A Deterministic Modeling Approach for Estimating Recharge in South Washington County

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Barr Engineering Company

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Washington County
City of Afton
City of Woodbury
Valley Branch Watershed District
South Washington Watershed District

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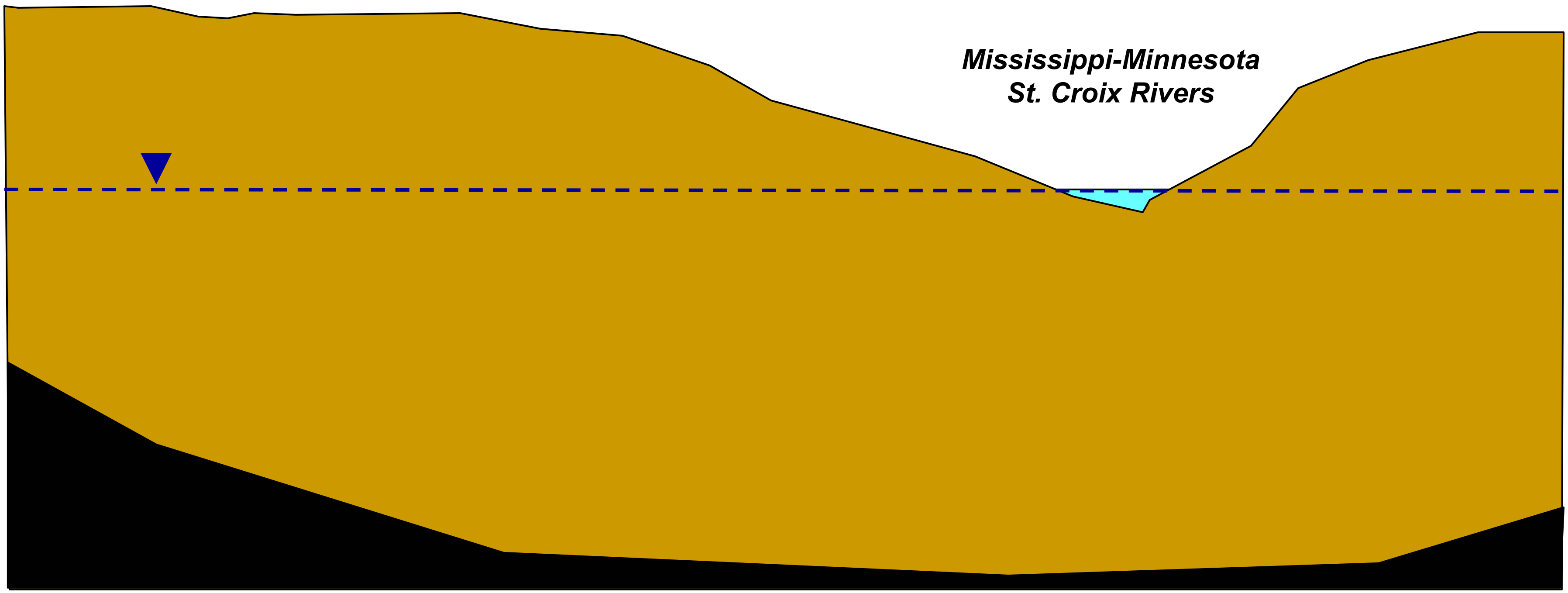
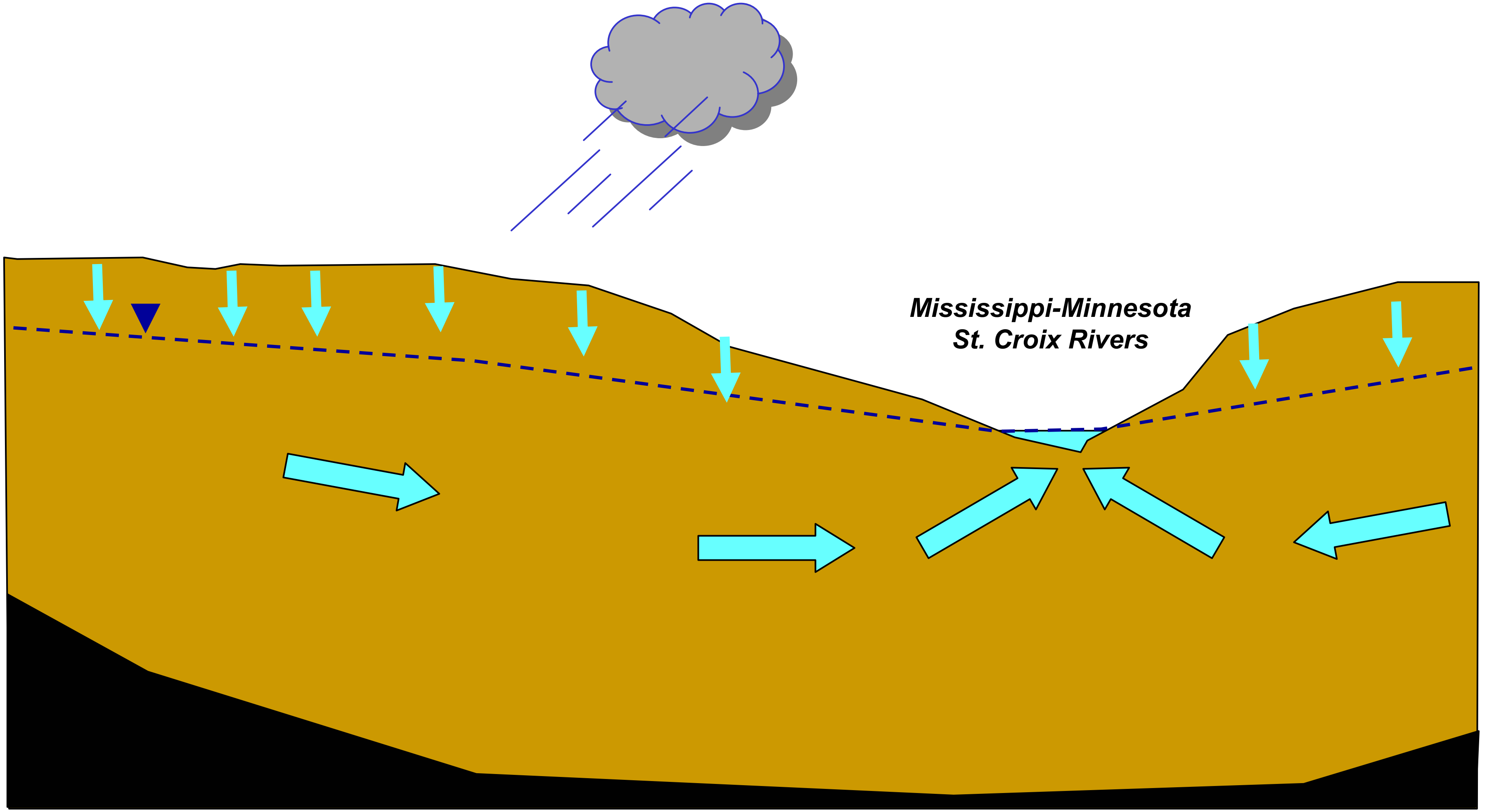
This talk addresses:

- “Traditional” approaches used to estimate recharge for groundwater flow models
- The contribution of recharge estimates to model uncertainty
- A deterministic approach to modeling the recharge process
- An example from southern Washington County
- Problems and challenges of this approach

In the Absence of Recharge the Potentiometric Surfaces Would be Flat



Recharge Causes the Potentiometric Surface to Rise and Groundwater to Flow



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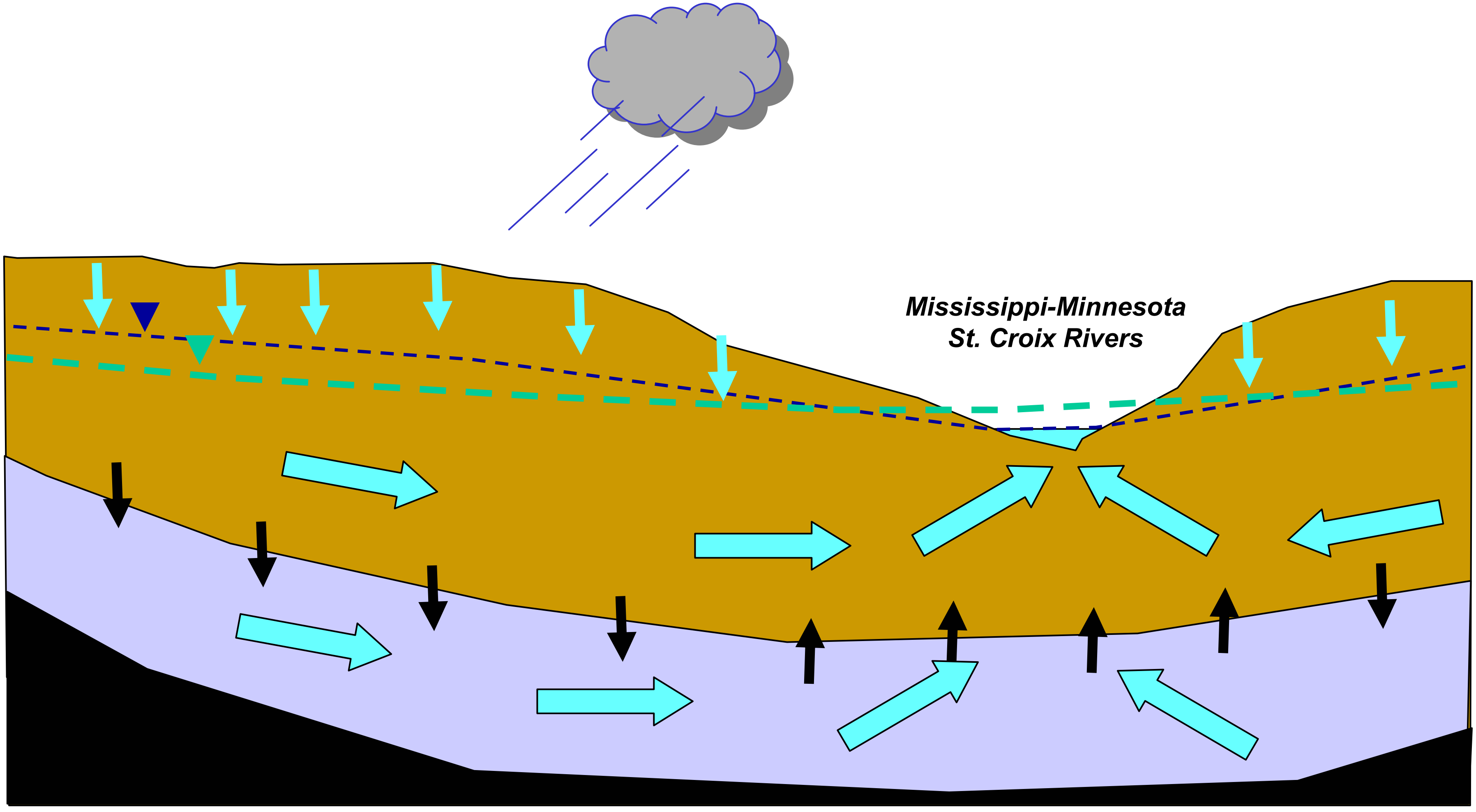
Leakage in a Multi-Aquifer System Distributes Recharge to Deeper Aquifers and Effects Potentiometric Surfaces



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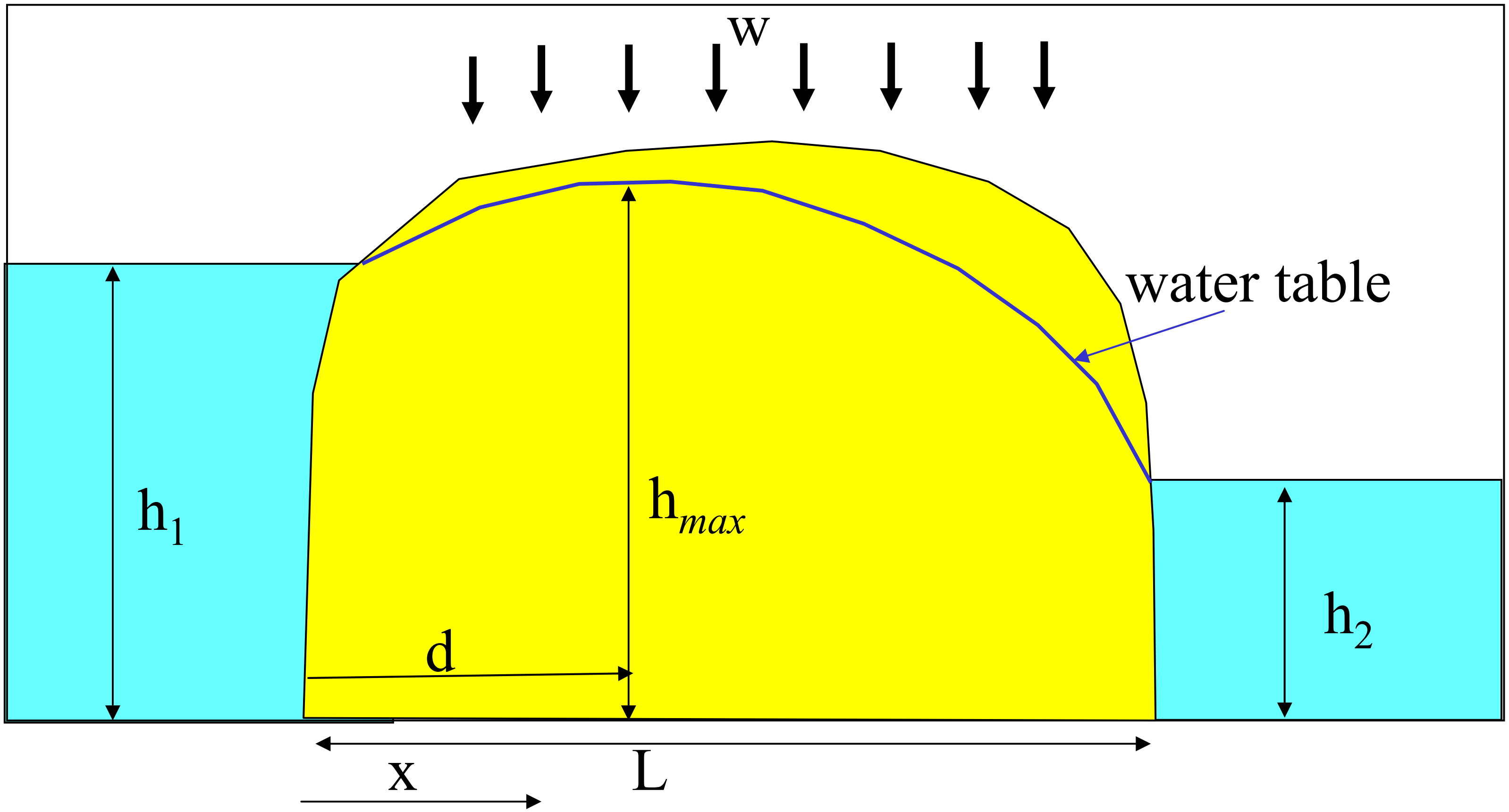
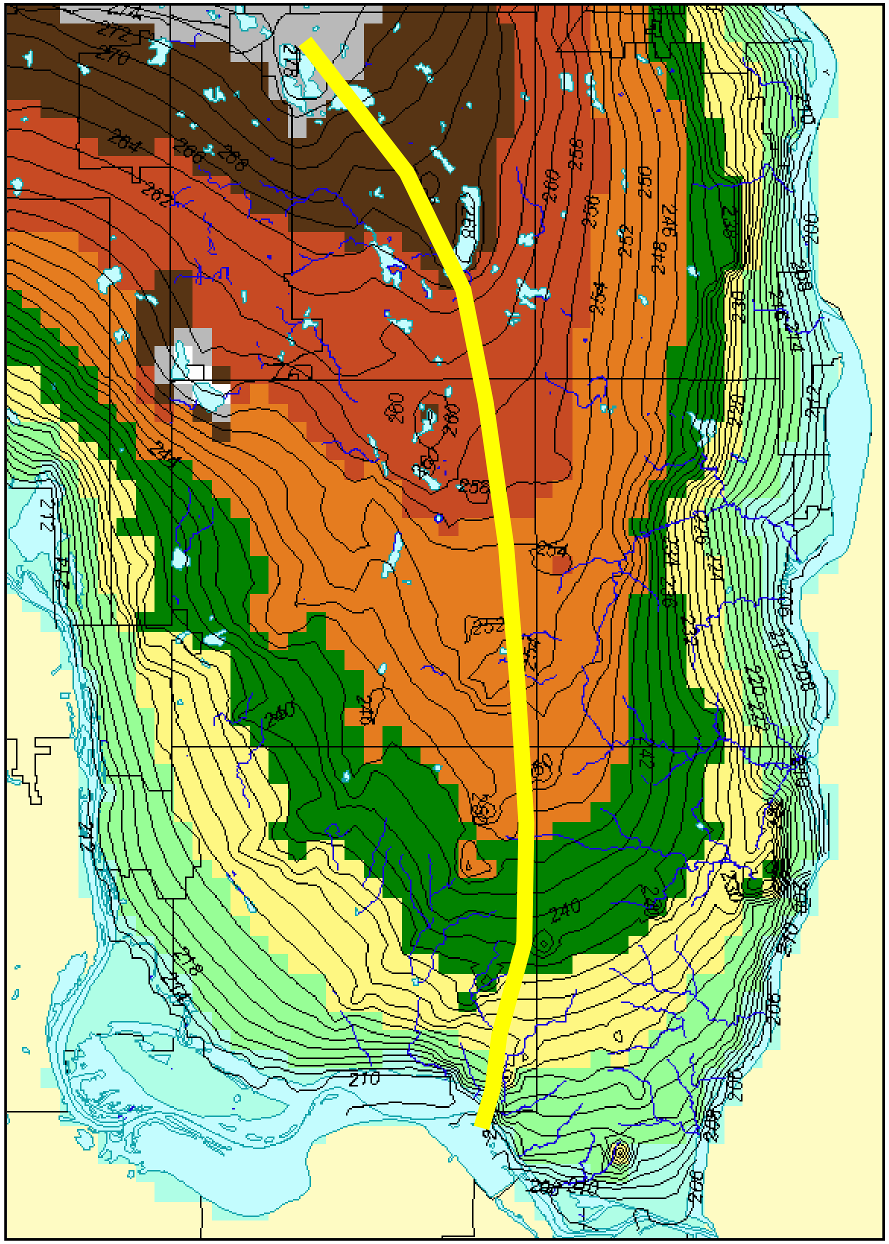


$$h = \sqrt{h_1^2 - \frac{(h_1^2 - h_2^2)\,x}{L} + \frac{w}{K}(L - x)x}$$

Dupuit Equation

Head is dependent on the ratio of Recharge to permeability



Southern Washington County in Geometrically Similar to a “Dupuit” Problem

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Estimating Recharge by the "Inverse Problem" Approach

Recharge / Aquifer Properties = Potentiometric Head Distribution

I vary this between
0 and annual precipitation

I "know" this from
Aquifer Tests

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Inverse Method Depends on Having a Higher Confidence in Transmissivity Values of Aquifers than in Recharge Estimates

- "I can reliably estimate transmissivity from pumping tests"
- "I can draw contour maps of aquifer thickness"
- "I can contour potentiometric heads from well data"
- "Recharge rates must be bounded between 0 and @ 30 inches per year"

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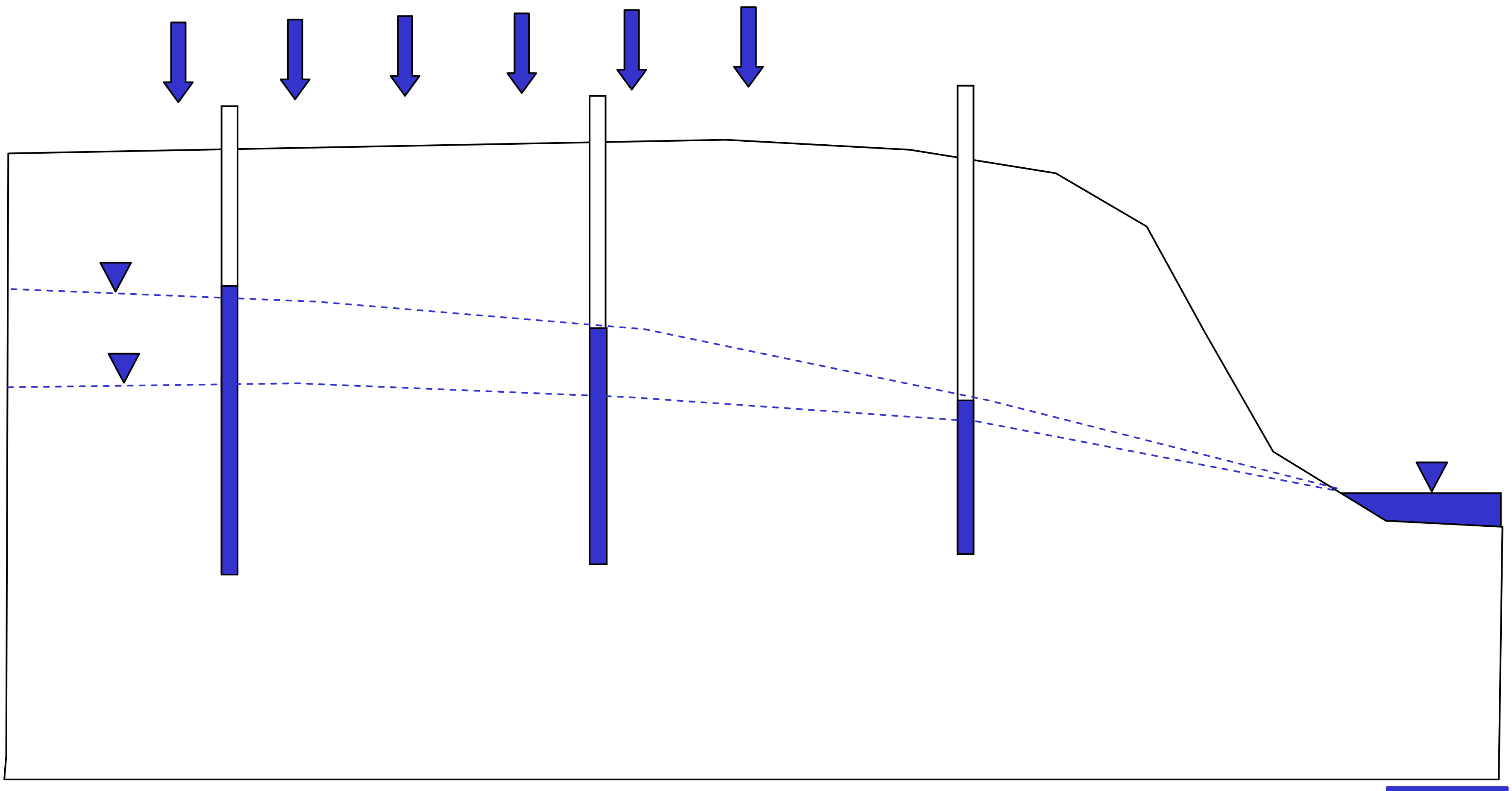
Recharge Values are Adjusted (and distributed over areas) Until Simulated Heads Match Measured Ground-Water Levels



Estimates Range from 4 to 12 inches per year (Average about 8-9 inches per year)

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There is inherent uncertainty in such recharge estimates

- Depends on transmissivity estimates
- Depends on how many (and how) aquifers and aquitards are included in a model
- Depends on model extent and boundary conditions
- Depends on how sources or sinks are represented in models

There is an inherent lack of uniqueness in inverse modeling approaches

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New Problems Have Increased the Interest in Recharge Estimation

- Issues of aquifer "sustainability" (driven by population growth)
- Quantifying predictions of effects of development and changes in land use
- Requirements for "zero-discharge" development
- Quantifying recharge augmentation
- Climate change issues

These types of issues are leading toward expectations of quantifying recharge rates and smaller and smaller scales

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Infiltration (Recharge) Derived from Deterministic Modeling of Surface Processes

Infiltration = Water that moves from the ground surface to the saturated zone and becomes groundwater

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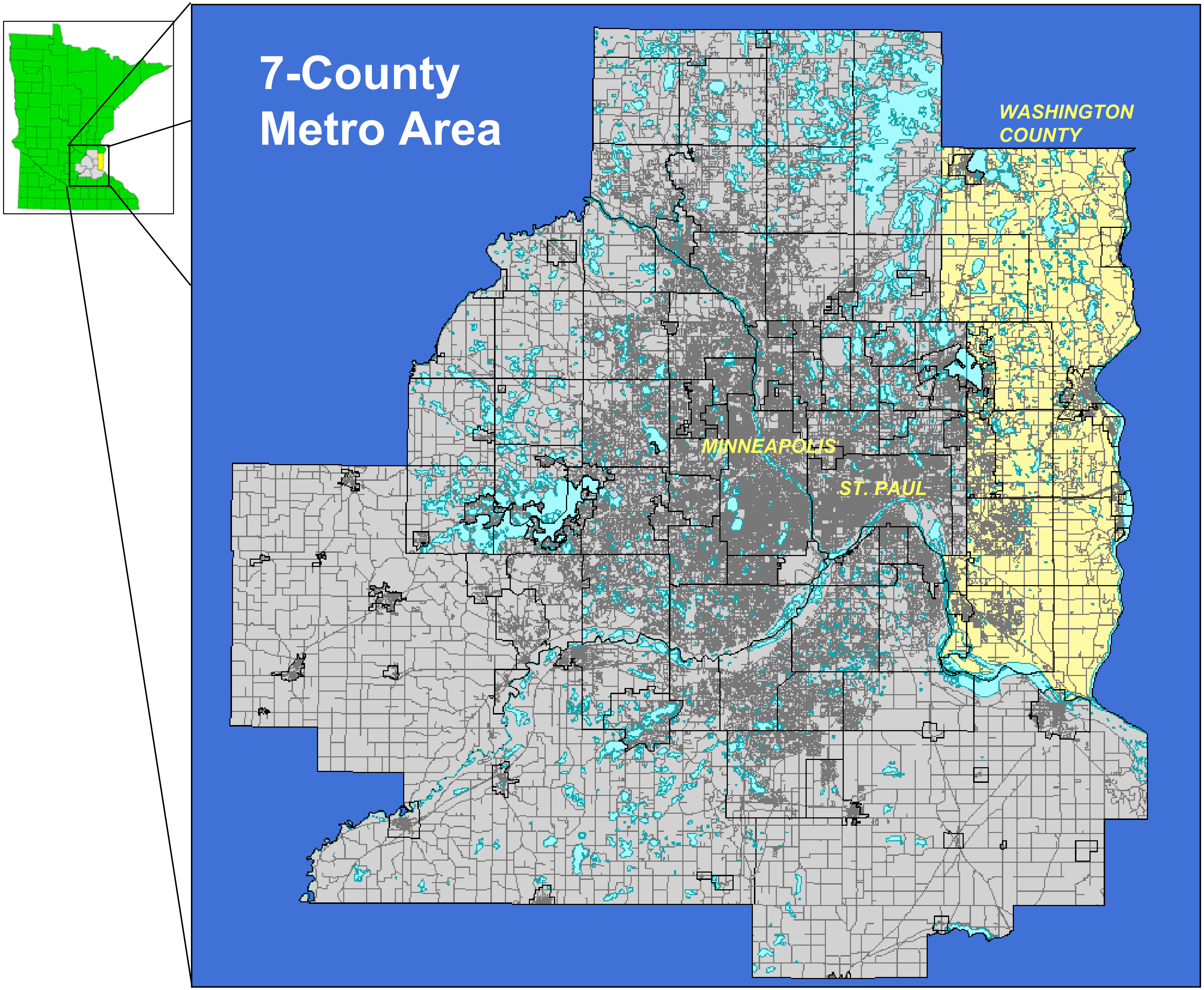

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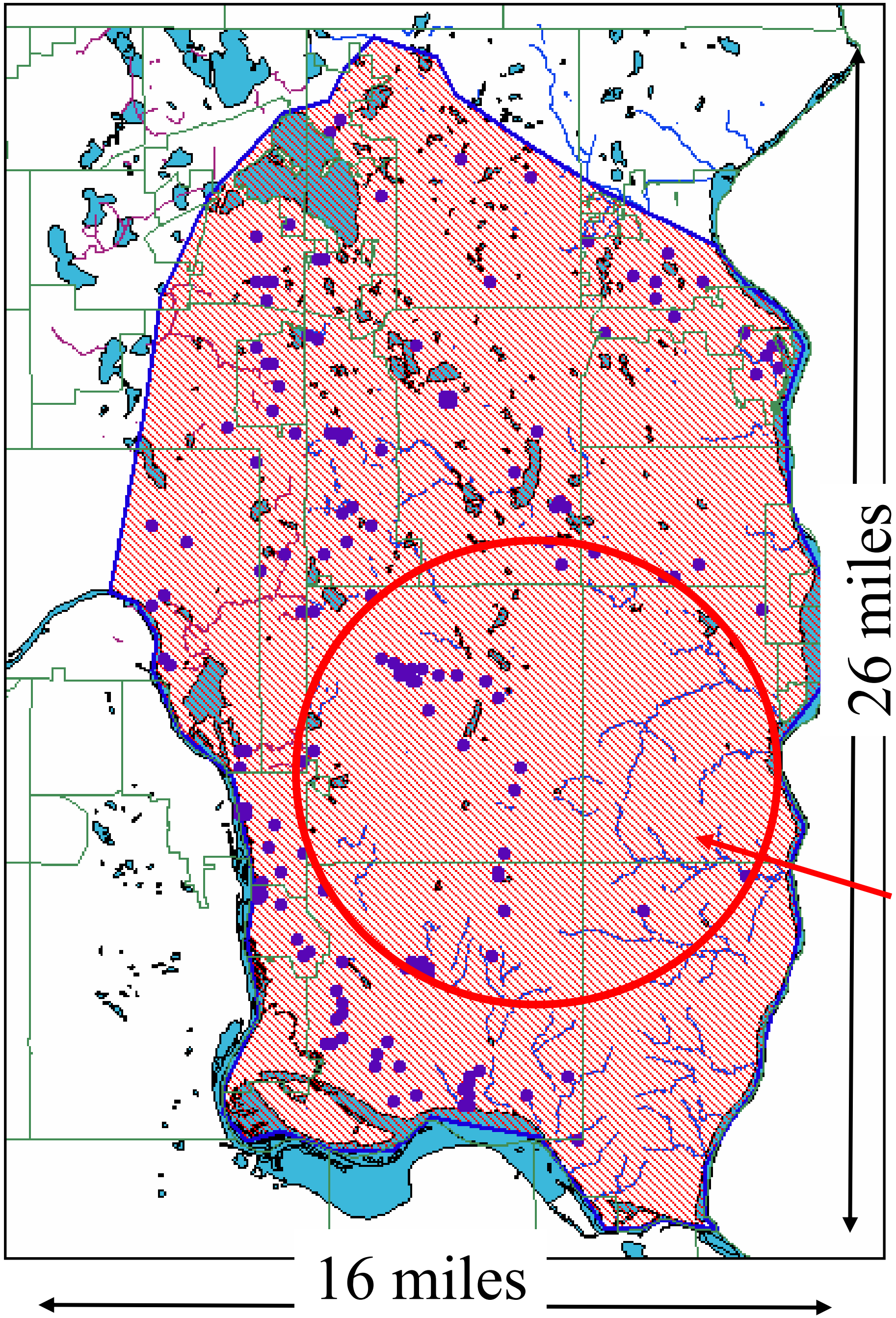
The Areas of interest



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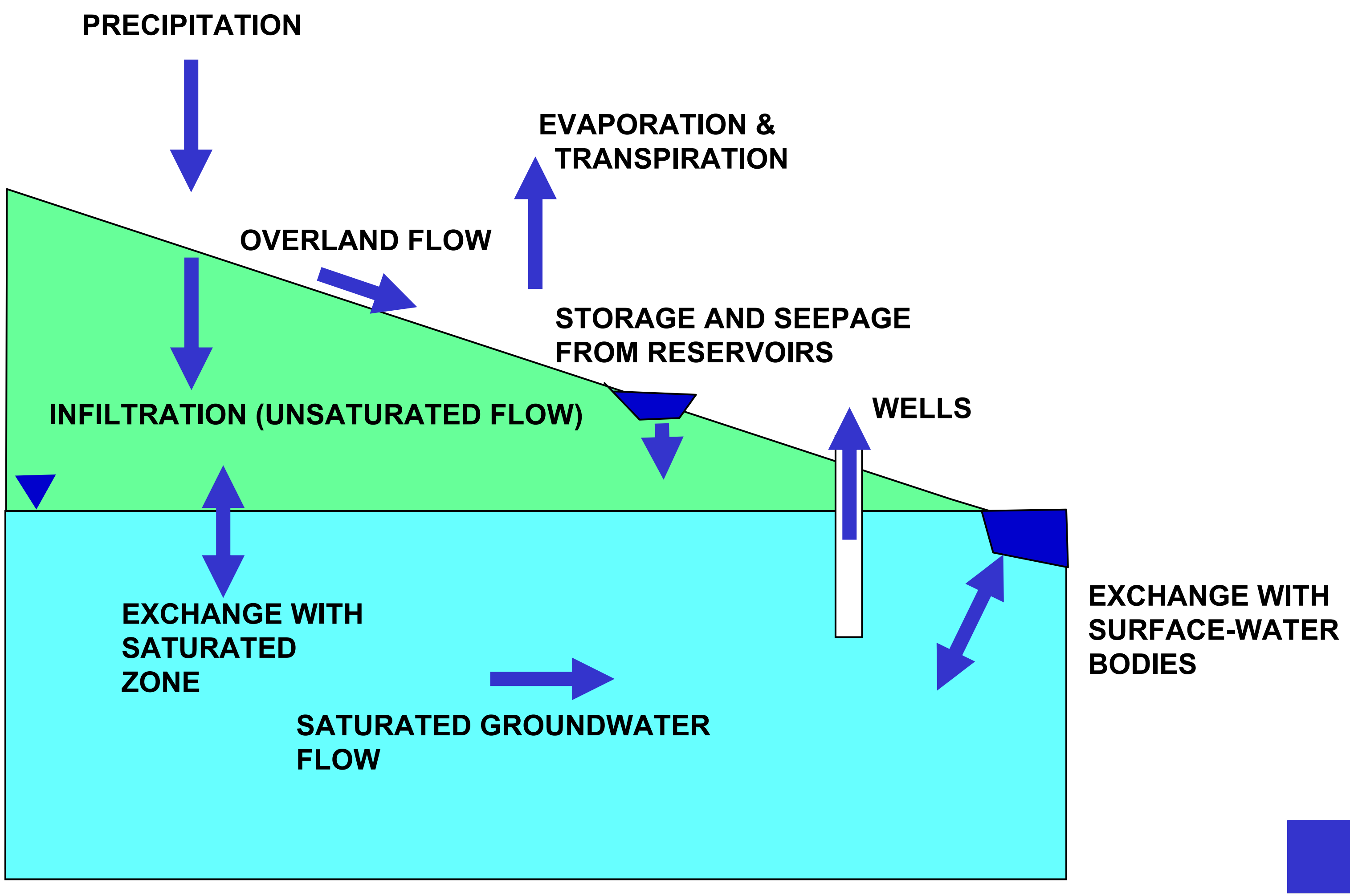
Conceptual Model of Processes



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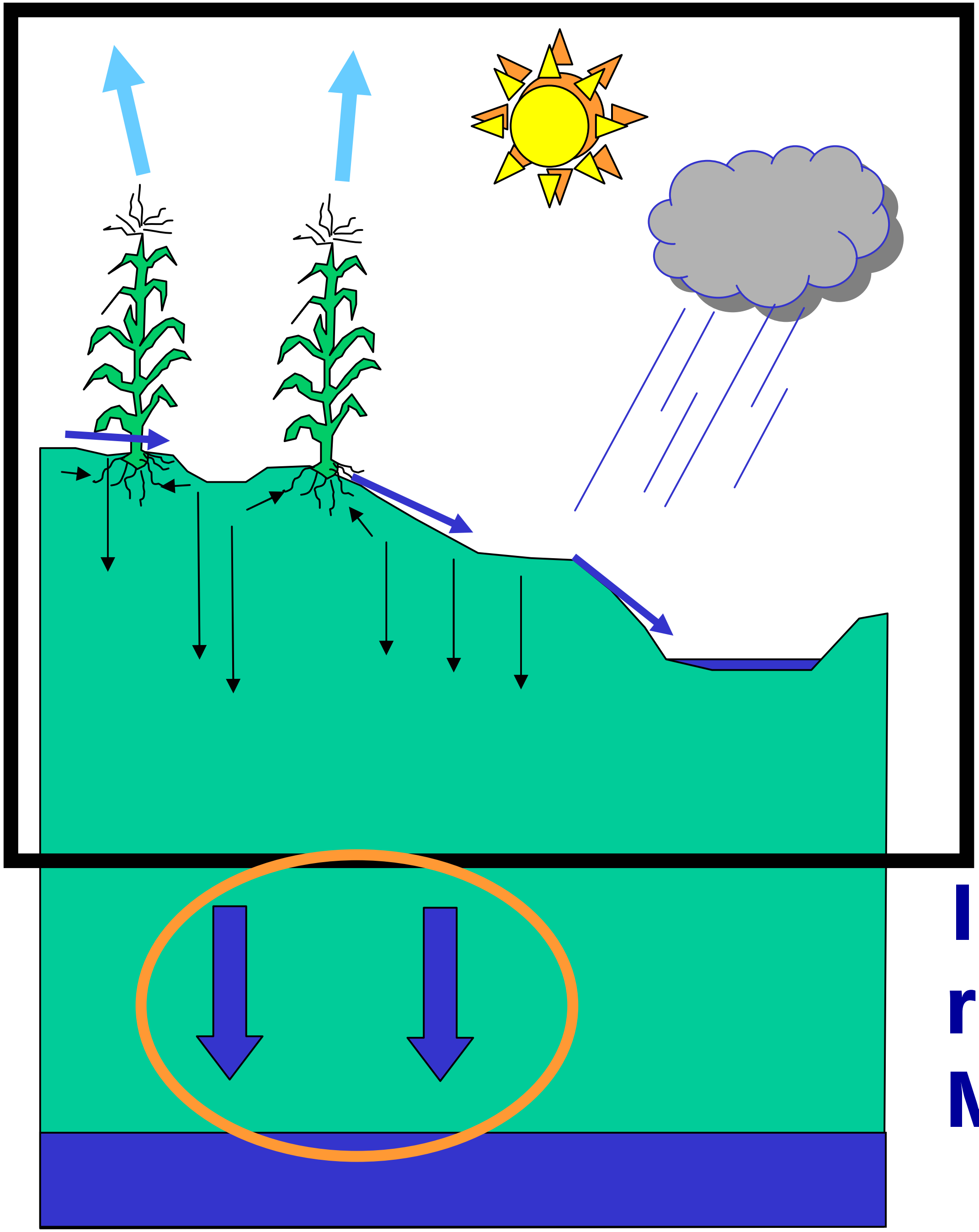
What is MIKE SHE

- MIKE SHE is *several* models, brought together into a single Graphical User Interface (GUI)
- Is capable of simulating:
  - precipitation
  - Evaporation (soil, free-water, and canopy)
  - transpiration
  - overland flow
  - channel flow
  - unsaturated flow
  - saturated flow

Why was MIKE SHE used?

- To obtain deterministic, distributed, climate and land-use based infiltration rates
- To constrain optimization and reduce parameter correlation in calibration
- To estimate infiltration for normal and dry conditions



MIKE SHE Processes

Infiltration rates to MODFLOW

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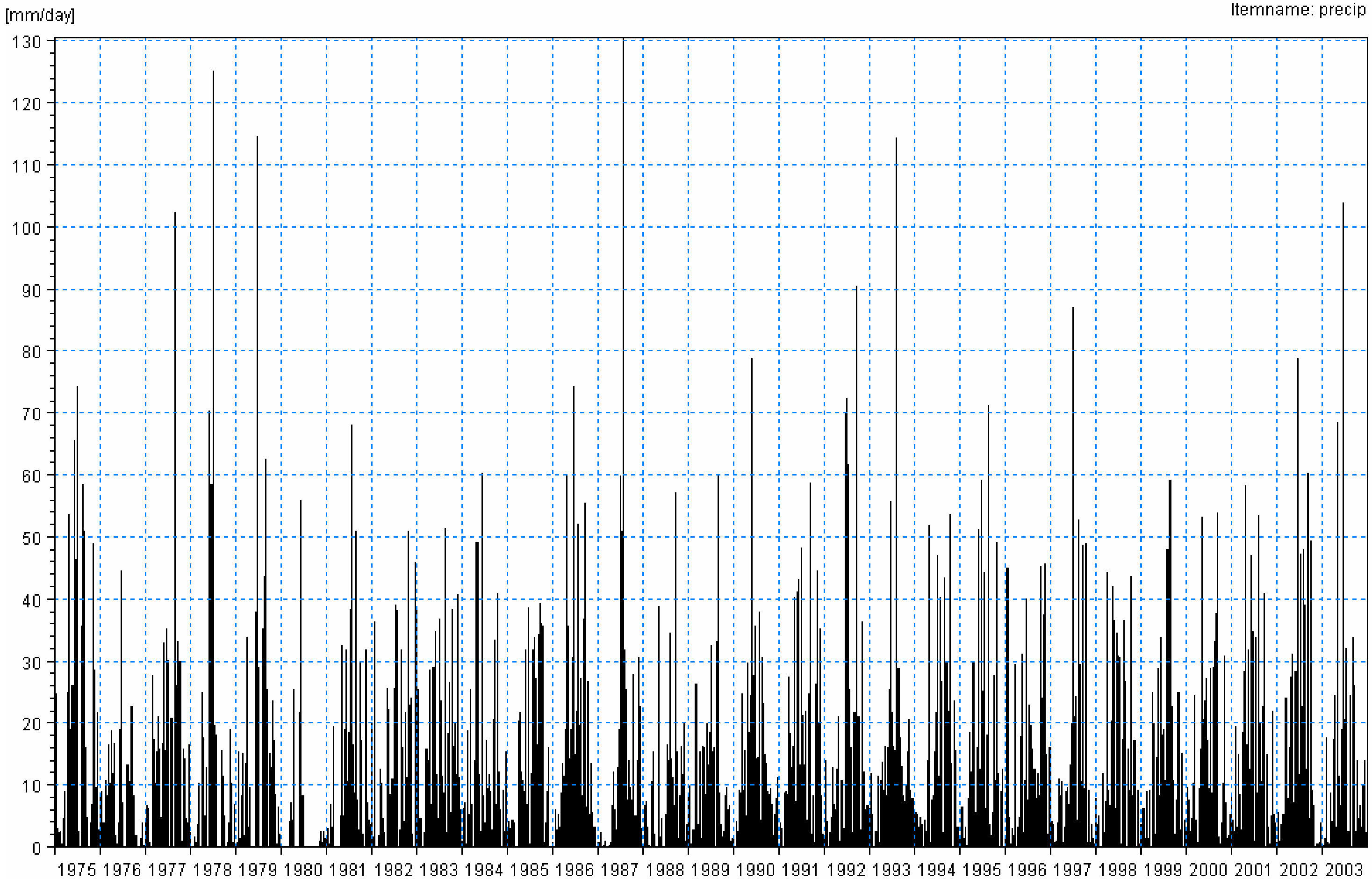
1. Precipitation

Daily Precipitation Data from St. Paul Metro Site (1975-2003)



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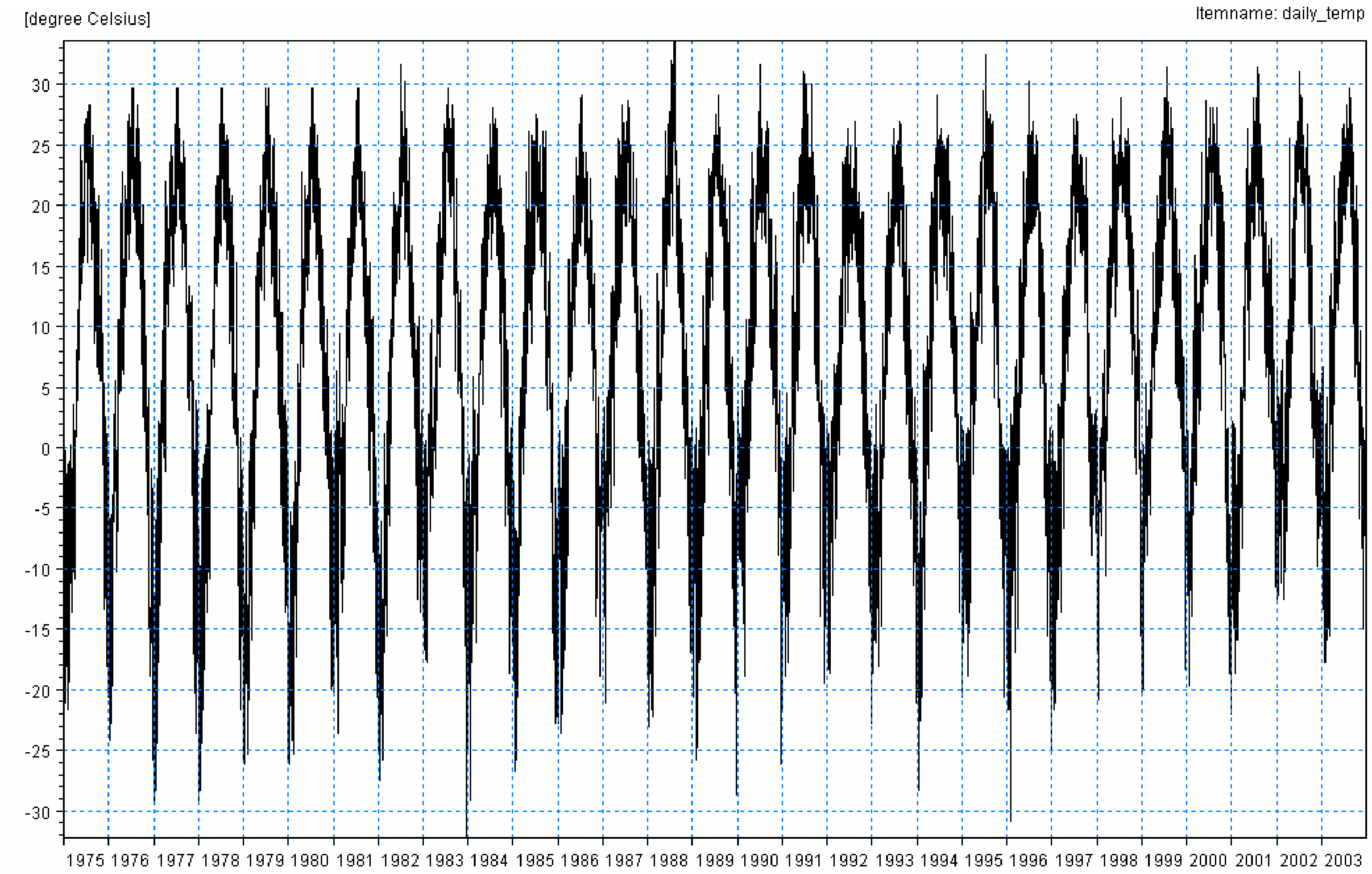
2. Temperature

Mean Daily Temp (C) from St. Paul Metro Site (1975-2003)



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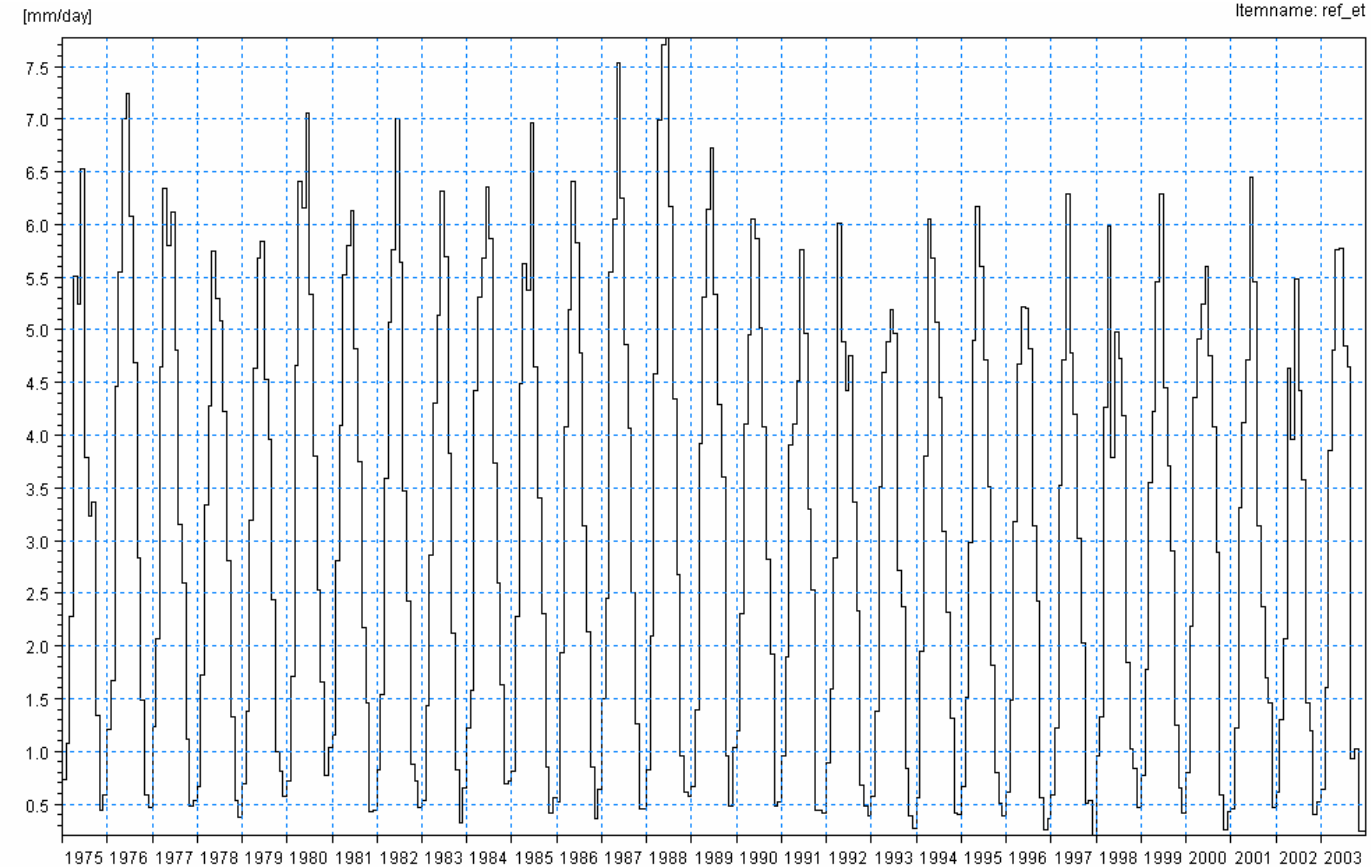
Temperature is used to…

- Determine if precipitation is stored as snow
- Determine when melting of snow pack begins
- Used in evaporation and transpiration calculations

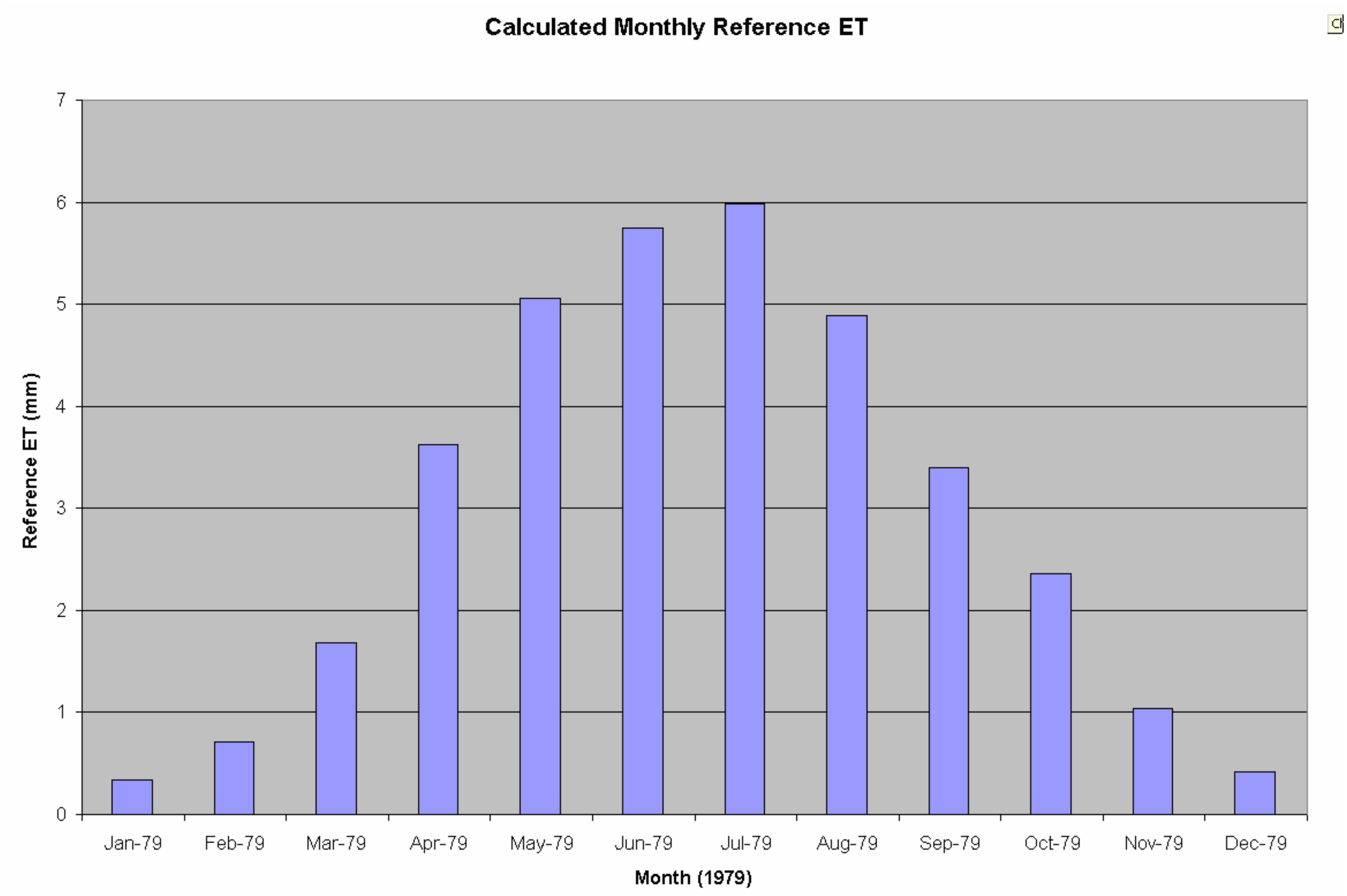
3. Reference Evapotranspiration

Reference ET: "a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23"



FAO Penman-Monteith equation used

Monthly variations in Reference ET



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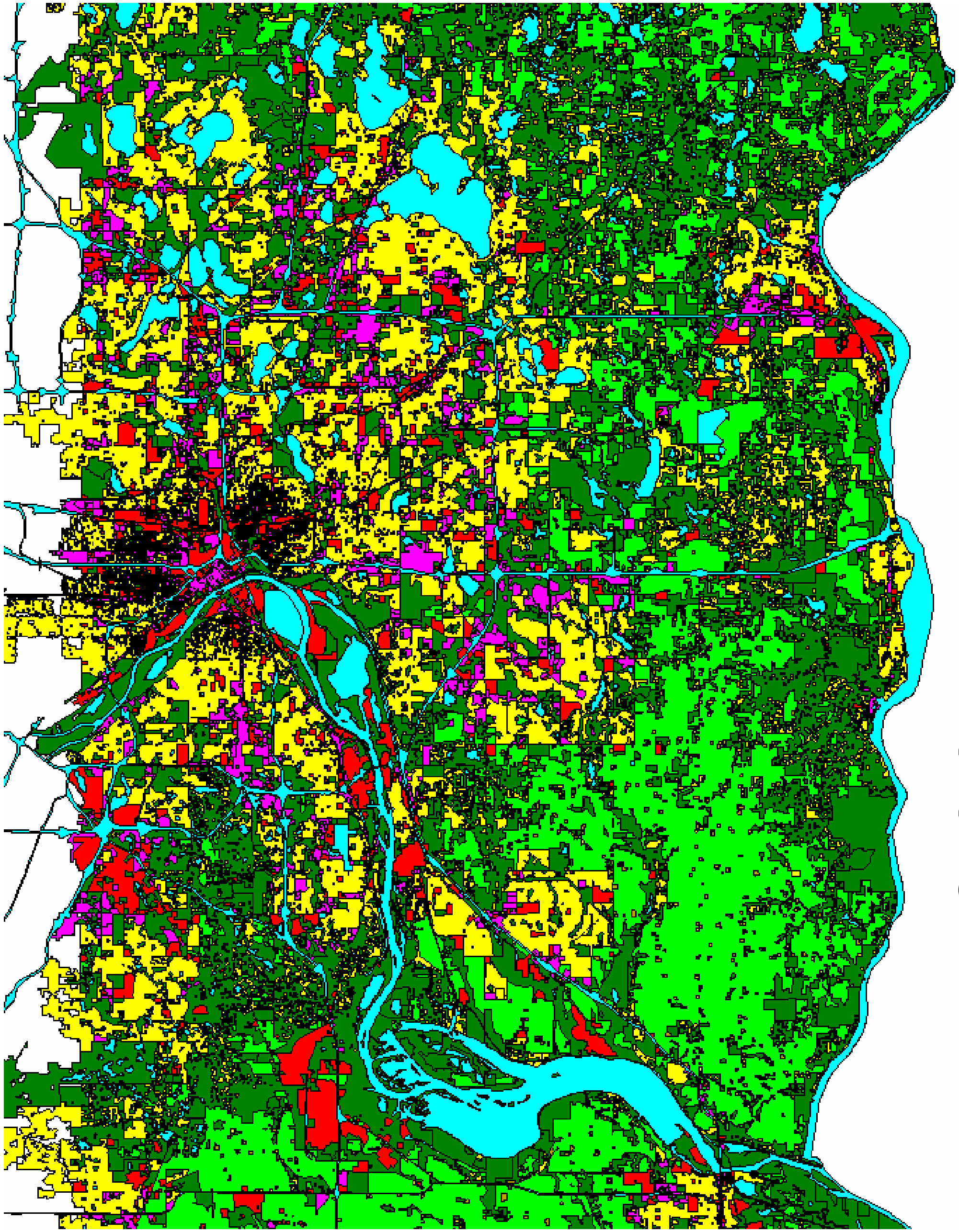
Factors included in Reference ET

- Latitude & Day and Month (sun angle)
- Mean daily wind speed
- Minimum and Maximum Temperature
- Dew Point/Relative Humidity
- Percent cloud cover

calculation methods source: http://www.fao.org chapters 2 and 3



4. Land Use/Vegetation

CORN/SOY BEAN
SINGLE FAMILY RESIDENTIAL
COMMERCIAL
INDUSTRIAL
FARMSTEADS
PARK LAND
OPEN WATER & PAVED

For each vegetation type, a “Leaf Area Index” (LAI) and “Rooting Depth” were estimated

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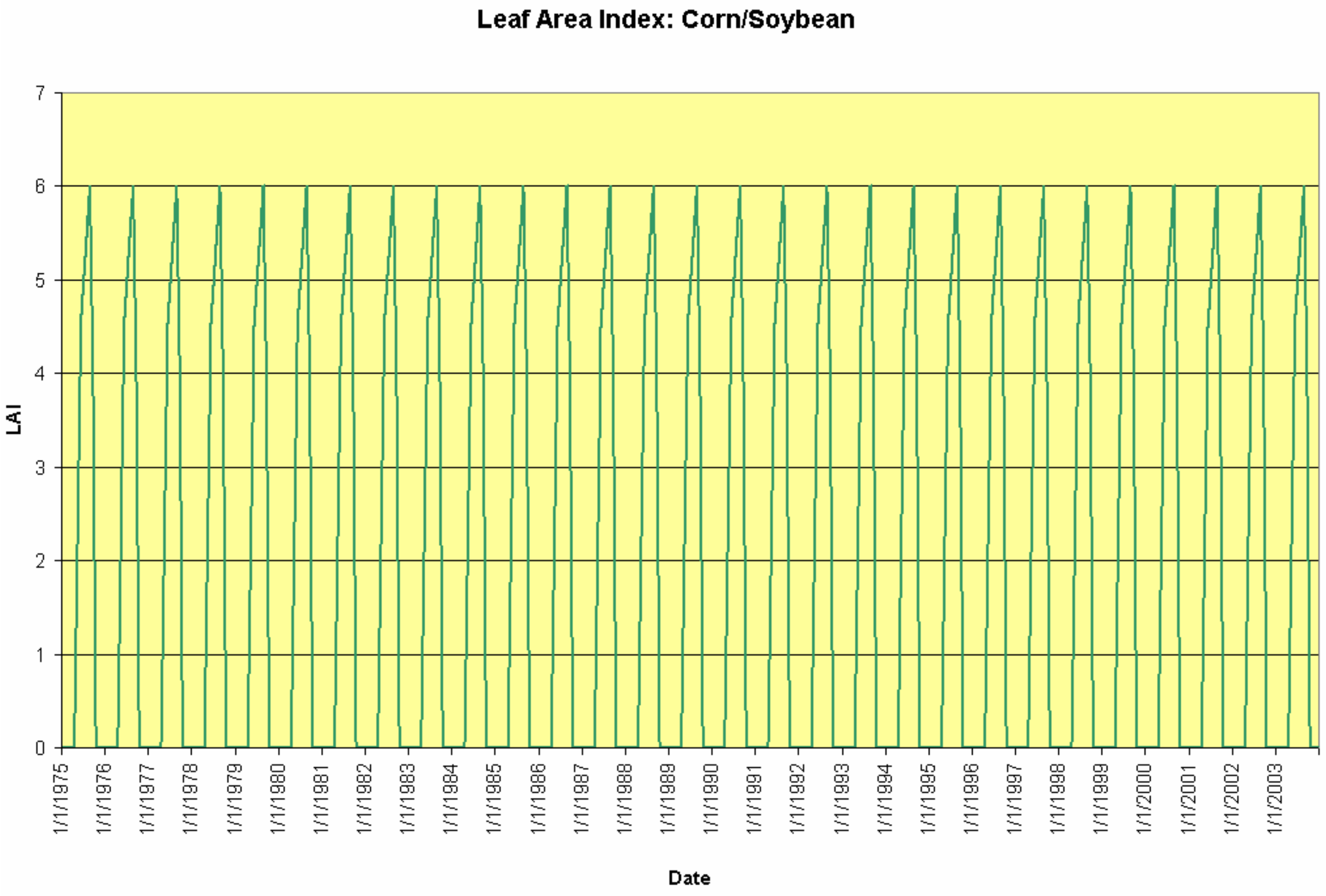
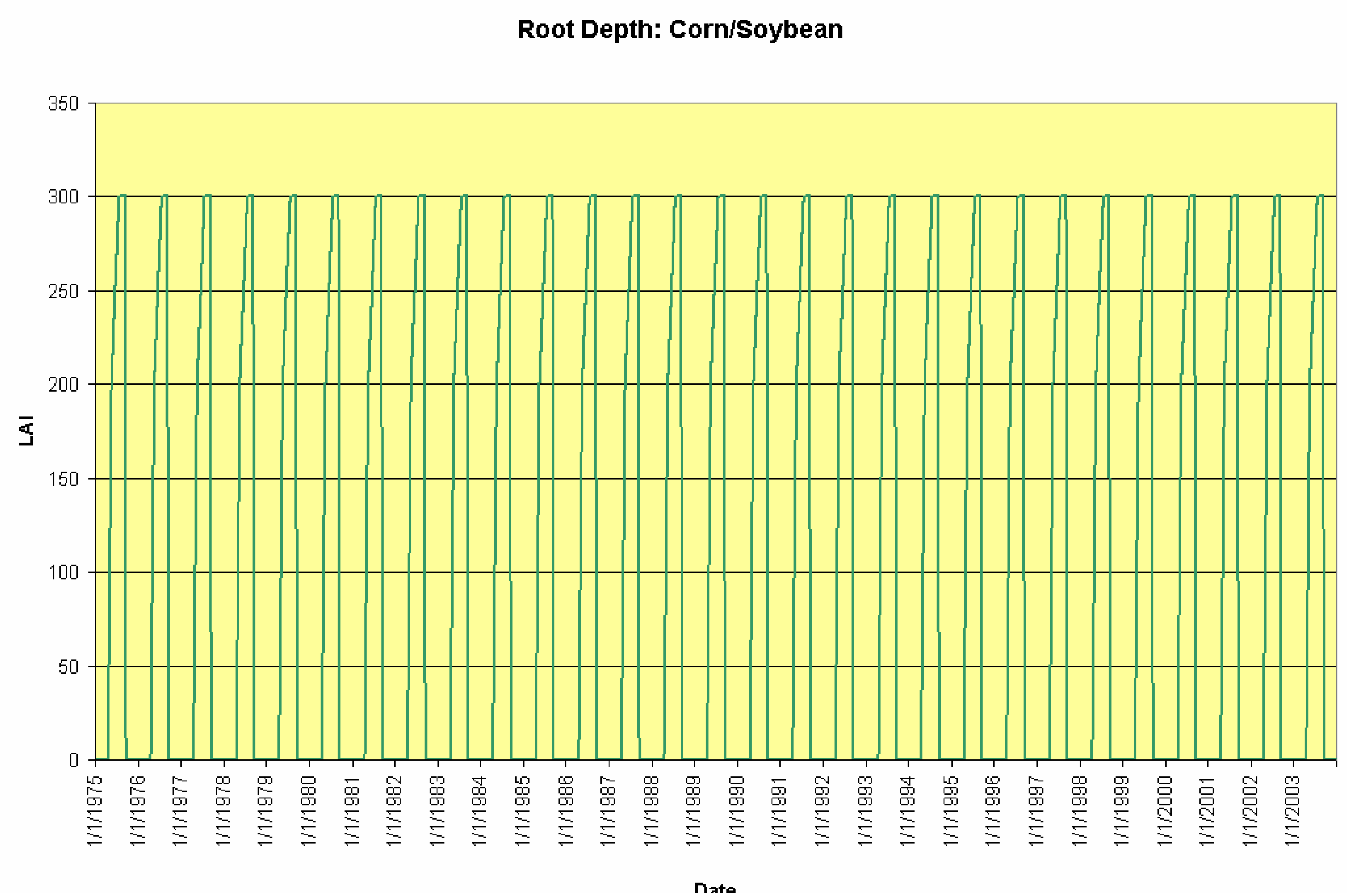
Leaf Area Index Example

source: http://www-eosdis.ornl.gov/vegetation/lai_support_images.html
“global leaf area index data from field measurements, 1932-2000, summary table



Root Depth Example



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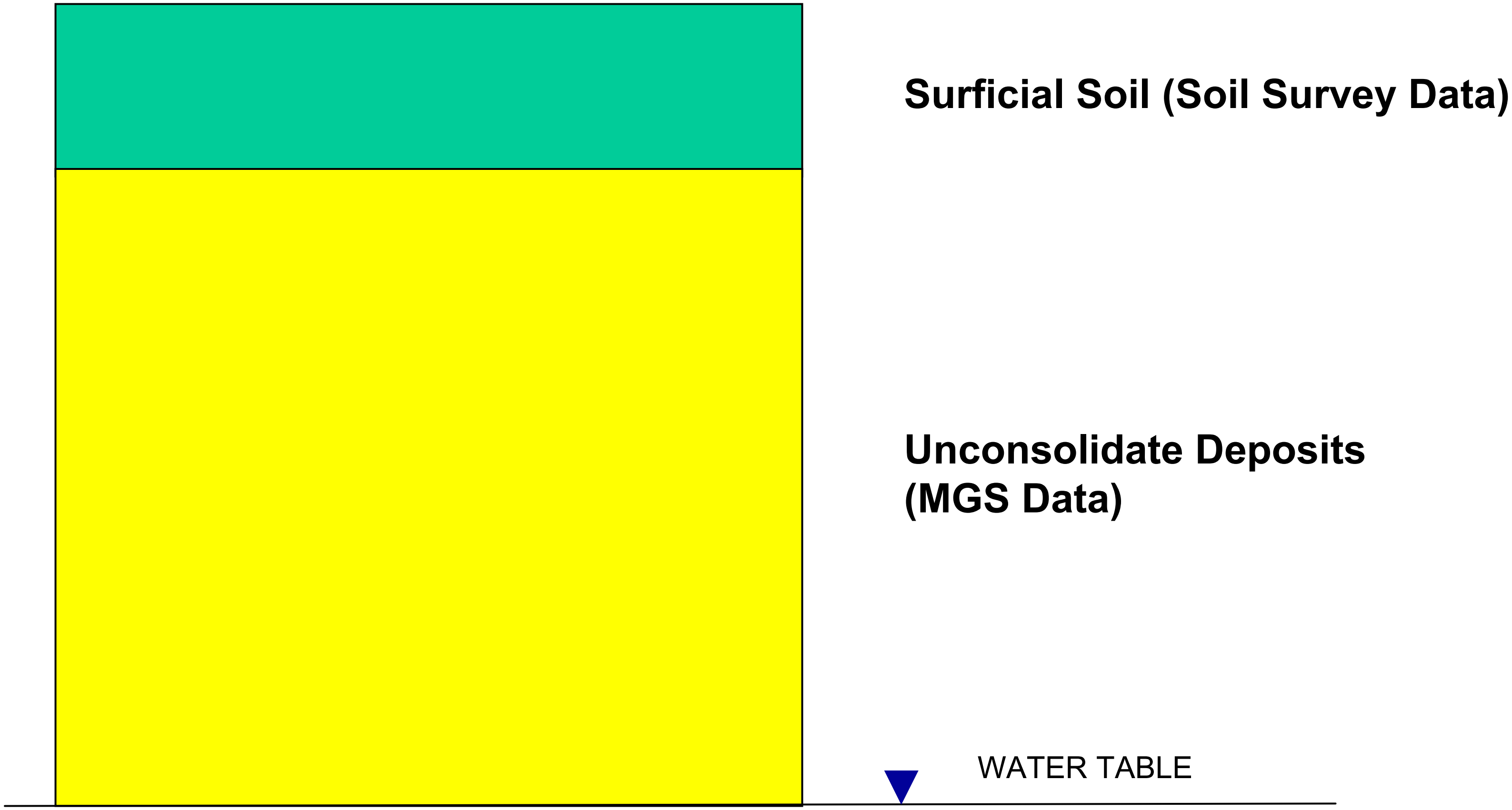
5. Vadose Zone Profile



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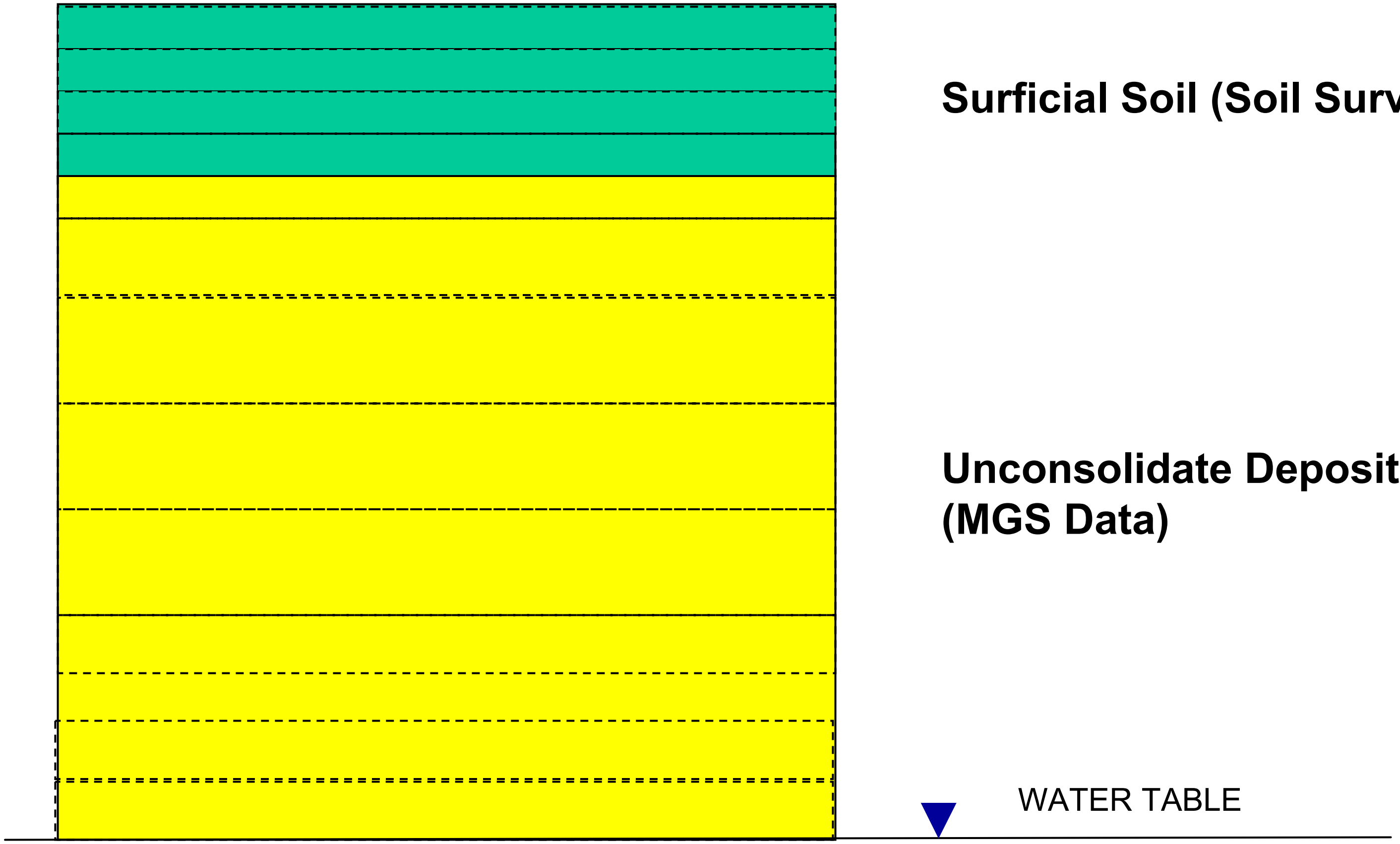
Computation Layers in Vadose Zone



Unsaturated Flow Uses Richards Equation

$$\frac{d\theta}{dt} = \frac{d}{dx} K \left(\frac{d\Psi}{dx} + \frac{dz}{dx} \right) + S$$

this says:
volumentric moisture content (θ) changes over time as a function of:
Ψ (the matric potential, which is a function of soil type)
K (hydraulic conductivity, which also changes with matric potential)
S, which is the input or output of water from the soil (e.g, infiltration, ET)

This is a very non-linear, difficult to solve problem without making simplifications

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The most important consideration is relating Hydraulic Conductivity to mositure content

$$K(\Psi) = K_s \frac{((1 + |\alpha\Psi|^n))^m - |\alpha\Psi|^{n-1})^2}{(1 + |\alpha\Psi|^n)^{m(l+2)}}$$

Van Genuchten Equation
(an approximation)

Large-scale values for the Van Genuchten variables were obtained for various soil types

	alpha(1/cm)	n	Ks (m/s)	m
Silty clay	0.013	1.32	7.13E-09	0.242
sandy clay	0.032	1.20	1.23E-08	0.167
clay	0.015	1.26	1.35E-09	0.206
silt	0.006	1.65	1.90E-07	0.394
clay loam	0.015	1.40	1.05E-08	0.286
sandy clay loam	0.017	1.32	1.30E-07	0.242
silt loam	0.005	1.65	1.46E-07	0.394
sandy loam	0.022	1.50	7.83E-07	0.333
loam	0.011	1.50	5.25E-07	0.333
sand	0.030	2.90	3.25E-06	0.655

Zhu, J., and B.P. Mohanty. Spatial Averaging of van Genuchten Hydraulic Parameters for Steady State Flow in Heterogeneous Soils. *Vadose Zone Journal*. 1:261-271, 2002.

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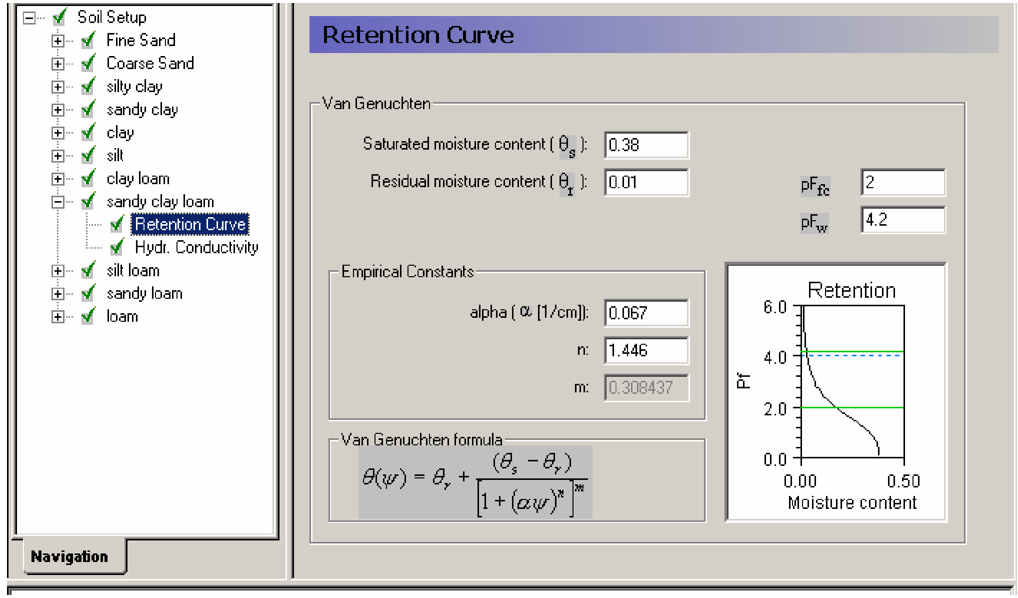
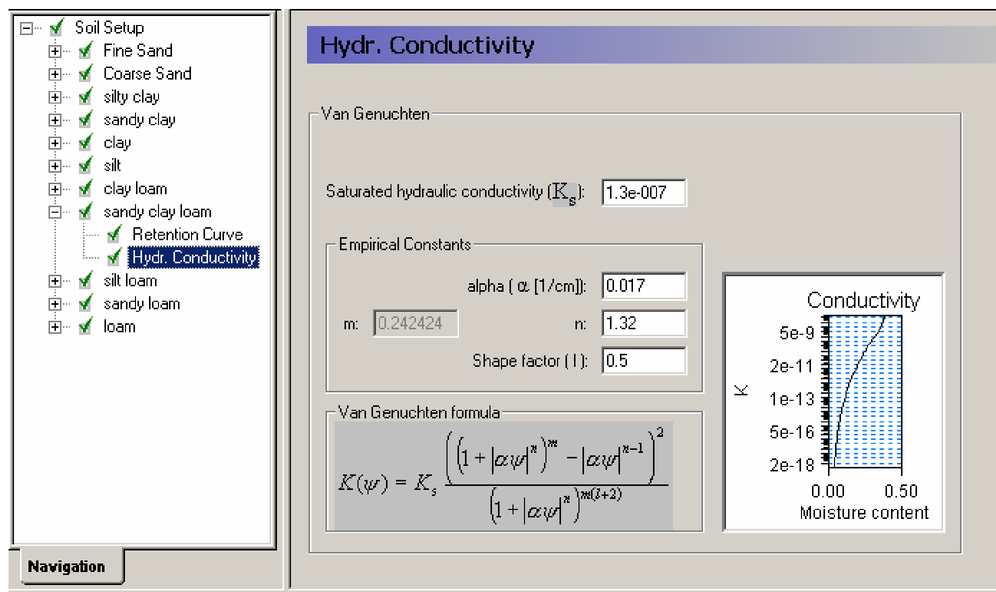
Soil Retention Curve and K sat Curve Developed for the 9 Soil Types

- Fine Sand
- Coarse Sand
- Silty Clay
- Clay
- Silt
- Clay Loam
- Sandy Clay Loam
- Silt Loam
- Loam





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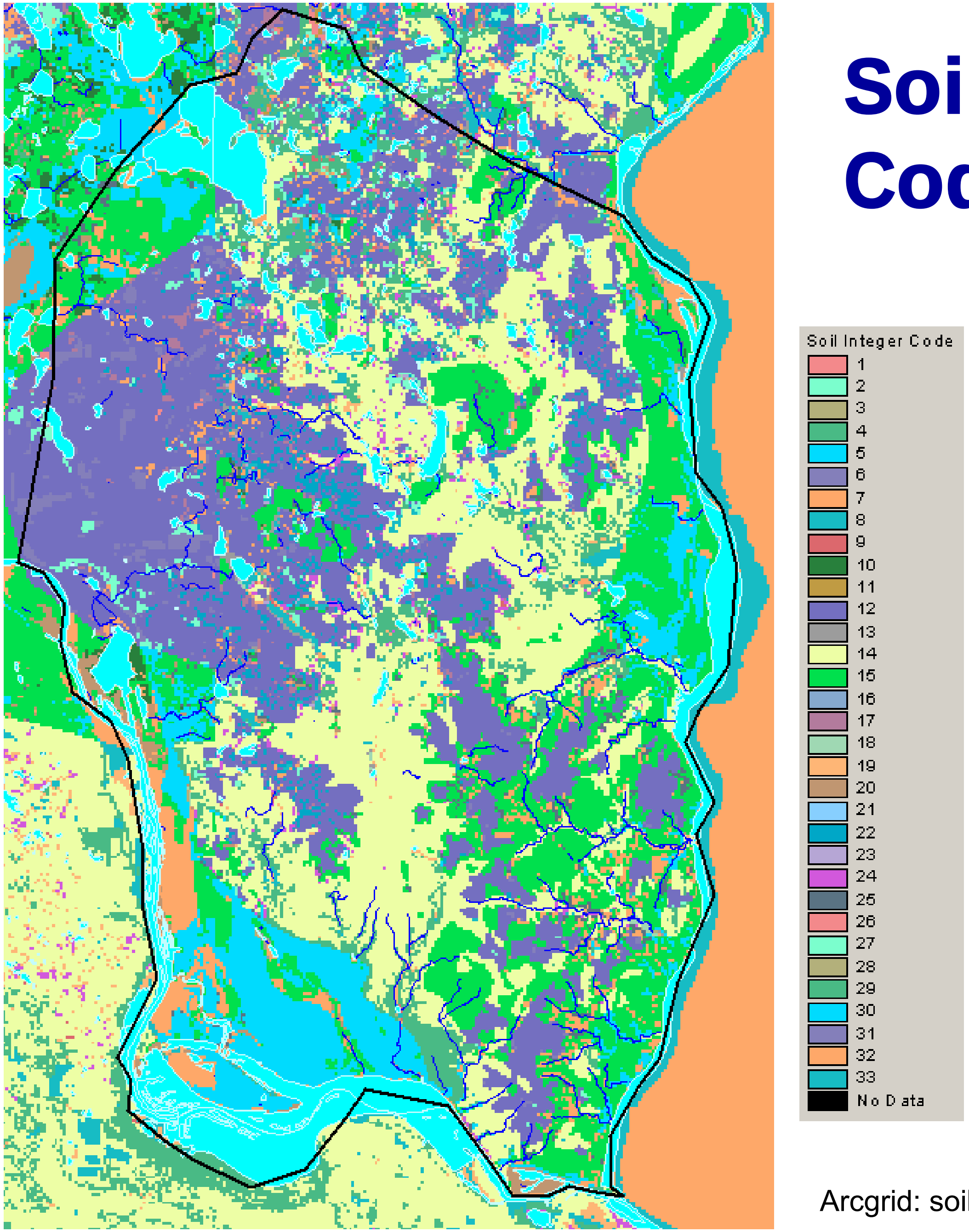
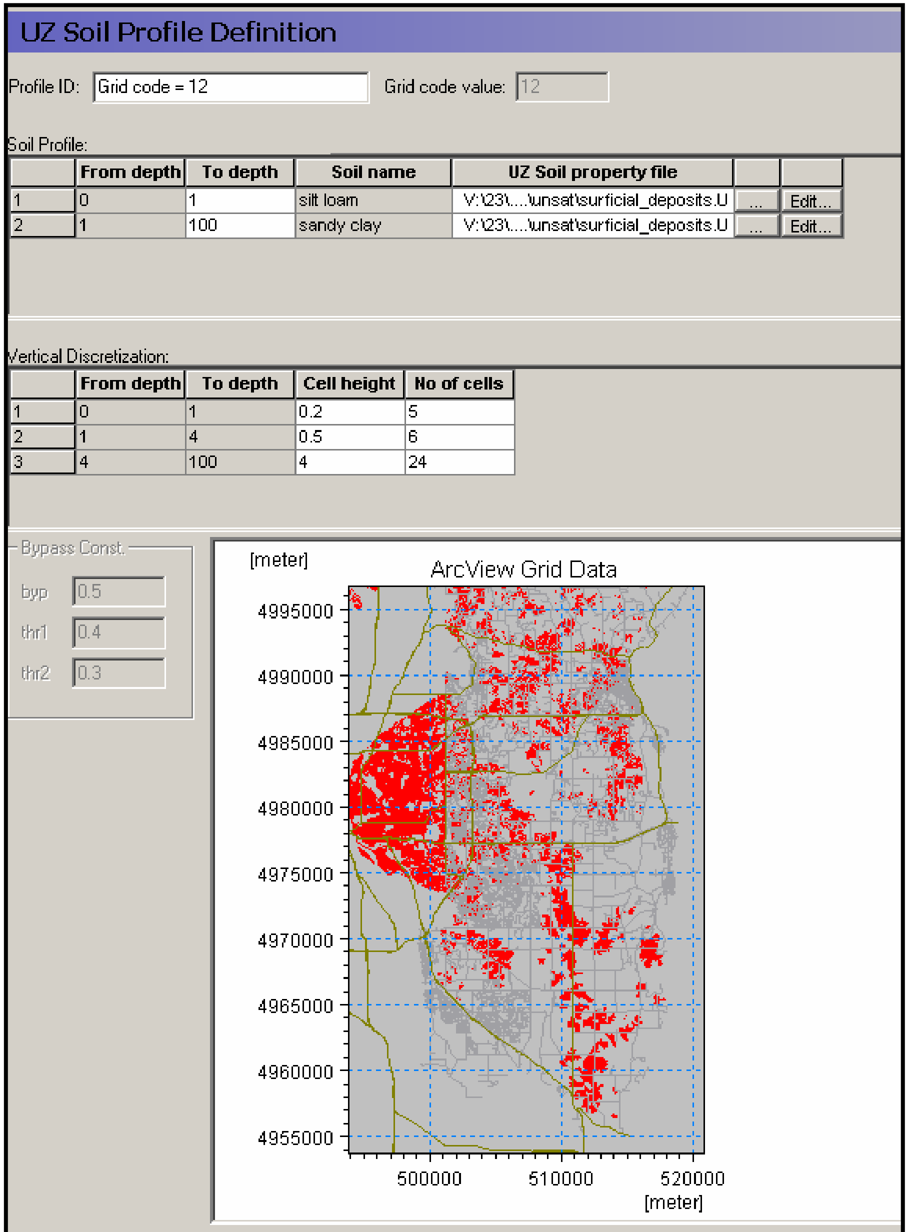
Soil Grid Integer Code



Synthesis of surface soil data and surficial geology data (above water table)

Arcgrid: soil_id



Soil Profile Definitions for Each Grid Code

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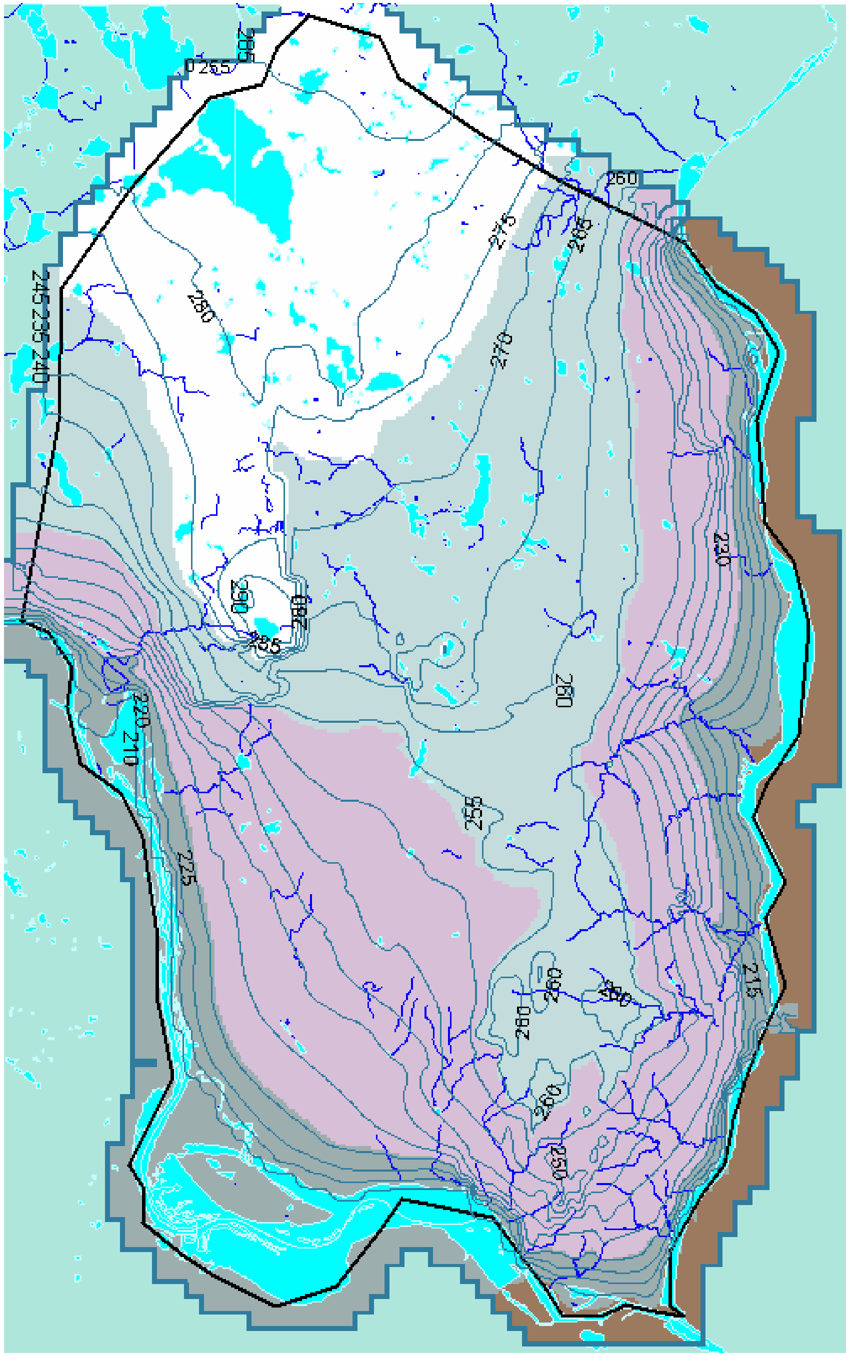
Water-Table Surface for MIKE SHE Computations



- 0 - 9.405
- 9.405 - 18.811
- 18.811 - 28.216
- 28.216 - 37.621
- 37.621 - 47.027
- 47.027 - 56.432
- 56.432 - 65.838
- 65.838 - 75.243
- 75.243 - 84.648
- 84.648 - 94.054
- 94.054 - 103.459
- 103.459 - 112.864
- 112.864 - 122.27
- 122.27 - 131.675
- 131.675 - 141.081
- 141.081 - 150.486
- 150.486 - 159.891
- 159.891 - 169.297
- 169.297 - 178.702
- 178.702 - 188.107
- 188.107 - 197.513
- 197.513 - 206.918
- 206.918 - 216.324
- 216.324 - 225.729
- 225.729 - 235.134
- 235.134 - 244.54
- 244.54 - 253.945
- 253.945 - 263.35
- 263.35 - 272.756
- 272.756 - 282.161
- 282.161 - 291.566

Arcgrid: wat_tab

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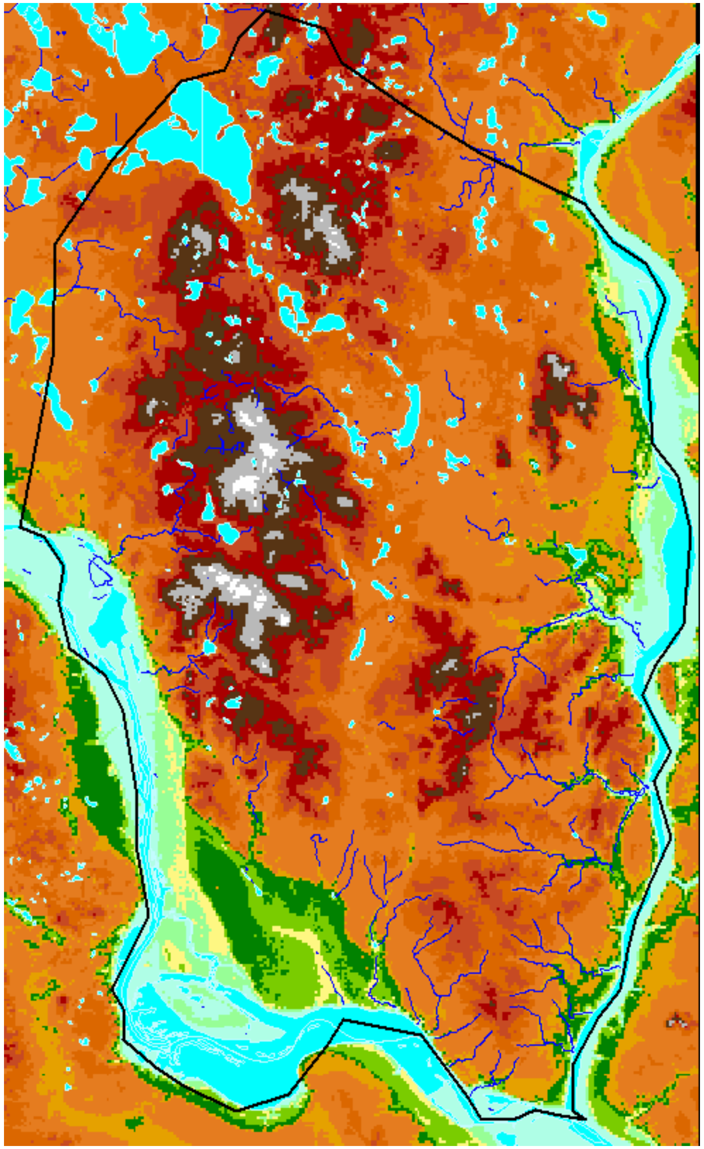
6. Overland Flow



100-m grid ground surface elevation (m, MSL)

202 - 211
211 - 220
220 - 229
229 - 237
237 - 246
246 - 255
255 - 264
264 - 273
273 - 282
282 - 291
291 - 300
300 - 308
308 - 317
317 - 326
326 - 335
No Data

Calculated from:

1. 20-m grid of Washington Co.
2. DEM (30-m)

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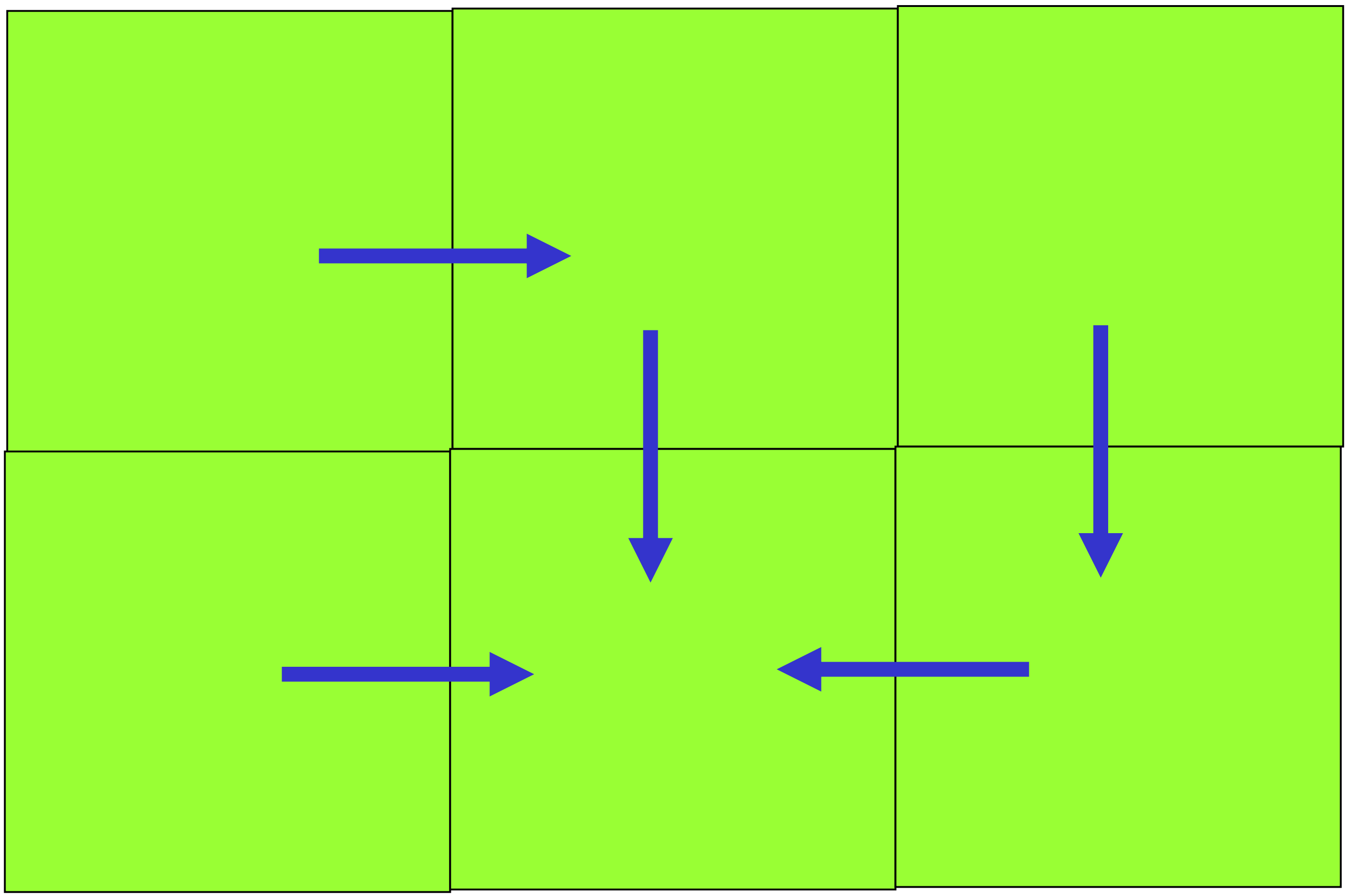
Overland Flow Computations

- Uniform Manning Number (1.5 $m^{1/3}$/S)
- Water depth threshold to initiate overland flow = 0.2 meters (based on topography and grid)

Overland Flow Routing is by Grid Cells



Running MIKE SHE to obtain infiltration

- Adaptive time stepping, based on precip and overland flow constraints (typically 12 minutes to 4 hours)
- Simulations for 1979-2003 took 6.5 days of continuous CPU time
- Channel flow (MIKE 11) set up but not in use (topography controls flow)
- Water table stationary (decoupled with saturated zone)

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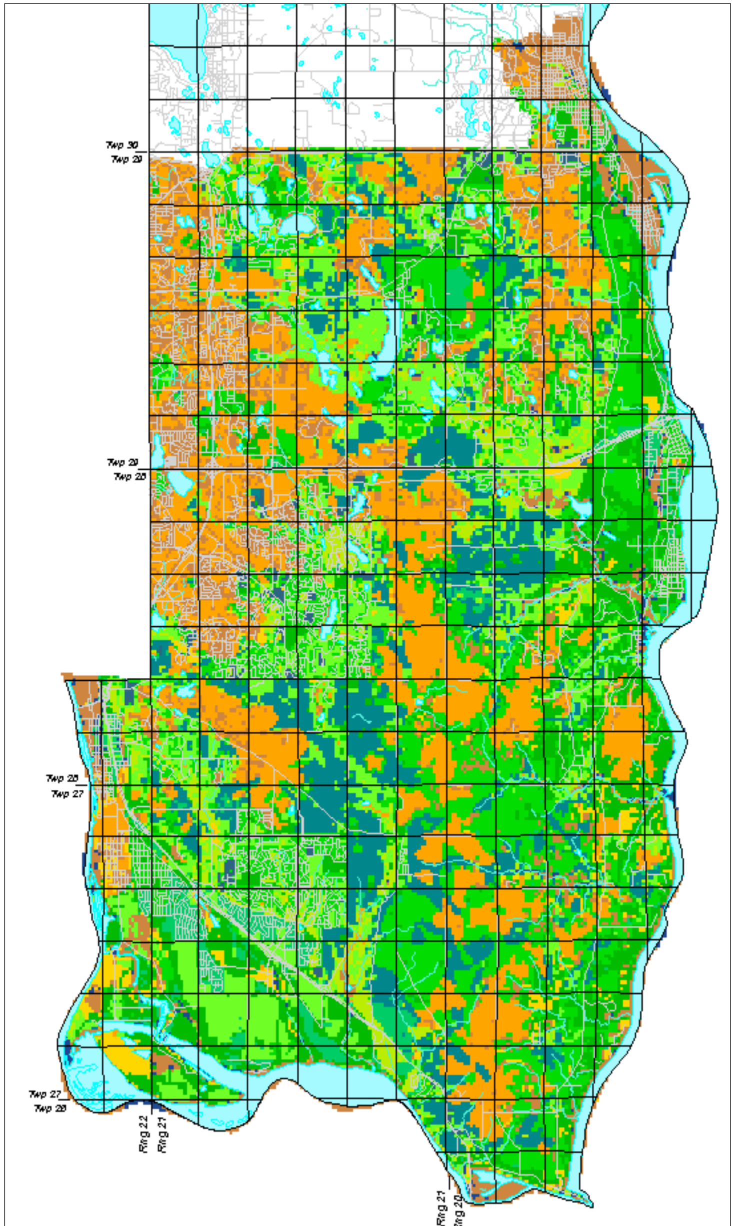
MIKE SHE Results

- Focused primarily on time-dependent exchange between saturated and unsaturated zone (i.e. recharge)
- Negative values do occur (ET pulling from capillary fringe)
- For MODFLOW model input, mean accumulated exchange calculated for calendar months



Average Recharge: 1979-2002

Average Annual Infiltration (inches)

- <2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16 - 18
- 18 - 20
- >20

Areally Averaged
Rate = 8.67 in/yr

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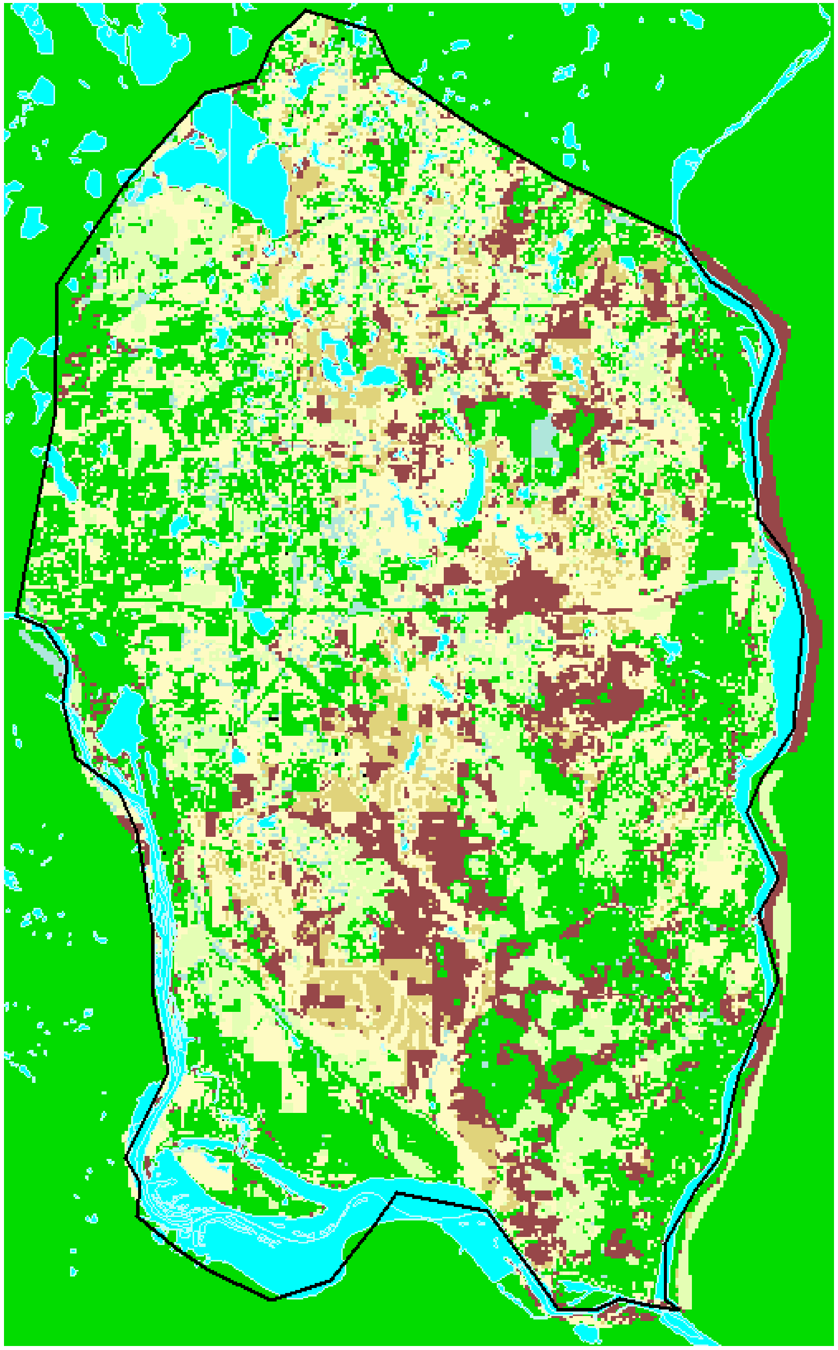
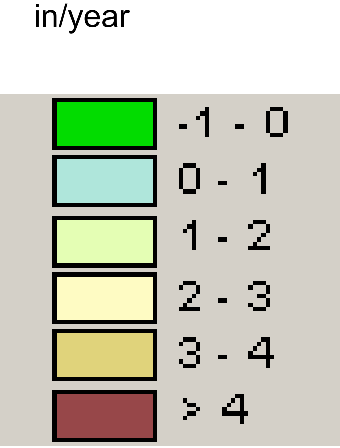
Difference in Annual Infiltration: Average vs 1988

1988 Annual total/model domain = 6.67 in/yr

Average Annual total/model domain = 8.67 in/yr





positive values indicate more infiltration during Average year

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This method… (the ugly)

- Is very data intensive
- Is very computationally intensive
- Is not calibrated and not verified in this application
- Is a vast simplification of many very complex processes

This method... (the not so ugly)

- Is based primarily on precipitation and land use/land form (not aquifer characteristics and water levels)
- Ties recharge to land use and soil characteristics
- Is sensitive to climatic conditions
- Can be used with data available for the metro area
- Is a vast simplification of many very complex processes