# Hydrologic Modeling Overview

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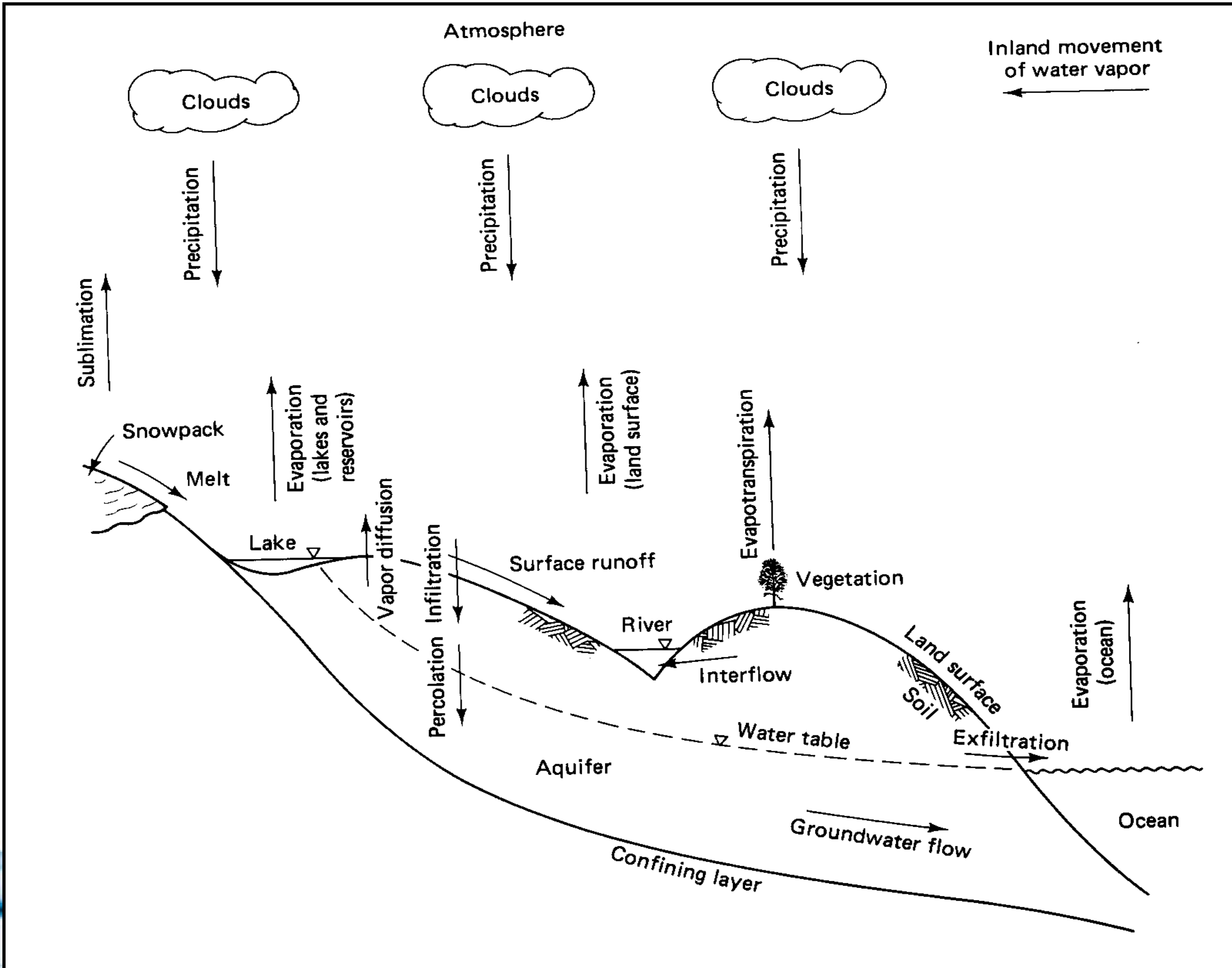
# Discussion Topics

1. Hydrologic processes
2. Hydrologic modeling
3. Hydrologic modeling approaches
   - Empirical, lumped parameter models
   - Distributed, physics based models
   - Hybrid models

# 1 - Hydrologic Cycle



# Sources of Stream Flow

- Hortonian, infiltration excess, runoff
- Saturated source areas
- Exfiltration
- Groundwater discharge to stream

# Infiltration Excess Runoff

- Infiltration excess runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil.
- Process described by Horton (1933), often referred to as Hortonian runoff.
- Dominant runoff mechanism in arid to semi-arid regions.
- Conditions conducive to infiltration excess runoff:
  - Fine texture soils
  - High intensity precipitation
  - Deep water table

# Saturated Source Areas

- When the storage capacity of the soils in the unsaturated zone is filled infiltration no longer occurs, and runoff is equal to the precipitation intensity.
- Described by Dunne and Black (1970).
- Dominant runoff production mechanism in humid regions.
- Conditions conducive to saturation excess runoff
  - Permeable soils
  - Low intensity precipitation
  - High water table

# Exfiltration

- When the elevation of the surface of the saturated groundwater exceeds the elevation of the land surface groundwater may discharge directly onto the land surface.
- Often called a seep or spring.
- Not typically a dominant runoff mechanism.
- Conditions conducive to seeps and springs
  - High water table
  - Breaks in slopes

# Groundwater Discharge to Stream

- When the elevation of the saturated groundwater surface exceeds the free water surface elevation in the stream, groundwater may discharge directly to the stream.
- Often referred to as base flow.
- Can be a significant portion of water balance in humid areas, especially in larger basins.
- Conditions conducive to groundwater discharge to the stream
  - High water table
  - Permeable subsurface materials
  - Extended periods of rainfall

# Mixed Basins

- Many basins are mixed basins
- Runoff is generated from a variety of methods
- Spikes in runoff are due to Hortonian flow
- Spikes in runoff may also occur due to saturation excess flow
- Long tails on hydrographs and base flow due to groundwater interaction with stream
- Streams gain and lose depending on location in stream and water table
- Different locations in the watershed may have different runoff mechanisms

# Special Considerations

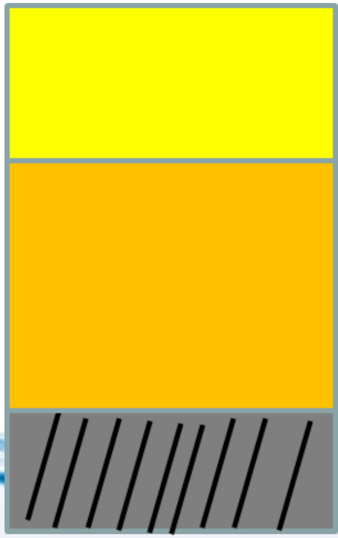
- Seasonality
- Soil layering

# Seasonal Considerations

- Seasonal plant changes also affect vegetative interception of rainfall
- Snowfall accumulation affects, and can dominate, the timing of runoff and stream flow.
- Frozen soils can greatly inhibit infiltration and produce enhanced runoff.
- In temperate zones, seasonal plant changes change result in large changes in canopy resistance during the year
  - Inverse of leave area index
  - Controlling factor in evapo-transpiration

# Soil Layering

- Soil layer can greatly affect infiltration
- Infiltration capacity, hydraulic conductivity, tends to be substantially lower in deeper layers
- Fragipans – very impermeable layers below the tilled soils, are common in agricultural areas
- Impermeable layers in the soil can cause perched water tables when ET is low
- Can result in a seasonality of the dominate runoff mechanisms
  - Hortonian for summer season
  - Saturation excess for winter/spring season



# 2 – Hydrologic Modeling Numerical Models

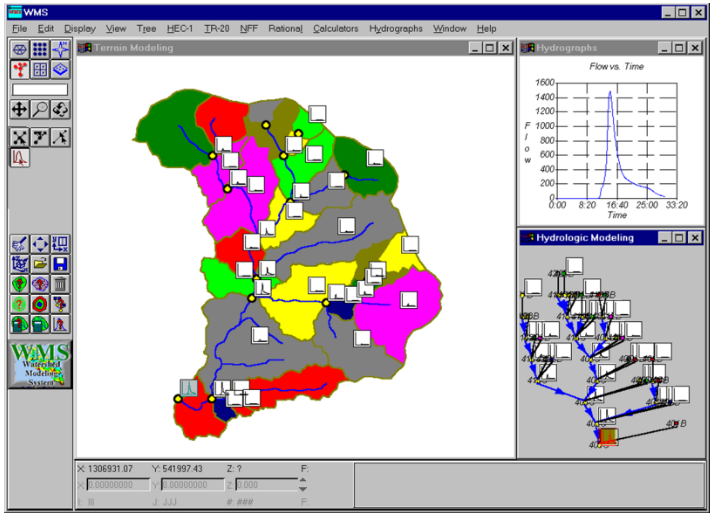
- Represent complex natural systems with mathematical and empirical relationships.
- System complexity is reduced, or processes are solved separately and then reassembled.
- Provide a mechanism for analyzing project alternatives and predicting the effects of future changes, such as: urban development, land use change, or climate change.

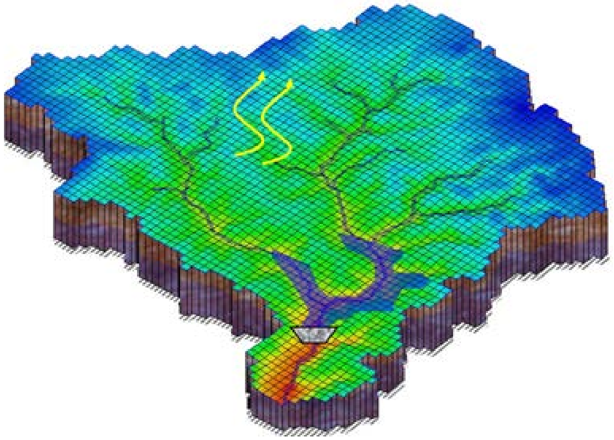
# Computation Element

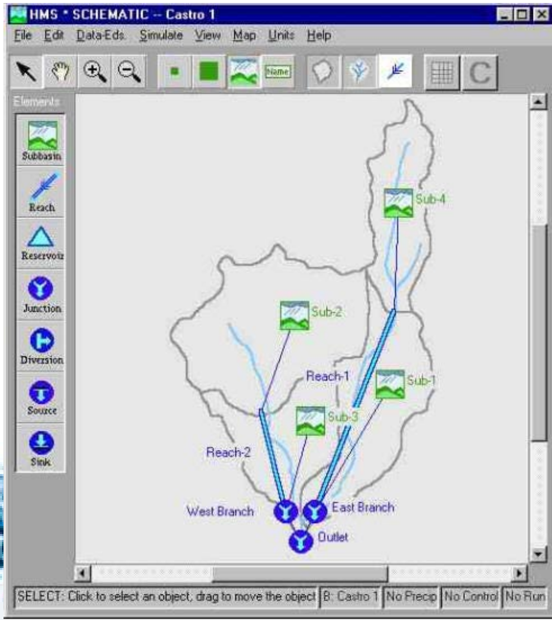
- Defined region in a model where calculations are performed
  - sub-watershed
  - grid cell
  - control volume
  - finite element node
- Physical conditions, and parameter values, are homogeneous throughout the computation element
- **Any heterogeneity within a computational element is lost, or must be implicitly included in the parameter values.**

# 3 - Hydrologic Modeling Approaches

- Empirically based, lumped parameter models
- Physically-based, distributed parameter models
- Hybrids – semi-distributed, quasi-physically based

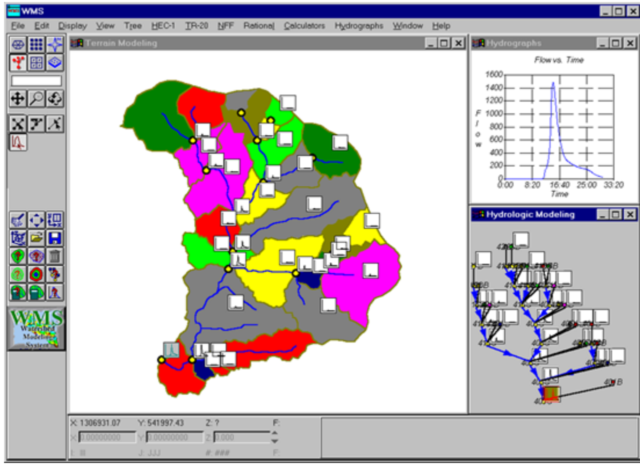


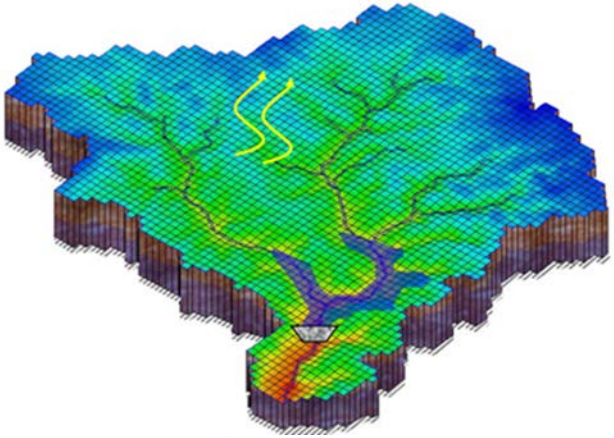





# Dual Modeling Theories

- Empirically-based, lumped parameter models – integrated over large enough time and space scales, the highly non-linear response of watersheds appears linear.
- Physically-based, distributed parameter models – broken down into small enough time and space increments, the physical processes occurring in the watershed may be explicitly simulated, and then integrated to produce the watershed response.



# Empirical verses Process Based Models

## Empirical (lumped) Approach

- Computational element is the sub-watershed.
- Subdivide watersheds into smaller sub-watersheds.
- A single parameter value represents processes the entire sub-watershed.
- Empirical relationships relate system response to hydrologic inputs.
- Sub-basins are connected with simplified flow relationships - link/node

## Process – (physics) Approach

- Computational element is the grid cell or node.
- Subdivide watersheds into cells/nodes.
- Parameter values can vary for each cell/node.
- Point physical processes (infiltration, ET, etc.) are computed at the cell/node level.
- Cell/node response is integrated to get system response (overland/subsurface flow, stream flow)

# Advantages/Disadvantages

## Empirical (lumped) Approach

- Simple to understand and use
- Long history of use
- Regulatory acceptance
- Short simulation times facilitate automated calibration methods
- Lumping of information
- No process information provided
- Parameters have limited physical meaning and may be difficult to estimate with changing conditions.
- Not reliable outside the range of calibration (verifiability problem)

## Process – (physics) Approach

- More difficult to use
- Relatively new technology
- May need to justify use to regulatory agencies
- Long simulation times can hamper calibration efforts
- Explicitly includes spatial heterogeneity
- Model helps user understand physical processes in the system
- Parameters have physical meaning and don't change with changing conditions.
- Model can be used for new conditions

# Hybrid Models

- Contain elements of lumped parameter and fully distributed, physics based models
  - Approach varies amongst models
- Mixture of empirical and physics based approaches within the model
- Semi-distributed models share many of the same advantages/disadvantages as simple lumped parameter models
  - Typically include greater spatial heterogeneity than simple lumped parameter models
  - May include more physically meaningful representation of processes than lumped models
  - Maintain the computational advantage over fully distributed, physics based models

# Lumped Modeling Example

- Analysis of riparian restoration of urbanized watershed in Washington D.C., Baltimore District – Anacostia River.
- Restore natural areas within the watershed to reduce runoff and erosion
- Developed HEC-1 model of the river basin
- Developed Curve Numbers from highly detailed land use and soil maps
- Calibrated Curve Numbers to current conditions
- Adjusted the Curve Numbers for changes in land use for restoration scenarios
- Restoration scenarios resulted in increased runoff!

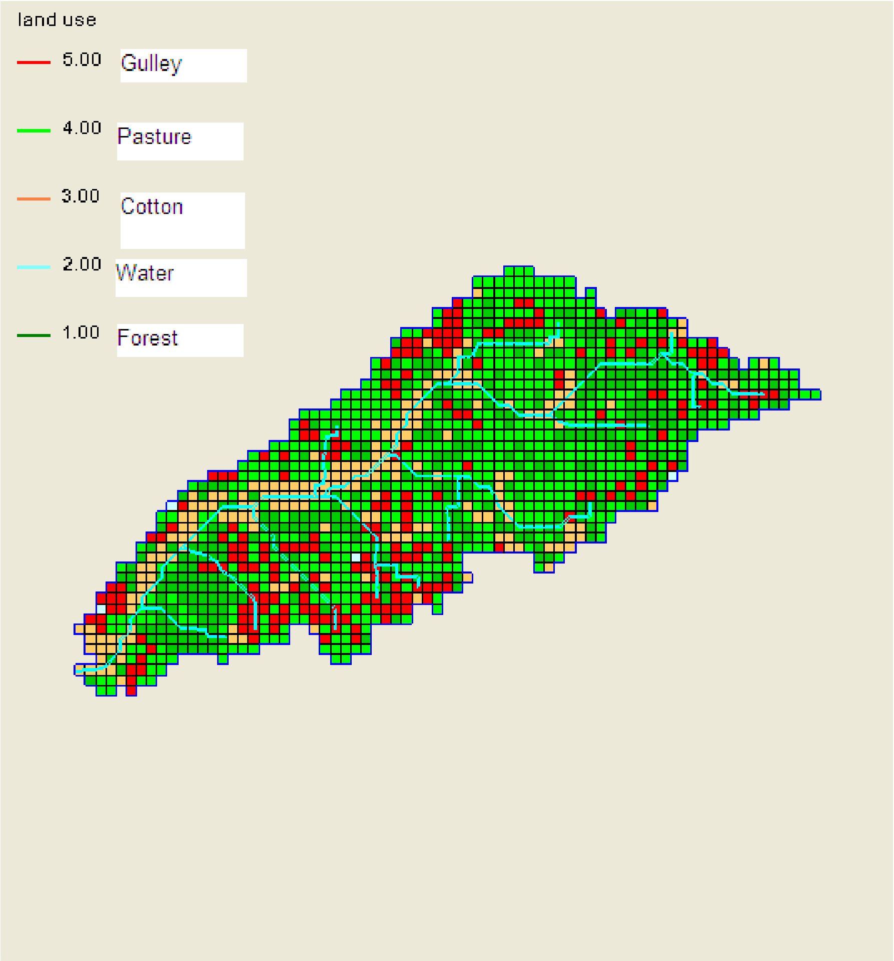
# Proper Use of Empirical, Lumped Parameter Models

- Empirical lumped parameter models are best used for analysis of current systems.
- Can be applied to analyze very large basins
- Can be used to provide predictions within the range of calibration
- Can identify areas of concern
  - hotspots
  - source areas

# A Better Lumped Model Example

- National Weather Service River Forecast Centers uses the Sacramento Model for flood predictions
- The Sacramental model is a simple volumetric model with compartments representing different hydrologic regions
  - surface water
  - unsaturated zone
  - groundwater
- Model is automatically recalibrated every evening
  - extend the range of calibration
  - account for changes to the system.
- Model typically performs very well for forecast.

# Distributed Modeling Example




- Goodwin Creek Experimental Watershed Erosion Modeling.
- Red and orange areas sources of sediment erosion.
- Green areas are sediment deposition areas.
- Only erosional areas near the stream contribute to the sediment load.
- The path matters!

# Modeling Philosophy

Model representation of the physical system should be as simple as possible, but no simpler

- Model should account for dominant physical processes
- Model must include important physical features (both temporal and spatial)
- Model should not contain undue complexity
- Different approaches for different problems

# Conclusions

- The hydrologic cycle is complex
- Hydrologic modeling aids in understanding and analyzing hydrologic systems
- Hydrologic modeling falls into two large classes
  - empirical, lumped parameter models
  - distributed, physics based models
- Hybrid models contain elements of both
- Different types are useful for different purposes
- Lumped models are best for analysis
- Physics based models are best suited for design
- Hybrid models
  - refine analysis
  - screen design
- Physics based models range greatly in complexity
- The appropriate model depends on the application