A View from Inside the Floridan Aquifer

Hydrogeologic Characterization of the Woodville Karst Plain, North Florida

Todd Kincaid, Ph.D.
H2H Associates, LLC

Rodney DeHan, Ph.D.
Florida Geological Survey

Christopher Werner, Ph.D.
Shell Oil Corp.

David Loper, Ph.D.
Florida State University

Gareth Davies
Cambrian Ground Water Company

Hal Davis
US Geological Survey

Groundwater Protection – *the real problem*

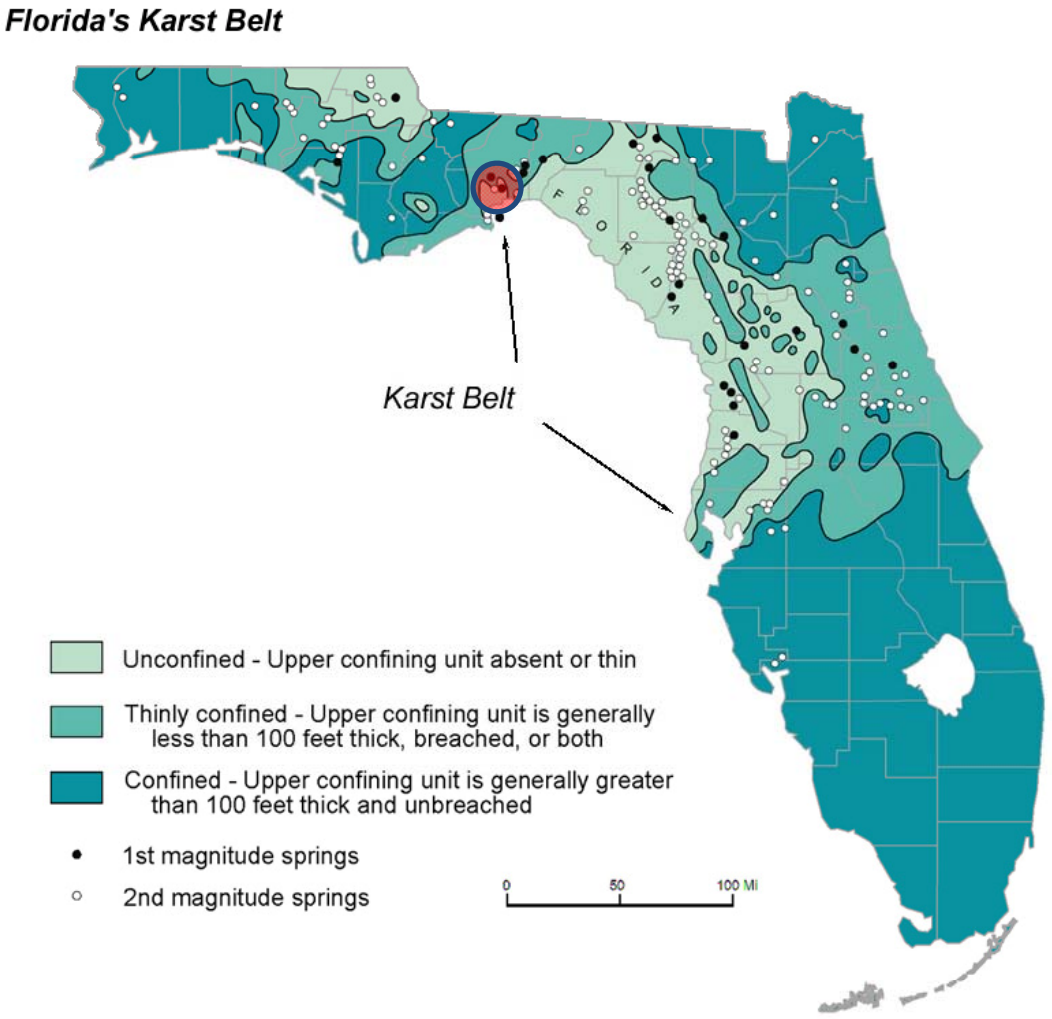
Lack of funding > > Funding driven by public interest
> > Measure of Interest?

Topic	*Internet Hits*
• global water resources:	24,800,000
• aquifer protection:	1,350,000
• water shortage:	8,130,000
• water crisis:	27,900,000
• water pollution:	34,400,000
• bottled water:	10,100,000
• Florida springs:	40,900,000
• Florida springs decline:	651,000
• Britney Spears:	49,800,000
• free porn:	188,000,000
• free sex:	366,000,000

Clean Water / Free Sex = < 10%

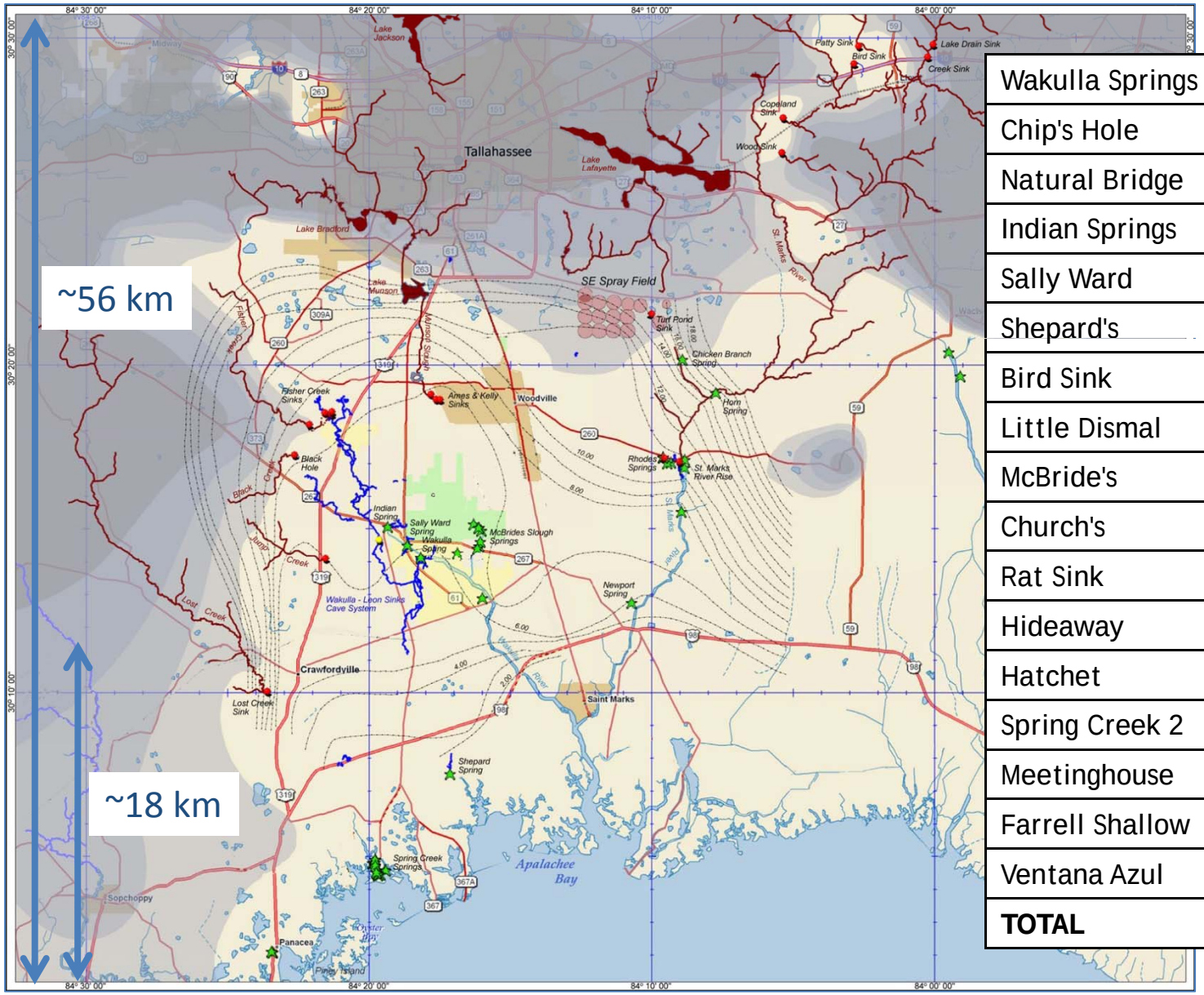
Clean Water / Britney Spears = 68%

The Floridan Aquifer



- 27 (>1/3) of the largest springs in North America discharge from the Floridan Aquifer
- Average discharge from those springs > 6.5 billion gpd
- All of those springs discharge from mapped underwater cave systems
- >90% of inhabitants use groundwater from Floridan Aquifer
- Conduit-dominated flow in unconfined sections
- Less known under confining layer

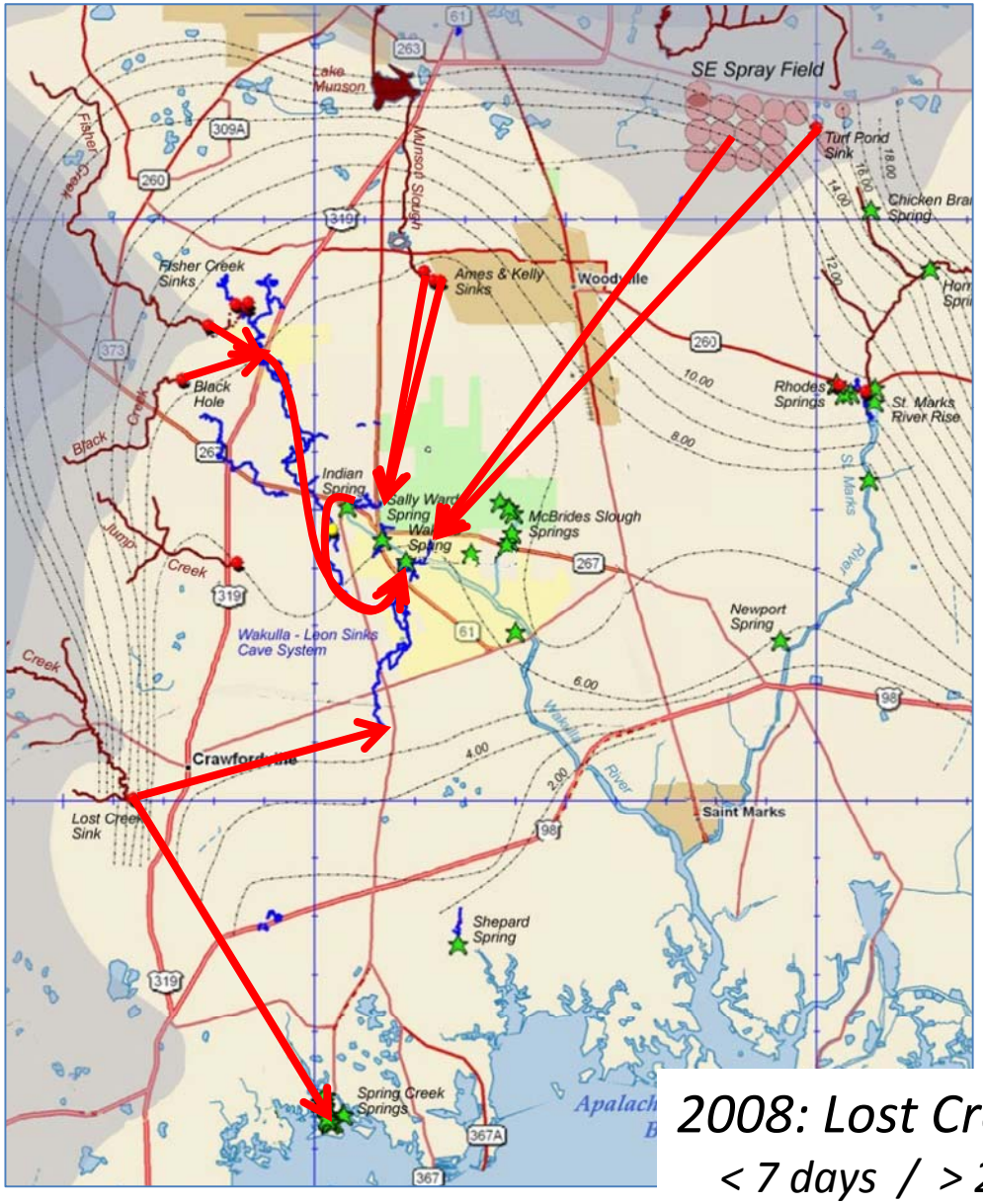
Caves in the WKP



	feet	*meters*
Wakulla Springs	168,900	51,484
Chip's Hole	22,292	6,795
Natural Bridge	12,108	3,691
Indian Springs	11,897	3,626
Sally Ward	6,857	2,090
Shepard's	5,689	1,734
Bird Sink	4,839	1,475
Little Dismal	2,968	905
McBride's	2,166	660
Church's	2,108	642
Rat Sink	1,463	446
Hideaway	1,228	374
Hatchet	1,120	341
Spring Creek 2	810	247
Meetinghouse	769	234
Farrell Shallow	566	173
Ventana Azul	363	111
TOTAL	**246,143**	**75,025**

Cave Exploration - 2006

Groundwater Tracing



2002: Fisher Creek – Emerald Sink

2,680 m / 56 hours (820 m/day)

2003: Black Creek – Emerald Sink

2,576 m / 76 hours (810 m/day)

2004: Emerald Sink – Wakulla Spring

16,550 m / 7.1 day (2,337 m/day)

2005: Kelly Sink – Indian Spring

8,400 m / 13.5 days (622 m/day)

2005: Ames Sink – Indian Spring

8,400 m / 17.2 days (506 m/day)

2005: Indian Spring – Wakulla Spring

8,790 m / 5.9 days (1,490 m/day)

2006: Wells – Wakulla Spring

16,800 m / 66.5 days (252 m/day)

16,800 m / 56 days (300 m/day)

2006: Turf Pond – Wakulla Spring

17,500 m / 56 days (312 m/day)

2008: Lost Creek – Spring Creek & Wakulla Spring

< 7 days / > 2 weeks

Comparison of Calculated Groundwater Velocities

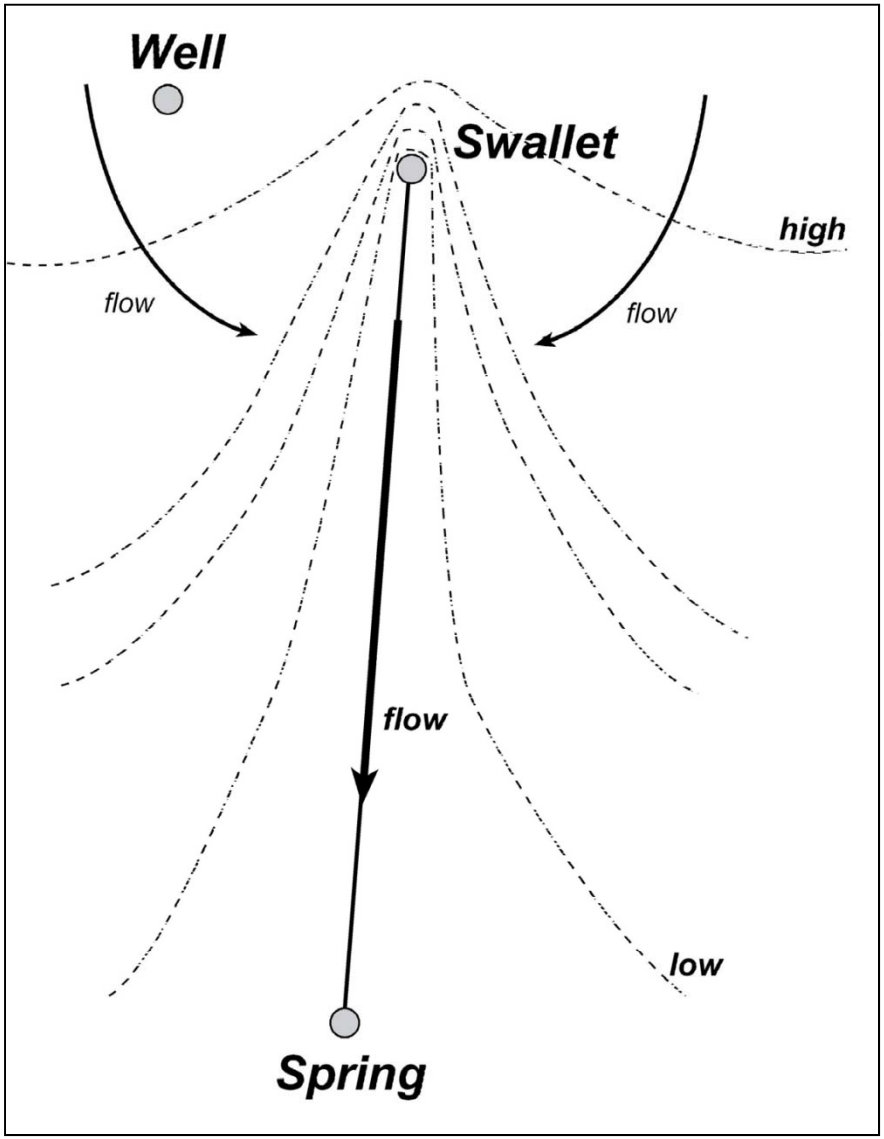
Woodville Karst Plain, North Florida

Method	Velocity (m/day)	Assumptions	Source
Tracing	252-2,337 m/day	none	5
Pumping Test Transmissivities	0.03-0.23 m/day	Calculated Gradient Aquifer b = 100m	1
Model Derived Transmissivities	0.03 – 1.17 m/day	Calculated Gradient Aquifer b = 100m	3
Geochemical age dates	7.5 – 15 m/day	Age ~20-40 years 100% of Recharge derived from top of basin (~110 km to north)	2, 4

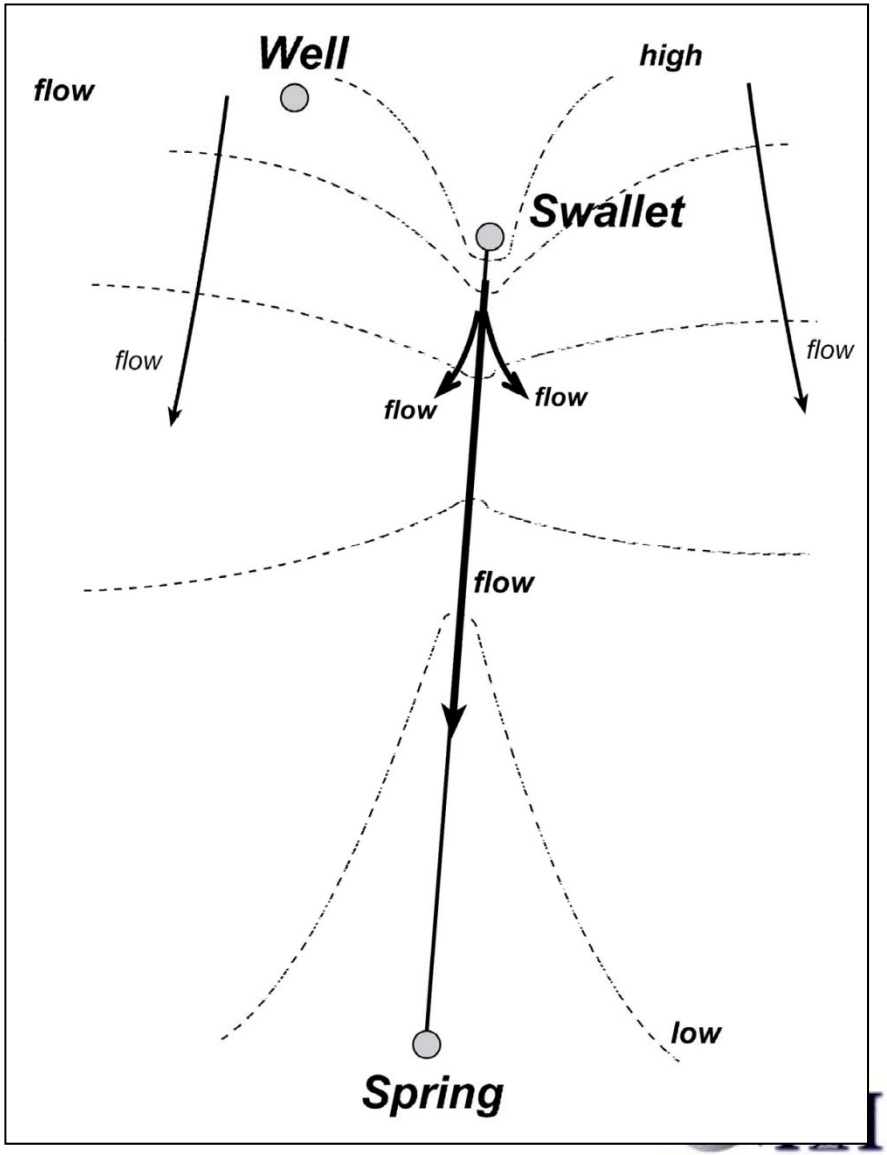
1. Bush, P.W., and Johnston, R.H., 1988. Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and parts of Georgia, South Carolina and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p.
2. Chanton, J. 2002. Unpublished data and report on stable isotopic age dating of waters in the Woodville Karst Plain, Florida for the Florida Geological Survey, Tallahassee, FL.
3. Davis, H. 1996. Hydrogeologic Investigation and Simulation of Ground-Water Flow in the Upper Floridan Aquifer of North-Central Florida and Delineation of Contributing Areas for Selected City of Tallahassee, Florida, Water Supply Wells: USGS Water-Resources Investigation Report 95-4296.
4. Katz, B.G., Chelette, A.R., and Pratt, T.R., 2004. Use of chemical and isotopic tracers to assess nitrate contamination and ground water age, Woodville Karst Plain, USA: Journal of Hydrology, v. 289, no. 1 /4, p. 36-61.
5. Kincaid, T.R. and Werner, C.L., 2008. Conduit Flow Paths and Conduit/Matrix Interactions Defined by Quantitative Groundwater Tracing in the Floridan Aquifer, in Lynn Yuhr, Calvin Alexander, and Barry Beck editors, *Sinkholes and the Engineering and Environmental Impacts of Karst: Proceedings of the 11th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst*, American Society of Civil Engineers.

Aquifer Hydraulics

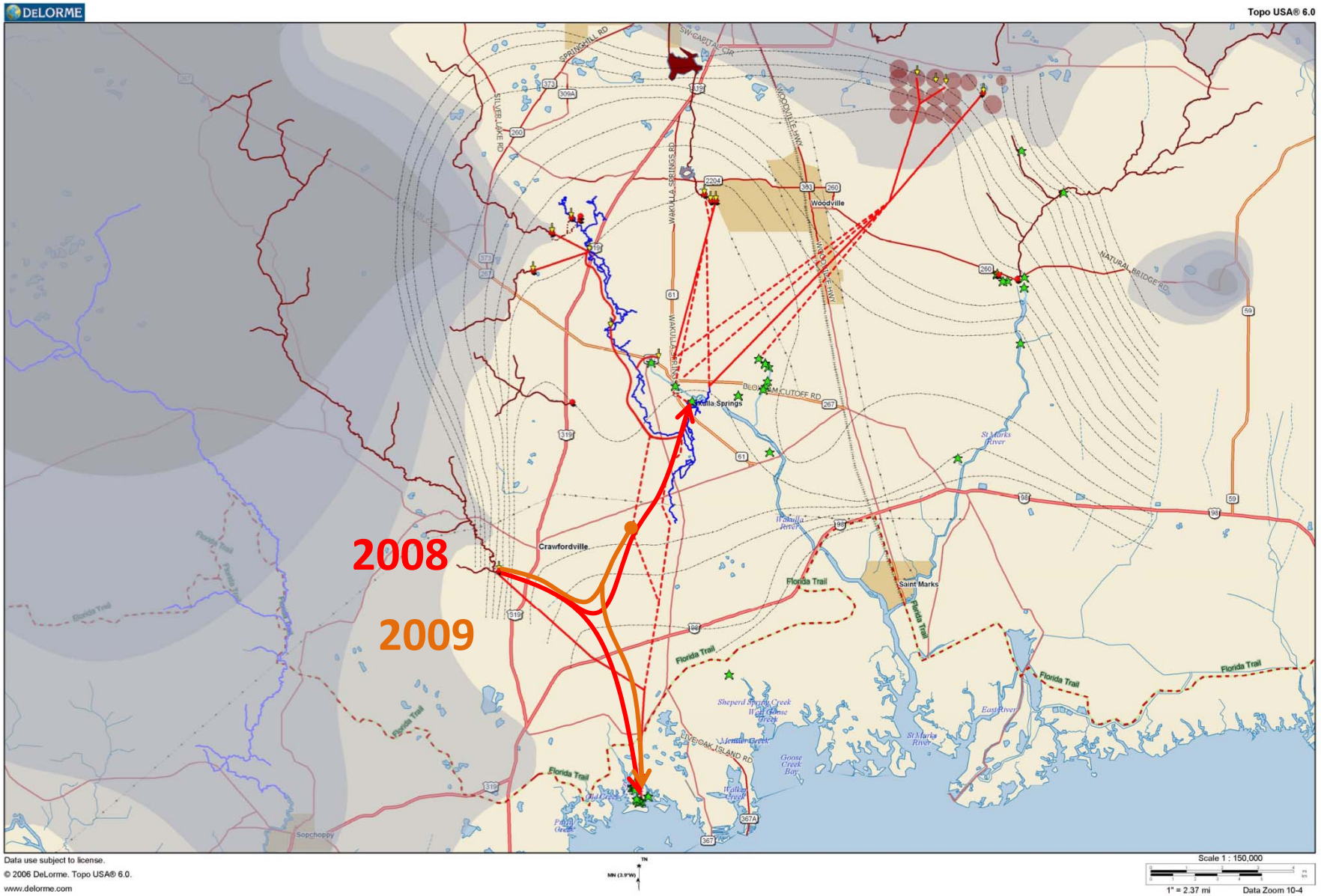
Low Flow



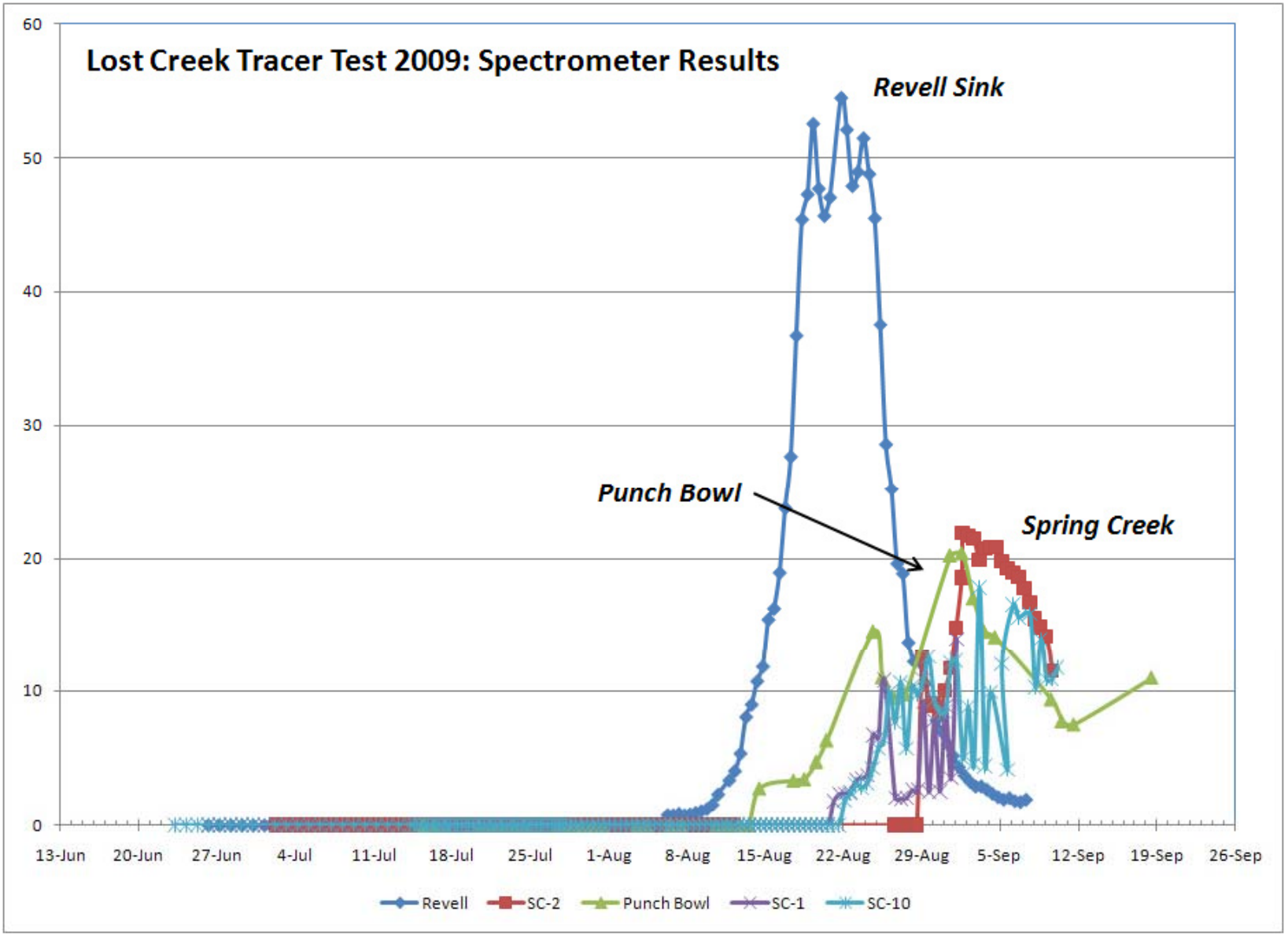
High Flow



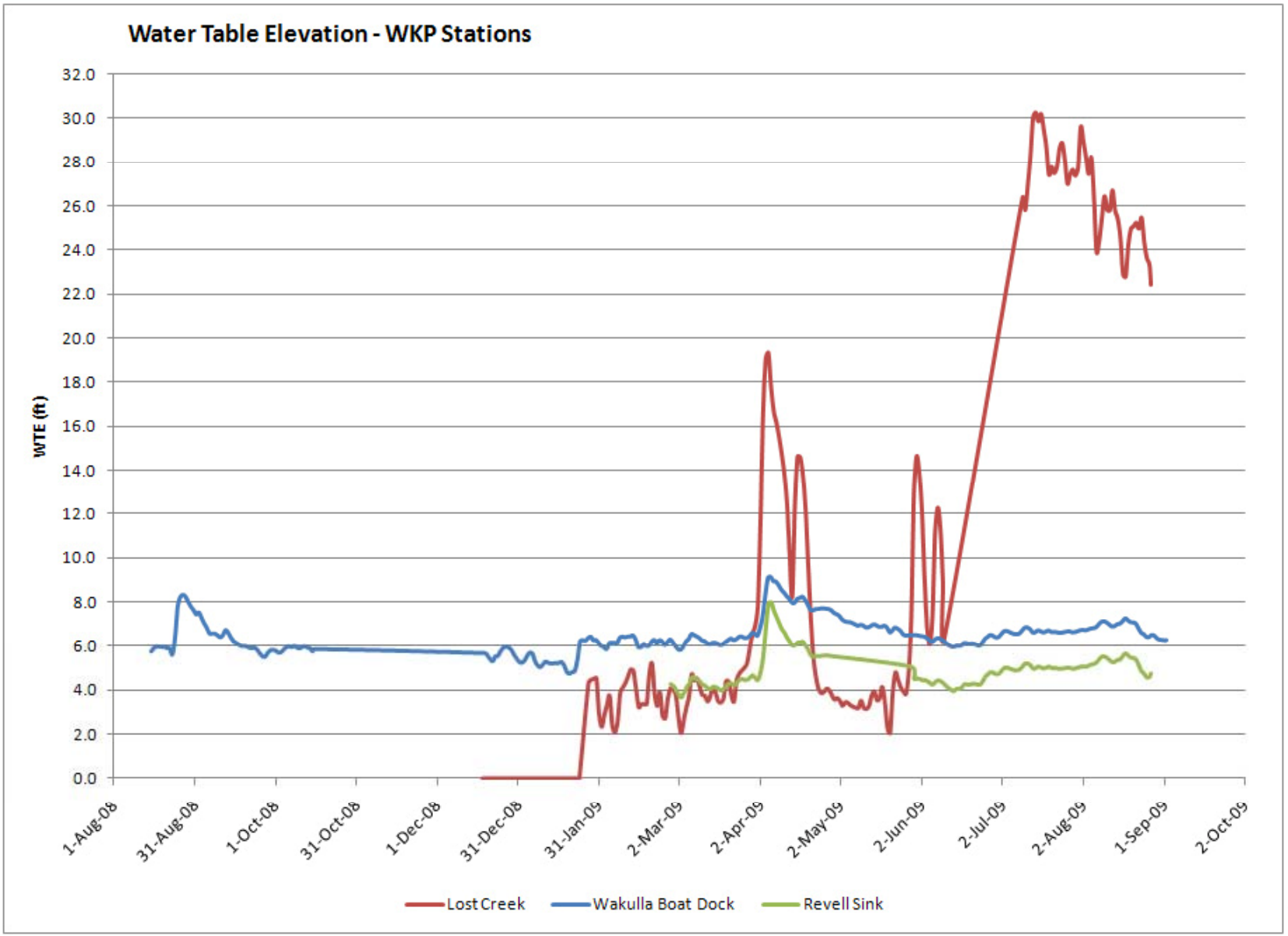
New Confirmed Pathways



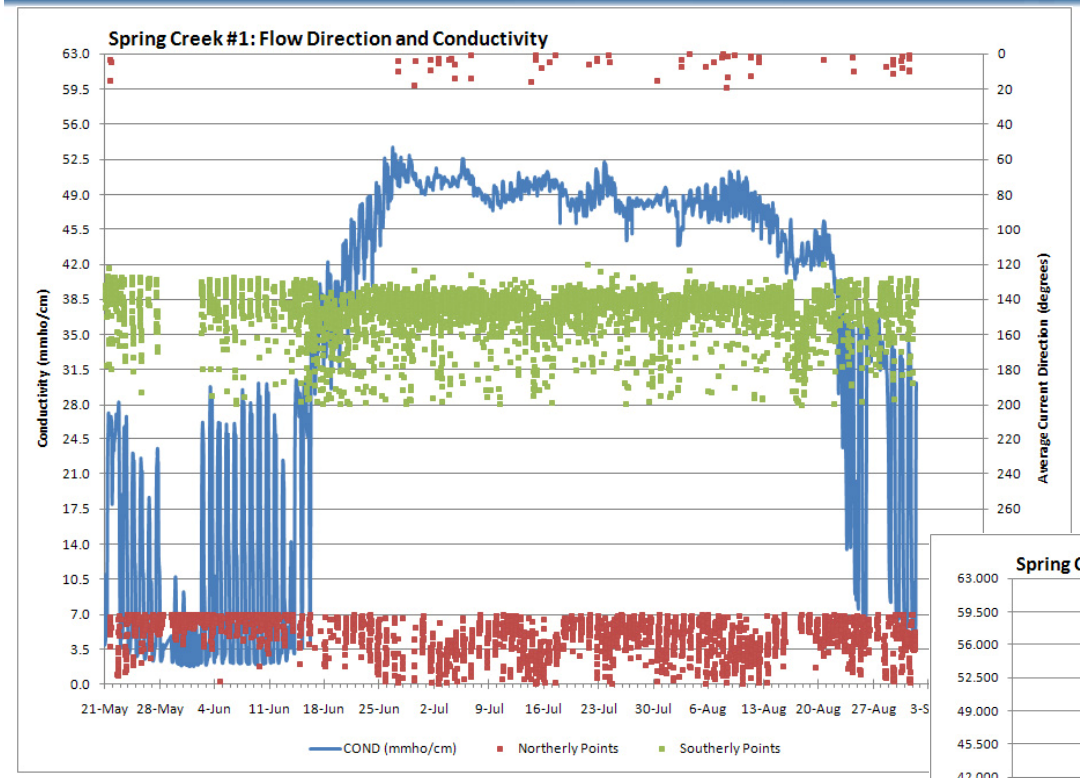
Tracer Detections

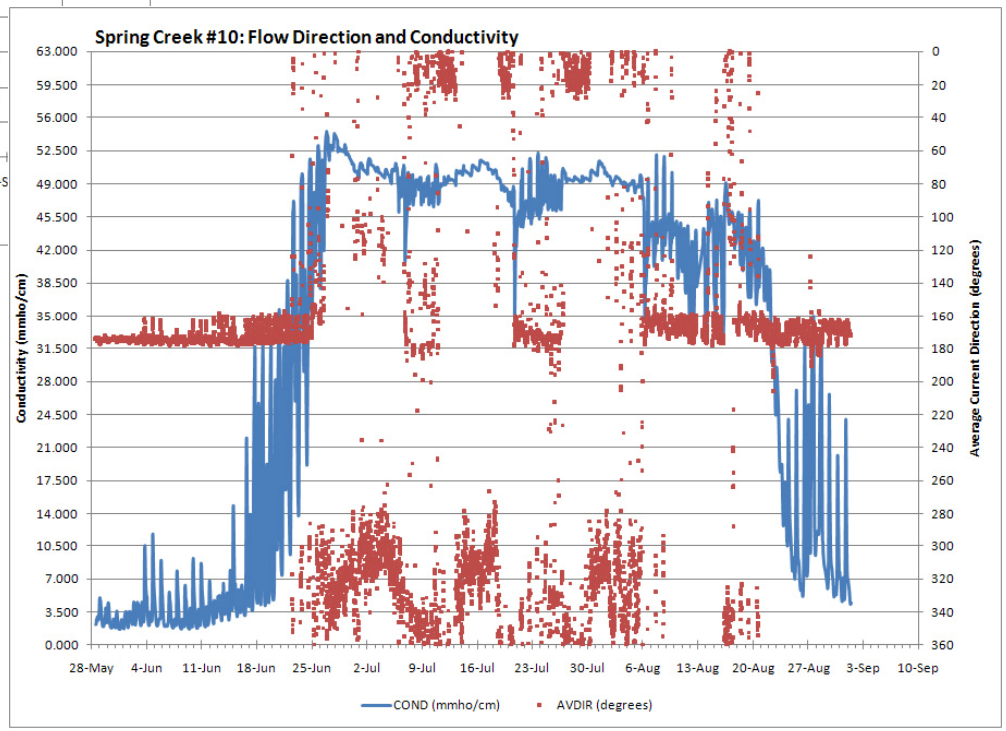


Water Table Elevations

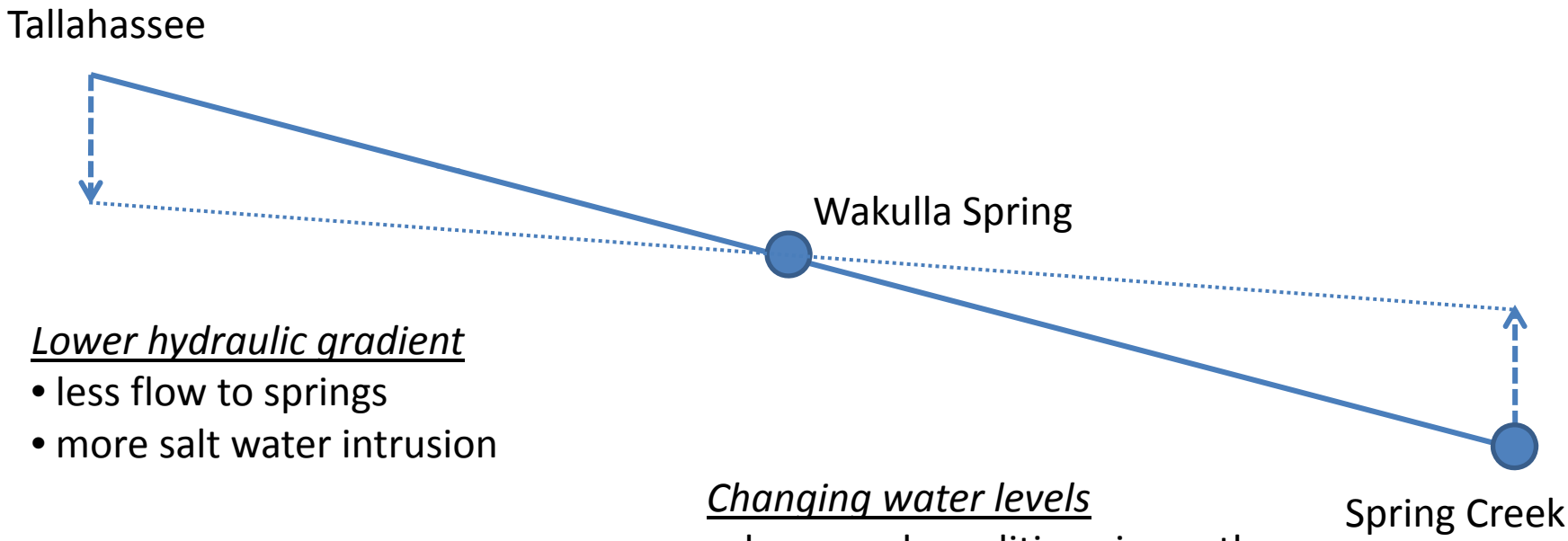


Spring Creek Reversals





Hydraulic Gradient



Lower hydraulic gradient
- less flow to springs
- more salt water intrusion

Changing water levels
- depressed conditions in north
- deeper unsaturated zone
- elevated conditions in south
- reduced unsaturated zone

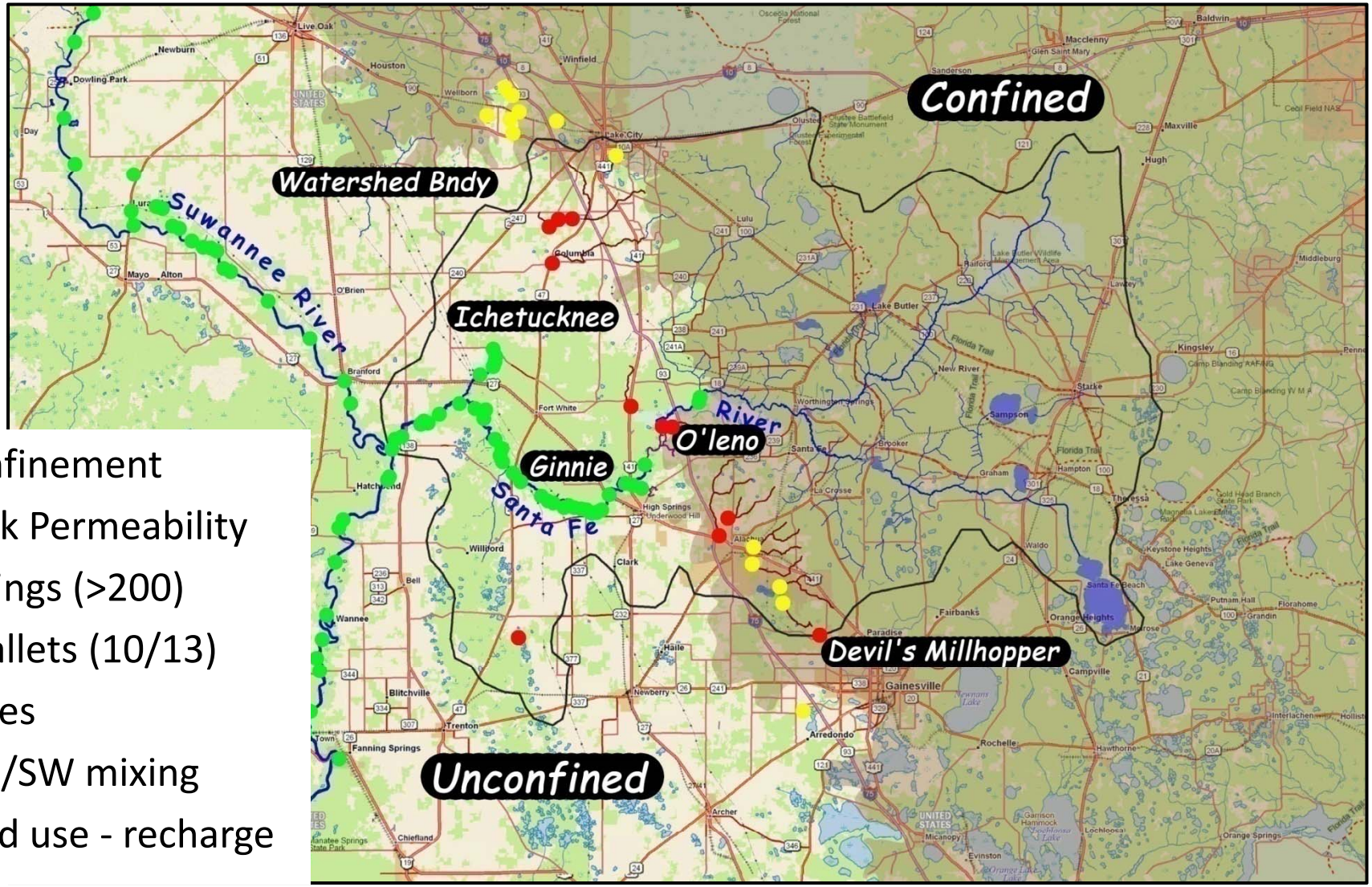
Summary - 1

- Wakulla and Spring Creek are connected by one or more large conduits.
- When Spring Creek reverses, Wakulla takes it's groundwater flow – i.e. the Wakulla Springshed expands to include all of the area that formerly contributed to Spring Creek.
- Under low flow conditions, high tides likely reverse gradient at spring Creek.
- Denser salt water flows into the large caves.
- Denser water requires relatively larger gradient to drive it out.
- Water levels in the southern part of the WKP stay high (flooded sinks…) until the groundwater gradient rises sufficiently to drive the salt water out of the Spring Creek caves.
- When the gradient reaches the critical level, the Spring Creek vents begin to flow, the elevated water levels in the south fall, and Wakulla's flow drops.

Summary - 2

- If trends continue (sea-level rise & groundwater level declines), the duration of Spring Creek reversals will increase.
- Reducing upland groundwater declines would contribute to reducing the duration of the Spring Creek reversals.
- Protecting water clarity requires an understanding of the groundwater budget and how extractions impact that budget.
- Achieving these protections will require continued (probably expanded) data collection.
  - Groundwater levels
  - Flows
  - Spring Creek variability
- More Information – www.h2hmodeling.com/FGS/Tracing/

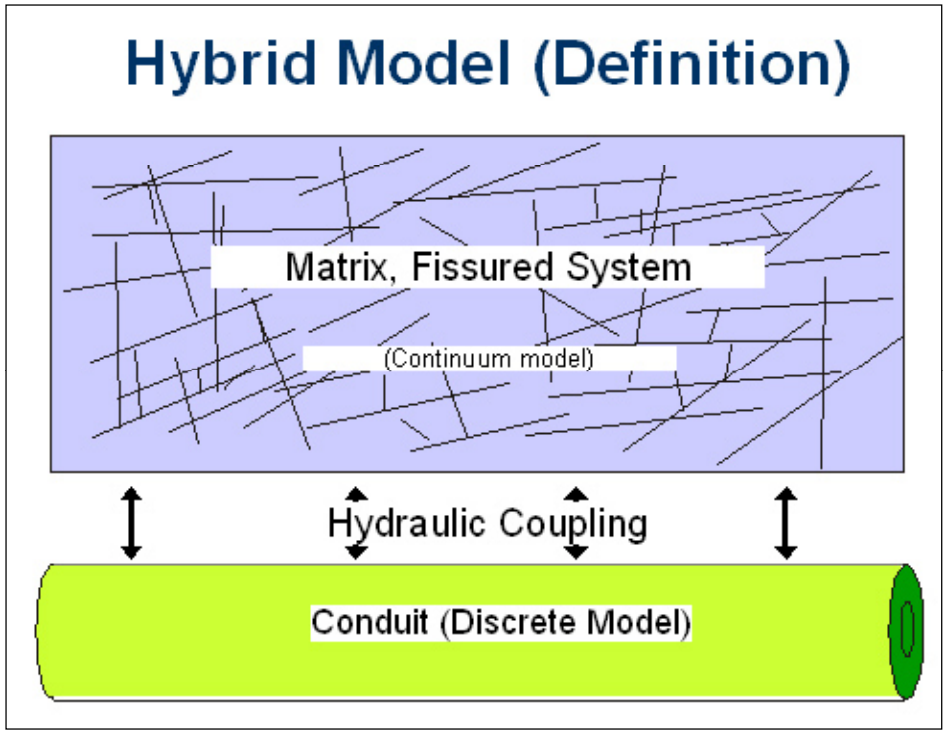
Karst Modeling: *Santa Fe River Basin*



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

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.

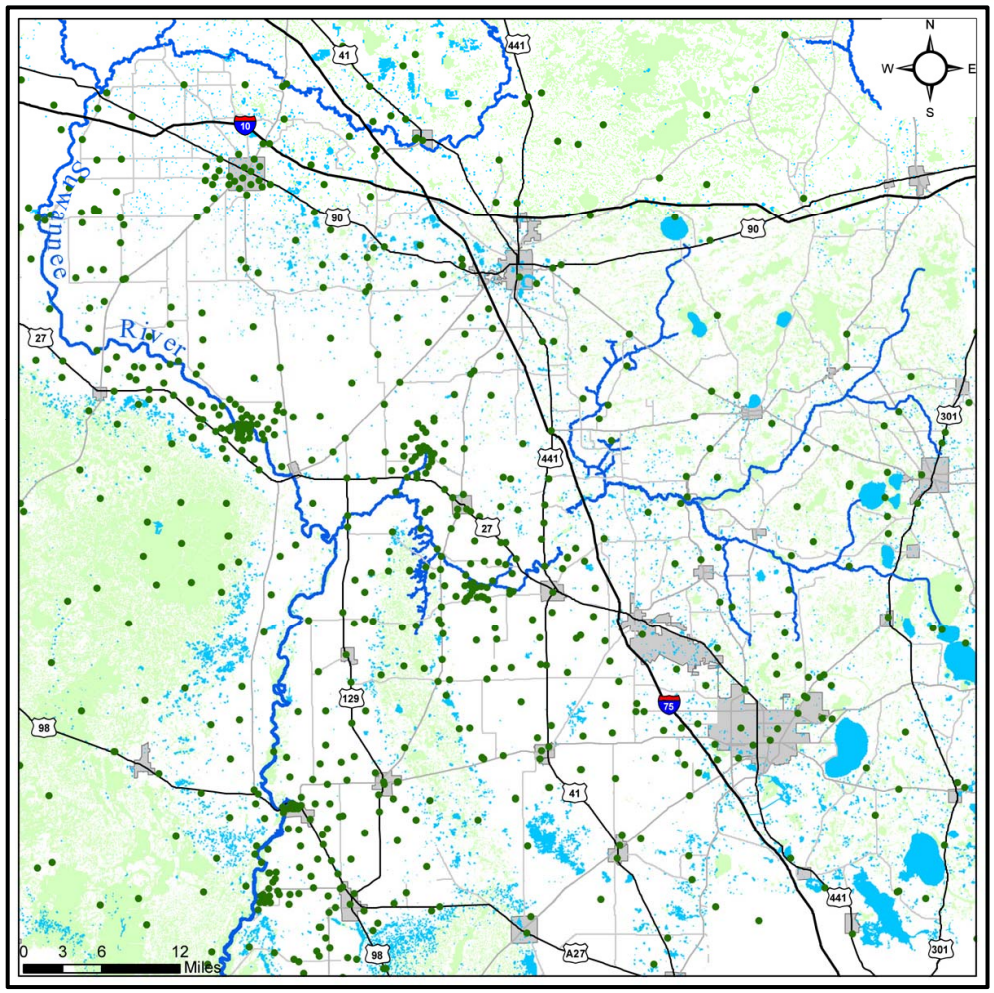


WASY Software FEFLOW WASY

http://www.feflow.info/

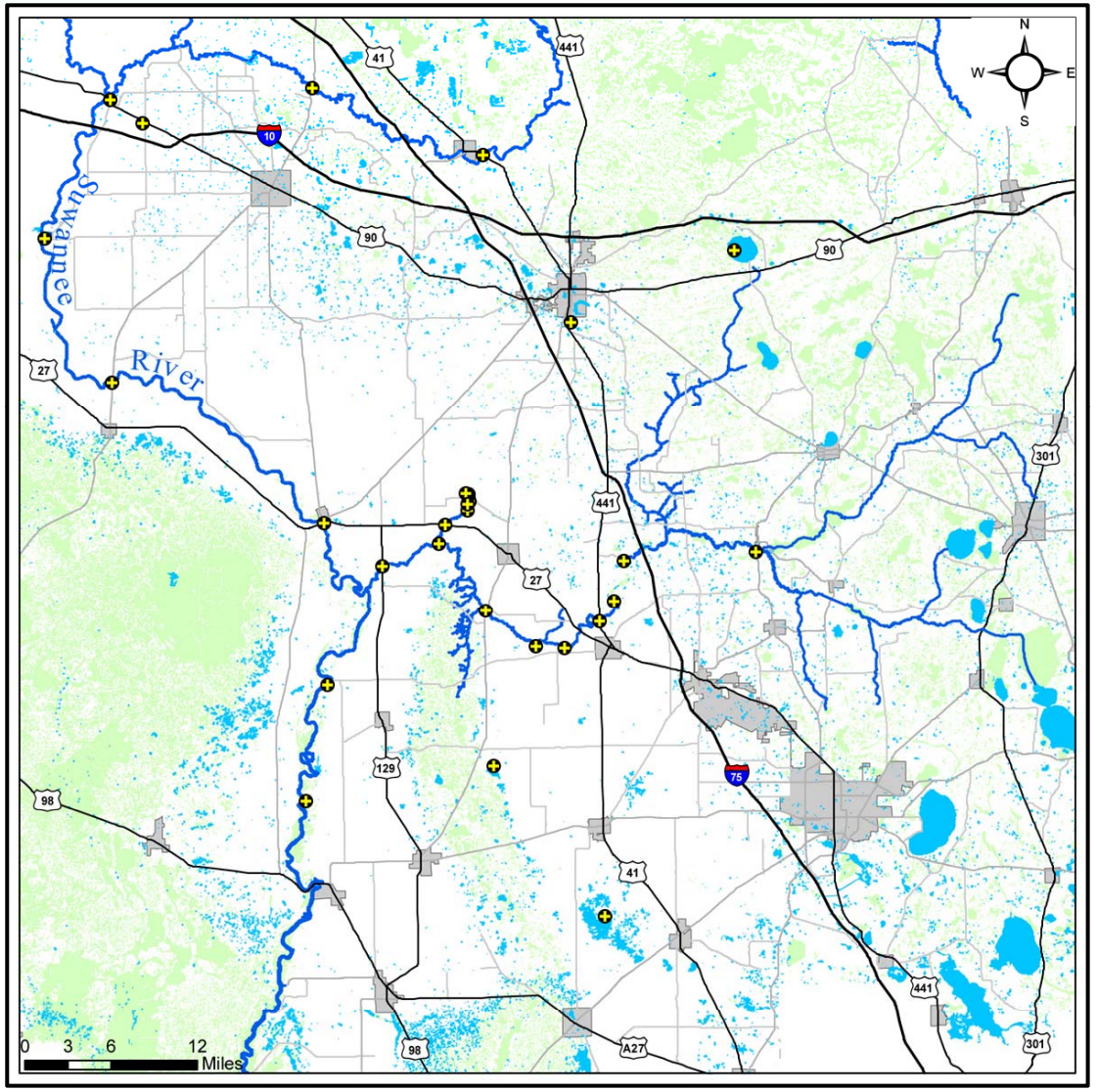
Data Compilation: *Groundwater Levels*

- Wells east of Suwannee River = 691
  - SWRWM = 484
  - ACEPD = 174
  - KES = 21
  - SRWMD & ACEPD = 6
  - ACEPD & KES = 6
- Wells in model area = 250
- Identified highest water periods as:
  - Jan 1998 – May 1999
  - Oct 2004 – Dec 2005
- High water period wells = 396
- Identified lowest water periods as:
  - Jan 2001 – Dec 2002
  - May 2007 – Oct 2007
- Low water period wells = 571



Data Compilation: *River, Lakes, & Springs*

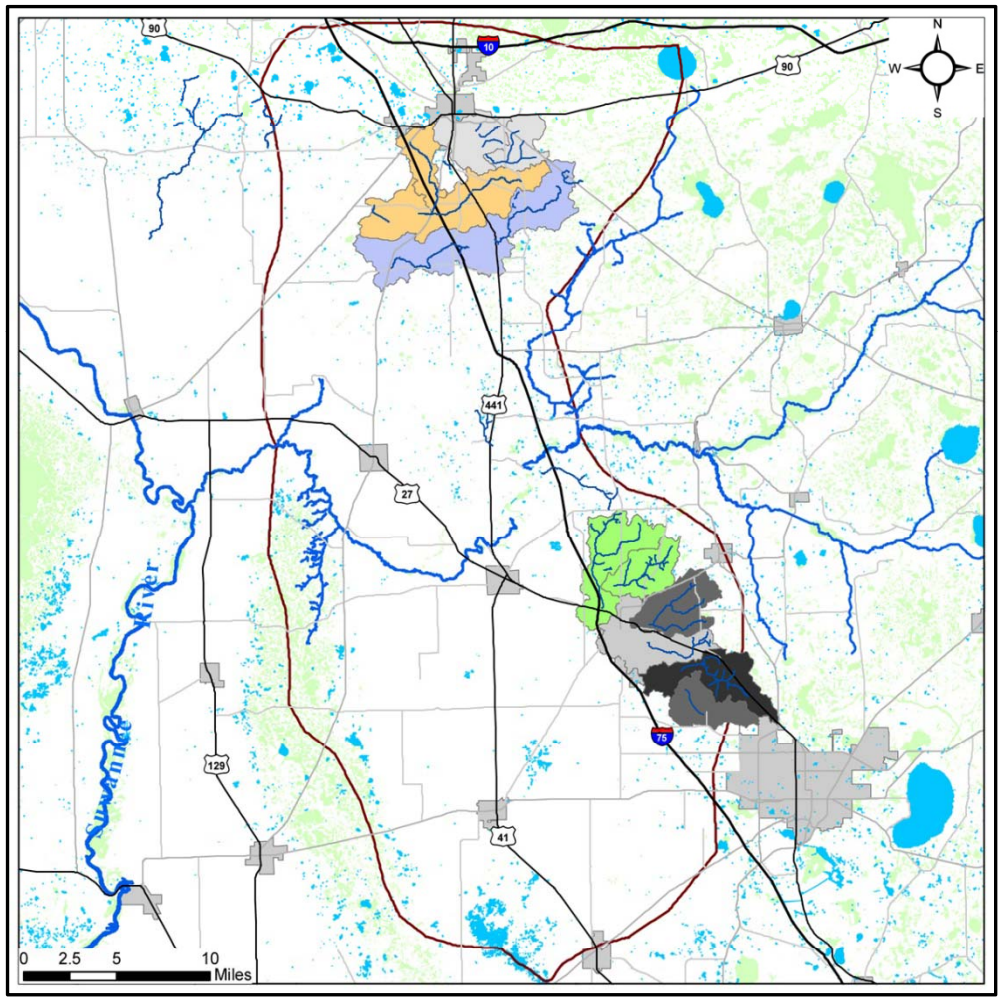
- Total stations = 30
  - Lakes: 4
  - Rivers: 14
  - Springs: 12
- Data sources
  - SRWMD
  - USGS
  - ACEPD



Estimating Individual Swallet Inflows

- Watersheds
  - Rose Creek = 70.1 sq. km
  - Clay Hole Creek = 52.8 sq.km
    - Clay Hole watershed 75% the area of Rose Creek watershed
  - Mill Creek = 57.2 sq. km
    - 1.08 times larger than Clay Hole Creek watershed
- Calibration
  - High water targets (calculations based on watershed size & Blue Hole / Mission Spring flux)
    - Rose Creek swallet = 140 cfs
    - Clay Hole Creek swallet = 105 cfs
    - Mill Creek swallet = 115 cfs
  - High water model in-flux
    - Rose Creek swallet = 144 cfs
    - Clay Hole Creek swallet = 102 cfs
    - Mill Creek swallet = 105 cfs
  - Assumed no sinking stream flow during low water conditions
    - Swallet nodes constrained as aquifer discharge boundaries only
    - No modeled in-flux

Swallet Watersheds



Groundwater Modeling Process

- Design model to match known physical conditions
  - geology, caves, well & spring locations, swallet inputs
  - Recharge ranges (bounded by rainfall data & landuse)
- Define physics of groundwater flow
  - Porous media in rock / Pipe flow in caves
- Run model and compare results against data
  - Groundwater levels, Spings, Groundwater velocities (tracing)
- Adjust model parameters *(within reasonable limits)*
  - Rock permeability, Cave locations & dimensions
  - Recharge *(bounded by data and zones defined by landuse)*
- 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

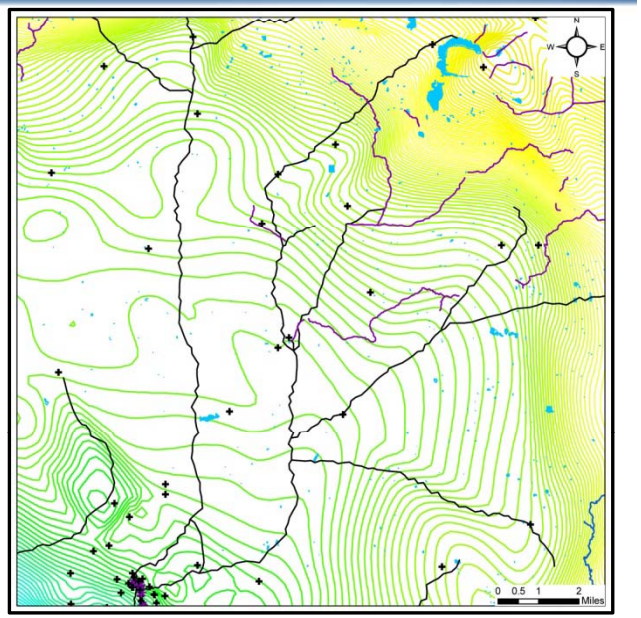
Coca-Cola north america

HH

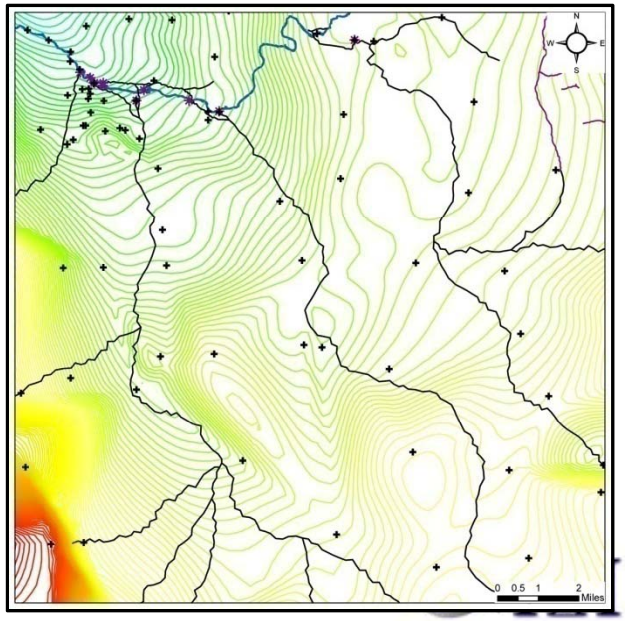
Conduit Locations & Assignments

- 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

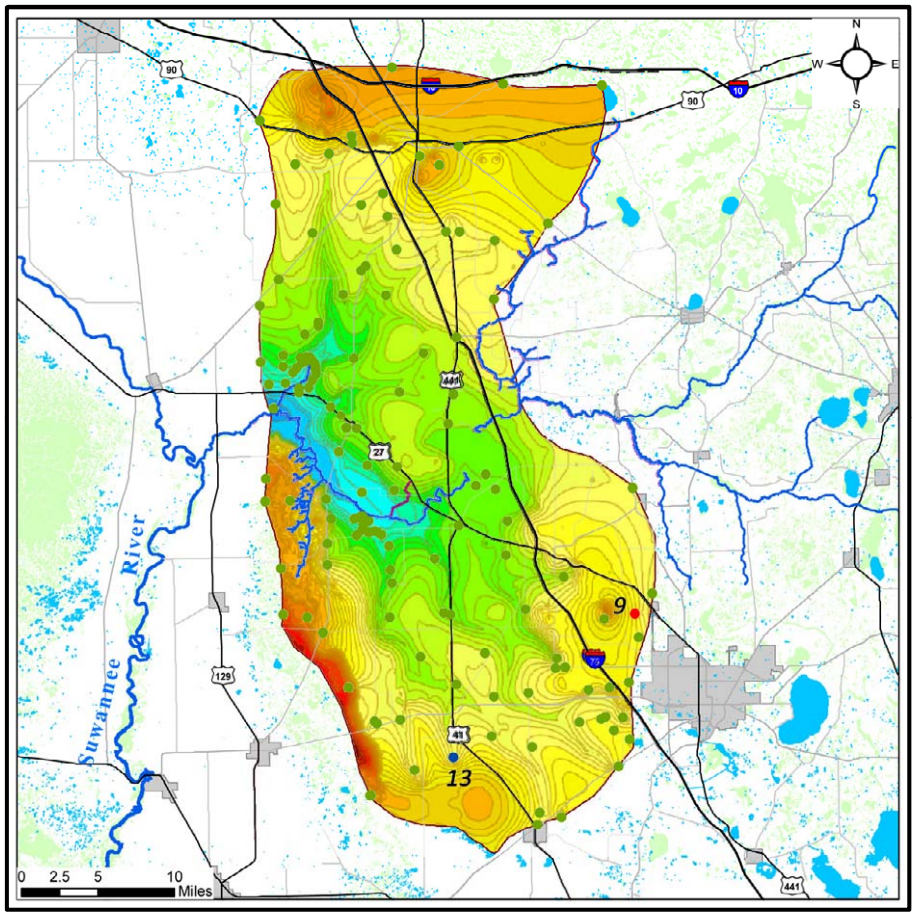


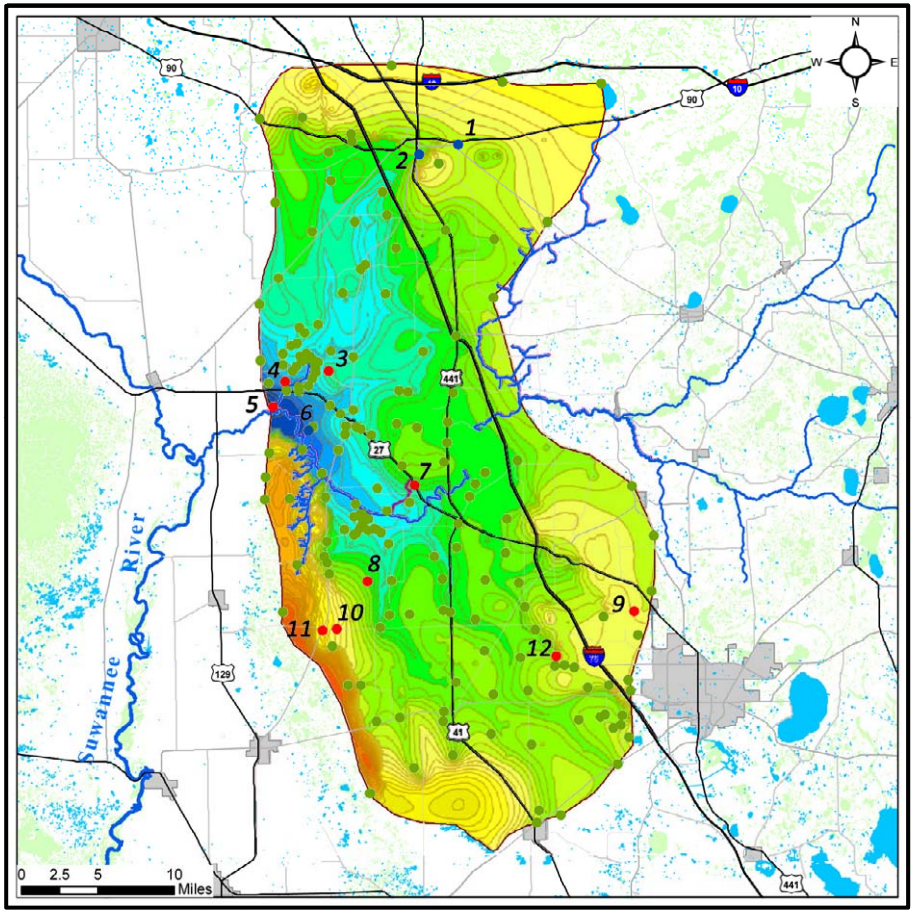
Southern Region



Coca-Cola north america

Model Calibration: *Groundwater Levels*



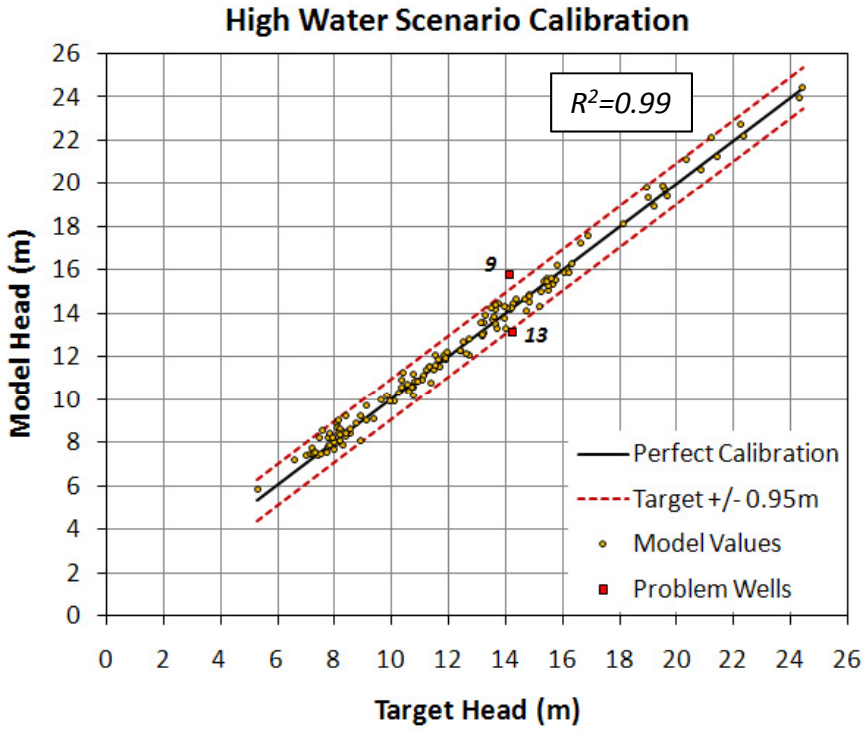


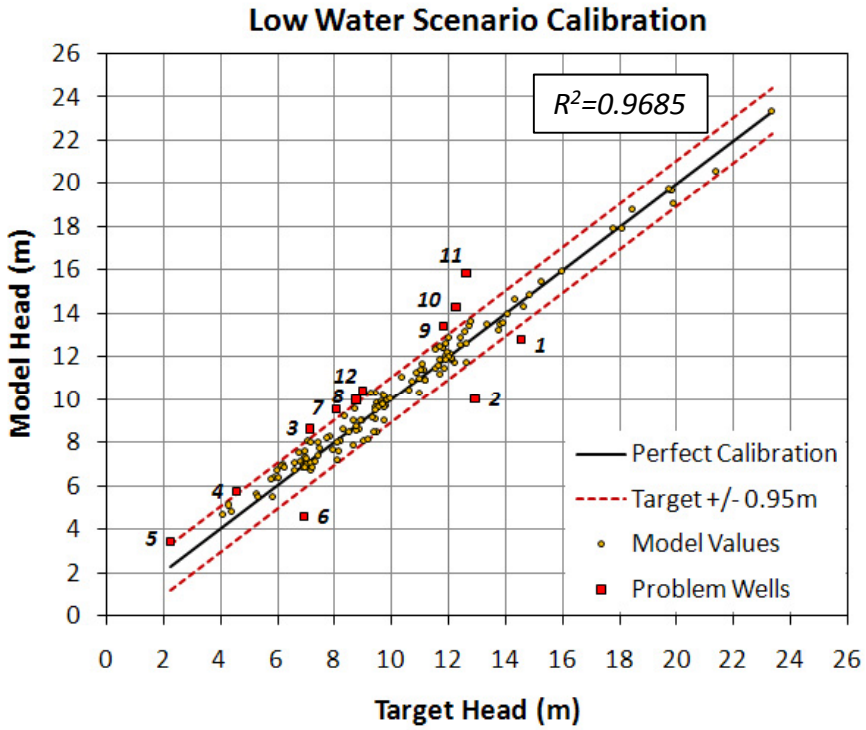
Green = calibrated (Red = high / Blue = low)

- High water: 143/145 wells calibrated
- +/- 0.95 m (~3 ft)
- Problems near mounds & conduits

- Low water: 176/188 wells calibrated
- +/- 1.05 m (~3ft)
- Problems near mounds & conduits

Model Calibration: *Groundwater Levels*



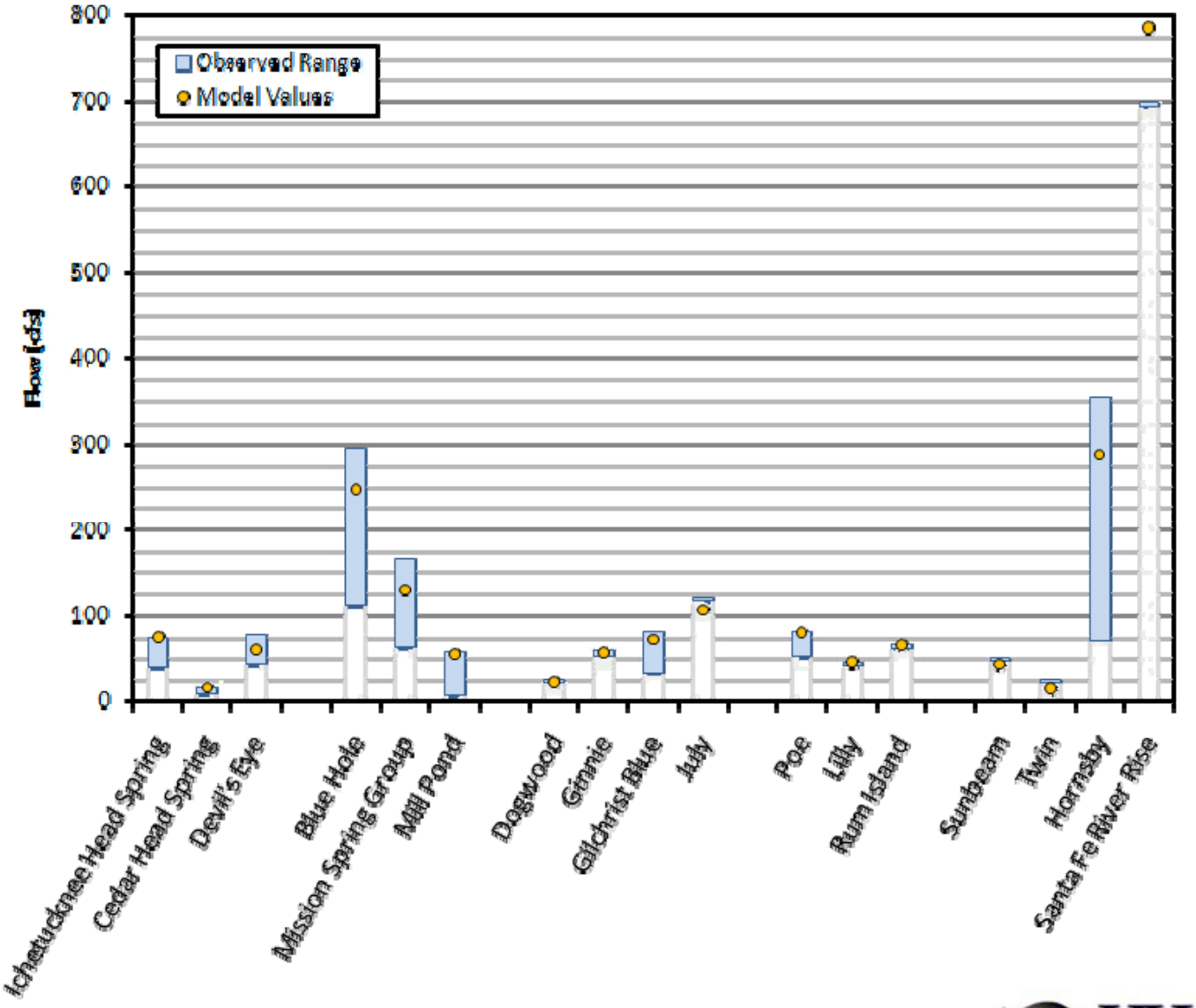


- Plots show how well the model simulates known groundwater levels.
- Perfect match would be the black line.
- All points within the red dashed lines are “calibrated.”
- Could not achieve this good of a match if it were not for including the conduits.
- Even the points that fall outside the red lines 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.

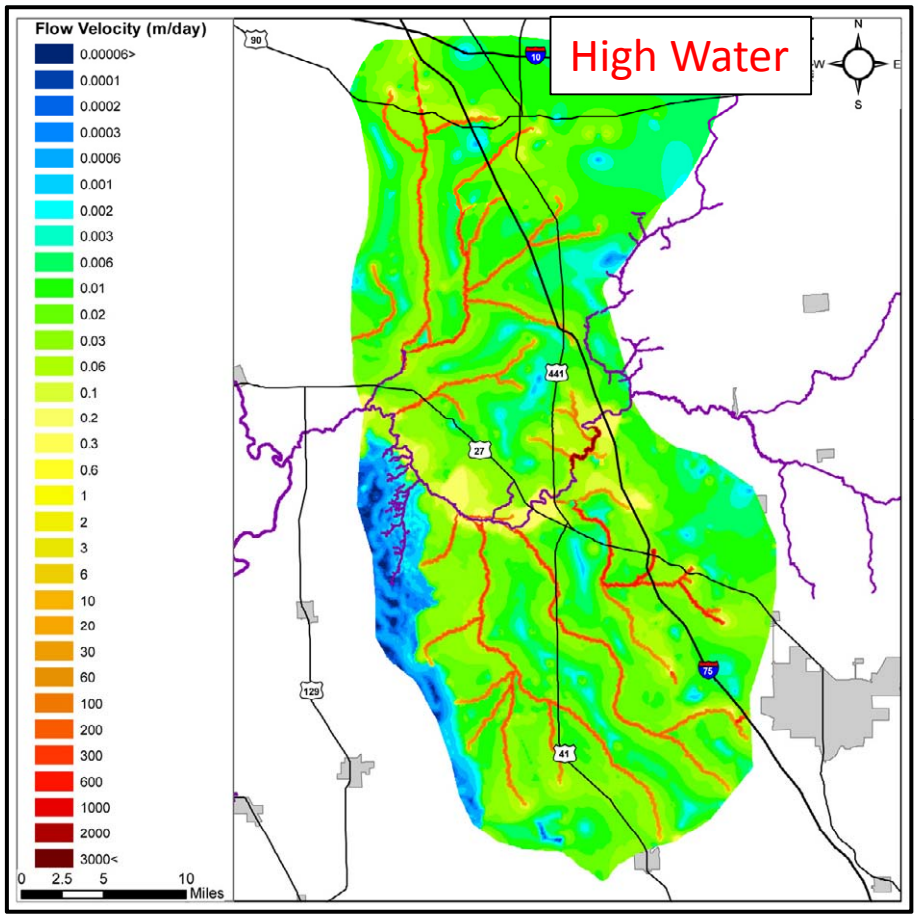
Model Calibration: *Spring Flows*

High Water Simulation

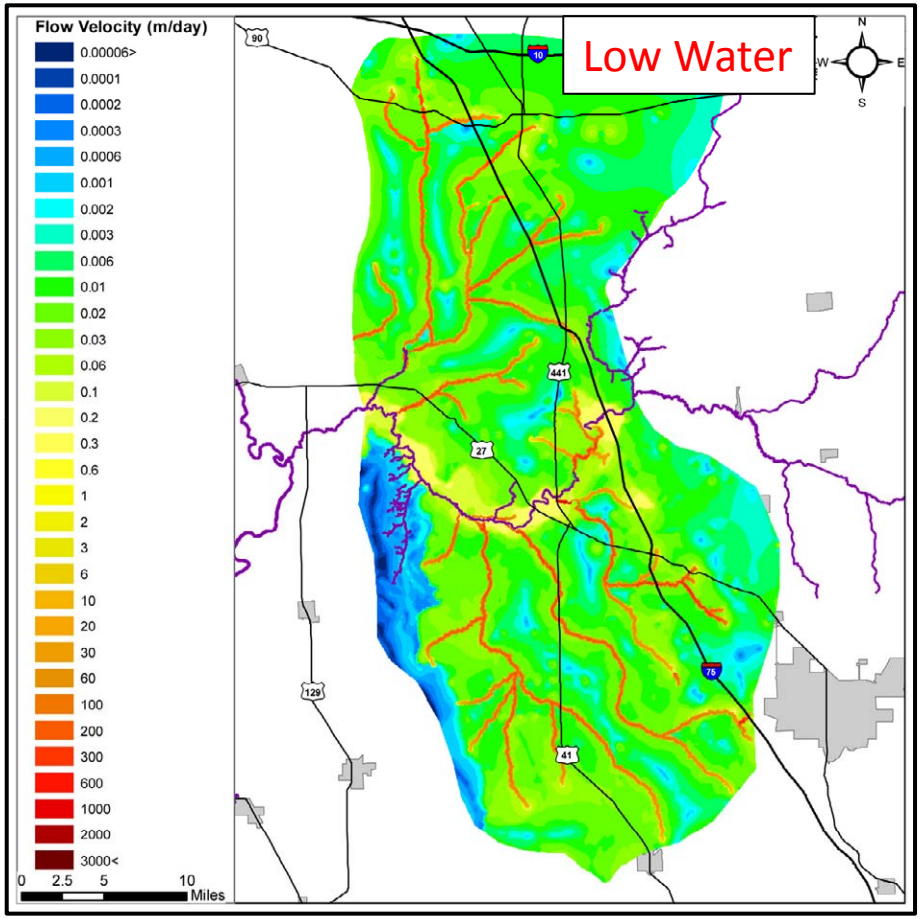
- Data for 17 springs
- Model within observed range at 13
- Model very close at 3
- Over estimated Santa Fe River Rise
- Does not impact groundwater flow because the conduit is mostly surface water



Model Calibration: *Groundwater Velocities*



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

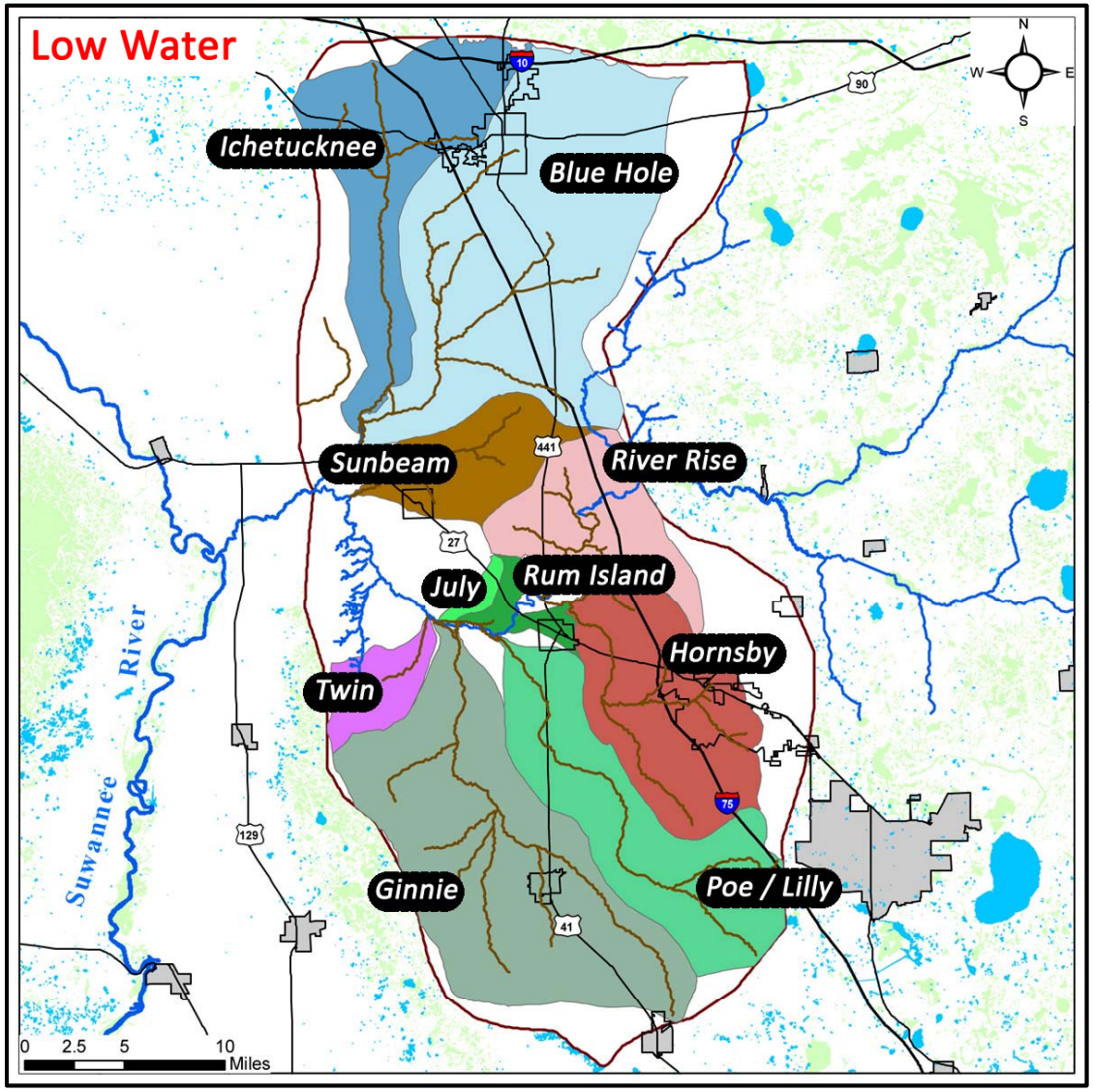


- Conduits model: ~ 100 to ~1000 m/day
- Conduits observed: ~ same
- Matrix model: ~ 10^{-3} to 10^{-1} m/day
- Matrix observed: ~ $10^{-?}$ To $10^{-?}$ m/day

Applications: *Springshed Delineations*

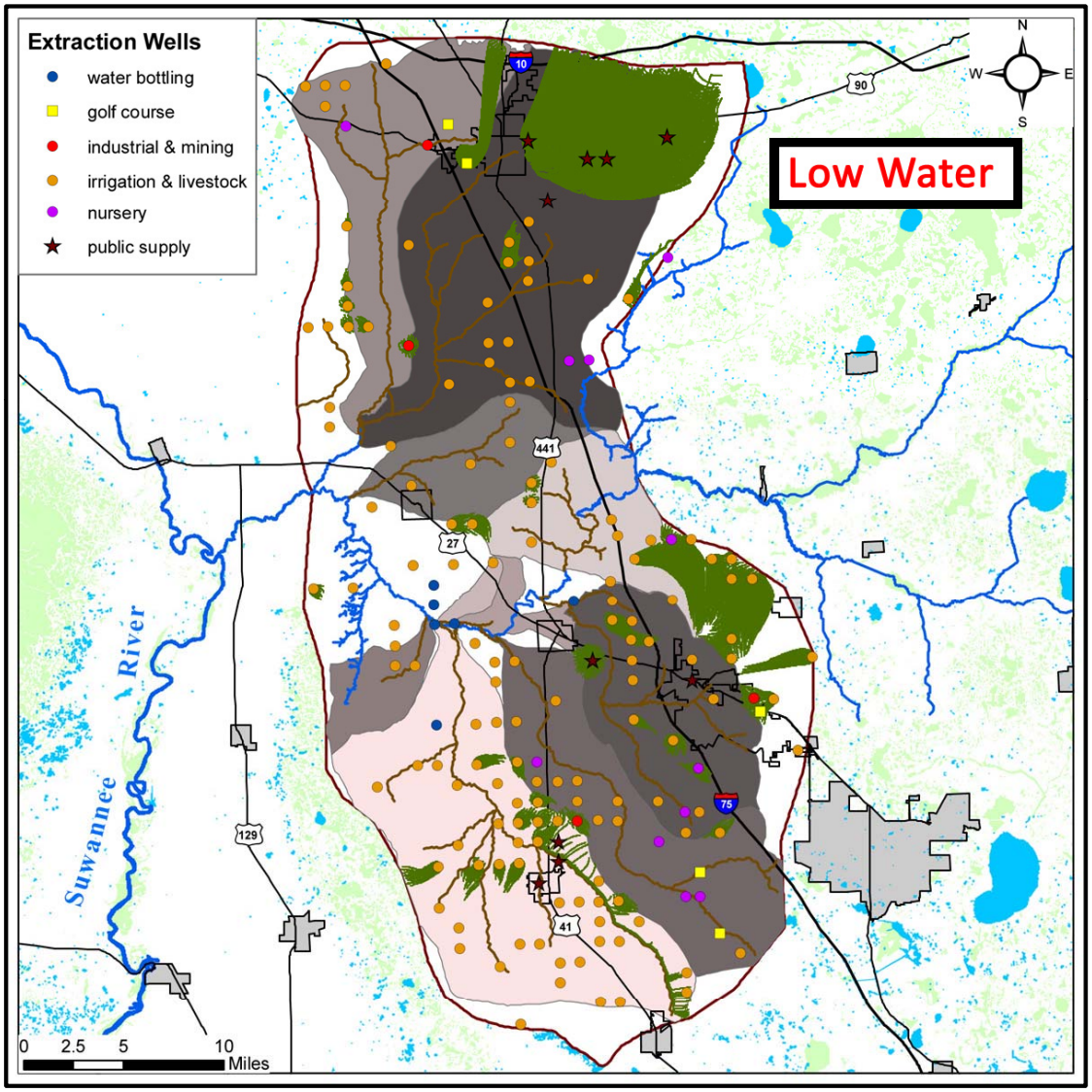
- Defined from forward particle track analysis
- Boundaries change between high water & low water conditions

Spring Group	High (km^2)	Low (km^2)
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



Applications: *Pumping Impacts*

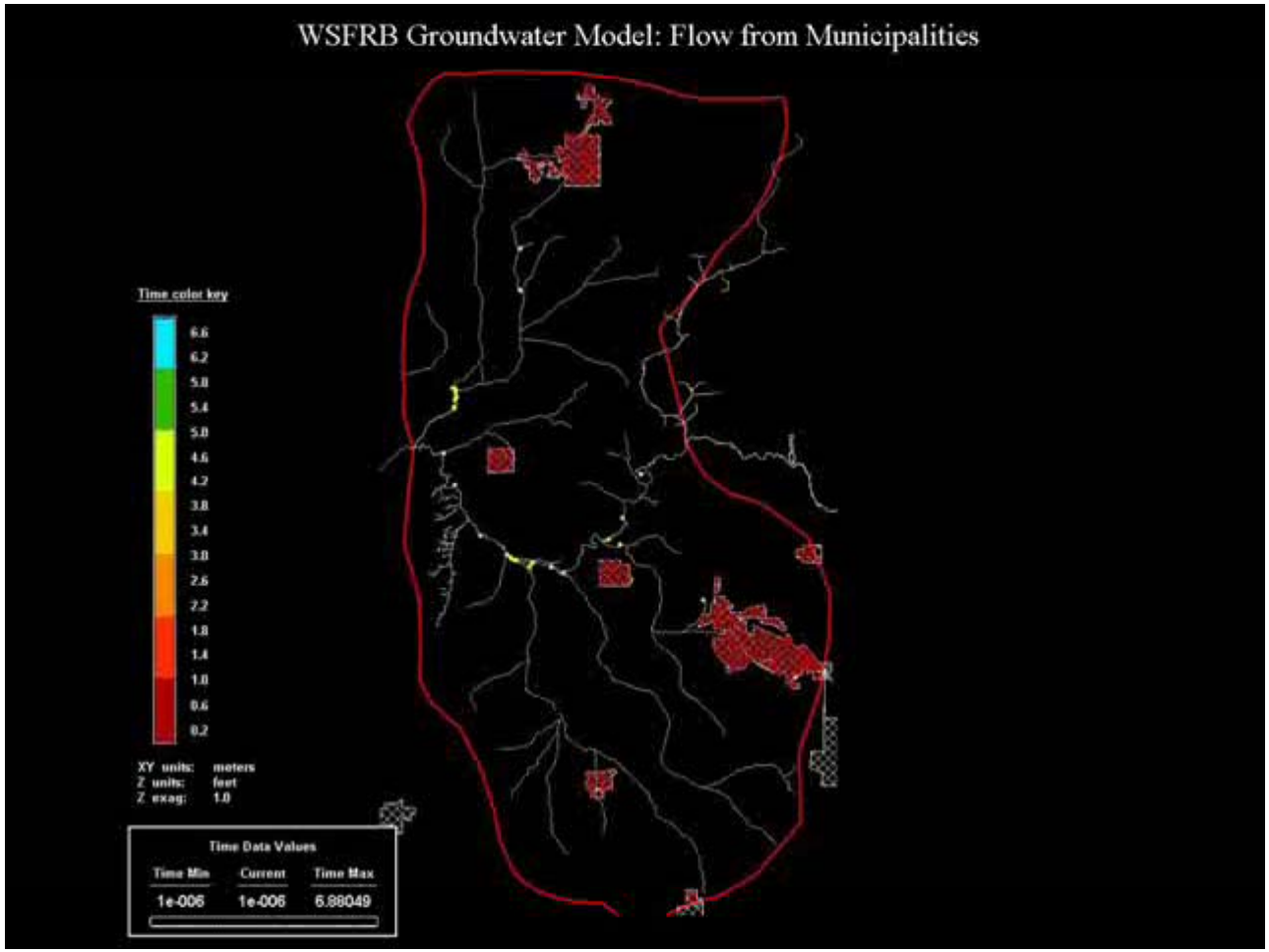
- Pumping diminishes spring flows within the impacted springsheds.
- Particle tracking shows that pumping impacts the size and shape of the springsheds.
- Model simulates impacts to flows & springsheds.
- Example: Lake City
  - Average rate: 4.5 MGD
  - No pumping springsheds
    - Ichetucknee: 248-222 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%



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*

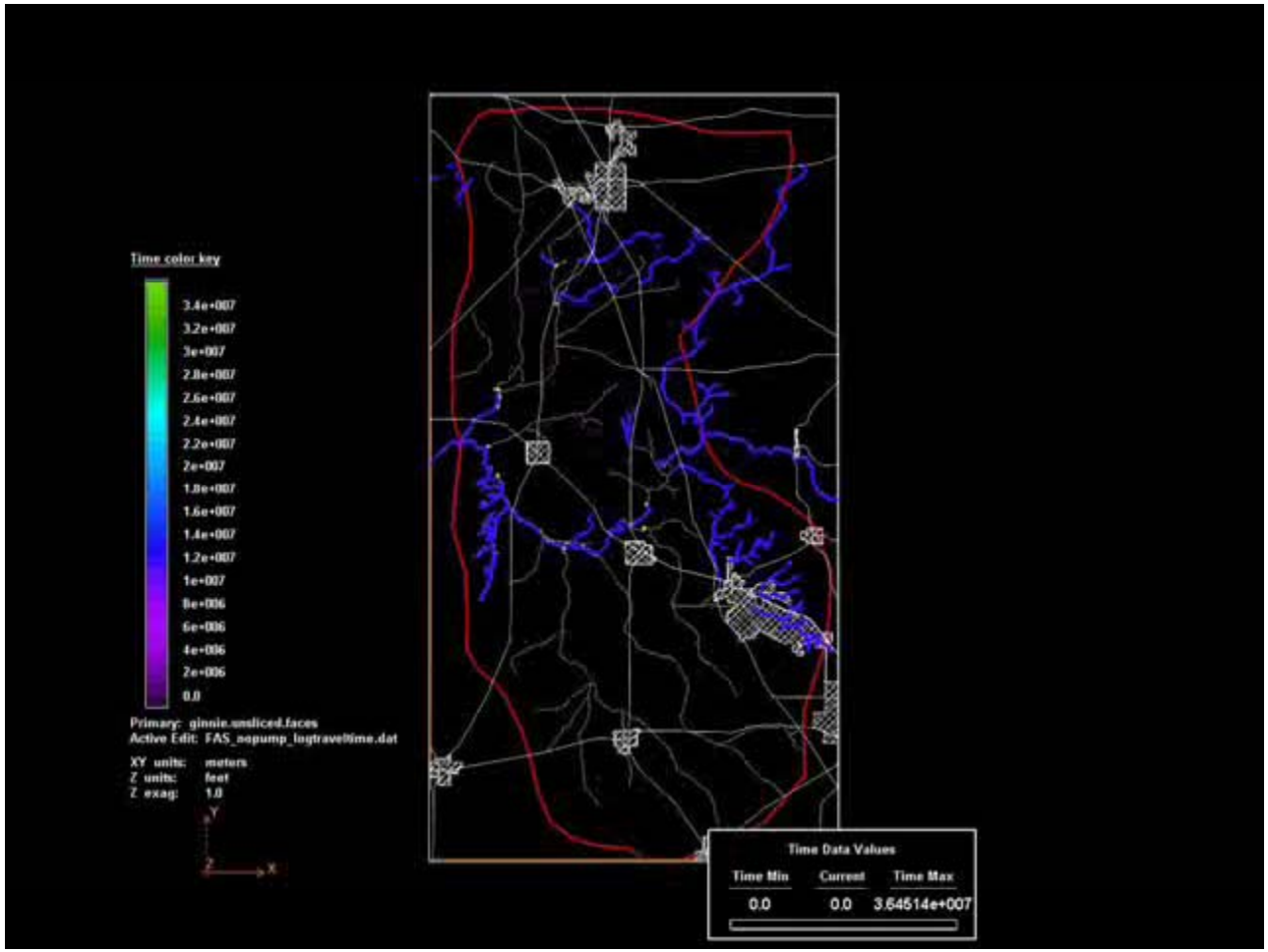


Applications: Source Water Protection

Springs Vulnerability: Santa Fe River Basin, Florida

Controlled by conduits

Simulated velocity range
- *10^{2} m/day*
- *10^{-3} m/day*



Summary - 3

- Most critical groundwater management decisions are being made based on models – ***Right Now***.
- We need to use existing tools to make better models & better decisions – ***Right Now***.
- Observable karst groundwater flow conditions in the Floridan aquifer (springs, traced groundwater flow paths and velocities, swallet inflows) have been effectively simulated with a dual-permeability steady-state finite element numerical model.
- Critical components of developing that simulation include:
  - Development and calibration to average high and average low water conditions
  - Calibration to springs and velocities as well as heads
  - Incorporation of anecdotal information to fill in (even if subjectively) data gaps
  - Willingness to adapt the simulated conduit structure as part of the calibration process
  - Use of a modeling code that allows the inclusion of conduits
- More information: www.h2hmodeling.com/CCNA
- *also – see our talk at AGU (Dan Doctor and Matt Covington's Session)*

Coca-Cola north america

H2H