time events (**disturbances**) can also be included

# Landscape Representation through Object Partitioning

- RHESSys **divides** the landscape into a series of successively **contained** partitions:

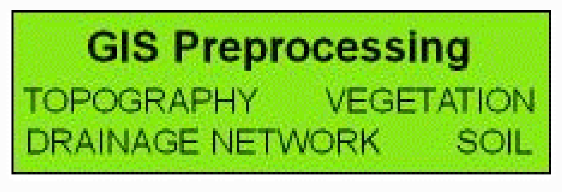
**1)**



**2)** The **method** for creating a partition is **determined** by the processes it will represent

**3)** Once landscape objects in a partition are defined, **parameters** at that level are determined

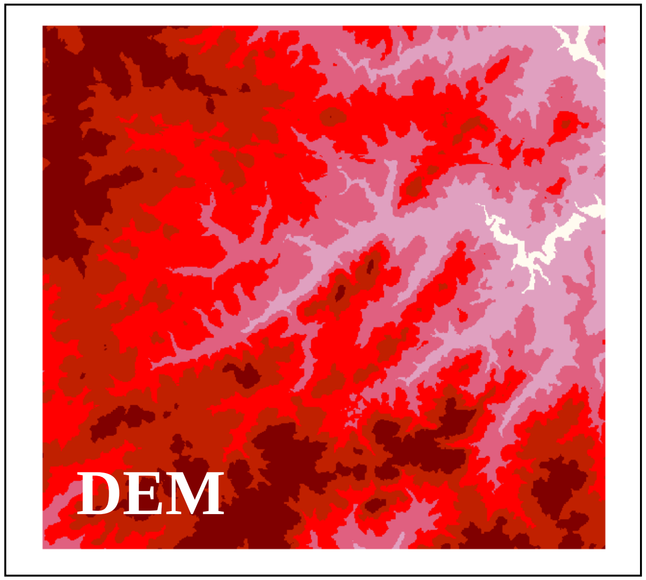
# RHESSys GIS Preprocessing



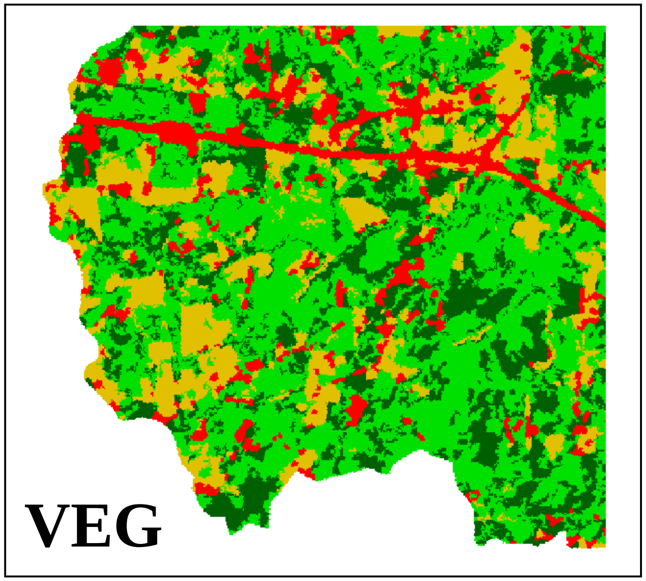
**GIS Preprocessing**

TOPOGRAPHY VEGETATION

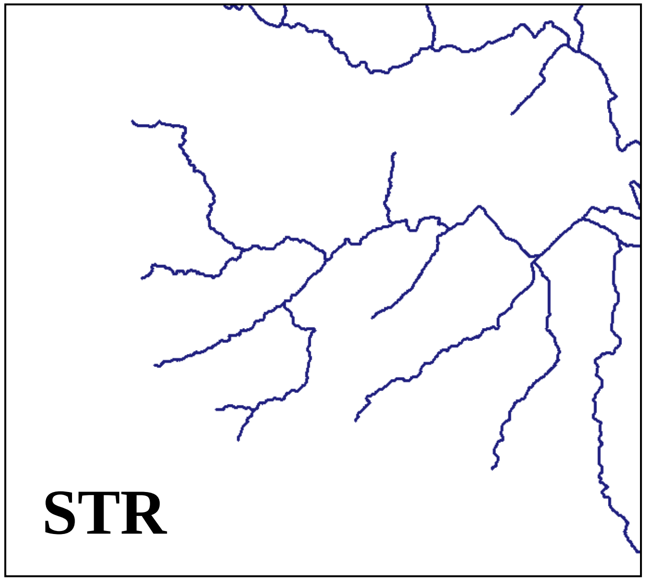
DRAINAGE NETWORK SOIL



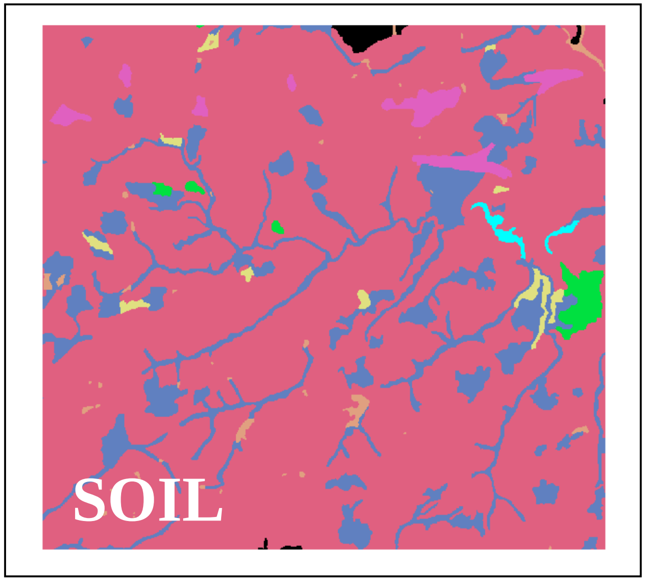
DEM



VEG



STR



SOIL

# Watershed (a.k.a. Drainage Basin, Catchment)

- A geomorphically distinct **landscape unit** defined by topographic boundaries, or drainage ‘divides’ that acts as a spatially discrete hydrological system

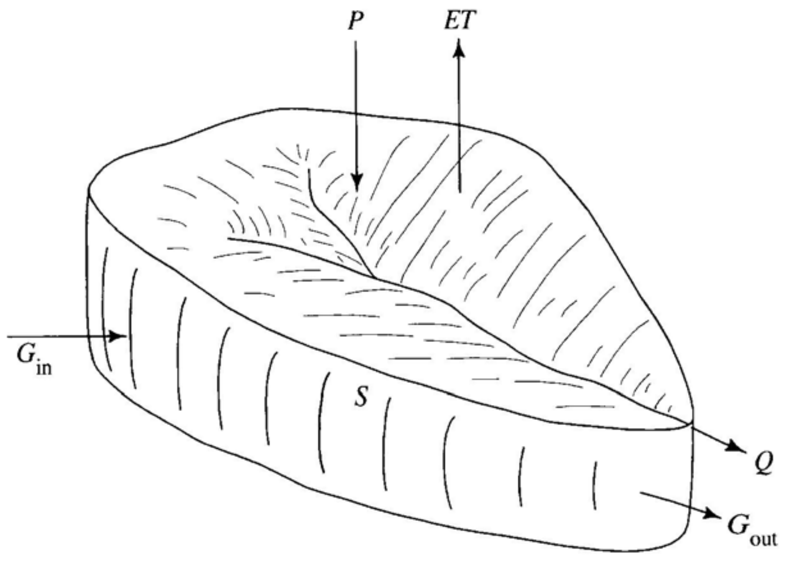


**FIGURE 2-3**

Schematic diagram of a watershed, showing the components of the regional water balance: $P$ = precipitation, $ET$ = evapotranspiration, $Q$ = stream outflow, $G_{in}$ = ground-water inflow, $G_{out}$ = ground-water outflow.

# Water Budget Equations

- You may recognize the following **equation**:

$$\frac{dV}{dt} = 0 = p - so - et \quad \text{or} \quad p = so + et$$

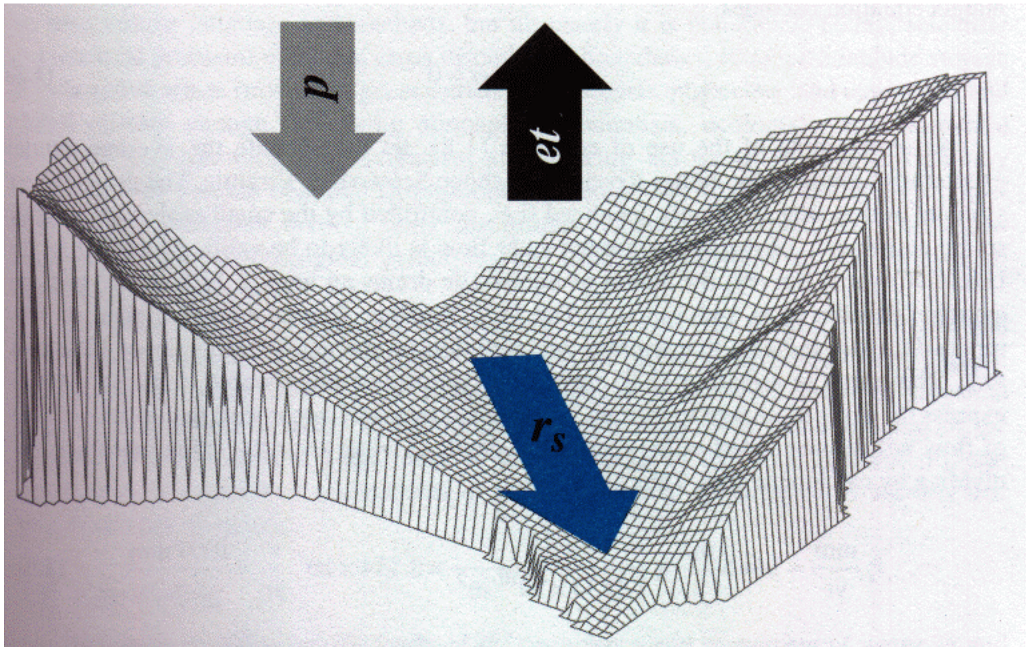


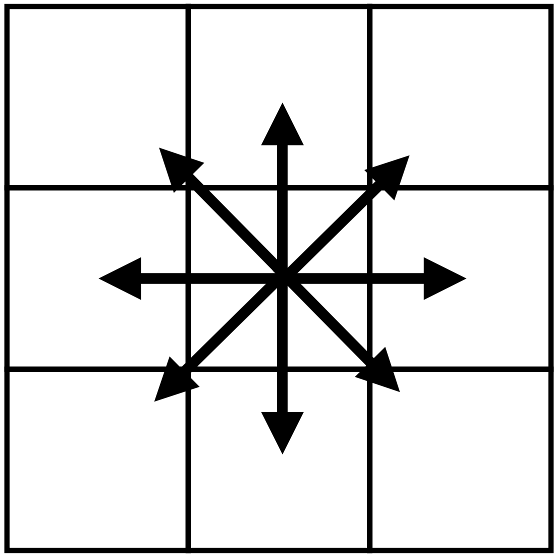
**Figure 1.5 The catchment.** The boundary of the catchment is referred to as a divide. If the catchment has been properly delineated, there should be no surface-water inflows or outflows across the divide, except at the outlet. In this case, the major inflow is precipitation ($p$), and the major outflows are evapotranspiration ($et$) and surface-water outflow through the catchment outlet ($r_s$). The topography of the land surface controls where divides are drawn. In the figure, two mountain peaks, and their adjacent ridges, constitute the divide.

Hornberger et al. 1998. Elements of Physical Hydrology. The Johns Hopkins University Press, Baltimore and London.

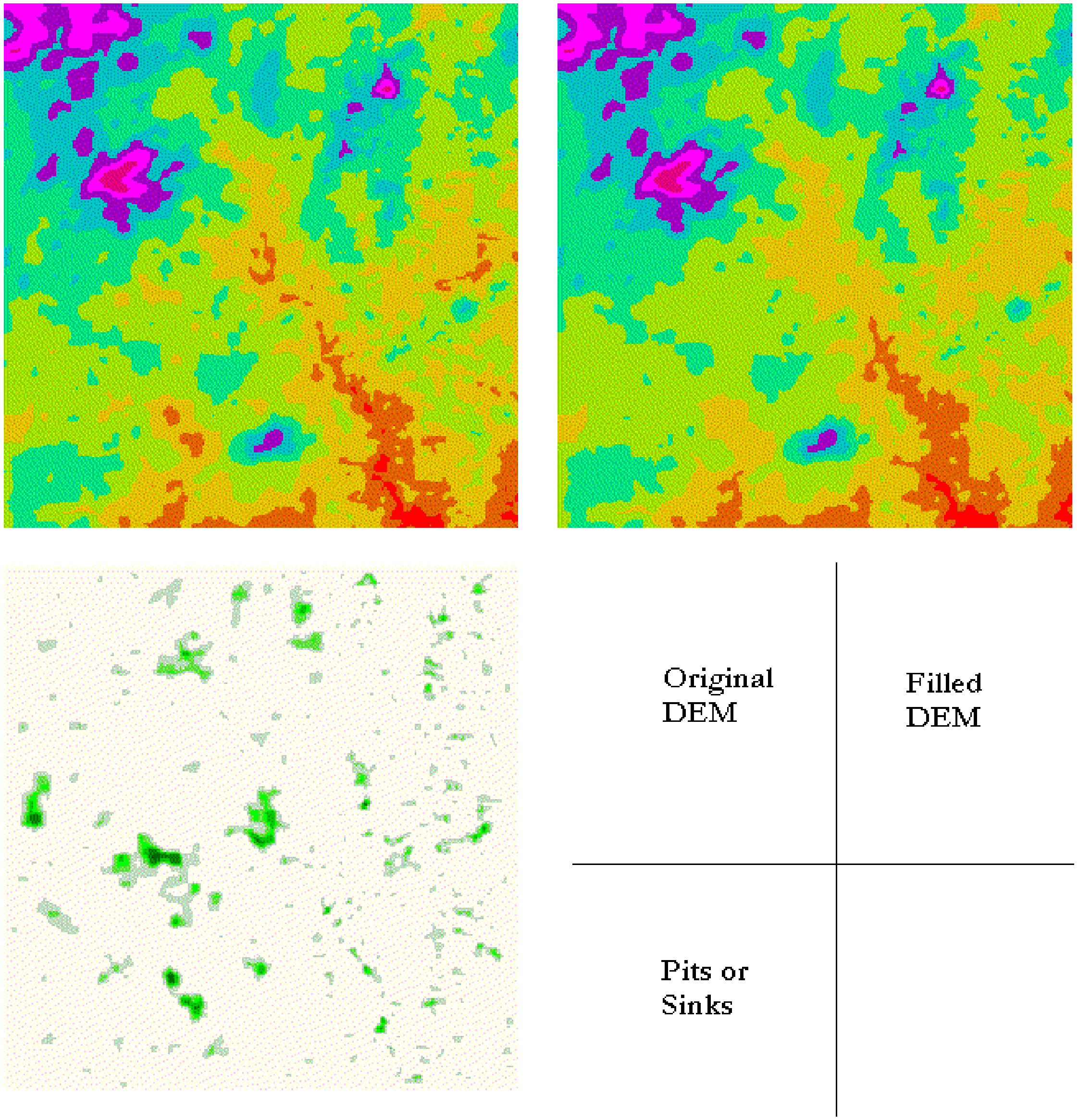
# D8 Analysis Sequence

- Assume we now have a raster DEM and we want to use it **find a watershed and drainage network** through D8 analysis
- We can follow this **sequence of analysis** steps, each of which involves a neighborhood analysis operation:
  - Fill Sinks
  - Slope
  - Aspect
  - Flow Direction
  - Flow Accumulation
  - StreamLink & StreamOrder
  - Watershed

**D8 Analysis**



# Fill Sinks

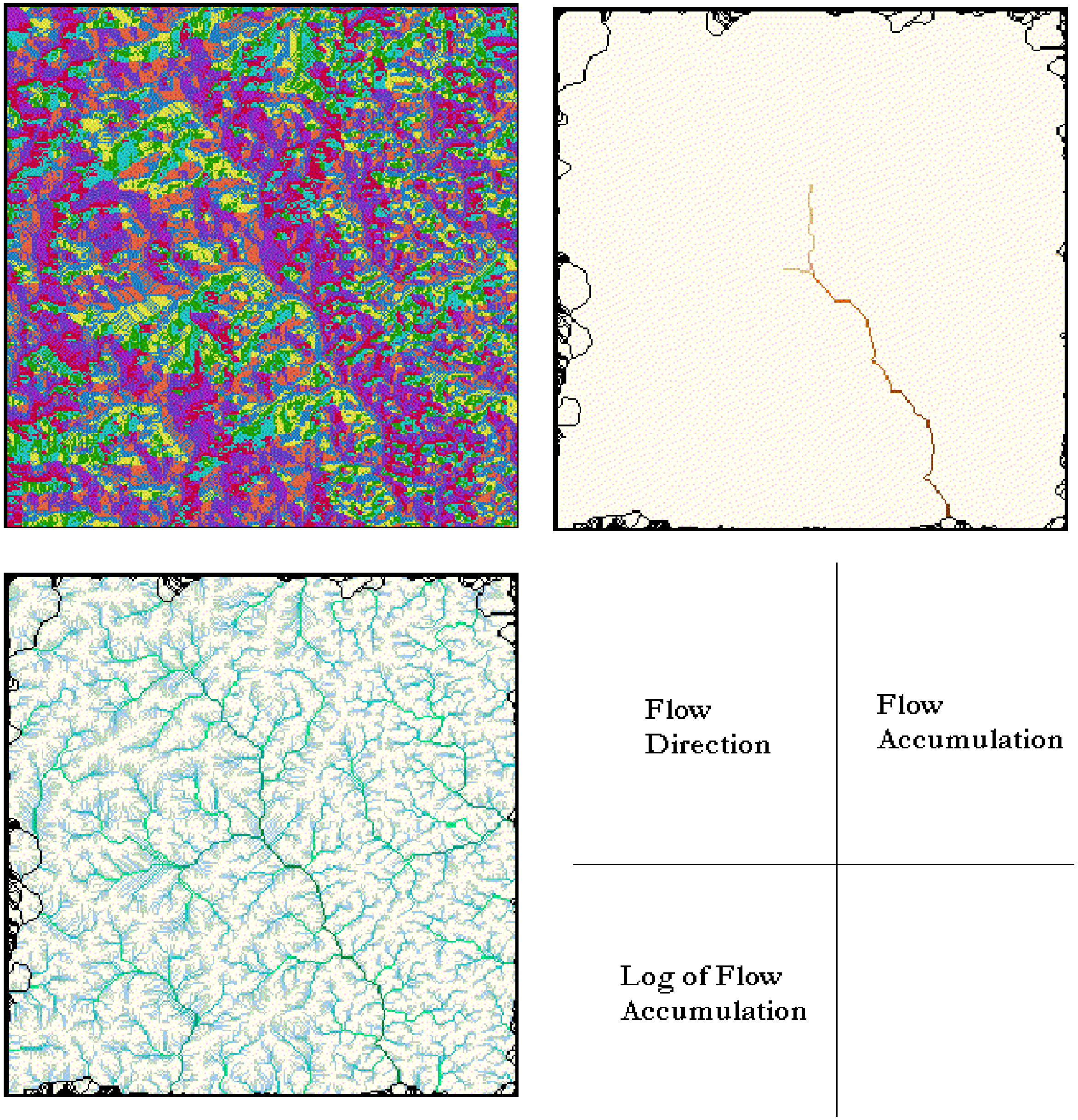


- We need a DEM that does not have any **depressions or pits** in it for D8 drainage network analysis

- The first step is to **remove all pits** from our DEM using a **pit-filling algorithm**

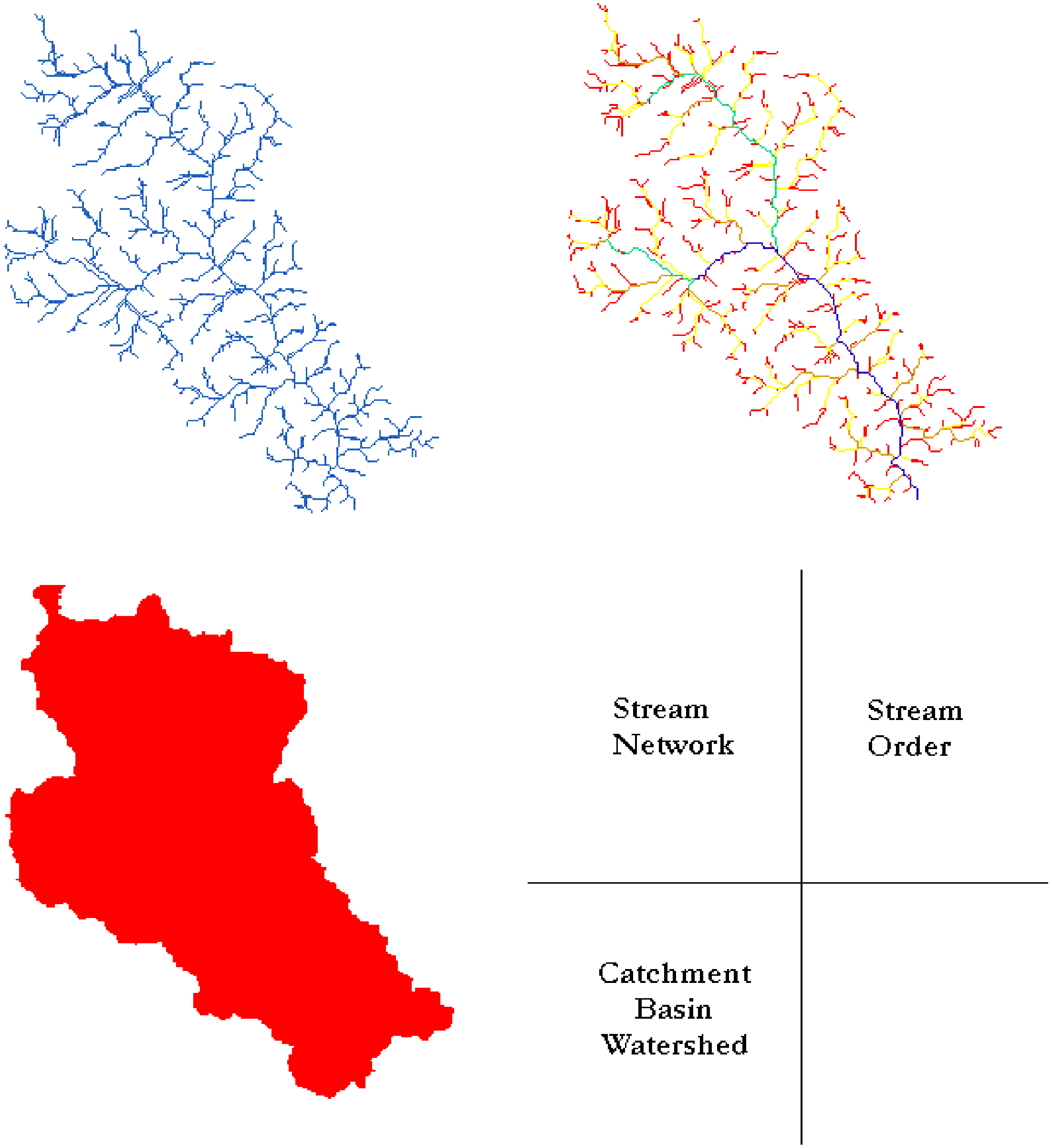
- This **illustration** shows a DEM of **Morgan Creek**, west of Chapel Hill

# Flow Direction and Accumulation



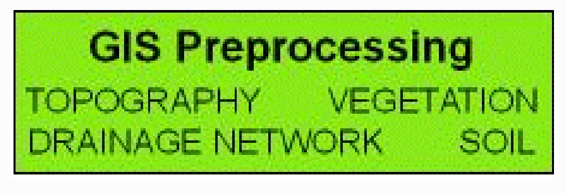
- Slope and aspect are needed to produce **flow direction**, which assigns each cell a **direction of steepest descent**
- **Flow accumulation** uses flow direction to find the **number of cells** that **drain to each cell**
- Taking the **log** of accumulation makes the **pattern** much easier to see

# Stream Links, Order, and Basins



- By selecting a **threshold value** for flow accumulation, we can produce a **stream network**
- This network can **divided** into **stream links**, which can in turn be assigned **stream order** values using network analysis methods
- Threshold=1 gives the **watershed**

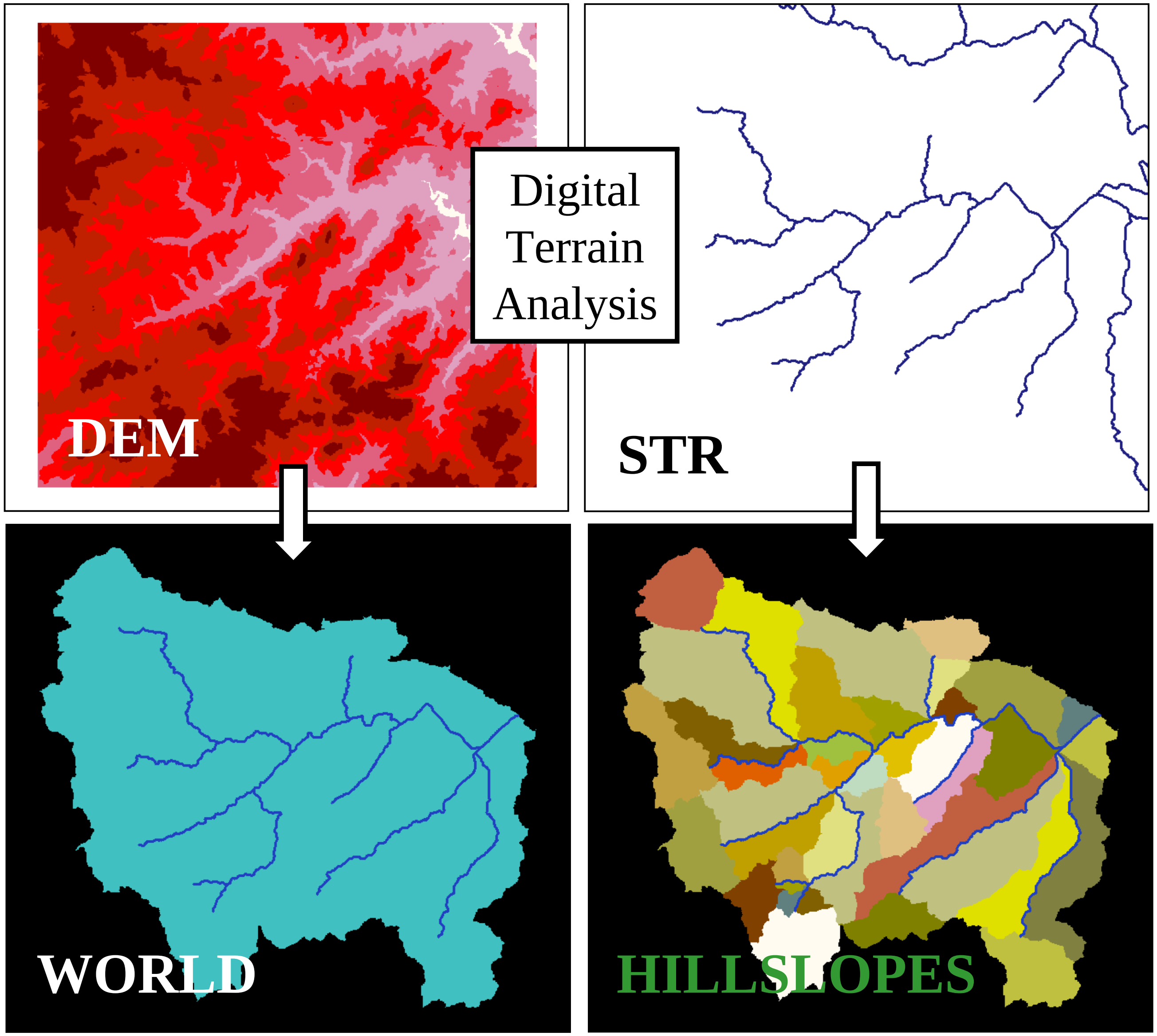
# RHESSys GIS Preprocessing



GIS Preprocessing

TOPOGRAPHY VEGETATION

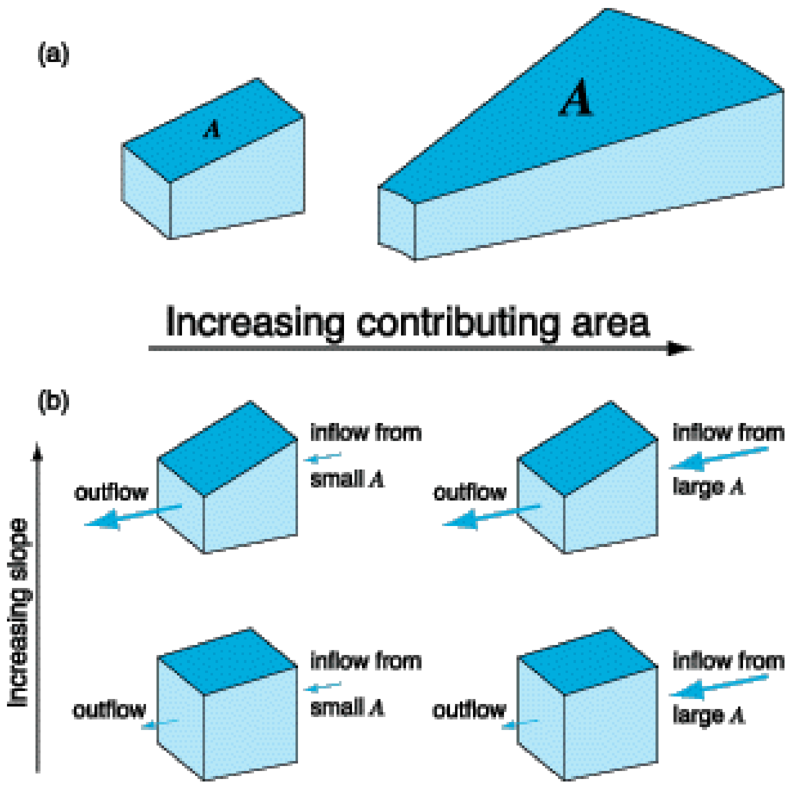
DRAINAGE NETWORK SOIL

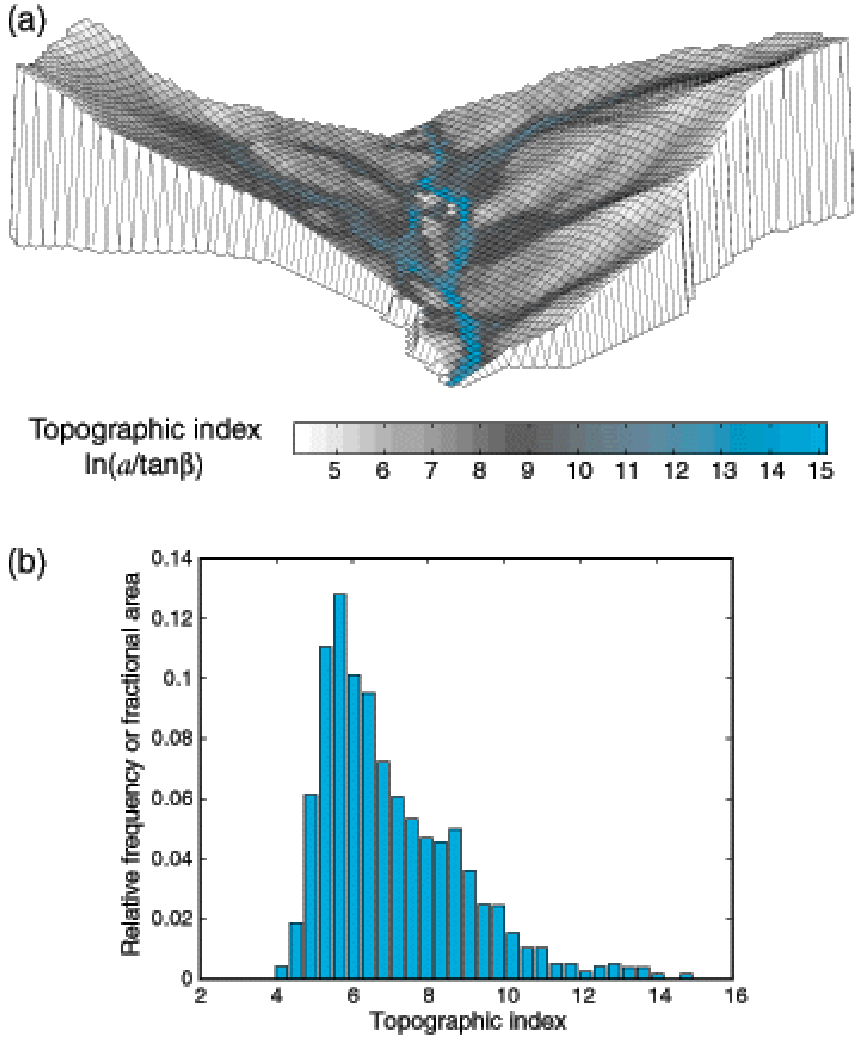


Digital Terrain Analysis

# Topographic Moisture Index

$$\mathrm{TMI} = \ln(a/\tan\beta)$$



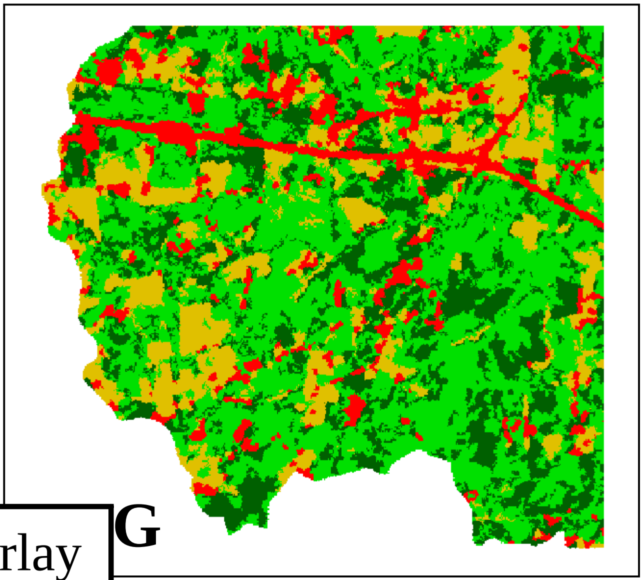


Hornsberger, G.M., Raffensberger, J.P., Wiberg, P.L. and K.N. Eshleman. 1998. *Elements of Physical Hydrology*, Johns Hopkins Press, U.S.A., p. 210 & p. 216.

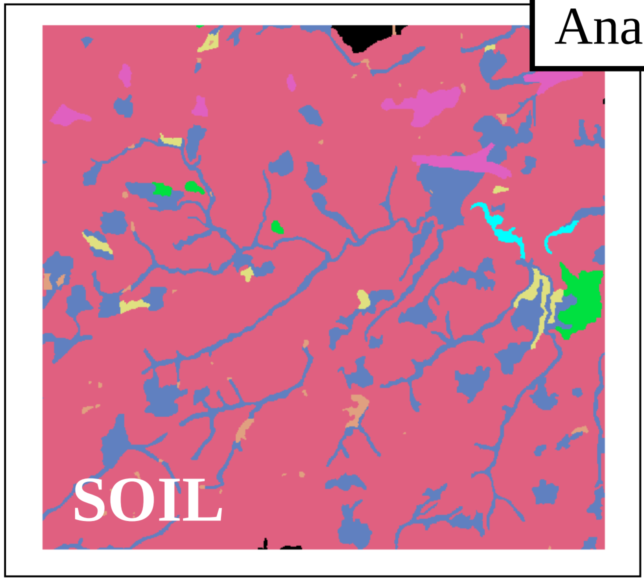
# RHESSys GIS Preprocessing

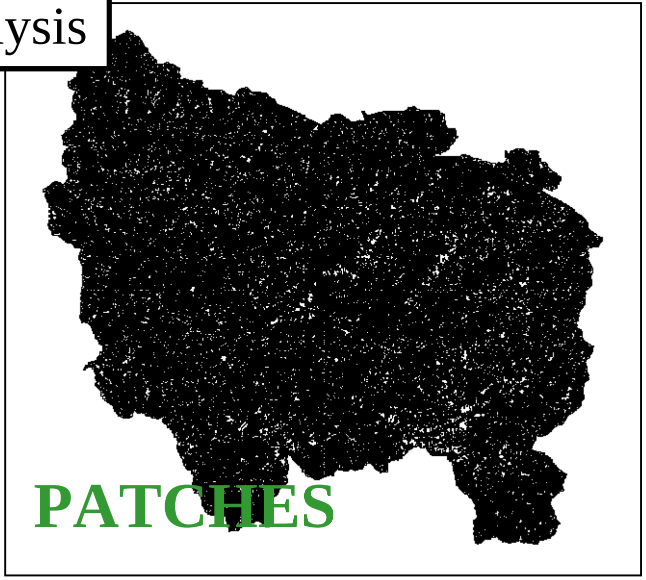
**GIS Preprocessing**

TOPOGRAPHY VEGETATION
DRAINAGE NETWORK SOIL

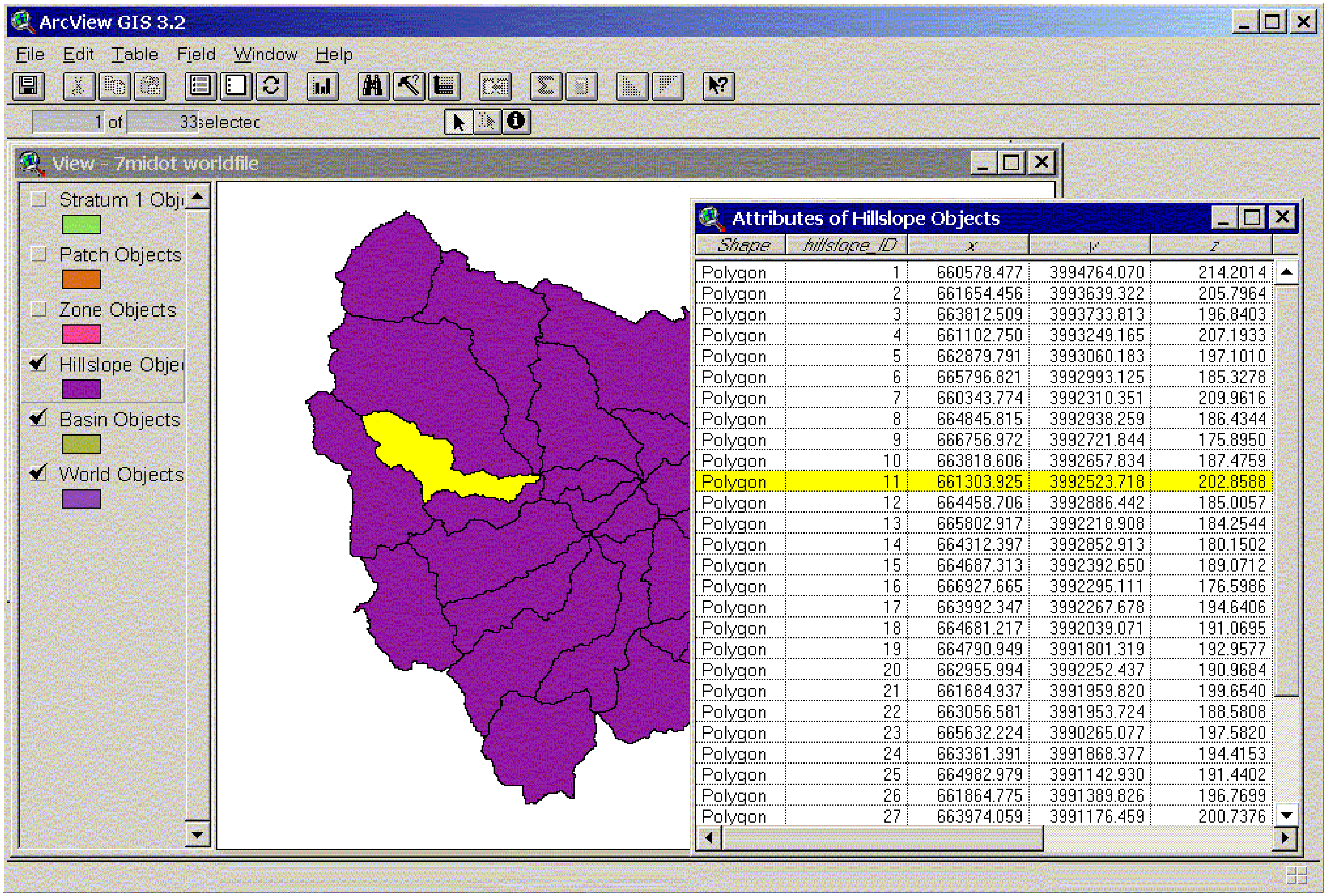


Overlay Analysis





# RHESSys GIS Preprocessing



| Shape | hillslope_ID | x | y | z |
|---|---|---|---|---|
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| Polygon | 2 | 661654.456 | 3993639.322 | 205.7964 |
| Polygon | 3 | 663812.509 | 3993733.813 | 196.8403 |
| Polygon | 4 | 661102.750 | 3993249.165 | 207.1933 |
| Polygon | 5 | 662879.791 | 3993060.183 | 197.1010 |
| Polygon | 6 | 665796.821 | 3992993.125 | 185.3278 |
| Polygon | 7 | 660343.774 | 3992310.351 | 209.9616 |
| Polygon | 8 | 664845.815 | 3992938.259 | 186.4344 |
| Polygon | 9 | 666756.972 | 3992721.844 | 175.8950 |
| Polygon | 10 | 663818.606 | 3992657.834 | 187.4759 |
| Polygon | 11 | 661303.925 | 3992523.718 | 202.8588 |
| Polygon | 12 | 664458.706 | 3992886.442 | 185.0057 |
| Polygon | 13 | 665802.917 | 3992218.908 | 184.2544 |
| Polygon | 14 | 664312.397 | 3992852.913 | 180.1502 |
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| Polygon | 17 | 663992.347 | 3992267.678 | 194.6406 |
| Polygon | 18 | 664681.217 | 3992039.071 | 191.0695 |
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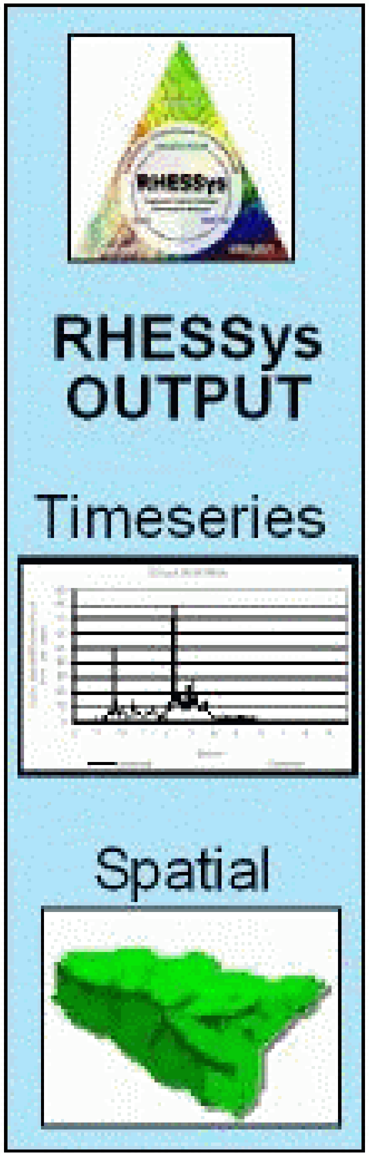
# RHESSys Output



- RHESSys can be used to track the **changes in a state variable over time**, in that the model produces a series of values for each timestep of the model run
- Key differences here are that RHESSys produces **hundreds of different output values** (various quantities related to water, carbon and nutrients) that can be consumed in this way for **EACH object**!
- Alternatively, the same value for each object from the same timestep can be **mapped**, to produce **spatial outputs** that show the **pattern of values**