Modeling Karstic Controls on Watershed-Scale Groundwater Flow in the Floridan Aquifer of North Florida

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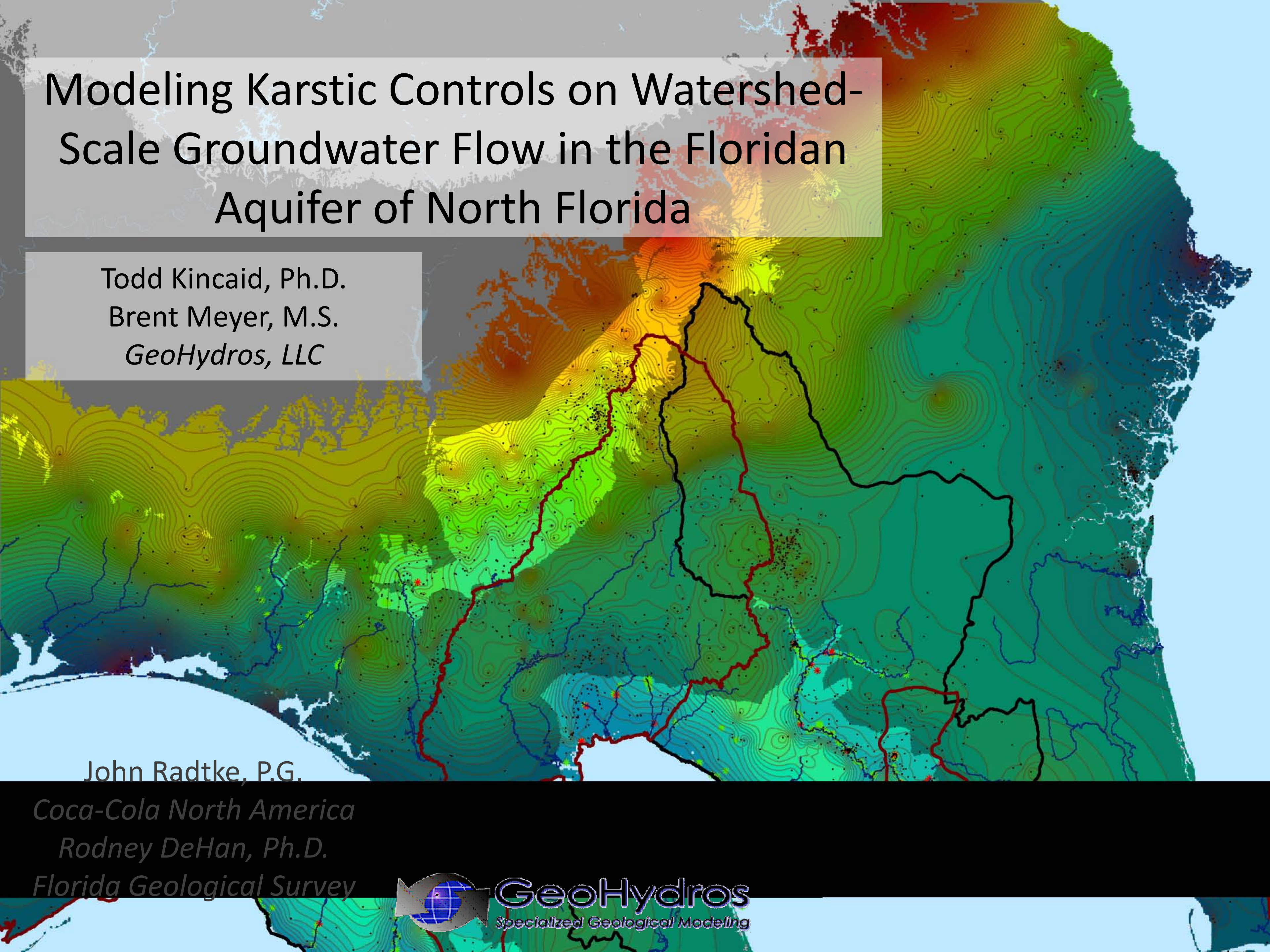

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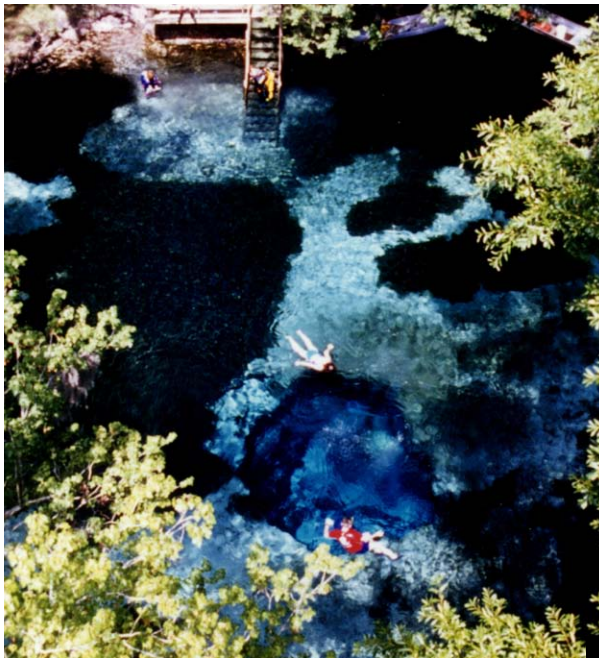
Guiding Philosophy

Design the simplest possible model that honors as many of the observable conditions as possible with the fewest hydrogeologically defensible assumptions as possible.

Important Hydrogeologic Complexities

Springs

large magnitude discrete discharges

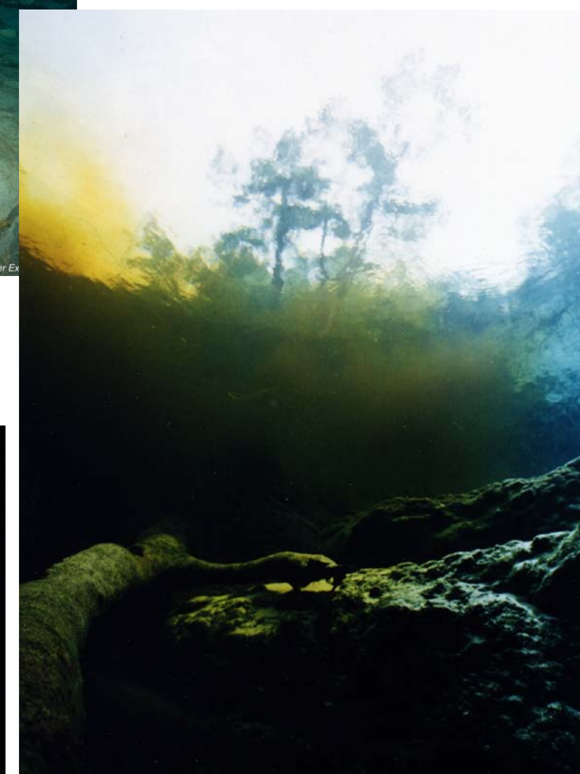


Conduits

Very significant preferential flow paths

GW / SW Mixing

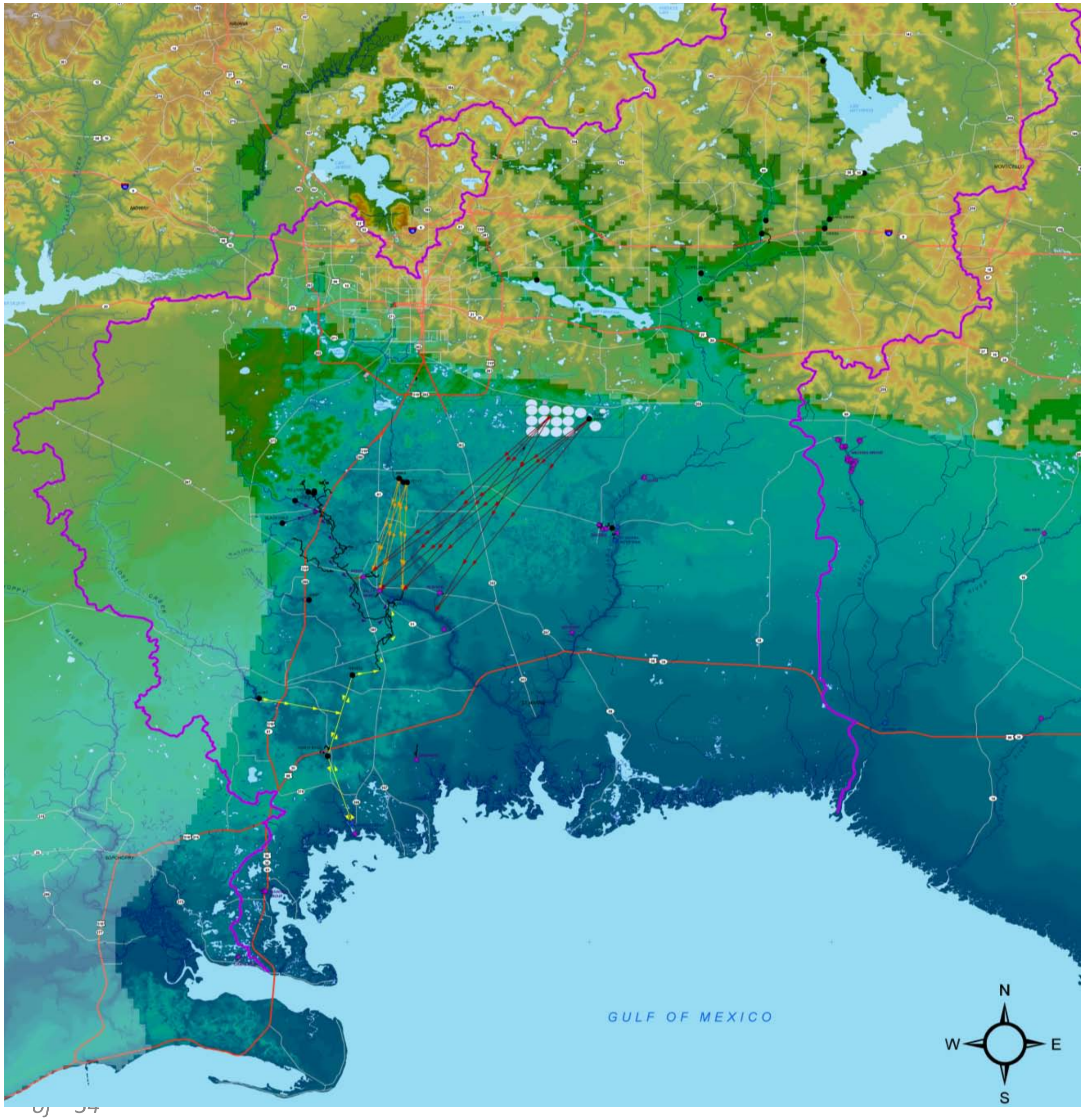
Impacts water budget



Swallets

Large magnitude discrete recharge

Hydrogeologic Complexities: WKP



- Confinement
- 1st Mag. Springs
  - Wakulla
  - Spring Creek group
  - St. Marks
  - Wacissa group
- 2nd Mag. Springs
  - Many
  - Not addressed yet
- Swallets
  - 12 primary
  - At least 5 secondary
- Caves
  - Mapped (~47 miles)
  - Tracer-defined
  - Inferred

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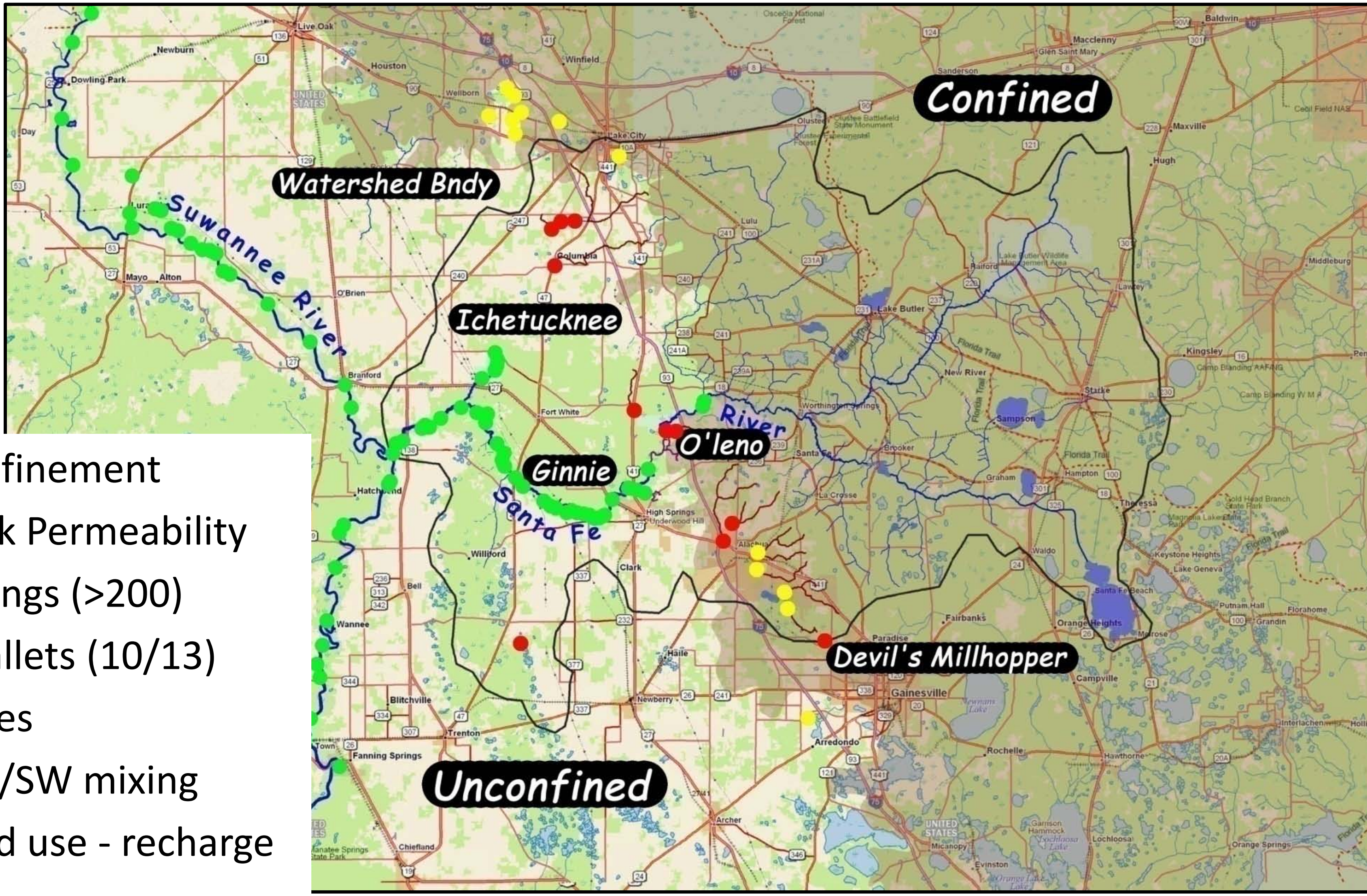
Hydrogeologic Complexities: SFRB



- Confinement
- Rock Permeability
- Springs (>200)
- Swallets (10/13)
- Caves
- GW/SW mixing
- Land use - recharge

Karst features create the dominant controls on flow

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Springs: *Discrete Large Discharges*

- More than 200 springs in the SRWMD
  - 1^{st} Mag (>= 100 cfs): 18
  - 2^{nd} Mag (10-100 cfs): 81
  - 3^{rd} Mag (1-10 cfs): 60
  - 4^{th} Mag (.1-1 cfs): 37
- 81 in the Santa Fe River Basin
  - 1^{st} Mag: 9
  - 2^{nd} Mag: 36
  - 3^{rd} Mag: 23
  - 4^{th} Mag: 8
- Not all springs are the same
  - Autogenic
    local recharge
  - Allogenic
    swallet recharge

Devil's Ear / Devil's Eye Springs

Hornsby Spring

Must address springs & spring types discretely

Swallets: *Discrete Rapid Recharge*

- Swallets: disappearing streams that fully connect the land surface to the FAS.
  - 11 known & documented features
  - O'leno Sink, Clay Hole Group (3), Rose Creek, Mill Creek (2), Hammock, Pareners Branch, Waters Lake, Devil's Millhopper
- Swallet-Seeps: basins containing perched water above FAS that deliver high recharge.
  - 13 features
  - Burnett's Lake, Lee Creek Sink, Turkey Creek Sink, Blues Creek Sink, Alligator Lake, Lake Luna, Lake Ogden, Lake Wilson, Hancock Lake, Orange Pond, "String of Ponds, " Lake Jeffrey, Hogtown Prairie

Swallets are significant components of the water budget

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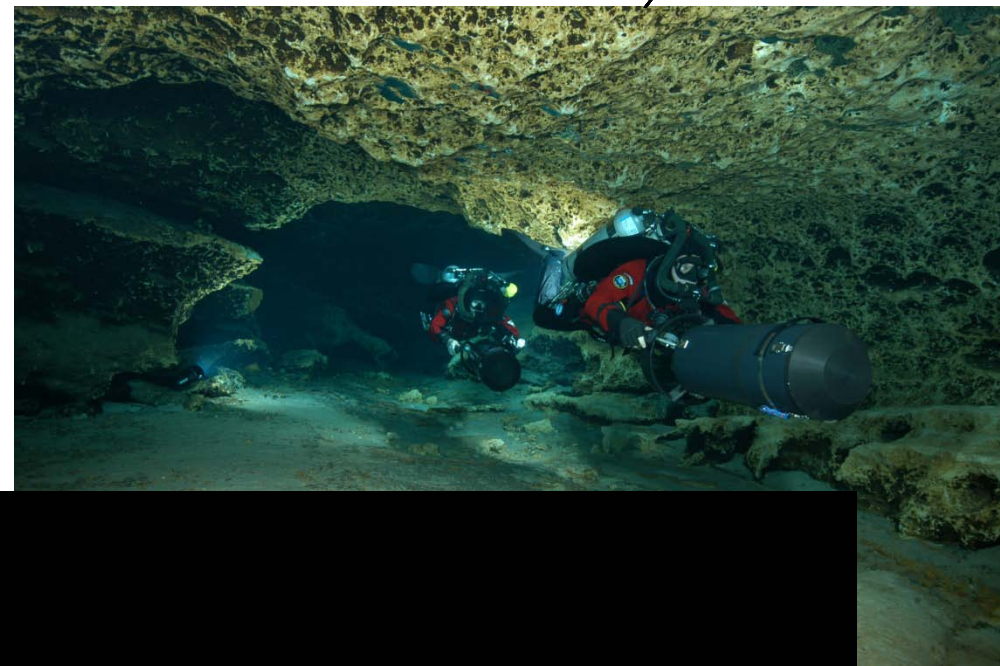
Caves: *Preferential Flow Paths*

Devil's Ear Cave System



- Numerous explored & mapped caves
  - Old Bellamy, Hornsby, Devil's Ear, Mill Creek, Rose Sink, Ginnie, etc.
  - Depths trend 75 – 150 ft
  - Diameters: ~3 – 30 ft
- More traced caves
  - Rose Creek, Clay Hole, Mill Creek, San Felasco, Ichetucknee, Ginnie
  - ~200 – 750 m/day
- Probably many more that have not been documented
- Large flow & velocity range
  - Spring caves
  - Sinkhole caves

Caves have significant control on flow patterns

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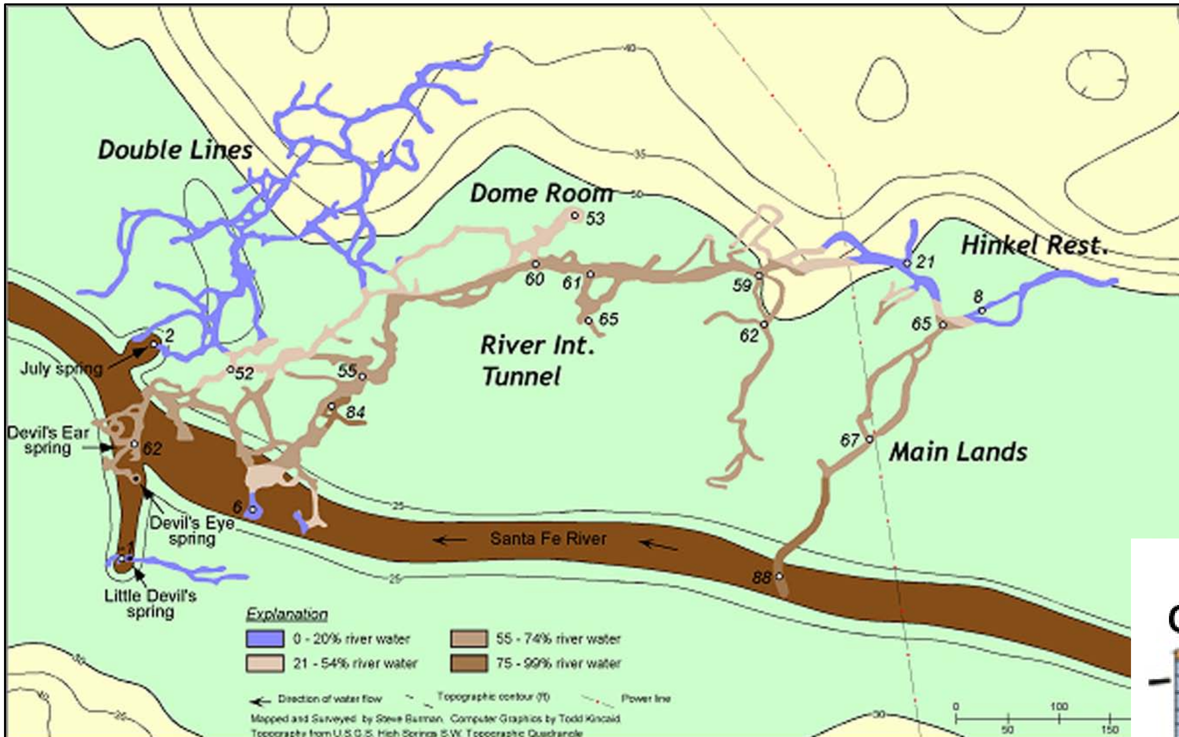
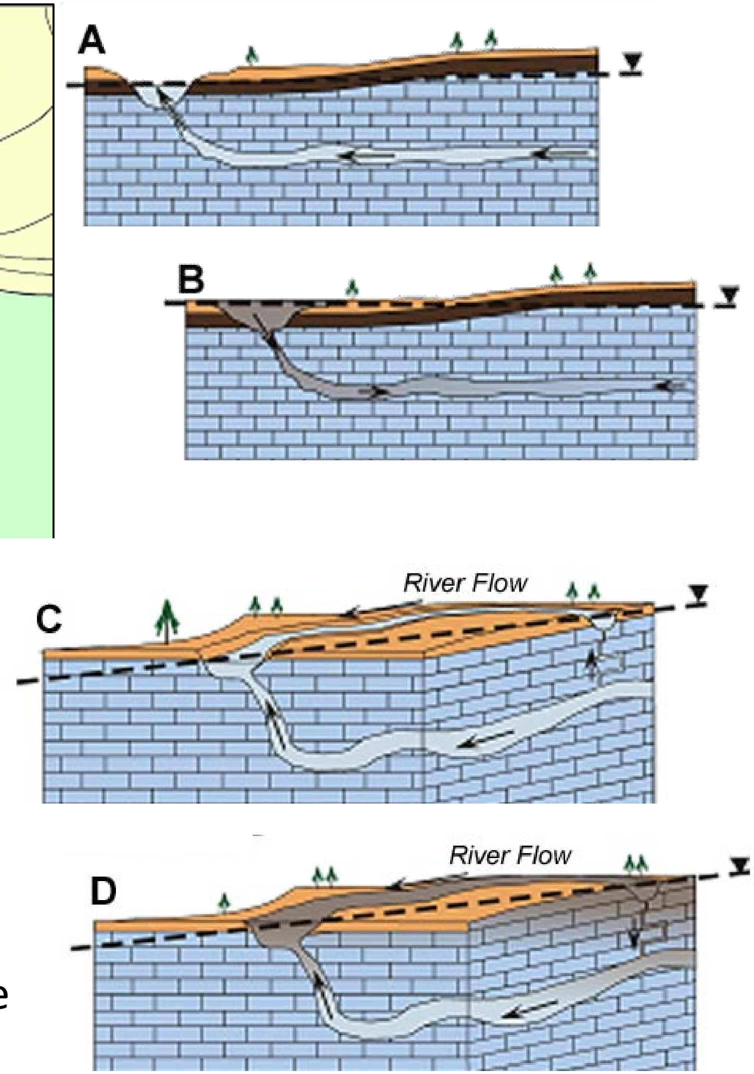
Groundwater / Surface Water Mixing





- Mixing occurs over very rapid time scales
  - *days rather than years*
- Can account for 50 – 100% of flow
- Degree of mixing is reflected by color of the discharge
- Need to constrain mixing in order to establish an accurate water budget

Mixing impacts the water budget

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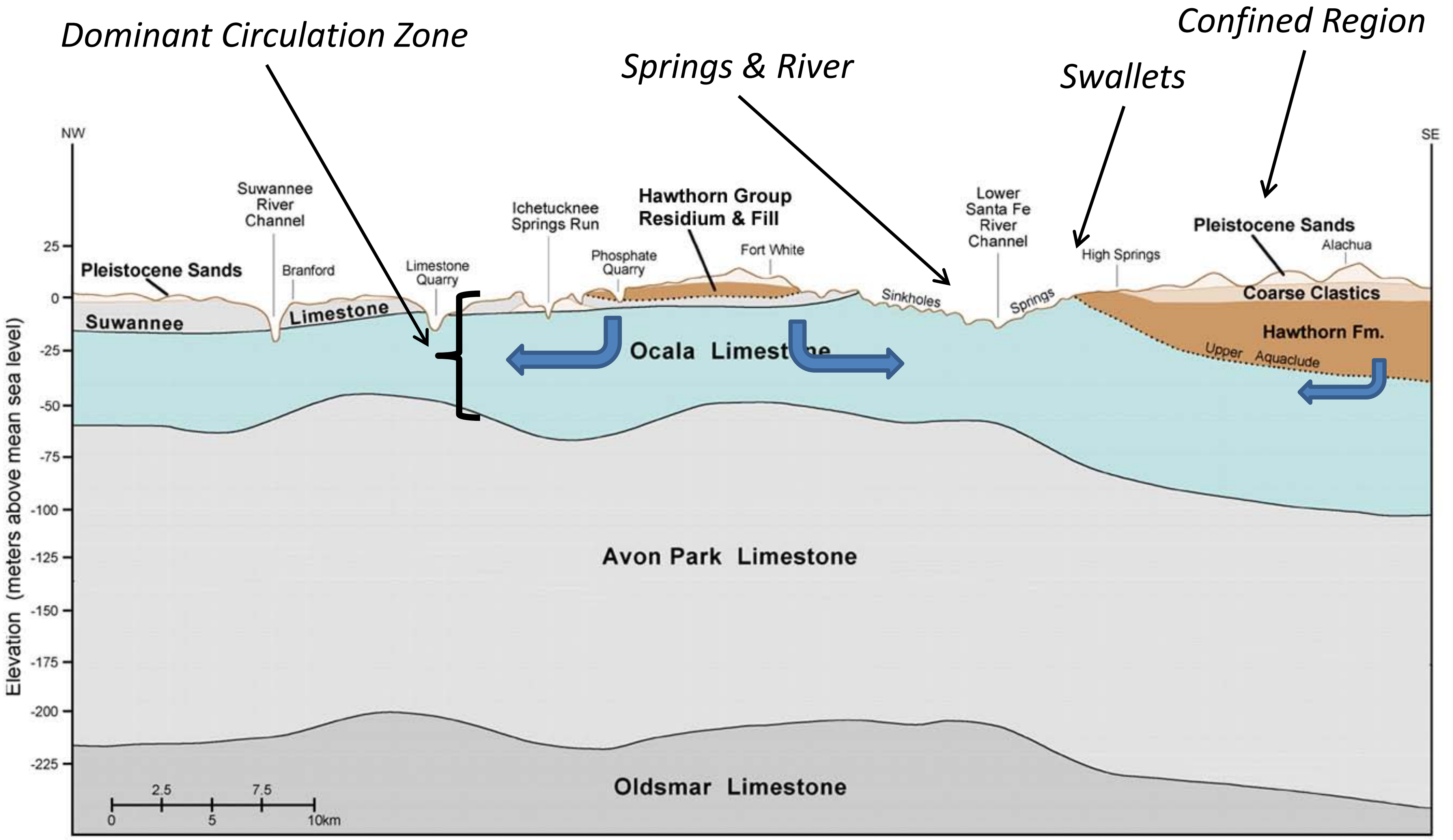
Hydrostratigraphy: *Aquifer Confinement*



Flow is 3D due to variable confinement

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Comparable Modeling Objectives

WKP

- Define all springsheds that may interact under varying conditions to control water and contribute water flow to Wakulla Spring.
- Develop a model that will deliver reliable predictions of travel-times.
- Develop a model that incorporates karst features and conduit flow patterns.
- Develop a model that calibrates to high and low water conditions.
- Solicit and incorporate sufficient feedback from the relevant stakeholders such that the model will be used by water resource managers as a decision support tool.

SFRB

- Define all springsheds that may interact under varying conditions and contribute water to Ginnie Springs & CCNA's well.
- Develop a model that will deliver reliable predictions of travel-times.
- Develop a model that incorporates karst features and conduit flow patterns.
- Develop a model that calibrates to high and low water conditions in the western Santa Fe River Basin.
- Develop a model that can be trusted by government resource managers.
- Share the model and model results with government resource managers and the public.

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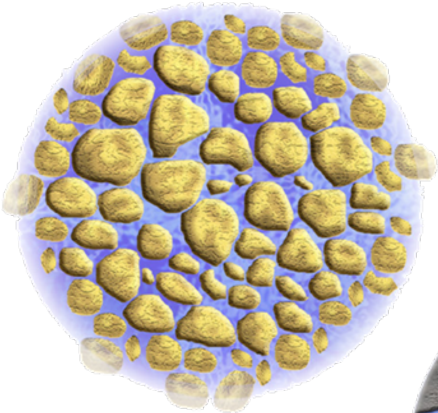
Basic Conceptualization Options

Porous Media

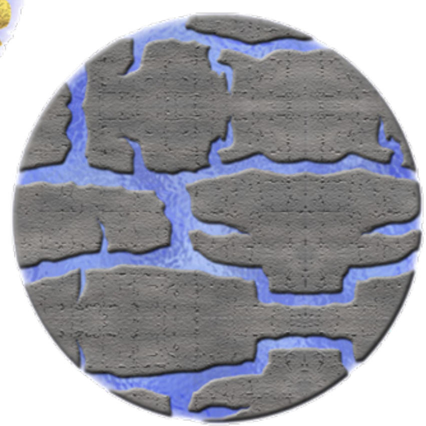


Most commonly assumed

sand / sandstone
easy to characterize
simplest math

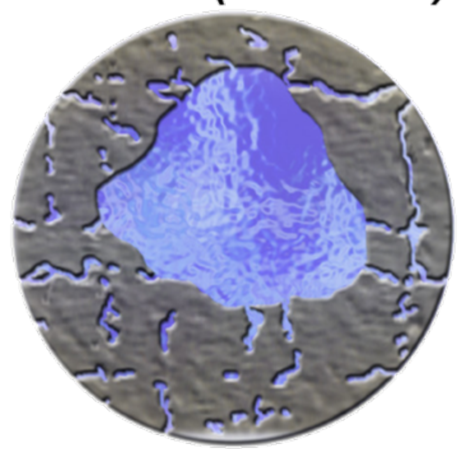
Most commonly true

Fractered Rock



hard rocks (shale, granite, etc)
can map from surface
harder to characterize
more difficult math

Karst (Conduits)

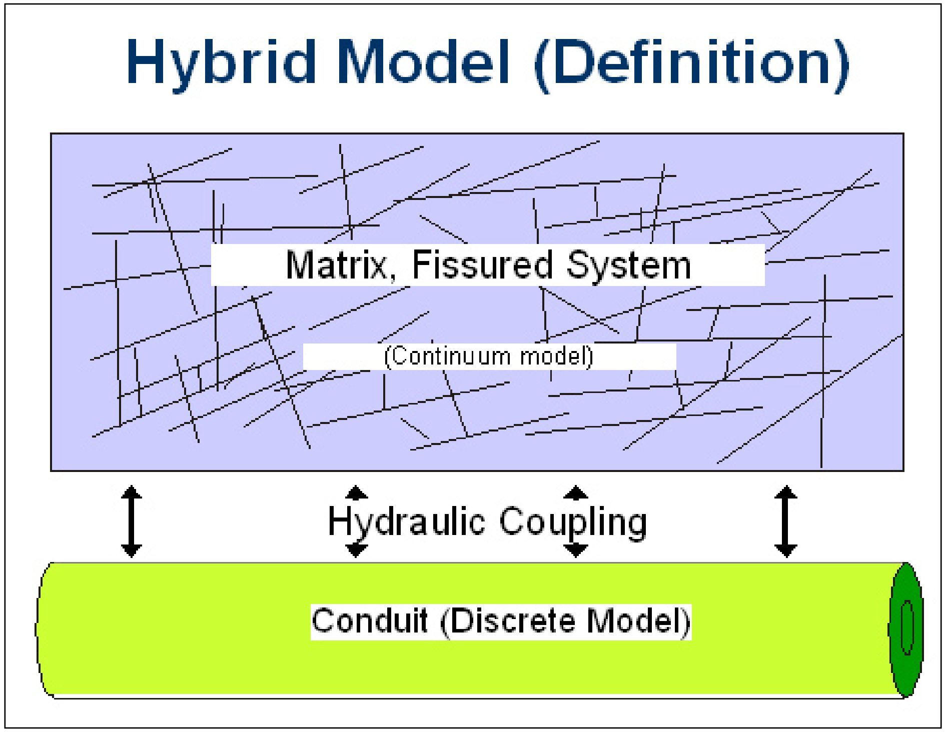


Limestone (Floridan Aquifer)
cannot typically be mapped
hardest to characterize
most difficult math

Start with an accurate conceptualization

Numerical Approach & Software

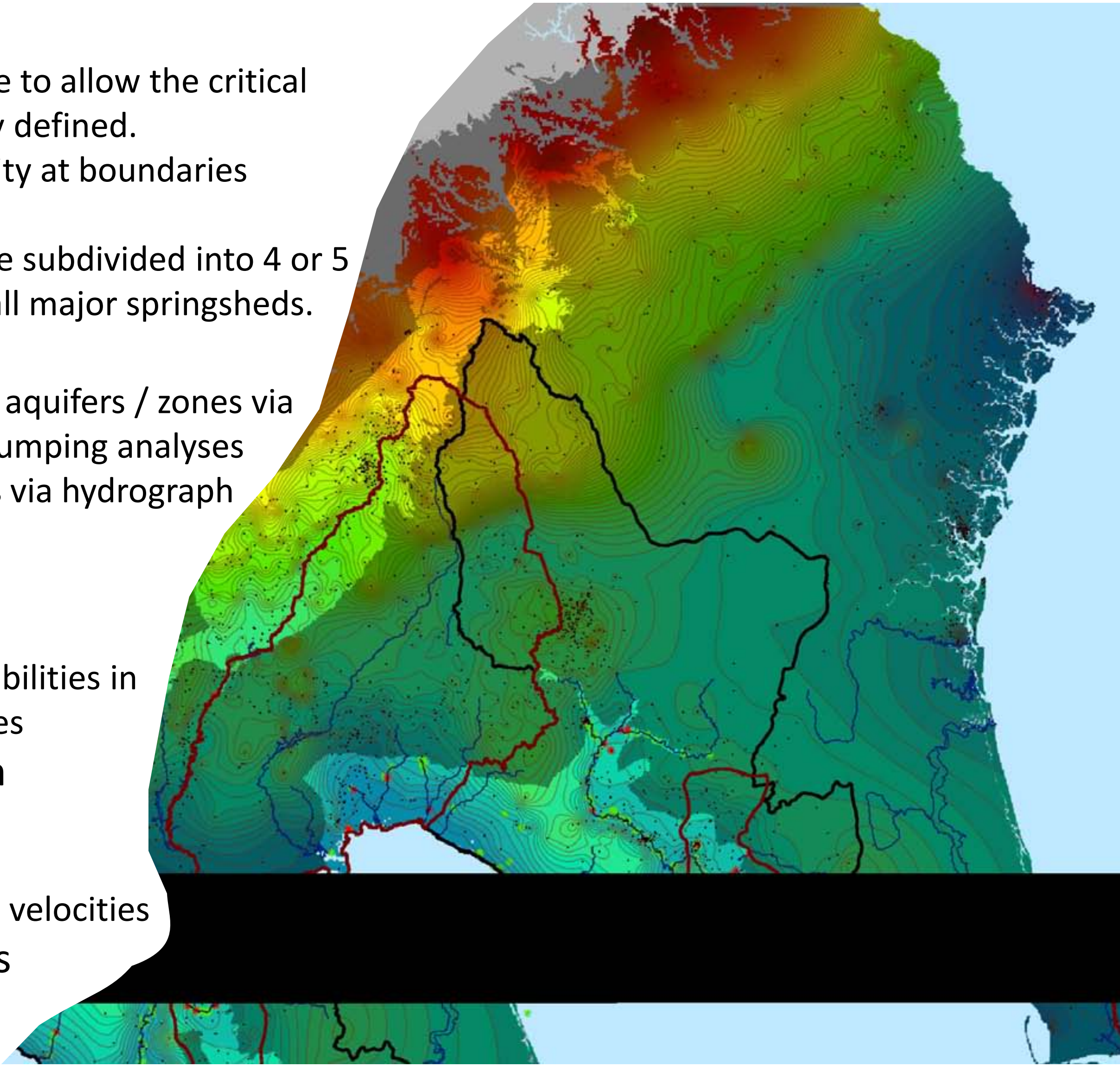
- Hybrid Model (Dual Permeability)
  - Continuum model for matrix *porous media > Darcy flow*
  - Discrete model for conduits *Pipe flow*
  - Flow can exchange between the two media
- Finite-element formulation
  - Maximum flexibility for geometric design
  - Computational efficiency *more model runs = higher confidence*
- FEFLOW™
  - Commercially available (DHI-WASY)
  - Commonly used by national laboratories & research institutions.
  - Discrete element features allow for hybrid model design.



WASY Software FEFLOW WASY

http://www.feflow.info/

Our Approach to Modeling Karst



- Watershed-scale models
  - Need to be sufficiently large to allow the critical springsheds to be internally defined.
  - Design to establish continuity at boundaries between adjacent basins.
  - Florida's Karst Belt would be subdivided into 4 or 5 basin models to delineate all major springsheds.
- Detailed data analysis
  - Delineate vertical extent of aquifers / zones via well completion, head, & pumping analyses
  - Expand calibration datasets via hydrograph analysis & correlation
- Dual-permeability
  - Explicitly define conduits
  - Use realistic matrix permeabilities in geologically defensible zones
- Multiple lines of calibration
  - Heads
  - Spring & river flows
  - Tracer/ hydrograph defined velocities
- Multiple calibration periods
  - High water
  - Low water
  - Possibly transient

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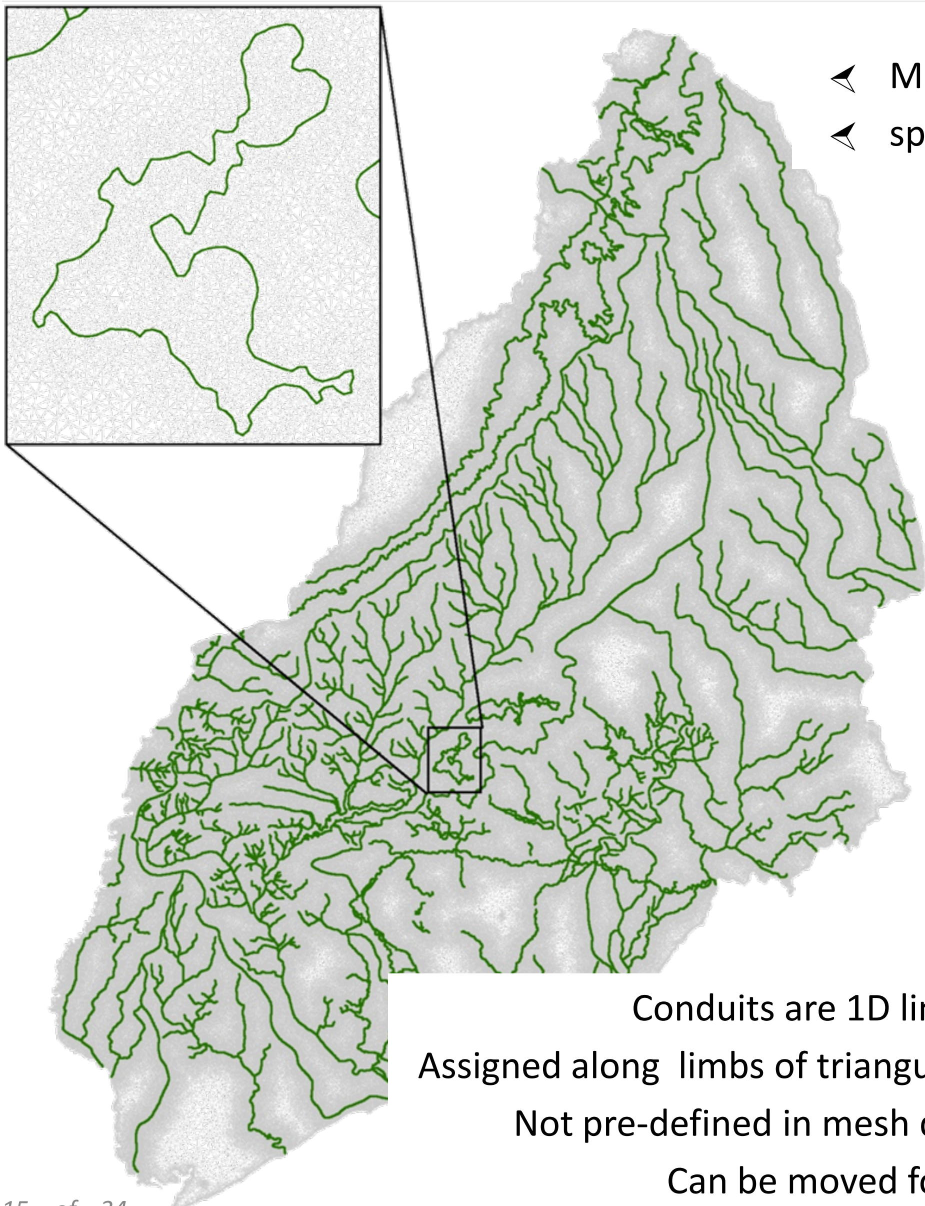
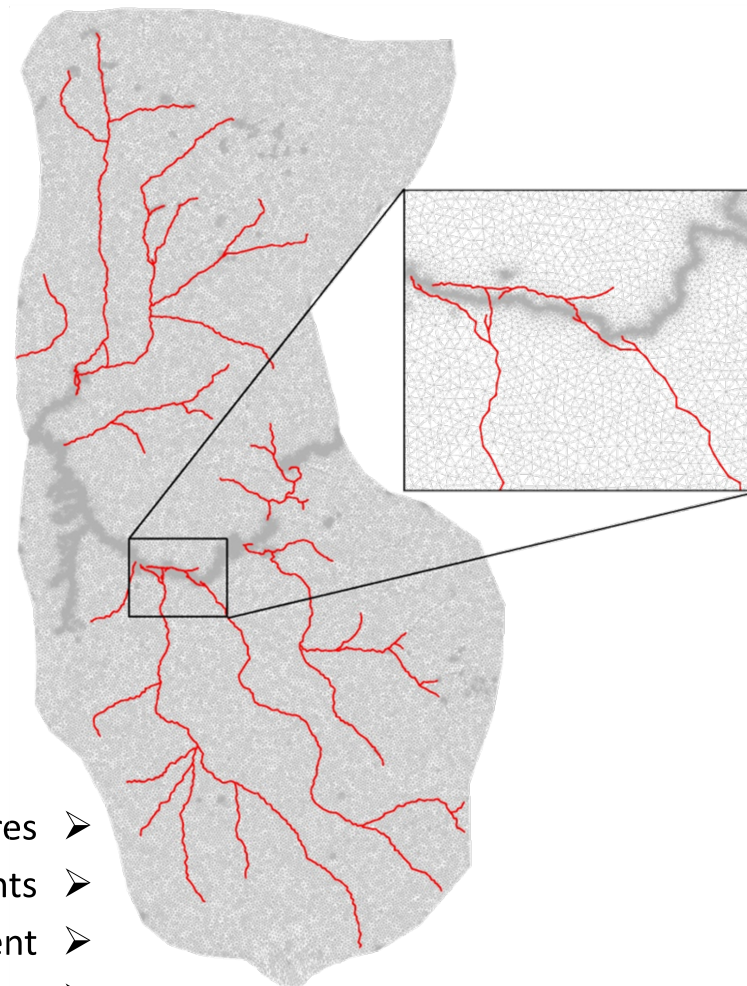
FE - Dual Permeability Mesh Design

- Mesh refined around all key hydrologic features
- springs, rivers, contacts, wells, etc





- Conduits are 1D linear features
- Assigned along limbs of triangular elements
- Not pre-defined in mesh development
- Can be moved for calibration

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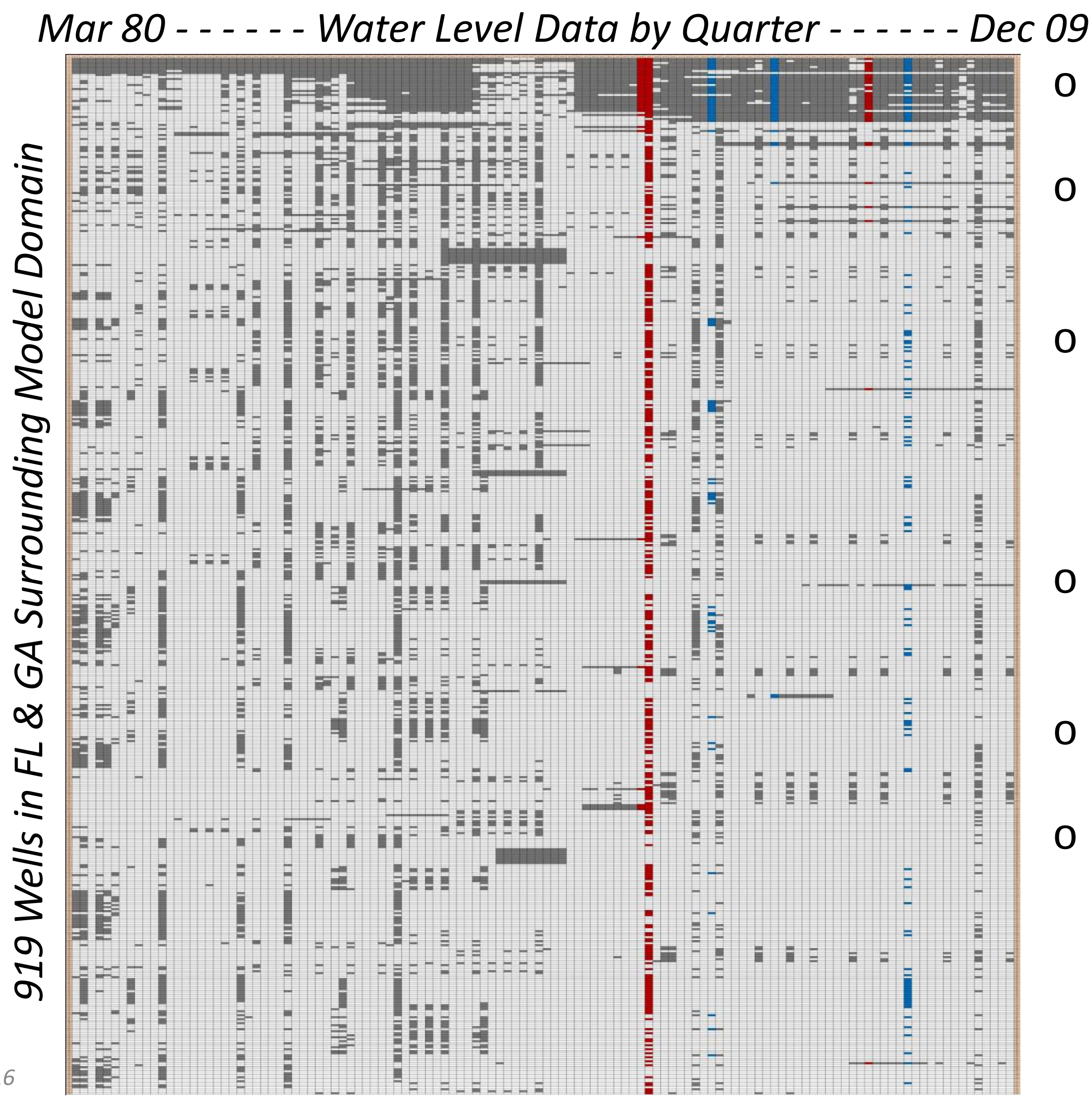
Developing a Calibration Dataset



- Dramatically increases data density for calibration
- Analyze data and bin into groups representative of high & low water periods
- Use well-well regression analyses on all wells to expand datasets with data from wells that correlate *(not performed yet for this model)*
- Use grouped data to develop high-water and low-water potentiometric surface maps
- Use pot surface maps to define initial conduit layout
- Use high-water and low-water datasets for model calibration

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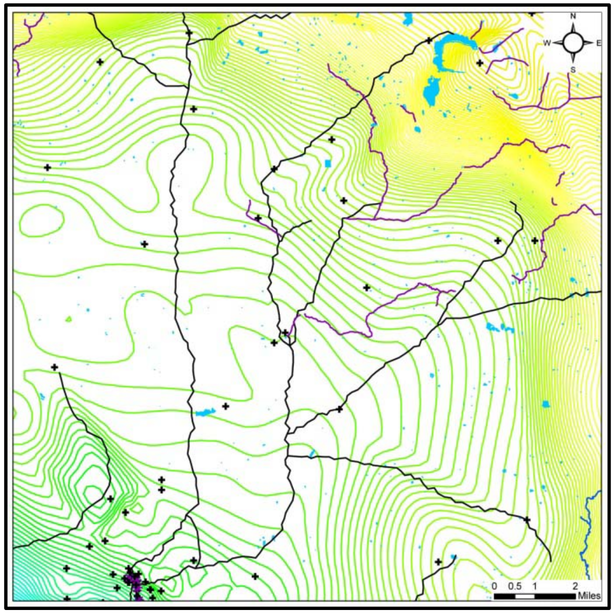
Groundwater Modeling Process

- Design model to match known physical conditions
    - geology, caves, well & spring locations, swallet inputs
    - Recharge ranges (bounded by rainfall data & land use)
- Define physics of groundwater flow
    - Porous media in rock / Pipe flow in caves
- Run model and compare results against data
    - Groundwater levels, Springs, Groundwater velocities (tracing)
- Adjust model parameters *(within reasonable limits)*
    - Rock permeability, Cave locations & dimensions
    - Recharge *(bounded by data and zones defined by land use)*
- Rerun model with new settings
- Repeat process until simulation matches data
- Run model with low water recharge (only adjust recharge)
- Compare results against data
- Adjust model parameters and rerun as necessary
- Repeat whole process until model simulates both high water and low water conditions with same parameter settings

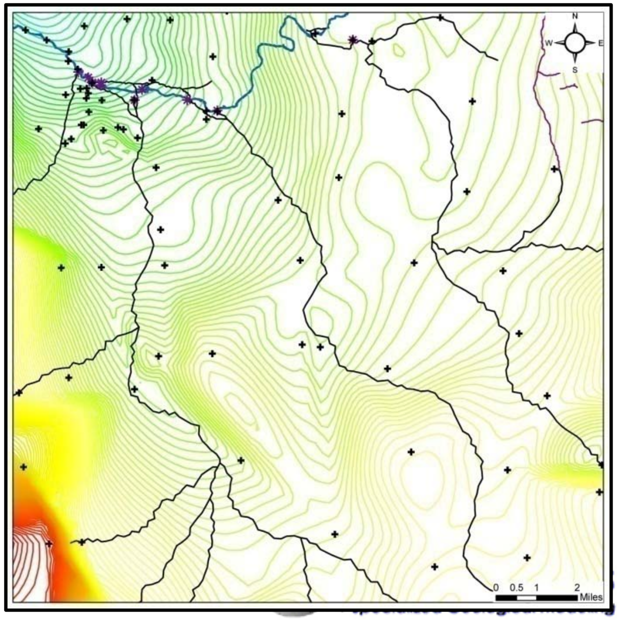
Modeling Conduits …

- What we know…
  - Conduits convey water rapidly to springs
  - Groundwater surface around conduits is depressed
  - Groundwater surface in sand would be smooth
  - Groundwater surface has troughs & ridges in the SFRB
  - The rocks are fairly similar across the region
- Assumptions …
  - Complexity in groundwater surface is due to conduits
  - Conduits follow troughs in the groundwater surface
- Step-1: Assign conduits to known locations
  - Mapped caves / Tracer defined pathways
- Step-2: Assign conduits along troughs
  - Between known connected points
  - Up-gradient from springs
  - Down-gradient from swallets
  - To unexplained closed depressions
- Step 3: Modify conduits to match data
  - Simplest possible pattern (low water conditions)
  - Dimensions set to carry necessary water to springs (high water conditions)

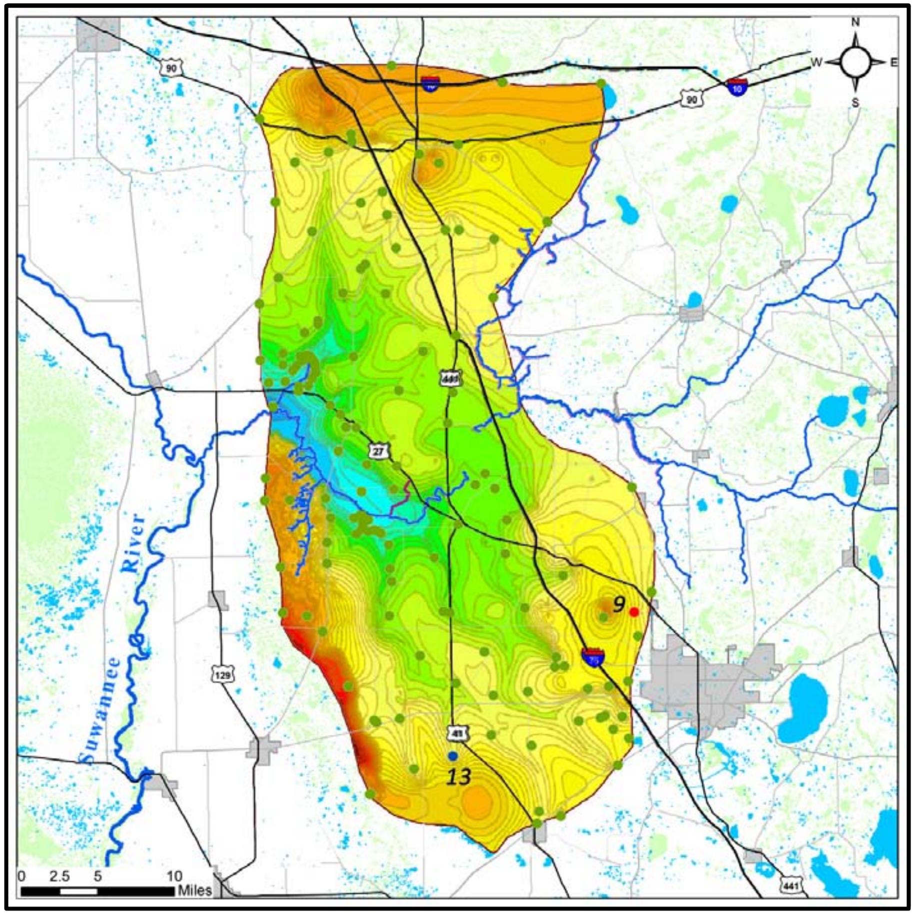
Northern Region

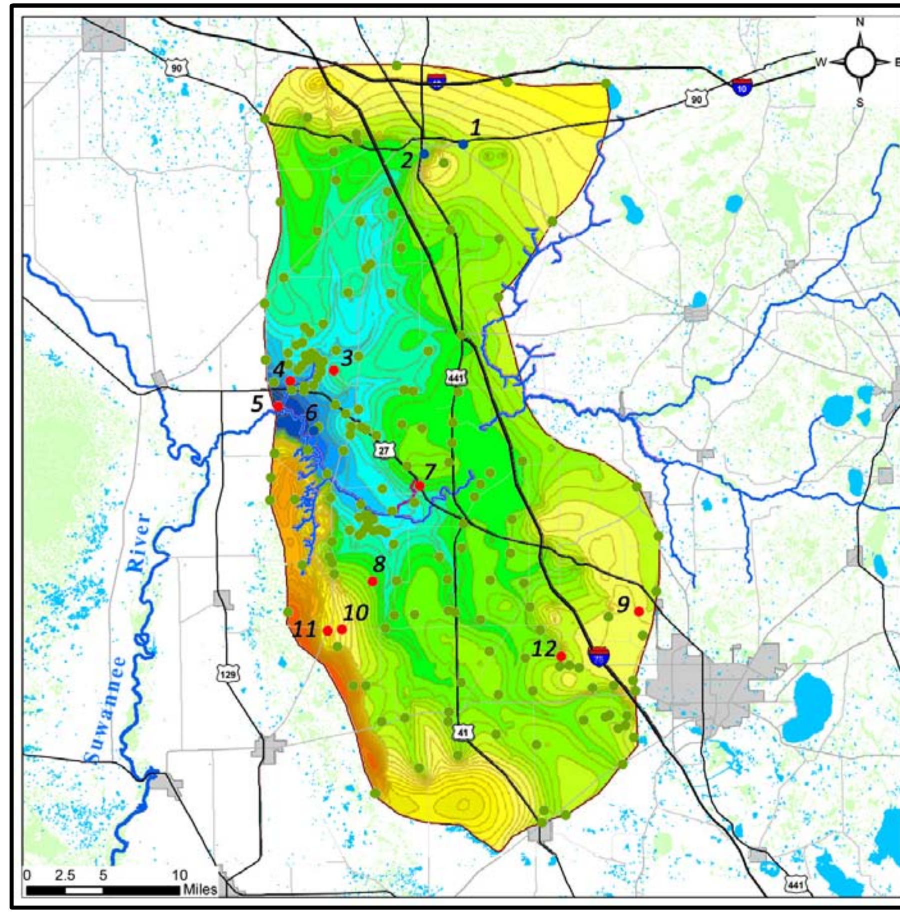


Southern Region



Model Results: *Groundwater Levels*





Green = calibrated (Red = high / Blue = low)

- High water: 143/145 wells calibrated
- 1998/1999; 2004/2005
- +/- 0.95 m (~3 ft)

- Low water: 176/188 wells calibrated
- 2001/2002; 2007
- +/- 1.05 m (~3ft)

Both scenarios are very well calibrated

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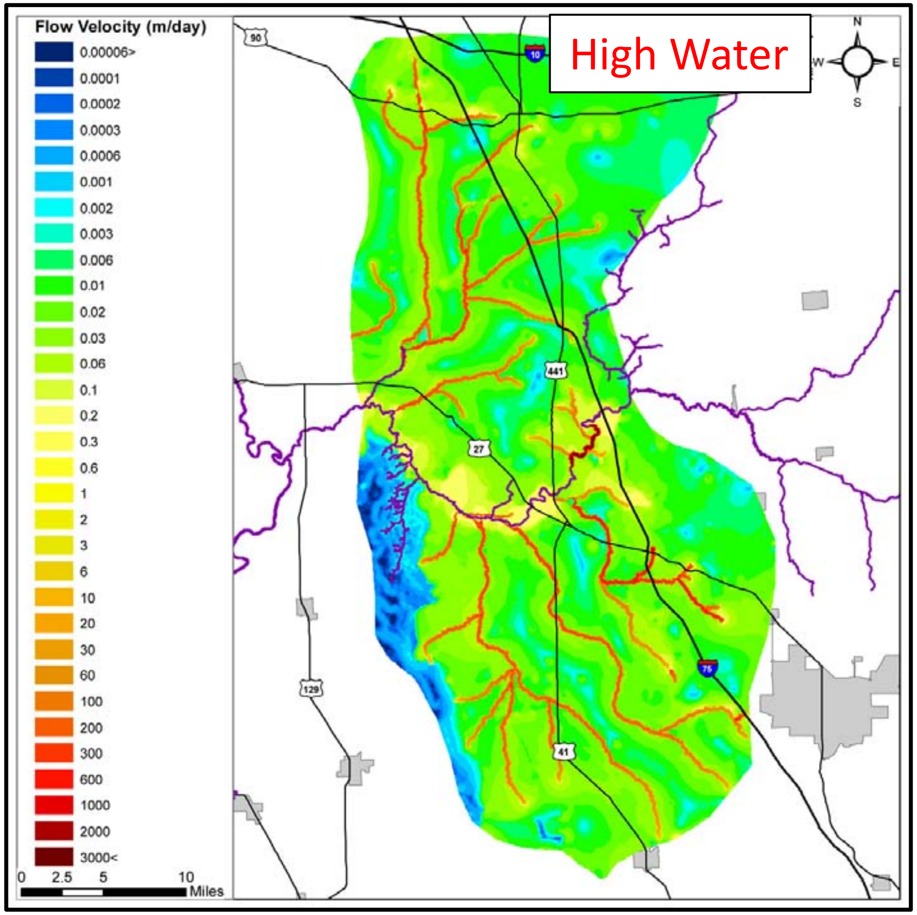
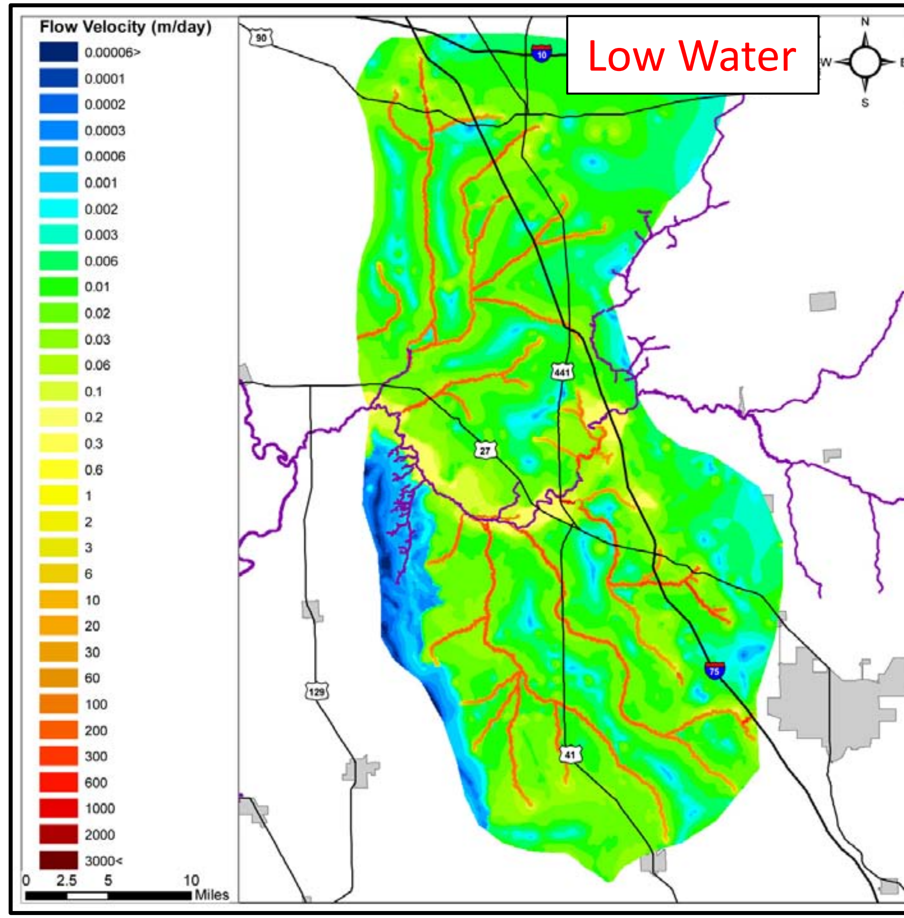
Model Results: *Groundwater Velocities*





- Conduits model: ~ 100 to ~3000 m/day
- Conduits observed: ~ same
- Matrix model: ~ 10^{-3} to 10^{-1} m/day
- Matrix observed: ~ 10^{-6} To 10^{-3} m/day

- Conduits model: ~ 100 to ~1000 m/day
- Conduits observed: ~ same
- Matrix model: ~ 10^{-3} to 10^{-1} m/day
- Matrix observed: ~ 10^{-6} To 10^{-3} m/day

Both scenarios are very well calibrated

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Applications: Aquifer Vulnerability

Municipalities: Santa Fe River Basin, Florida

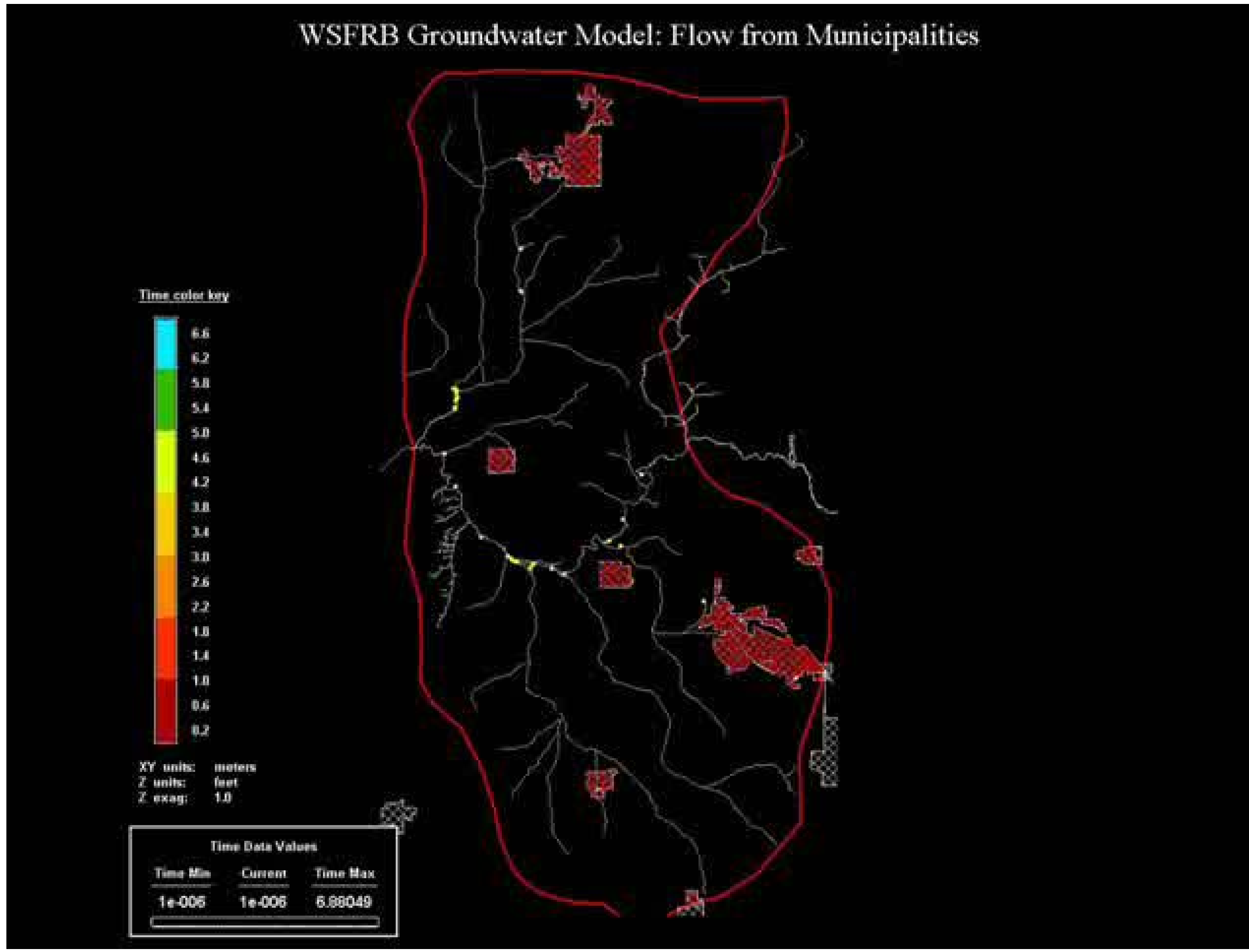
Flow is to closest conduits

Closest towns not always of most concern

Newberry – Ginnie Spring
- *~12 miles*
- *~1000 days*
- *conduit flow*

Alachua – Hornsby Spring
- *~7 Miles*
- *~500 days*
- *conduit flow*

High Springs – River
- *~2 miles*
- *~10,000 days*
- *no conduit*

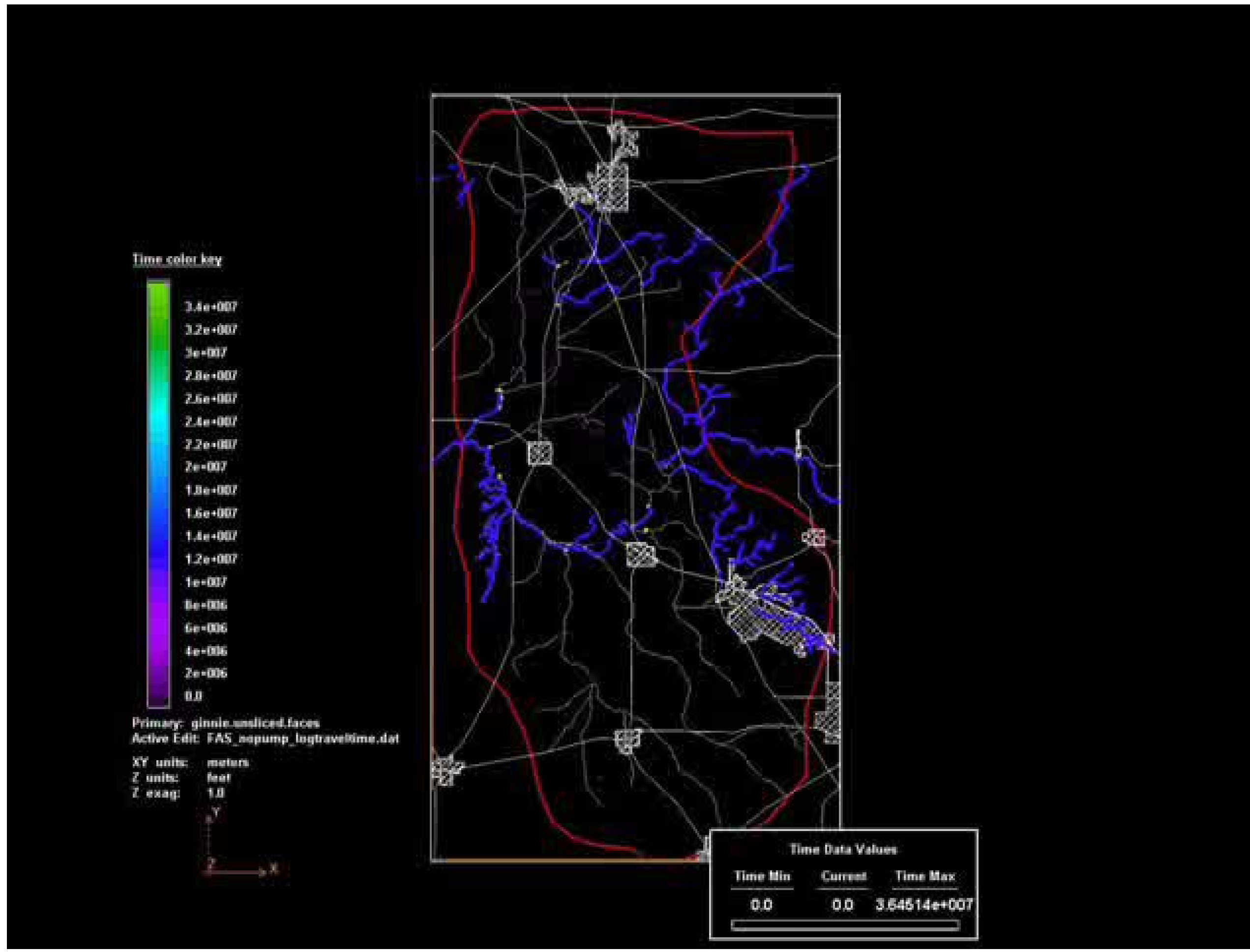


Applications: Source Water Protection

Controlled by conduits

Simulated velocity range
- *10^3 m/day*
- *10^{-3} m/day*

Springs Vulnerability: Santa Fe River Basin, Florida



Coca-Cola north america

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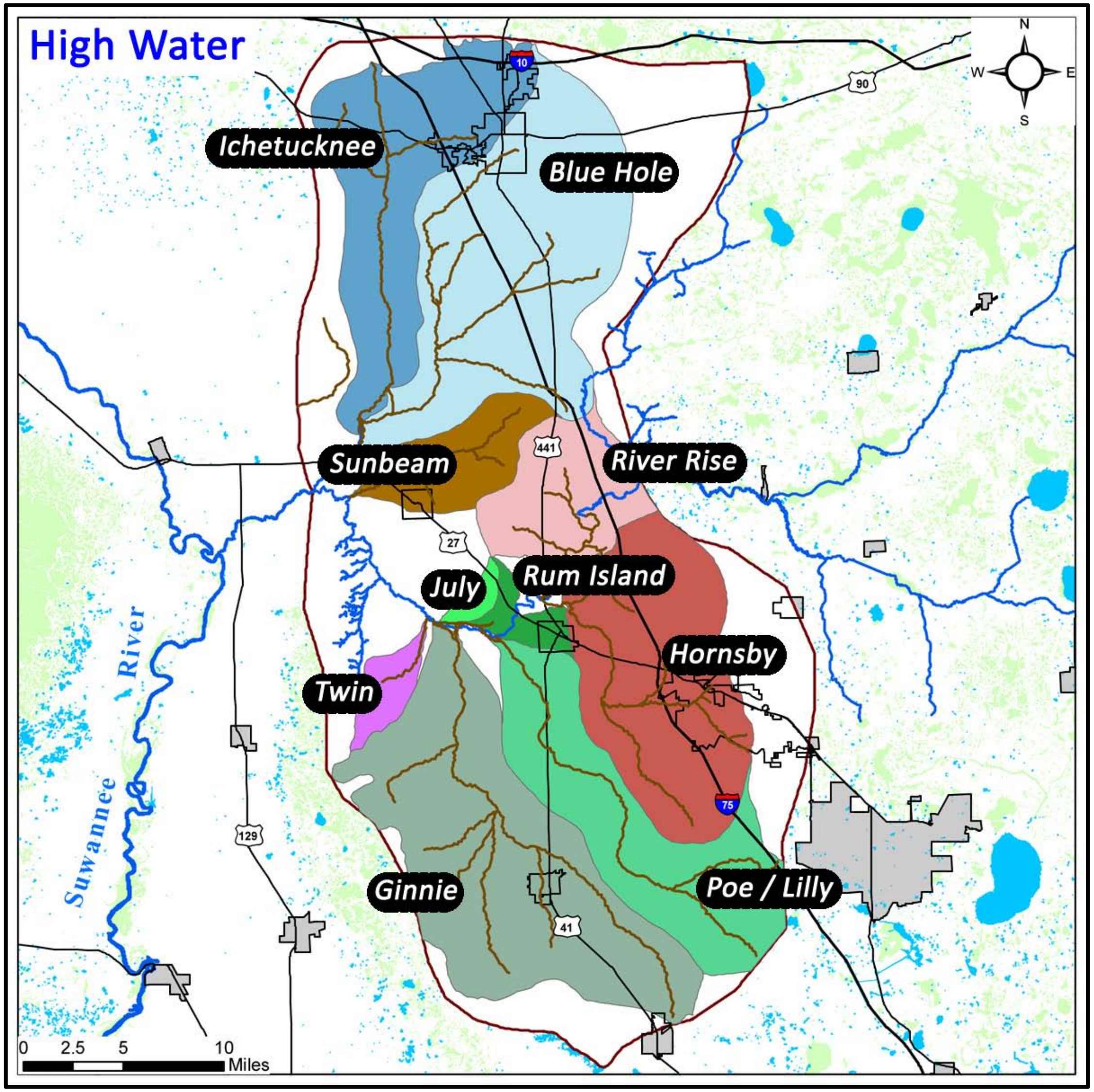
Applications: *Springshed Delineations*

- Defined from forward particle track analysis
- Boundaries change between high water & low water conditions

Spring Group	High (km²)	Low (km²)
Ginnie / Blue	395	414
Blue Hole Group	377	488
Hornsby	274	210
Ichetucknee	248	222
Poe / Lilly	237	241
River Rise	116	134
Sunbeam	80	103
Twin	29	49
Rum Island	24	26
July	12	11



Model has defined springsheds based on flow

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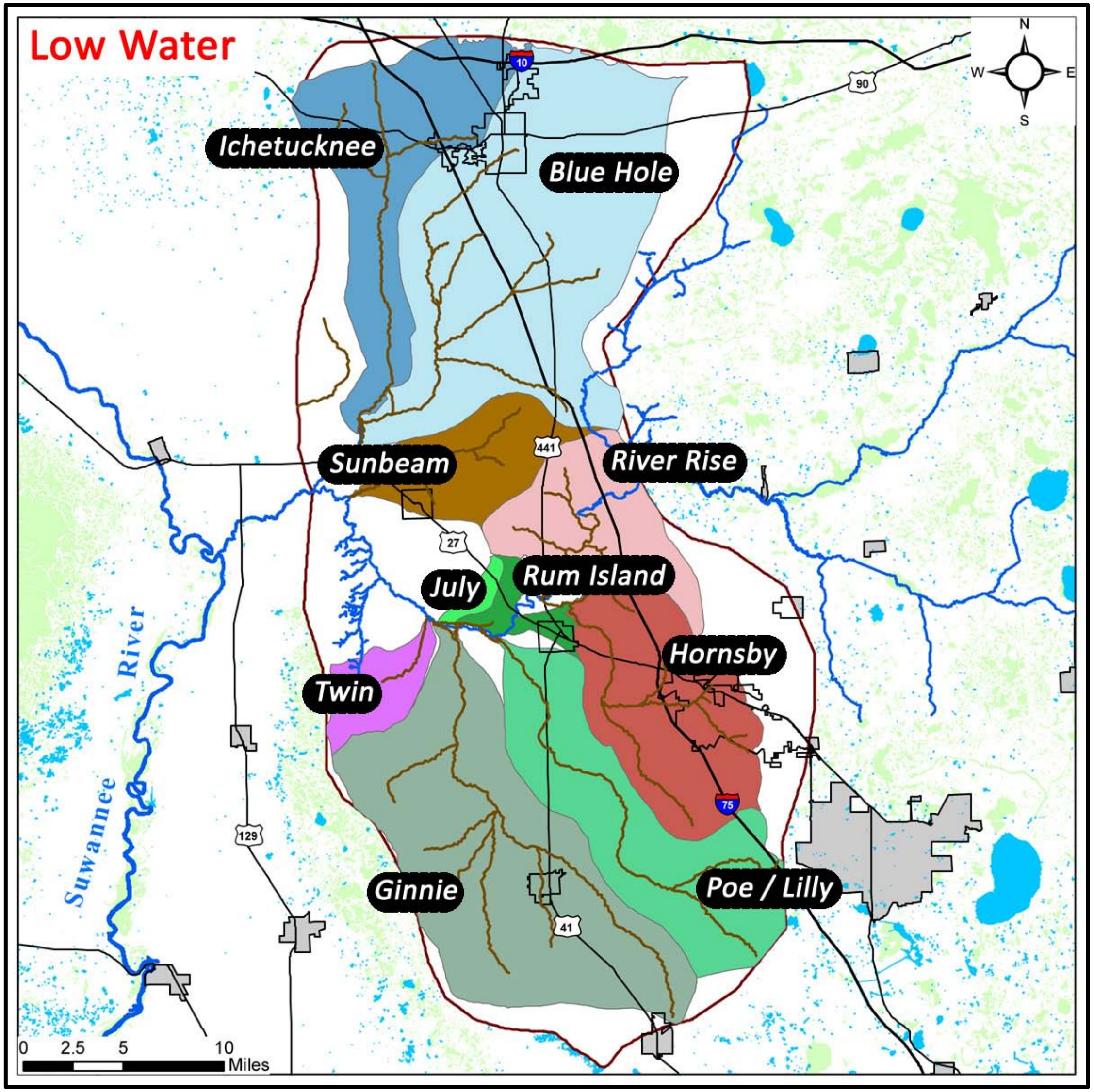

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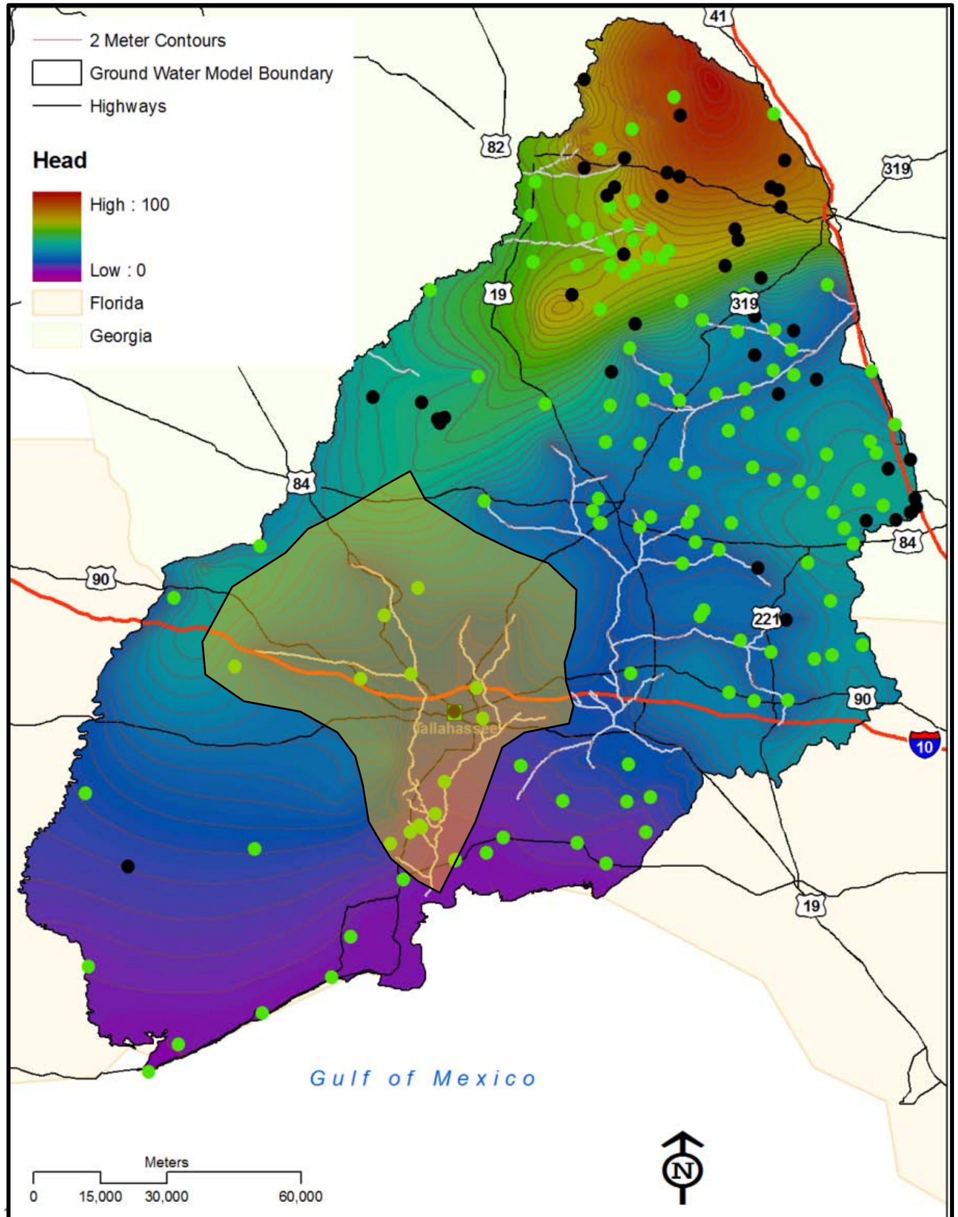
Model Results: Wakulla Springshed



- Wakulla & Spring Creek springsheds cannot be truly segregated because both springs are connected to the same conduit network.
- When Spring Creek stops flowing, water from nearly all of the combined springshed flows to Wakulla.
- When Spring Creek is flowing, it probably takes water from the western part of the combined springshed.

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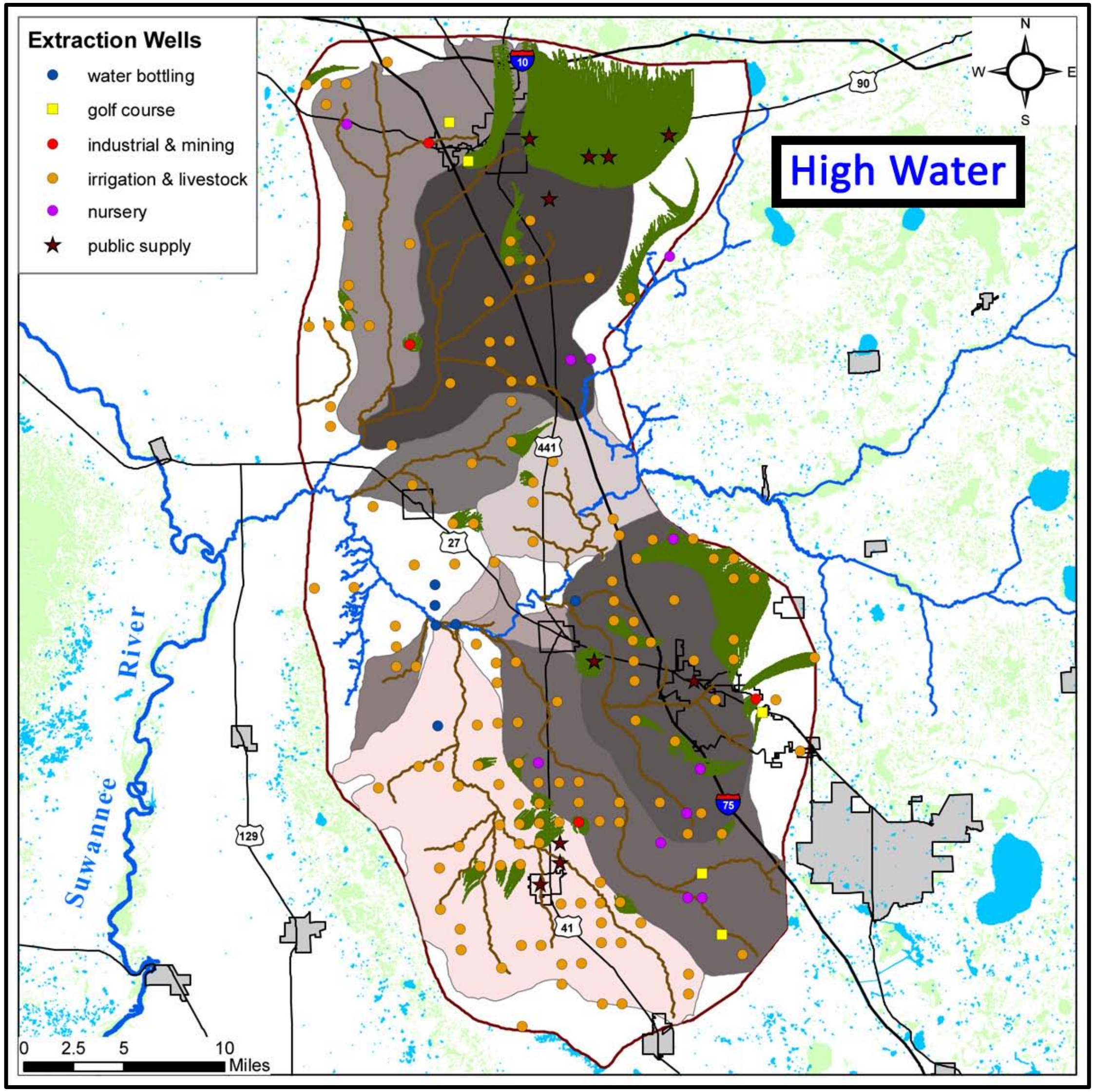
Applications: *Pumping Impacts*

- Pumping diminishes spring flows within the impacted springsheds.
- Particle tracking shows that pumping impacts the size and shape of the springsheds.
- Model simulates impacts to flows & springsheds.
- Example: Lake City
  - Average rate: 4.5 MGD
  - No pumping springsheds
    - Ichetucknee: 248-222 km^2
    - Blue Hole: 377-488 km^2
  - Pumping springsheds
    - Ichetucknee: 245-222 km^2
    - Blue Hole: 316-377 km^2
  - Reductions
    - Ichetucknee: -1% / 0%
    - Blue Hole: -19% / -30%



Model simulates pumping impacts under varying conditions

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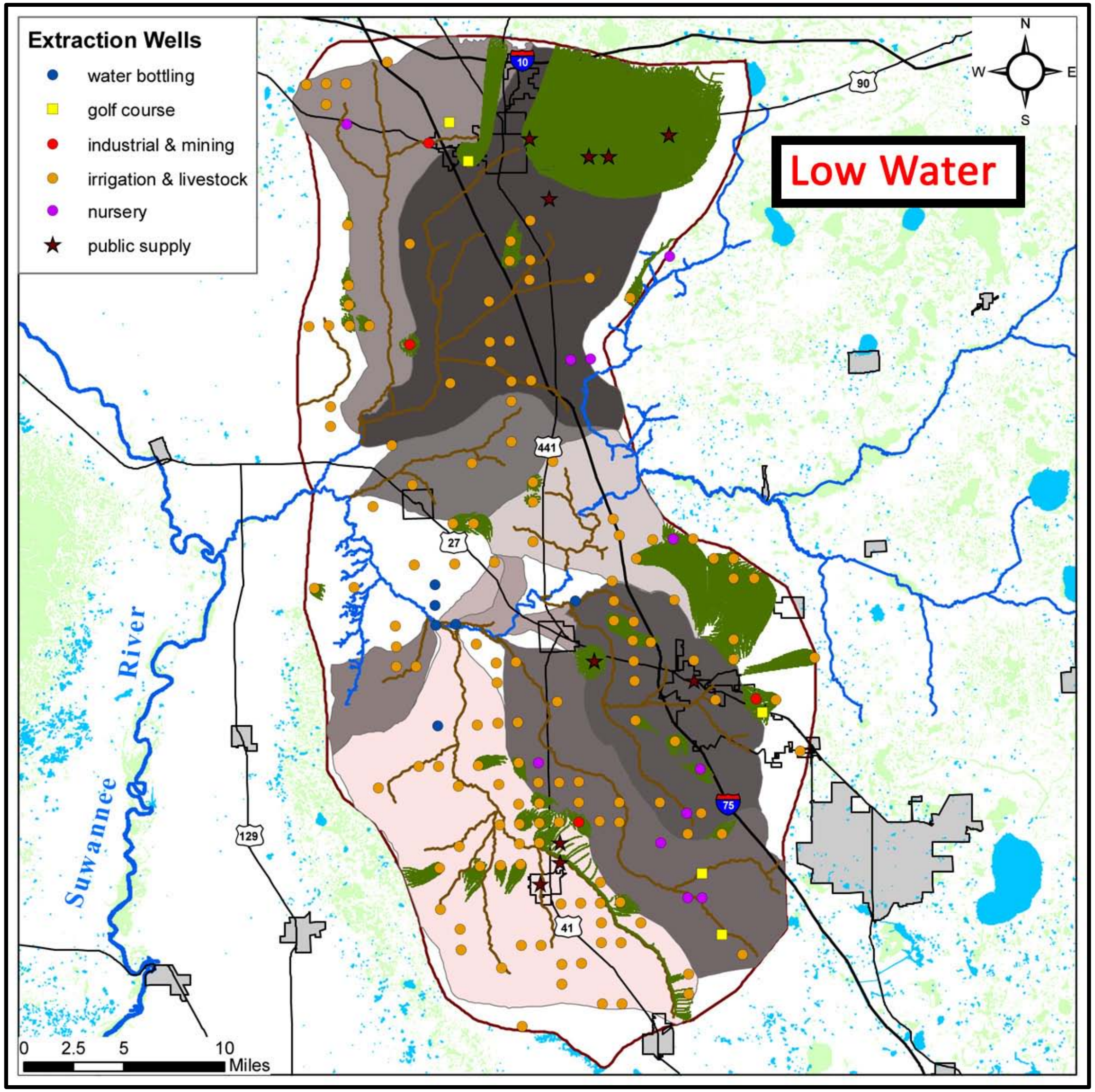

Model simulates pumping impacts under varying conditions

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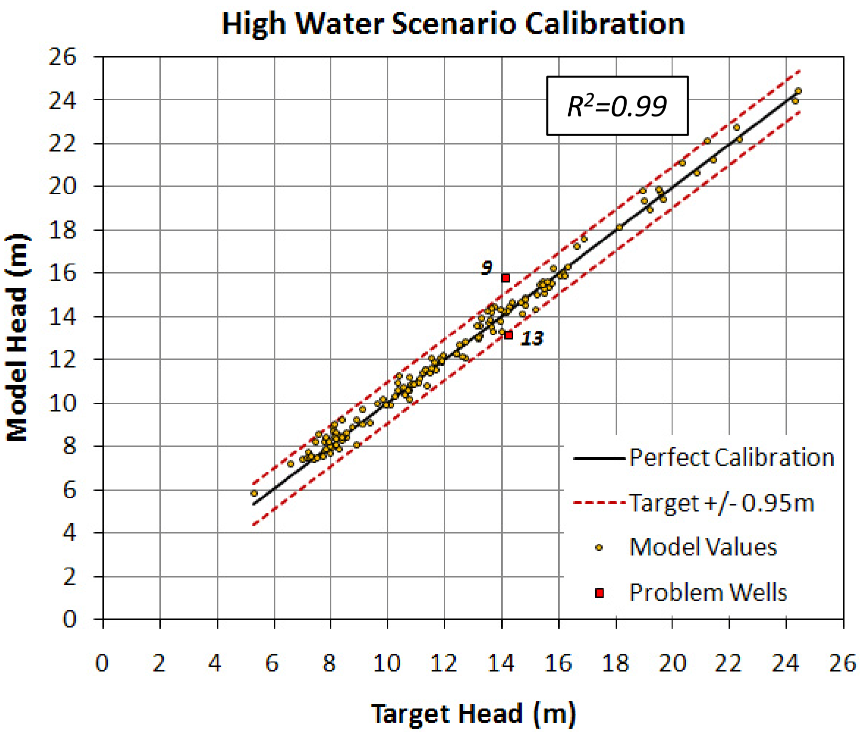
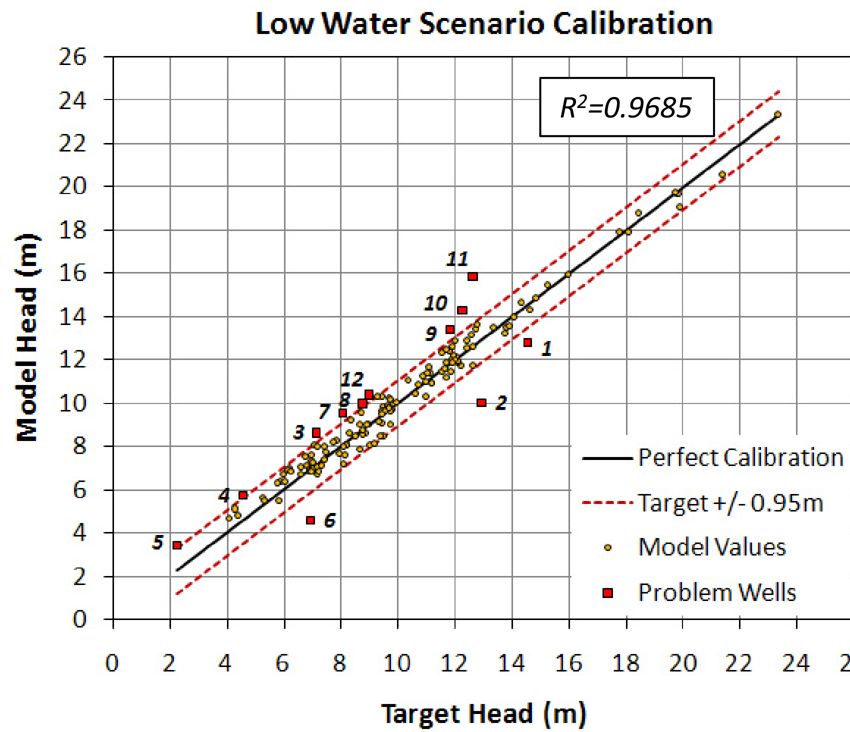
Model Calibration: *Groundwater Levels*





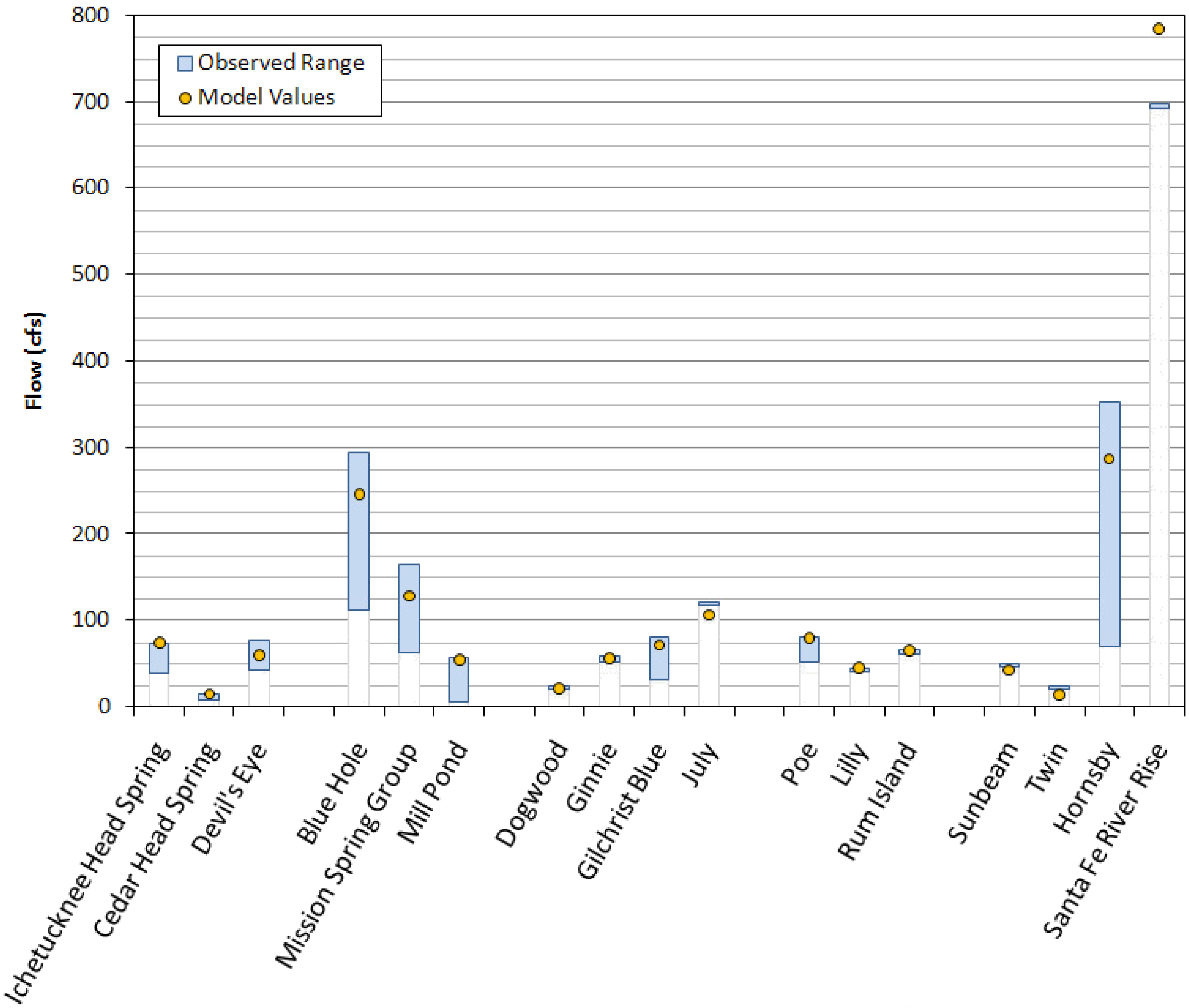
- Plots show how well the model simulates known groundwater levels.
- Perfect match would be the black line.
- All points within the red dashed lines are “calibrated.”
- Could not achieve this good of a match if it were not for including the conduits.
- Even the points that fall outside the red lines are close to target levels.
- Additional small adjustments to the conduit locations could probably get all points within range.
- Those adjustments will not significantly impact the model predictions.

Both scenarios are very well calibrated

Model Calibration: *Spring Flows*

High Water Simulation

- Data for 17 springs
- Model within observed range at 13
- Model very close at 3
- Over estimated Santa Fe River Rise
- Does not impact groundwater flow because the conduit is mostly surface water



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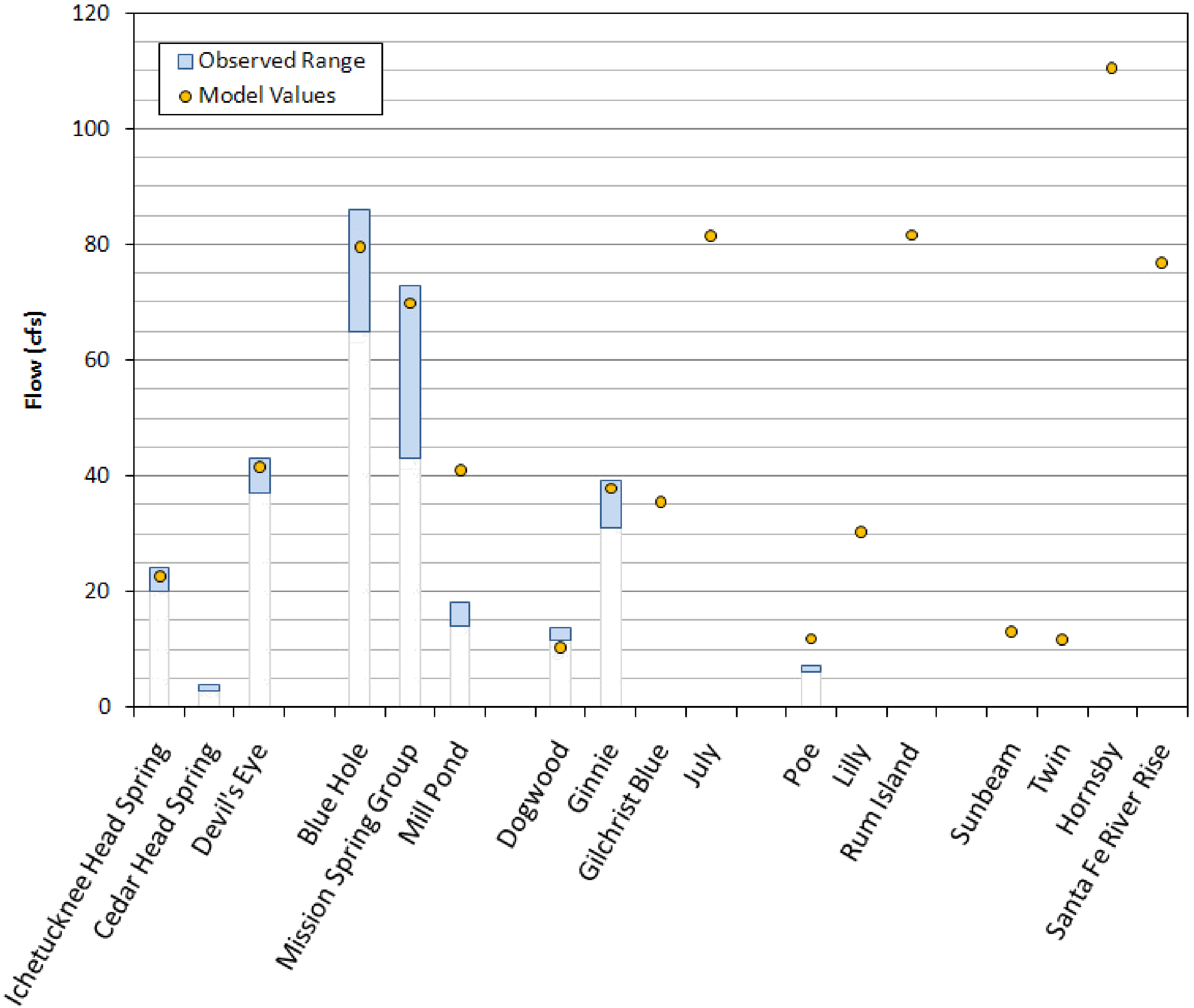
Model Calibration: *Spring Flows*

Low Water Simulation

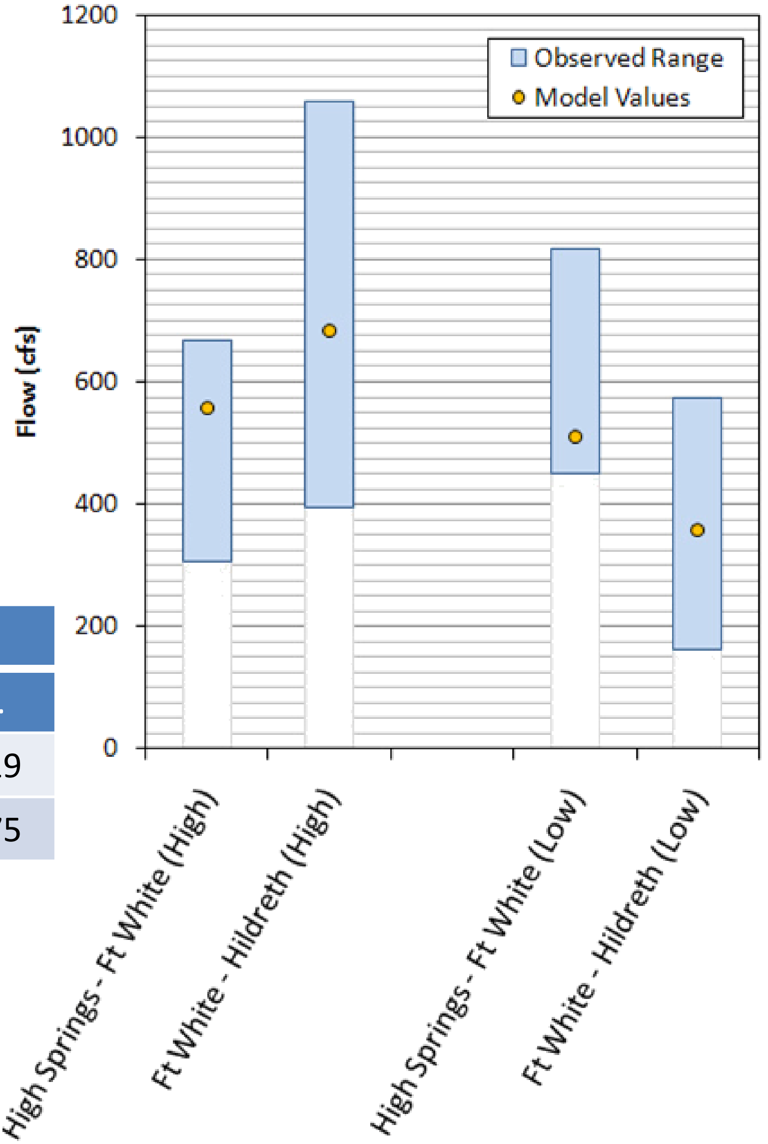
- Fewer data points
- Data for 8 springs
- Model within observed range at 5
- Model very close at 2
- Over estimated Mill Pond
- Still within reasonable range given "average conditions" simulation



Model Calibration: *River Gains*

- Aggregate river gains also used as calibration targets
- Accounts for springs and diffuse flow to rivers
- Model matches observed ranges

	High Water		Low Water	
River Stretch	Model	Meas.	Model	Meas.
High Springs – Ft. White	557	307-669	511	449-819
Ft. White - Hildredth	685	395-1059	357	162-575



Matches both discrete discharges & aggregate gains

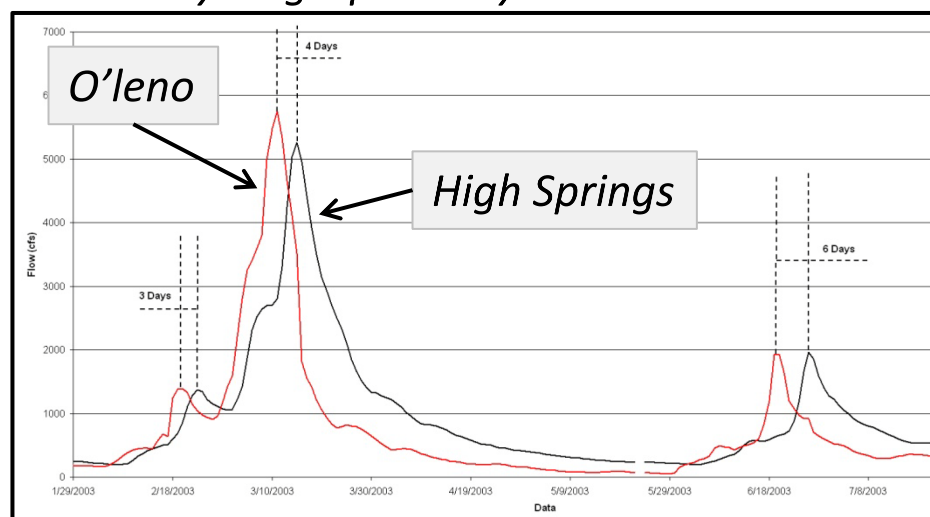
Velocity Calibration

Potential range in conduit groundwater velocities estimated from…

- Tracer Tests (Karst Env. Services)
  - Mill Creek & Lee Sinks – Hornsby Spring
    - 430 – 730 m/day
    - Constraint on Mill Creek flow paths
  - Rose Creek & Clay Hole Sinks – Blue Hole & Mission Springs
    - 210 – 330 m/day
    - Constraint on other pathways except Old Bellamy flow path
- Hydrograph Analysis:
  O'leno State Park – High Springs
  - 2125 – 4250 m/day
  - Used to constrain Old Bellamy

Fluorescent Tracer Testing

Hydrograph Analysis – Stream Pulses



Conduit velocities constrained by indirect measurements

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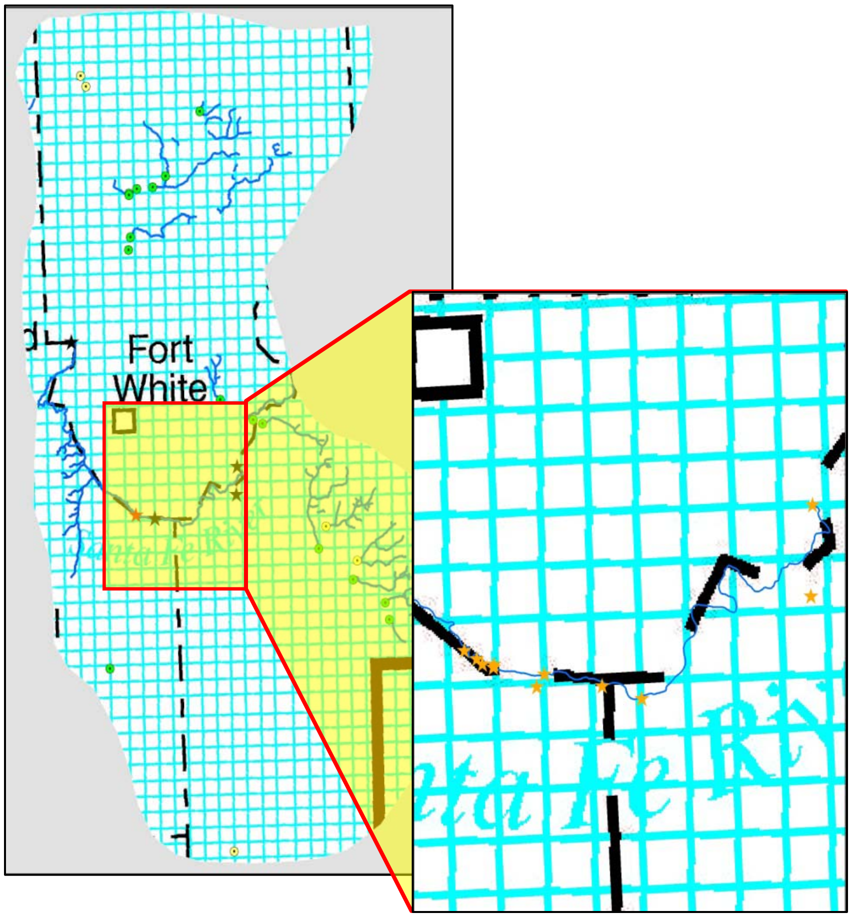
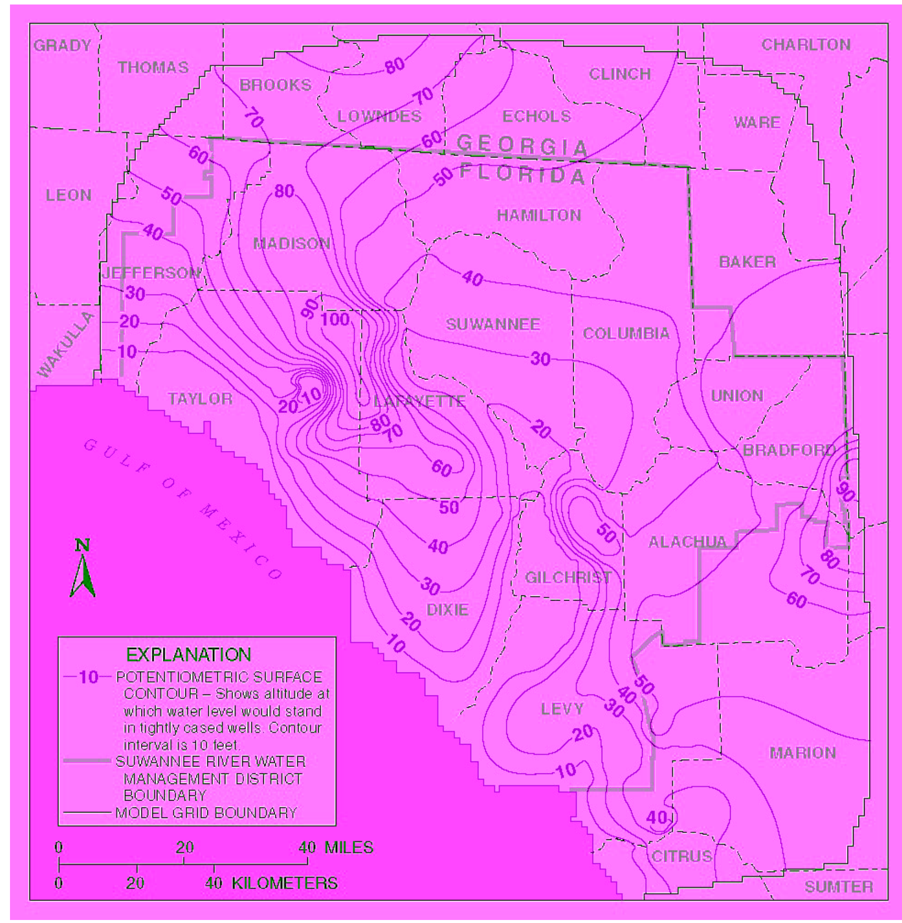
Different approach can be significant

USGS Suwannee River Basin Model

Flow field open to the north





Summary & Conclusions

- Model successfully simulates realistic flow conditions to springs in the WSFRB.
- Model can be used to evaluate both water quantity and quality issues and concerns relative to springs protection.
- Better models can be constructed in Florida's Karst Belt if adequate time is taken to thoughtfully address important karst data (spring flows, caves, swallets, tracer testing)
- Models that don't address these features can be dangerously wrong and misleading. If the models we've been using were working well, we might not be here today.

- Coca-Cola's Santa Fe River Model is now publically available.
- Coca-Cola is hopeful that it will be used in a constructive manner to support water resource protection in the WSFRB.

  www.geohydros.com/CCNA/

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Why Coca-Cola Built This Model?

- Vested interest in sustained clean freshwater discharge to the Western Santa Fe River
  - Threats to water quality or quantity threaten their business
  - Diminished water quality & quantity diminish their business and their brand
- Corporate commitment to water sustainability

  "Our goal is to safely return to communities and nature an amount of water equivalent to what we use in all of our beverages and their production."

  - *The Coca-Cola Company*

  - http://www.thecoca-colacompany.com/citizenship/water_main.html
- Our project began in 2005
  - *Build the best possible model*
  - *Make it honor the springs, caves, and swallets*
  - *Make it public when your done*

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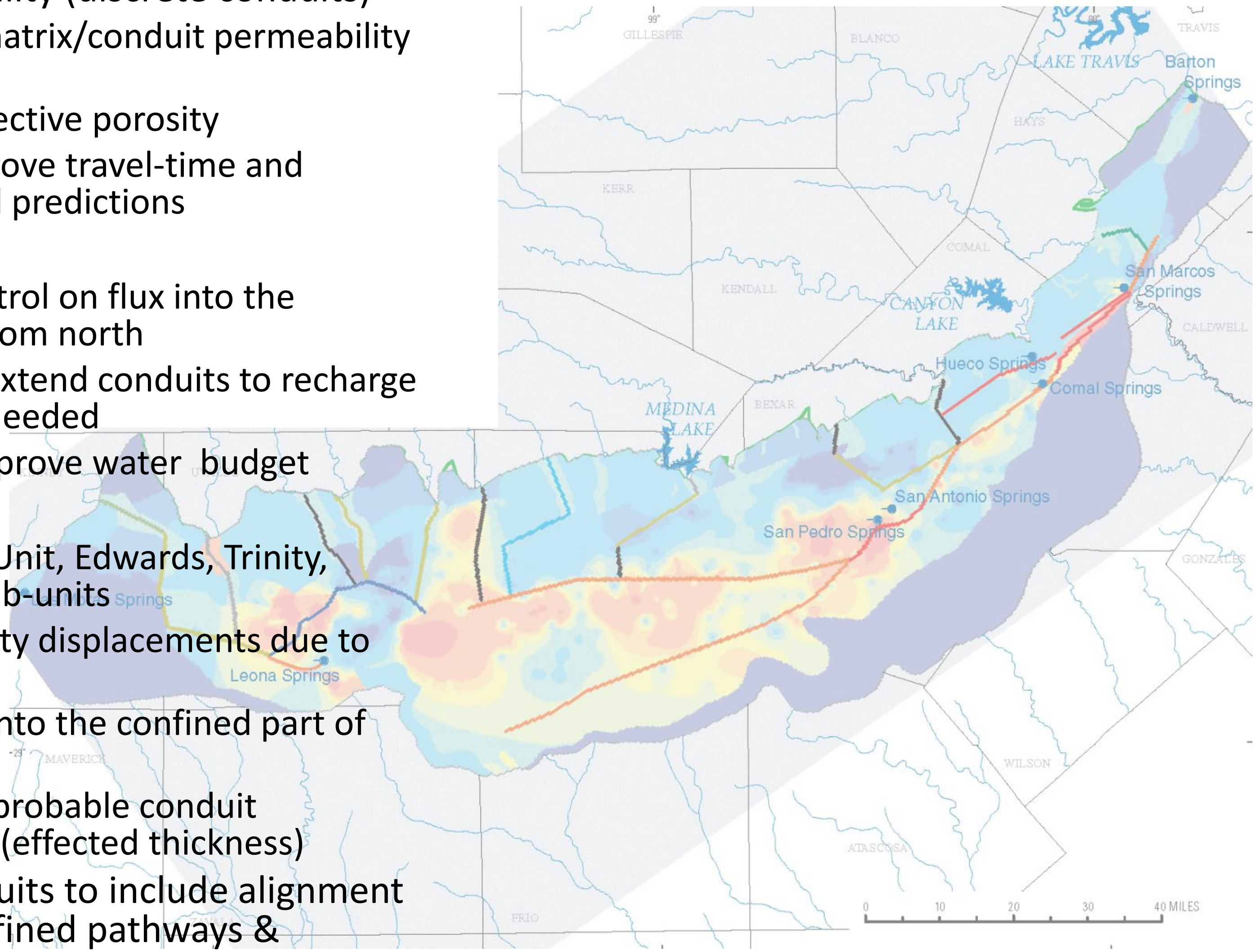
Questions?

How would FEFLOW approach differ from existing model?

- Dual-permeability (discrete conduits)
  - stronger matrix/conduit permeability contrast
  - reduce effective porosity
  - Likely improve travel-time and springshed predictions
- Include Trinity
  - Better control on flux into the Edwards from north
  - Ability to extend conduits to recharge areas – if needed
  - Goal to improve water budget
- 3D
  - Confining Unit, Edwards, Trinity, possibly sub-units
  - Permeability displacements due to faulting
  - Recharge into the confined part of Edwards
  - Delineate probable conduit elevations (effected thickness)
- Redefine conduits to include alignment with tracer-defined pathways & velocities



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