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High-resolution, multi-scale modeling of watershed hydrology

An Opportunity to Integrate Remote Sensing Observations, Field Data Collection and Distributed Modeling in a Hydrologic Observatory

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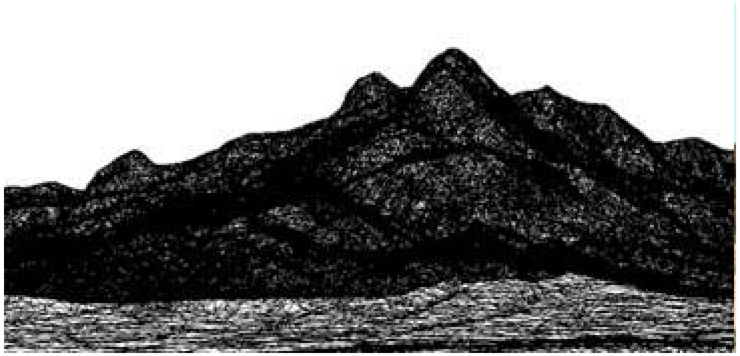
Real and Virtual Hydrologic Observatories



Field Data and Remote Sensing

• Continuous in-situ measurements over spatially distributed locations within nested watersheds.

• Repeat-visit, high-resolution, hyper-spectral observations from spaceborne and airborne sensor platforms.

Physically-based Distributed Models

• Process-based representations of basin hydrology, geomorphology and land-atmosphere interactions.

• Incorporation of spatial and temporal distribution of topography, rainfall, soils, vegetation, meteorology, soil moisture.

Outline

1. Hydrologic Observatories
2. Multiple-resolution Distributed Hydrologic Modeling
3. Illustrative Modeling Scenario
4. A Semi-Arid Real and Virtual Hydrologic Observatory
5. Concluding Remarks

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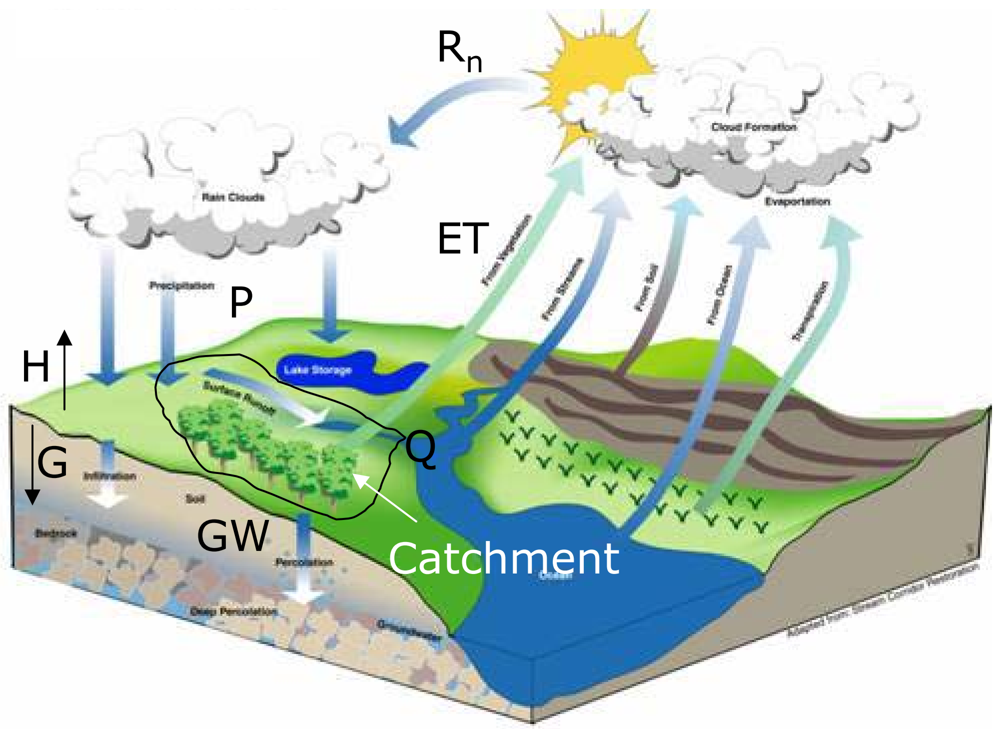
Hydrologic Cycle



Earth's Hydrologic and Energetic System:
Water and Heat Storages and Transports over Many Time and Space Scales

Catchment Hydrology

Solar radiation drives the hydrologic cycle over the land-surface:

(1) Evapotranspiration (ET)

(2) Cloud Condensation and Precipitation (P)

(3) Streamflow Runoff (Q)

(4) Aquifer Recharge (GW)

Hydrologic Balance

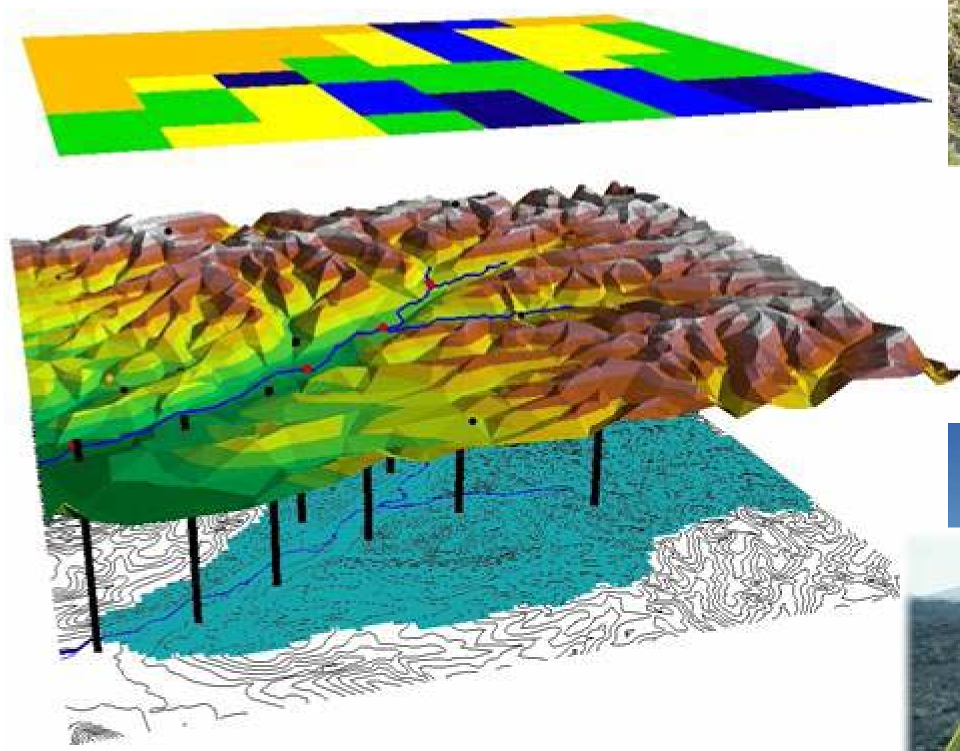
$$\Delta S = P - ET + Q - GW$$

Energy Balance

$$R_n - G = \lambda ET + H$$

Hydrologic Observatories

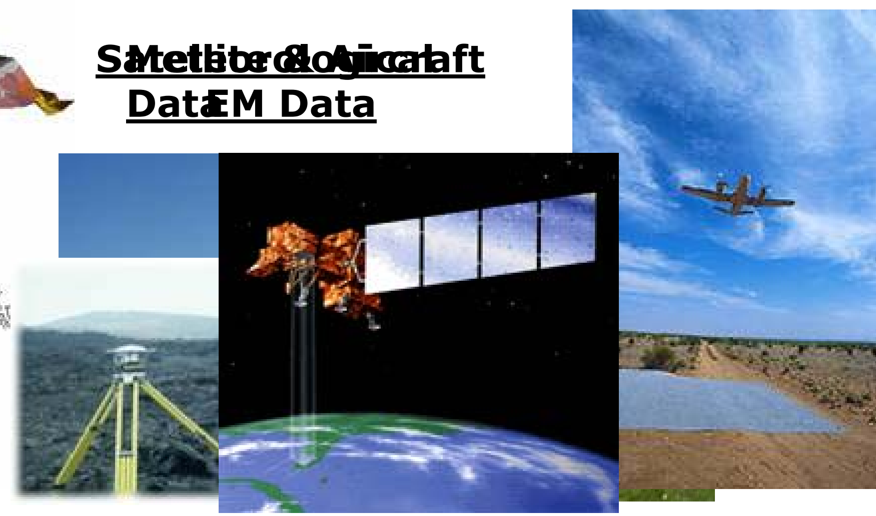
Field and Remote Sensing Data over Hydrologic Catchments



Hydrologic Data

Satellite & Aircraft EM Data

Meteorological Data

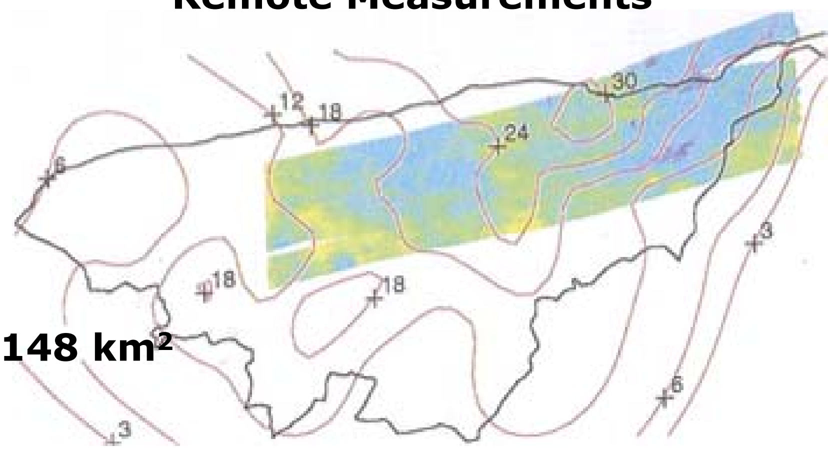


Hydrologic Observatories

Remote Sensing Data

• Basin-scale remote data retrievals leading to high spatial-temporal resolution hydrologic observations.

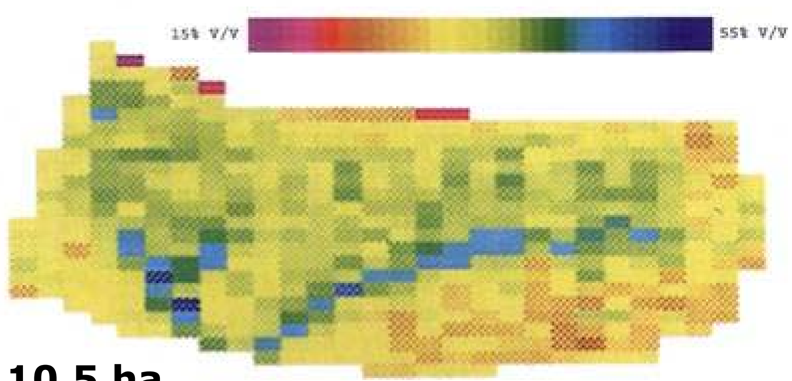
Remote Measurements



148 km²

Houser et al. (2001) PB Microwave Radiometer Derived Soil Moisture

In-situ Measurements



10.5 ha

Western and Grayson (2001) Measured Volumetric Soil Moisture

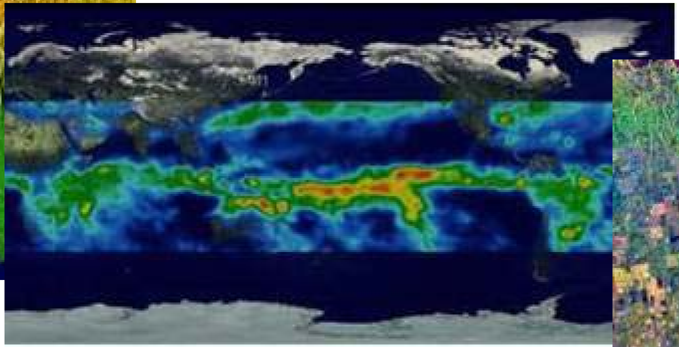
Field Data Collection

• Catchment-scale measurements leading to understanding time-changing spatial pattern of hydrologic processes.

Hydrologic Observatories

<u>Major</u> advances in remote sensing have improved our capabilities to simulate and forecast watershed hydrology. Numerical models capable of utilizing these data sources at multiple scales are required.

Measurements of Earth's Topography



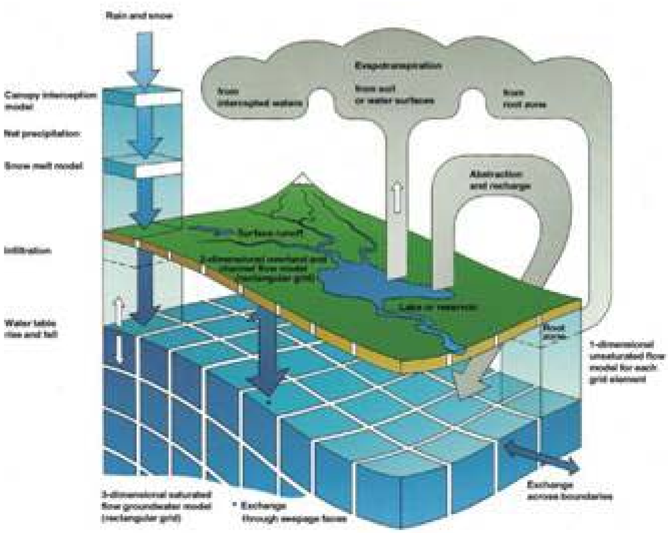
Measurements of Earth's Precipitation

Measurements of Earth's Hydrologic Variables

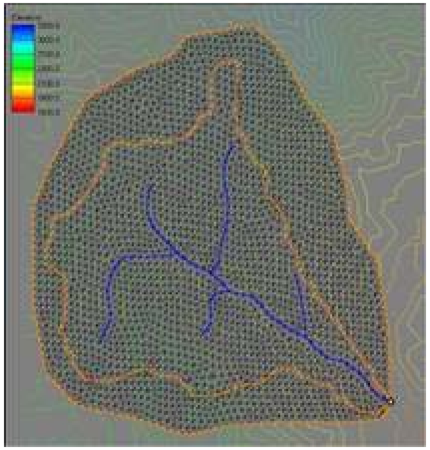
Distributed Hydrologic Modeling

Numerical simulations of catchment hydrologic processes require a method for representing a basin. Methods can be categorized as **lumped versus distributed modeling** (contours, grids, polygons, TINs).

Basin-Averaged Models (e.g. HEC-HMS)



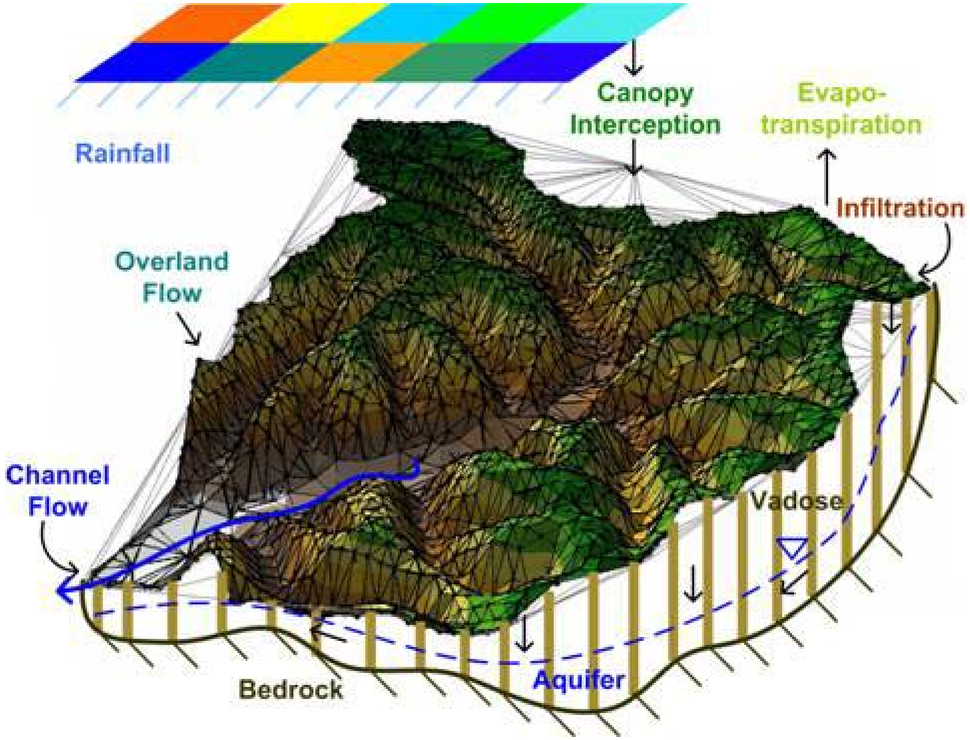
Raster-Grid Models (e.g. MIKE SHE)



Triangular Irregular Network Models (e.g. WMS)

Distributed Hydrologic Modeling

TIN-based Real-time Integrated Basin Simulator (tRIBS) is a fully-distributed model of coupled hydrologic processes.



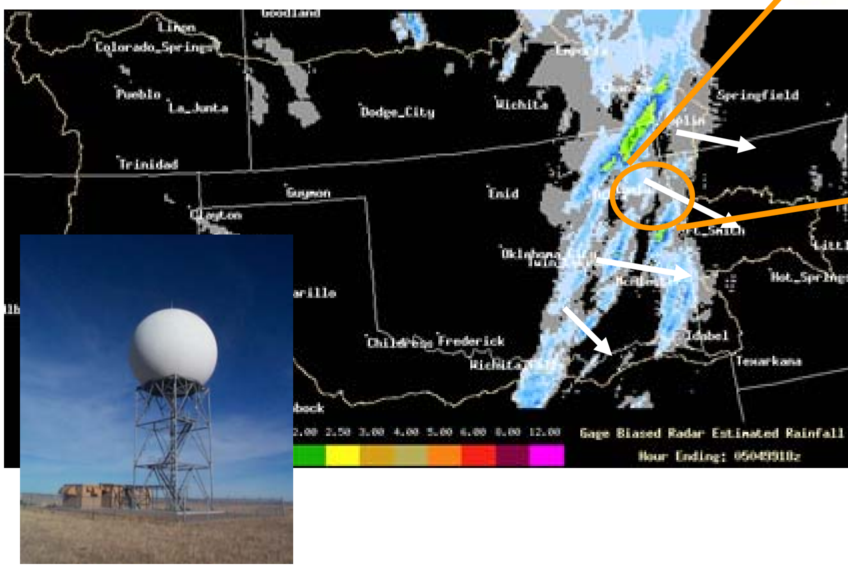
Surface-subsurface hydrologic processes over complex terrain.

Distributed Hydrologic Modeling

- Coupled vadose and saturated zones with dynamic water table.
- Moisture infiltration waves.
- Soil moisture redistribution.
- Topography-driven lateral fluxes in vadose and groundwater.
- Radiation and energy balance.
- Interception and evaporation.
- Hydrologic and hydraulic routing.

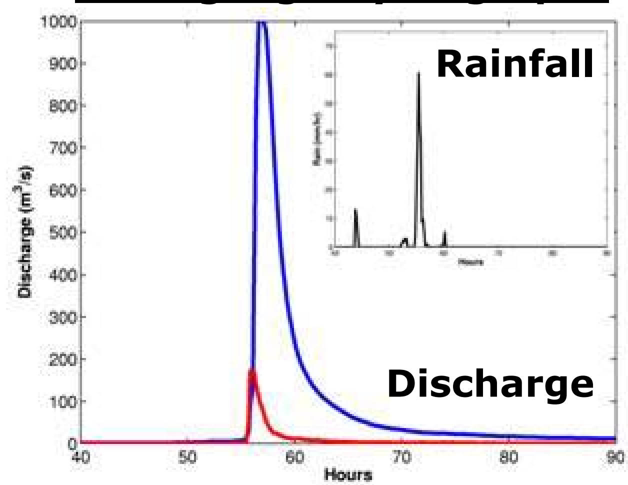
Distributed Hydrologic Modeling

Distributed Rainfall Estimation and Forecasting



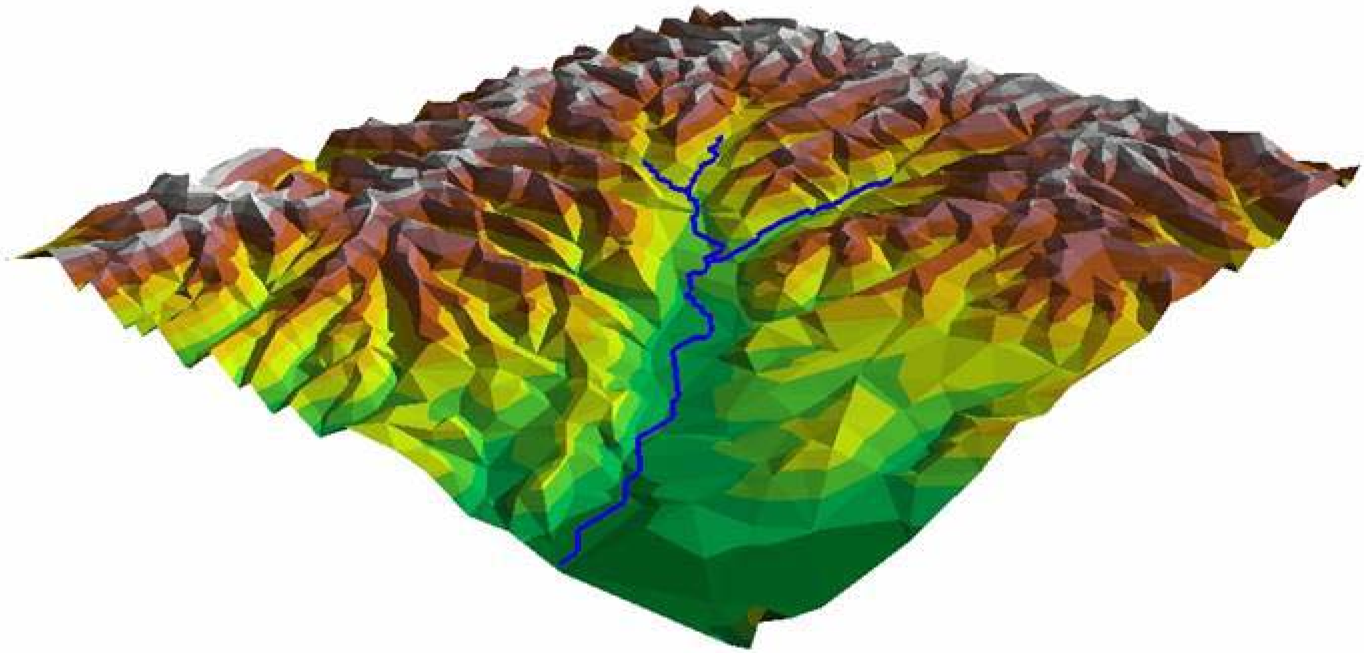
NEXRAD Radar Rainfall Composite + Hydrologic Model Simulation

Multi-gauge Hydrographs



Multiple Resolution Terrain Models

TINs are a piece-wise surface interpolations of *x, y, z* points consisting of triangular elements of varying size resulting in multiple resolution models.



Digital Elevation Model (DEM) → **Triangulated Irregular Network (TIN)**

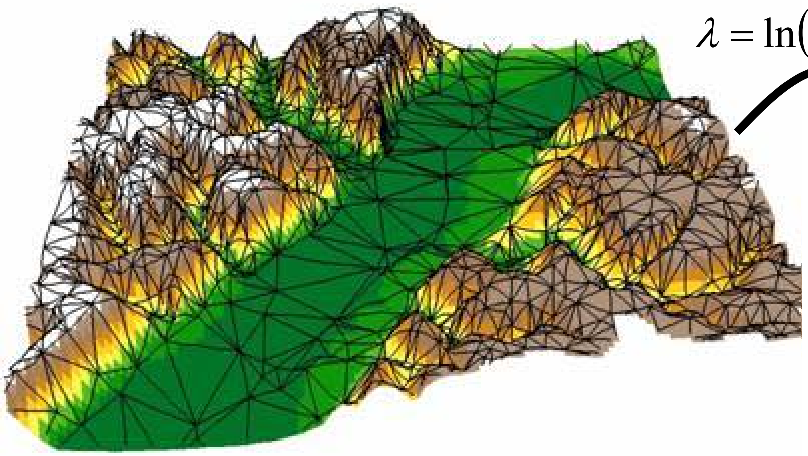
Multiple Resolution Terrain Models

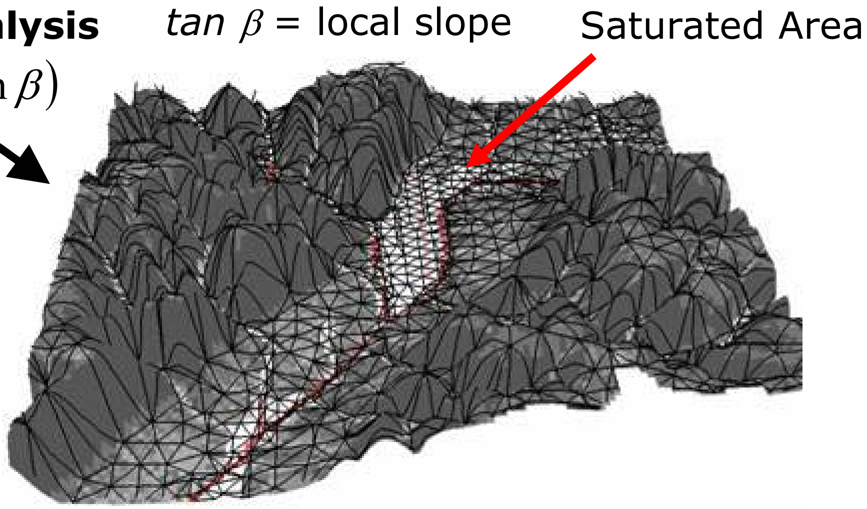
TINs allow adaptive, multi-resolution representations that capture topographic or hydrologic variability over many scales and nestings.

Terrain Analysis

$$\lambda = \ln(a/\tan\beta)$$

a = upslope area
tan β = local slope





<u>Traditional TIN Models</u>
Topographic Slope Criteria

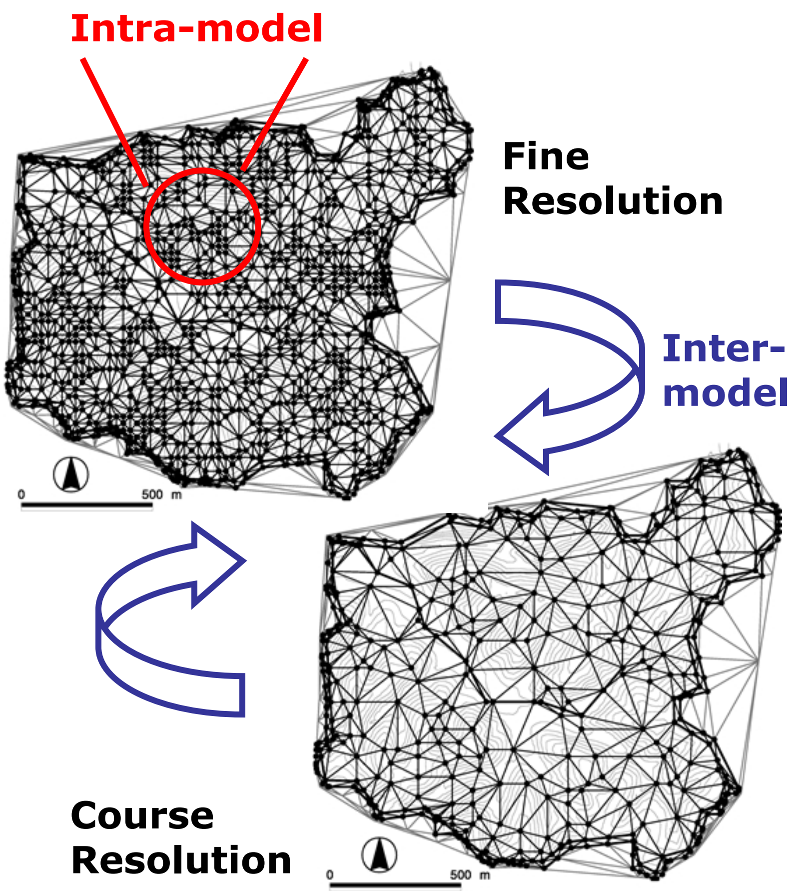
- Multiple resolution using slope variability
- Low-resolution in flat floodplains
- High-resolution in rugged hillslopes

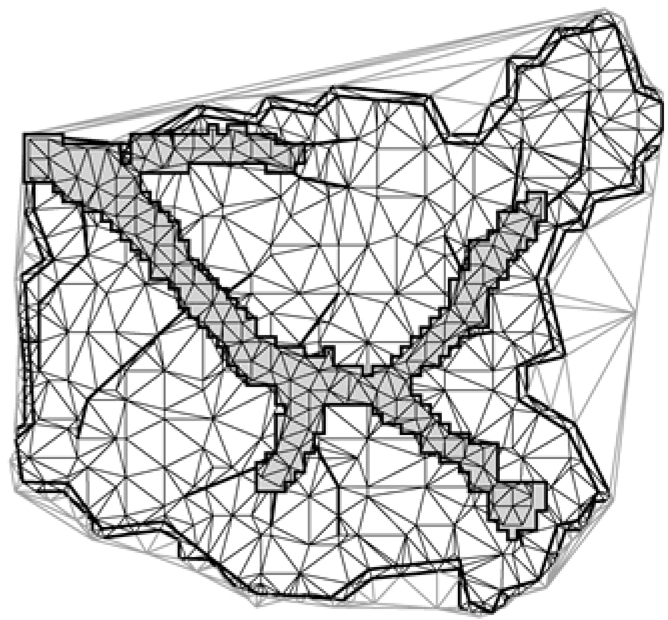
<u>Similarity TIN Models</u>
Hydrologic Index Criteria

- Multiple resolution using hydrologic variability
- High-resolution in saturated floodplains
- Low-resolution in dry hillslopes

Multiple Resolution Terrain Models

Both intramodel and intermodel resolution variability allows for flexible design of model domain. Nesting of variable resolution domains.



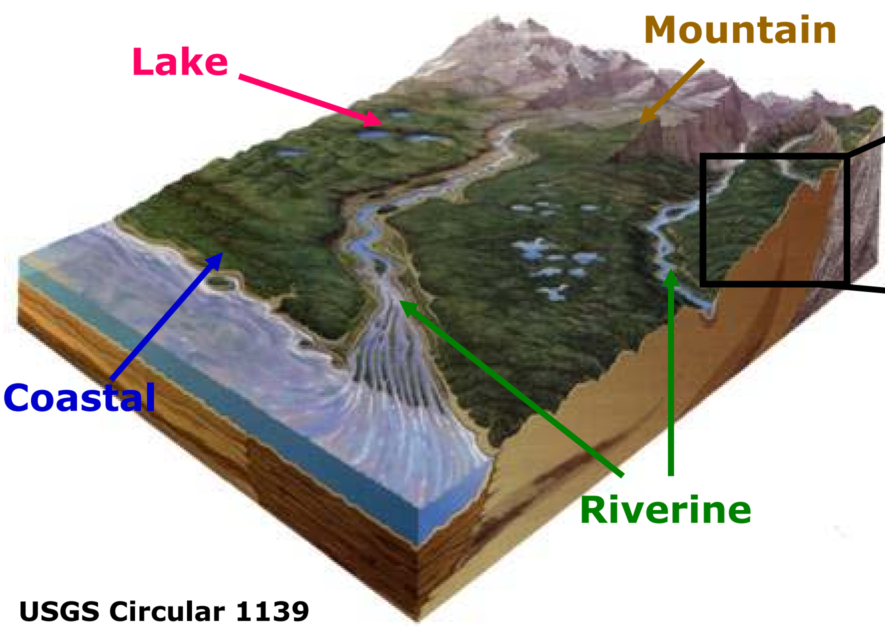


<u>Multiscale Domain Nesting</u>

- Nesting of high-resolution interior basins.
- Nesting of floodplain regions.
- Multiple nested basins at different resolution.

Hydrological Processes

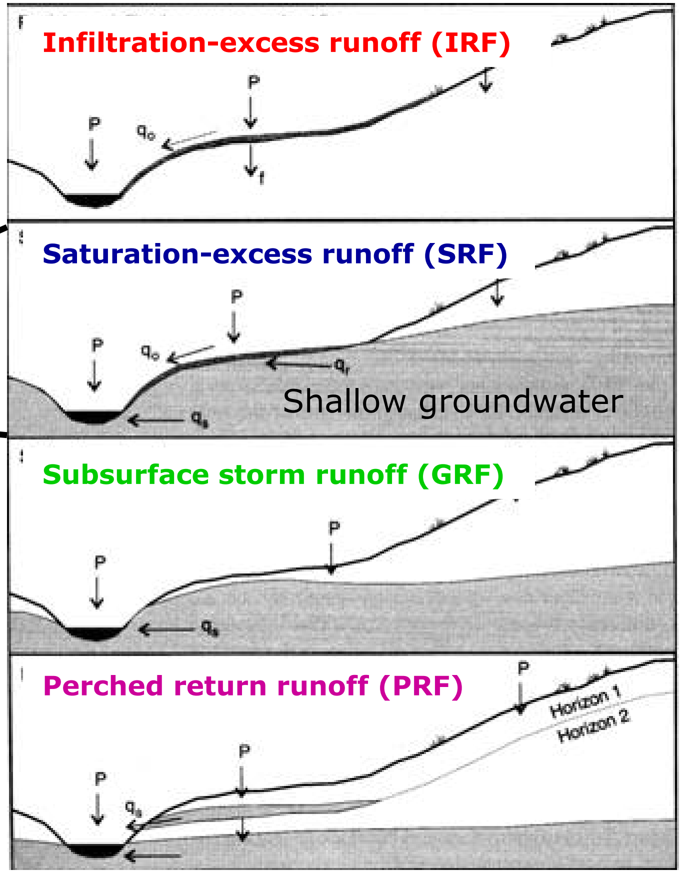
Rainfall-Runoff Transformation



USGS Circular 1139

Surface-Groundwater Interactions in different Landscapes and Scales

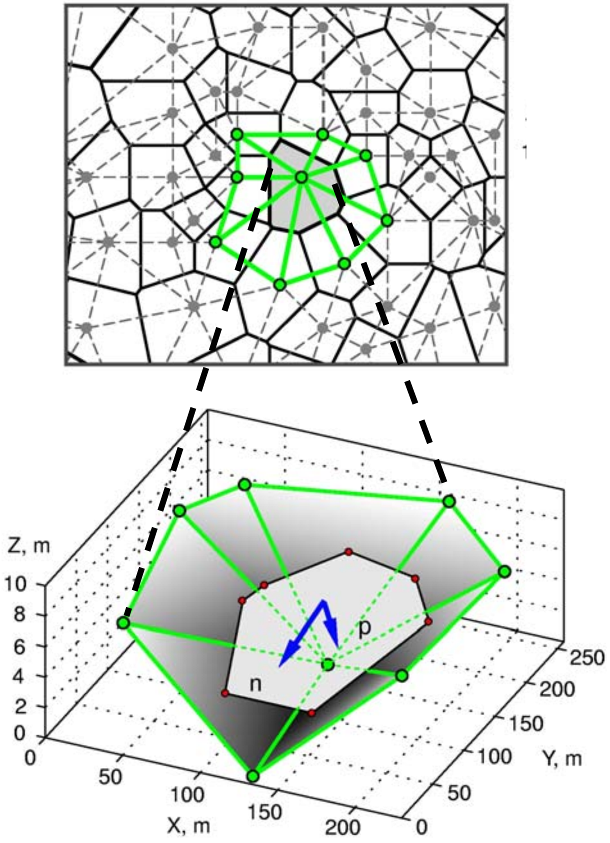
Hillslope runoff processes



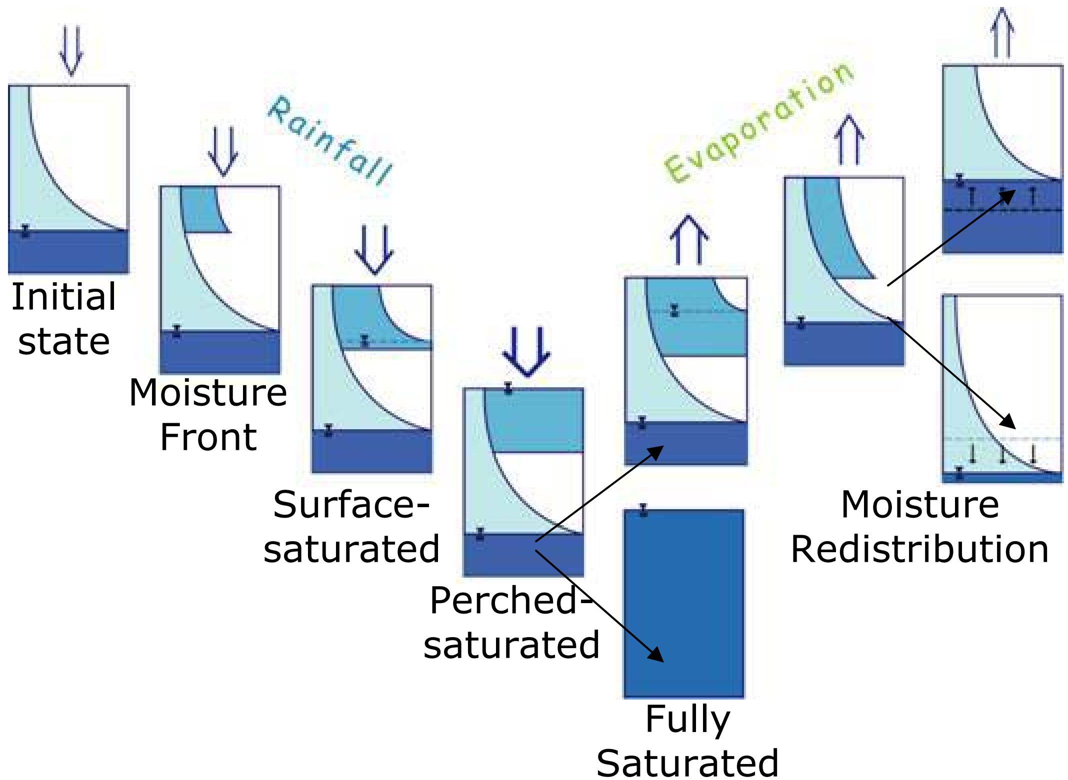
Beven (2001) Rainfall-Runoff Modeling

Hydrological Processes

Voronoi Polygon Network



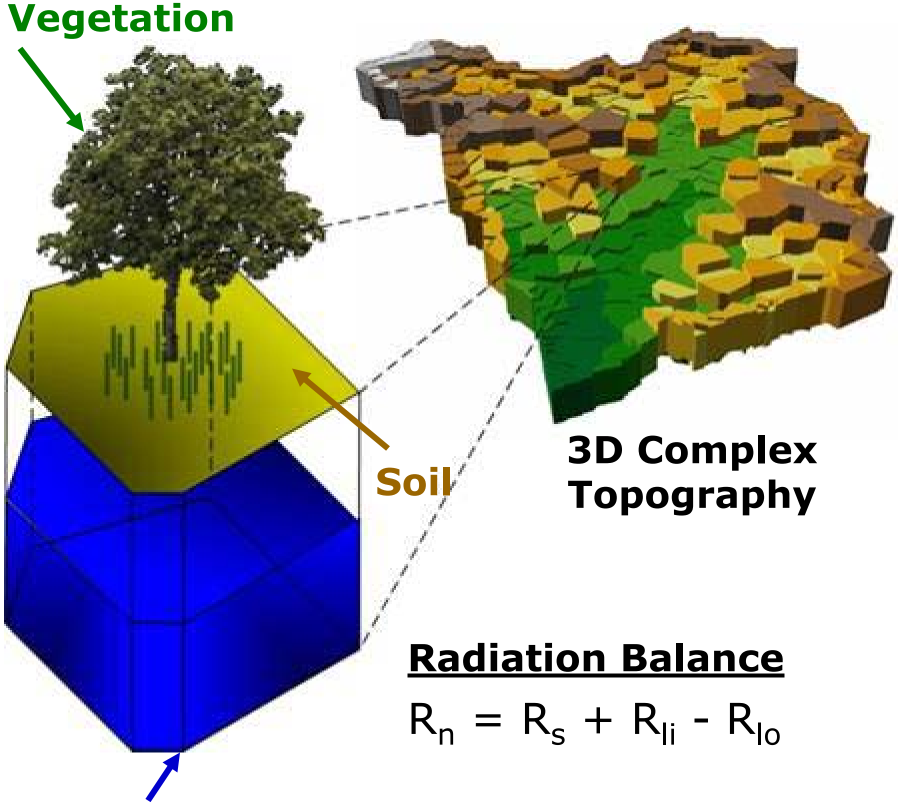
Voronoi Node Wetting and Drying Cycles



Coupled Unsaturated-Saturated Dynamics in Response to Rainfall and Evapotranspiration

Hydrological Processes

Atmosphere-Land-Aquifer Interactions



Radiation Balance

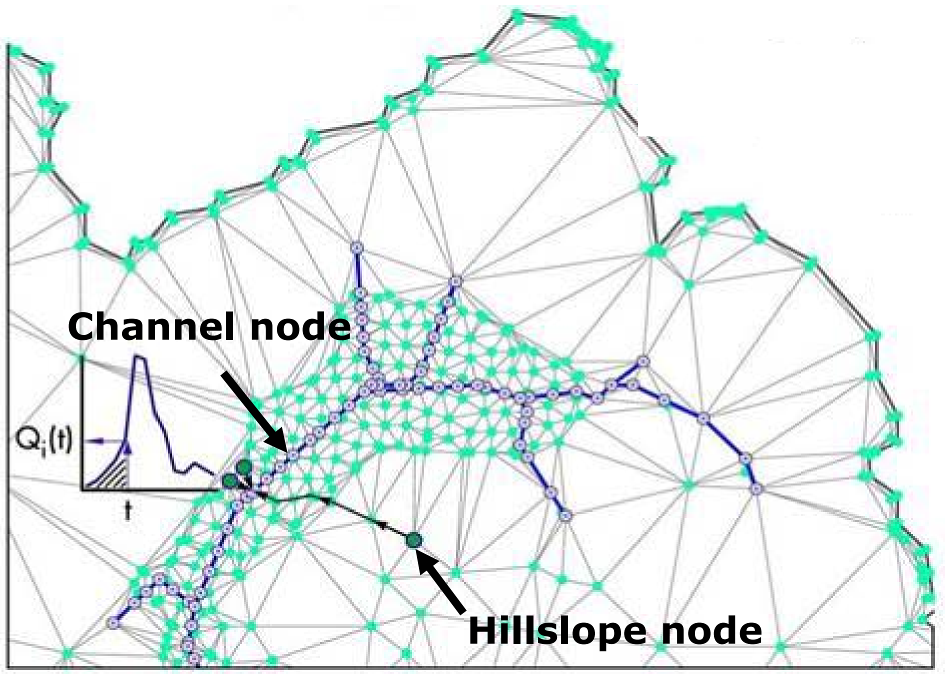
$$R_n = R_s + R_{li} - R_{lo}$$

Coupled Energy and Hydrology Processes on Complex Terrain

- **Radiation:** Incoming short-wave and long-wave, outgoing long-wave radiation including effects of terrain.
- **Vegetation:** Canopy interception, drainage, throughfall and evaporation using vegetation functional type.
- **Energy Balance:** Net radiation, ground heat, sensible heat and latent heat fluxes.
- **Evapotranspiration:** Soil-moisture controlled bare soil evaporation and canopy transpiration in root zone.

Hydrological Processes

Hydrologic routing on hillslopes is tied to channel node discharge where a 1-D FEM hydraulic channel routing scheme is implemented.

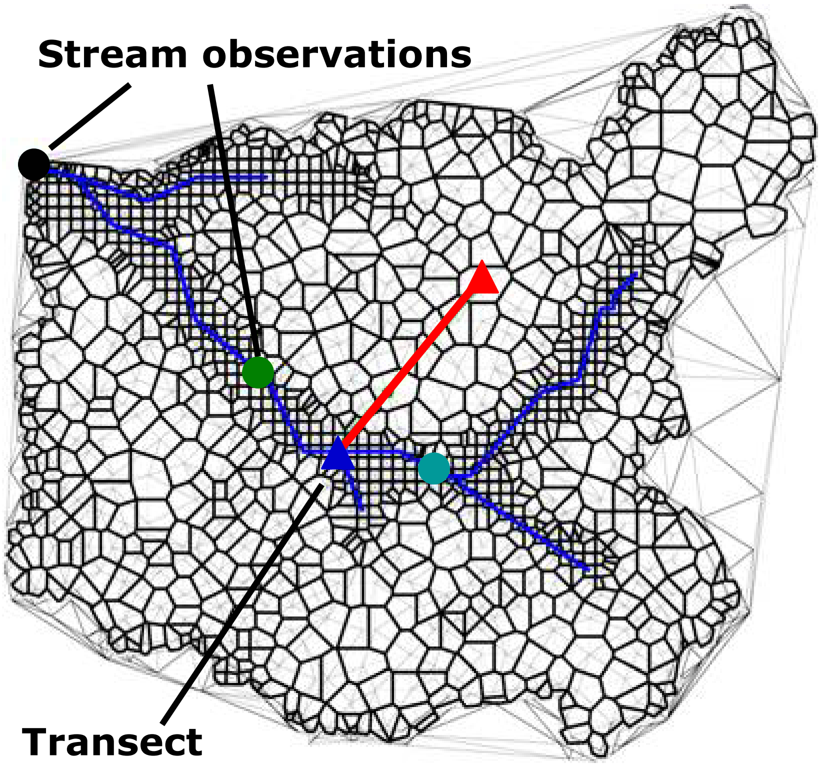


Stream and River Processes

- Stream channel definition within TIN model based on available hydrography
- One-dimensional TIN-based hillslope routing to nearest stream node.
- Hydrologic river routing of various runoff mechanism.
- Hydraulic routing in main channel.
- River discharge and water depth at multiple interior gauging stations.

Illustrative Example: Model Geometry

Multiple-resolution voronoi polygon network, stream reaches, channel flow observations and transect.



Computational Domain

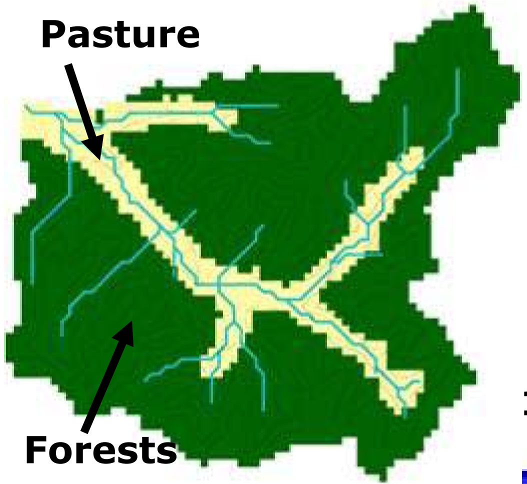
- 1370 nodes and voronoi polygons ranging in size from 30 to 12700 m^2.
- Multiple interior gauging stations along the stream reaches.
- Hydrologic observations also made across a hillslope transect.
- High-resolution valley bottom.

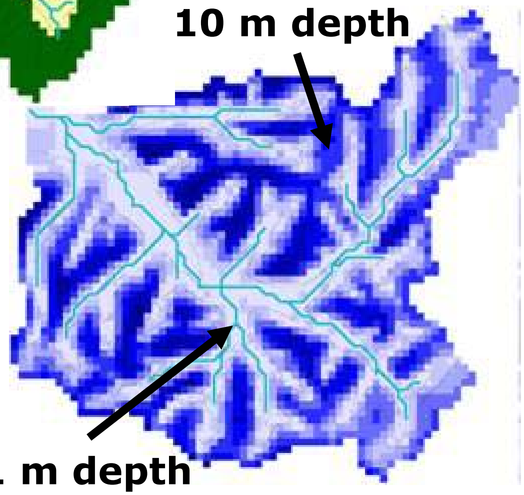
Simulation Characteristics

- Period 11/1998 – 7/2000.
- Radar rainfall and meteorological forcing.

Illustrative Example: Soils, Plants, Water

Model parameterizations and initialization conditions based on available land-surface descriptors and streamflow observations.





Parameterizations

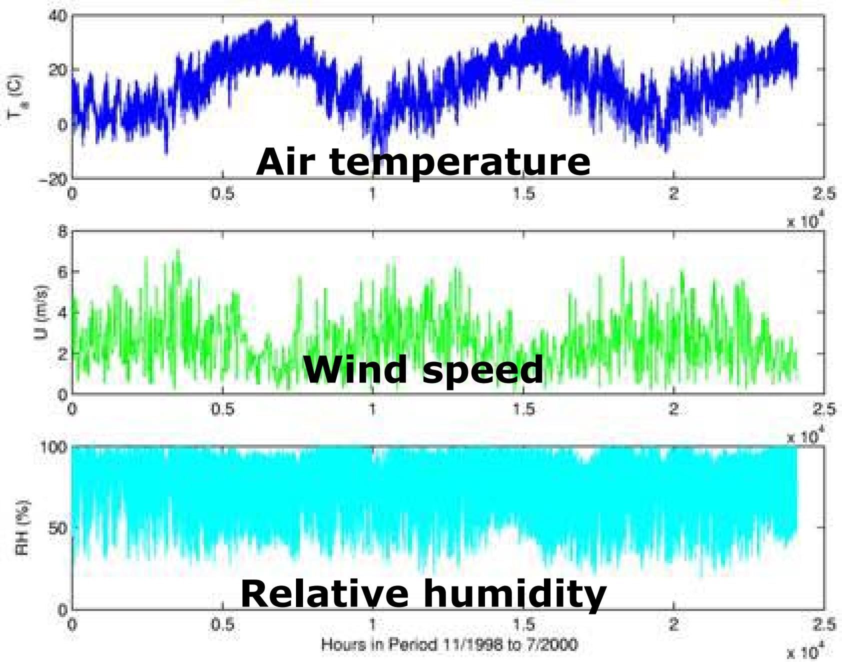
- Soil hydraulic and thermal properties.
- Canopy biophysical, geometric and optical properties.

Initialization

- Initial groundwater based on TOPMODEL method and observed baseflow.
- Water table position fixes initial soil moisture profile.

Illustrative Example: Hydrometeorology Data

One-way coupling to atmospheric forcing drives the soil surface and canopy water and energy balance components.



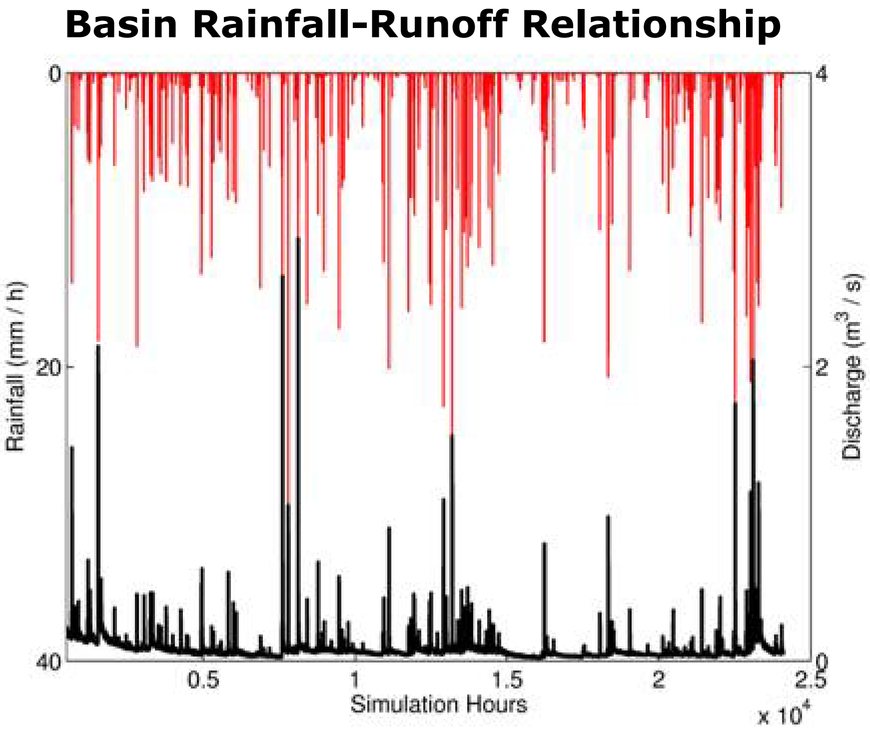
Hours in Period 11/1998 – 7/2000

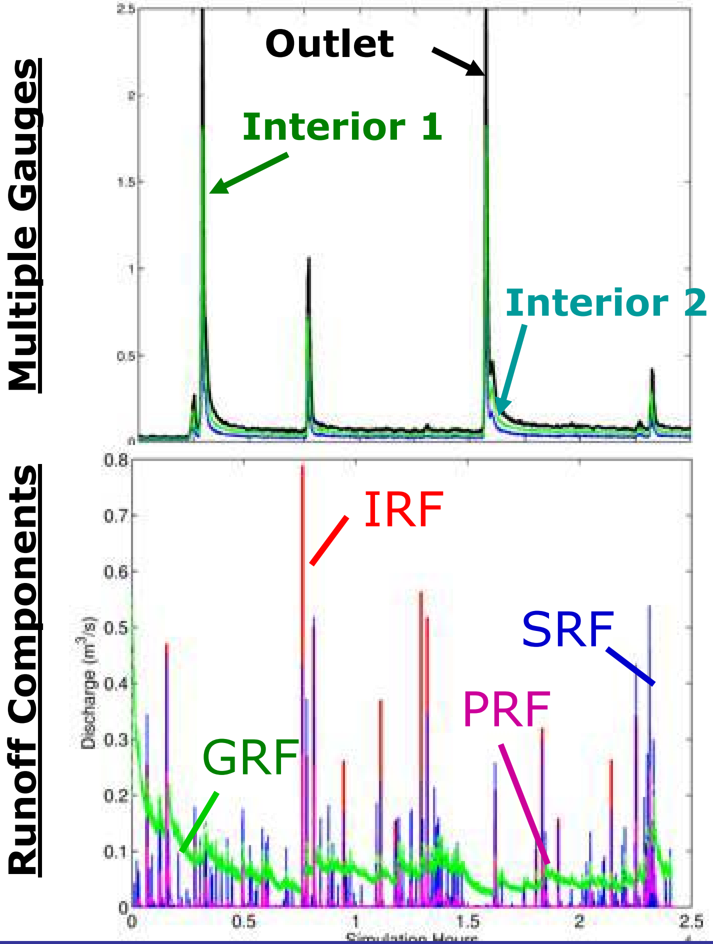
Hydrometeorological Forcing

- Radar rainfall data from **NEXRAD** (4km and 1-hr resolution)
- Weather station data providing hourly values at a point:
  - Air temperature
  - Dew point
  - Wind speed
  - Sky cover
  - Atmospheric Pressure

Illustrative Example: Multiple-gauge Flow

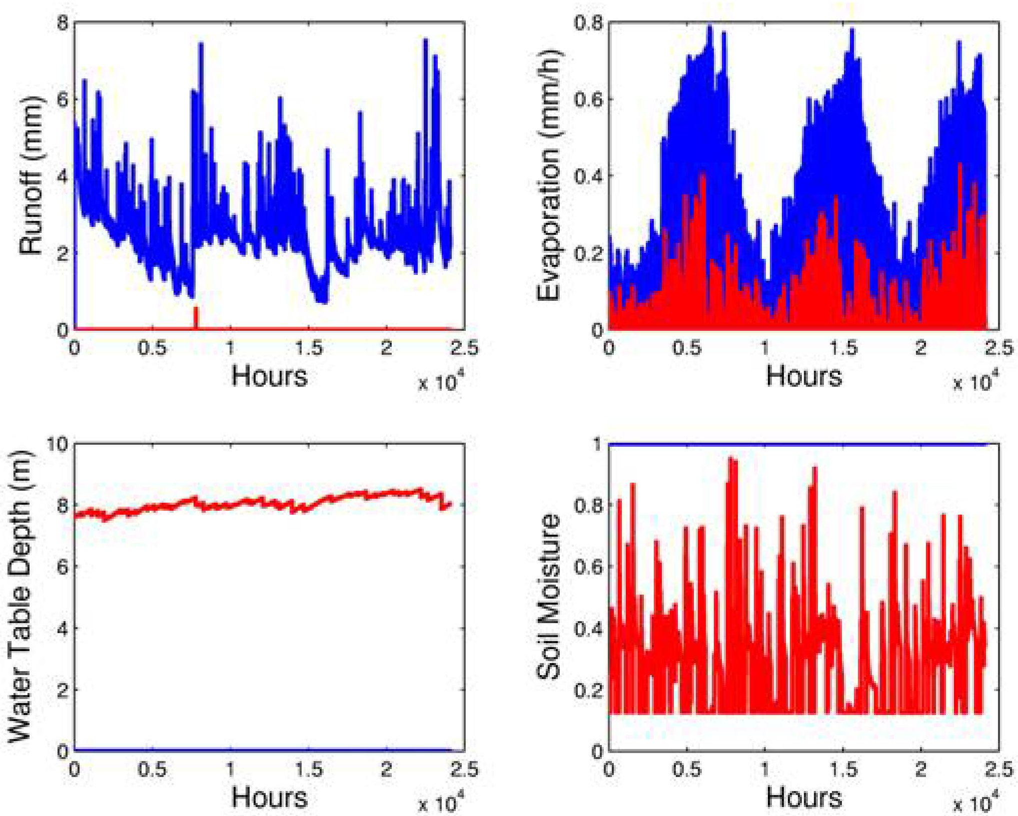
Hydraulic channel routing permits discharge and depth predictions in all interior basins draining to network.





Illustrative Example: Hillslope Transect

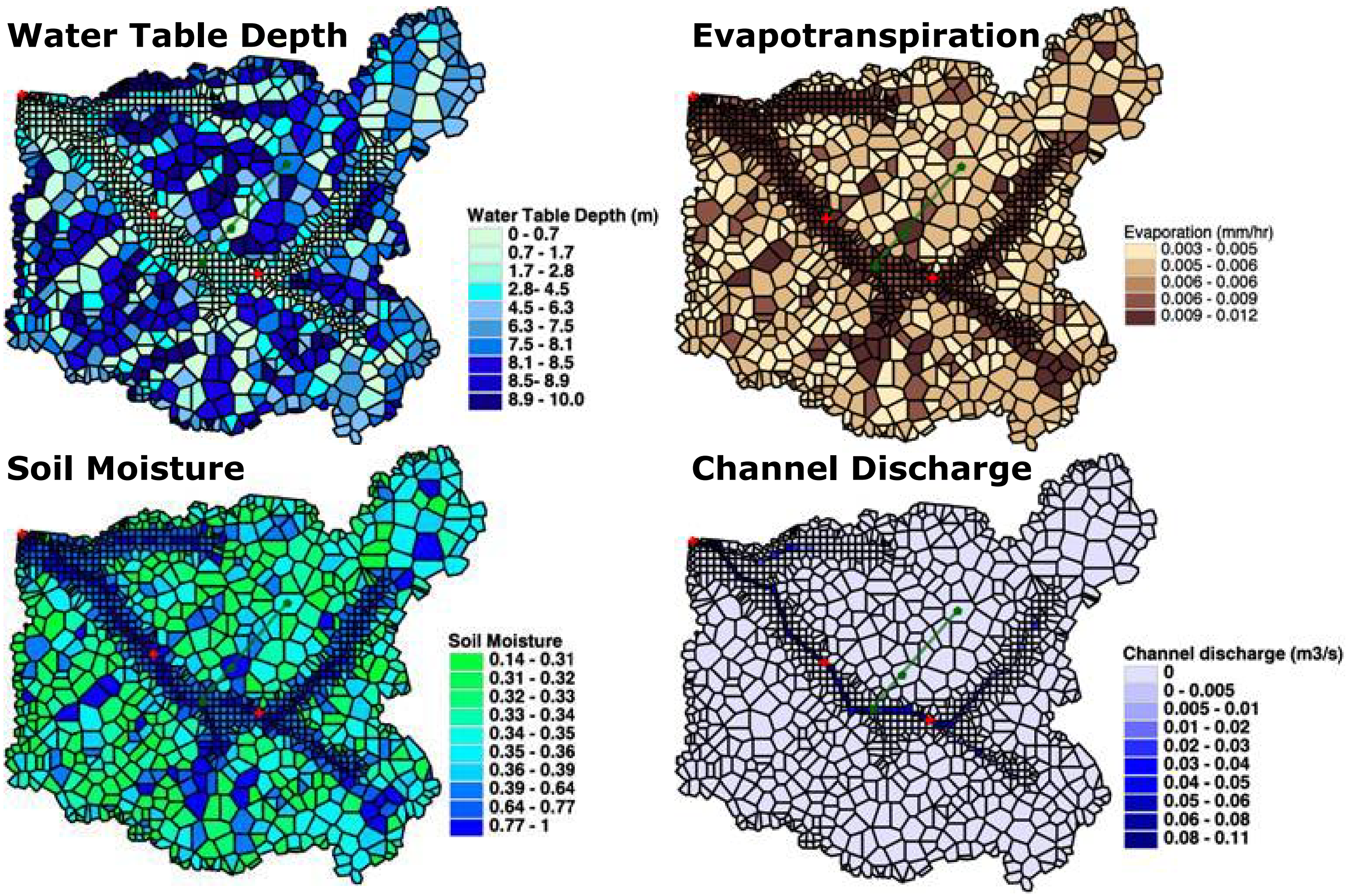
Variation in hydrologic response is evident across the hillslope transect. Blue = hillslope bottom; Red = hillslope summit.



Hillslope response

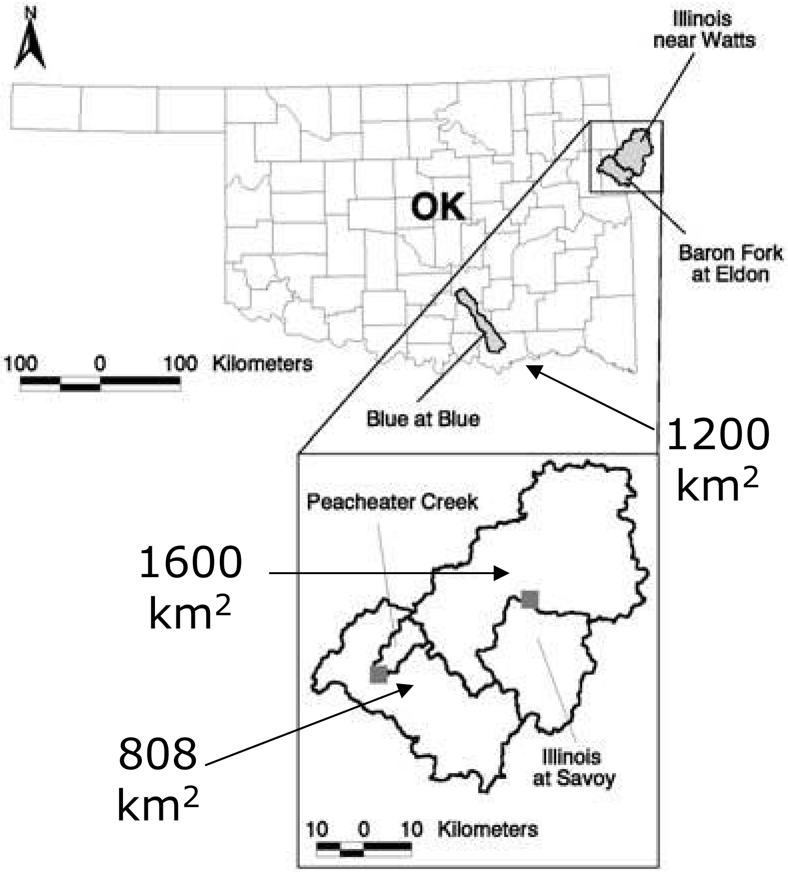
- Greater runoff production in convergent hillslope bottom.
- Soil moisture remains in fully saturated condition for bottom.
- Water table at the surface for hillslope bottom.
- Greater moisture leads to higher evapotranspiration in riparian valley.

Illustrative Example: Spatial Patterns



Distributed Model Applications

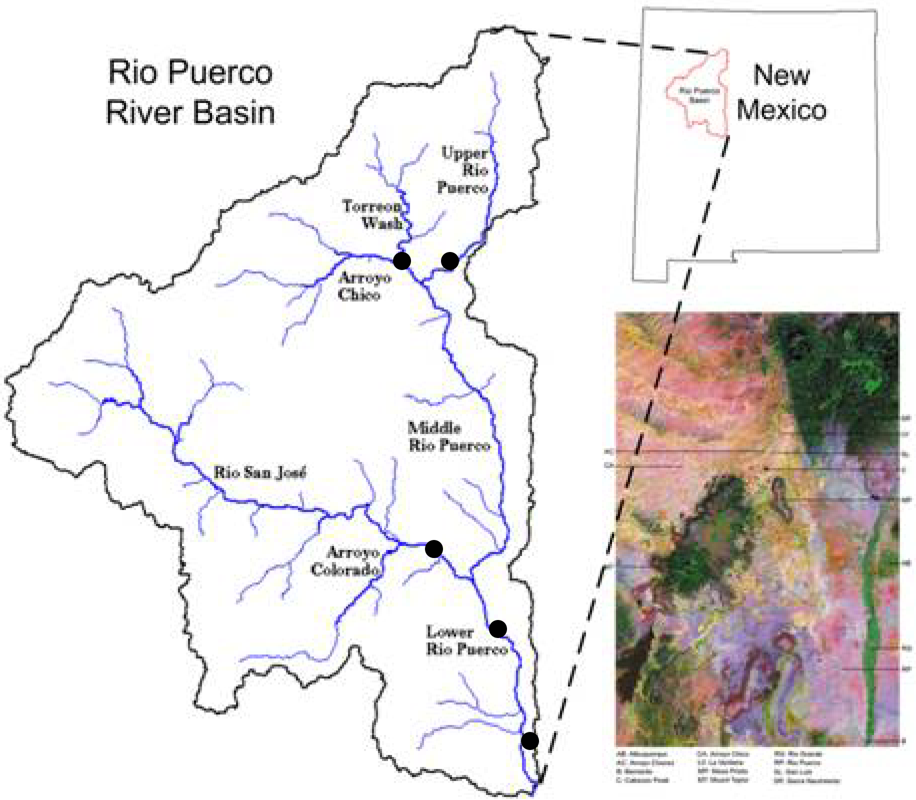
Multi-year simulations in operational-scale NWS basins with multiple gauging stations carried out using tRIBS over 1993-2000.



Multi-year Flood Simulation

- Comparisons to lumped and semi-distributed models through NWS Distributed Model Intercomparison Project (DMIP, 2001-2002)
- Demonstrated clear feasibility of fully-distributed TIN approach for large regional watersheds.
- Improved performance for cases with no model calibration permitted as compared to lumped model.

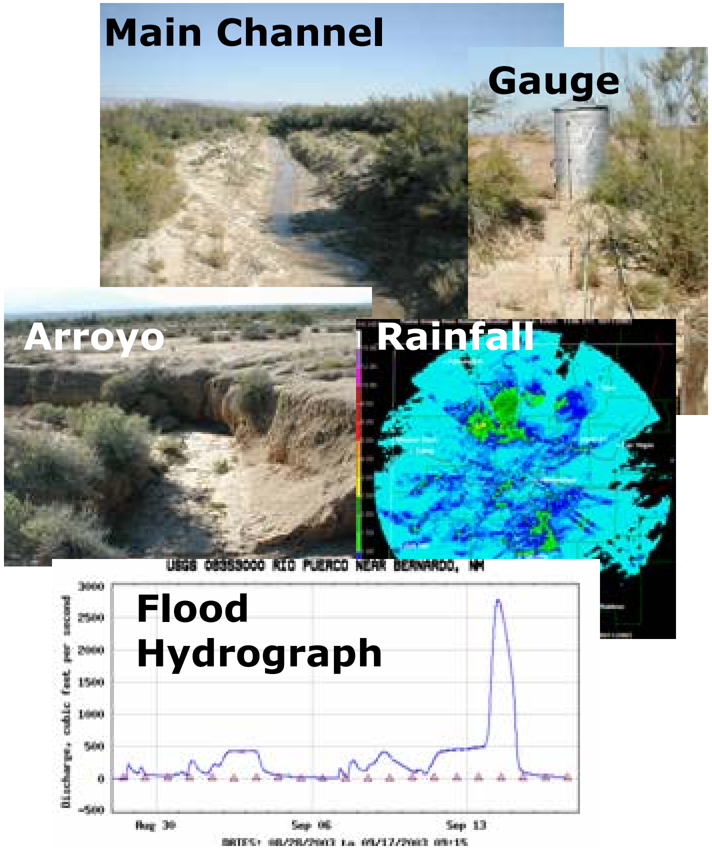
A Semi-Arid Real and Virtual Observatory



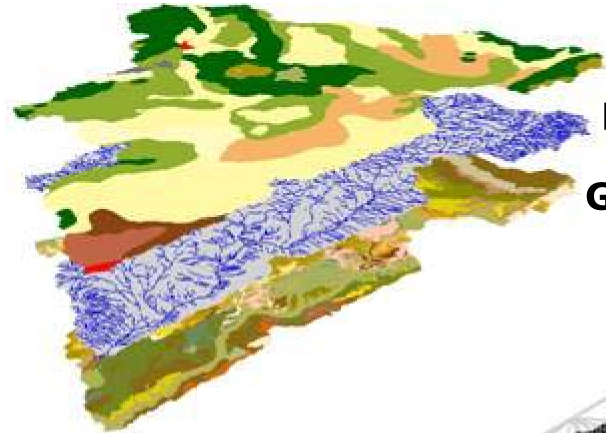
Rio Puerco River Basin

- Relatively unregulated flow in large regional watershed (16,000 km^2).
- Hydrologic and geomorphic research relating to arroyos and gullies and hyperconcentrated flow.
- Important subbasin for Rio Grande with confluence in Sevilleta LTER.
- Complex topography and geology.
- Summer monsoon thunderstorms leading to flood events.
- Sensitive to climate, land-use change.
- EPA Watershed Initiative Basin.
- USGS Global Change Research Basin.

A Semi-Arid Real and Virtual Observatory

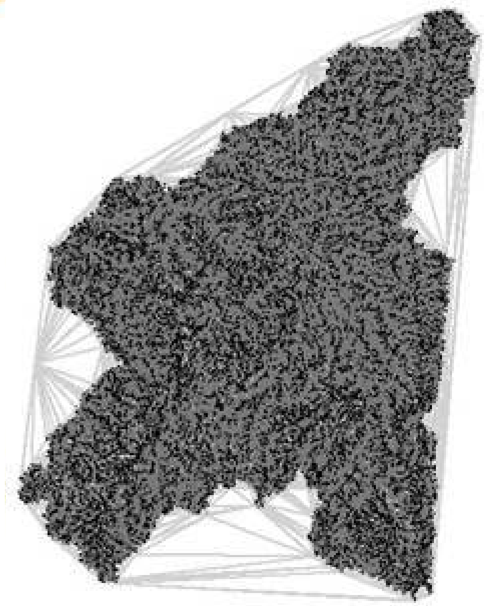


Field and Remote Sensing Data in Real Observatory



GIS Data Layers

DEM ($24x10^6$ cells) and Multiple-resolution TIN (10^6 cells)



Distributed Modeling in Virtual Hydrologic Observatory

Concluding Remarks

Real and Virtual Hydrologic Observatories

- Advance hydrologic science through combined field data collection, remote sensing and modeling.
- Interface with other disciplines (geomorphology, ecology, geophysics, atmospheric sciences).

Multiple resolution Distributed Modeling

- Provide flexible model representation for large-scale watersheds.
- Allow resolution to vary with topography or hydrology and within nested basin scales.
- Provides basis for high-performance computing initiatives in hydrology.

For more information, visit http://www.ees.nmt.edu/vivoni

Questions?