Forecasting the Role of Groundwater in Nutrient Transport across the Chesapeake Bay Watershed

Kathy Boomer
The Nature Conservancy
Smithsonian Environmental Research Center

Acknowledgements: Judy Denver and Ward Sanford (USGS), Gopal Bhatt and Chris Duffy (Penn State), Yong Li (Chinese Academy of Sciences), Huan Meng (NOAA), Gary Shenk (CBP), and Todd Walter (Cornell)

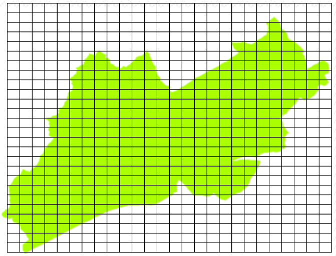
Cleaning up the Chesapeake Bay – Management Needs:

- **Estimate nutrient source-sink transport times**

  (e.g., lag time between fertilizer application or BMP implementation to influence surface water quality)

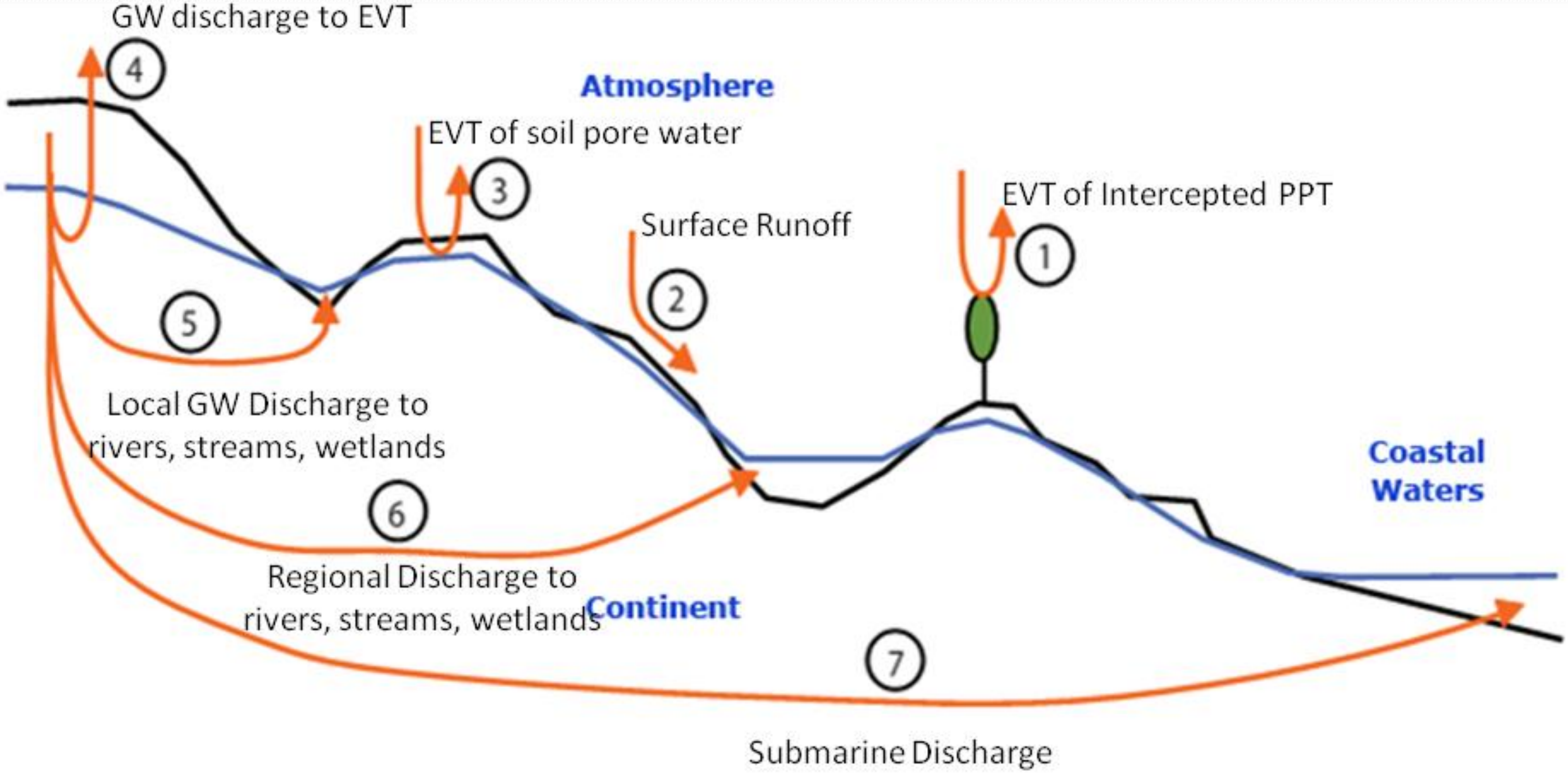
- **Guide BMP implementations**
  - **Identify optimal BMPs**
  - **Estimate BMP requirements**
  - **Prioritize BMP locations**

Modeling Nutrient Transport in Groundwater
Current Forecasting Tools



- Lumped-parameter models
  - CBP Hydrologic Simulation Program – Fortran 5.3 (CBP5)
  - Soil Water Assessment Tool (SWAT)
  - General Watershed Loading Function
- Numeric Models
  - ModFlow
  - Penn State Integrated Hydrologic Modeling System
- Combination Lumped/Numeric Models
  - GS Flow

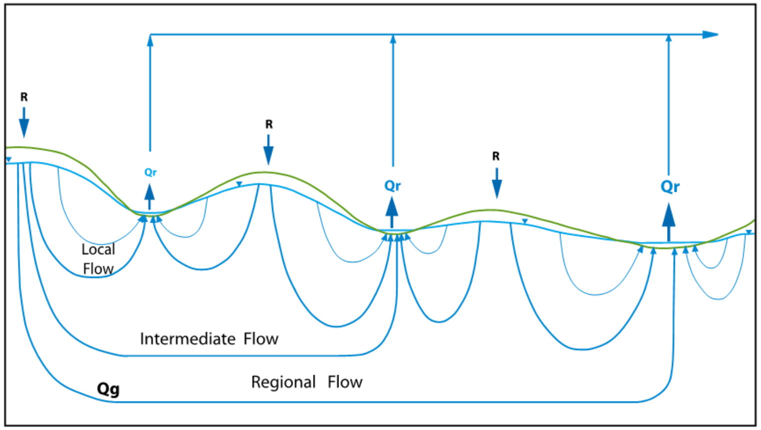
Conceptual Framework: Surface and Ground-Water Hydrology



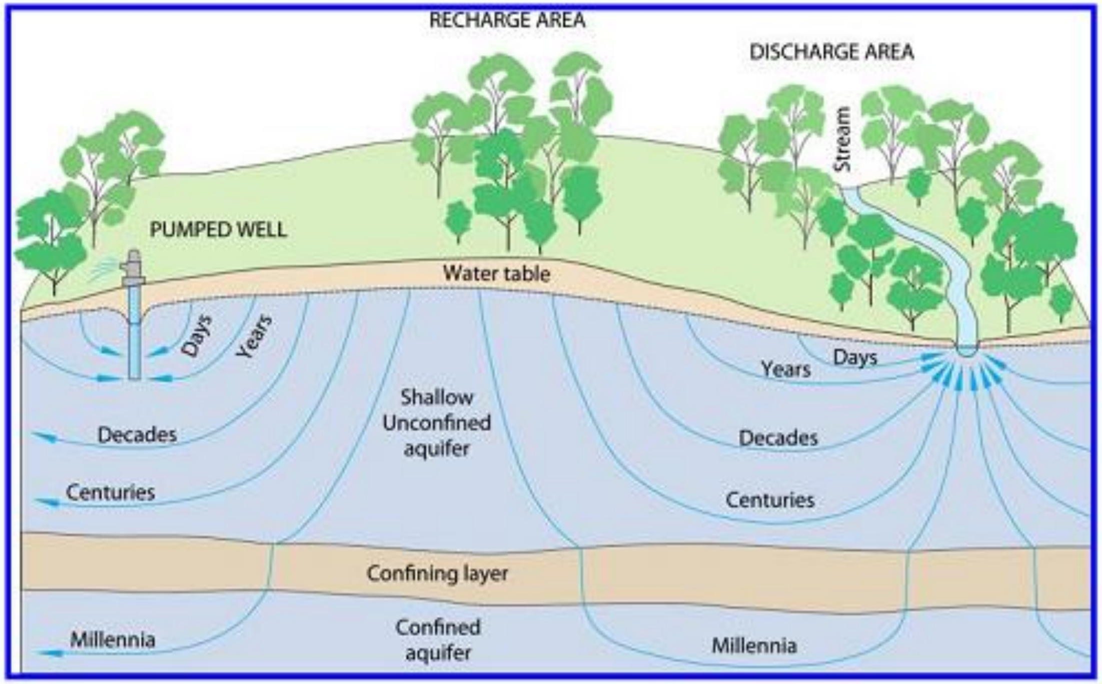
Modified from Schaller and Fan 2009

Conceptual Framework

Conceptual Framework: Surface and Ground-Water Hydrology



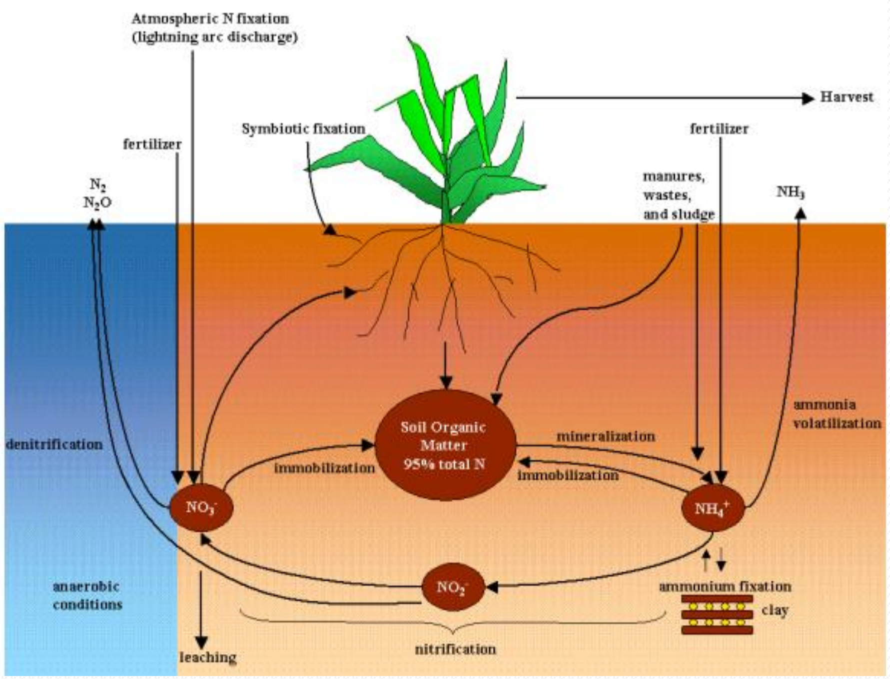
Schaller and Fan 2009
modified from Toth 1963



Pucket et al 2011

Conceptual Framework: Nutrient Dynamics

Nitrogen Dynamics



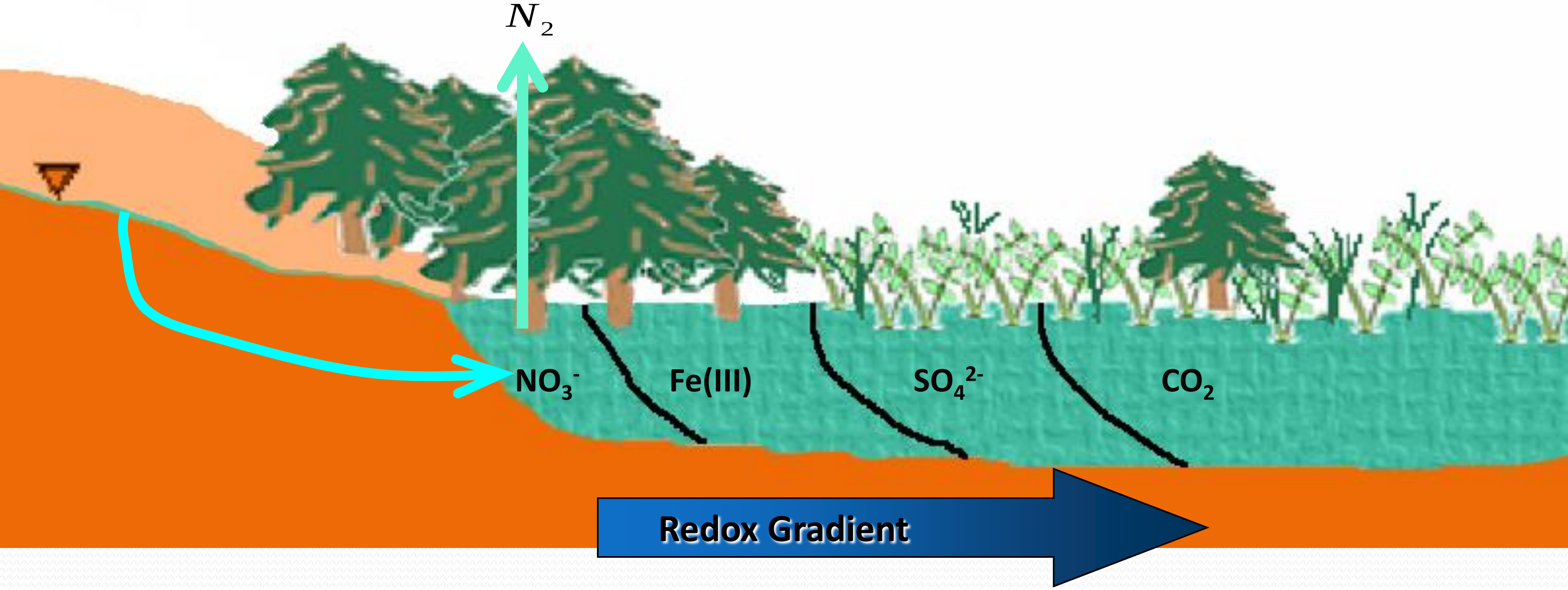
Neitsch et al 2002

Factors potentially affecting stream nitrate :

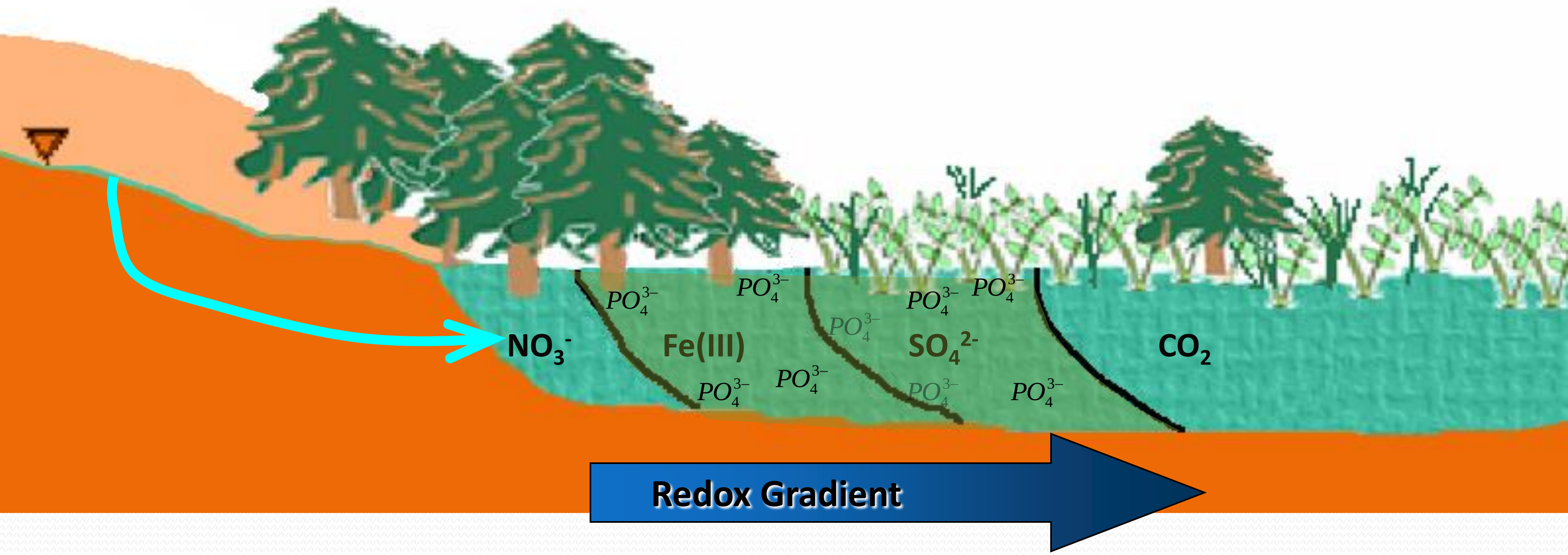
- Fertilizer and manure application (cropland area)
  - Spatial distribution of croplands and livestock
- **Age distribution of baseflow**
  - Date/Year of sample collection
- Depth to water table
- **Denitrification Potential**
  - **Wetlands**
  - **Subsurface**

Sanford and Pope 2009

Conceptual Framework: Nitrogen Transport and Retention

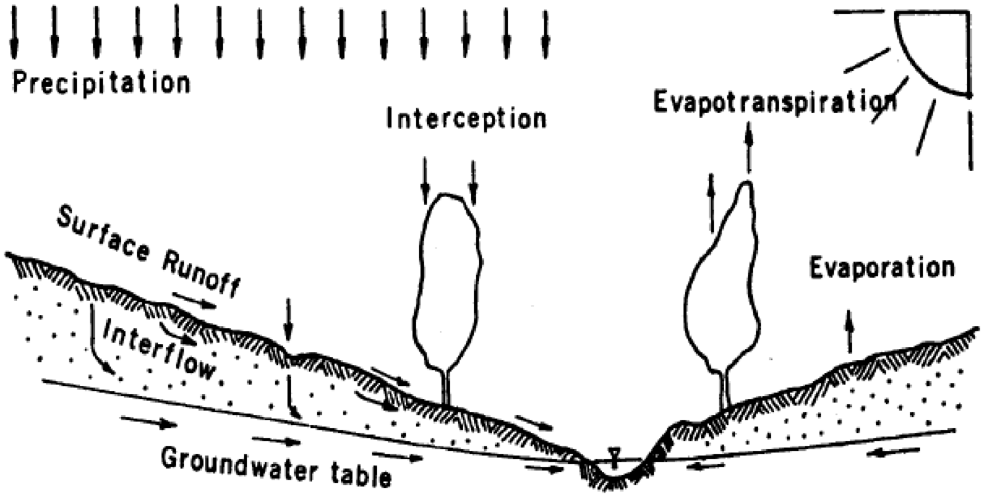


Conceptual Framework: Phosphorus Transport and Retention



Forecasting Tools

Lumped Parameter Models: CBP5-HSPF

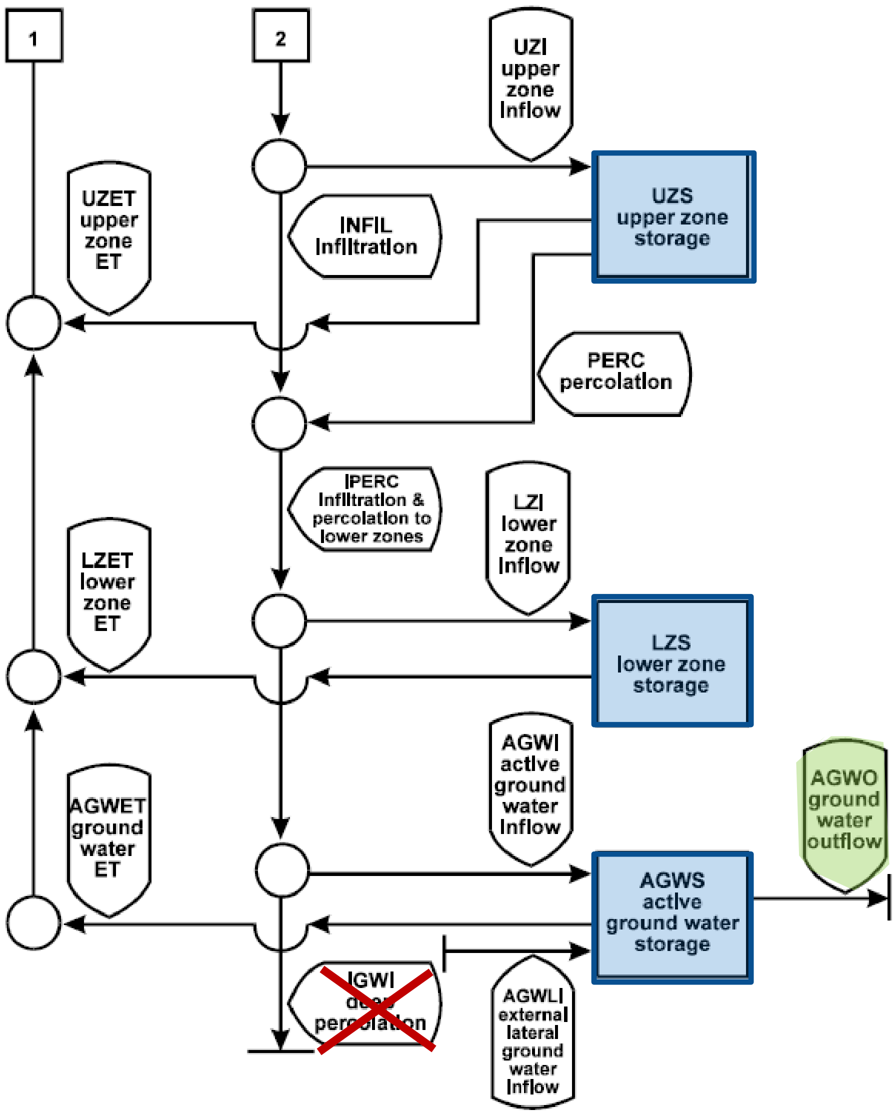


- Surface Runoff
- Interflow
- "Active" ground-water discharge (baseflow)

- No loss to deep groundwater

Modified from Raffensperger 2004

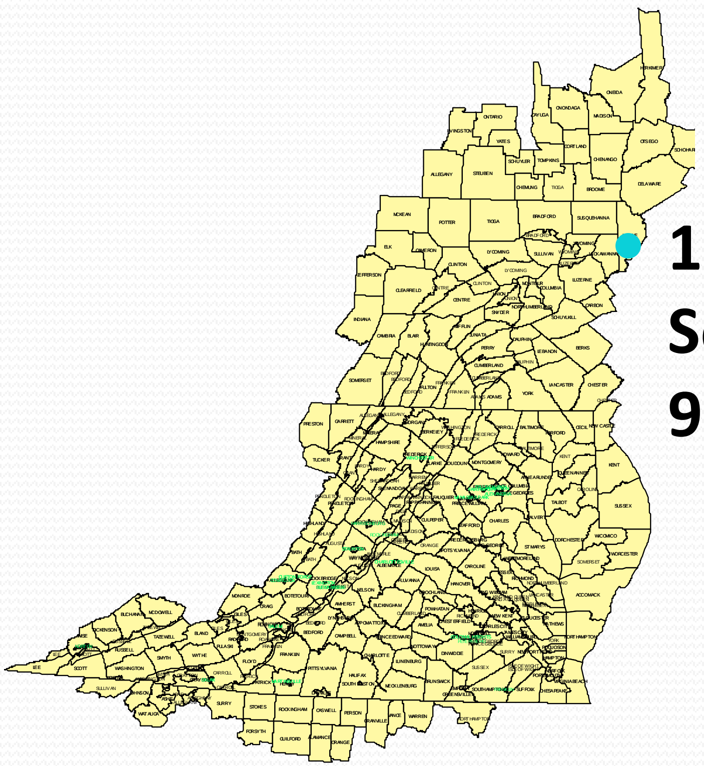
CBP-HSPF Flow Simulation



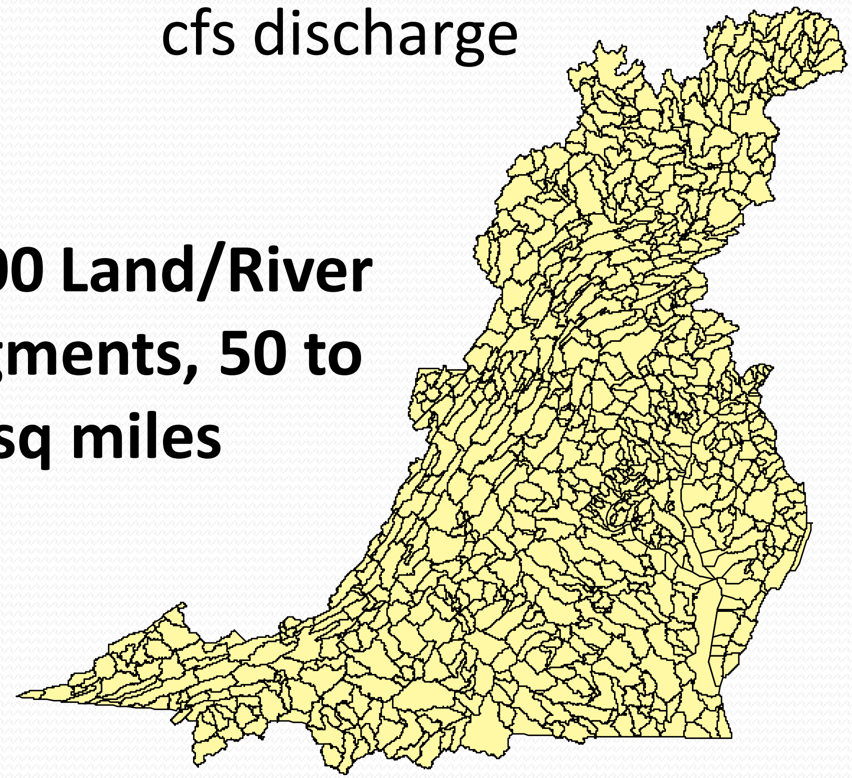
- **Key Calibration Parameters:**
  - EVT coefficient
  - Infiltration rate
  - Soil Moisture Storage Index
  - Interflow:Runoff ratio
  - Interflow recession coefficient
  - EVT from Groundwater

CBP5 Modeling Segmentation:
Combination of Land & River Segments

- County-based Land Segments

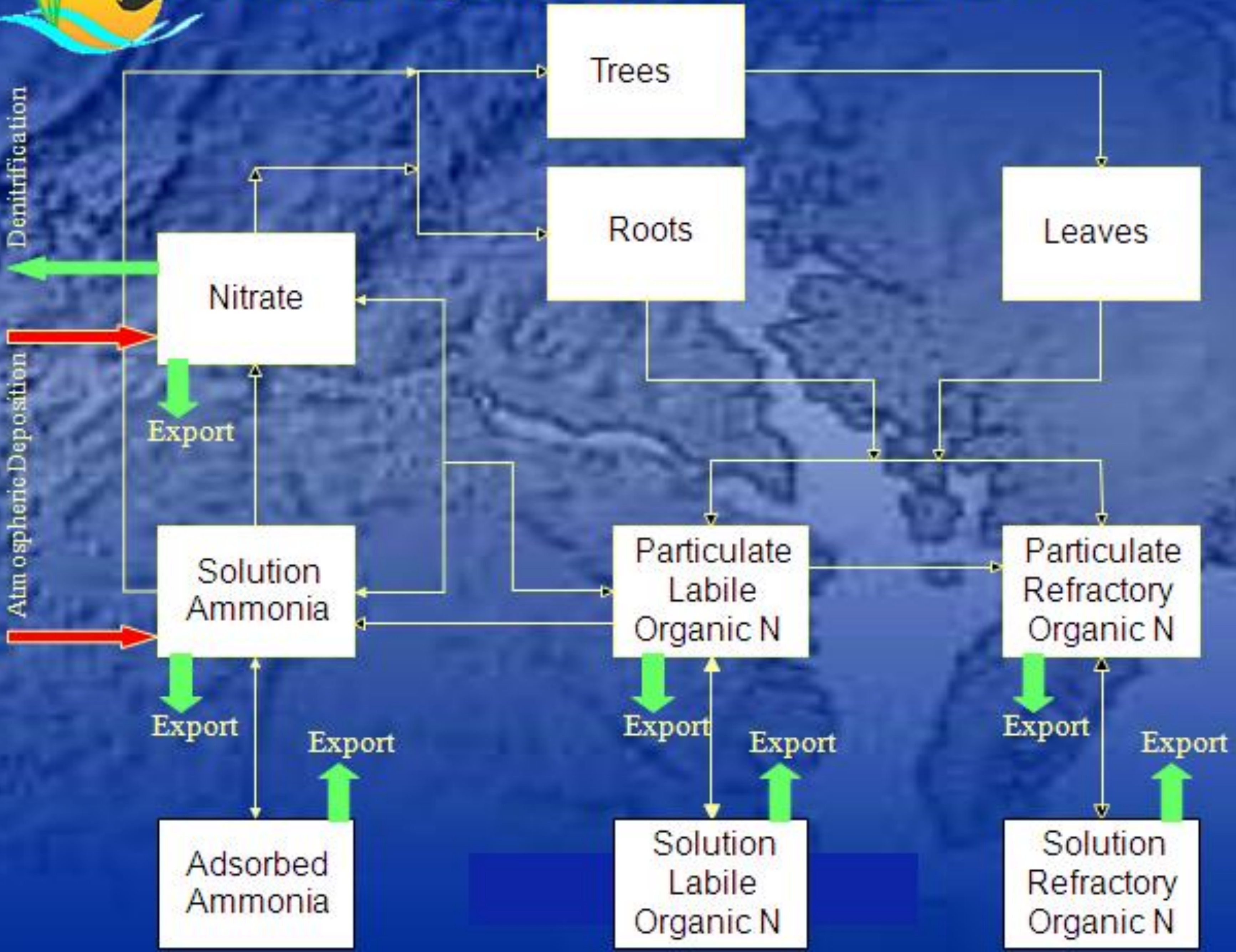


- Gauged River Segments and/or greater than 100 cfs discharge

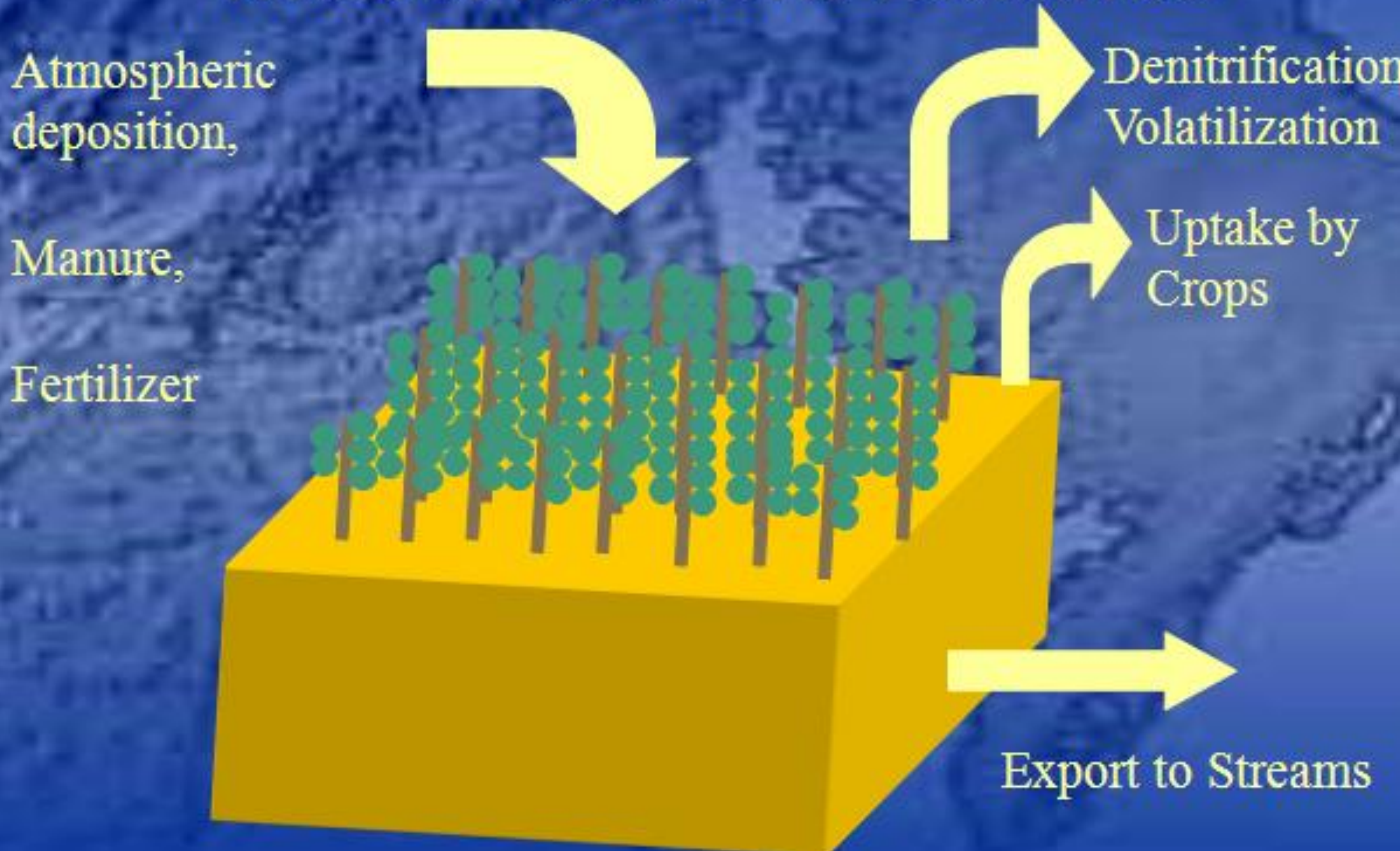


- **1000 Land/River Segments, 50 to 90 sq miles**

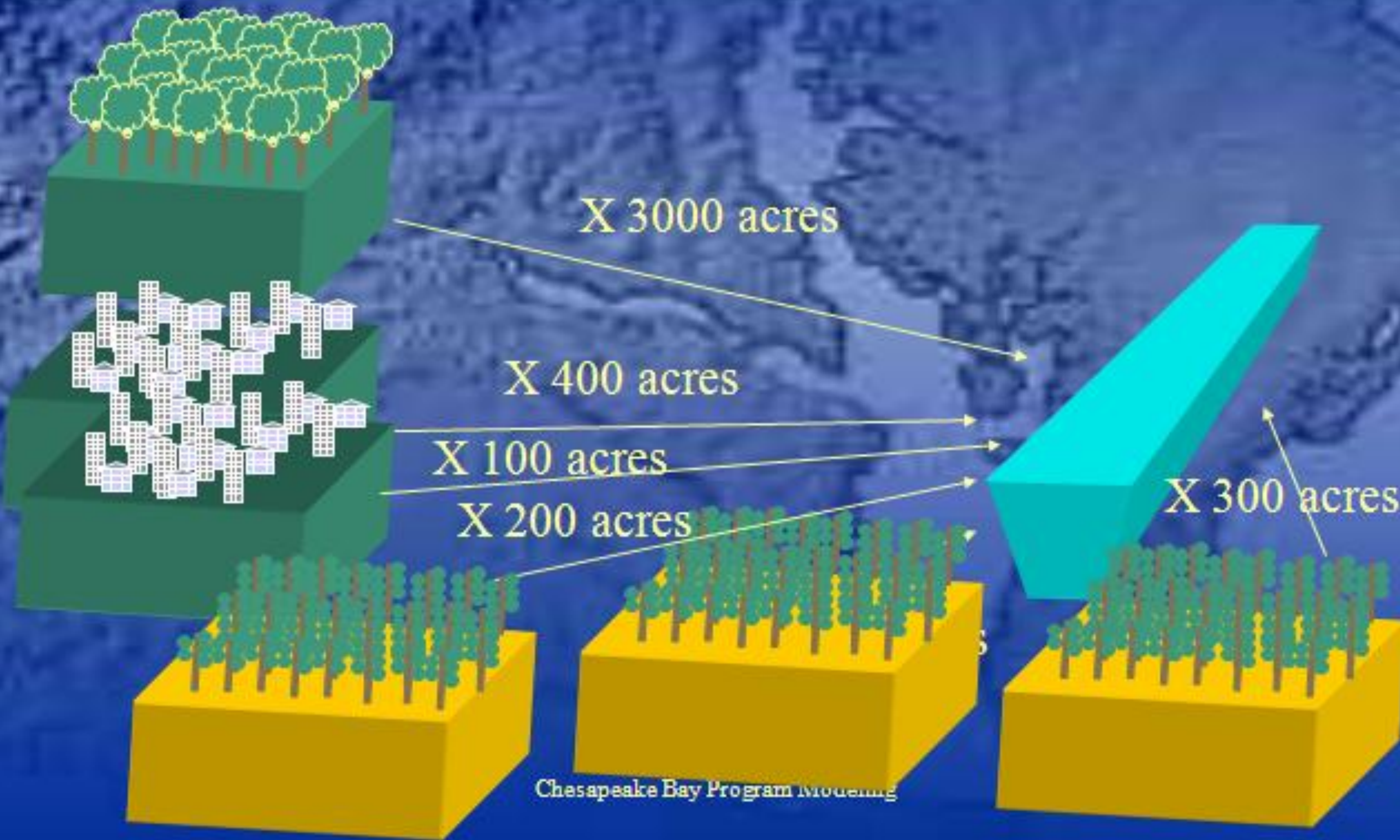
Nitrogen Cycle in Watershed Model Forest



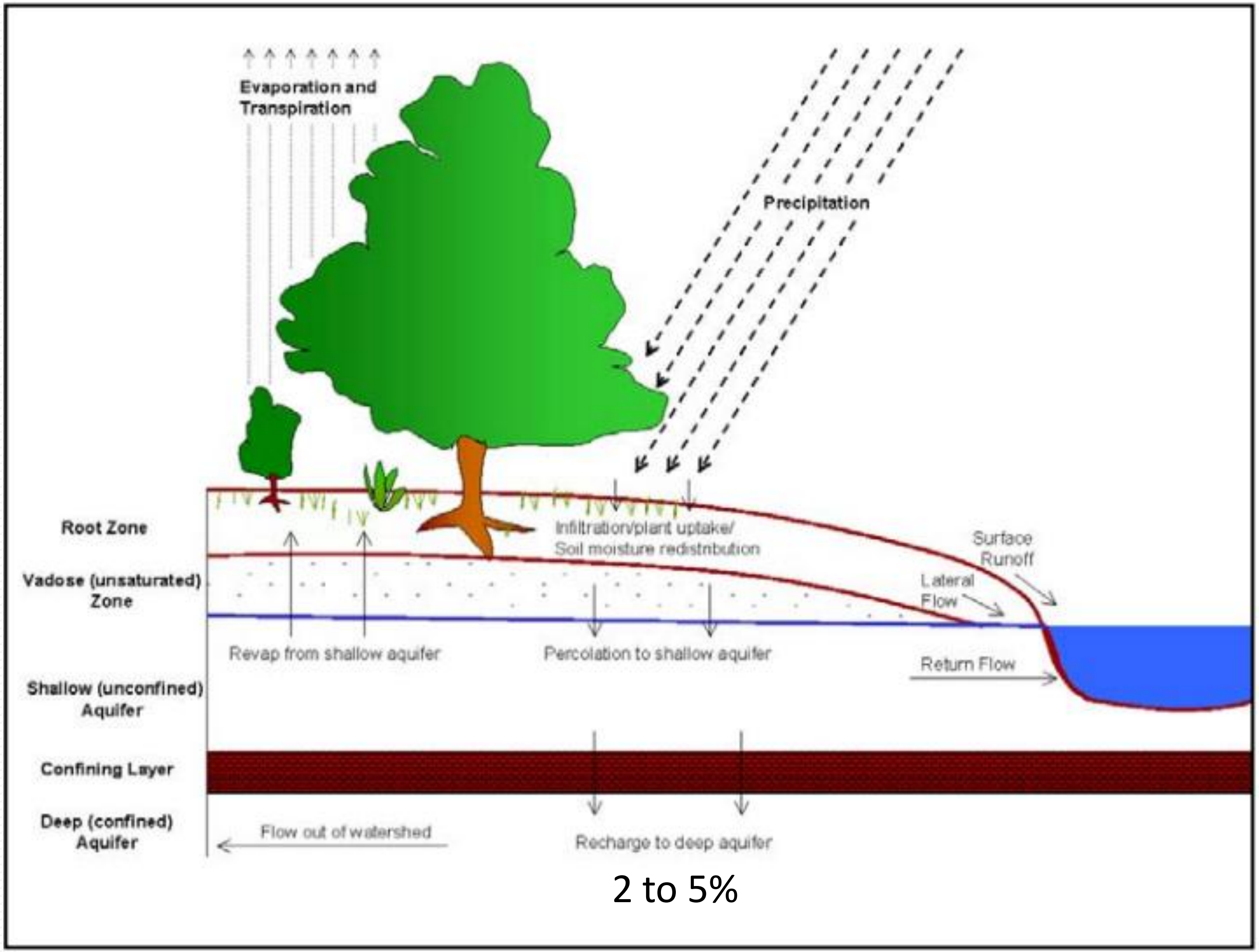
Model Nutrient Balance



Land-Water Connection

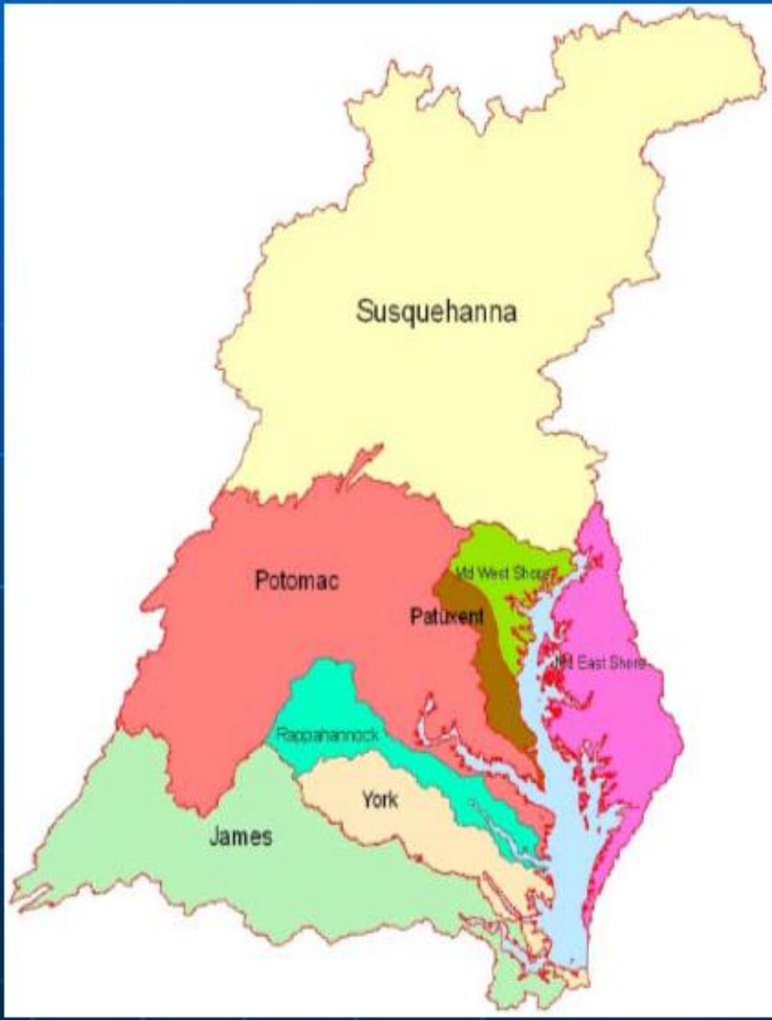


Lumped Parameter Models: SWAT



SWAT for CB Watershed

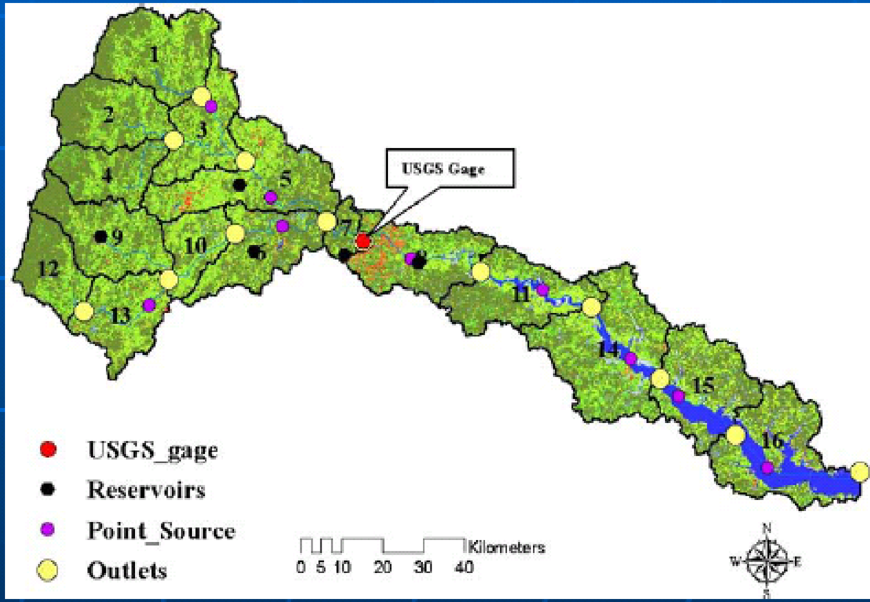
- CB watershed: six major river basins & MD shores
- An independent SWAT model for each major river basin and some secondary river basins on the MD shores
- Pilot river basin: Rappahannock River basin



Meng et al 2009

Model Configuration (2)

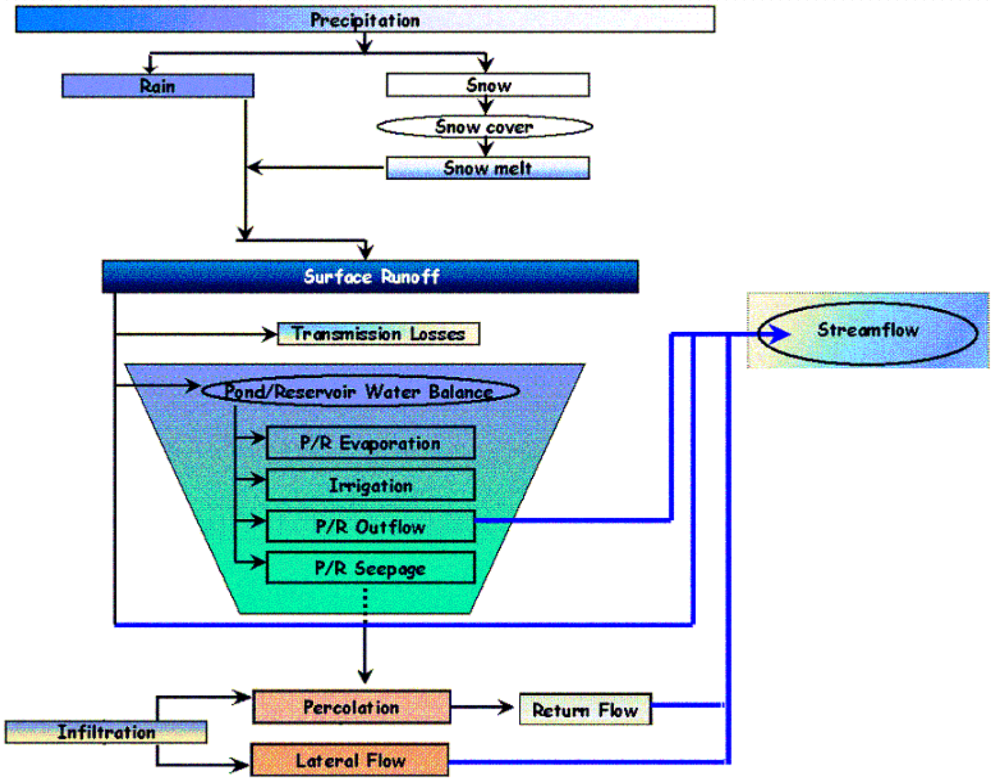
- **Basin setup**
  - 16 sub-basins, 264 HRUs
  - 3 slope classes & 10% threshold
  - 10% soil threshold
    ⇒ 36 classes
  - 5% land use threshold
    ⇒ 9 classes



  - Outlet of sub-basin 7 = USGS station for cal/val

Meng et al 2009

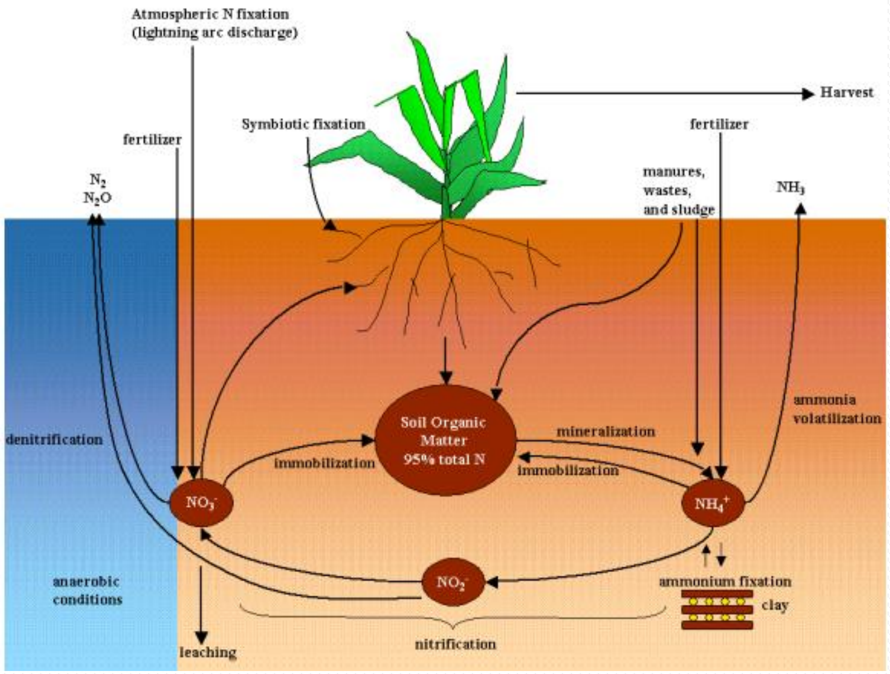
Lumped Parameter Models: SWAT



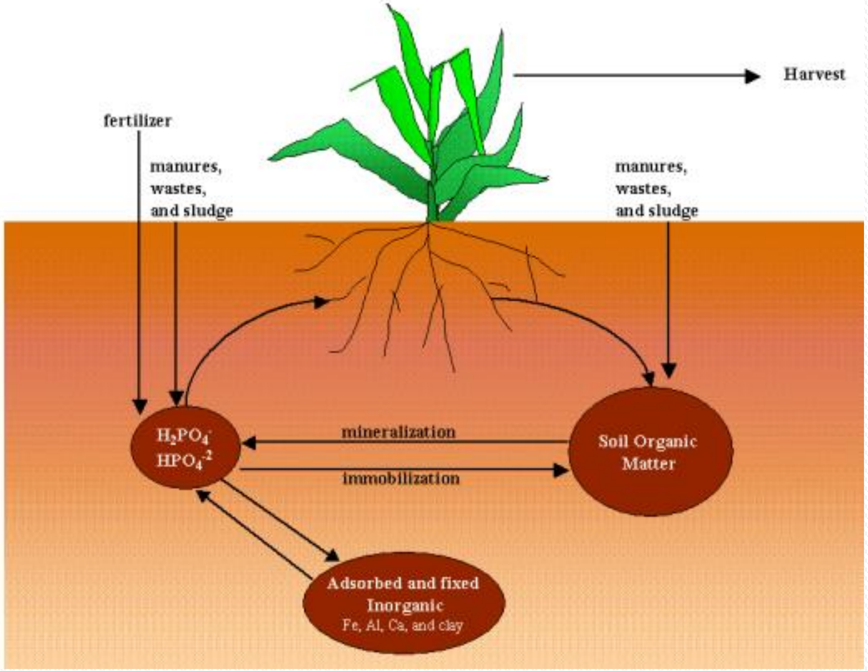
- **Key Calibration Parameters:**
  - Recharge
  - GW flow response to recharge
  - GW Delay Coefficient
  - Stream Channel K
  - Runoff SCS Curve Number
  - Rain-to-Snow Temp
  - Saturated K

Conceptual Framework: Nutrient Dynamics

Nitrogen Dynamics



Phosphorus Dynamics



Neitsch et al 2002

Lumped Parameter Models: GWLF

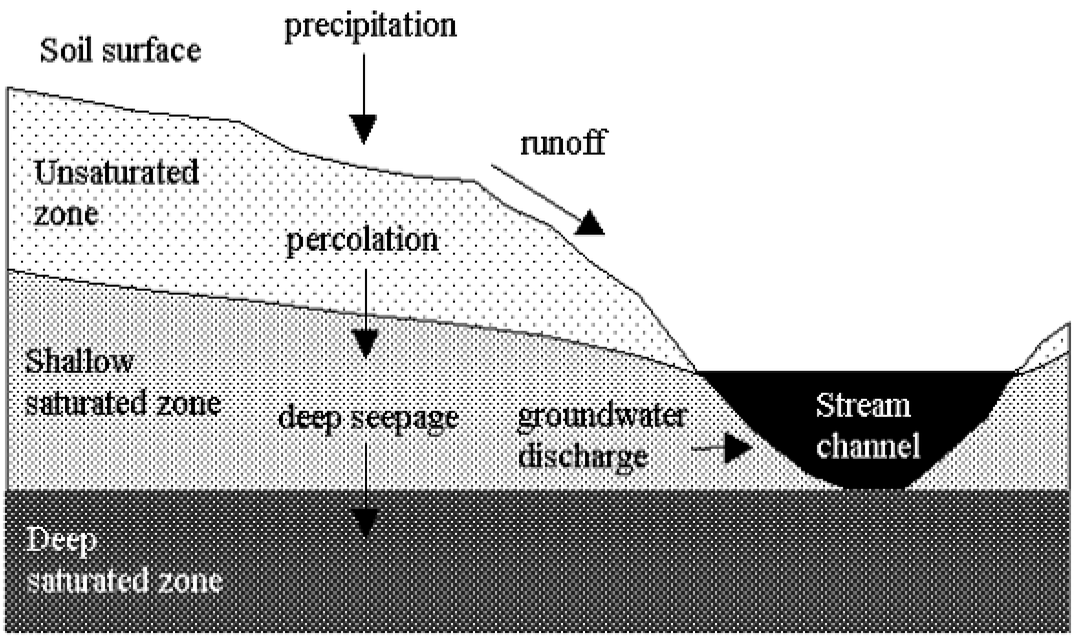
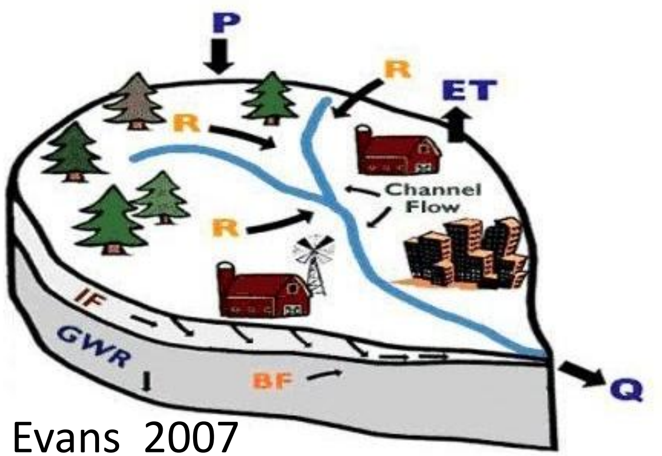


Figure 1. Sub-division of modeling components within GWLF (adapted from Haith et al., (1992)).

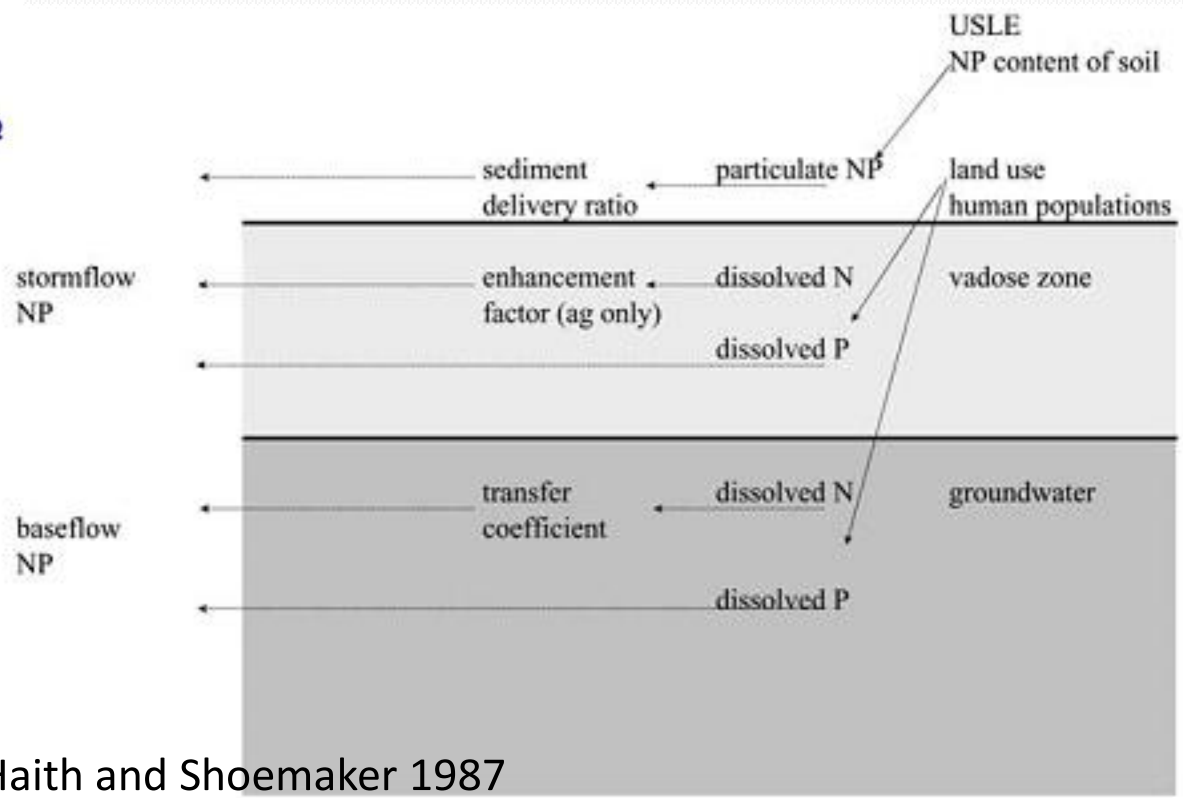
- **Key Calibration Parameters:**
  - Groundwater recession constant
  - N concentration in runoff

Haith and Shoemaker 1987

Lumped Parameter Model: GWLF

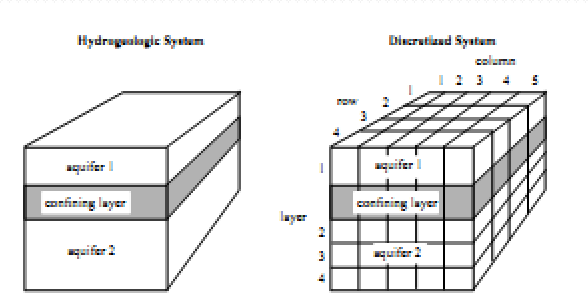


Evans 2007



Haith and Shoemaker 1987

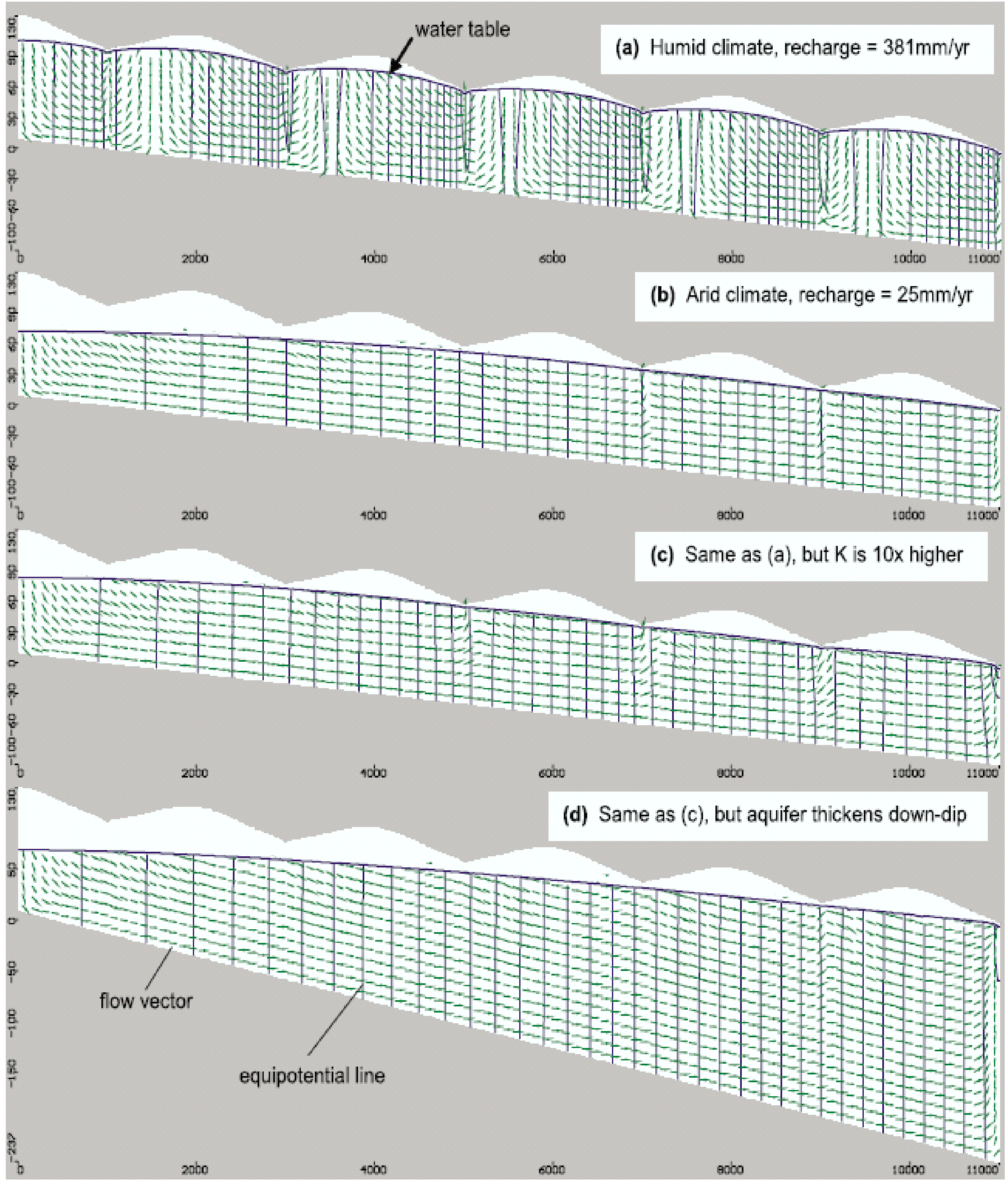
Numerical Models: ModFlow



Key Calibration Parameters:

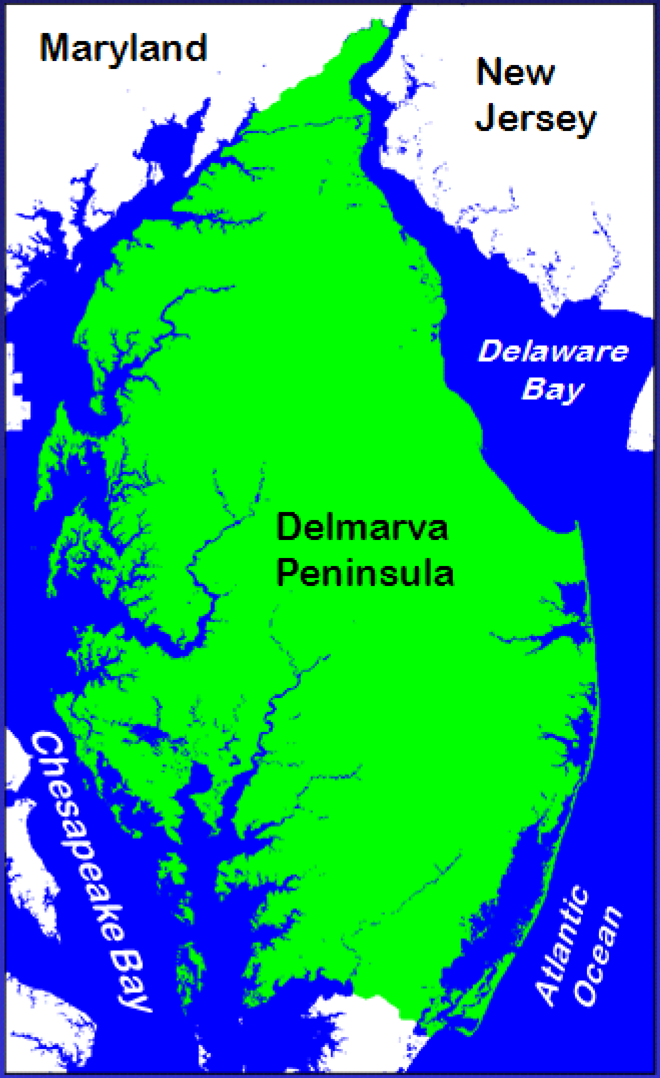
- **Recharge Rate**
- **Hydraulic K**
- **Aquifer Thickness**

Schaller and Fan 2009



Groundwater Model of the Delmarva Peninsula

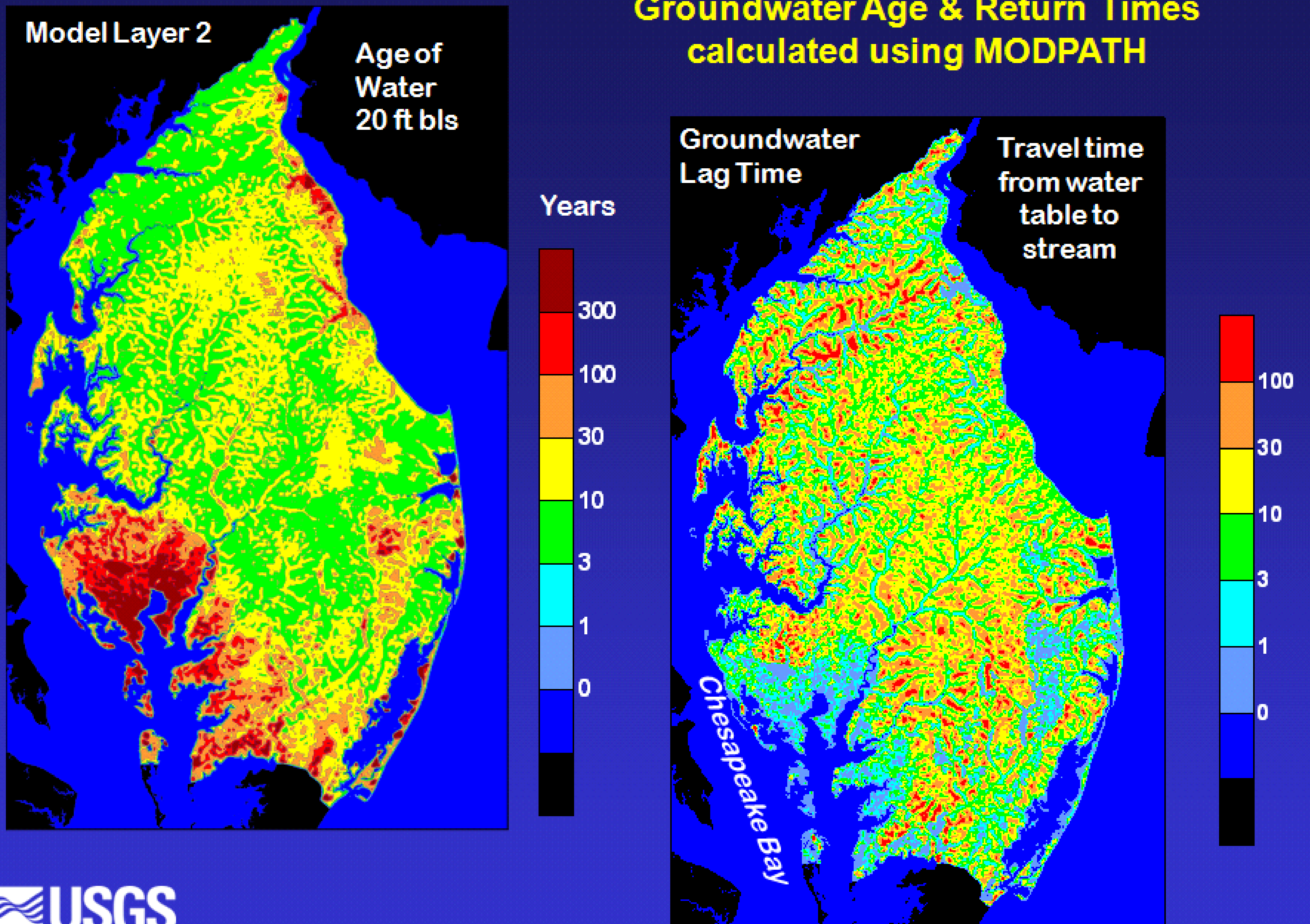
- MODFLOW 2005
- 150 m cell resolution
- 5 Layers, 100 m deep
- 6.25 million cells
- Recharge and Drains
- General-Head Boundary
- 2-m LiDAR-based DEM
- Steady State Flow
- 48 water levels, 24 ages



USGS

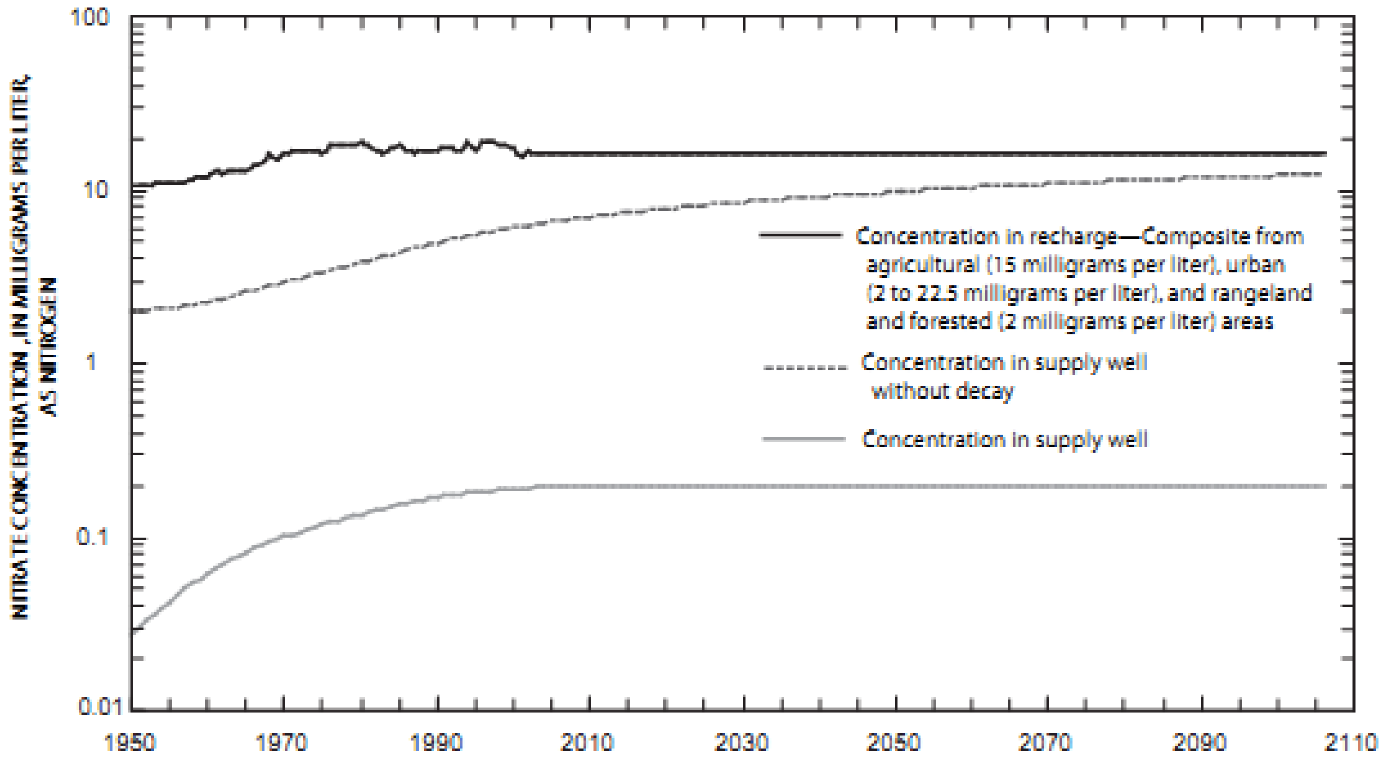
Sanford and Pope 2009

Groundwater Age & Return Times calculated using MODPATH

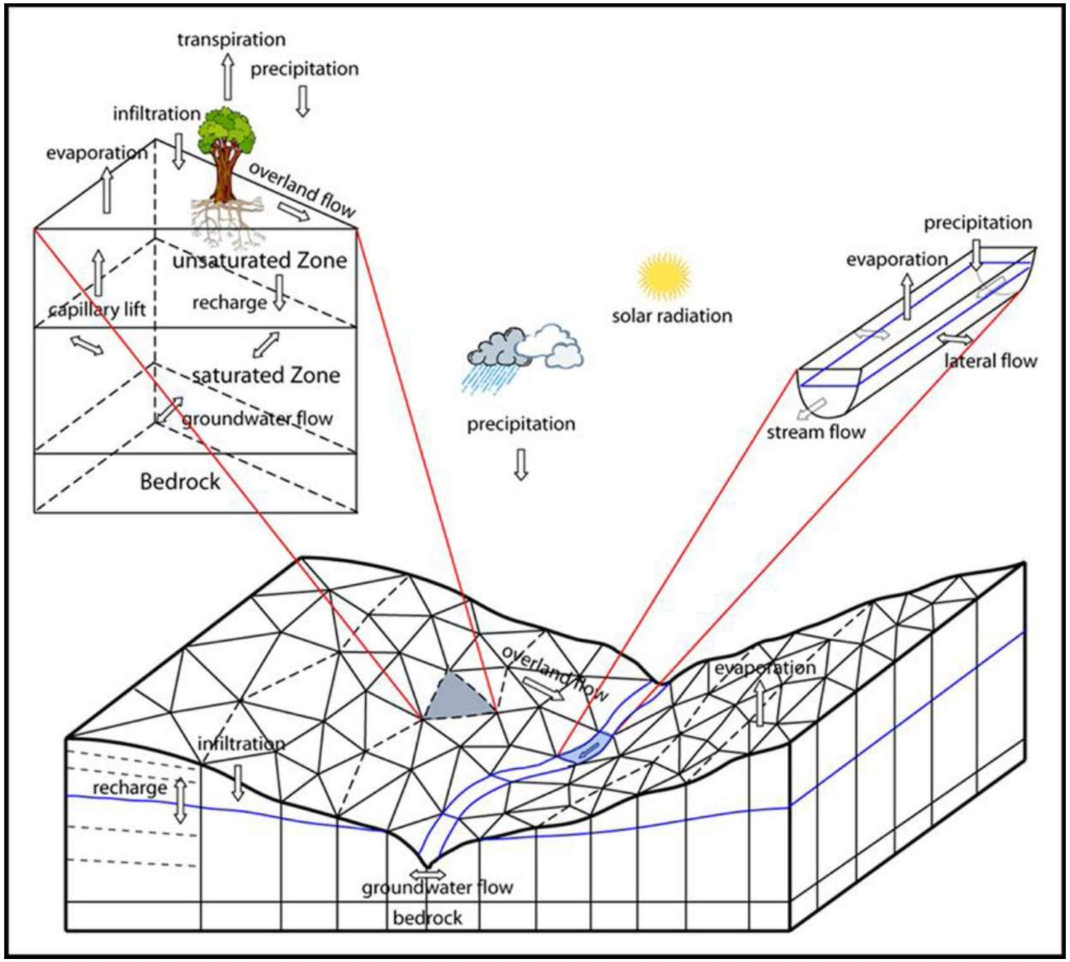


Sanford and Pope 2009

Numerical Models: ModFlow, with ModPath Particle Tracking Package



Numerical Models: PIHM

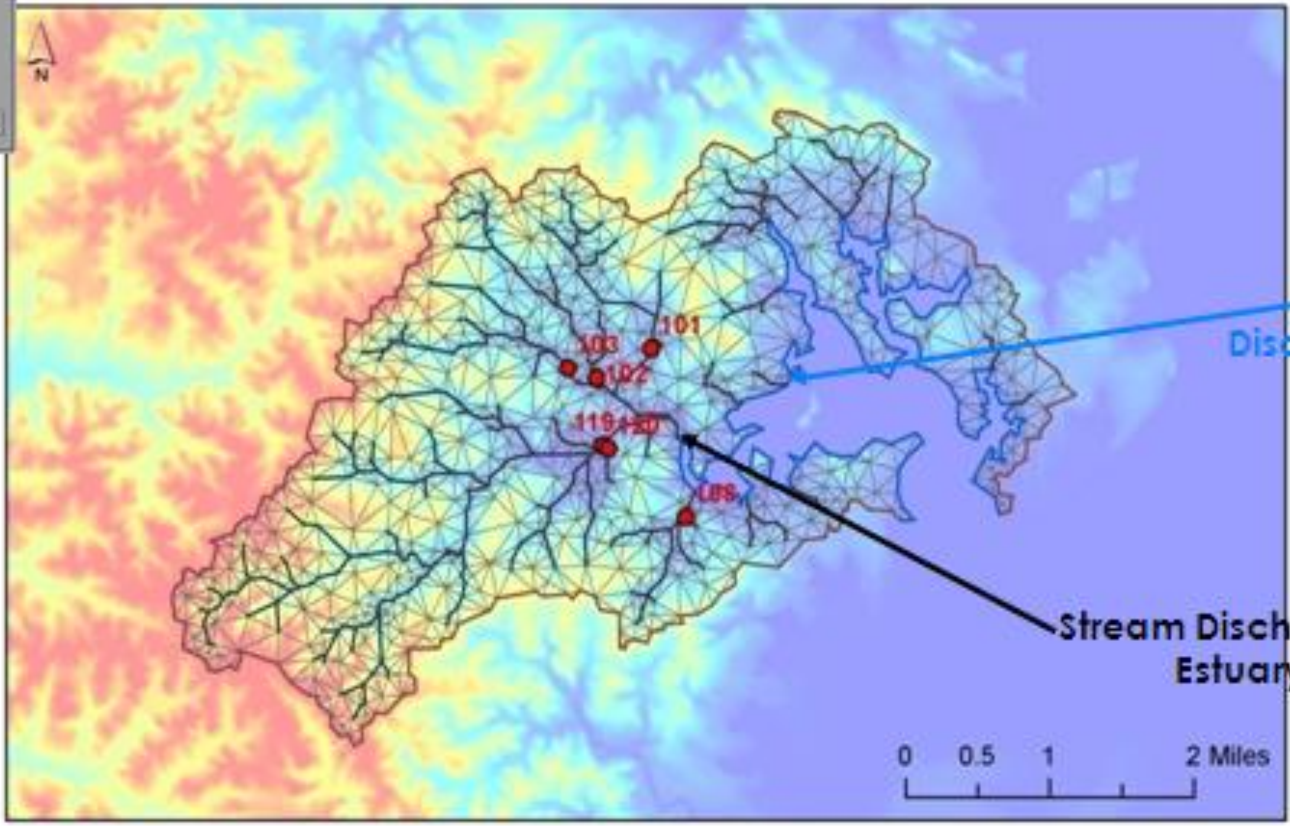


Watershed >> Domain Decomposition >> Model Kernels

Bhatt and Duffy

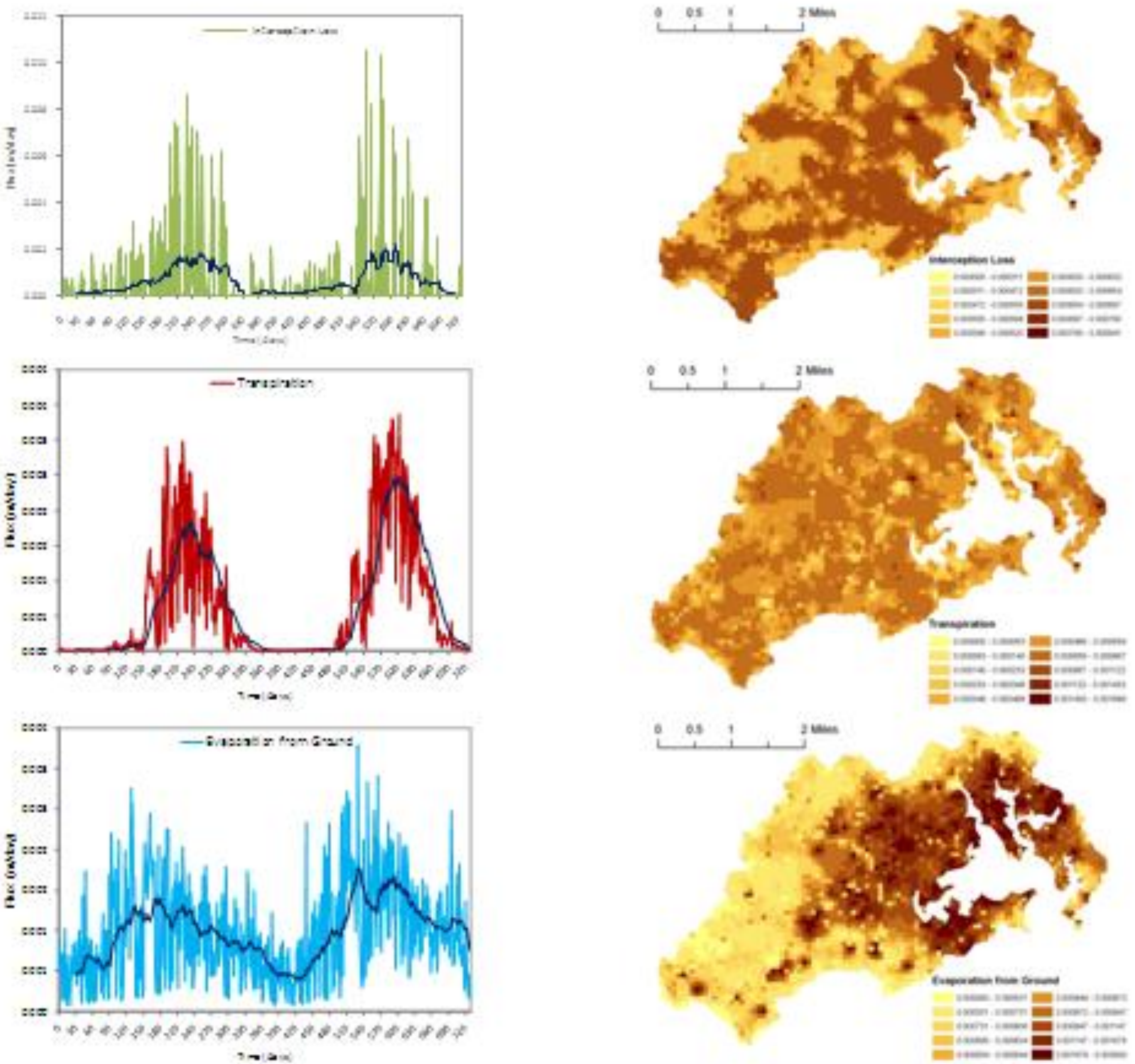
Estuarine :: Rhode River Watershed (82 sq. km.)

Dominant processes in Fresh Water contribution to Estuary?



Bhatt and Duffy

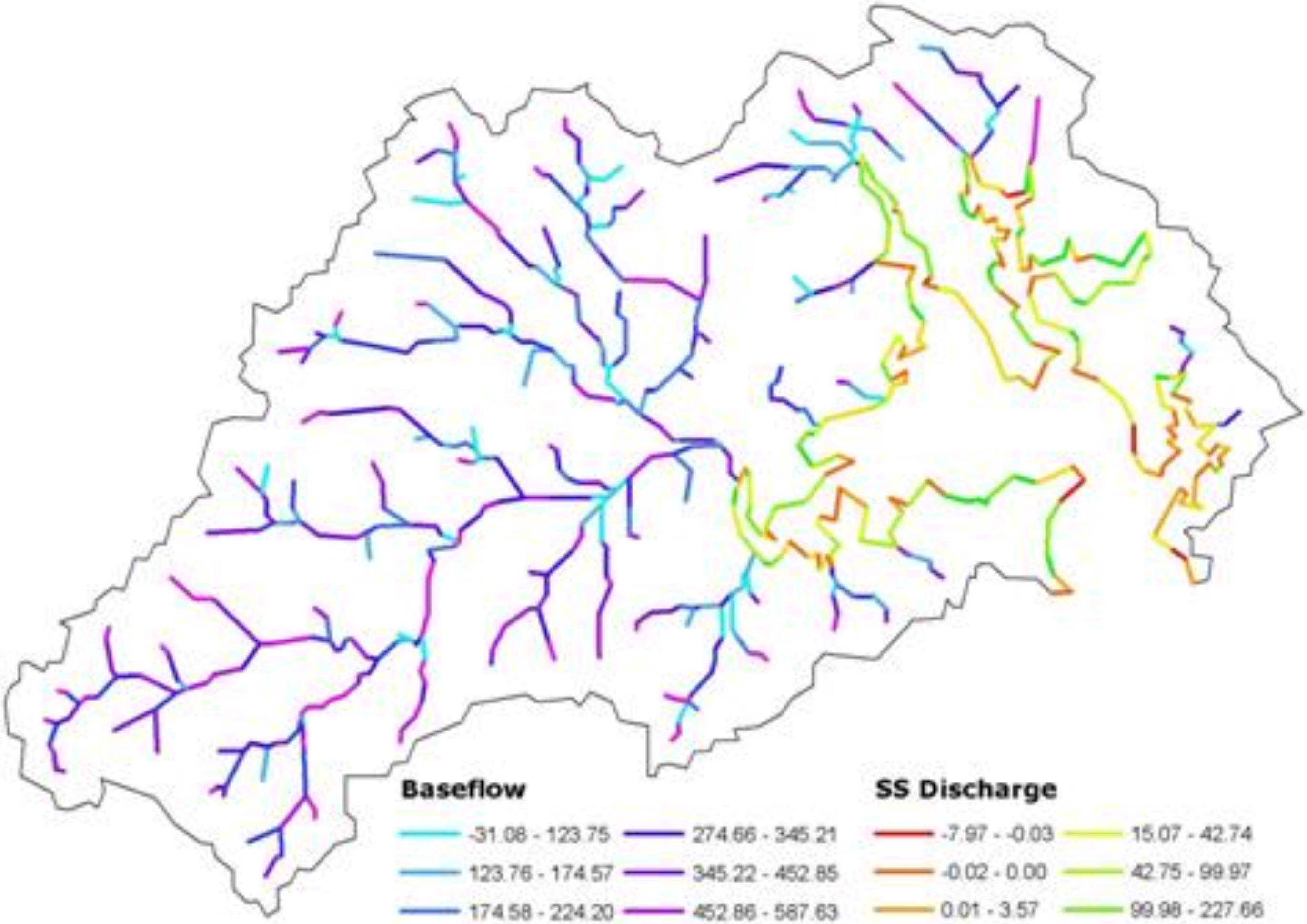
Bhatt and Duffy



Evapotranspiration is a function of Climate, Vegetation and **Available Water**

Spatial Distribution of Freshwater Discharge

Bhatt and Duffy



Topography & local hydrologic properties controls the spatial response

Watershed Model Comparison

- Lumped Parameter (bucket) Models:
  - **CBP5-HSPF**
    - Land-River segments
    - Lag time constant: 10 yrs
    - Shallow soil nutrient dynamics
    - Constant nutrient load reduction proportional to buffered stream length
  - **SWAT**
    - HRU segments
    - Calibrated Groundwater Delay Factor
    - Shallow soil nutrient dynamics
    - Nutrient Delivery Lag : exponential decay weighting function
  - **GWLF**
    - Delineated watershed subbasins
    - TN increases directly with cropland area
    - TN retention based on transport coefficient
    - No nutrient transport lag time (estimates represent long-term average)

Numerical (interpolation) Models:

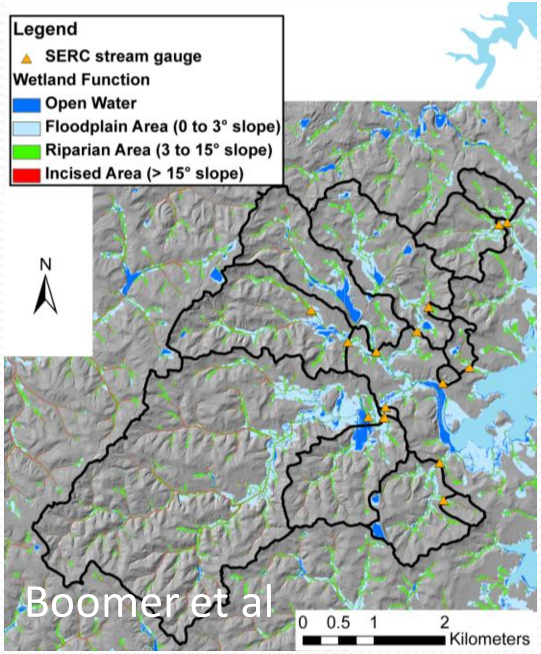
- **ModFLOW**
  - 3D grid based on stratigraphy
  - GW residence time related to flow length estimates and hydraulic K
  - MODPATH particle tracking overlay simulates nutrient bio-retention
- **PIHM**
  - Triangulated network
  - GW residence time related to flow length estimates and hydraulic K
  - Nutrient transport dynamics in development

Summary Findings & Conclusions

- All agreed: nutrient transport and storage in regional aquifers insignificant compared to local, unconfined aquifers.
- Critical Science:Management gap: Hydrologic Controls
  - Lumped parameter models indicate runoff and/or EVT
  - Numerical models indicate infiltration
- Critical Science:Management gap: Locating and quantifying biogeochemical "hot spots" for nutrient removal
  - Data on BMP effectiveness
  - Research inefficiencies due to data access issues (lack of "data hub")
- With increasing data availability and computer power, distributed, numerical models are feasible for regional analysis.
  - Provides information at scale relevant to land managers.
  - Provides framework for integrating field-based science research.

Potential Future Pathways/Strategies

- Integrate models.
  - Use ModFLOW results to define more precise lag times
  - Incorporate spatially explicit biogeochemical models.



- Adopt multiple watershed model framework.

- Enhance efforts to centralize raw and derived model input data.

Summary Findings & Conclusions

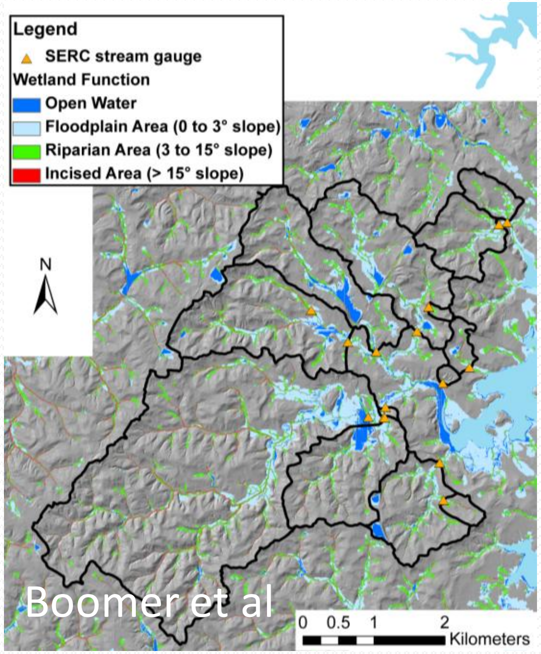
- All agreed: nutrient transport and storage in regional aquifers insignificant compared to local, unconfined aquifers.

- Critical Science:Management gap: Hydrologic Controls
  - Lumped parameter models indicate runoff and/or EVT
  - Numerical models indicate infilitration

- Critical Science:Management gap: Locating and quantifying biogeochemical "hot spots" for nutrient removal
  - Data on BMP effectiveness
  - Research inefficiencies due to data access issues (lack of "data hub")

- With increasing data availability and computer power, distributed, numerical models are feasible for regional analysis.
  - Provides information at scale relevant to land managers.
  - Provides framework for integrating field-based science research.

Potential Future Pathways/Strategies



- Integrate models.
  - Use ModFLOW results to define more precise lag times
  - Incorporate spatially explicit biogeochemical models.
- Adopt multiple watershed model framework.
- Enhance efforts to centralize raw and derived model input data.