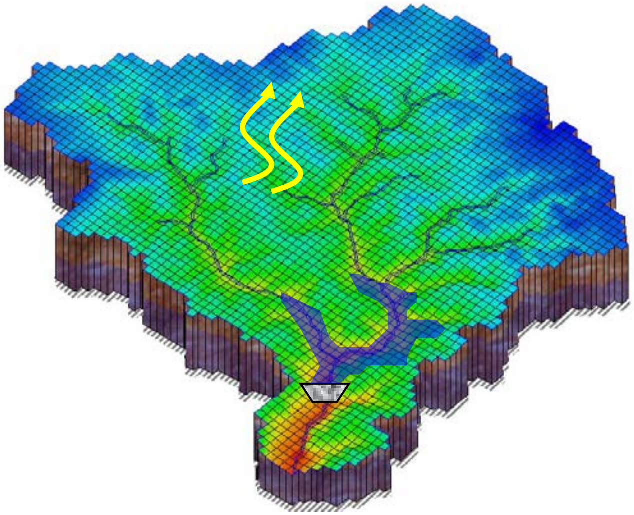
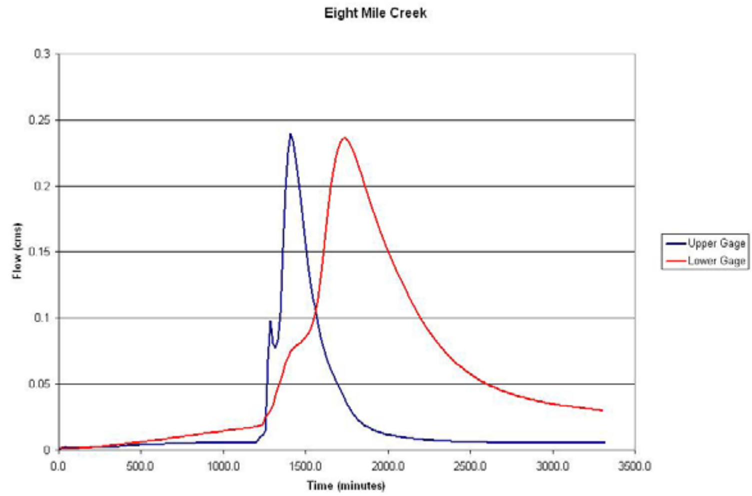
Groundwater Modeling Basics





Chuck Downer, PhD, PE

US Army ERDC

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W(x,y,t)$$

Why Surface Water Modelers are Terrible Groundwater Modelers

Surface water modeling is VERY different from groundwater modeling.

In this lecture I will:

- Discuss the differences between surface water and groundwater modeling.
- Try to stress the points that surface water modelers have the hardest time grasping.

Note:

- I can't teach you groundwater modeling in course of an afternoon.
- Now I will begin trying to teach you groundwater modeling in the course of an afternoon.

Surface Water Modeling

In surface water modeling

- The domain is predetermined, the watershed.
- The problem is pre-conceptualized, you already know what you are going to model.
- Forcing dominates the process – precipitation and ET are controlling variables.
- The system has short memory.
  - What happens early in the simulation has little bearing on what happens later in the simulation.
  - The simulation time is long compared to the system history.

Groundwater Modeling

In groundwater modeling

- The need for boundary conditions dominates the domain selection.
- You must conceptualize the subsurface system, try to figure out how it works, and then devise a plan to represent system *function*.
  - There will be many unknowns.
  - You may not be able to represent the system the way you imagine it.
  - Your goal is to able to reproduce the system response for your purposes.
- Boundary and initial conditions are the controlling variables.
- The system has a long memory.
  - Initial conditions can dominate the entire simulation.
  - The system response is slow compared to the simulation time.

Expansion on Groundwater Modeling

- Groundwater modeling requires extensive up front effort.
- Steps to take before simulations begin
  - Conceptualize the system
  - Locate appropriate boundaries
  - Define the boundary conditions
  - Develop initial conditions

Conceptualize the System

- Conceptualizing the hydrologic system is key to groundwater modeling.
- For the purposes of GSSHA applications our focus is on figuring out how the subsurface water affects the surface water flow. In keeping with that we are most concerned with the shallow aquifer, which may be local.
- Groundwater affects the surface water in the following ways
  - High groundwater contributes directly to the stream in the form of base flow and quick flow.
    - As the water table falls streams contribute back to the groundwater.
  - A high groundwater table can result in reduced infiltration, no infiltration, and even exfiltration back on the overland flow plane.
  - Groundwater interacts with reservoirs in a similar fashion.

Conceptualize the System

Key Questions

- Is the system local or regional?
  - If the system is local then you are more likely to get away with using the watershed boundary as a no-flow boundary condition.
- What is beneath the ground?
  - What is the substrate made of?
  - Is it homogeneous?
  - Are there layers?
- Where is the water?
  - How deep is the water table?
  - Are there multiple groundwater systems?
  - Which of these systems, if any, interact with the surface water?

Conceptualize the System

Model Considerations

- Your conceptualization must be consistent with the model you have selected.
- GSSHA simulates 2 dimensional lateral groundwater flow and solves the free surface groundwater flow equations.
- This representation of the groundwater is likely sufficient for the purpose that groundwater modeling is conducted within the GSSHA framework – that is to determine the influence of groundwater on the local surface water system.
- This formulation may not be appropriate if
  - Deep aquifers in layered systems must be simulated explicitly
  - The shallow aquifer is artesian

Conceptualize the System

Data Requirements

- You must have sufficient information to represent your conceptualization of the system.
- If the data are not sufficient you must collect more data (unlikely) or simplify your approach (more likely).
- Simplifying the model
  - Single layer
  - Assumed aquifer bottom
  - Homogeneous substrate
  - Simplified approach

Conceptualize the System

Conceptualization takes Research!

Sources of Information

- USGS and other publications
- Previous modeling efforts
- Borehole data bases – USGS, State Agencies
- Well data bases – USGS, State Agencies
- Talk to local USGS and state agency personnel familiar with the subsurface, the aquifers, and previous modeling efforts.
  - Ask them how the system works.
  - Keep in mind they are likely to be concerned with the regional system and may be more interested in aquifers not salient to your model.
- Stream gages – USGS, USACE, local sources

Locating Model Boundaries

- Establishing appropriate boundary conditions is key successful groundwater modeling.
- The study domain cannot be established without considering the boundary conditions.
- Landscape features that make natural boundary conditions are:
  - Ridges – groundwater divide
  - Water bodies – rivers, canals, lakes, reservoirs, the ocean
- In areas with adequate relief the watershed boundary can be used as the groundwater boundary.
- Even in watersheds with significant relief in the uplands, the watershed boundary near the outlet may not be a groundwater divide.

Boundary Condition Types

- Specified flow – no flow boundary condition
- Specified head

Establishing Boundary Conditions

- Natural boundaries
  - Groundwater divides (watershed boundary) – no flow condition
  - Water bodies – head boundary
- Boundaries from data
  - Specified head boundaries can be determined from
    - Observation wells
    - Boundaries from larger scale model
- Extend the study domain so that the boundary has limited affect on the area of concern.
- Use a large scale model to bring in the boundary condition to your domain
  - Large scale model extends out to good boundary condition
  - Large scale model extends out well beyond area of interest

Another Thing You Will Hate

Initial Conditions

- In surface water hydrology the initial condition has only a temporary effect on the outcome.
  - Senerath et al. (2000), determined that the effect of the initial moisture estimate had little effect on model results after the first storm event in a continuous simulation.
  - Surface water processes are relatively rapid.
    - The simulation time is long relative to the movement of water in the system.
- Because water movement is slow in the subsurface, the initial condition will likely affect the entire simulation.
  - The simulation time is short relative to the movement of water in the subsurface.
  - Much of the water in the groundwater domain will likely remain in the system for the entire simulation, maybe forever – or close enough.

Establish Initial Conditions

There is a multi-step process to establishing initial conditions for a groundwater model.

- Step 1 - Establish a crude estimation of the groundwater heads.
- Step 2 - Use the model to smooth out the initial estimate.
- Step 3 - Conduct additional simulations with forcing data to develop a reasonable approximation of groundwater heads.
- Step 4 - Simulate all data up the point of interest.
- Step 5 - Include a start up period in the model simulations.

Establish Initial Conditions

Step 1 - Establish a crude estimation of the groundwater heads.

Observations

- Well data
- Model results – regional model
- Interpolate measured or model data to the grid.
- Estimated depth to groundwater
  - Subtract estimated depth to groundwater from the land surface elevations on grid.

These methods may (will) produce unrealistic groundwater levels.

- The worse this estimate is, the longer it will take to do the next steps.
  - Groundwater may be above land surface in the cell it is in or in downstream cells.
  - Groundwater surface may be irregular and unrealistic.

Saving Grace of Groundwater Modeling

- Groundwater flow is a diffusion process.
  - At least that is how we simulate it.
- Diffusion tends to smooth things out without tremendous numerical difficultly
  - As opposed to advection, which dominates surface flows.
- Thus the groundwater model itself is perfect tool to smooth out irregularities with the initial water surface .
- And we will use the model to help us establish appropriate initial conditions.

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W(x,y,t)$$

Establish Initial Conditions

Step 2 - Smooth this crude estimate by running the model to get a reasonable groundwater surface map.

- First without rainfall and without streams
- Add streams – still no rainfall
- In each case run the model in long term mode repeatedly, feeding the results of the last simulation in as a starting point for the next.
    - Hot start – GSSHA automatically outputs a file called "hotstart_file" to your project directory. This is a map of the ending groundwater heads.
- Do this until the model "calms down" or reaches near steady-state
    - Surface is no longer flooded – summary file
    - Stream flow is sane – summary file, outlet hydrograph
    - Heads are not changing rapidly – difference between initial values and final values.
- DON'T WORRY ABOUT THE MODEL OUTPUT!!!!!!!!!!!!!!!!!!!!!
    - We are only trying to get a good starting point, the hotstart_file.

Establish Initial Conditions

Step 3 - Use the results of the last effort to establish actual initial conditions for simulations.

- Starting with the heads from Step 2 run the full model, streams on, etc., with the actual forcing data (rainfall, Hmet).
- May have to run your period of record repeatedly to establish a good initial condition.
- When are you done?
  - Groundwater elevations match observed
  - Base flow is approximately correct

Establish Initial Conditions

Step 4 - Using the result of your previous effort, run the model up until the time of start of the actual simulation.

- You need to have forcing data prior to your period of simulation.
- You should stop this simulation some period of time before you wish to begin your actual simulations.
- Use the results of this simulation to start your actual simulations, including a start up period.
- For example, if you want to simulate 2008, you would run this model for an extended period up until Dec 2007. You would start your simulations in Dec 2007 using the results of this simulation.

Establish Initial Conditions

Step 5 - In your simulations always include a start up period

- Prior to when you need results
- Gives model a chance to shake out any starting jitters
- Typically on the order of weeks

The Good News…Mostly

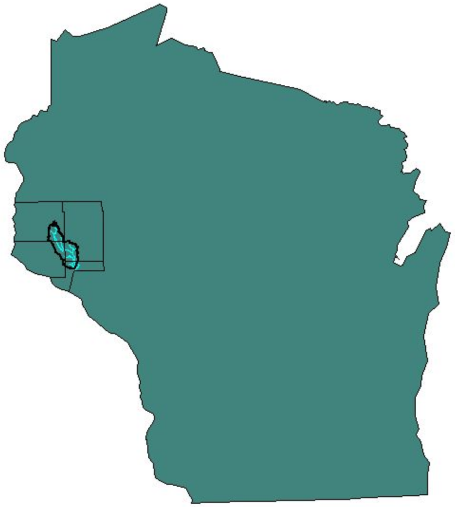
Once you have the initial condition developed you never have to do this again. Unless…

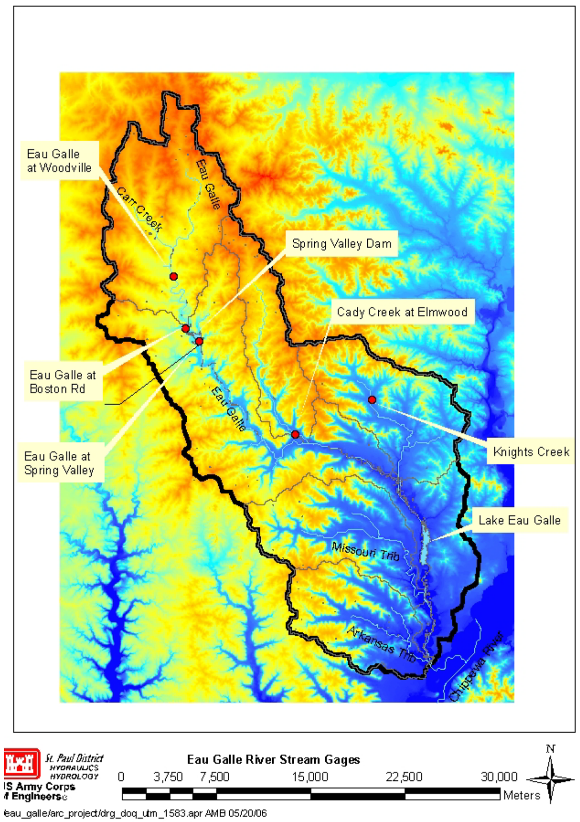
- The values you used for hydraulic conductivity and porosity were completely unreasonable.
- In that case the gradients in your watershed may be out of whack (remember Darcy's law?), therefore your groundwater levels are also out of whack.
- You may have to repeat the last steps to establish a reasonable starting point for your simulations using reasonable groundwater parameter values.

Examples

- Eau Galle River Watershed
  - Upper Eau Galle River Watershed
    - 8 Mile Creek Watershed
- JD31
- Goose Prairie Creek

Eau Galle Watershed Model

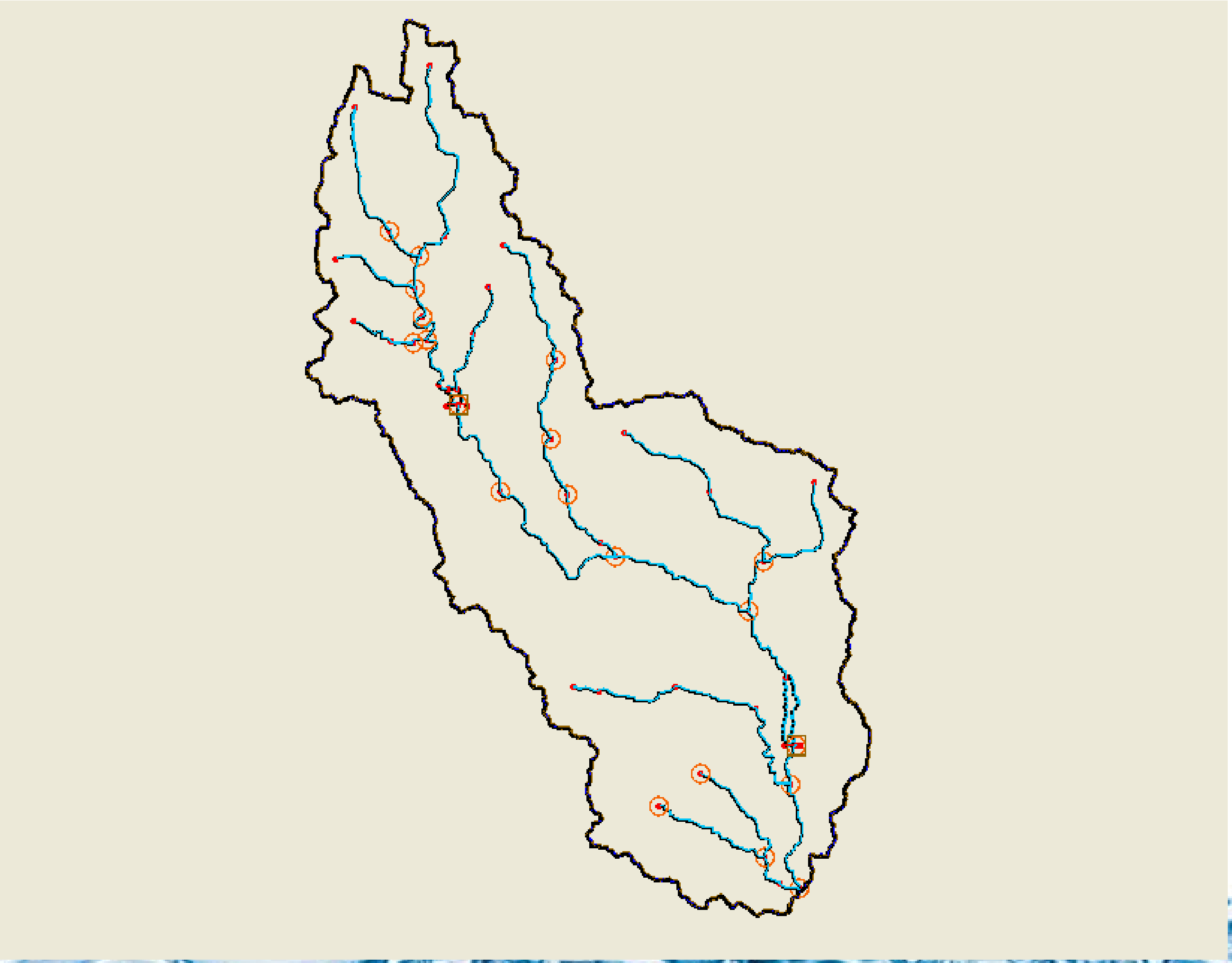




Model within a model within a model

1. Large model of entire watershed
2. Subset of large model
3. Smaller models within the sub-model

Eau Galle River Watershed Model

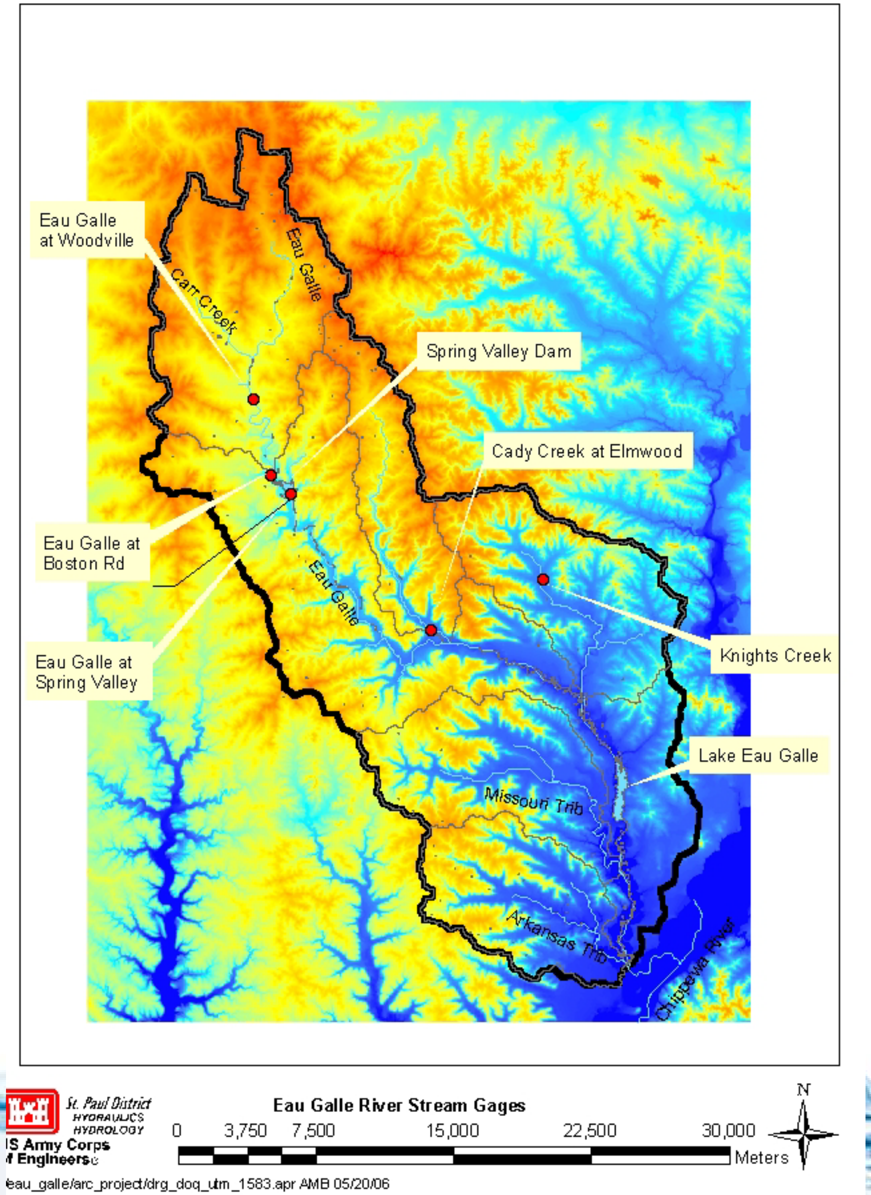


- 100m resolution
- 65,000 grid cells
- Two reservoirs
- No subsurface info
- Limited x-sect info
- Limited rainfall data

Sources of Information

- Limited description of subsurface system from publications
- Detailed description of subsurface system from local USGS contact
- State maintains data base of wells and borehole information *Wisclith*
- USGS and USACE stream monitoring data

Historic Surface Water Records



Historical Local Data

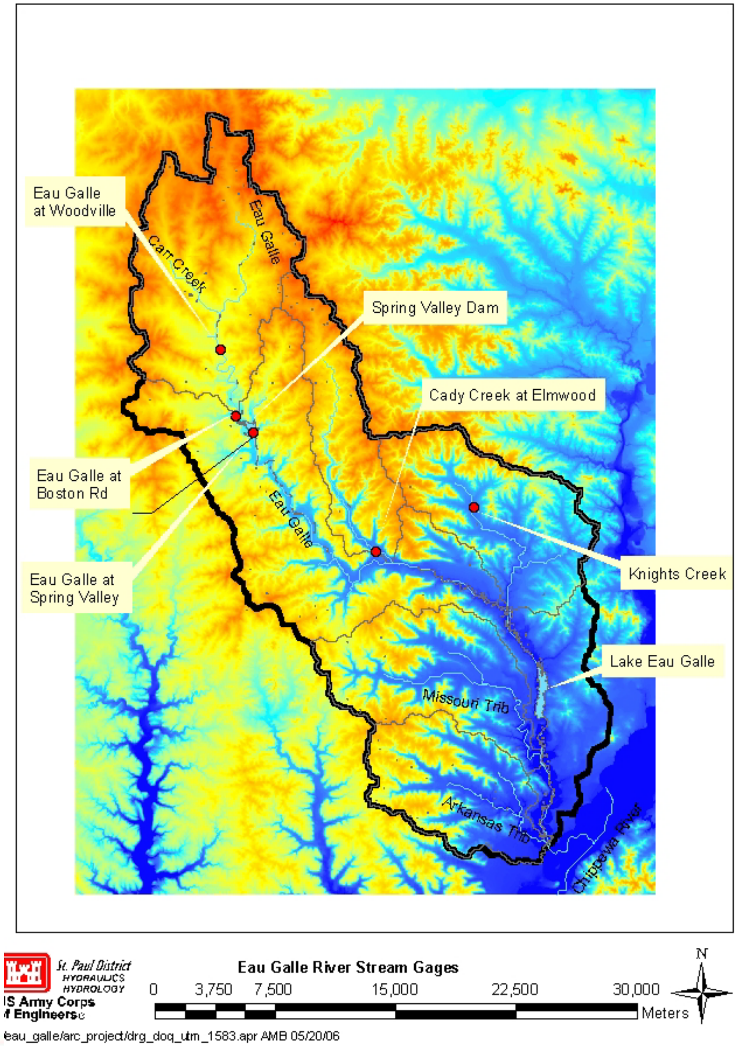
- 6 stream flow gages in the upper watershed (2002 -2003).
- Nutrient, sediment, and basic water quality parameters at multiple locations (2003-2003).
- 8 precipitation stations.
- Sampling effort directed at upper water, i.e. the portion of the watershed above Spring Valley Lake.

Subsurface Conceptual Model

- Watershed is comprised of unconsolidated materials overlying partially consolidated rock layers
- Regional aquifer lies below these materials
- Rock layers are eroded away to varying degrees in the watershed
- Aquifer bottom is taken as the shallowest existing rock layer
- Groundwater bottom looks like a series of stair steps
- Infiltrated water flows along a confining layer until it either hits a stream or intersects the next confining layer

Boundary Conditions

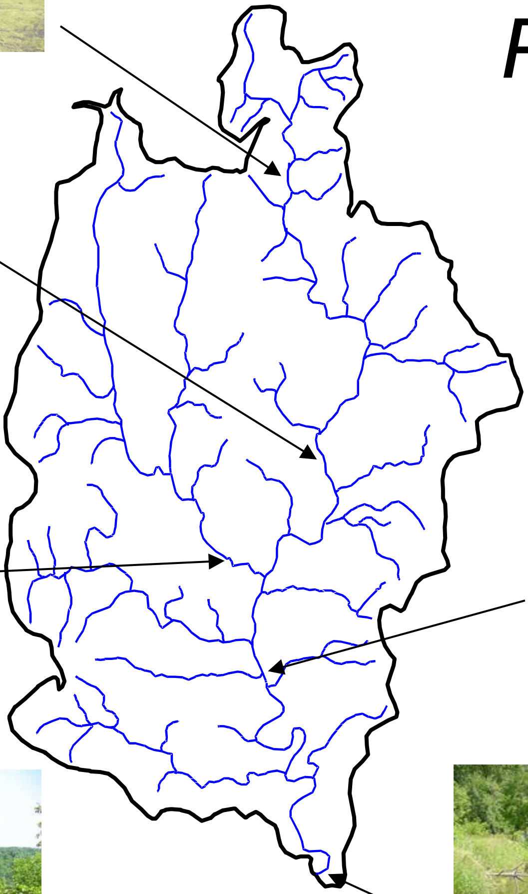
- Where applicable (upper watershed), no flow boundary conditions were applied.
- In lower watershed head boundary conditions were developed from stream and well data.
- Stream and well data were used to interpolate to the grid, also providing initial water table.



Depth to Bedrock

- Bedrock elevations were developed from the *Wisclith* data base of borehole data
- Bedrock elevations were developed for the larger Eau Galle River model from 1,299 data points in and around the watershed
- Bedrock elevation was established by looking for the first confining layer in the record (based on local knowledge of the layers), or when the boring was stopped due to hitting an impermeable layer.
- WMS was used to interpolate the data.
  - Maximum elevations were enforced to keep the bedrock below the land surface.

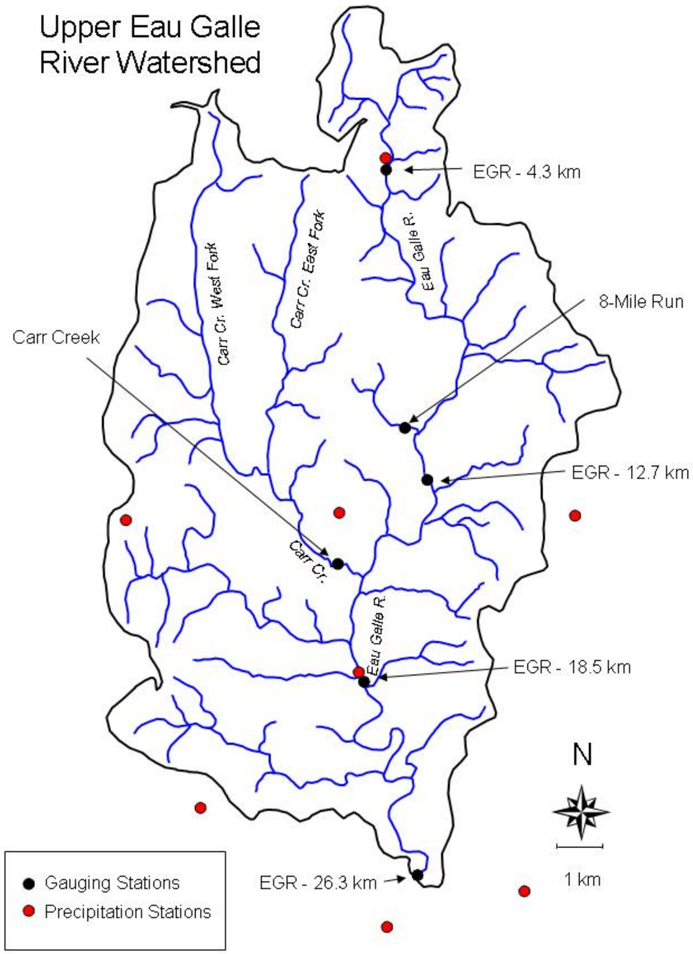
Upper Eau Galle River



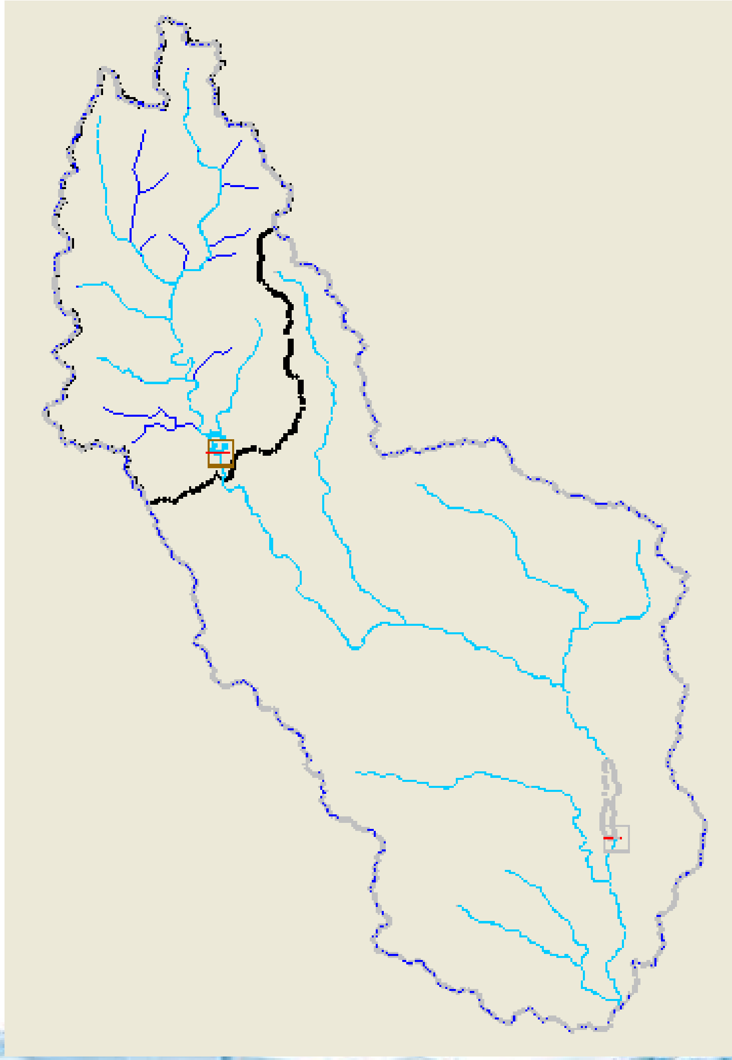
Upper Eau Galle River Watershed

- 123 km^2 watershed located in the glaciated region
- Diverse land use
  - Annual and perennial crops (corn, oats, alfalfa, grass hay, soybeans) for livestock production
  - Woodlots and CRP
  - Little urban development
- Groundwater recharge in the lower basin

Sampling Locations

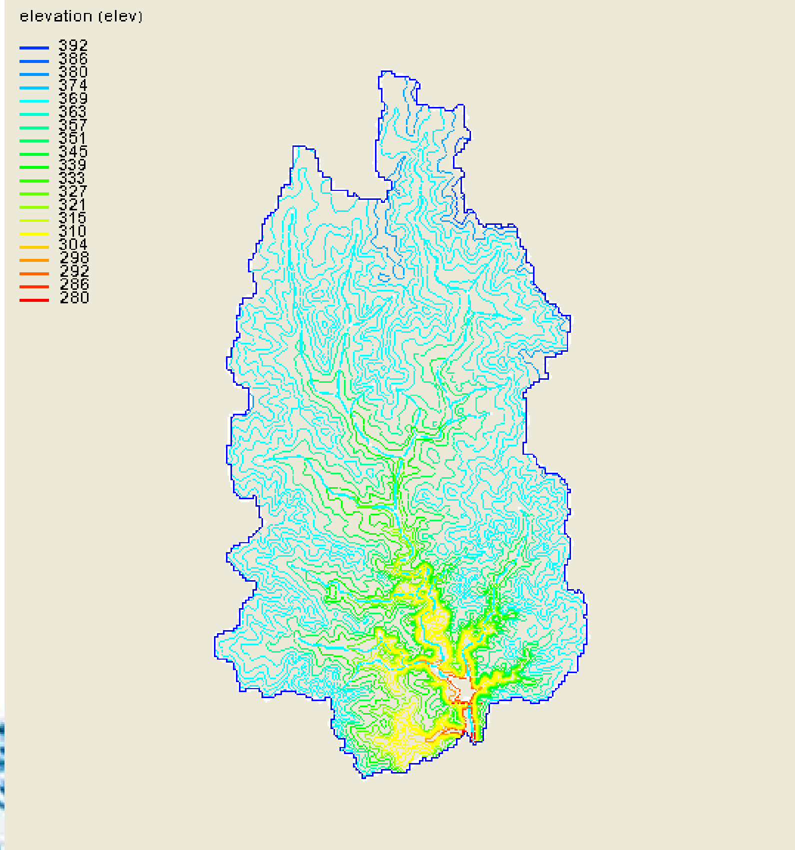


Demo Domain



Demo domain developed so that groundwater divides could be used as no flow conditions

Boundaries away from our area of concern



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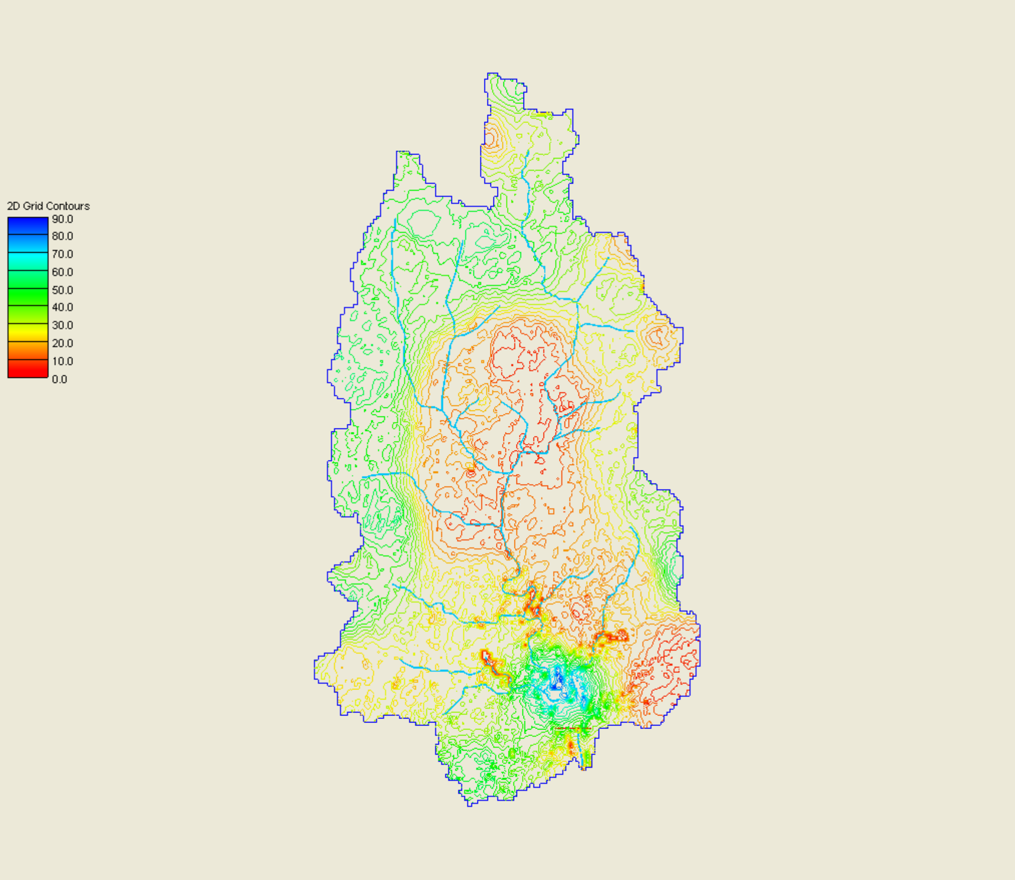
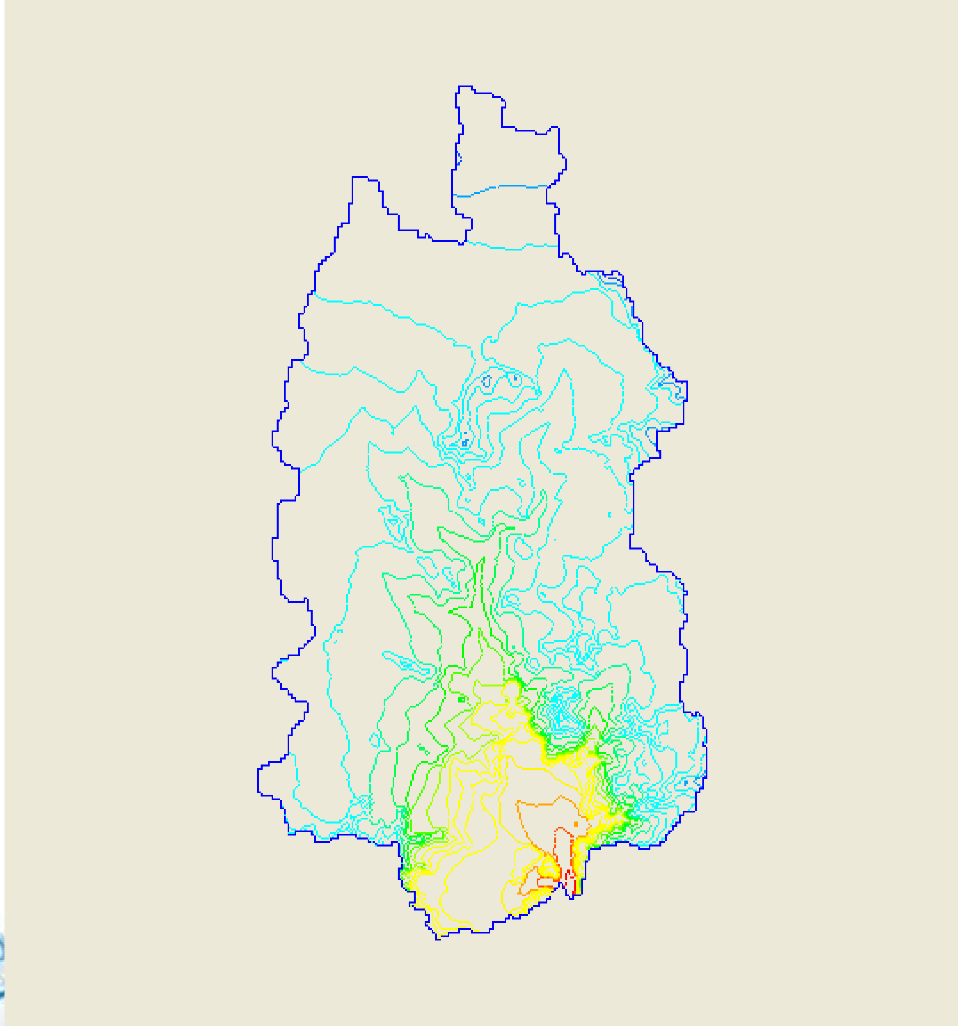


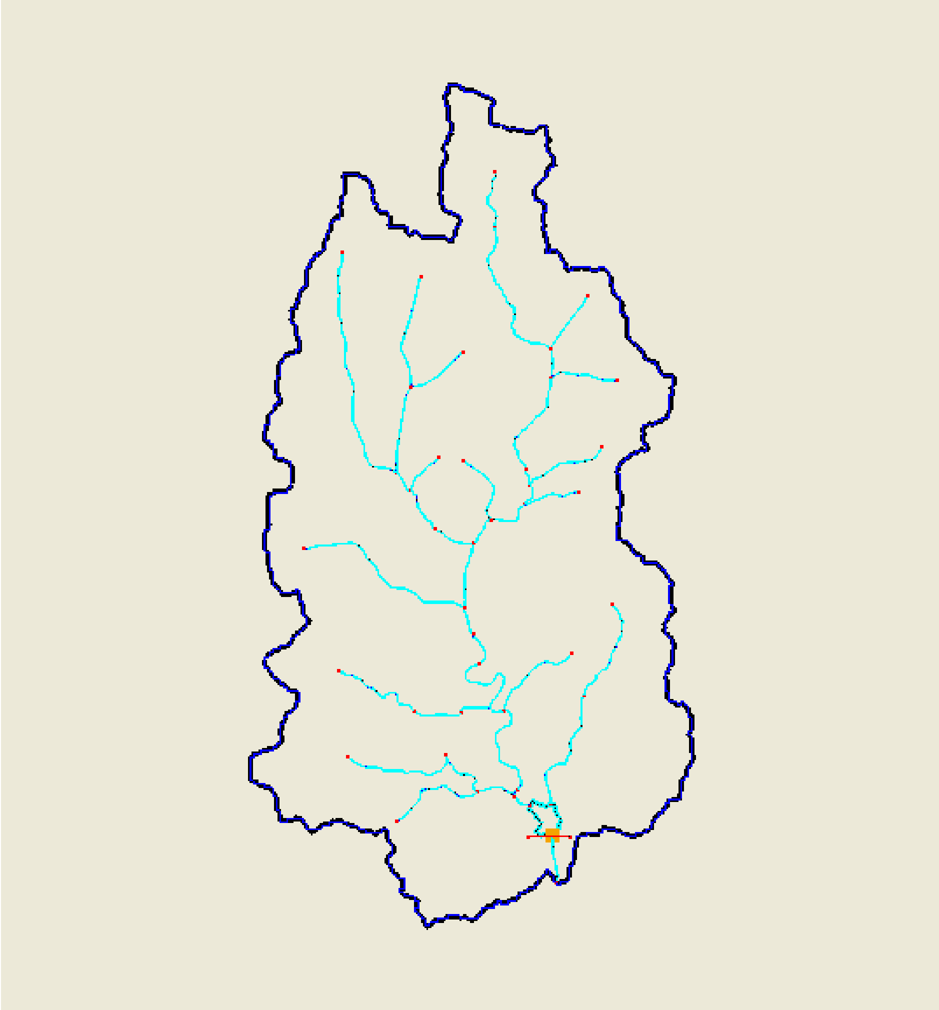
Initial Conditions

- Water table assumed to be at depth below land surface
- Coupled surface water groundwater model run until
  - Water table stable
  - Base flow reproduced
  - Match observed data
- One data point available for comparison
- Represent May 15, 2002 conditions



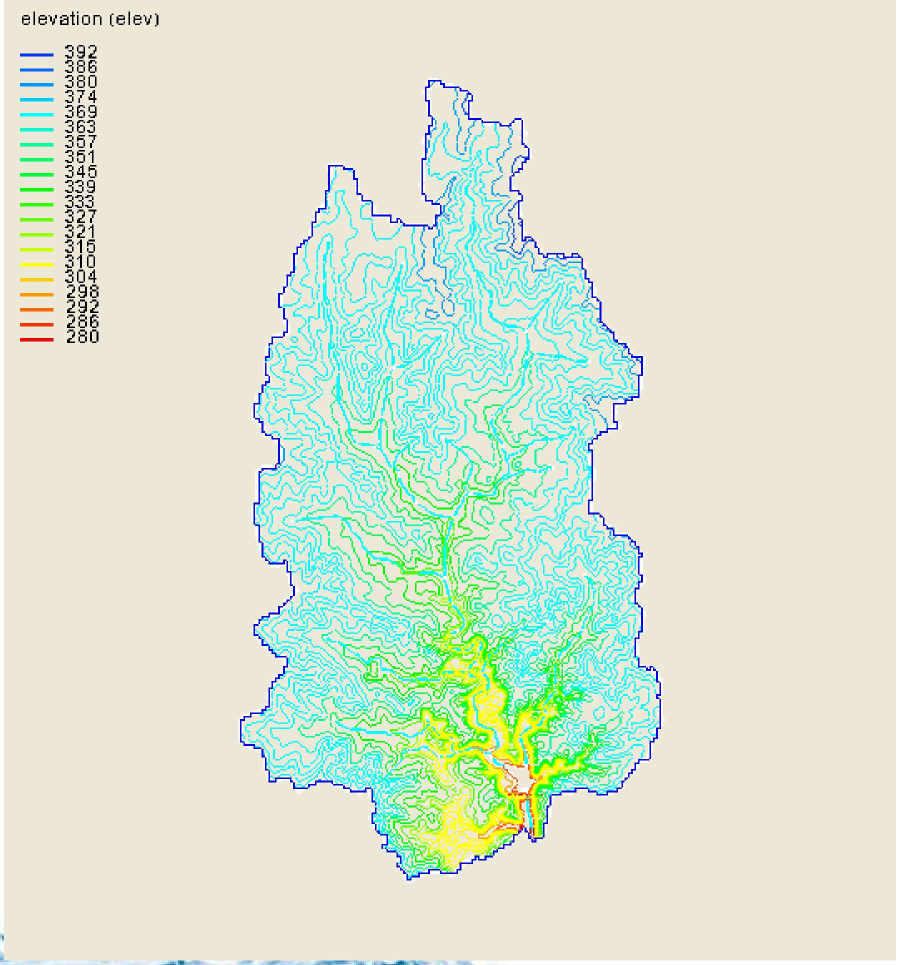
Stream Network Development

- All first, second, and third order streams
- 854 nodes ~ 90m
- Trapezoidal cross sections developed from field measurements
- Groundwater interaction in all stream segments
- Reservoir with specified rating curve for discharge
- Reservoir interacts with groundwater

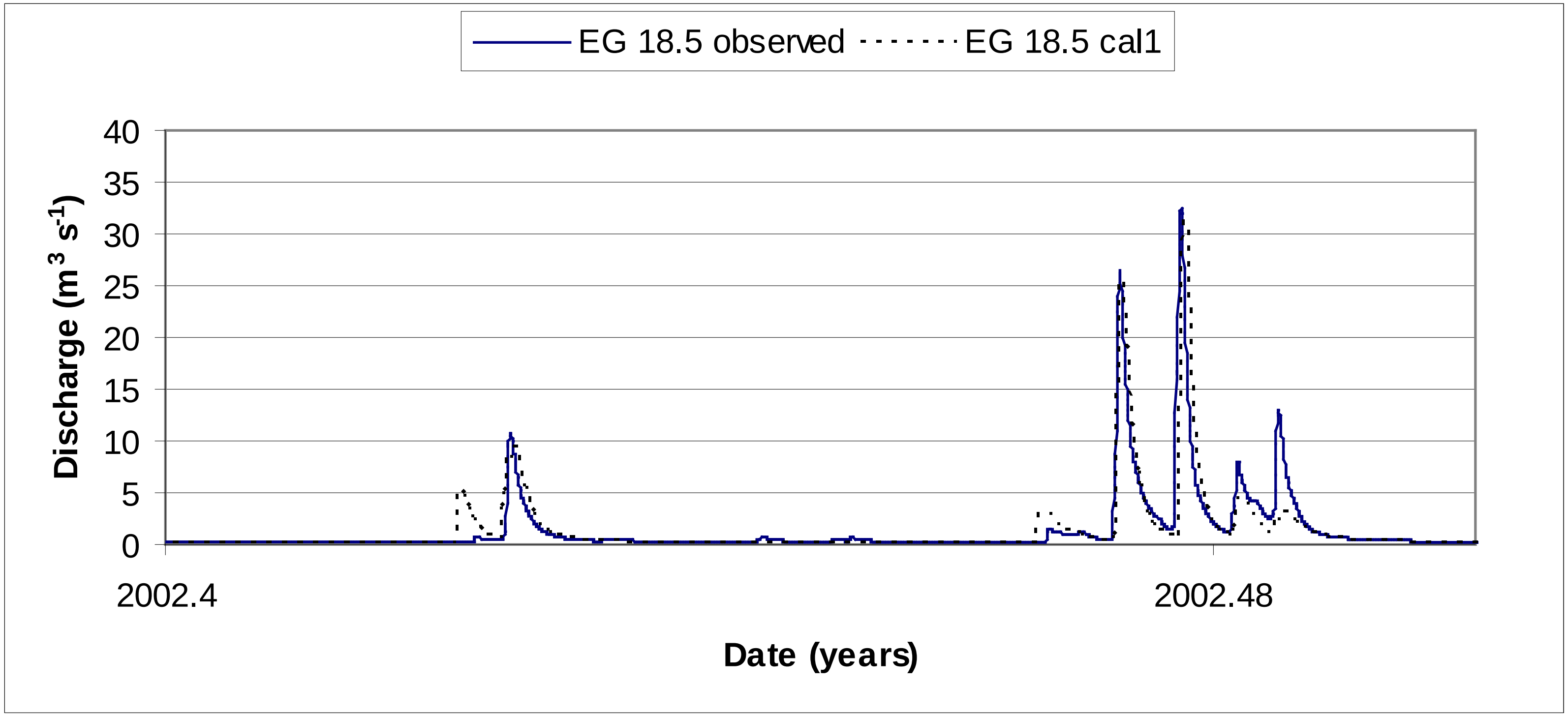


Elevations

- 100 m grid elevations were developed from NED 30 m data
- Elevation data are used for
  - overland flow calculations
  - surface/groundwater interactions
  - stream bed elevations



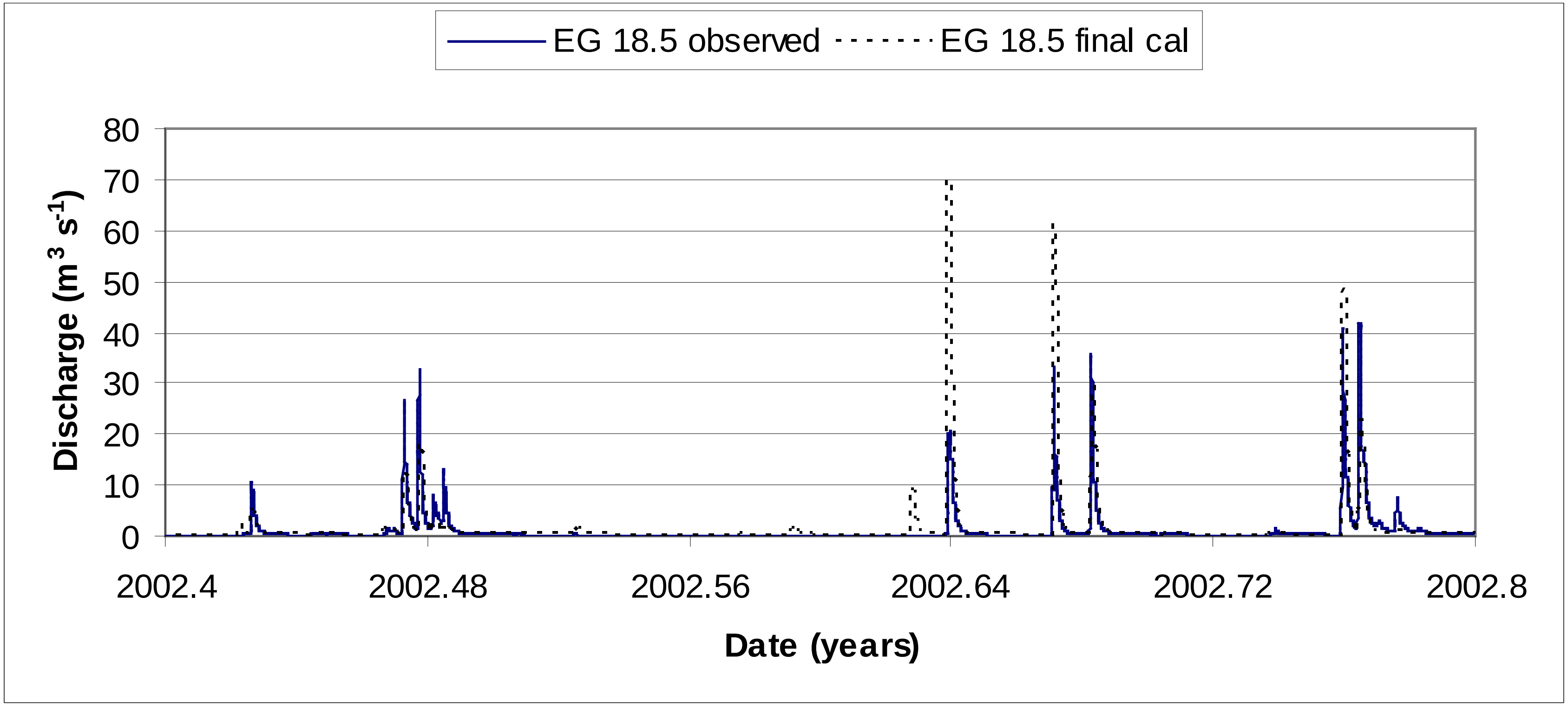
Initial Discharge Calibration



Peak Mean Absolute Error (MAE) – 3%

Total Discharge Error – 1.5%

Final Discharge Calibration



Peak (MAE) – 42%

Total Discharge – 7%

Water Budget

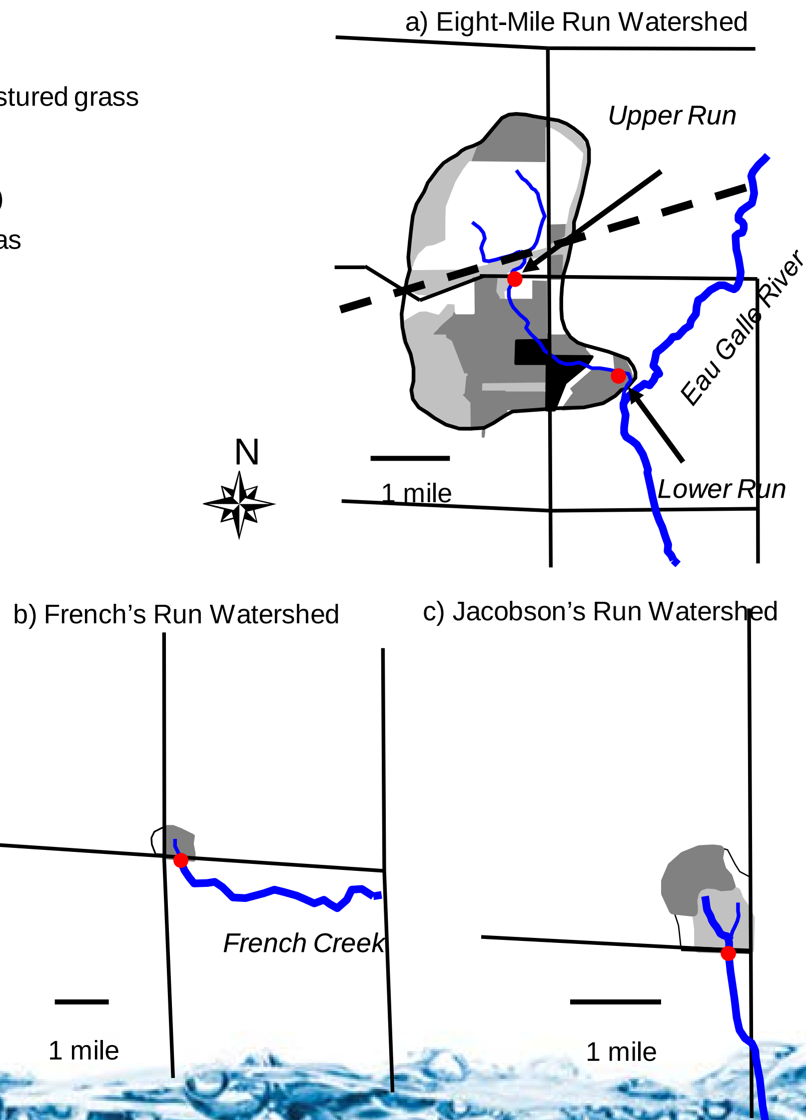
Table 2
Spring Valley Dam Watershed Water Budget, May 15 – October 19, 2002

Input	Volume 10^6 m^3	Percent of Precipitation
Precipitation	1256	
Interception	79	6
Infiltration	1026	82
Evaporation	859	68
Groundwater recharge	234	19
Discharge	250	20
Lateral flow into channels	200	16
Groundwater flow into channels	45	4

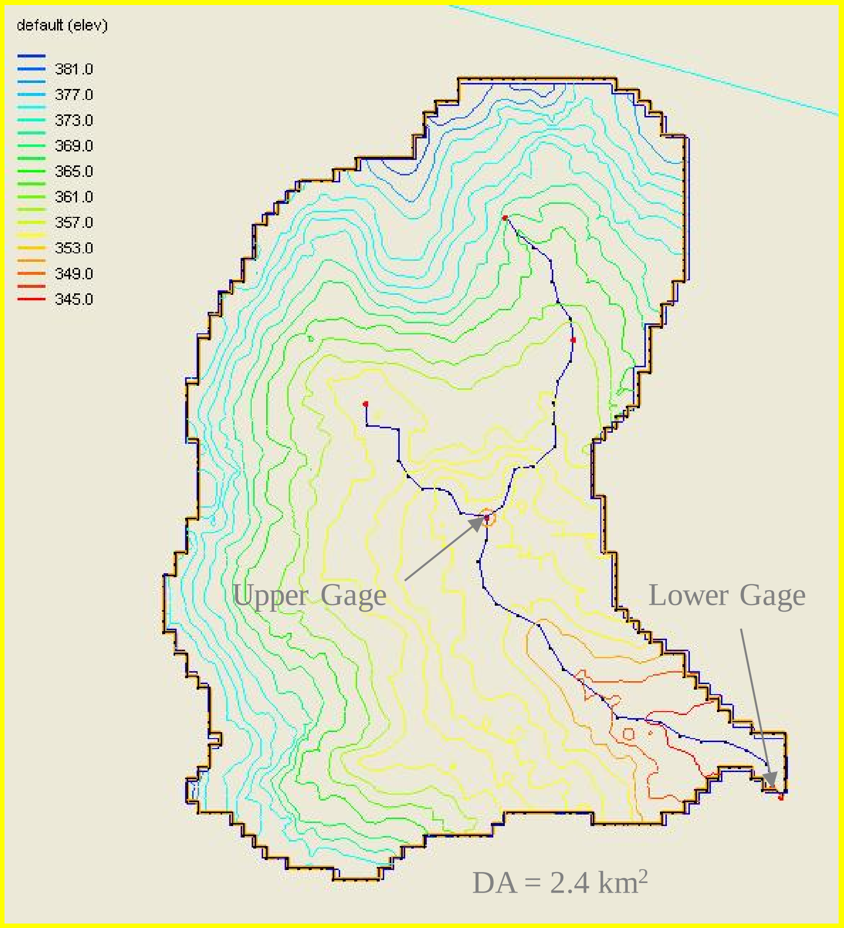
Summary

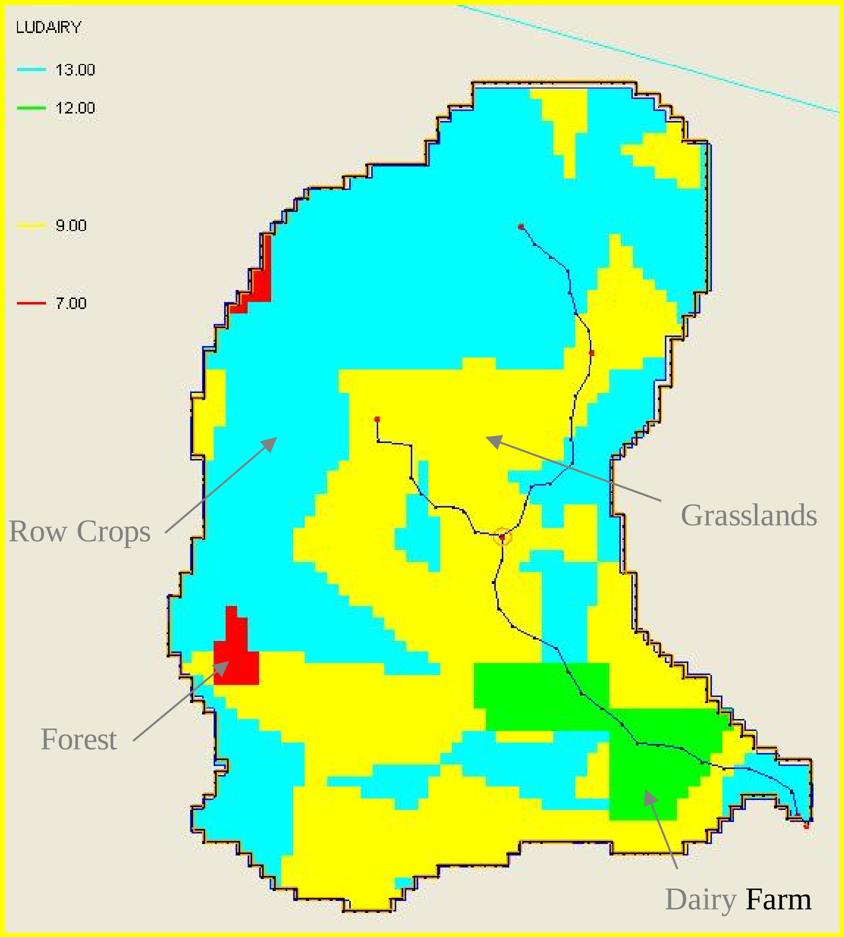
- The Eau Galle watershed upstream of the Spring Valley Dam was successfully simulated with the GSSHA model.
- Stream discharge was reproduced within normal standards.
- Reservoir stage and discharge were also simulated within acceptable standards.
- The model helped identify problems with the rating curve.
- Sediment discharge (TSS) was very accurately simulated.
- Simulating sediment discharge requires accurate simulation of hydrologic processes.
- *By coupling the hydrologic processes together, along with the erosion and sediment transport processes, we are able to more accurately model the system and changes in the system.*

Models Within the Sub-Model



Eight Mile Creek Watershed

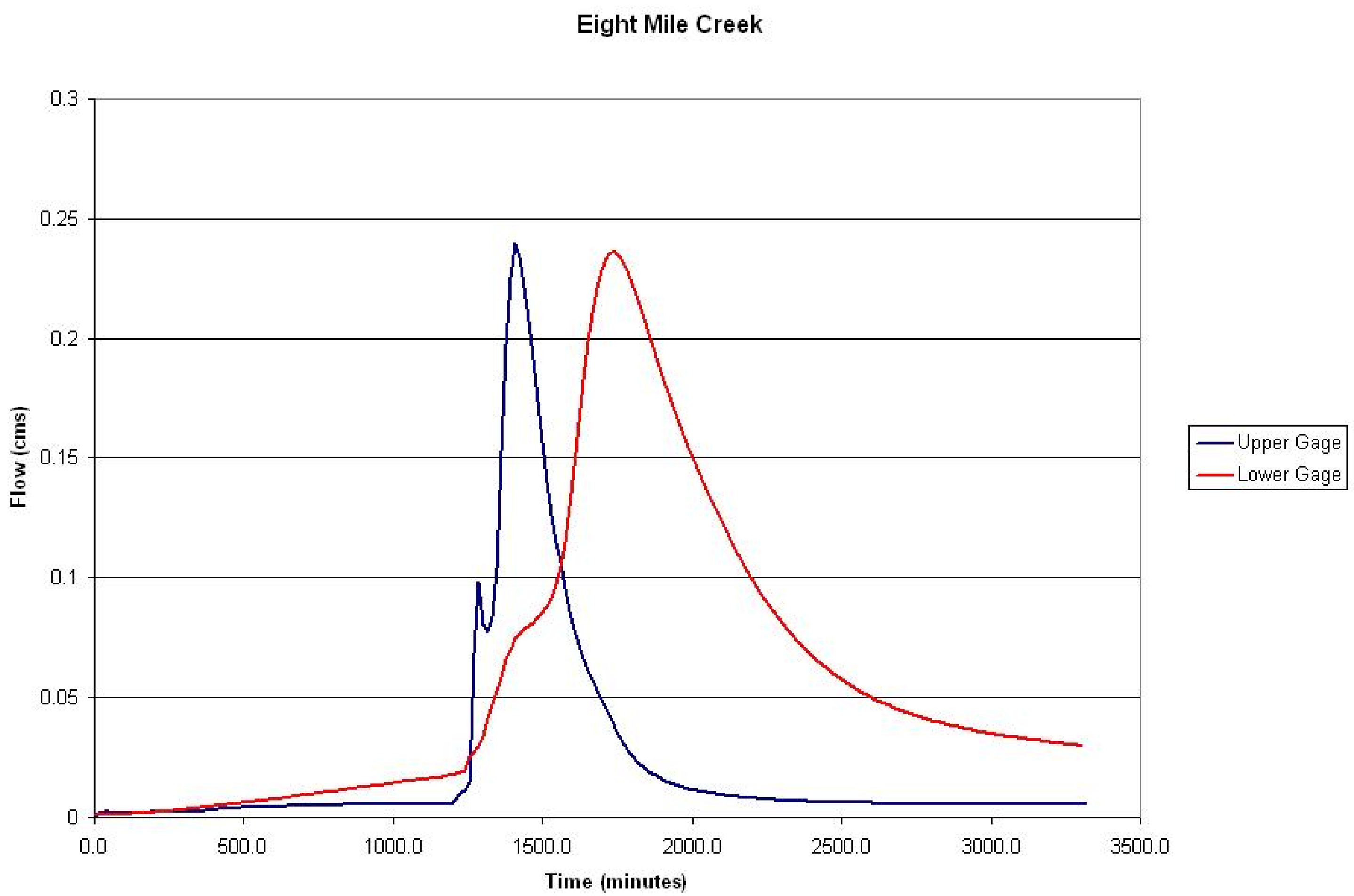




Groundwater Model

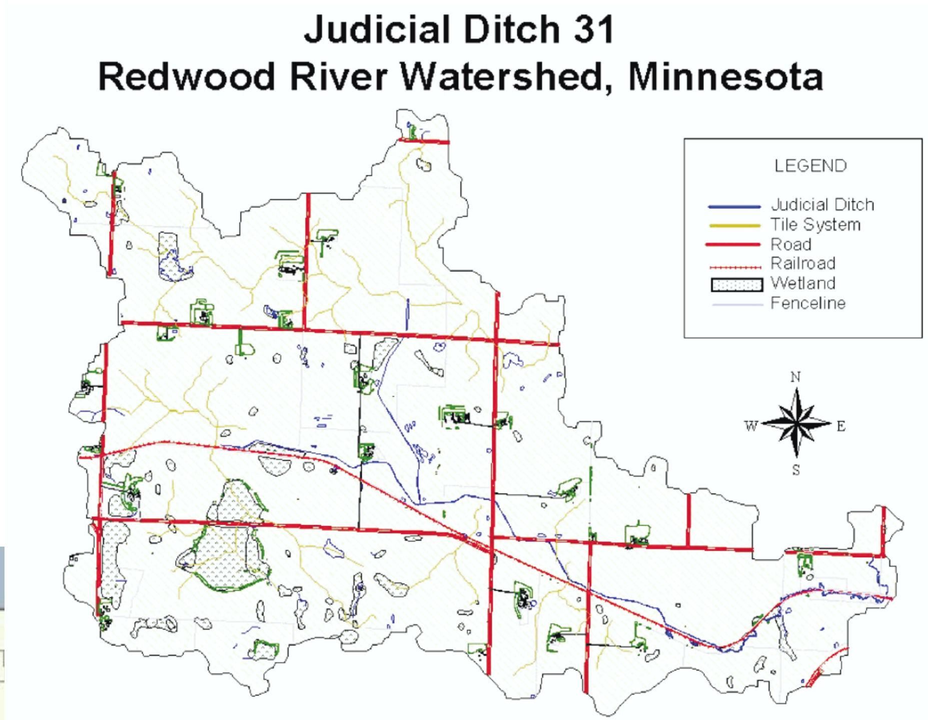
- Conceptualization same as Eau Galle
- Developed from larger model
  - Boundary conditions
  - Initial water table
  - Bedrock elevations
- Values in Upper Eau Galle model grid used to develop scatter sets
- Scatter sets interpolated to finer grid in 8 Mile Creek Model
- Values of hydraulic conductivity and porosity (which are uniform) taken from the larger model
- Limited smoothing of initial water table
- No calibration of groundwater parameters required

Eight Mile Creek Flow



Conceptualizing Coon Creek Watershed – JD31

- Wetlands converted to agriculture
  - Drainage ditch
  - Tile drains
- Needed information
  - Examine wetland restoration scenarios
  - Assess stream flow impacts
- Unknowns/Uncertainty
  - Subsurface information
  - Tile drain system



Conceptualization

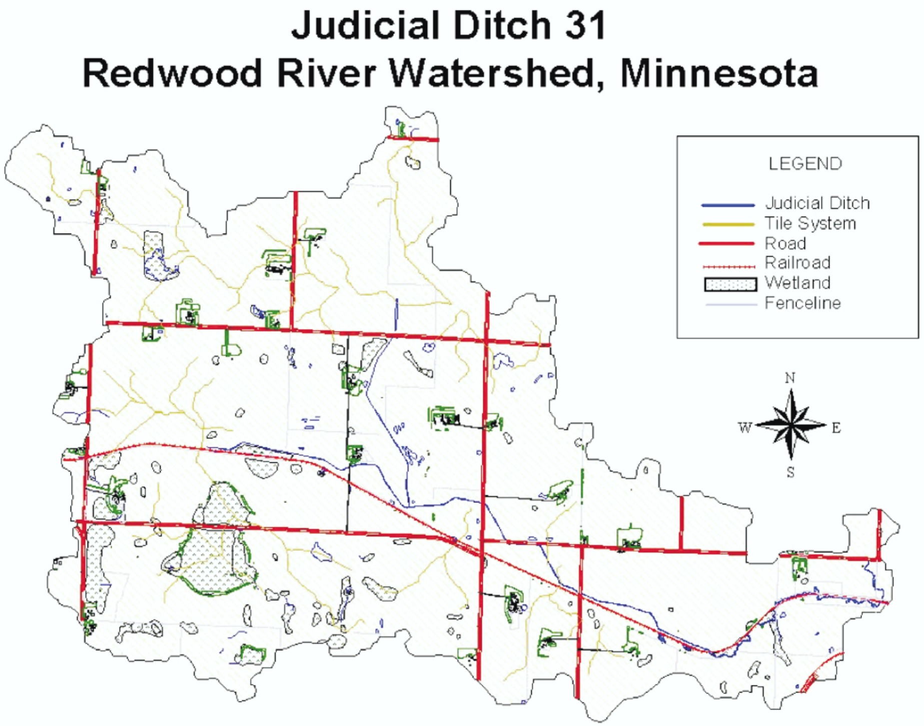
Geologic Setting

- Deep glacial till
- Bedrock elevation varies from 350-380m
- Bedrock slopes to the SE

Sources of Information

- Limited publications (one) with descriptions of subsurface soils and bedrock (USGS)
- No wells or boreholes in watershed
- No previous groundwater modeling efforts
- Limited well data (USGS) outside the study domain
- Observed rainfall and discharge for the year 2000

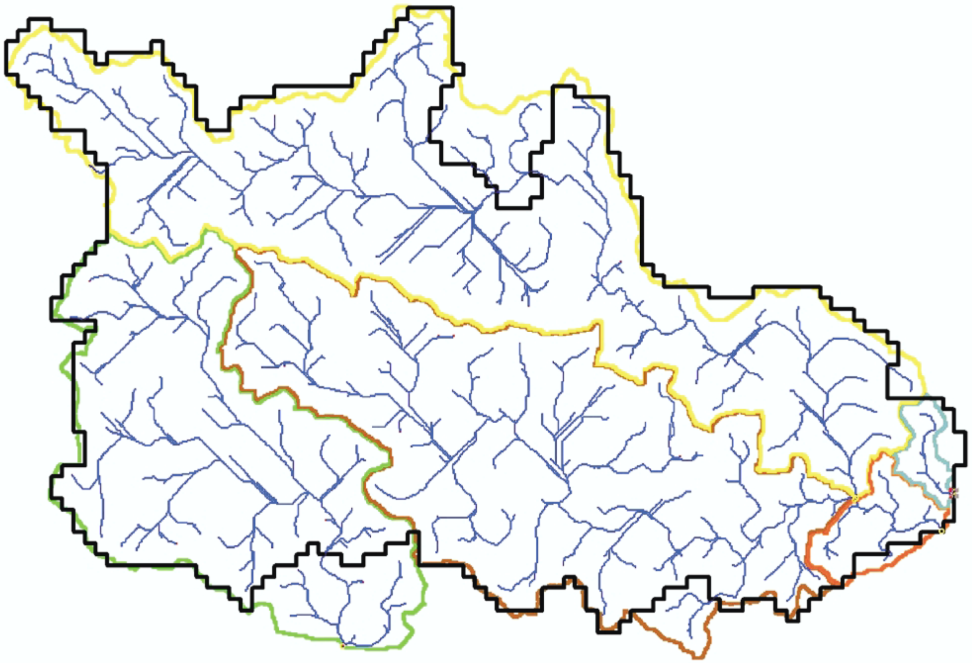
JD31 "Watershed" Cuts Across Multiple Watershed Boundaries



JD31 Watershed – left, cuts across

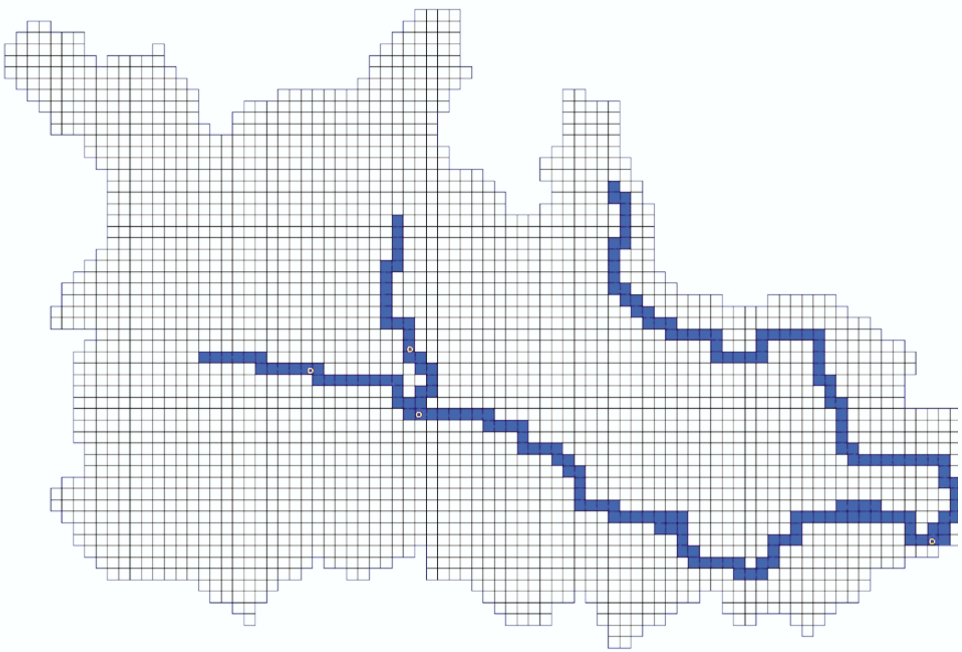
multiple watershed boundaries – below.

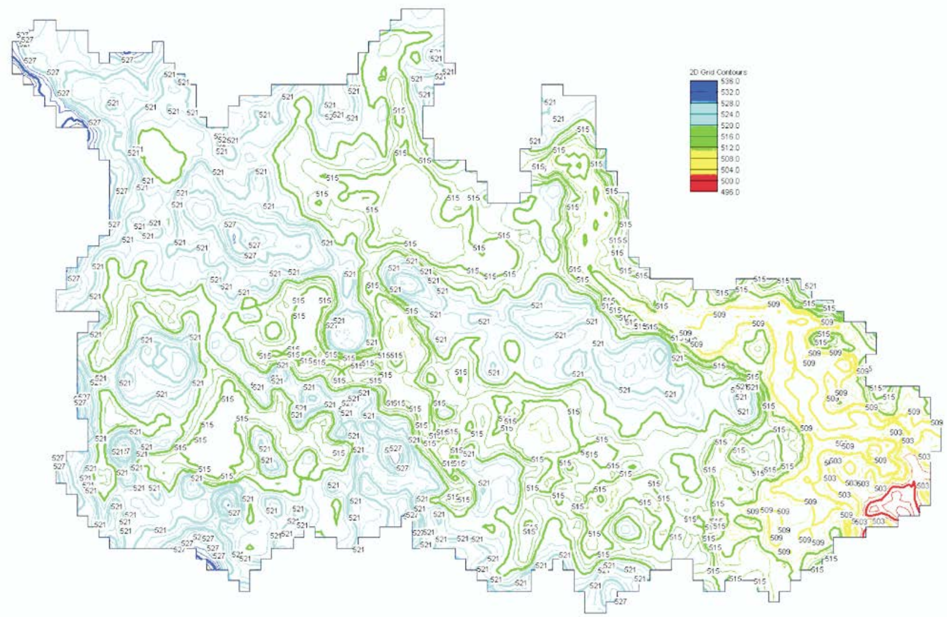
The JD31 Watershed boundary is not an adequate groundwater divide.



Solution

- Extend the model boundary (below -right) out to include the actual groundwater divides.



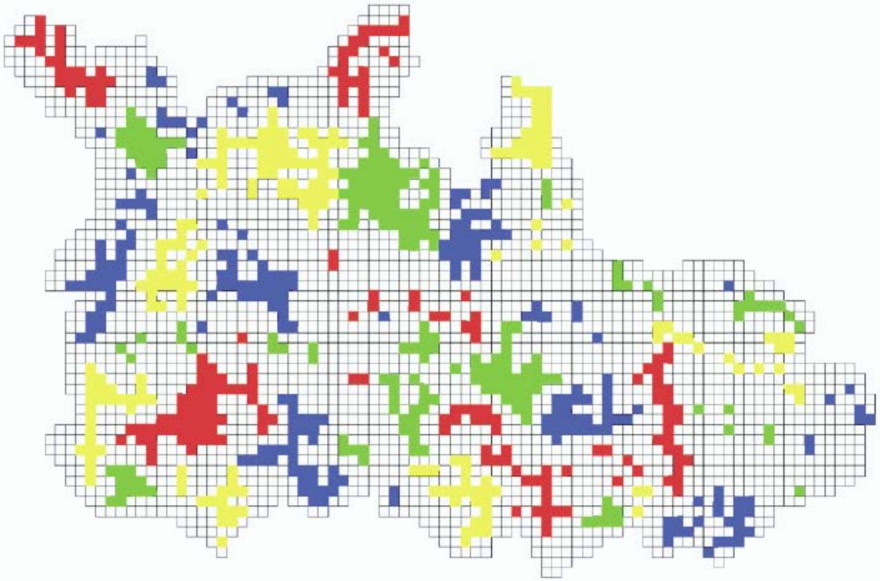


Model Representation of System

- Homogeneous soils in the domain
- Bedrock slopes from NW to SE, 380-350m
- No leakage in the bedrock
- No flow boundary conditions around extended domain
- Model solution is in the X direction
- Simplified connection between surface soils and deep soils (GAR)
- To establish initial condition, the point well data was interpolated to grid with the restriction that the groundwater table is at least 2 m below the land surface
- June/July period was used to establish initial water table condition used for the simulations.

Modeling Approach

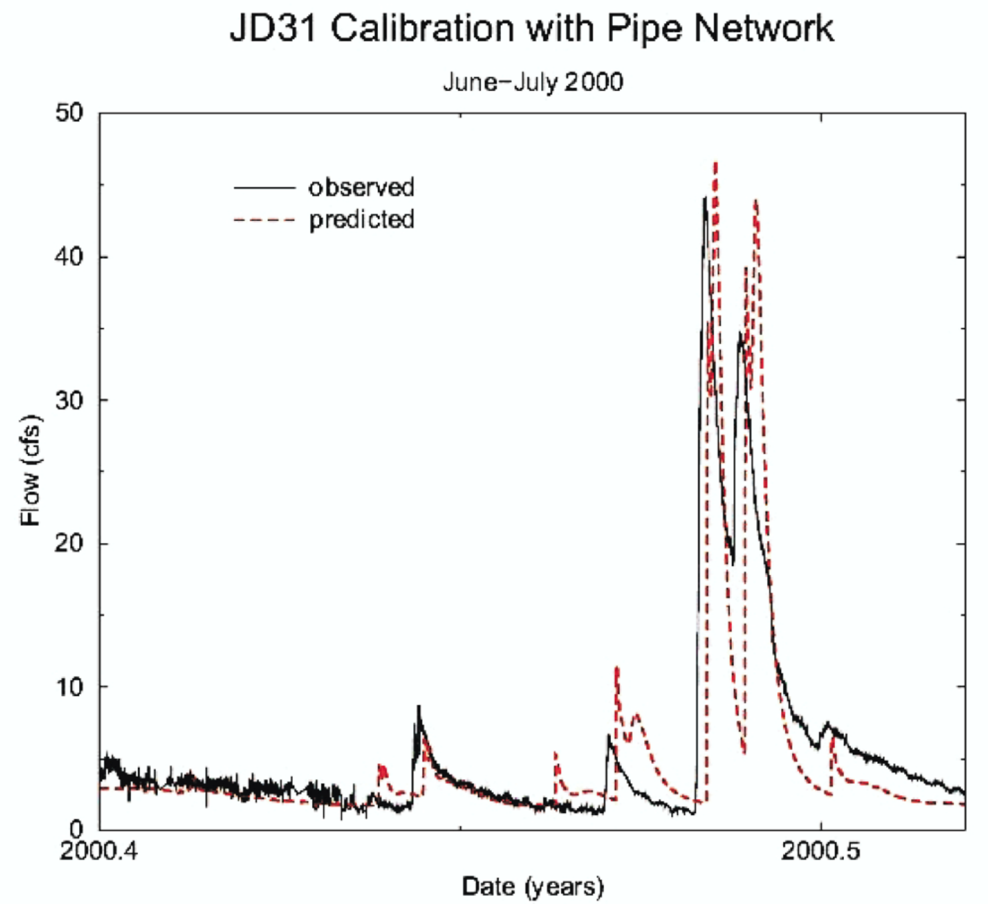
- Apply the GSSHA model
- Couple the GAR infiltration model to the saturated groundwater model
- Groundwater consist of homogeneous material
- Represent only the major drainage system as streams with groundwater recharge
- Compute 0%, 25%, 50%, 75%, 100% restoration of wetlands

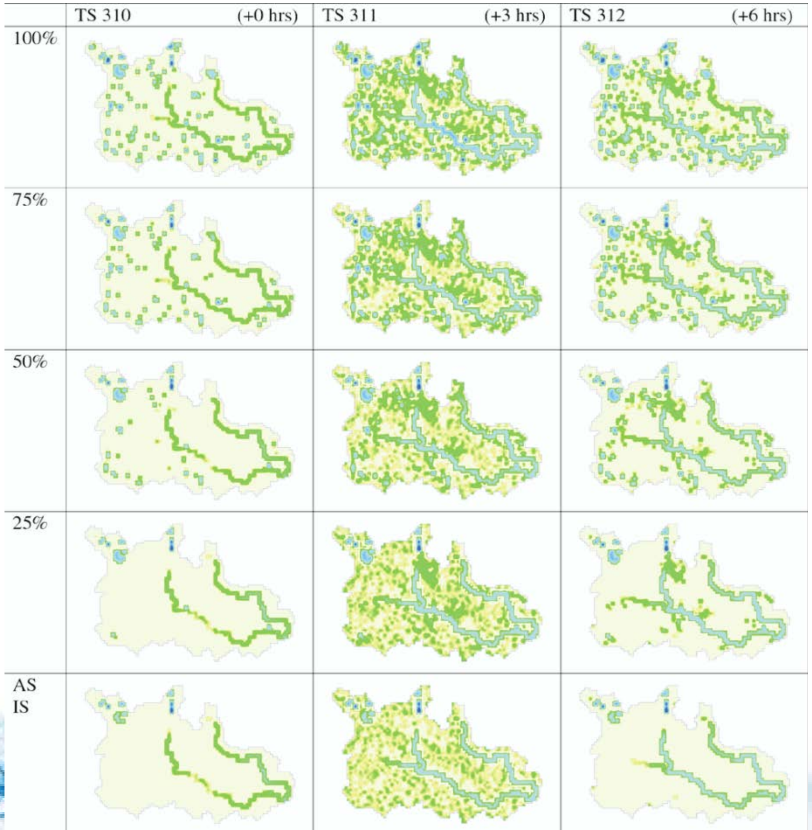


Results of Modeling Process Changes

Resulting model able to history match flows resulting from surface water, groundwater, and drainage network

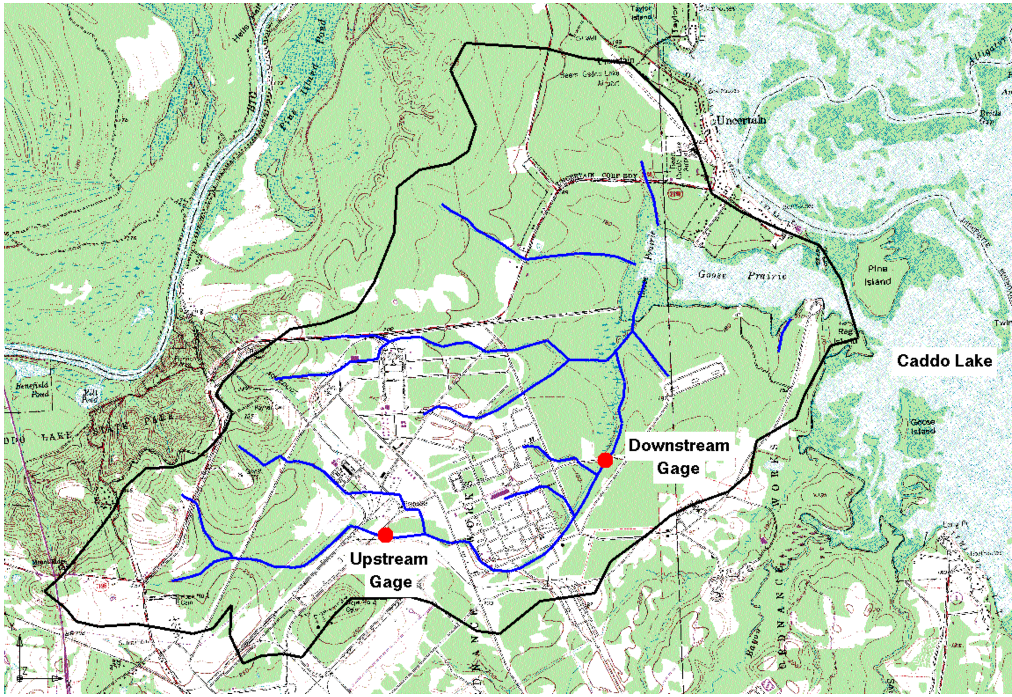
Model rapidly assesses varying wetland restoration configurations





Goose Prairie Creek - LHAAP

- Goose Prairie Creek watershed/groundwater system – Longhorn Army Ammunition Plant, Karnack Texas
- System
  - Small watershed
  - Humid regions
  - Deep sandy soils
  - Mixed hydrologic inputs to stream
    - Overland flow
    - Losing/gaining stream
    - Saturated source areas
- Requirements
  - Stream discharge, both volume and timing, to receiving water body (Caddo Lake, Wetland of International Significance)



Groundwater Conceptualization

Groundwater Setting

- Subsurface is composed of very deep sands
- Upland areas draining into valley
- Loosing streams in uplands
- Gaining streams in valley
- Upland areas provide groundwater divide
- Caddo Lake provides downstream condition

Available Information

- 2 Stream Gages
- 2 Rainfall Gages
- Local expert (TPWD) describes soils and setting
- FEMWATER model of entire facility

Model Conceptualization

- Aquifer bottom assumed to be very deep, flat, with significant leakage
- Homogeneous subsurface material – sand
- Boundary condition in upland is no flow
- Boundary condition in valley is head from FEMWATER model
- Streams interact with groundwater
- Stream boundary condition is Caddo Lake elevation
- Initial conditions from FEMWATER model
  - Initial condition smoothed using observed forcing data from gages within the basin

Results

- Model able to accurately duplicate stream flow for both storm and base flow conditions