# Hydrologic Modeling Overview

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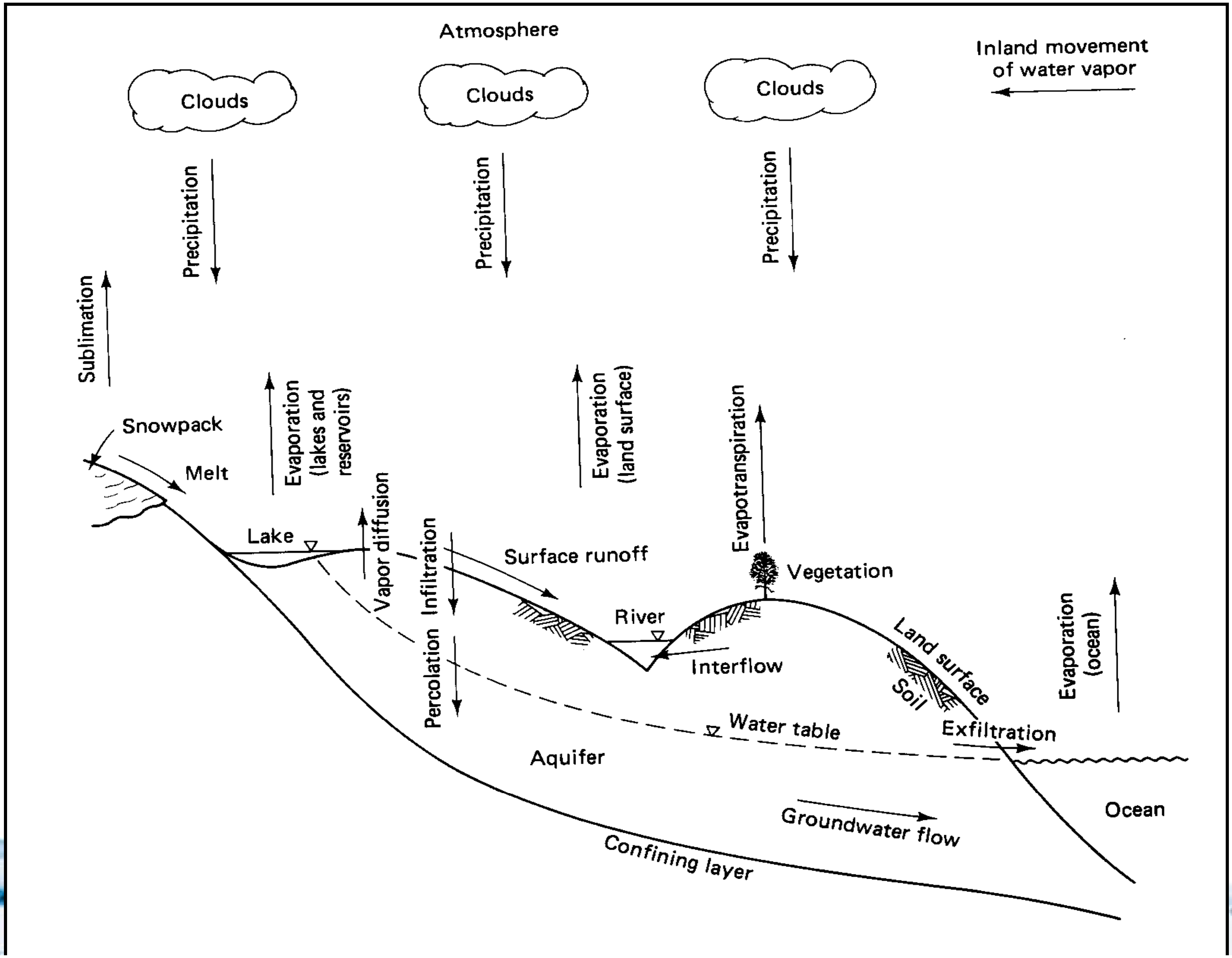
# Discussion Topics

- Hydrologic processes
- Hydrologic modeling
- Hydrologic modeling approaches
  - Empirical, lumped parameter models
  - Distributed, physics based models
  - Hybrid models

# 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), sometimes referred to as Dunne runoff.
- 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

- 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
- Seasonal plant changes also affect vegetative interception of rainfall

# 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

# 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

# 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.

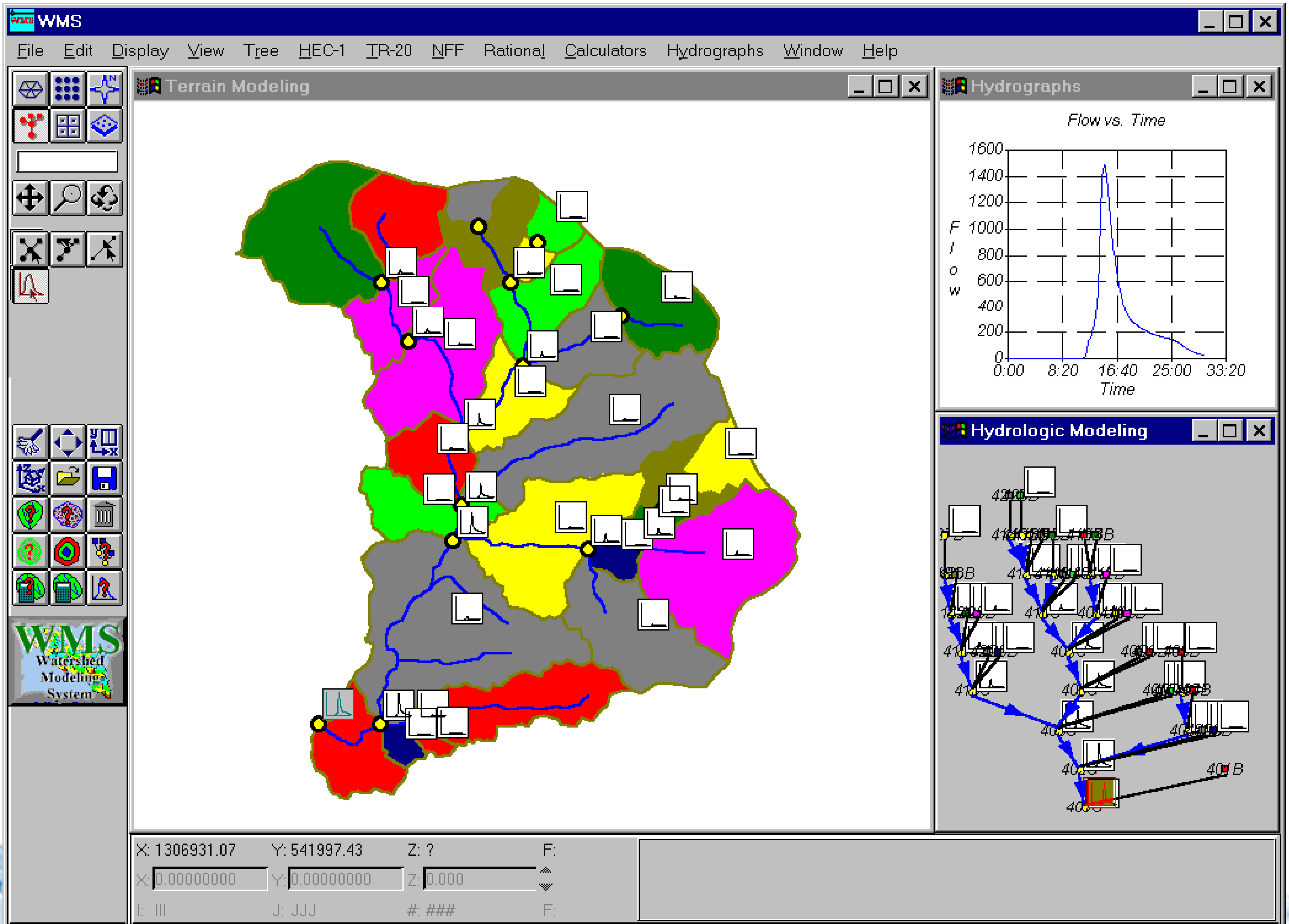
# Lumped Parameter Models

- The system response, which behaves linearly at sufficient scale, is simulated, not the underlying physical responses, which are highly non-linear.

# Empirically Based, Lumped Models

- 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 response to hydrologic inputs.
  - Curve number – fraction of rainfall converted to runoff
  - Similar approaches for other processes
    - erosion
    - constituent uptake/decay
- Sub-basins are connected with simplified flow relationships - link/node

# Lump Model Watershed Representation



# Example Models

- Rational Method
- TR-20
- HEC-1
- Sacramento Model
- HSPF

# Advantages

- Conceptually simple
- Easy to program
- Easy to apply
- Simulation time is trivial
  - enhanced calibration – automated methods
- Can be applied to enormous basins
- Generally accepted by regulators
- Long history of use

# Disadvantages

- Requires substantial calibration data
- Not useful outside the range of calibration
- Do not provide process information
- Lack of spatial heterogeneity in the models
- Lack of verifiable results

# Lumping of Information

- Selection of sub-watersheds (the computational element) is based primarily on need for output
  - subdivide the watershed where you need information
- Even at the finest discretization, sub-watershed are highly variable
  - land use
  - slope
  - soils
  - depth to the water table
  - spatial distribution of features
- Proper element response means the parameters must contain this information – i.e. this information is "lumped" into the sub-watershed parameter

# Calibration

- Because response, not process, is simulated the parameters must be tuned to the current system.
- For the model to function over a large range of conditions, the model must be calibrated to these conditions.
- Application of the model outside this range is dangerous as changes in process may occur with no way of knowing or nor accounting for the change.

# Parameter Values

- Parameter values for sub-watersheds implicitly contain the process information particular to that sub-watershed.
- Determining parameter values for changing conditions is difficult
  - land use
  - project alternatives

# Example

- Analysis of riparian restoration of urbanized watershed in Washington D.C., Baltimore District
- 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

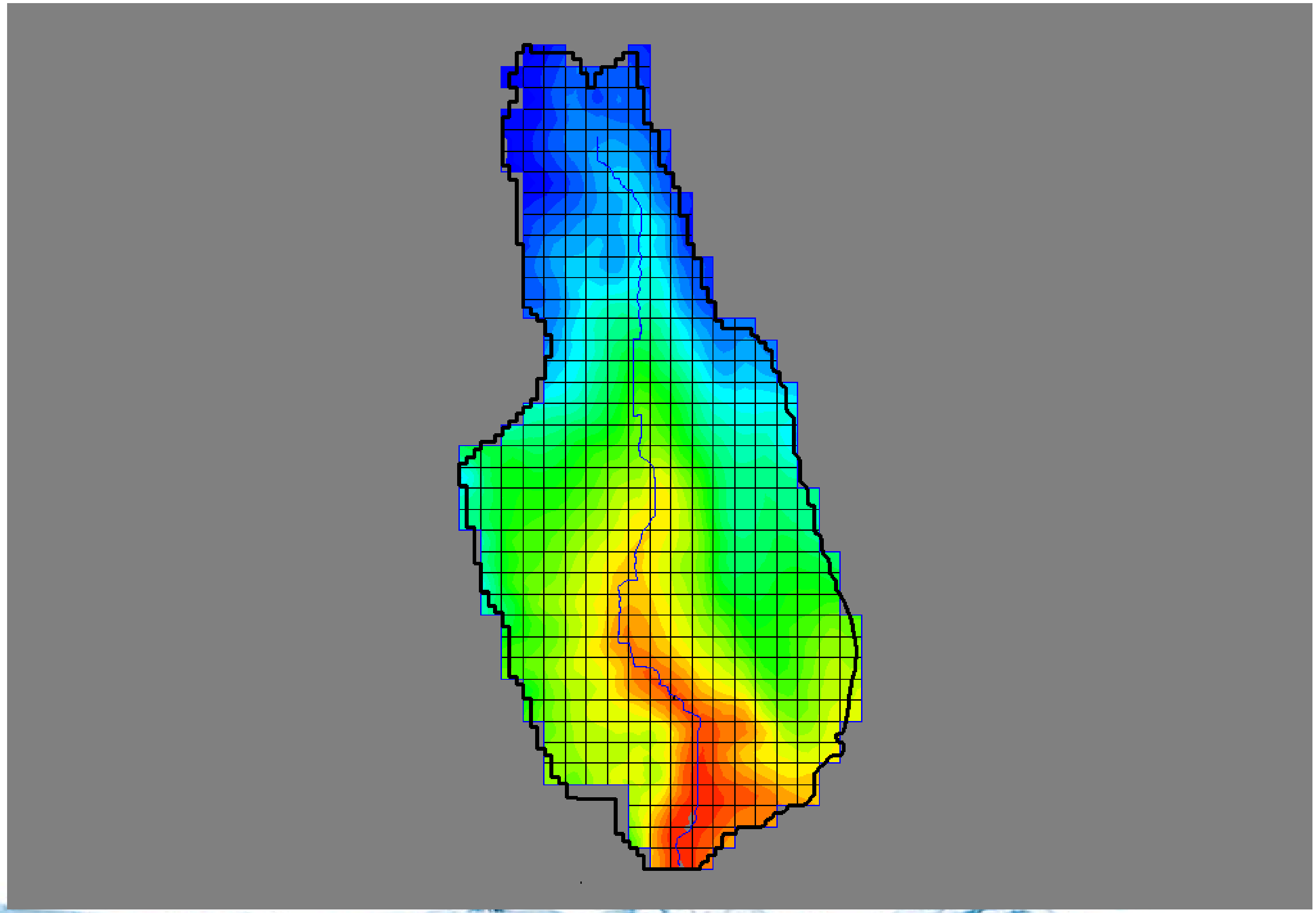
# Example

- National Weather Service 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.
- Results would be very difficult to reproduce with other models and methods .

# Physically-based, Distributed Models

- Fine scale physical processes are simulated at the elemental level.
  - Plant interception
  - Infiltration
  - Runoff
  - Evapo-transpiration
- The elemental responses are integrated to determine the system response.

# Distributed, Two-dimensional Representation of Watershed



# Advantages

- Simulates physical processes
- Explicitly includes spatial heterogeneity
- Provides information at the sub-watershed level
- Requires less calibration data
- Extendible beyond calibration range
- Can be used to analyze changing conditions
    - land use changes
    - project alternatives
    - climate change

# Disadvantages

- Numerical modeling concepts can be difficult to grasp
- Code develop is difficult
- Application is difficult compared to lumped parameter models
- Data intensive
- Computational penalty
  - Simulation times can be long
  - Simulation times increase with increasing complexity and resolution
  - Hampers calibration

# Applicability

- Watersheds with minimal calibration data
- Analyze land use or climate change, project alternatives, or any conditions outside the range of calibrated values.
- Inherently distributed processes - sediment erosion and deposition, non-point source pollution, surface water/groundwater interaction

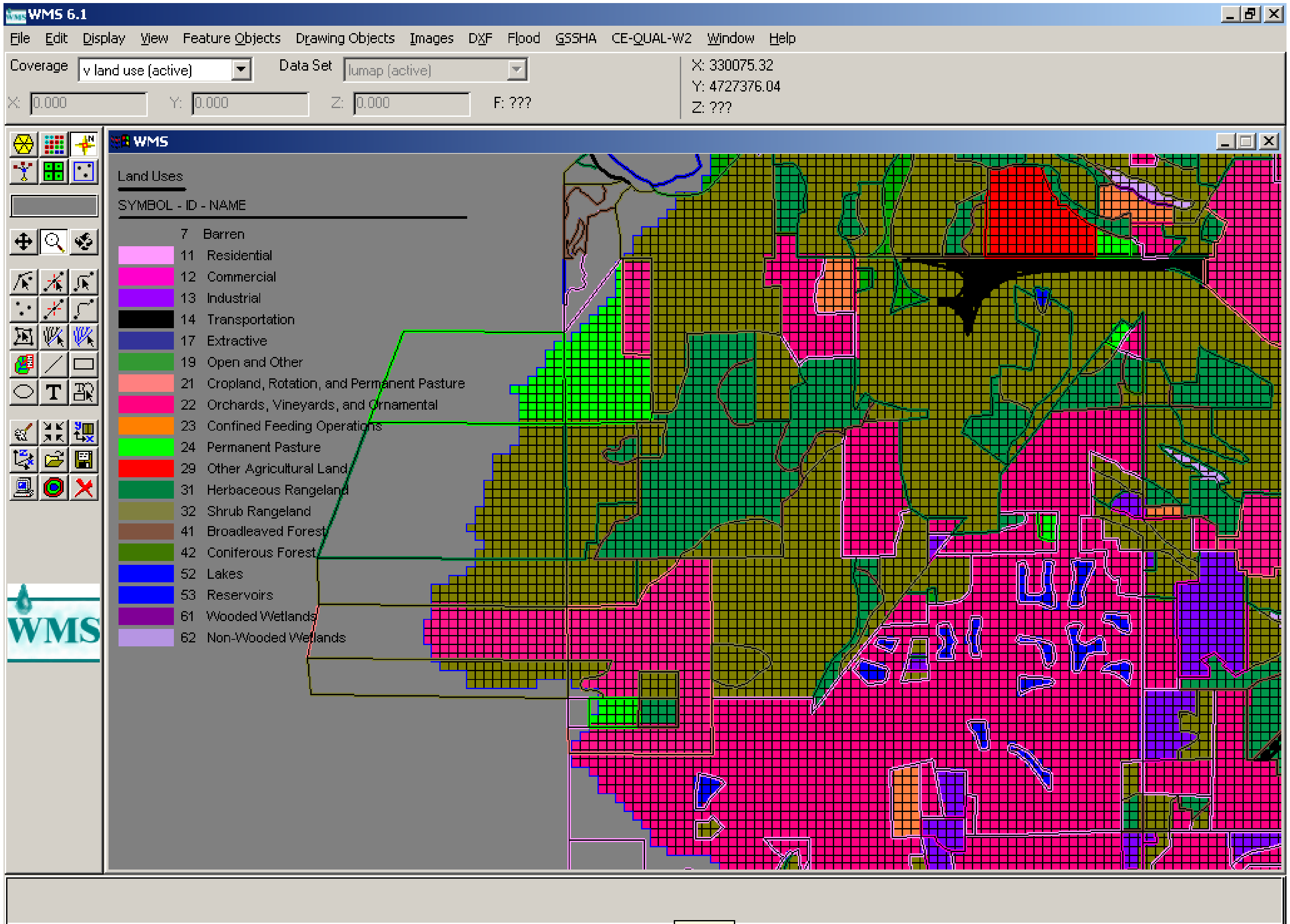
# Examples

- GSSHA
- MIKE-SHE
- MODHMS
- WASH123D
- ADH

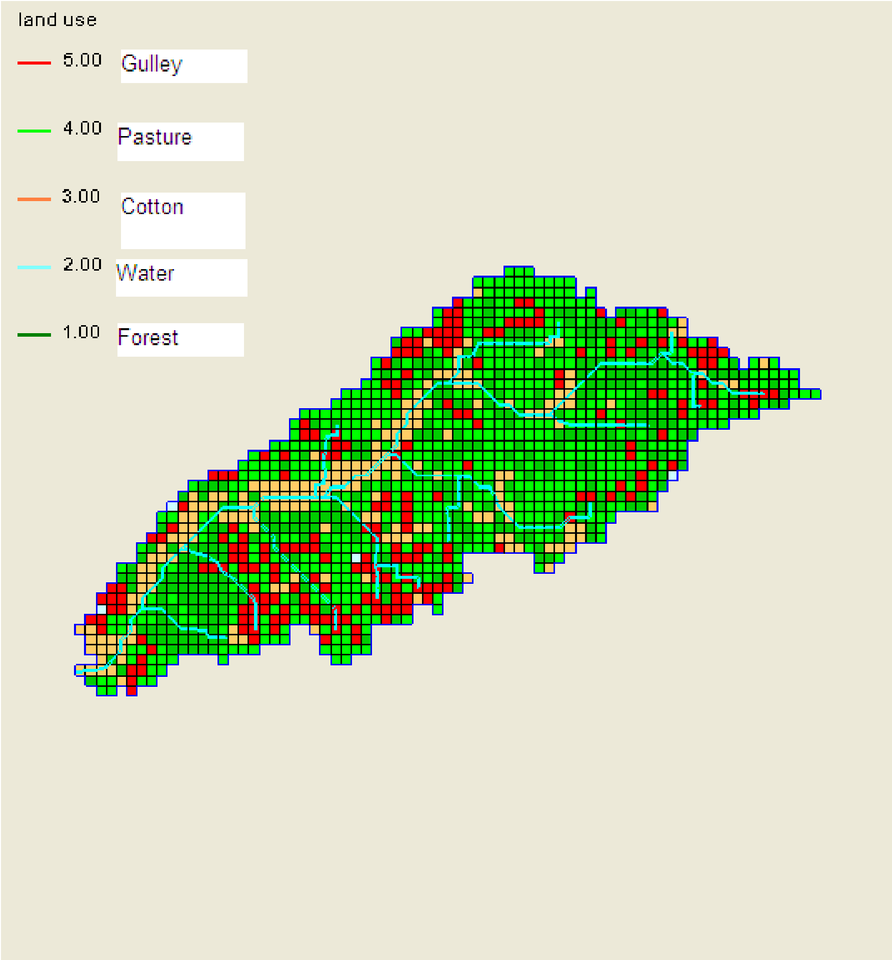
# Discretization

- Watershed is discretized based on resolution required to simulate dominate features and processes.
- Parameters are prescribed to each computational element based on the physical properties of the element
  - land use
  - soils

# GSSHA Representation of Land Use



# Example – Goodwin Creek Erosion



# Calibration

- Initial values are assigned based on literature and field values
- Parameters must be calibrated
  - values are uncertain
  - model formulation introduces errors
  - discretization introduces errors

# Parameter Values

- Calibrated values are based on physical conditions in the computational element
- The tie to physical conditions provides a means to logically alter parameters based on changing conditions.

# Model Which Processes? And How?

- Extend capability
  - include more processes
  - general treatment

- Added complexity
  - increases the number of parameters
  - increases difficulty in using model
  - increases computation time

# Hybrid Models

- Contain elements of lumped parameter and fully distributed, physics based models
- Approach varies amongst models
- Typically include greater spatial heterogeneity than simple lumped parameter models
- May include more physically meaningful representation of processes
- Mixture of empirical and physics based approaches within the model

# Examples

- HEC-HMS
- TOPMODEL
- SWAT

# Advantages/Disadvantages

- Semi-distributed models share many of the same advantages/disadvantages as simple lumped parameter models
- The advantage over simple lumped parameter models are
  - increased spatial resolution
  - better process descriptions
- Semi-distributed models maintain the computational advantage over fully distributed, physics based models

# Example with HMS

- Problem
  - Simulate existing system
  - Evaluate alternatives for reducing flood damage
- Modeling Approach
  - Subdivide domain based on data availability.
  - Estimate parameters for infiltration model, i.e. Green Ampt.
  - Runoff
    - Use quasi-distributed approach if there is a good source of gridded precipitation.
    - Use Unit hydrograph if there is regional calibration data available.
  - Apply physical channel routing methods
    - kinematic
    - Muskingum-Cunge
- Analysis
  - Apply frequency events to get appropriate runoff.
  - Compute frequency curve for each alternative and compare.

# 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