Overland Flow

GSSHA Basics

Overland Flow Represented as Sheet Flow

- Water running over the land surface
  - Broad, shallow flow
  - Interacts with small-scale topography (retention)

Generation Mechanisms

- Infiltration excess (Hortonian)
- Saturation excess
- Exfiltration (Groundwater discharge)
  - Seep, Spring
- Storm surge
- Out-of-bank stream flow

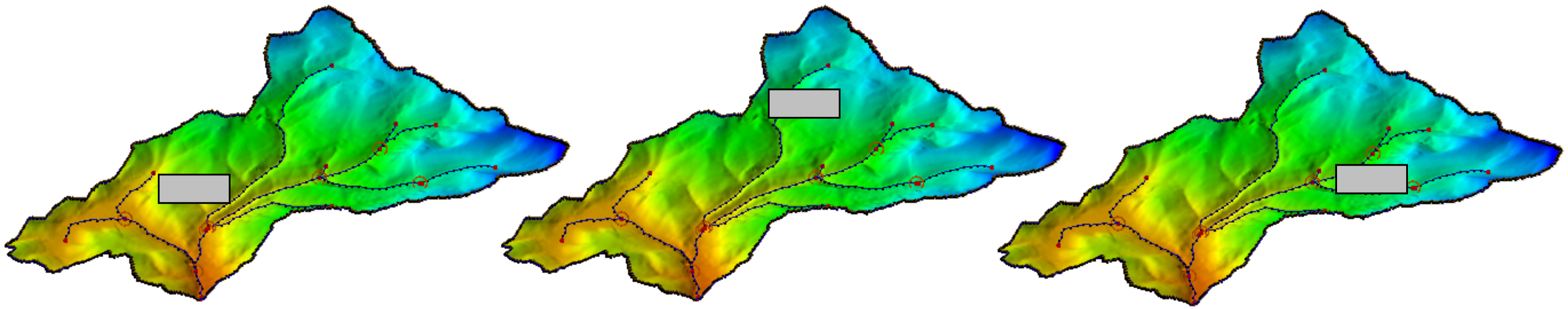
Overland Flow Model v. Runoff Transformation

Overland Flow Runoff Model

- Model spatial interactions
  - Spatial-specific data

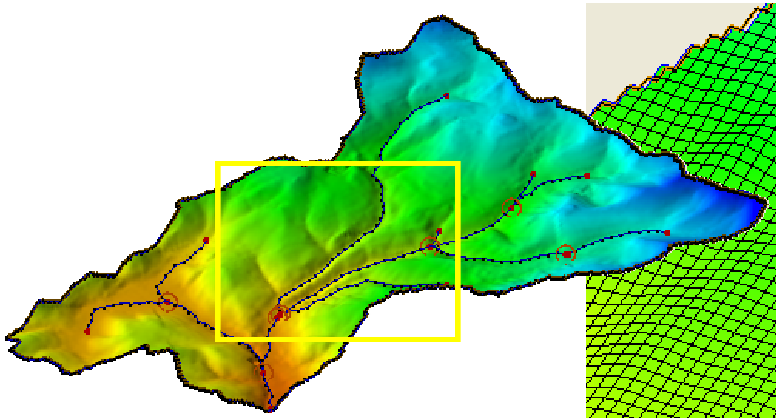
Runoff Transformation

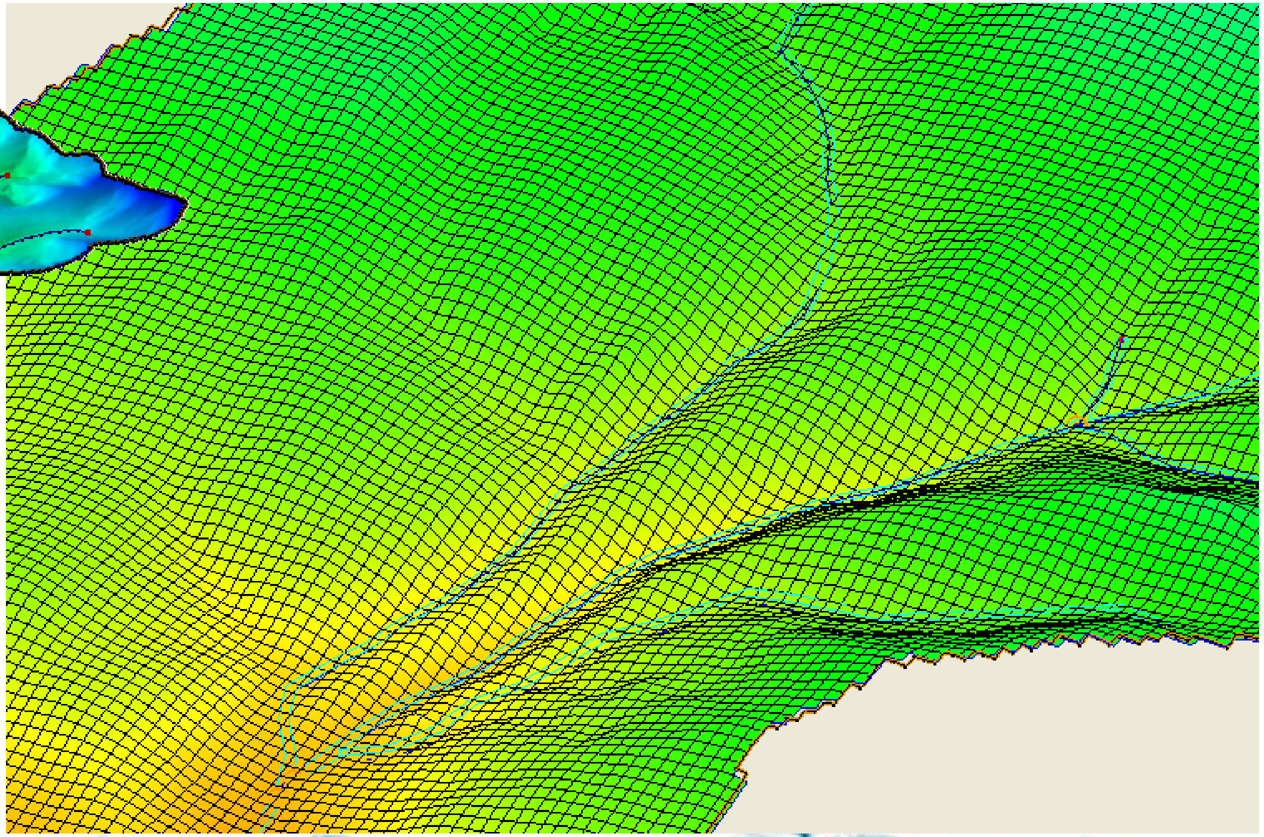
- Lump together spatial interactions (across sub-basin)
  - Spatial-general data



Overland Flow in GSSHA

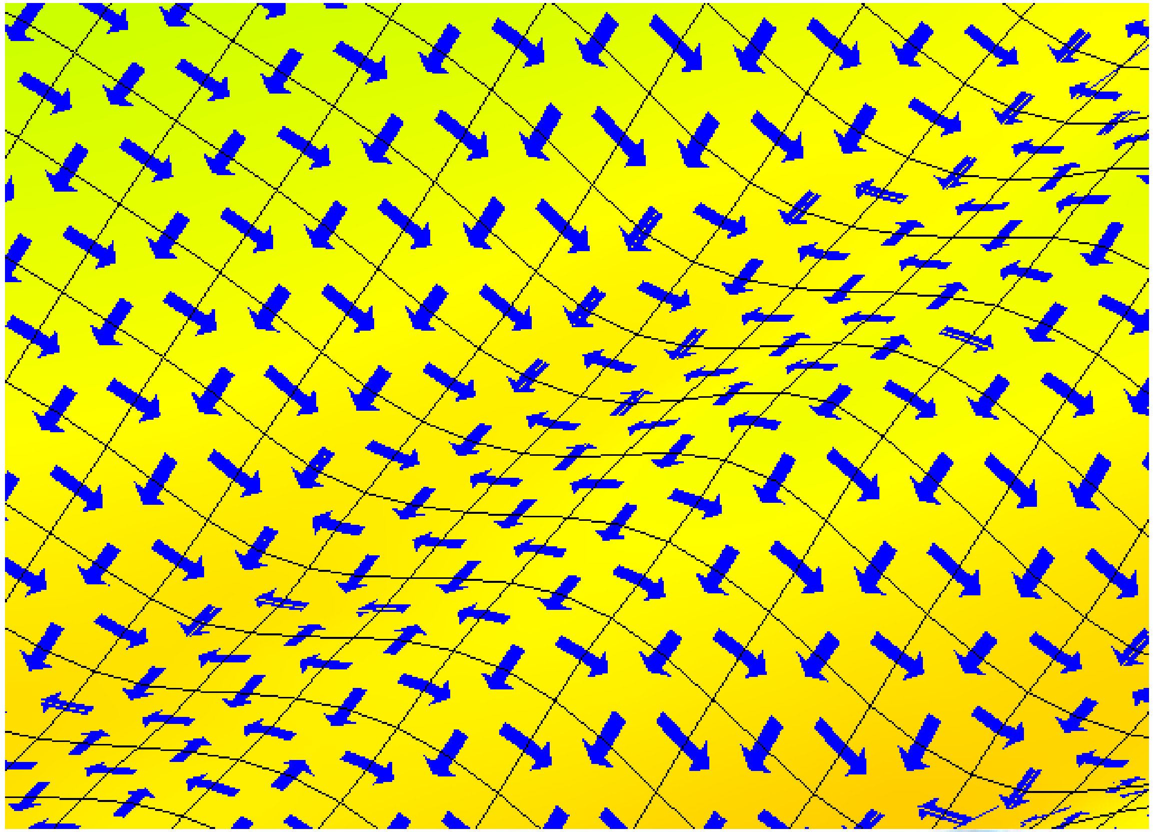
- 2D grid of interconnected cells





Overland Flow in GSSHA

- Four-point flow

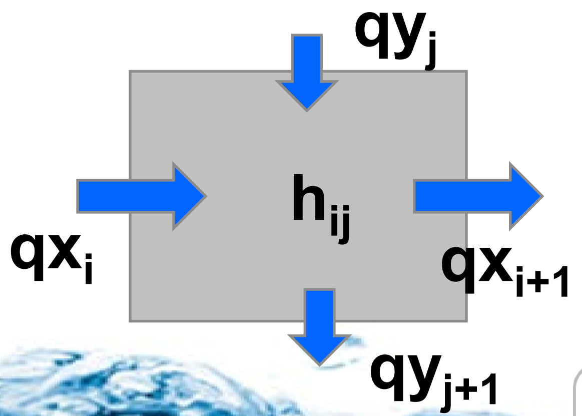


Continuity Equation

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0$$

In finite difference form

$$h_{ij}^{n+1}=h_{ij}^{n}+\frac{\Delta t}{\Delta x}\left(qx_{i-1}-qx_i+qy_{j-1}-qy_j\right)$$



Calculation of Flow

- Shallow water wave equations in one direction (x)

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{q^2}{h}\right] + \frac{gh\partial(h+z)}{\partial x} + \frac{gn^2q^2}{h^{7/3}}$$

Acceleration Advection Pressure Friction

q = unit flow
h = depth
z = elevation
n = roughness
t = time
x = distance

- If the pressure term is large compared to the other terms then

$$\frac{gh\partial(h+z)}{\partial x} = 0$$

- Which can be rearranged to put into what is called the diffusive wave equation

Diffusive Wave Equation

In X Direction

$$\frac{\partial h}{\partial x} = S_{ox} - S_{fx}$$

h = depth
S_{ox} = land slope x direction
S_{fx} = water surface slope x direction

In Y Direction

$$\frac{\partial h}{\partial y} = S_{oy} - S_{fy}$$

h = depth
S_{oy} = land slope y direction
S_{fy} = water surface slope y direction

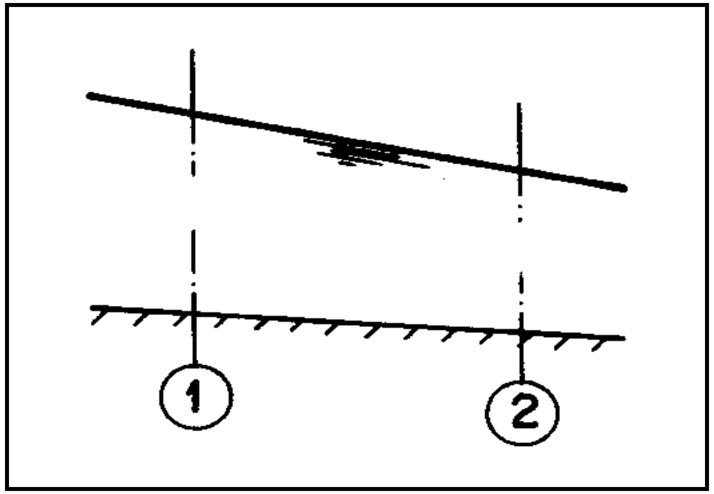
Friction Slope in Finite Difference Form

In X direction

$$S_{fx} = S_{ox} - \left(\frac{h_i - h_{i-1}}{\Delta x} \right)$$

In Y direction

$$S_{xy} = S_{oy} - \left(\frac{h_j - h_{j-1}}{\Delta y} \right)$$



Substitute into Manning Equation

Flow in the x direction

$$q_x = \frac{1}{n} h^{5/3} S_{fx}^{1/2}$$

Flow in the y direction

$$q_y = \frac{1}{n} h^{5/3} S_{fy}^{1/2}$$

Solution

- Finite volume
- Forward weighted (dependent on flow direction)
- Explicit
  - One-pass, time-variable solution
  - Compute q_x, q_y, then update heads
- ADE
  - One-pass, time-variable solution
  - Compute q_x, update heads, compute q_y, update heads
- ADE-PC
  - Two-pass ADE
  - Uses a weighted average of the steps to compute the new heads

Scheme Properties

- Does not require continuous media (avoiding wet/dry issues)
- Avoids problems with shocks found in dynamic and kinematic flow equations
- Diffusion smooths transitions in flow
- Captures backwater effects
- Can be used to bring in outside boundary conditions (tidal surge)
- Has some issues
  - Manning roughness is not constant with depth
  - Can smear the water surface profile near transitions
  - Because the flow has no momentum, flow direction can change due to only small changes in water surface elevation, can become a problem

Special Considerations for Flood Waves

- Depth varying Manning roughness
- Inertial formulation of discharge
- Blockage of cells due to buildings

Depth Varying Manning Roughness

- Resistance to flow (expressed as roughness) varies as the depth of flow varies
  - Overland flow roughness values are about an order of magnitude greater than channel roughness parameters
  - In flooding situations, overland flow roughness values calibrated for normal runoff may be way too high
  - For a model to work in all possible conditions the roughness needs to vary with the depth
  - There are many potential forms of depth varying overland roughness, GSSHA employs an exponential function $n=n_o e^{-ah}$ where:
    - n is the depth varying roughness
    - n_o is the overland roughness value
    - a is an exponent between 0 and 1, typical value of 0.5
      - At a = 0, n=no (default)
    - h is the depth of flow (m)

Inertial Formulation

- Shallow water wave equations in one direction (x)

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{q^2}{h}\right] + \frac{gh\partial(h+z)}{\partial x} + \frac{gn^2q^2}{h^{7/3}}$$

Acceleration Advection Pressure Friction

- If we ignore advection, this can be rewritten as:

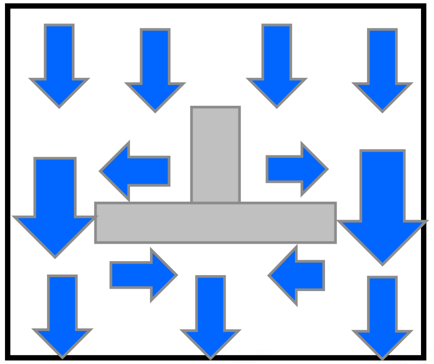
$$q_{t+\Delta t} = \frac{q_t - gh_t \Delta t S_f}{1 + gh_t \Delta t n^2 / h_t^{10/3}}$$

- Substituted for q based on the Manning formula for the continuity equation
- In theory, is more stable for flooded conditions because giving the water momentum should reduce rapid flow direction changes

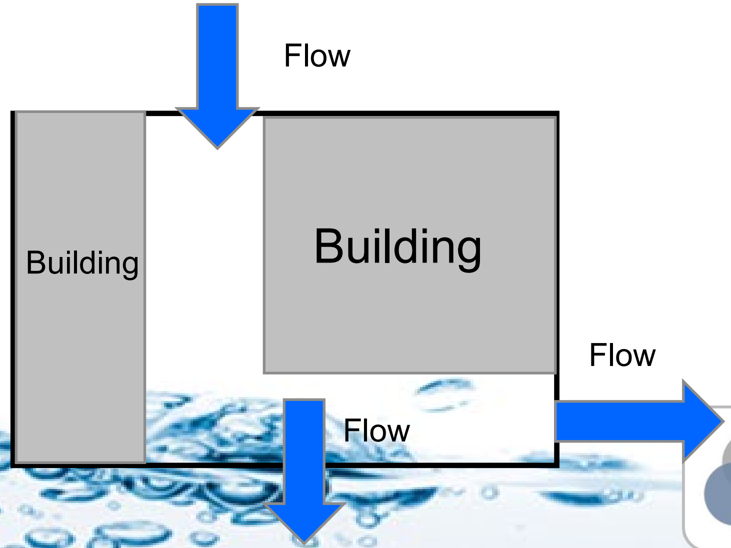
Flow Blockage

- When urban areas flood, buildings can affect the flow paths of flood waters.
- Ignoring buildings could lead to underestimating flow depths, and coverage, as well as timing issues.
- The effects of buildings, or other impediments to flow, can be included by utilizing the cell blocking feature in GSSHA where the flow area is reduced for cells with obstructions.

Flow around obstruction in grid



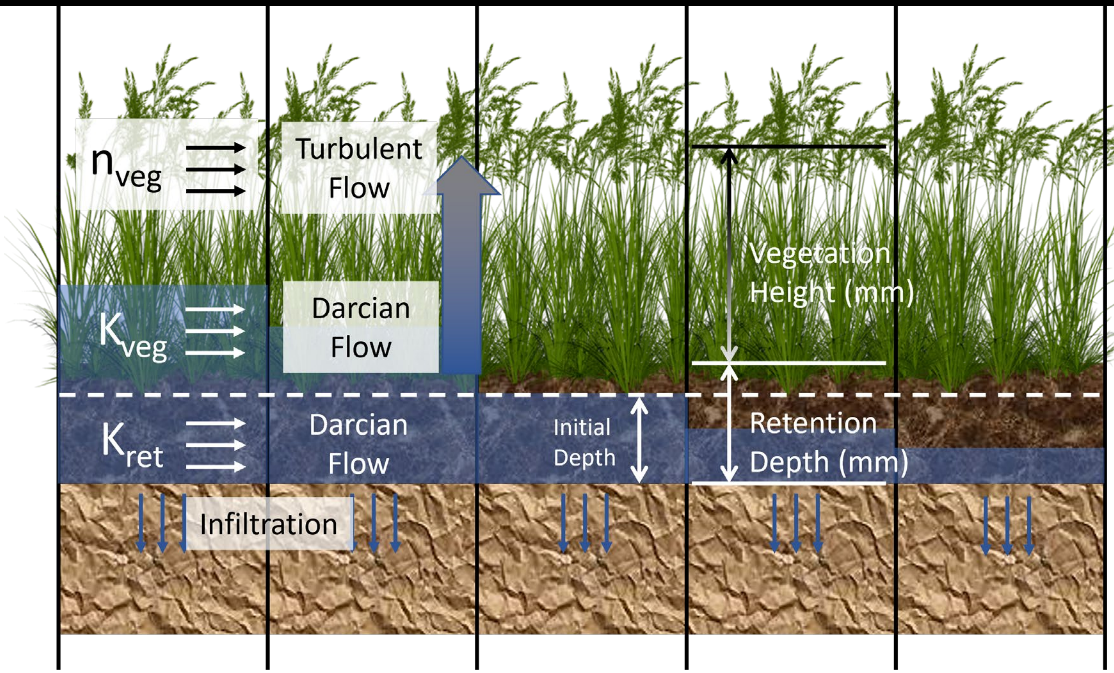
Partially blocked cell



Wetlands

- Wetlands are special overland flow cells with three types of flow
  - Turbulent flow above the vegetation
  - Darcy flow through the vegetation
  - Darcy flow through the peat layer

- The three layer captures effects that cannot be duplicated by simple overland flow, even with extensive retention depth



https://www.wetlands-initiative.org/what-is-a-wetland

Basic Model Requirements

- Land surface elevation → DEM
- Manning's roughness
- Retention depth

  } → Land Use
- Rainfall input →
  - Uniform
  - Gage
  - Radar
- Outlet location and slope → DEM
- Cell Size
- Time Step

  } → User defined

Cell Size Selection

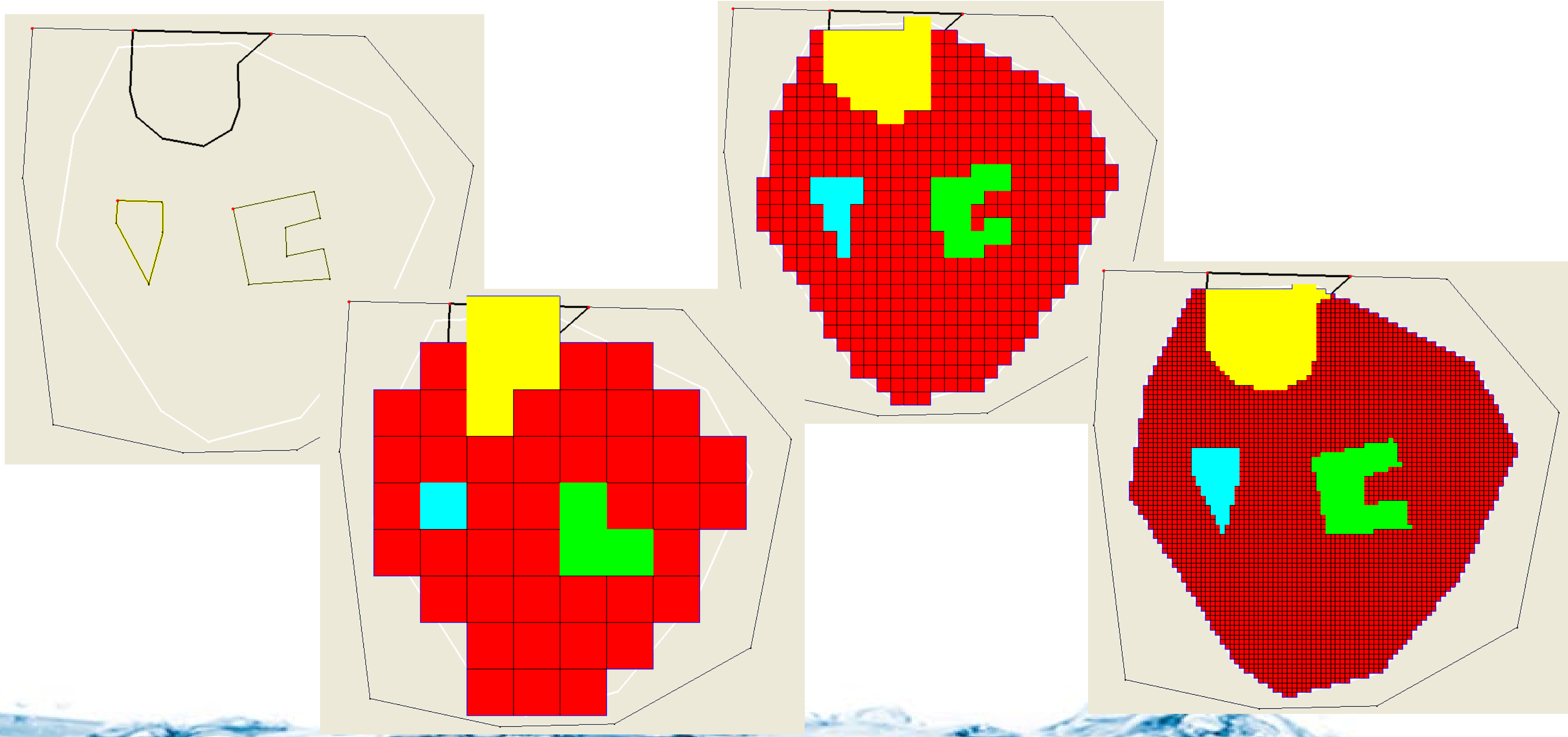
- The grid is the basis of the model.
- Information at the sub-grid level is lost.
- Things to consider.
  - What is the resolution of your input data?
    - Don’t make grid size smaller than the resolution of your DEM
  - What features are you trying to capture?
  - What is the purpose of your model?
  - What are the dominant processes?
  - Computational burden.
    - Watershed size
    - Computing power
      - Current computing power supports models with 10^6 to 10^7 cells

Cell Size Selection: Computational Requirements

- 100 ac
  - 10m = ~4000 cells
  - 50m = ~160 cells
  - 100m = ~40 cells
  - 200m = ~10 cells
- 100 mi^2
  - 10m = ~2,600,000 cells
  - 50m = ~104,000 cells
  - 100m = ~26,000 cells
  - 200m = ~6,500 cells
- 10 mi^2
  - 10m = ~260,000 cells
  - 50m = ~10,400 cells
  - 100m = ~2600 cells
  - 200m = ~650 cells
- 1000 mi^2
  - Ouch!
  - 10m = ~26,000,000 cells
  - 50m = ~1,040,000 cells
  - 100m = ~260,000 cells
  - 200m = ~65,000 cells

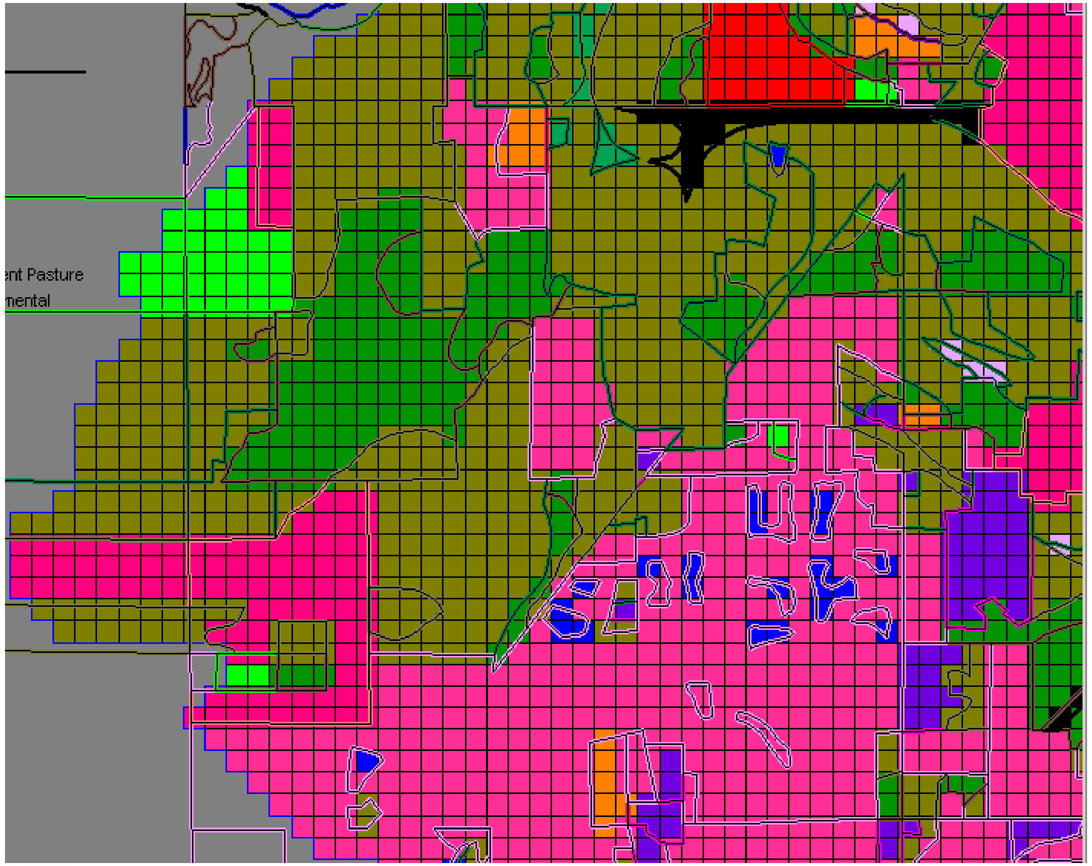
Cell Size Selection: Data Requirements

- Must consider scale of important features

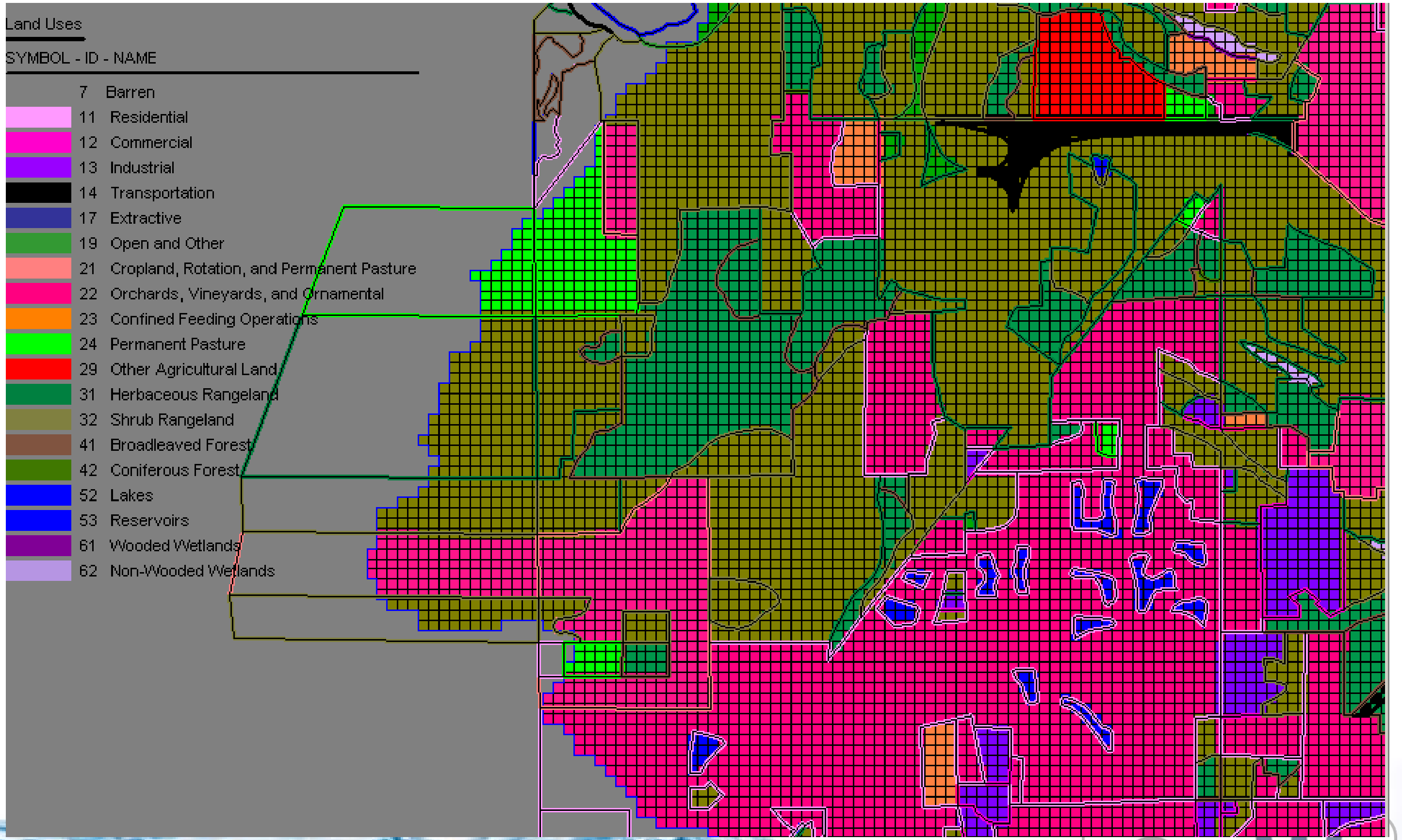


Capturing Land Use

100 m Grid

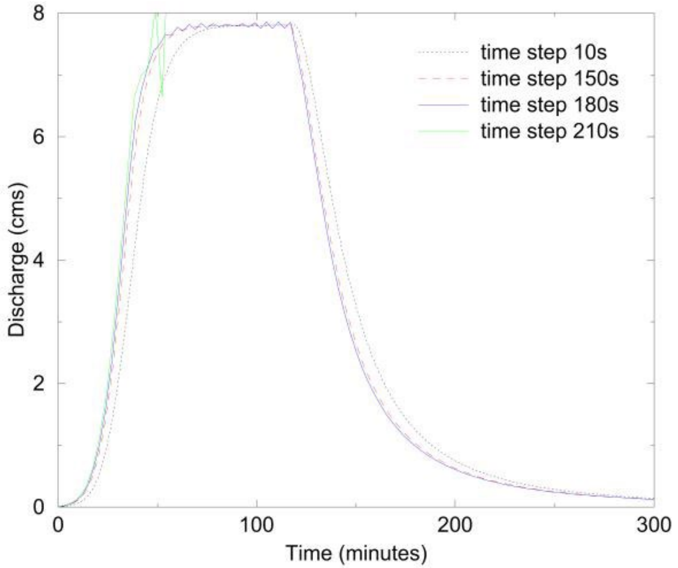


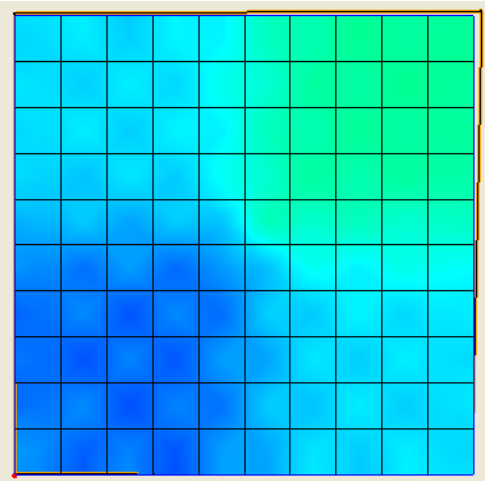
50 m Grid



Time Step Selection

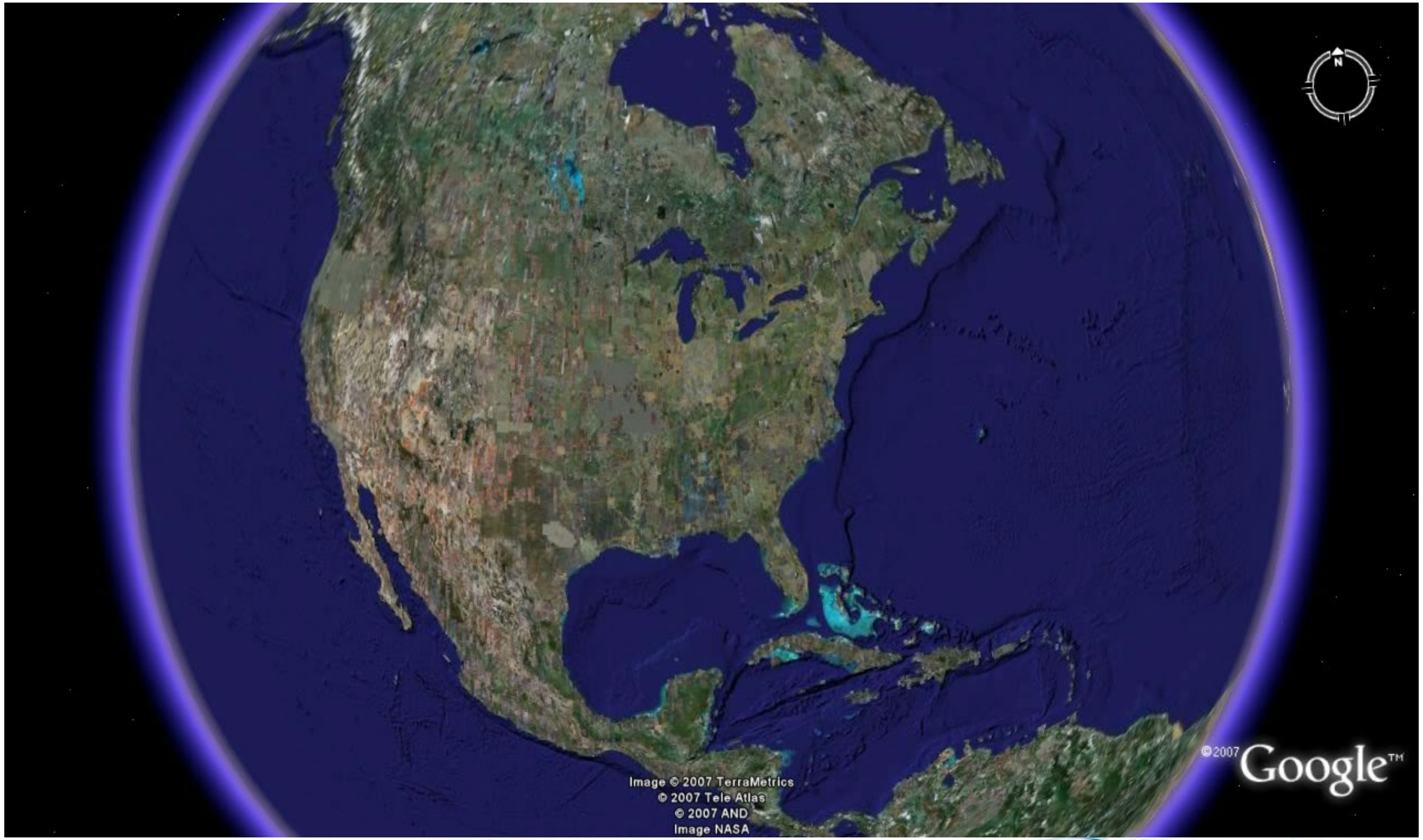
- There is an important relationship between flow velocity, cell size, and the model time step. The flow velocity cannot exceed the grid velocity: $\Delta x/\Delta t$





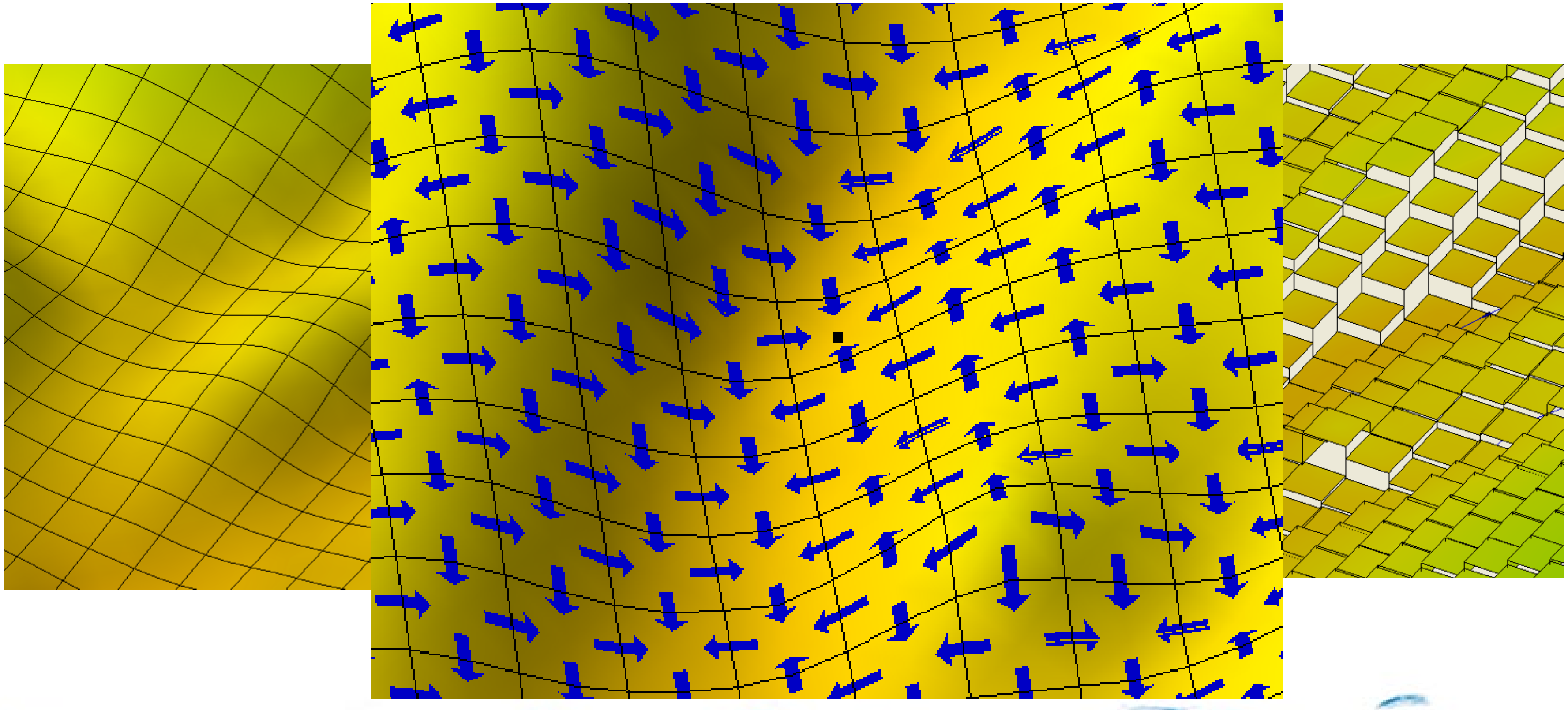
- For stability the time step must satisfy the courant criteria.
- For accuracy and efficiency the time step should be maximized.
- Time step is determined by a convergence study.
- Indications time step is too large.
    - Model crashes
    - Oscillations in hydrograph
    - Checker-boarding
    - Mass balance errors

Hypothetical Storm Surge Charleston

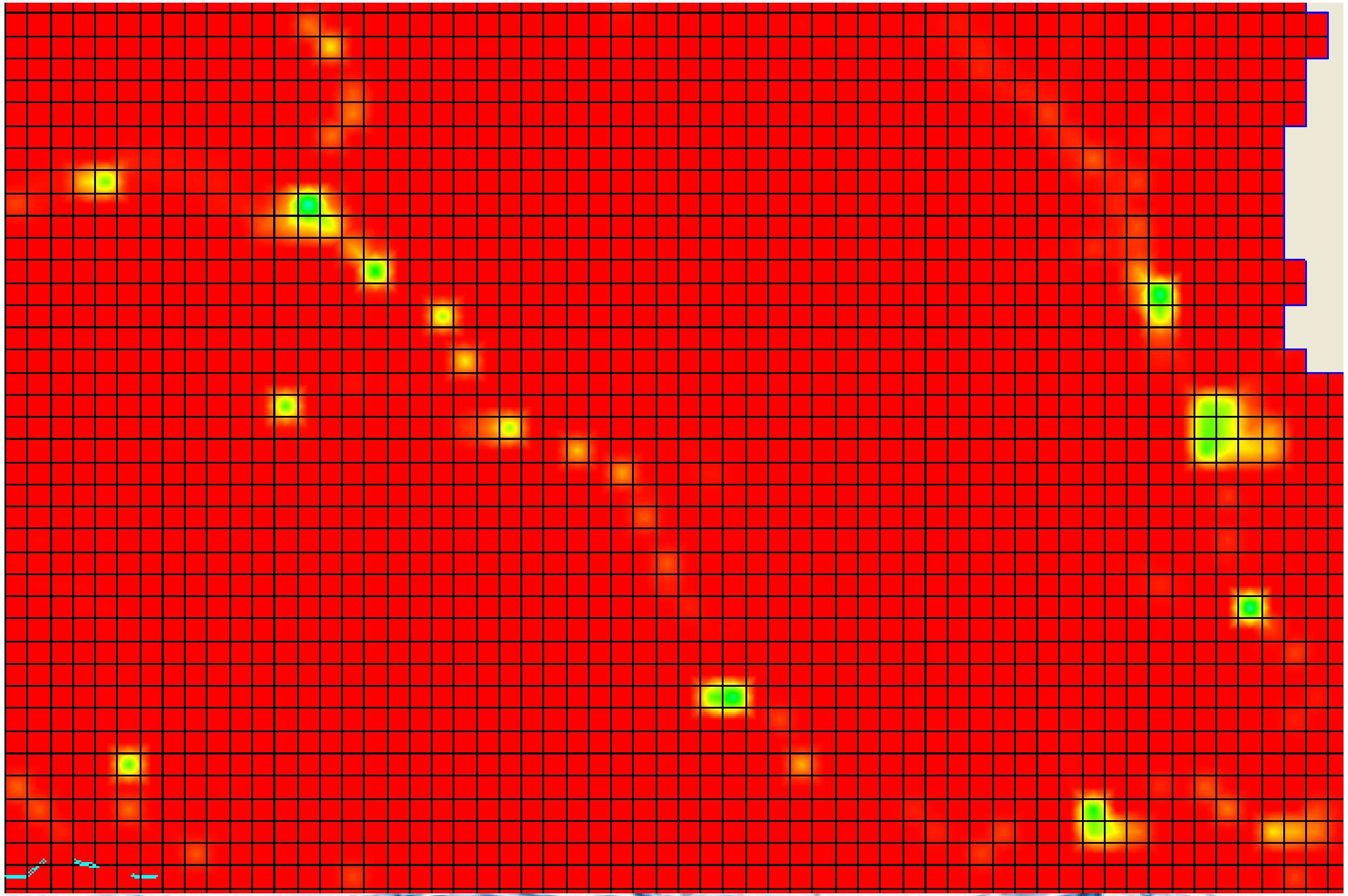


A Problem You Will Run Into

- Digital Dams



Digital Dams



Keys to Success: Start simple and build on success

- Build the basic model
  - Start with overland flow, uniform roughness, and uniform precipitation
  - Work out digital dams
  - Add land use, spatial roughness
  - Add retention depth
- Add processes and detail to satisfy the demands of your project
- You have to conceptualize your physical system and build a model that simulates the system properly.
- Don't include needless detail that adds nothing to your solution.