



Hydrologic Modeling Overview

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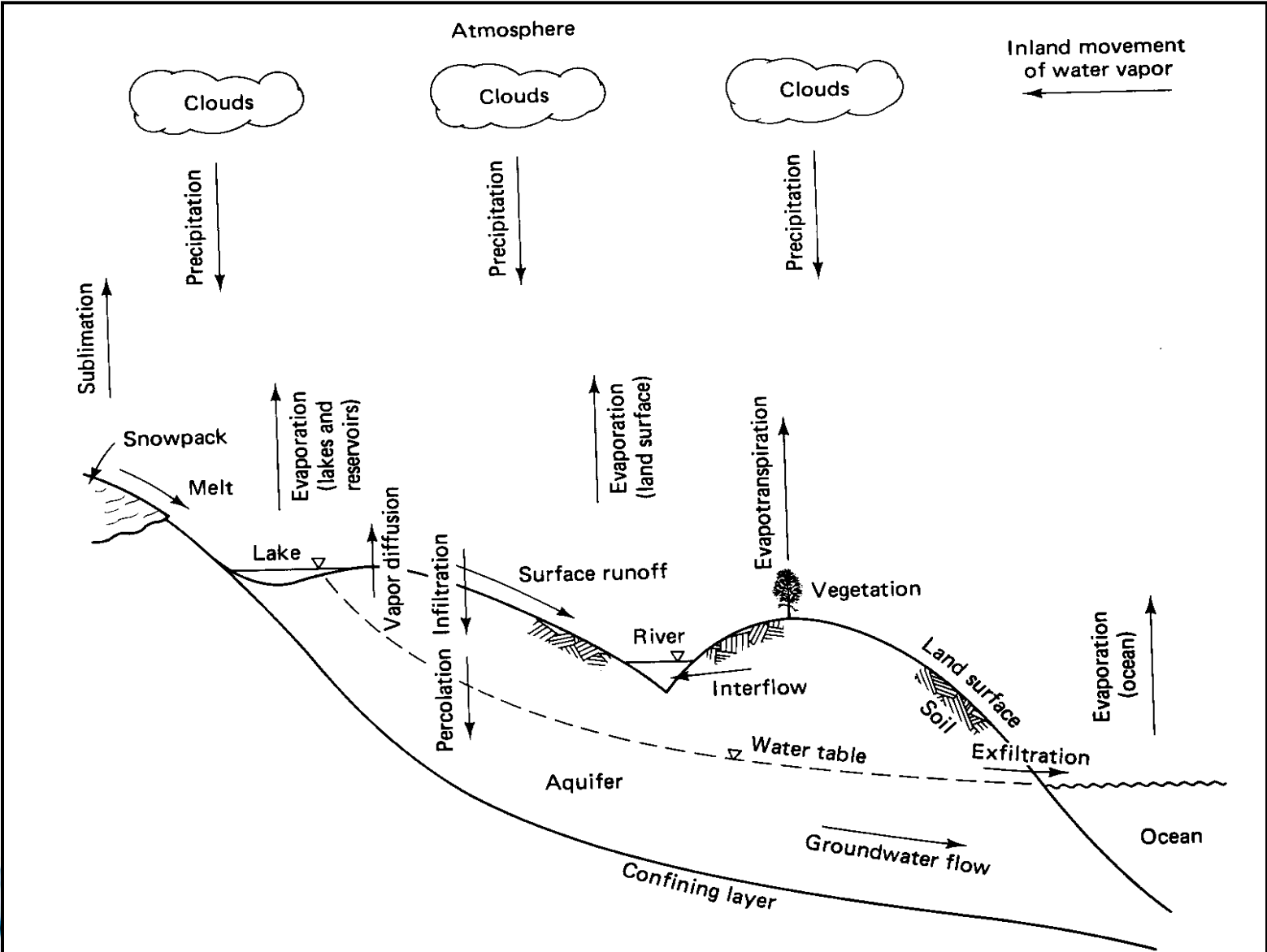
Discussion Topics

- 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).
- 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.



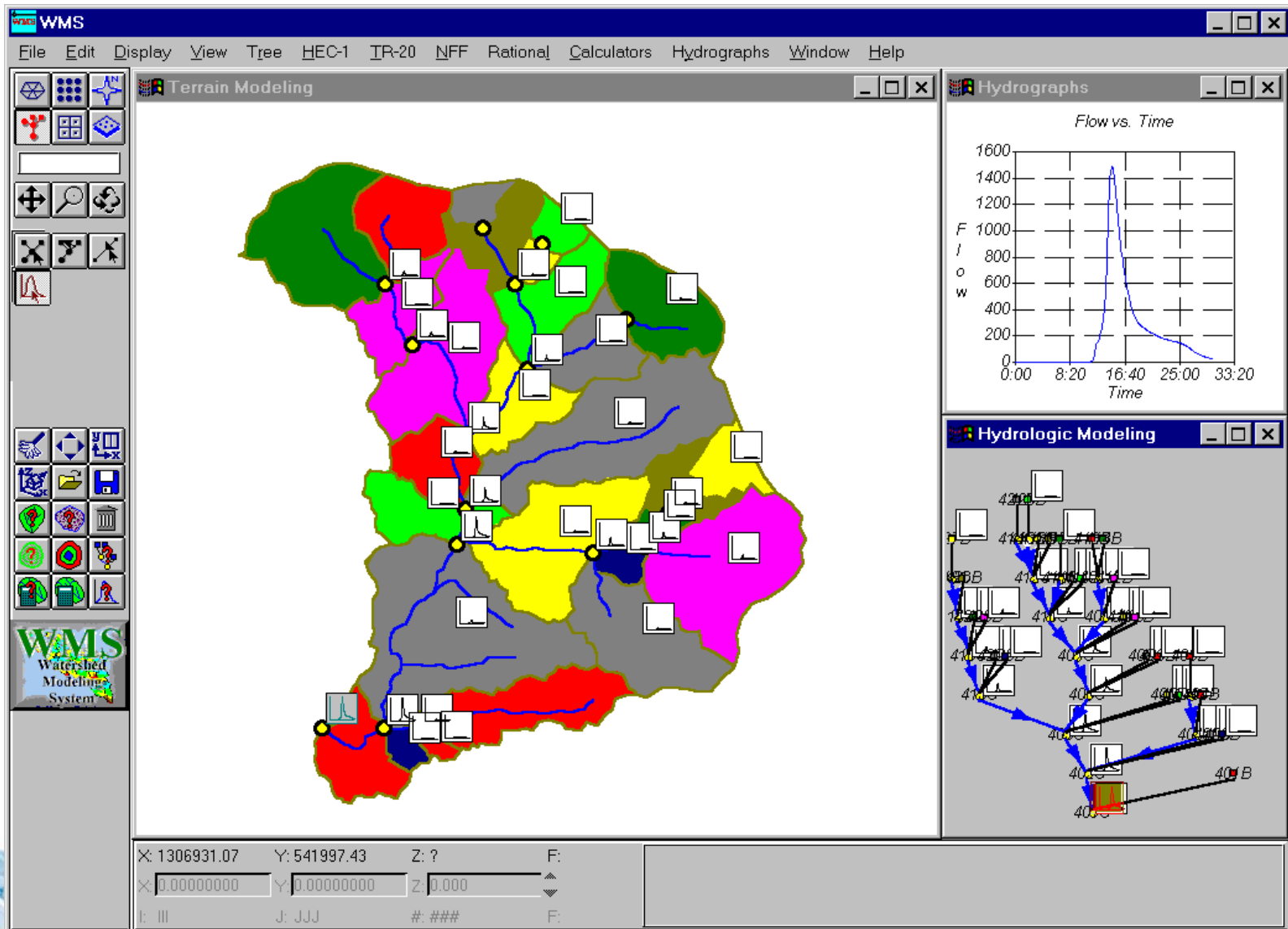


Empirically Based, Lumped Models

- 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



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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 .





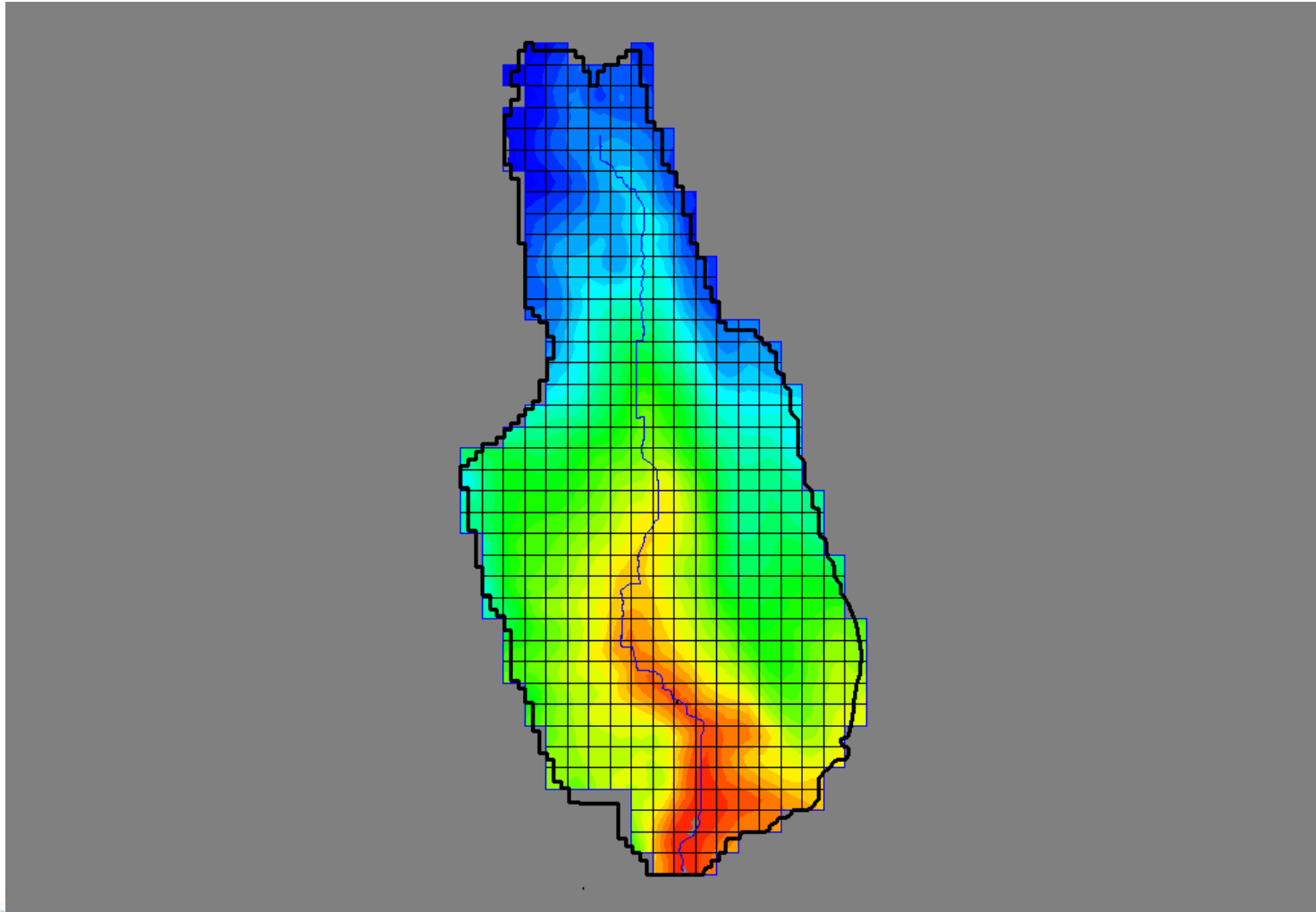
Physically-based, Distributed Models

- 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
- WASH_{123D}
- ADH





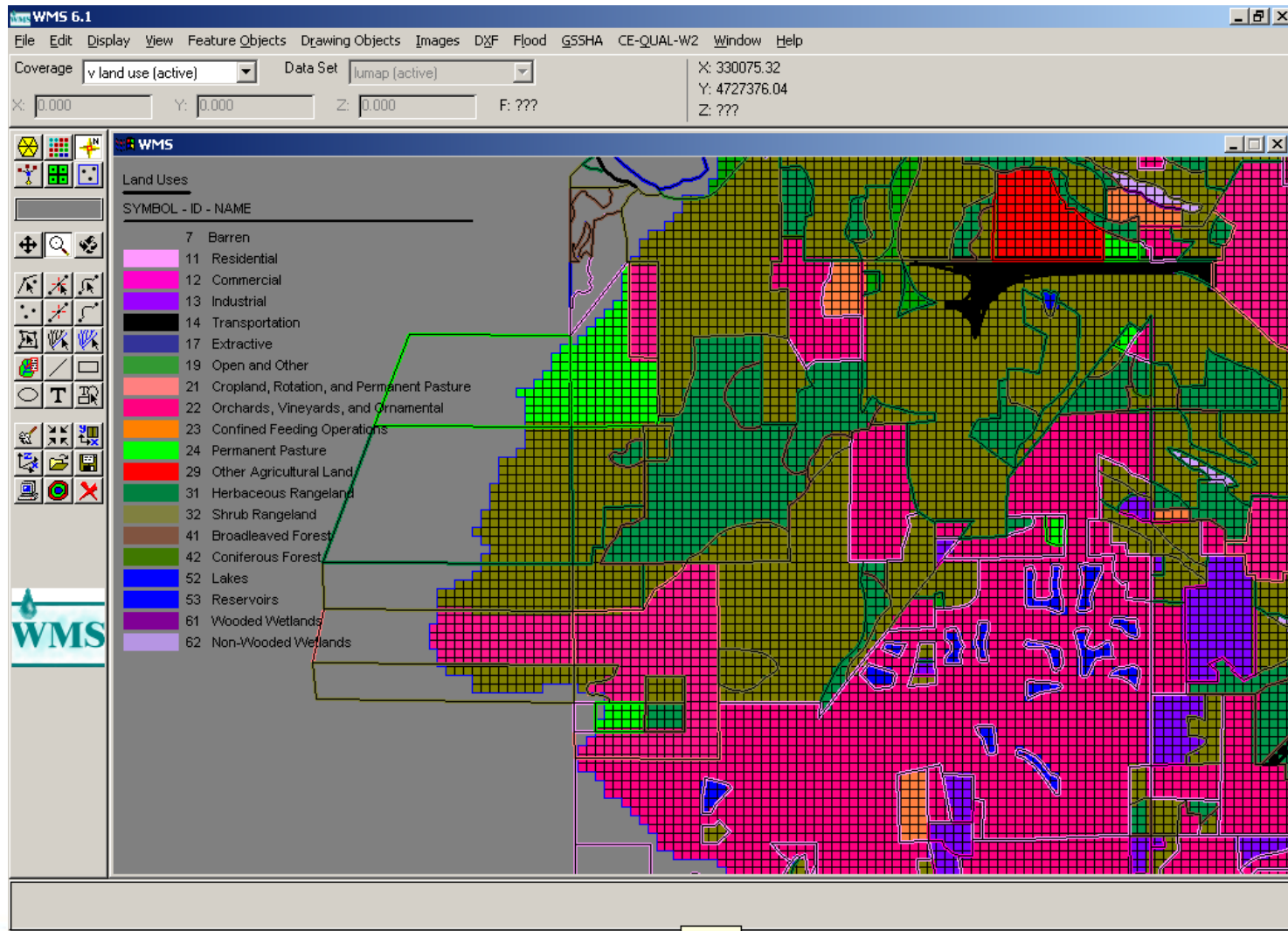
Discretization

- 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



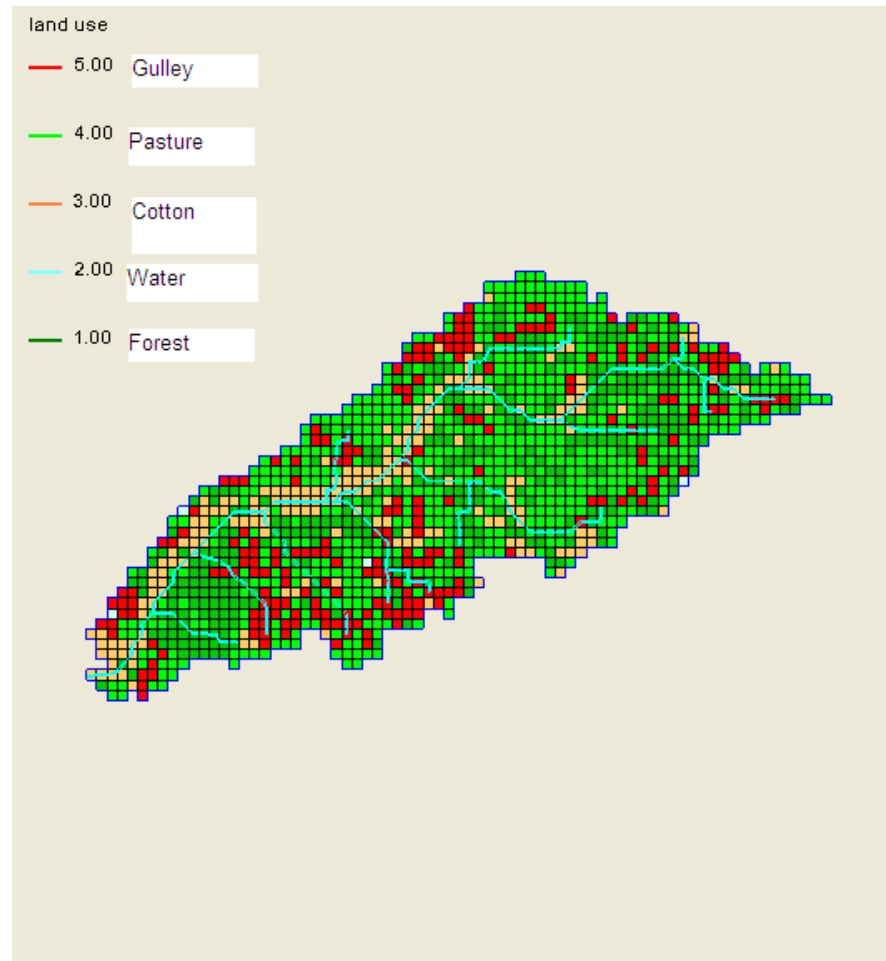


GSSHA Representation of Land Use





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





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





- 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

