Western Santa Fe River Basin Groundwater Resource Model

Modeling Results & Methods

Todd Kincaid, Ph.D.[2], Brent Meyer, M.S.[2], & Jon Radtke, P.G.[1]

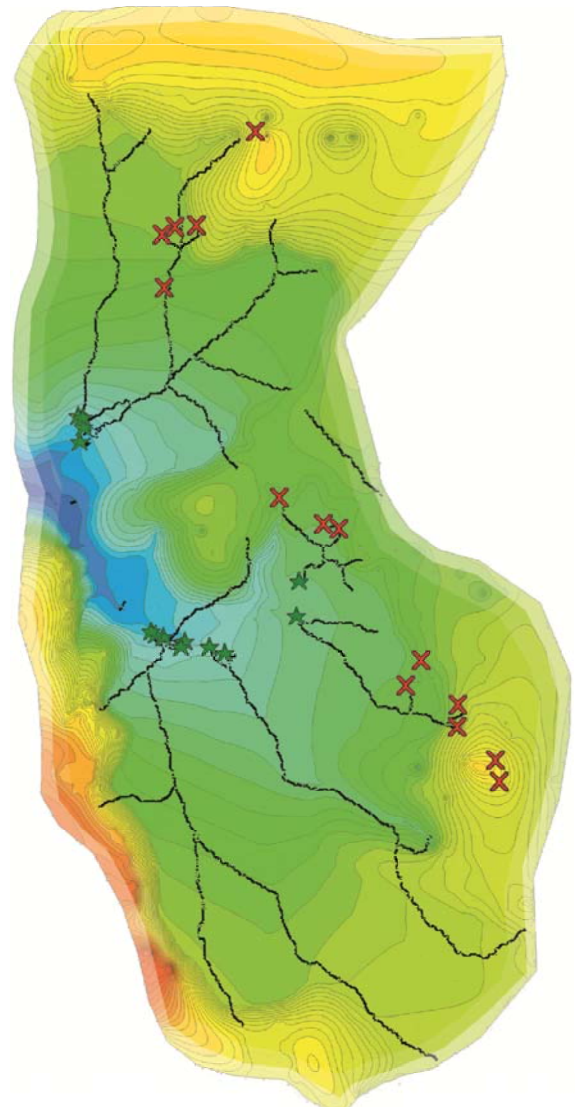
August 3, 2009

CCDA Waters LLC – Water Bottling Facility

High Springs, Florida

[1] Coca-Cola North America

[2] GeoHydros, LLC

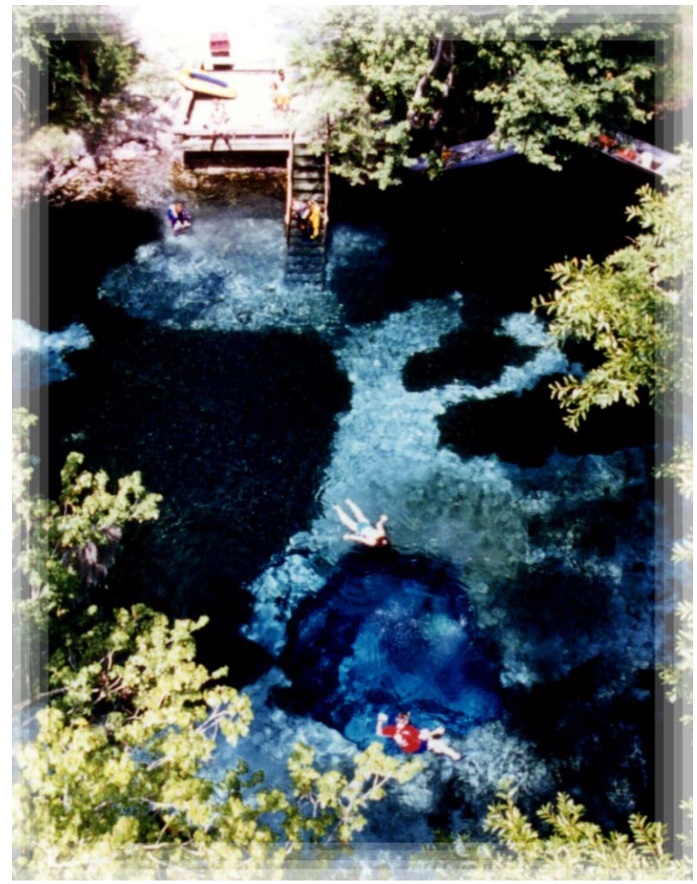


Coca-Cola & Environmental Stewardship

Jon Radtke, P.G.
Director – North America Water Resources
Atlanta, GA

- Watershed Sustainability Commitment
- Source Vulnerability Assessment
- Source Water Protection
- Community Relations

Protecting Ginnie Springs

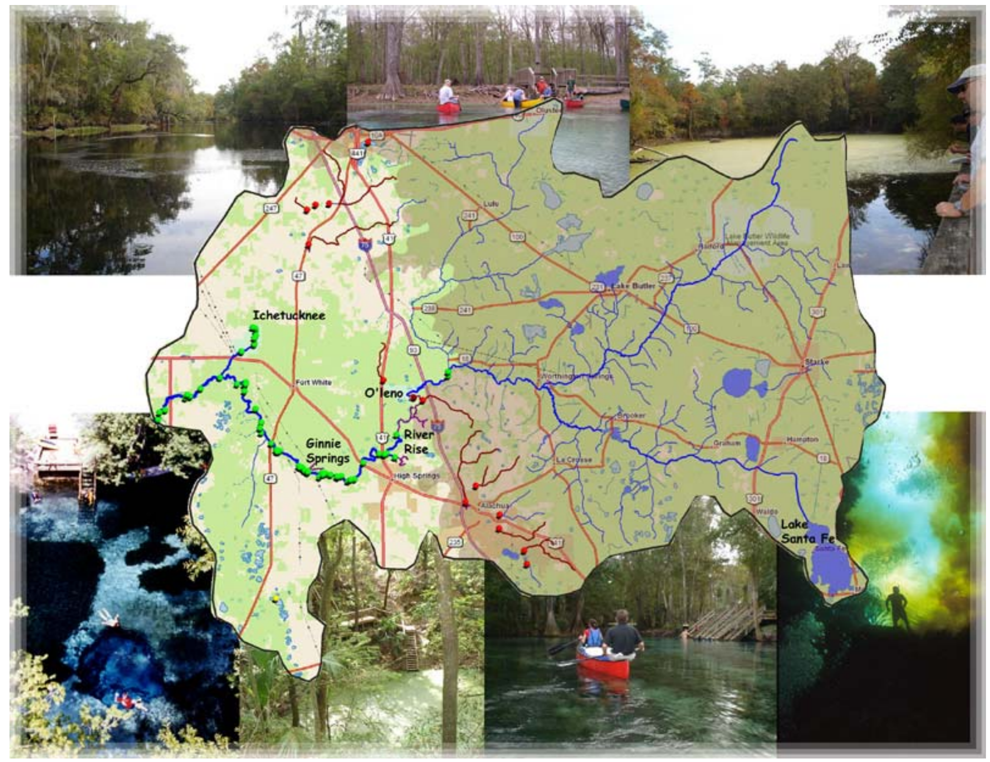


Key Point: Coca-Cola is committed to protecting Ginnie Spring

Why did Coca-Cola build this model?

- Need to quantify Coca-Cola's impacts to spring flows in the Santa Fe River.
- Need to identify how and where source water is vulnerable to contamination and/or depletion.
- Recognition of karst complexities and the limitations of available models.
- Fulfill commitment to watershed stewardship & community involvement.

Florida's Santa Fe River Basin



Key Point: Protecting the springs is in Coca-Cola's best interest.

Overview & Agenda

Todd Kincaid, Ph.D.
Group Leader – GeoHydros, LLC
Reno, NV

Ph.D. – Univ. of Wyoming
M.S. & B.S. – Univ. of Florida
Modeling & Karst Work for 16+ years

- Modeling Objectives & Results
- Data Synthesis & Model Setup
- ↔ Discussion / Q&A
- Lunch, Discussion / Q&A
- ↔ Discussion / Q&A
- Plant Tour
- Water Budget & Calibration
- Confidence & Limitations
- ↔ Discussion / Q&A
- Model Evolution & Future Applications
- Summary, Modeling Lessons Learned
- ↔ Discussion / Q&A
- Model Release Objectives
- Closing remarks / Adjourn
- ↔ Discussion / Q&A

Key Point: Please don't leave with unanswered questions.

Overall Modeling Objectives

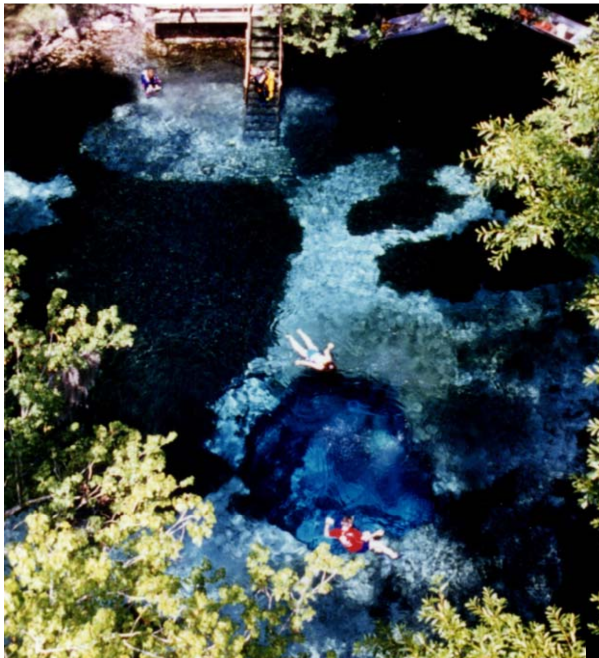
- Develop a steady-state groundwater flow model for the western Santa Fe River Basin.
- Make the model large enough to accurately define the major springsheds on the south side of the river that may be impacted by CCNA's groundwater withdrawals and therefore be a component of the source water.
- Develop a model that incorporates and describes karst features and conduit flow patterns.
- Develop a model that will deliver reliable predictions of travel-times from various points in the springsheds (aquifer vulnerability mapping).
- Develop a model that can be trusted by government resource managers.
- Share the model and model results with government resource managers and the public.

Key Point: Build the best possible model for the area springsheds.

Important Hydrogeologic Complexities

Springs

large magnitude discrete discharges



Conduits

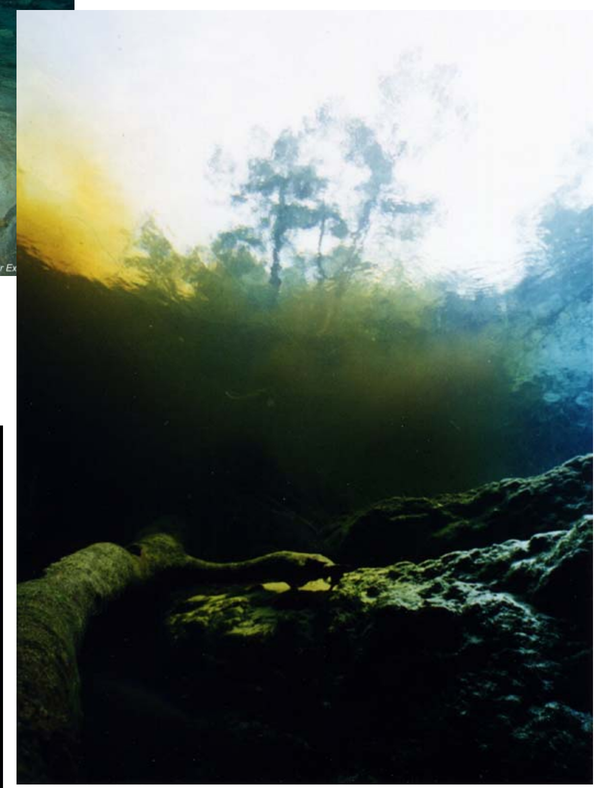
Very significant preferential flow paths

Swallets

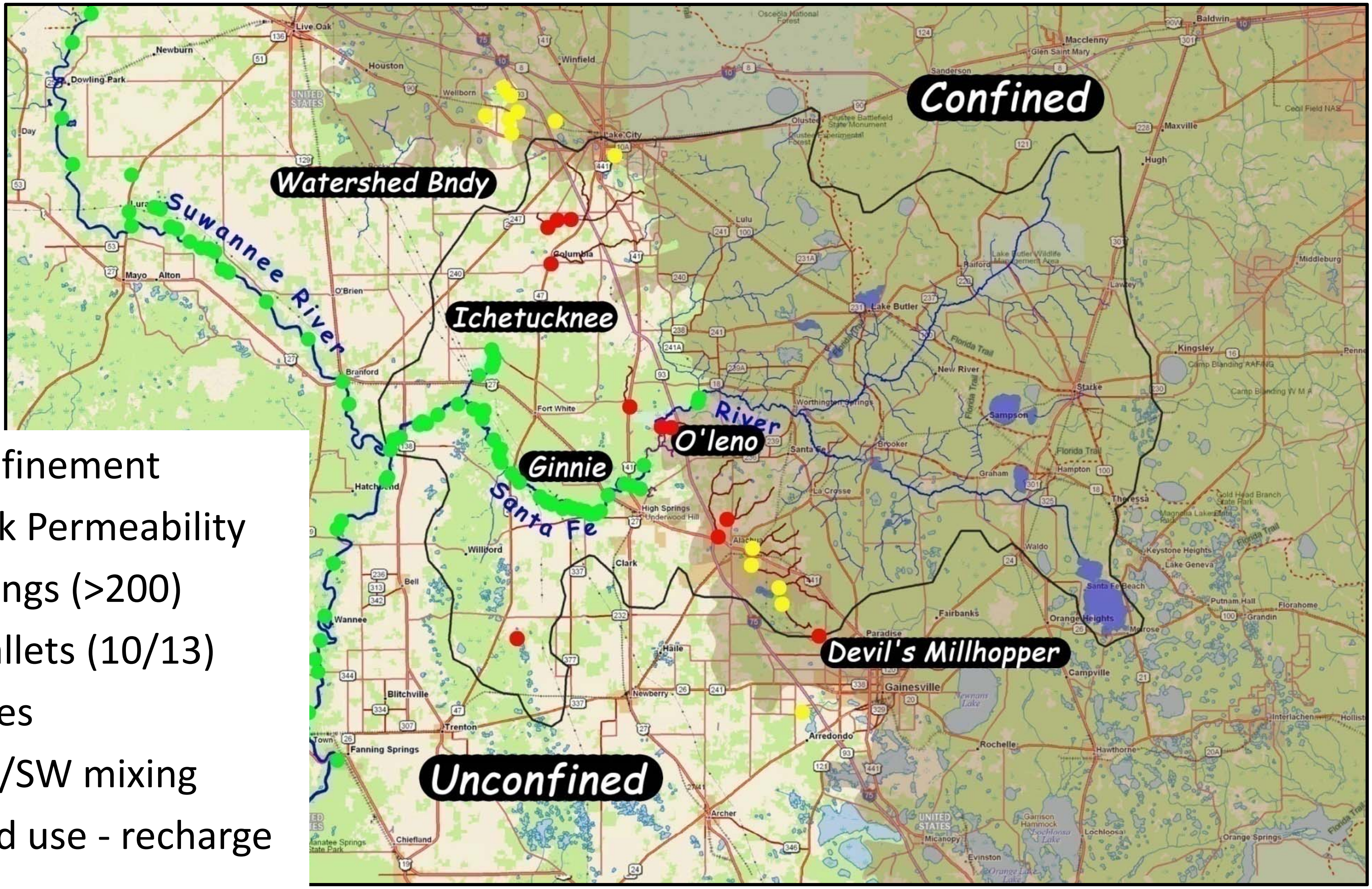
Large magnitude discrete recharge

GW / SW Mixing

Impacts water budget



Important Hydrogeologic Complexities



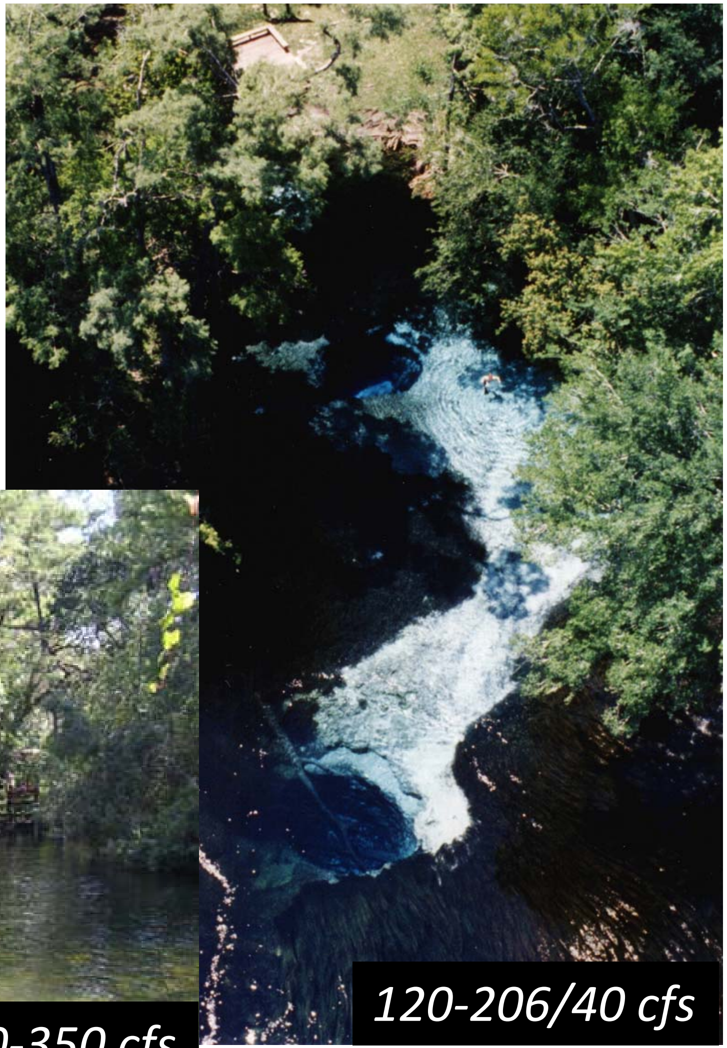
- Confinement
- Rock Permeability
- Springs (>200)
- Swallets (10/13)
- Caves
- GW/SW mixing
- Land use - recharge

Key Point: Karst features create the dominant controls on flow

Springs: *Discrete Large Discharges*

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

Devil's Ear / Devil's Eye Springs



Hornsby Spring

Key Point: Must address springs & spring types discretely

Swallets: *Discrete Rapid Recharge*

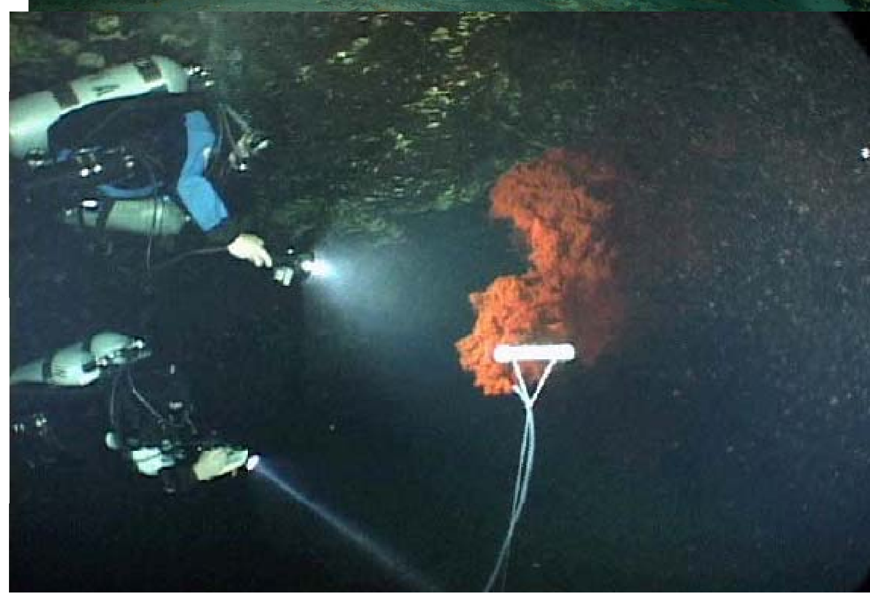
- Swallets: disappearing streams that fully connect the land surface to the FAS.
  - 11 known & documented features
  - O'leno Sink, Clay Hole Group (3), Rose Creek, Mill Creek (2), Hammock, Pareners Branch, Waters Lake, Devil's Millhopper
- Swallet-Seeps: basins containing perched water above FAS that 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

Key Point: Swallets are significant components of the water budget

Caves: *Preferential Flow Paths*

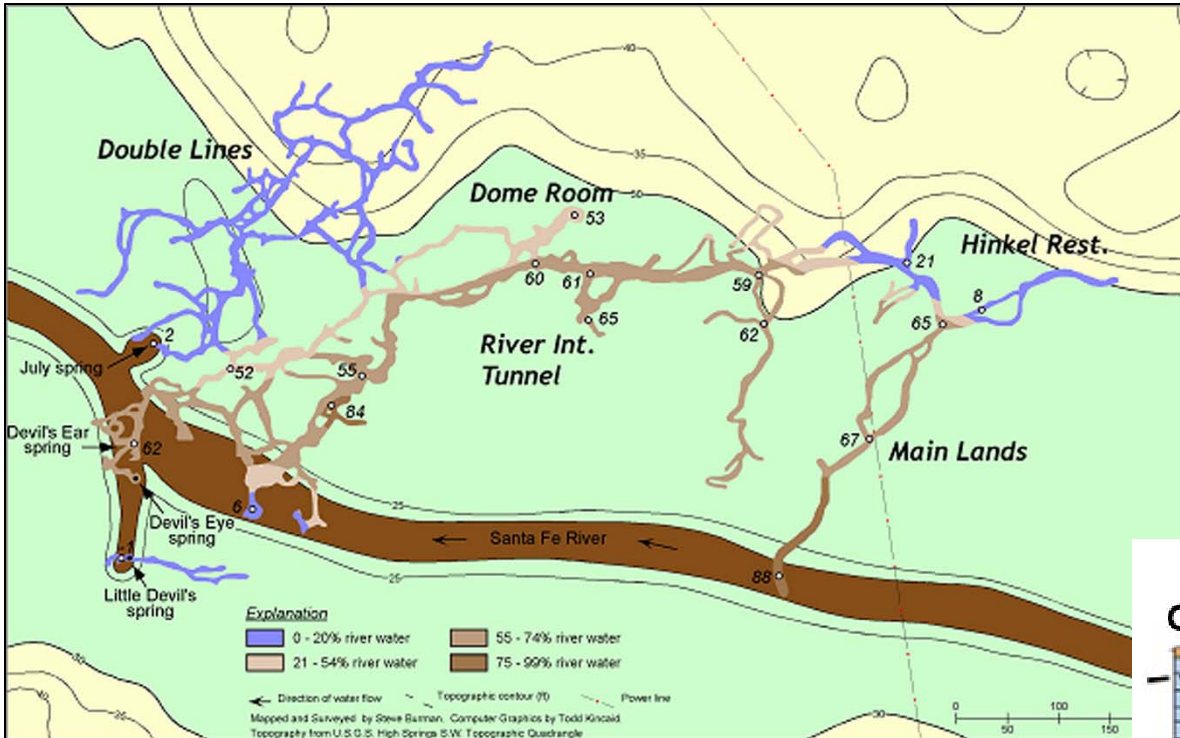
- Numerous explored & mapped caves
  - Old Bellamy, Hornsby, Devil's Ear, Mill Creek, Rose Sink, Ginnie, etc.
  - Depths trend 75 – 150 ft
  - Diameters: ~3 – 30 ft
- More traced caves
  - Rose Creek, Clay Hole, Mill Creek, San Felasco, Ichetucknee, Ginnie
  - ~200 – 750 m/day
- Probably many more that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

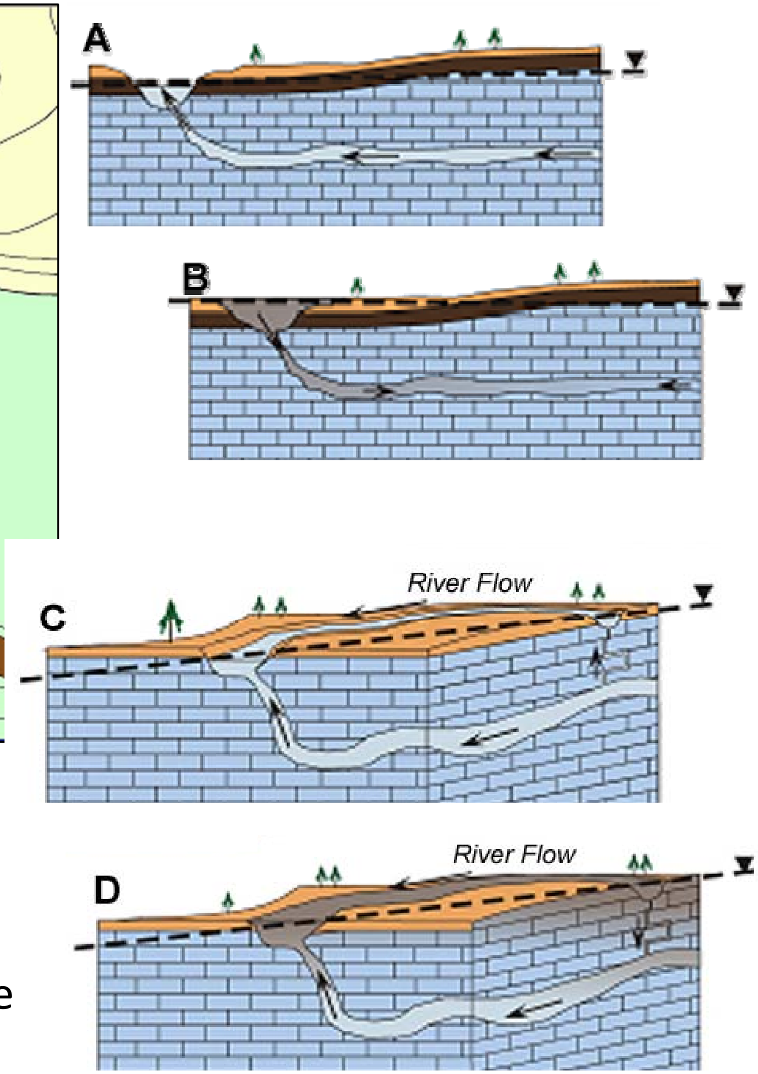
Devil's Ear Cave System



Key Point: Caves must have significant control on flow patterns

Groundwater / Surface Water Mixing

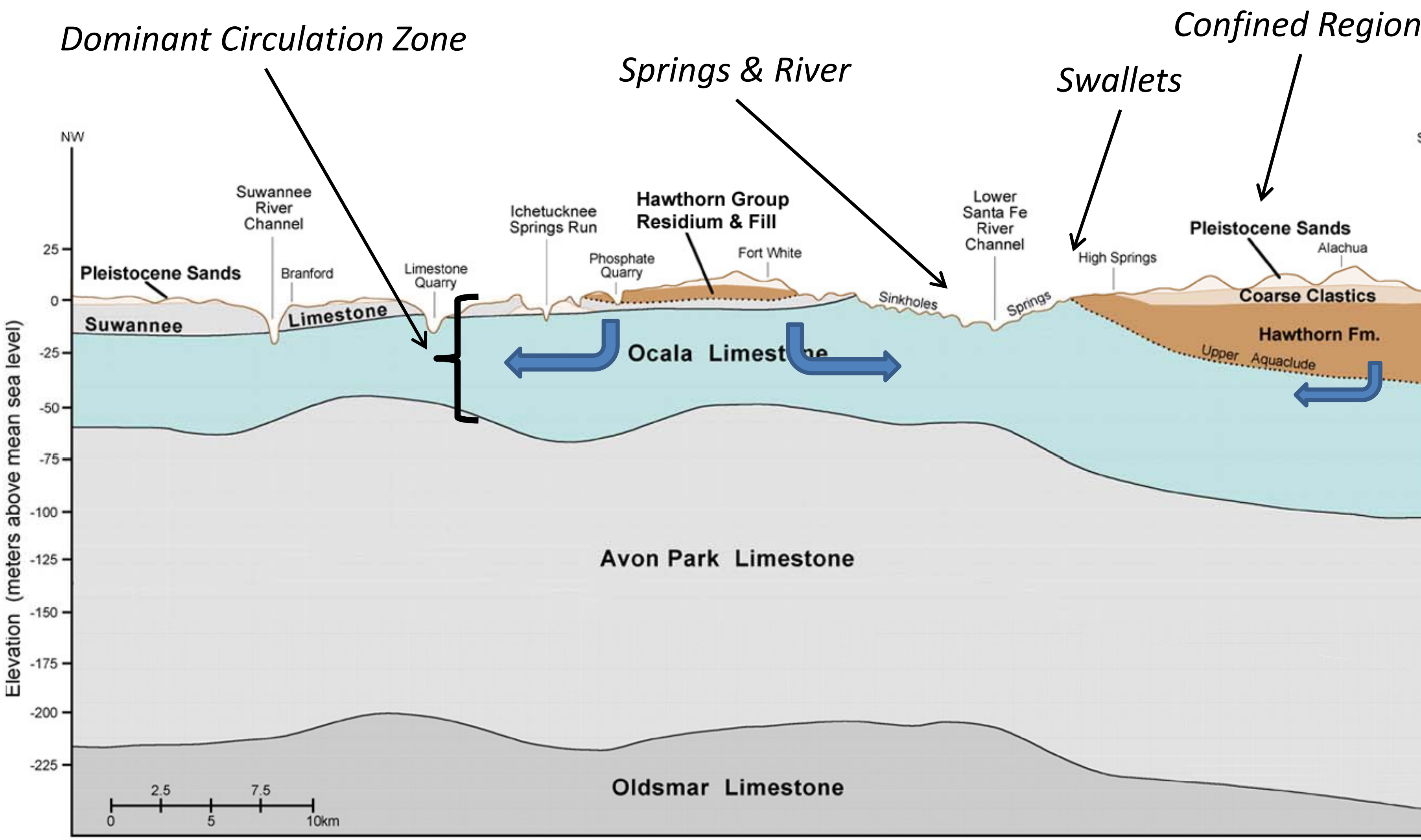




- Mixing occurs over very rapid time scales
  - *days rather than years*
- Can account for 50 – 100% of flow
- Degree of mixing is reflected by color of the discharge
- Need to constrain mixing in order to establish an accurate water budget

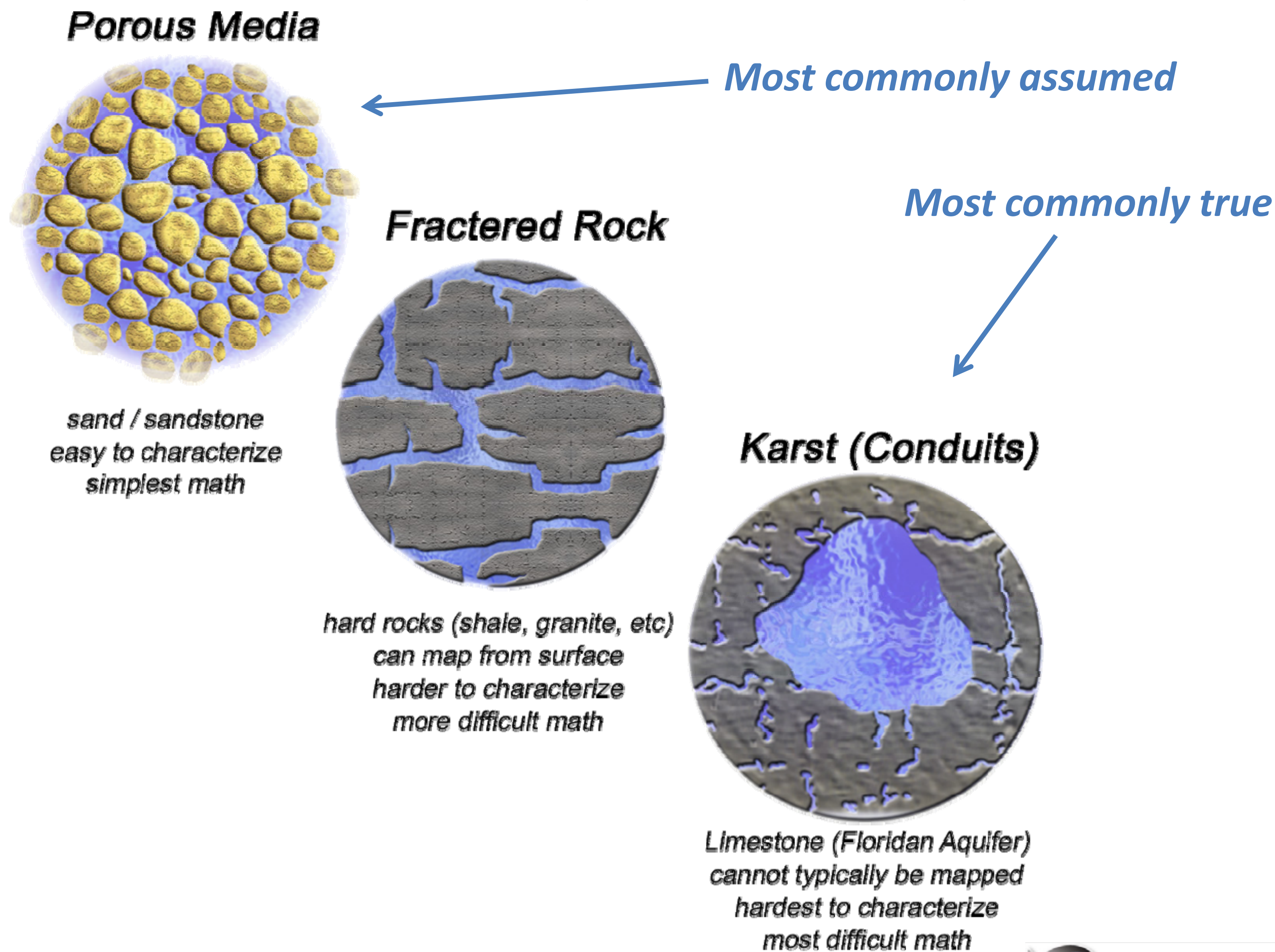
Key Point: Mixing impacts the water budget

Hydrostratigraphy: *Aquifer Confinement*



Key Point: Flow is 3D due to variable confinement

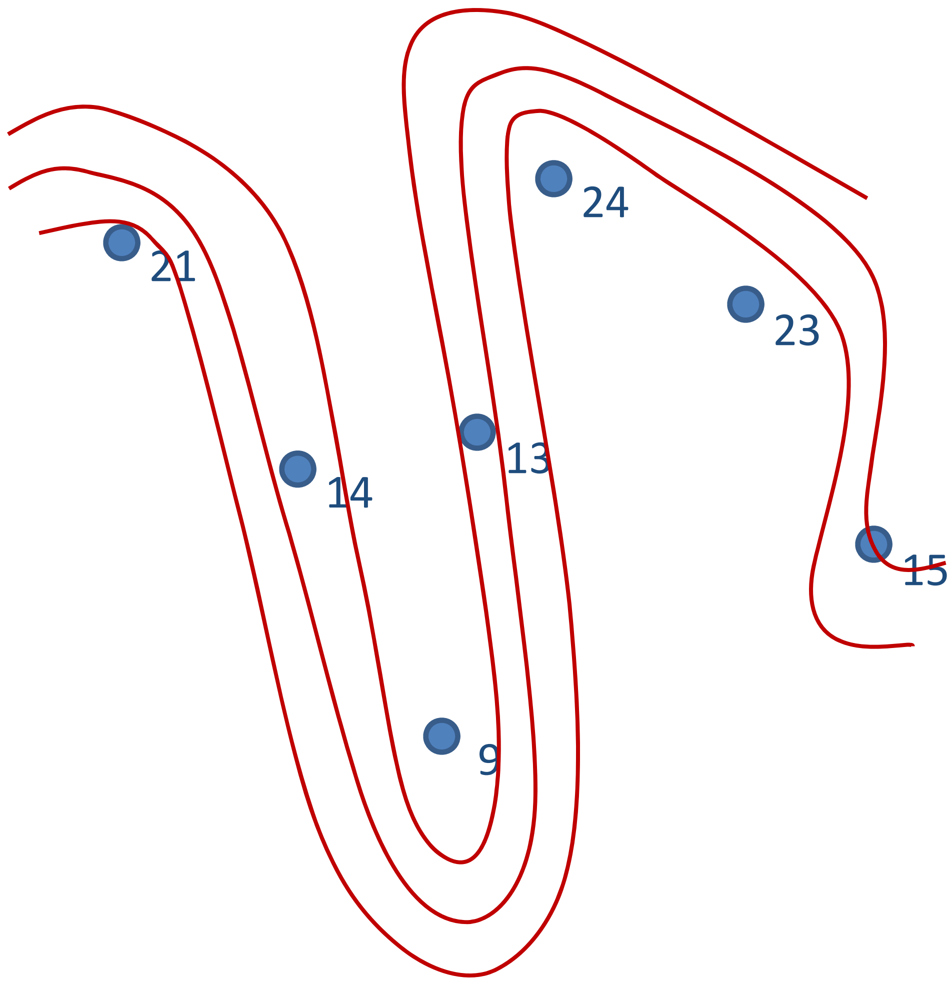
Basic Conceptualization Options



Key Point: Start with an accurate conceptualization

Impact of Assumptions: *Head Potentials*

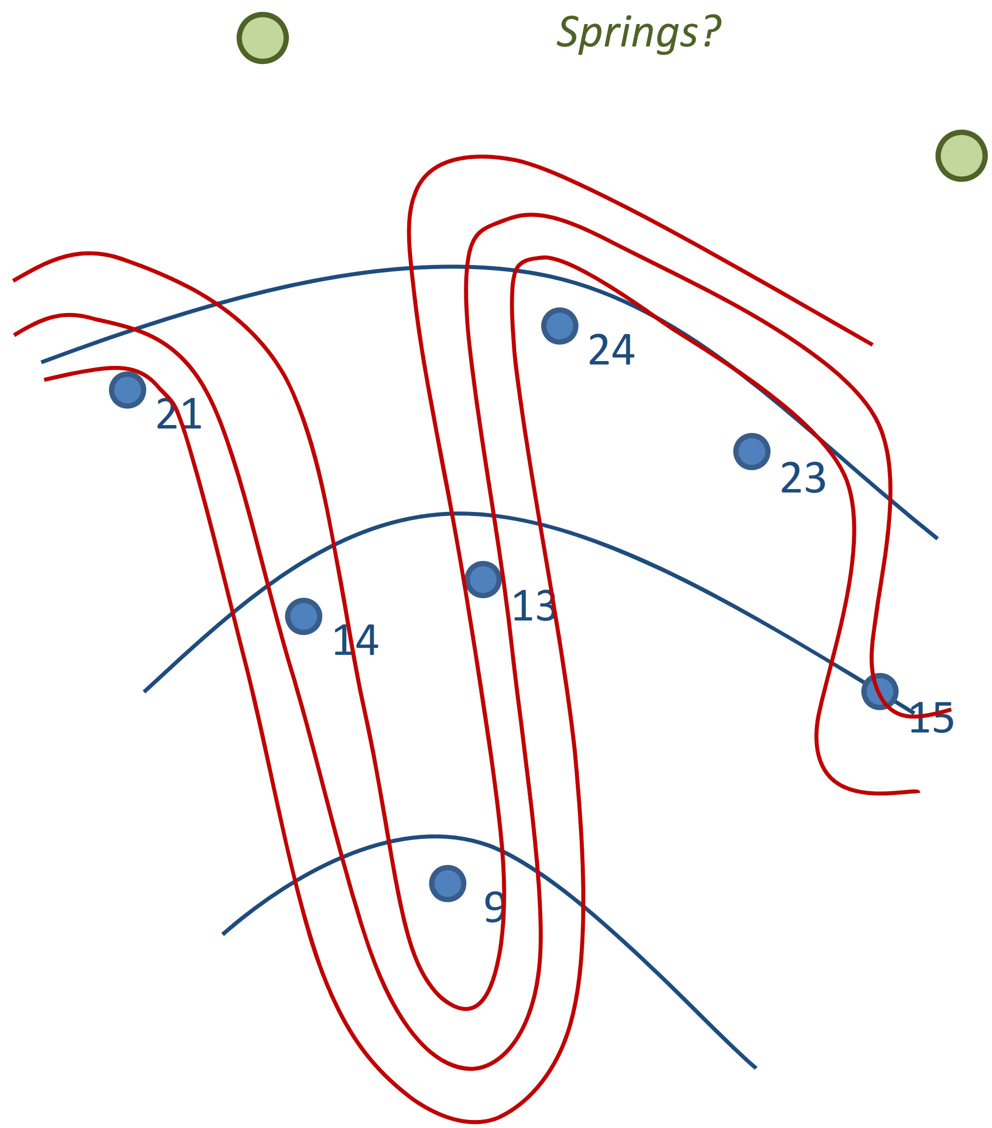
- Assumptions are necessary.
  We always make assumptions.
- We make assumptions in our thinking as well as our mathematics.
- It is critical to recognize what assumptions are being made and rather or not they are valid for the problem being addressed.
- The assumptions we make often reflect our biases about how we think the world works.
- Think about the prevalence of assumptions of isotropy and homogeneity …
  - Groundwater models
  - Pumping test analysis
  - Potentiometric surface contouring



Key Point:

Impact of Assumptions: *Head Potentials*

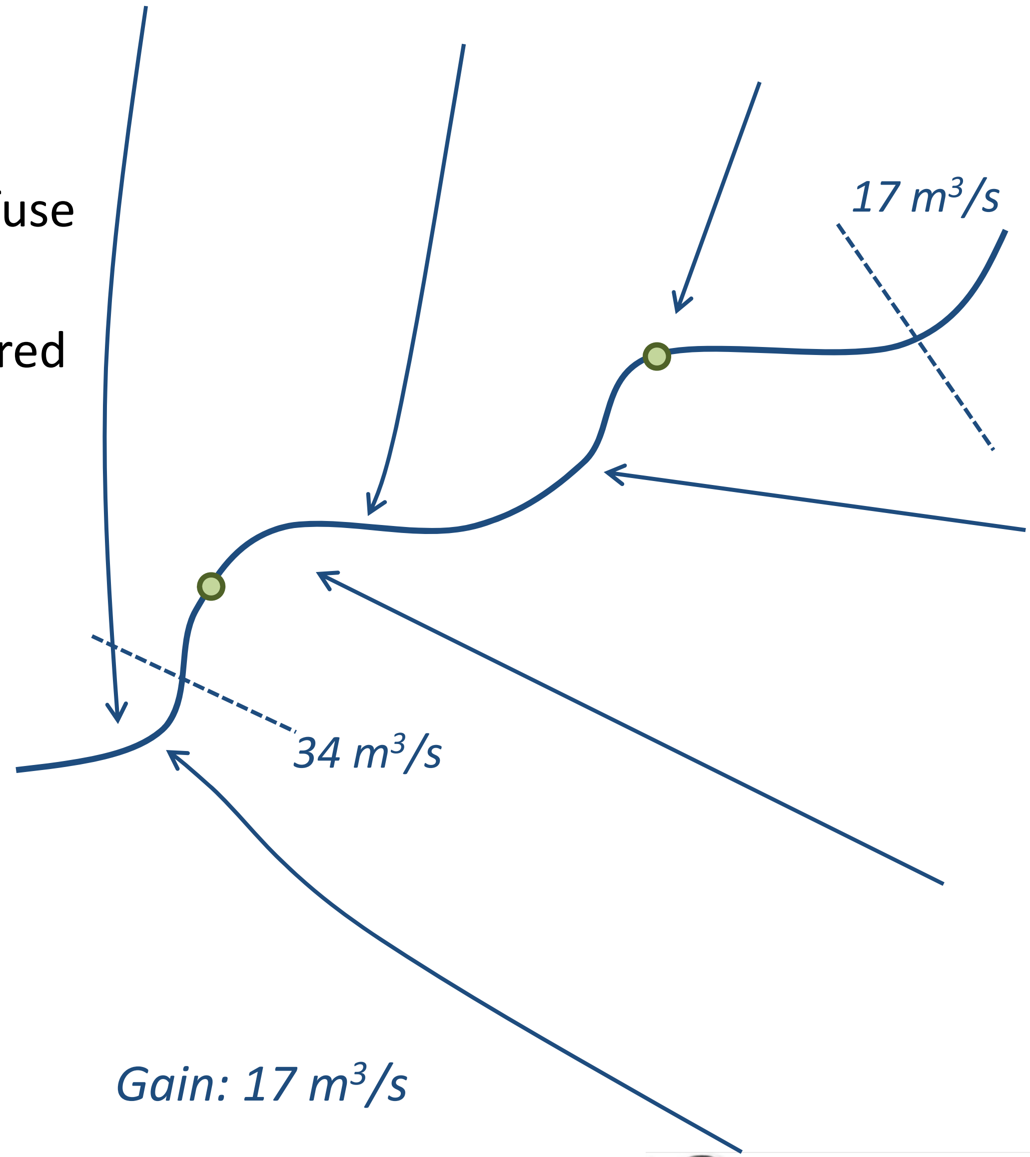
- Sand or Karst?
- How would you tell the difference?
- Data must be evaluated in context of regional setting.



Key Point: Assumptions should fit the model environment

Impact of Assumptions: *Flows*

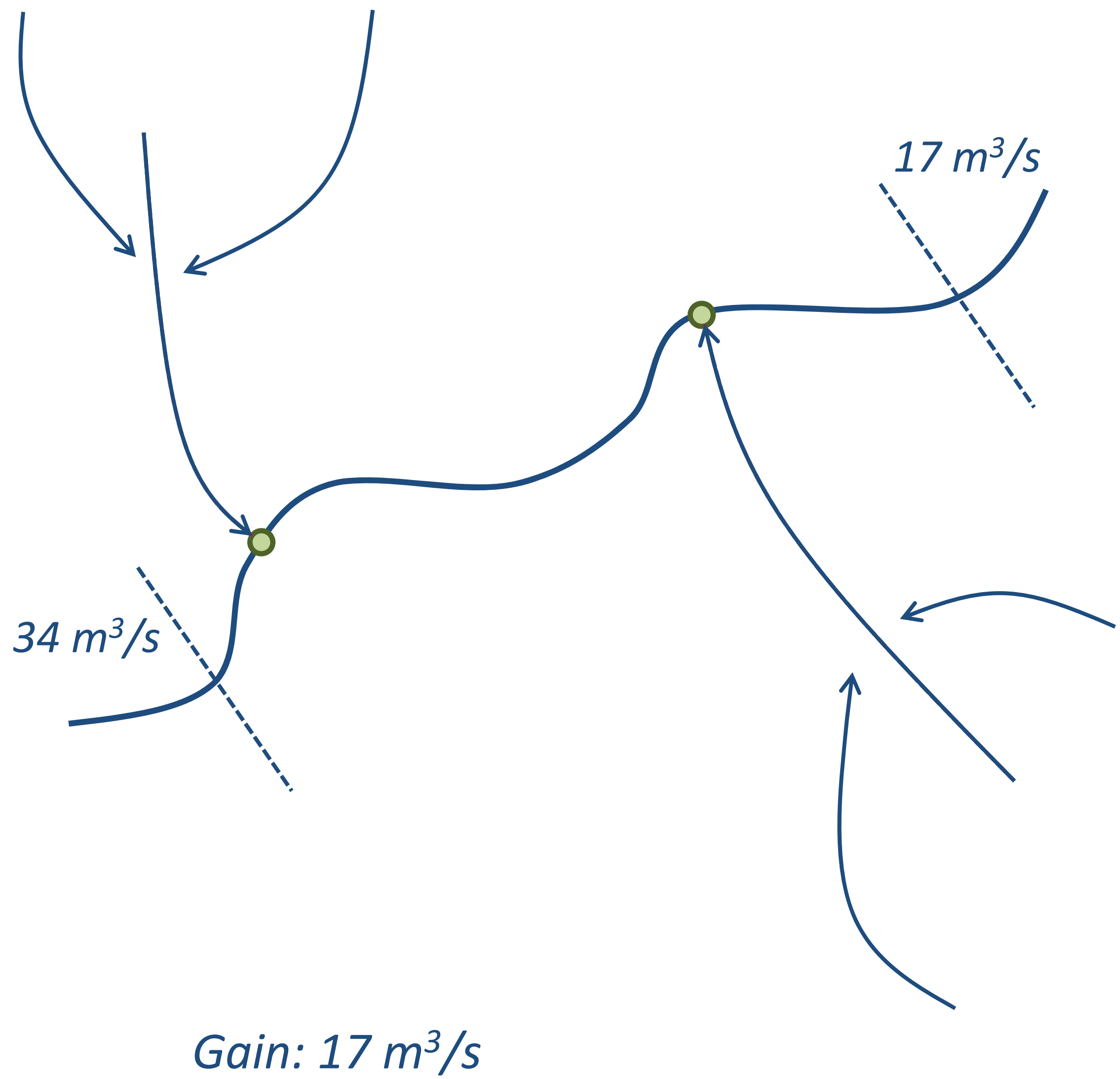
- View springs as part of river
  Standard approach
- flow to river is simulated as diffuse
- Assumed correct if simulated aggregate flow matches measured gain in the river
- But…
  Does this simulate reality?
- What is purpose of the model?
  - Gross flow to river? or..
  - Simulate flow patterns and velocities?



Key Point:

Impact of Assumptions: *Flows*

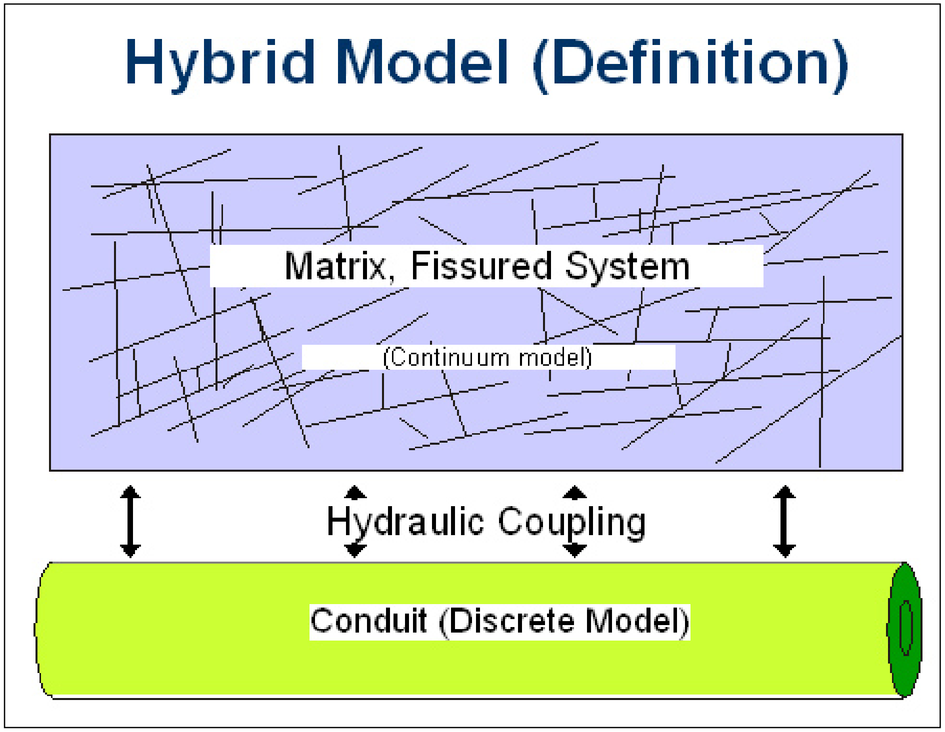
- View as discrete discharges responsible for majority of measured gain.
- Recognize that large discrete discharges are only possible via discrete high-K pathways.
- Force flow to river through discrete locations
- Will produce dramatically different flow patterns and velocities.



Key Point: Assumptions should fit the model environment

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.



http://www.feflow.info/

Key Point: Model is constructed in FEFLOW

Modeling Objectives Recap…

- Synthesize all available data (flows, levels, pathways, geology, land use, etc).
- Estimate variables for key features for which there is little or no available data (spring flows, swallets inflows, conduit locations & dimensions, etc).
- Identify and utilize the best available "off the shelf" technology for simulating groundwater flow in an extremely karstified aquifer.
- Develop a philosophy and methodology for karst aquifer modeling.
- Develop a robust calibration approach to render the model as widely applicable as possible.
- Identify and describe the limitations on model applicability.
- Identify and describe data and technological needs for improving the model and/or expanding its applicability.

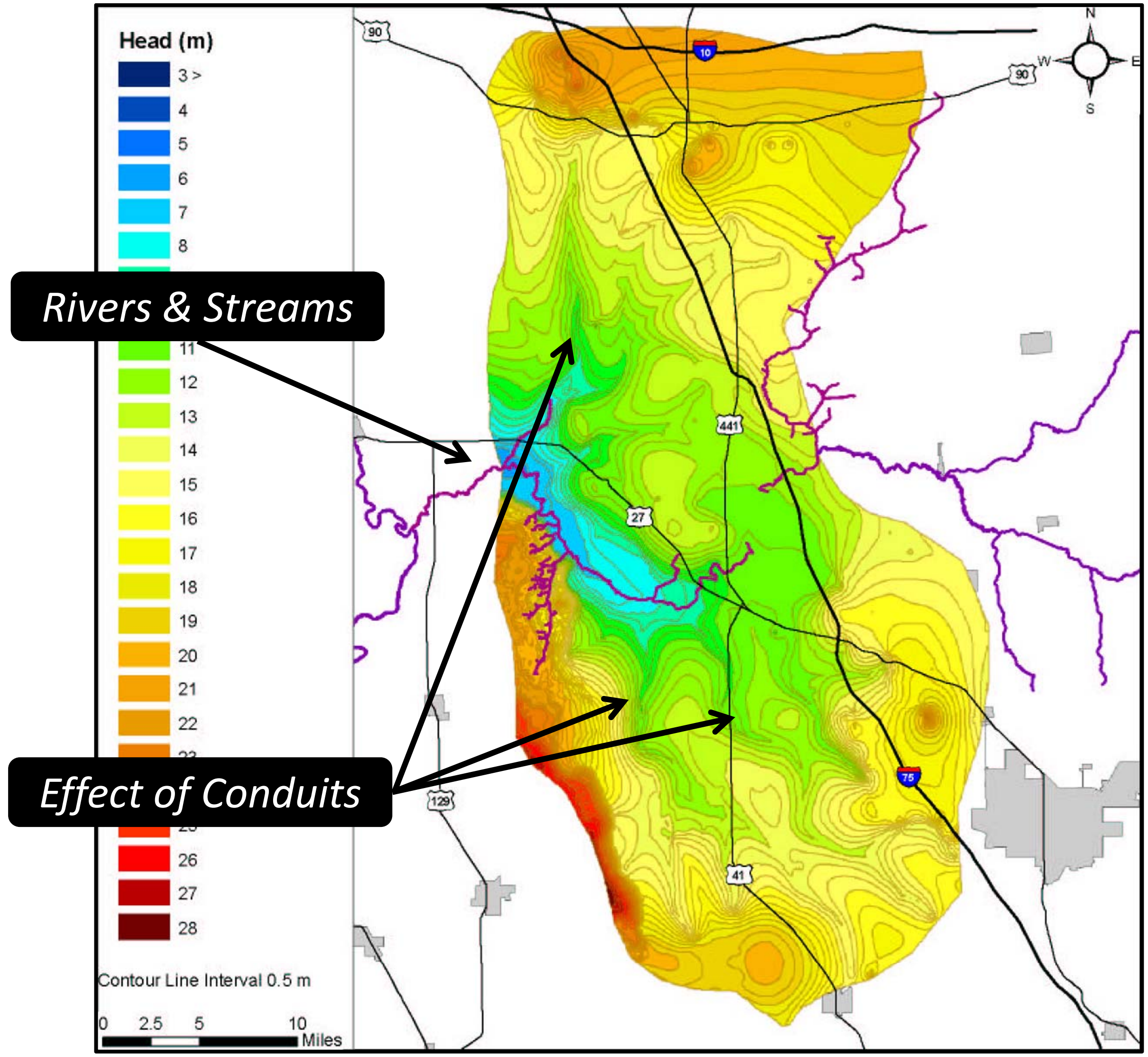
Key Point: Build the best possible model for the area springsheds.

Modeling Results: Overview

- Approach: calibrate to both average high water & average low water conditions
  - Develop single permeability framework (conduits & matrix)
  - Adjust recharge to accommodate the different calibration scenarios
  - Why?
    - Must do in order to accurately define the conduits
    - Also, significantly improved reliability
- Heads & velocities from calibration scenarios
- Calibration results: heads, flows, velocities
- Immediate applications
  - Particle tracking
  - Springshed delineations
  - Time-of-travel zones
  - Pumping impacts
- Future applications
  - Fate & transport
  - transient

Calibrated High Water Head Field

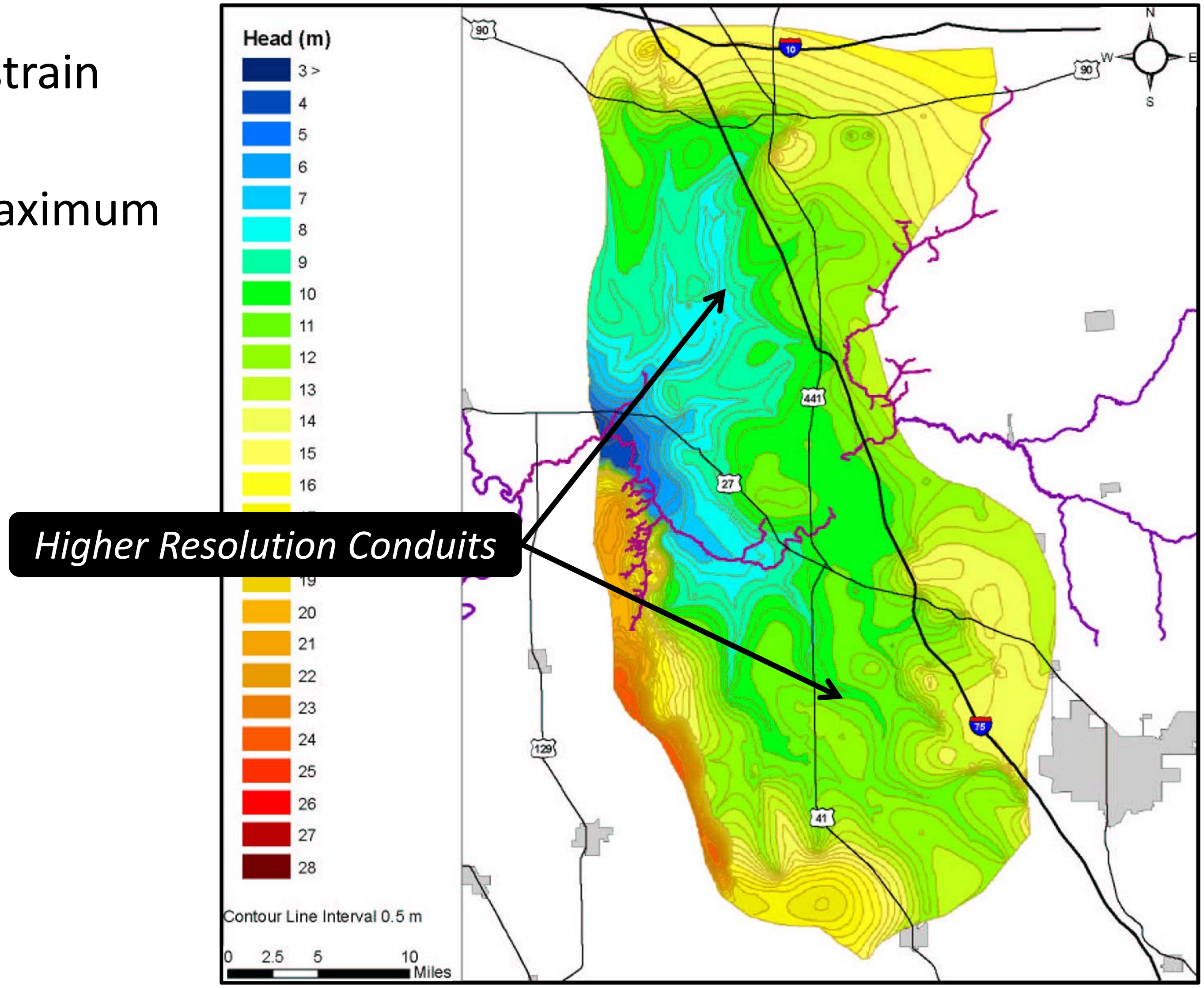
- Necessary to constrain conduit capacities
- Lesser ability to resolve locations
- Model boundaries discussed later



Key Point: High water conditions determine conduit capacities

Calibrated Low Water Head Field

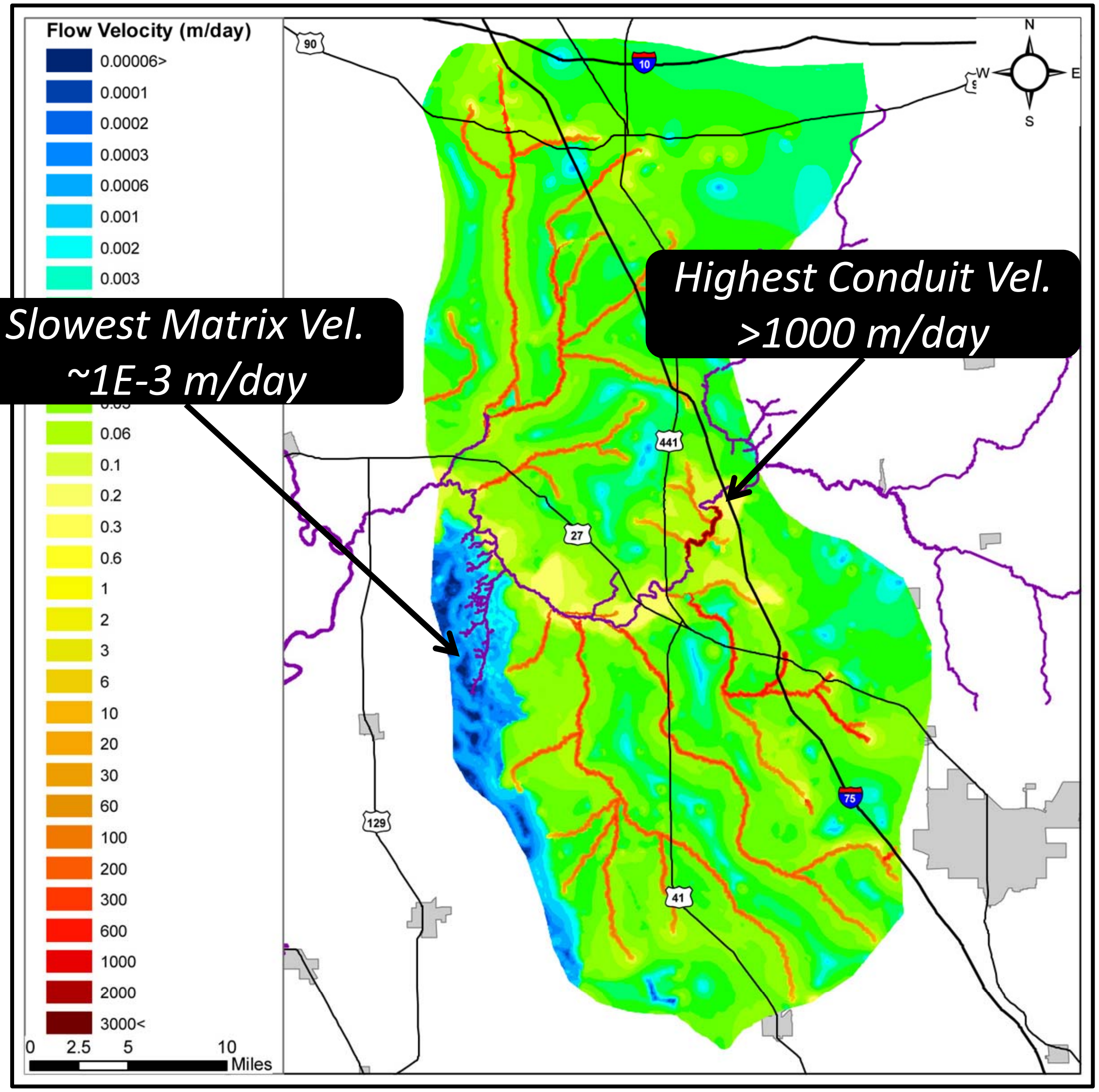
- Necessary to constrain conduit locations
- Cannot resolve maximum flow capacities



Key Point: Low water conditions determine conduit locations

Calibrated High Water Velocity Field

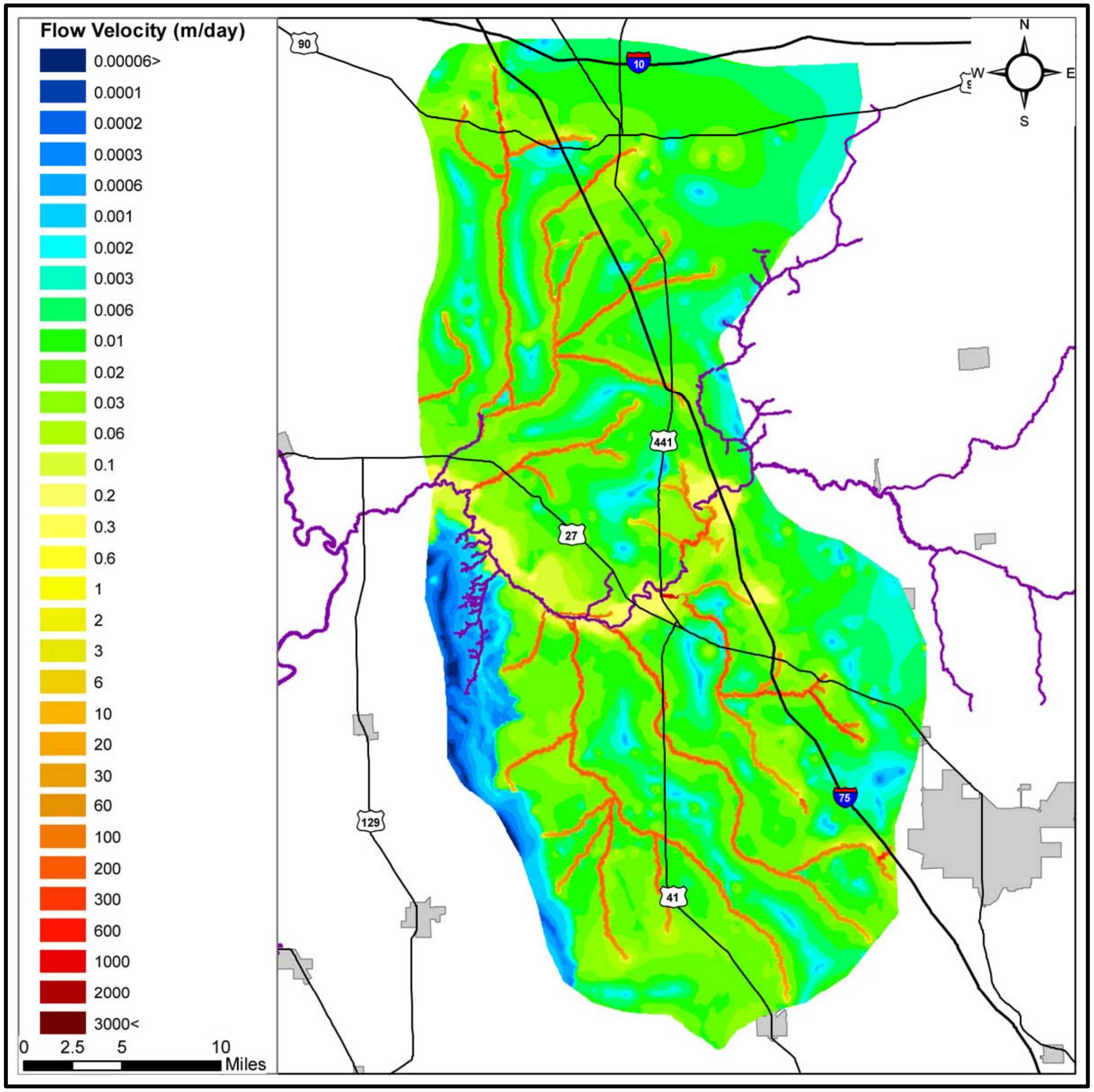
- 10 - >1000 m/day in conduits
- 1e-3 – 1 m/day in matrix
- Lowest matrix velocities under ridges
- Highest matrix velocities near river
- Highest conduit velocities in Old Bellamy Cave between O'leno Sink & the River Rise
- Slowest conduit velocities in small tributary conduits



Key Point: Reasonable & expected distribution of velocities

Calibrated Low Water Velocity Field

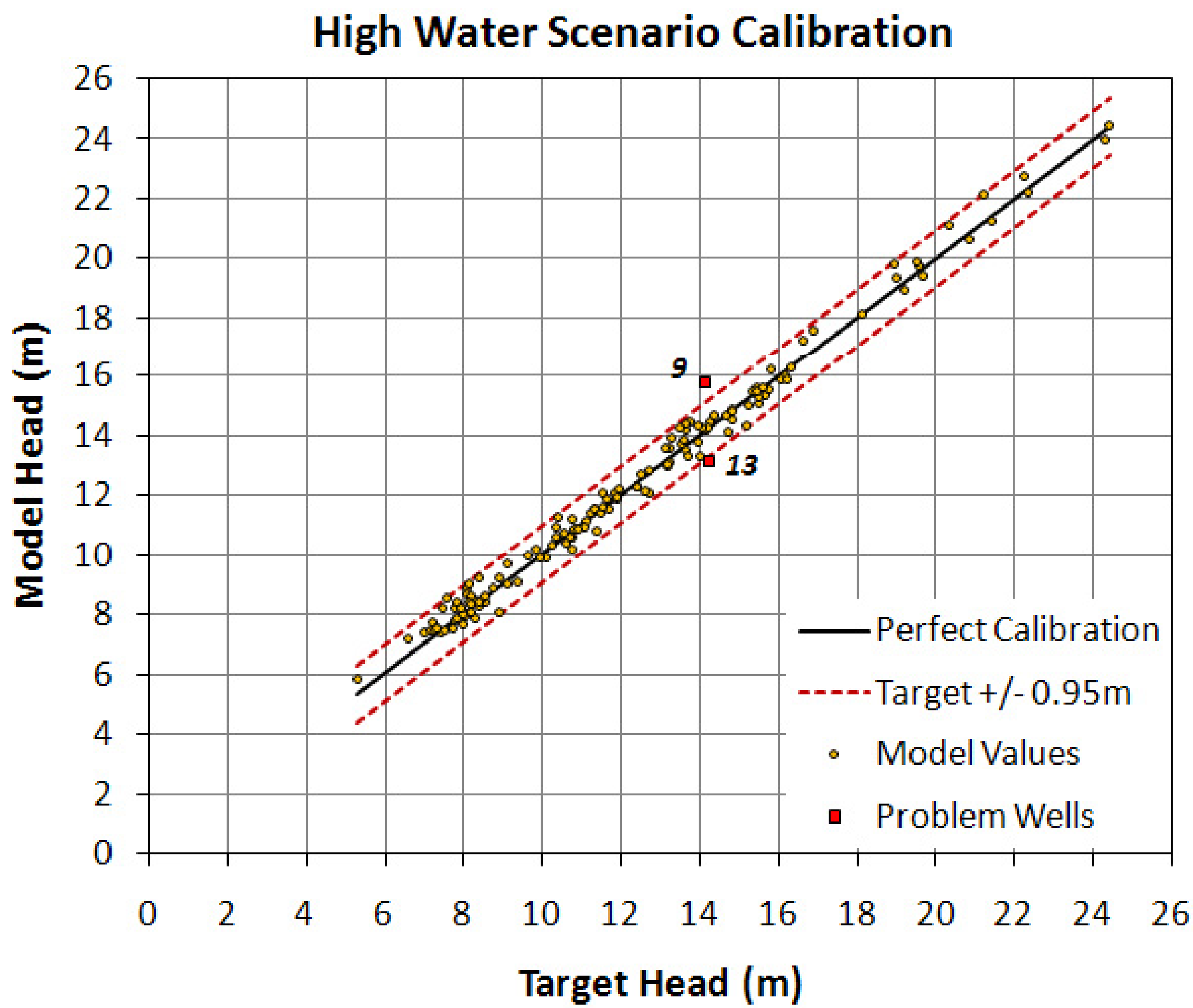
- Reduced recharge = reduced gradient = reduced matrix velocities
- Similar conduit velocities except where they are dominated by swallet inflow
  - i.e. Old Bellamy Cave
  - zero direct swallet input = reduced conduit velocities
- Same distribution of velocity as in the high water scenario



Key Point: Reasonable & expected distribution of velocities

Head Calibration: *High Water Scenario*

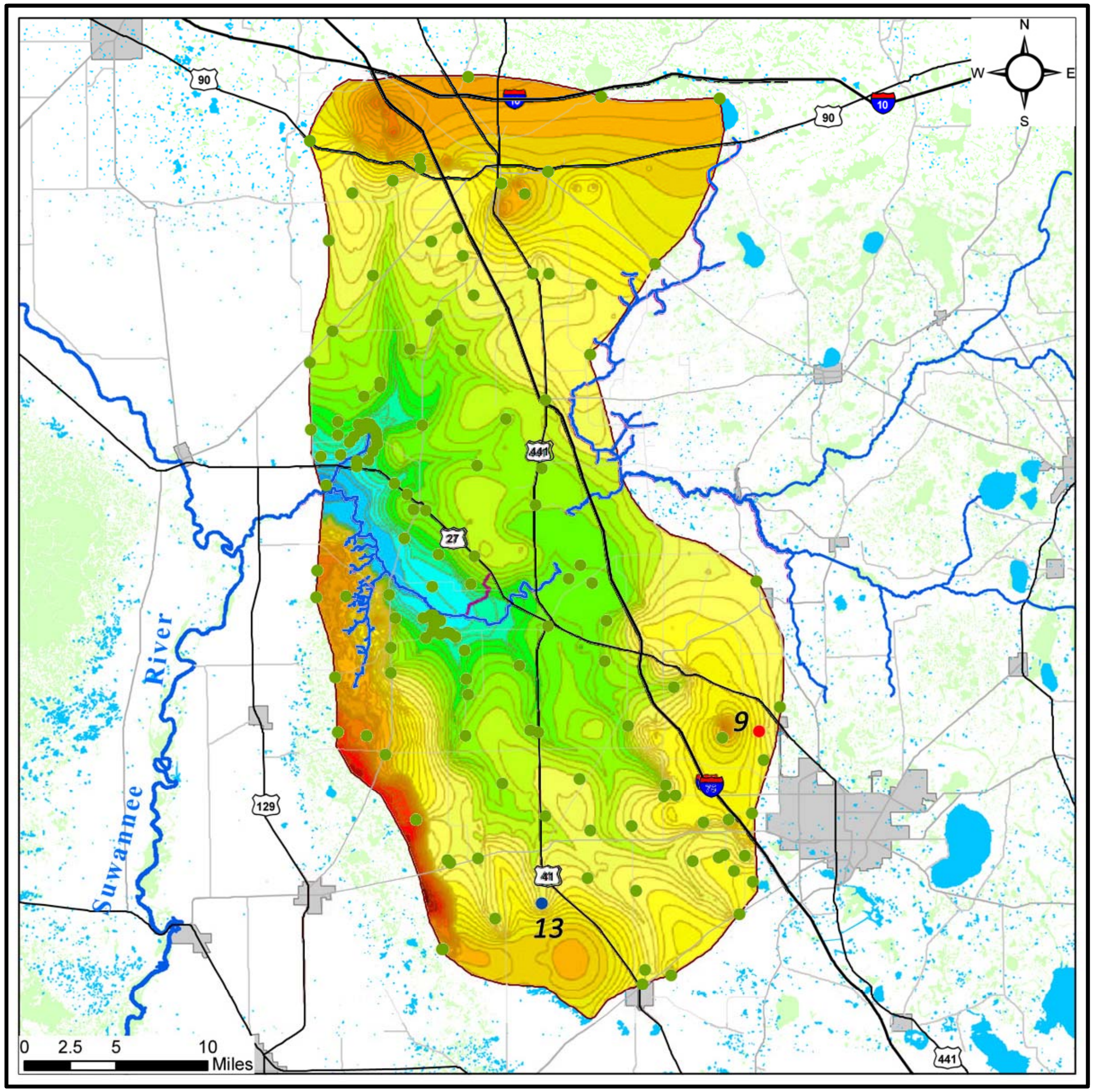
- Matches 99% of data
- 143 of 145 wells
- Criteria: +/- 0.95 m
  (5% of head range)



Key Point: Adding conduits improves calibration

Head Calibration: *High Water Scenario*

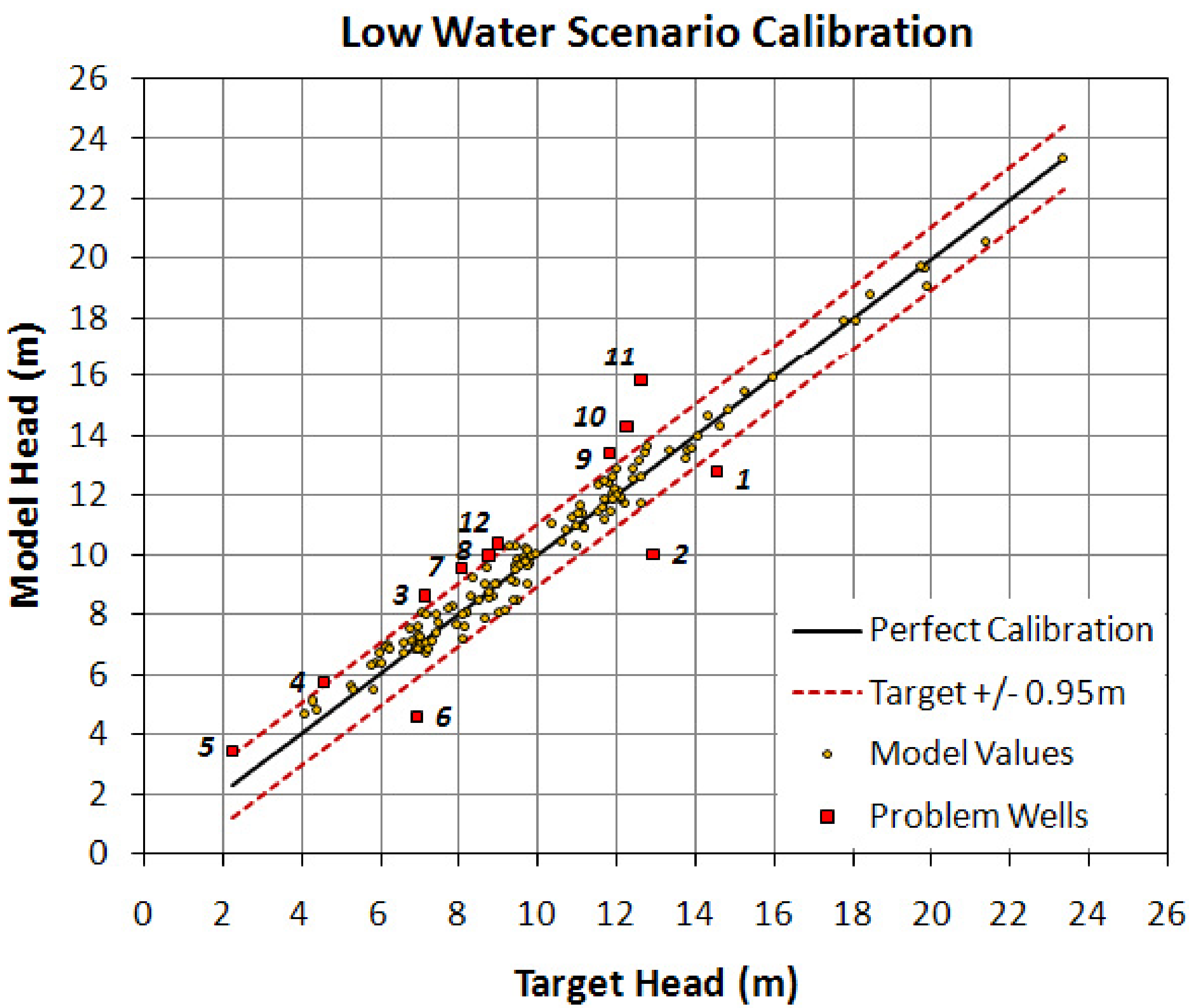
- Green = calibrated
- Red = high
- Blue = low
- #9: 14.1 / 15.8
- #13: 14.2 / 13.1
- Problems near mounds & conduits



Key Point: High water scenario is very well calibrated

Head Calibration: *Low Water Scenario*

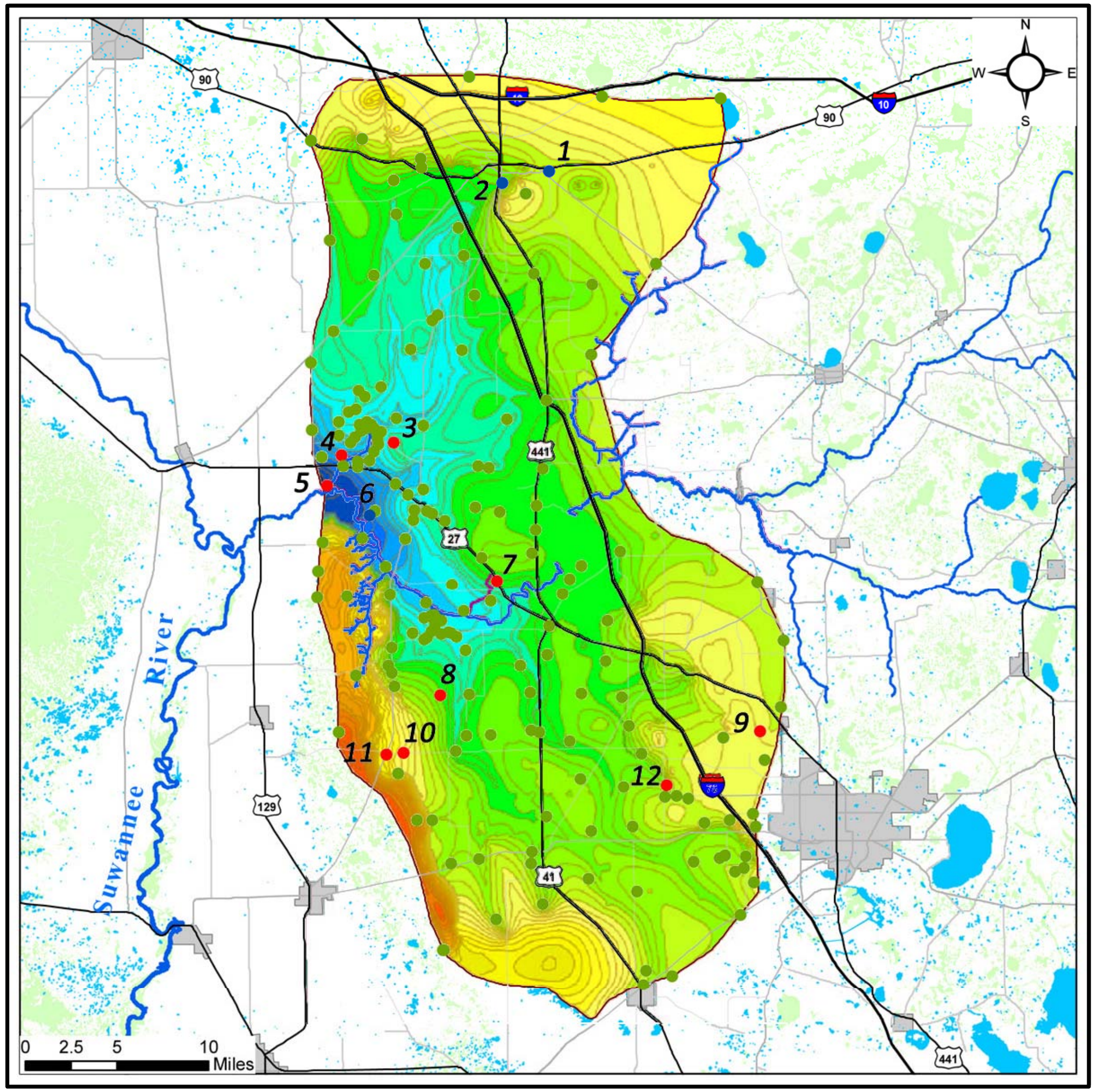
- Matches 94% of data
- 176 of 188 wells
- Criteria: +/- 1.05 m
  (5% of head range)



 Key Point: Adding conduits improves calibration

Head Calibration: *Low Water Scenario*

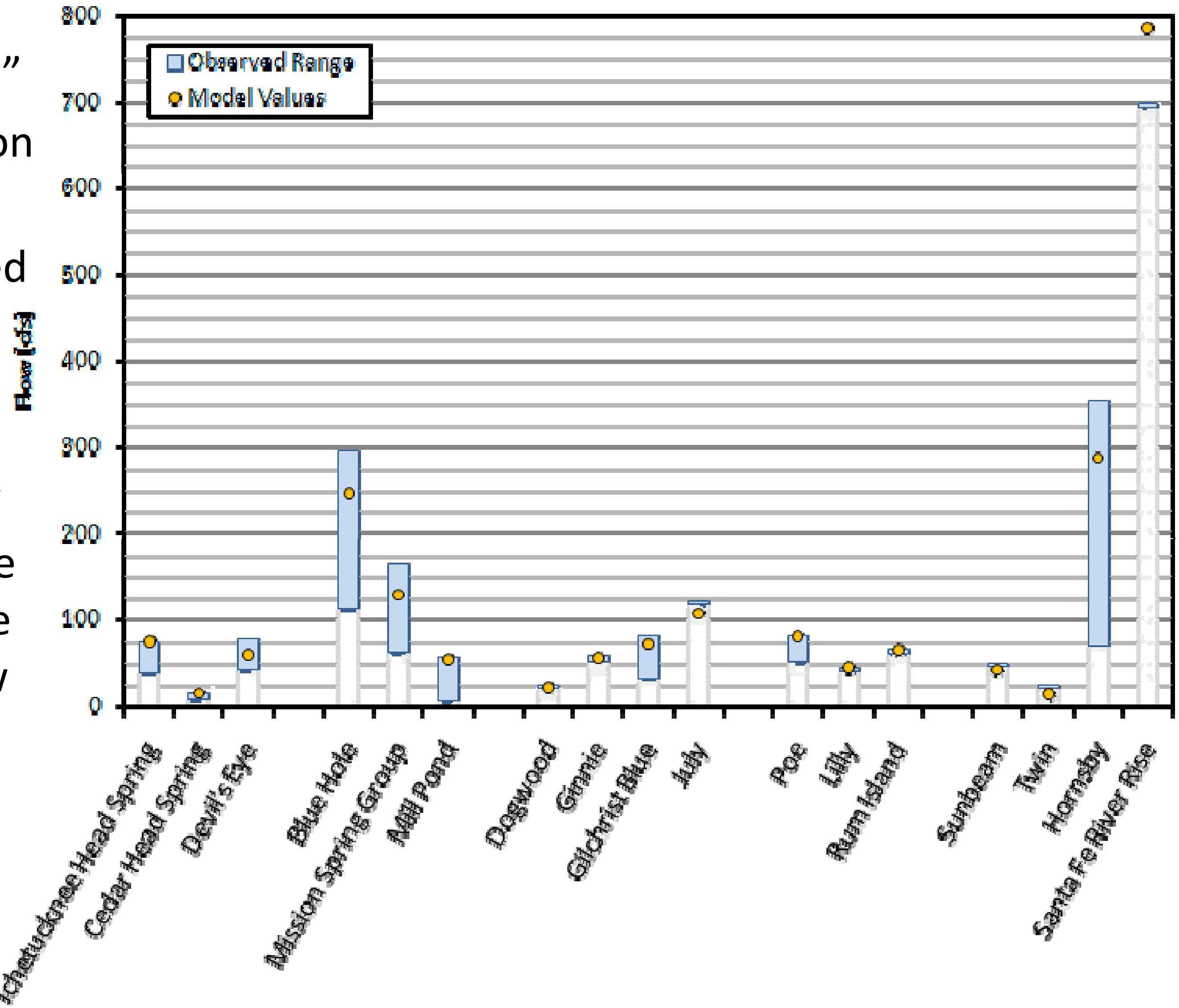
- Green = calibrated
- Red = high
- Blue = low
- Problems near mounds
  - #9: 11.8 / 13.4
  - #10: 12.3 / 14.2
  - #11: 12.6 / 15.8
- Problems near conduits
  - #1: 14.5 / 12.8
  - #2: 12.9 / 10
  - #3: 7.1 / 8.6
  - #4: 4.6 / 5.7
  - #5: 2.3 / 3.4
  - #6: 6.9 / 4.5
  - #7: 8.1 / 9.5
  - #8: 8.8 / 10.0
  - #12: 9.0 / 10.3



Key Point: Low water scenario is well calibrated

Discharge Calibration: *High Spring Flows*

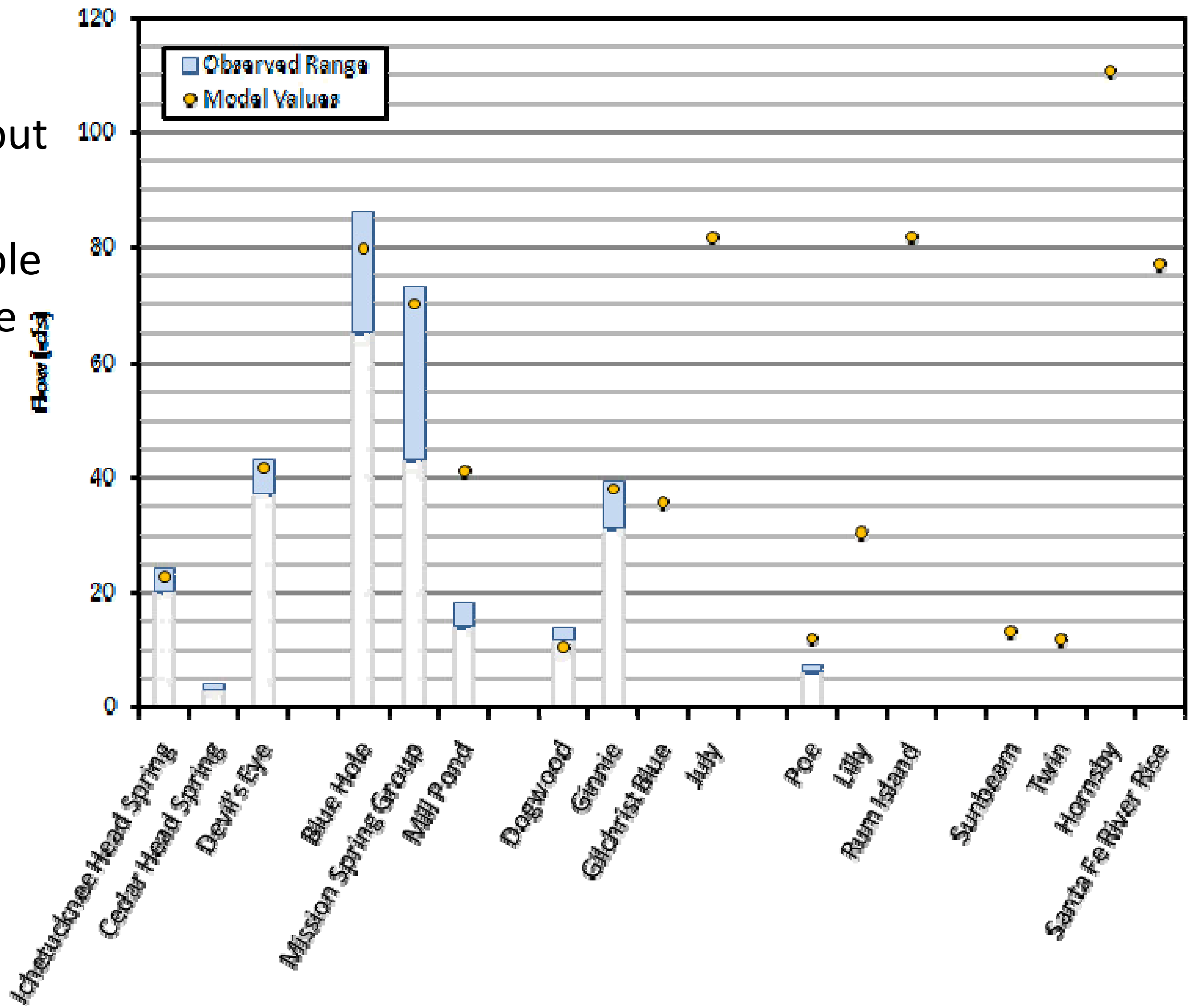
- Spring flows not "set"
- Flows were calibration targets
- Conduits & K adjusted until model flows closely matched observed flows
- Fairly broad range of acceptability because model is steady-state "average" high & low
- High water scenario closely matches observed ranges



Key Point: Model matches individual spring flows rather than gains

Discharge Calibration: *Low Spring Flows*

- Fewer data points
- Close match for all but Mill Pond
- Still within reasonable range given "average conditions" simulation



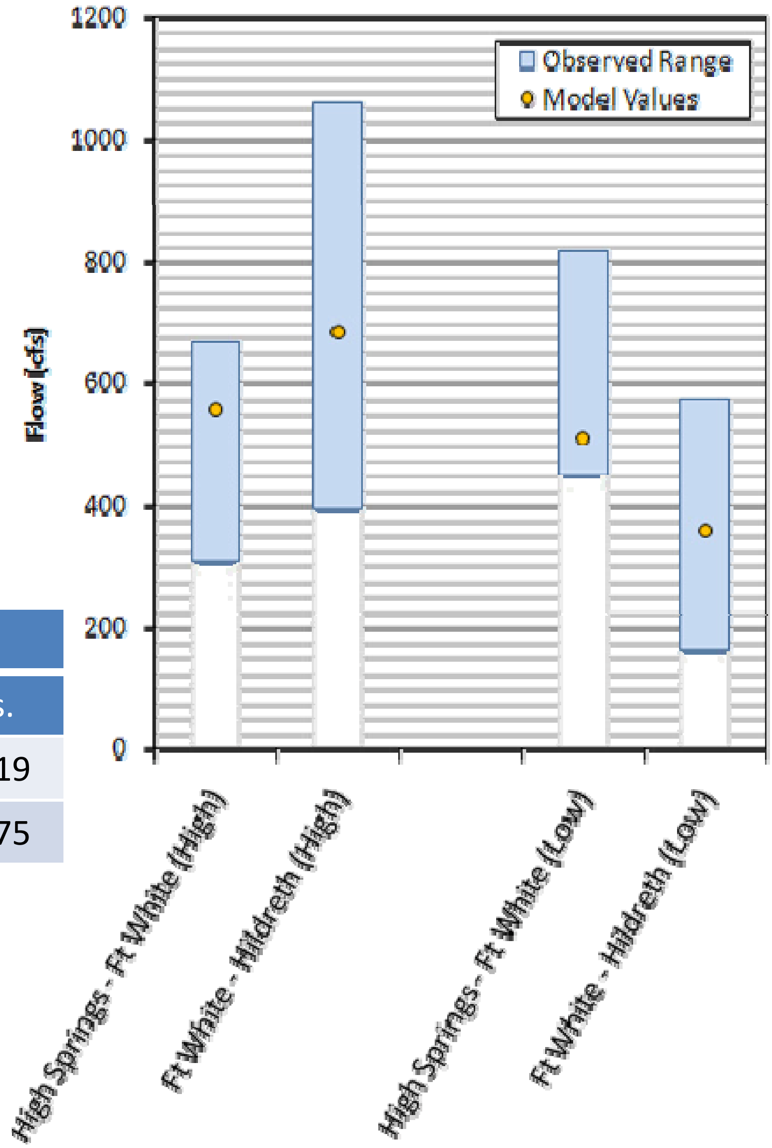
Key Point: Same framework matches high & low flows

Discharge Calibration: *Spring Flows*

	High Water		Low Water	
Spring	Model	Meas.	Model	Meas.
Ichetucknee Head	74	39-73	23	20-24
Cedar Head	14	7-15	0	3-4
Devil's Eye (Ichetucknee)	59	42-77	42	37-43
Blue Hole	246	112-294	80	65-86
Mission Spring Group	128	62-165	70	43-73
Mill Pond	54	6-57	41	14-18
Dogwood	21	21	10	12-14
Ginnie	56	51-18	38	31-39
Gilchrist Blue	71	32-80	36	-
July	106	117	81	-
Poe	79	51-80	12	6
Lilly	44	40	30	-
Rum Island	65	61	82	-
Sunbeam	42	46	13	-
Twin	13	20	12	-
Hornsby/Columbia	286	69-352	110	-
River Rise	784	693*	77	-

Discharge 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

Key Point: Matches both discrete discharges & aggregate gains

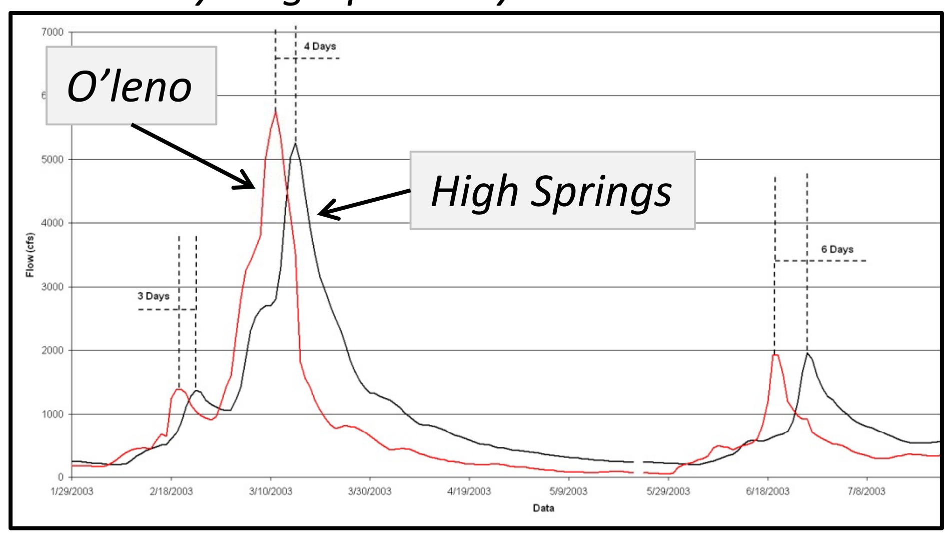
Velocity Calibration

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

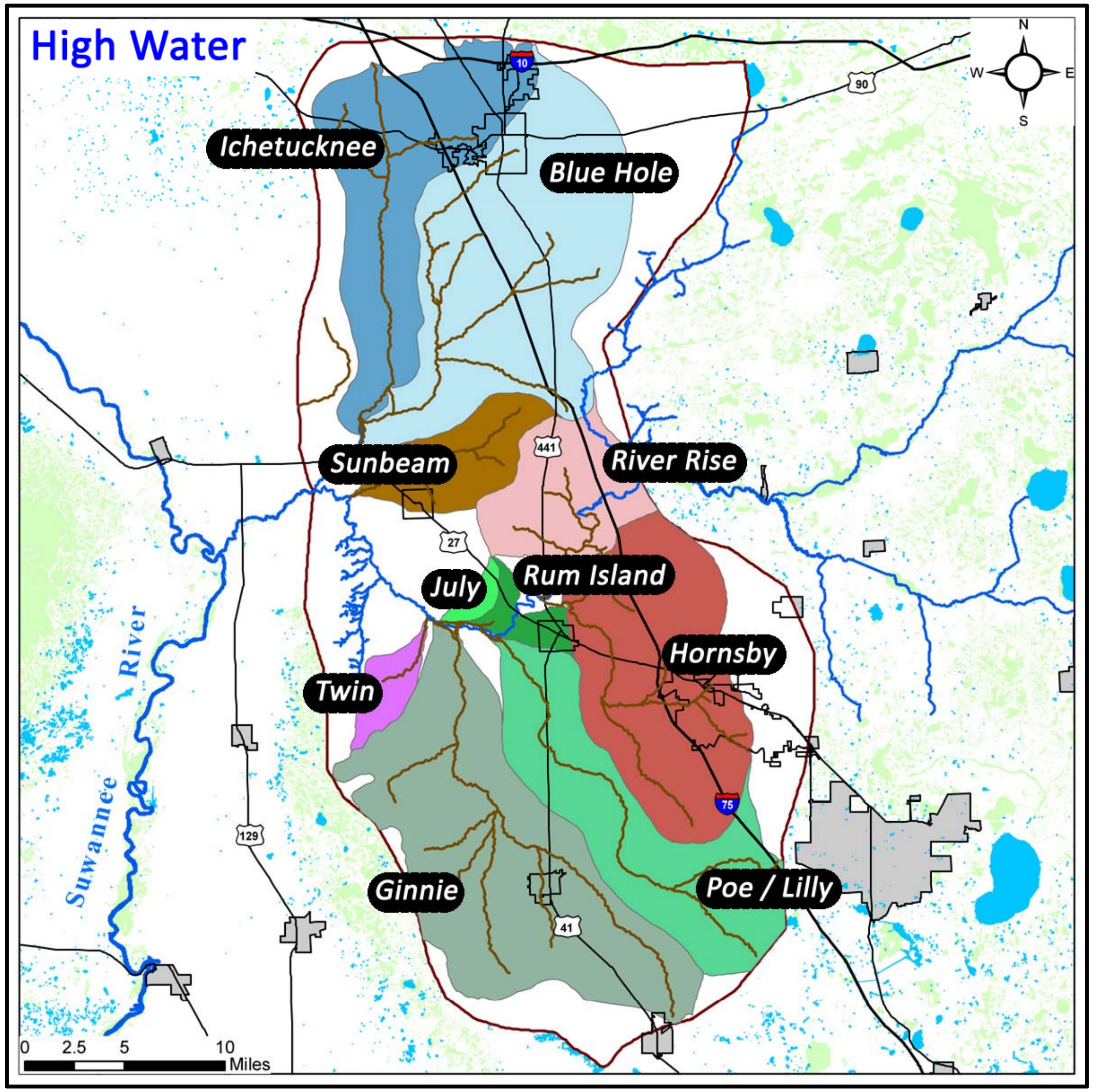


Key Point: Conduit velocities constrained by indirect measurements

Applications: *Springshed Delineations*

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

Spring Group	High	Low
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



Key Point: Model has defined springsheds based on flow

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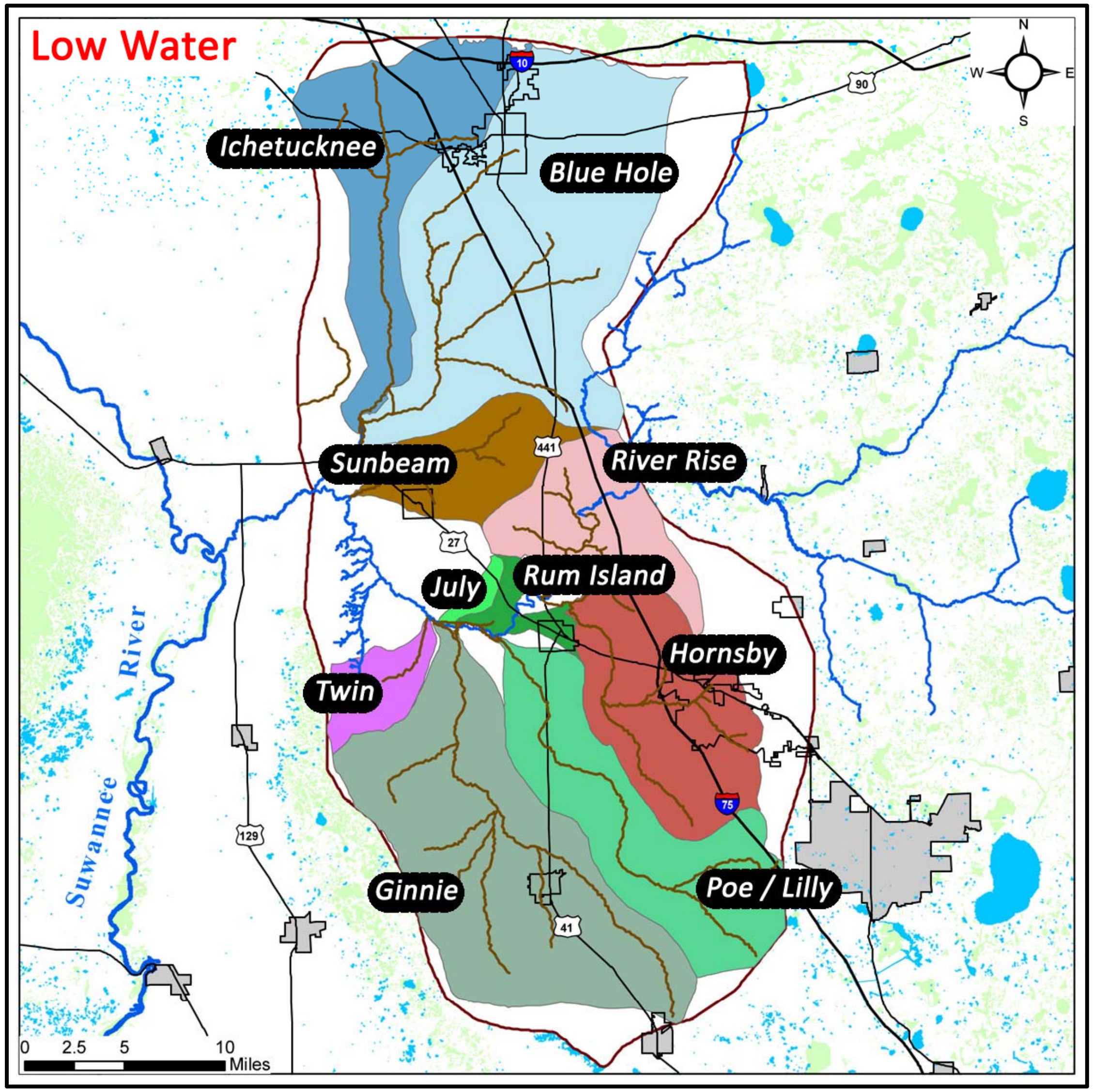

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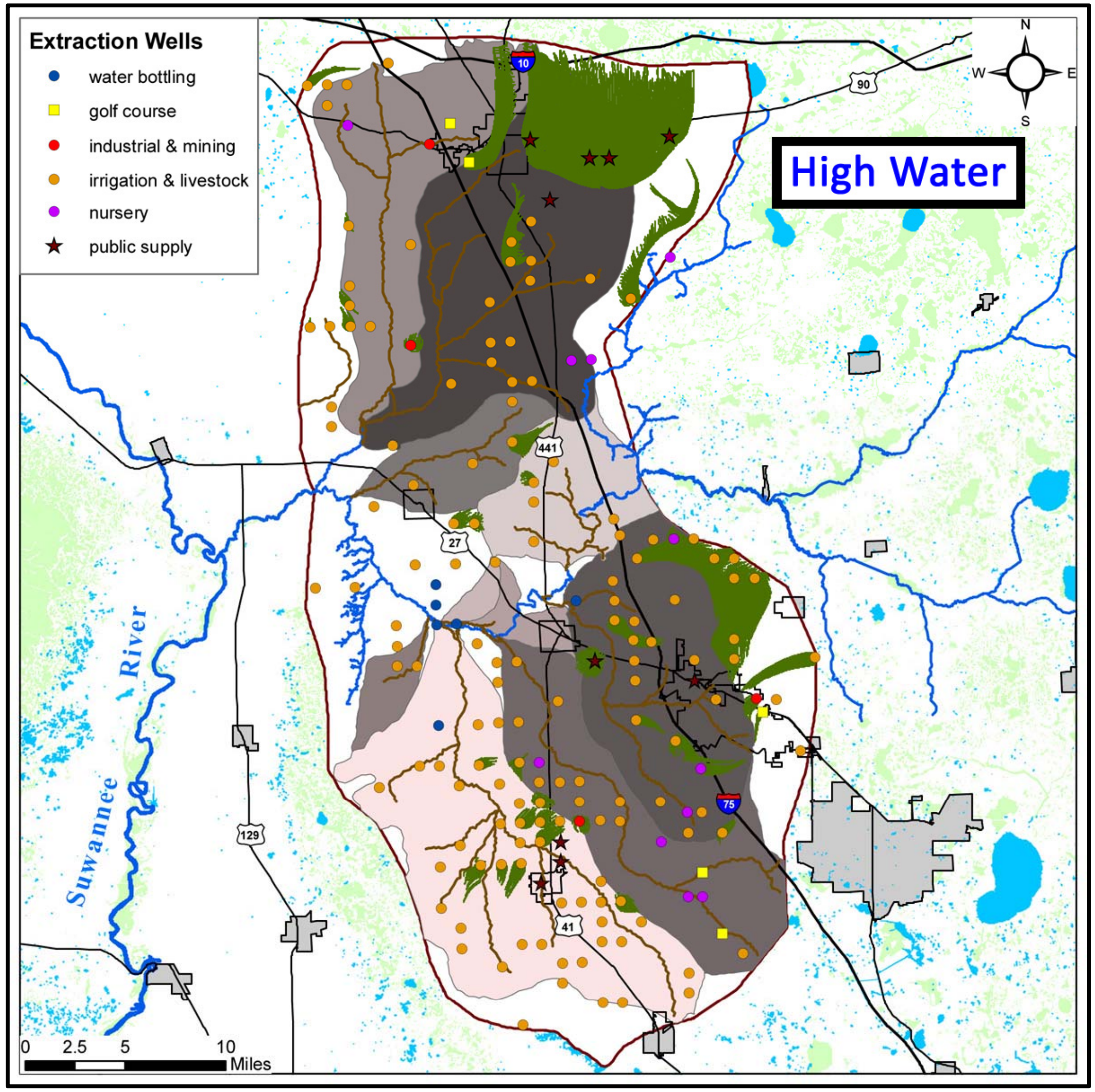
Applications: *Springshed Delineations*

Spring Group	High Water Area/Flow (km^2/cfs)	Low Water Area/Flow (km^2/cfs)	Change (km^2/cfs)	% Change
Ginnie / Blue / July	407/253	425/165	+18/-88	+4/-35
Blue Hole Group	377/427	488/190	+111/-237	+29/-55
Hornsby / Columbia	274/286	210/110	-64/-176	-23/-62
Ichetucknee	248/147	222/64	-27/-83	-11/-56
Poe / Lilly / Rum Island	261/188	267/124	+5/-64	+2/-34
River Rise	116/784	134/77	+18/-707	+15/-90
Sunbeam	80/42	103/13	+23/-28	+28/-68
Twin	29/13	49/12	+21/-2	+73/-11

Key Point: Loosing swallet inflows significantly impacts springsheds

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%



Key Point: Model simulates pumping impacts under varying conditions

Applications: *Pumping Impacts*

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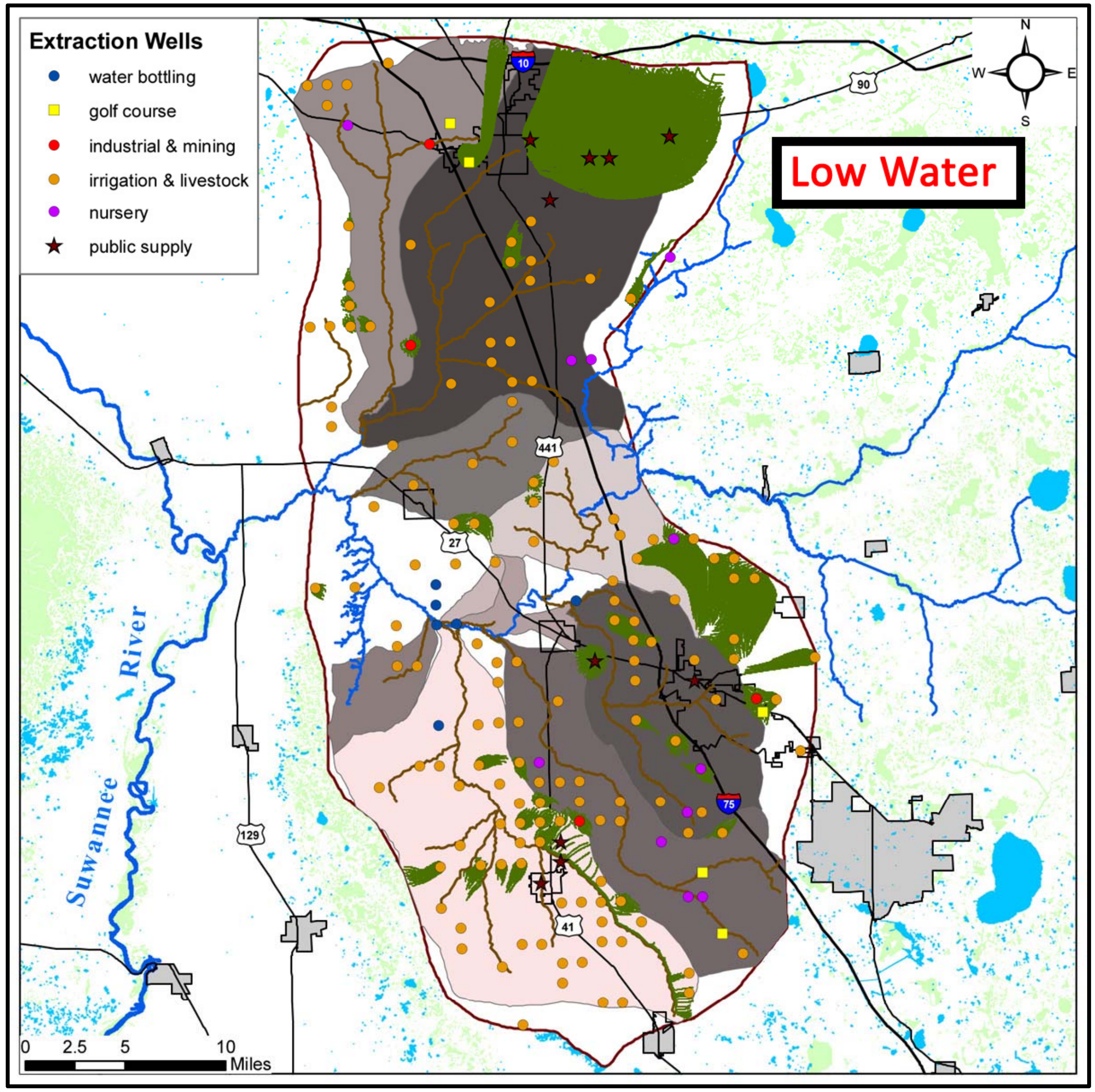
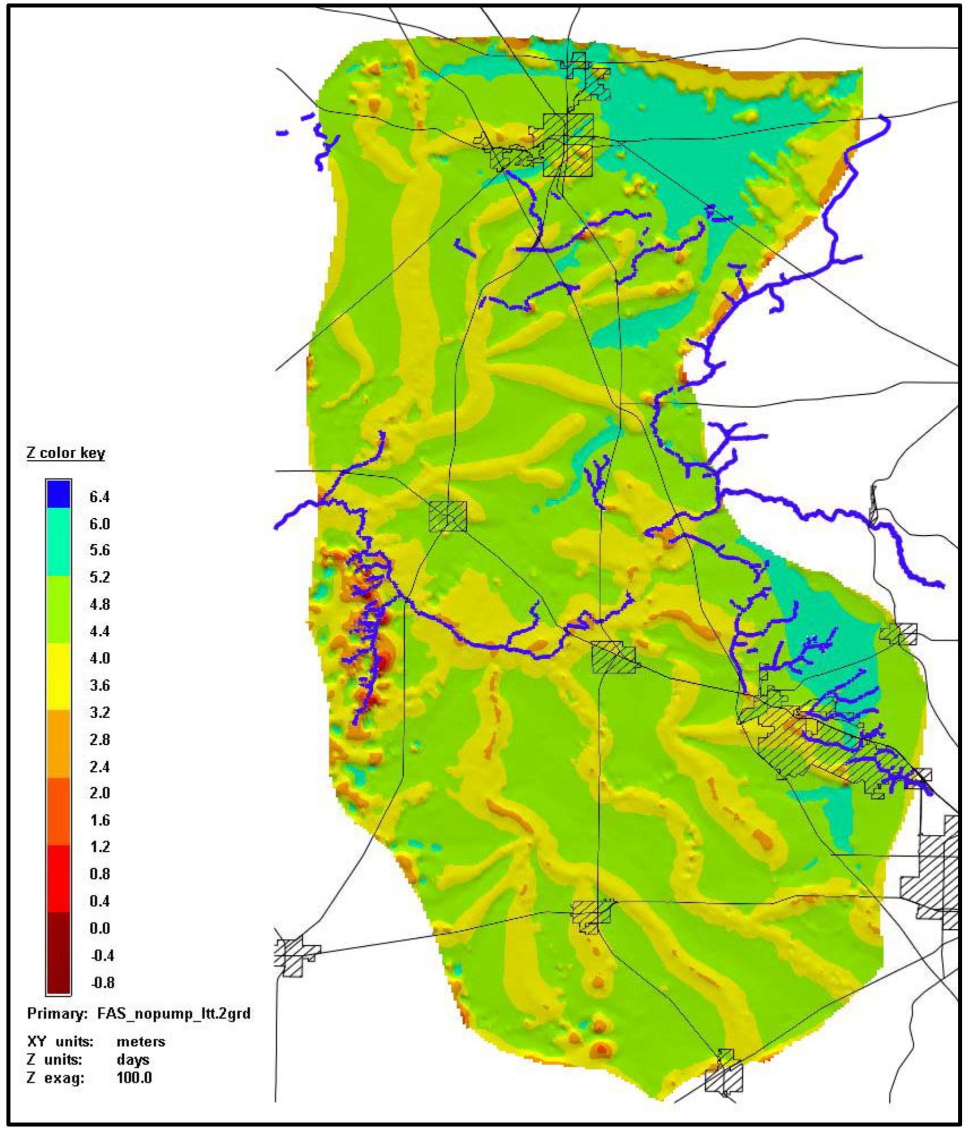


Key Point: Model simulates pumping impacts under varying conditions

Applications: *Aquifer Vulnerability*

- Forward particle tracks used to delineate time of travel in FAS from all points in springsheds to the springs.
- No perceptible change from high water to low water conditions.
- Highest vulnerability zones (fastest travel-times) create zone around conduits.
- Distance to conduits far more important than distance to spring.



Key Point: Model travel-times equate to aquifer vulnerability

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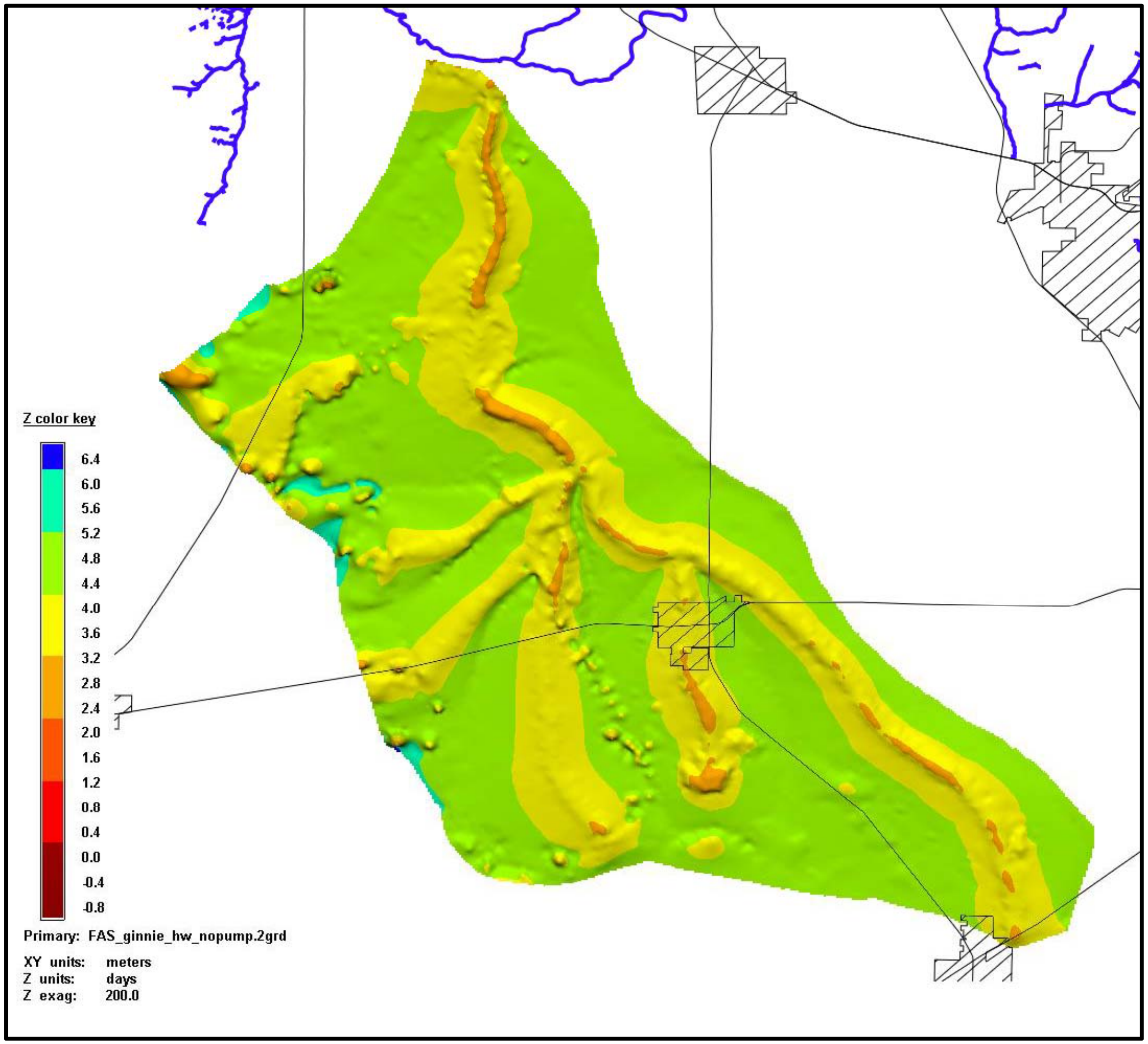
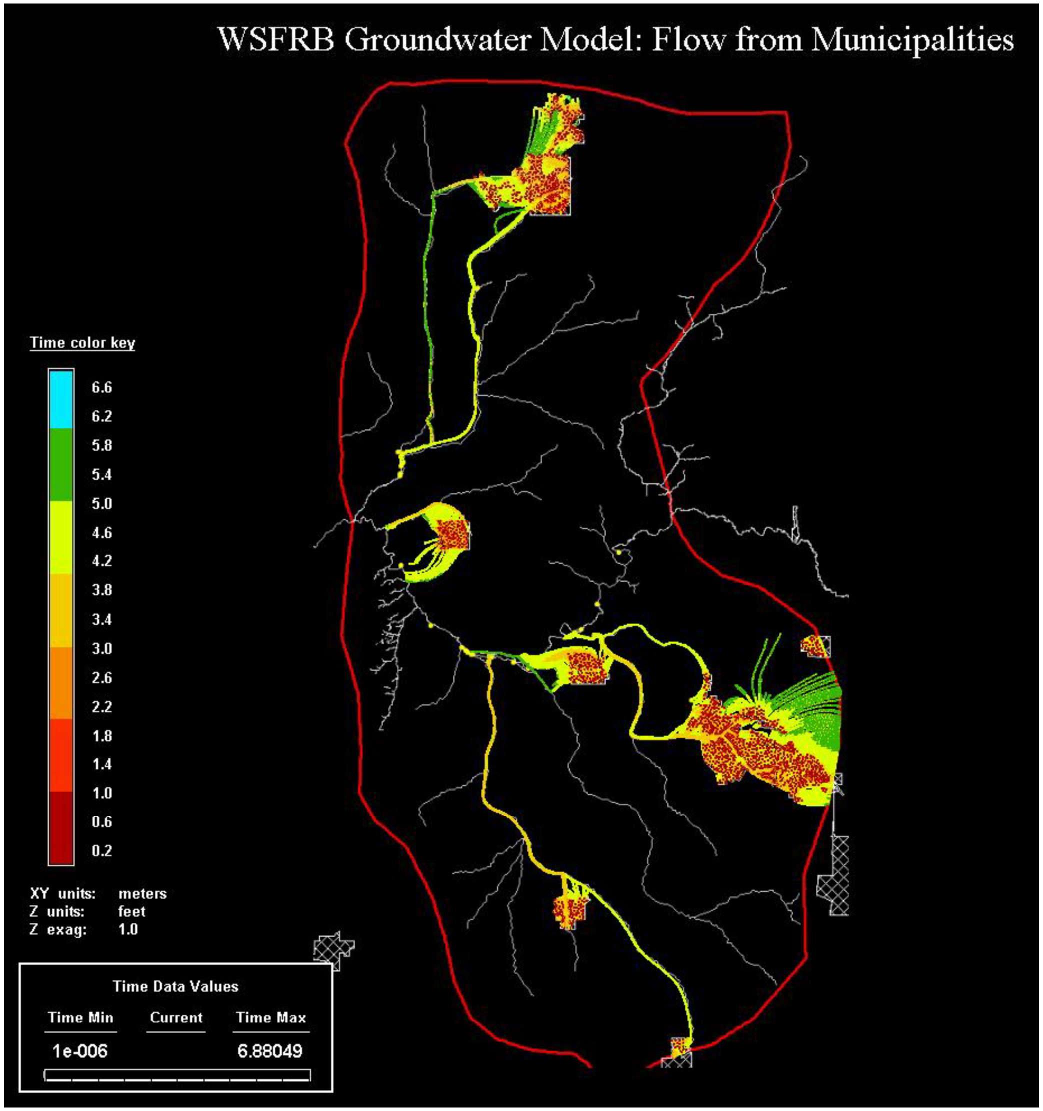


Key Point: Model travel-times equate to aquifer vulnerability

Applications: *Particle Tracking- Transport*

- 3D Particle tracks used to evaluate transport from specific locations.
- 3D particle tracks exported from FEFLOW to EarthVision for visualization & analysis.
- Emphasizes significance of conduits – distance from spring far less important than distance from conduits.
- Visualizations created by seeding area municipalities and evaluating particle tracks / time of travel.
- Produces worst-case scenario – no dilution or retardation.
- Some tracking problems associated with dual permeability architecture.



Key Point: Flow model can be used to evaluate potential transport

Applications: *Particle Tracking - Transport*

Tracking water flow from municipalities in the Santa Fe River Basin, Florida

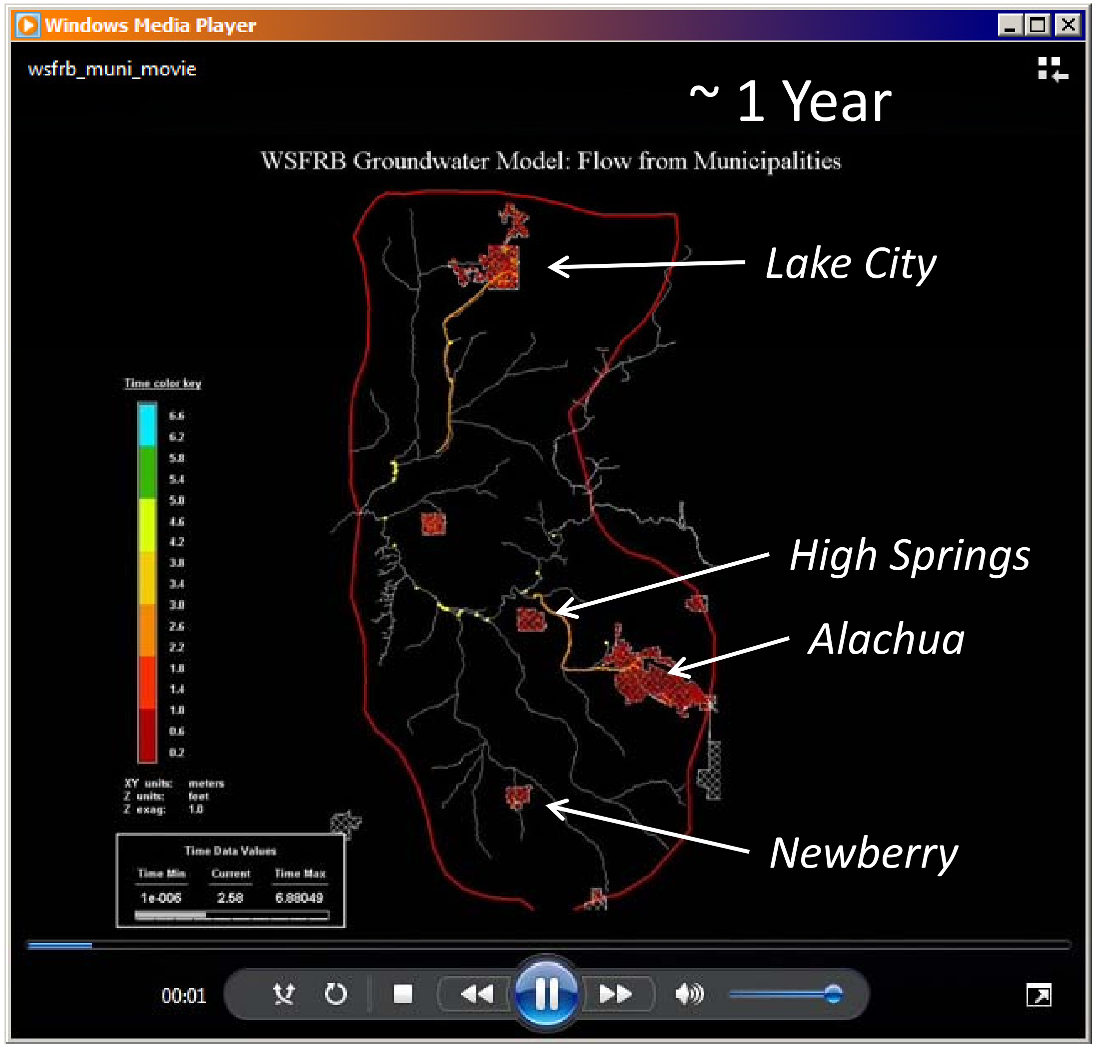
Flow is to closest conduits

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*



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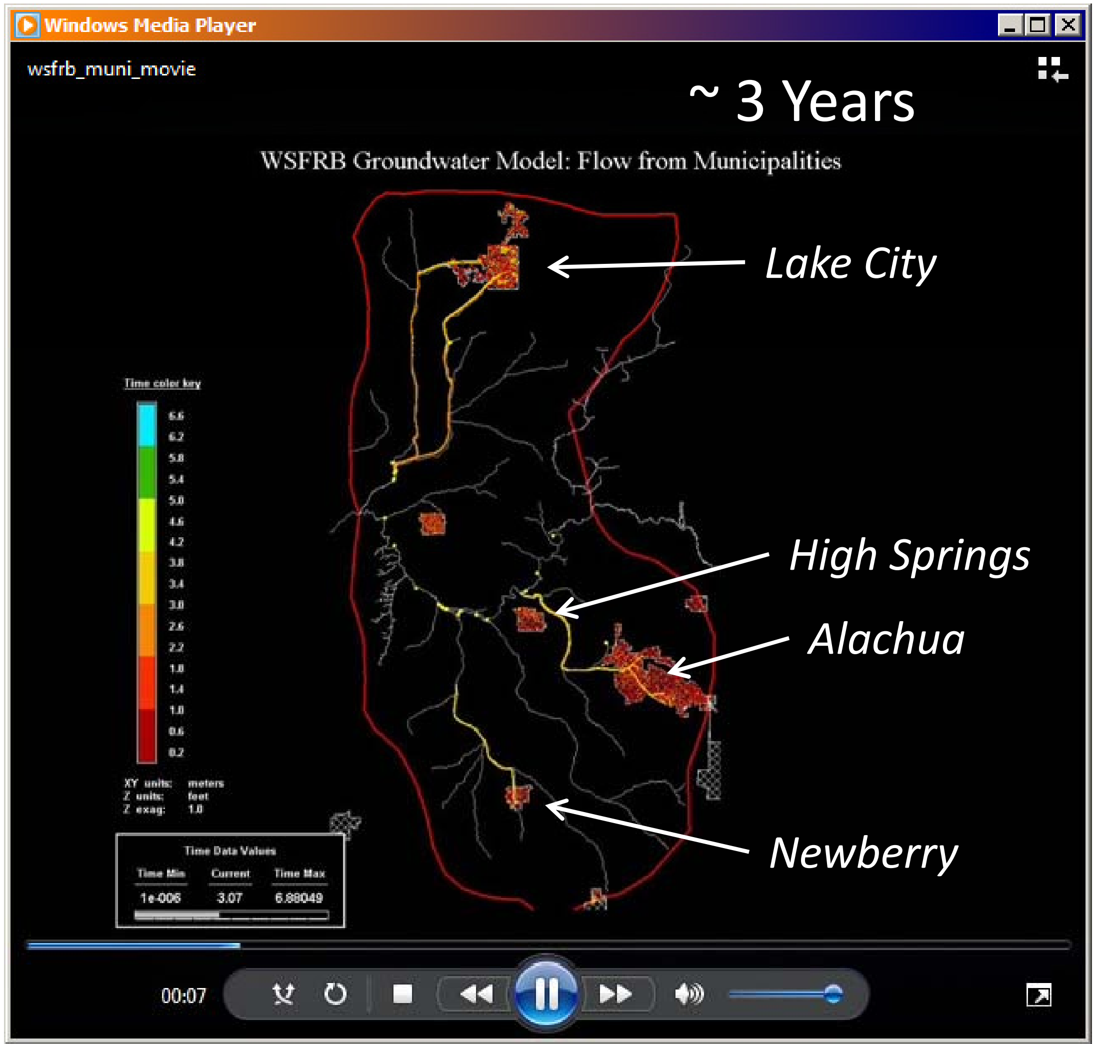

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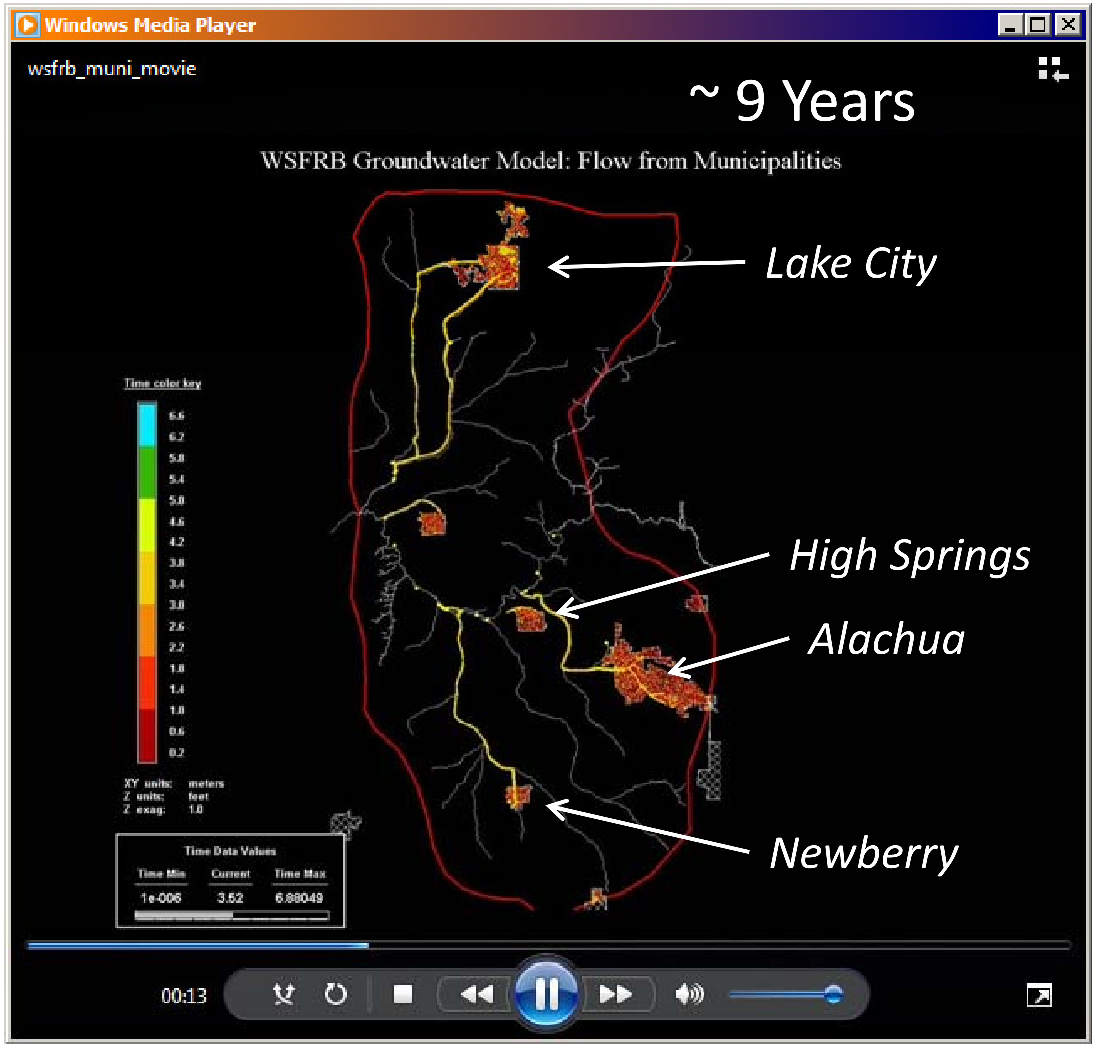

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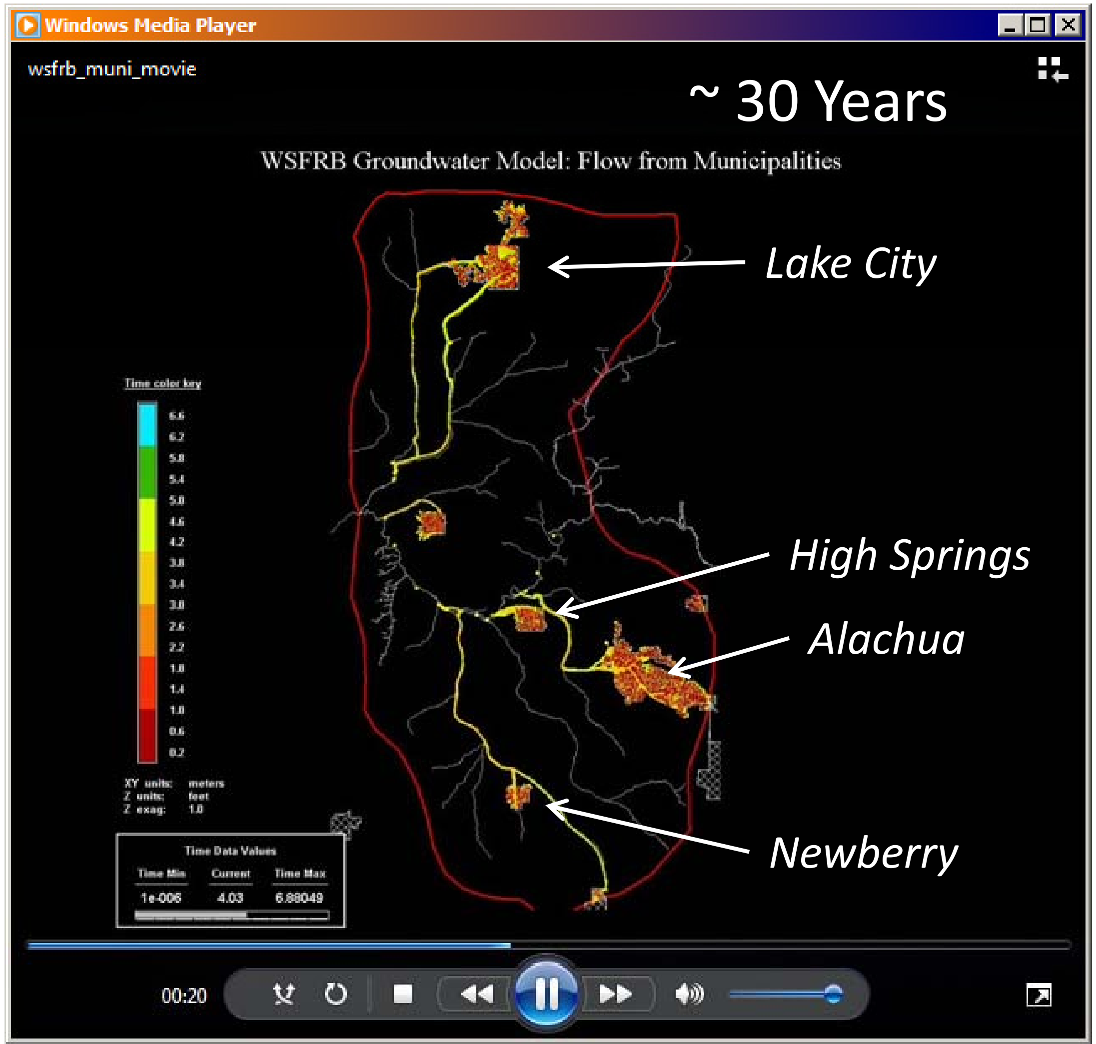

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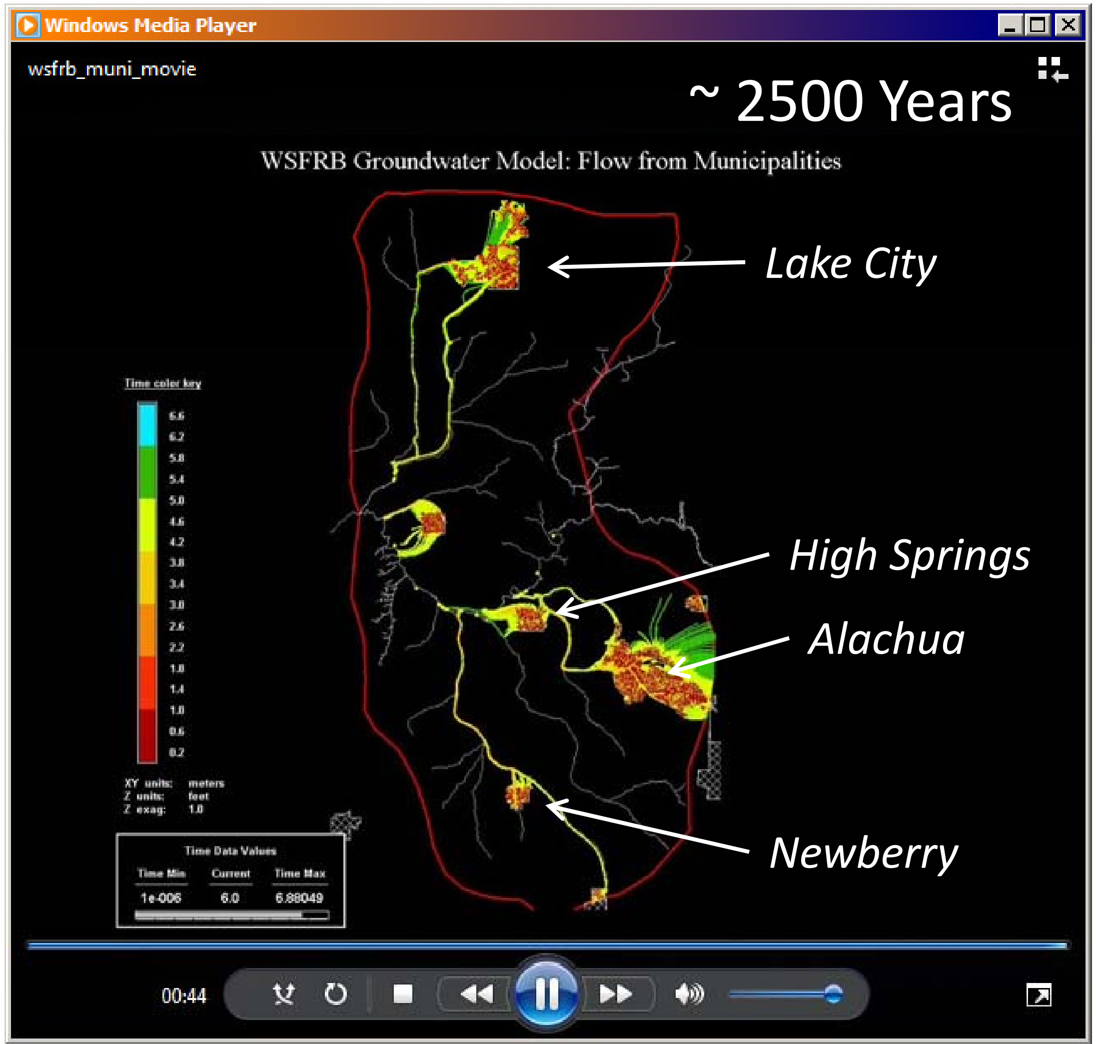
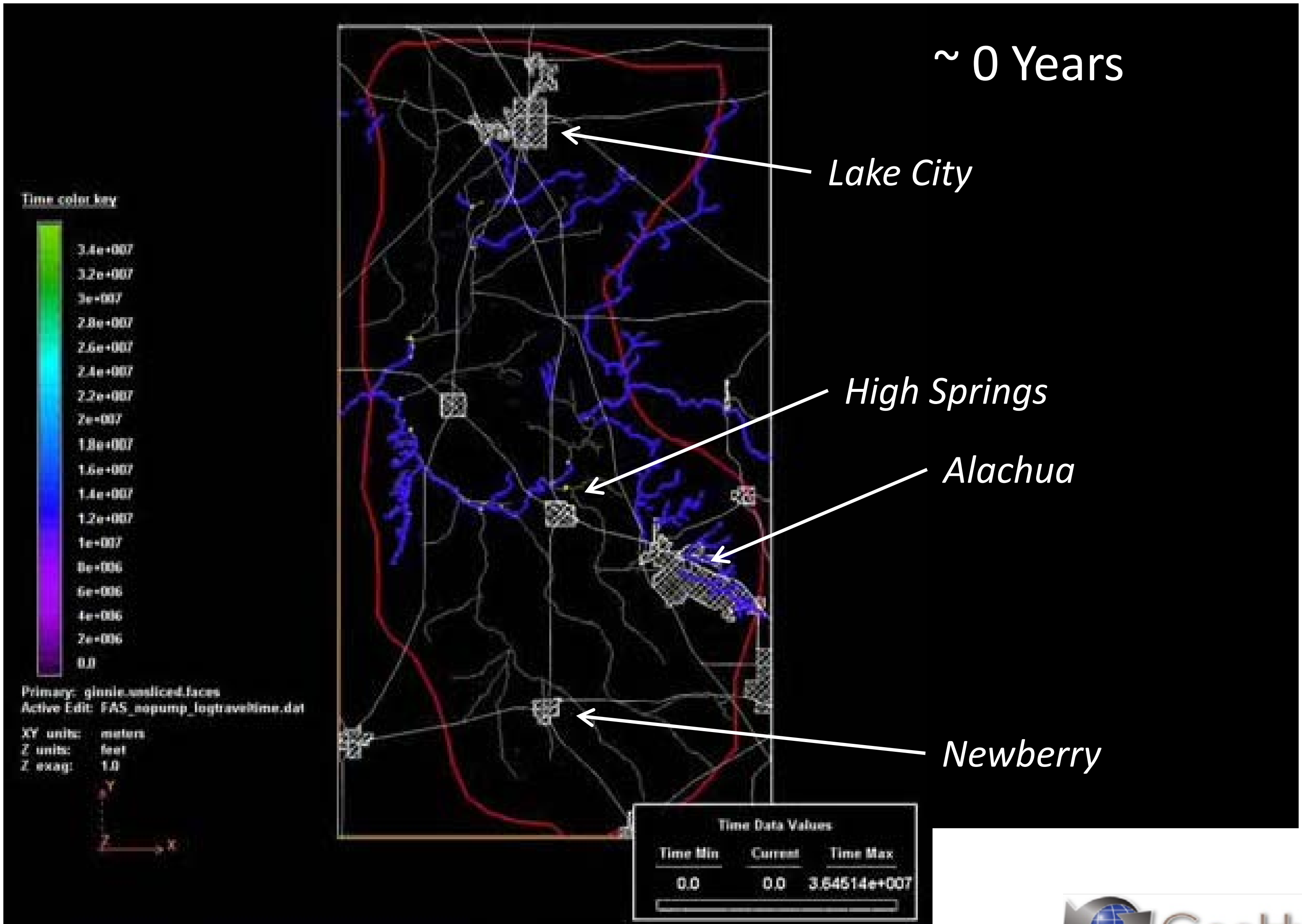


Key Point:

Applications: Springs Vulnerability

Travel-time to discharge from points within the Santa Fe River Basin, Florida



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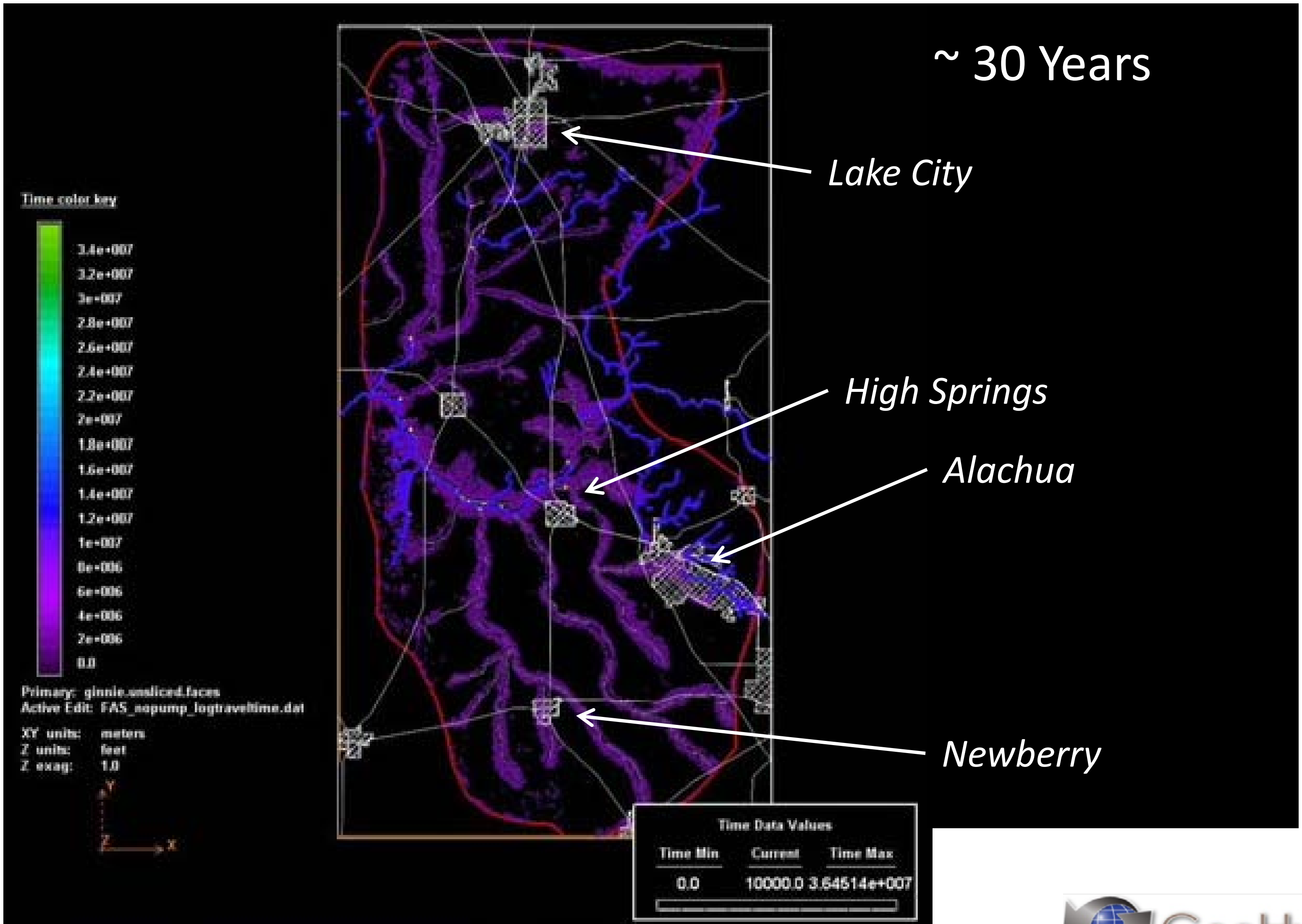

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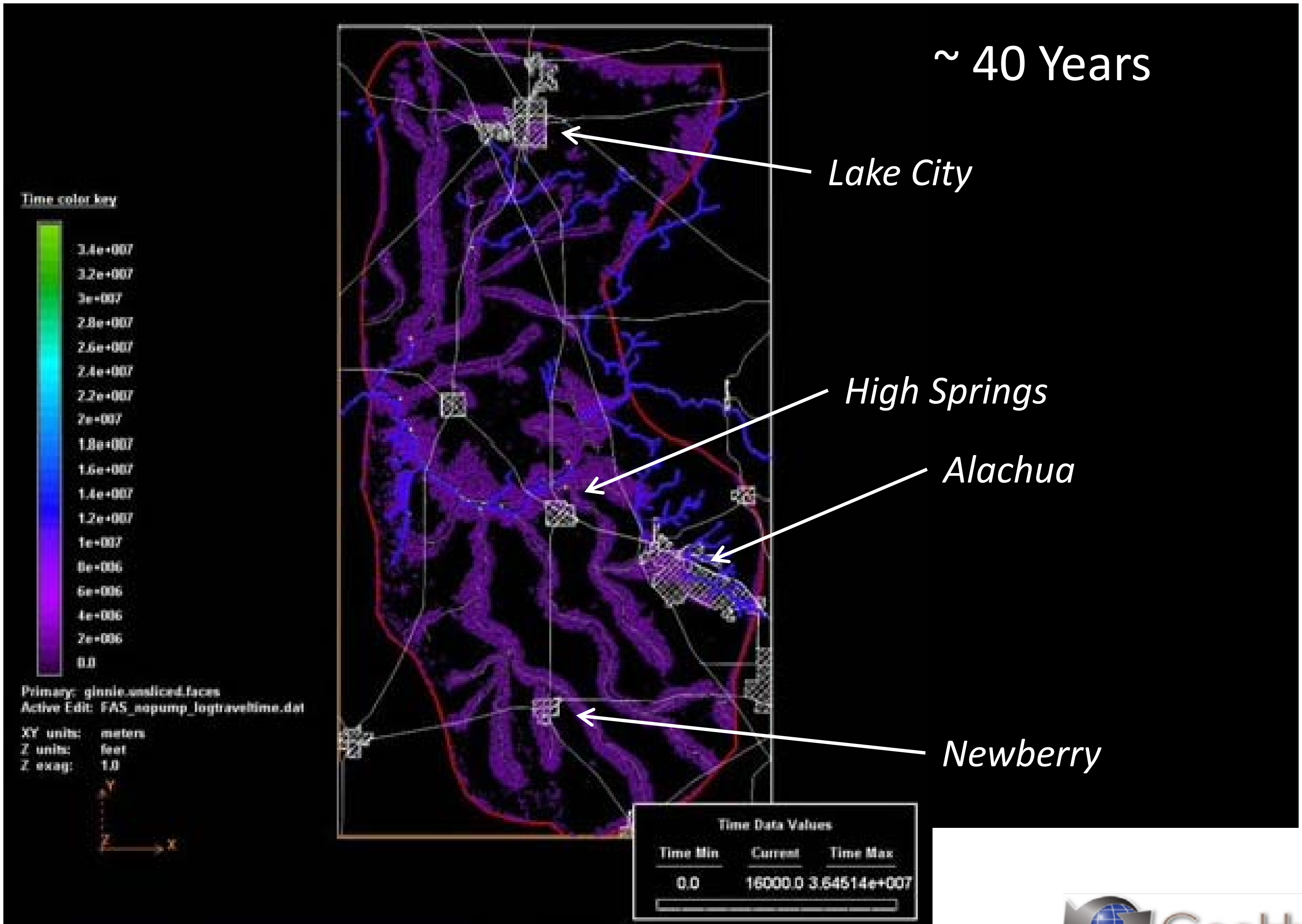

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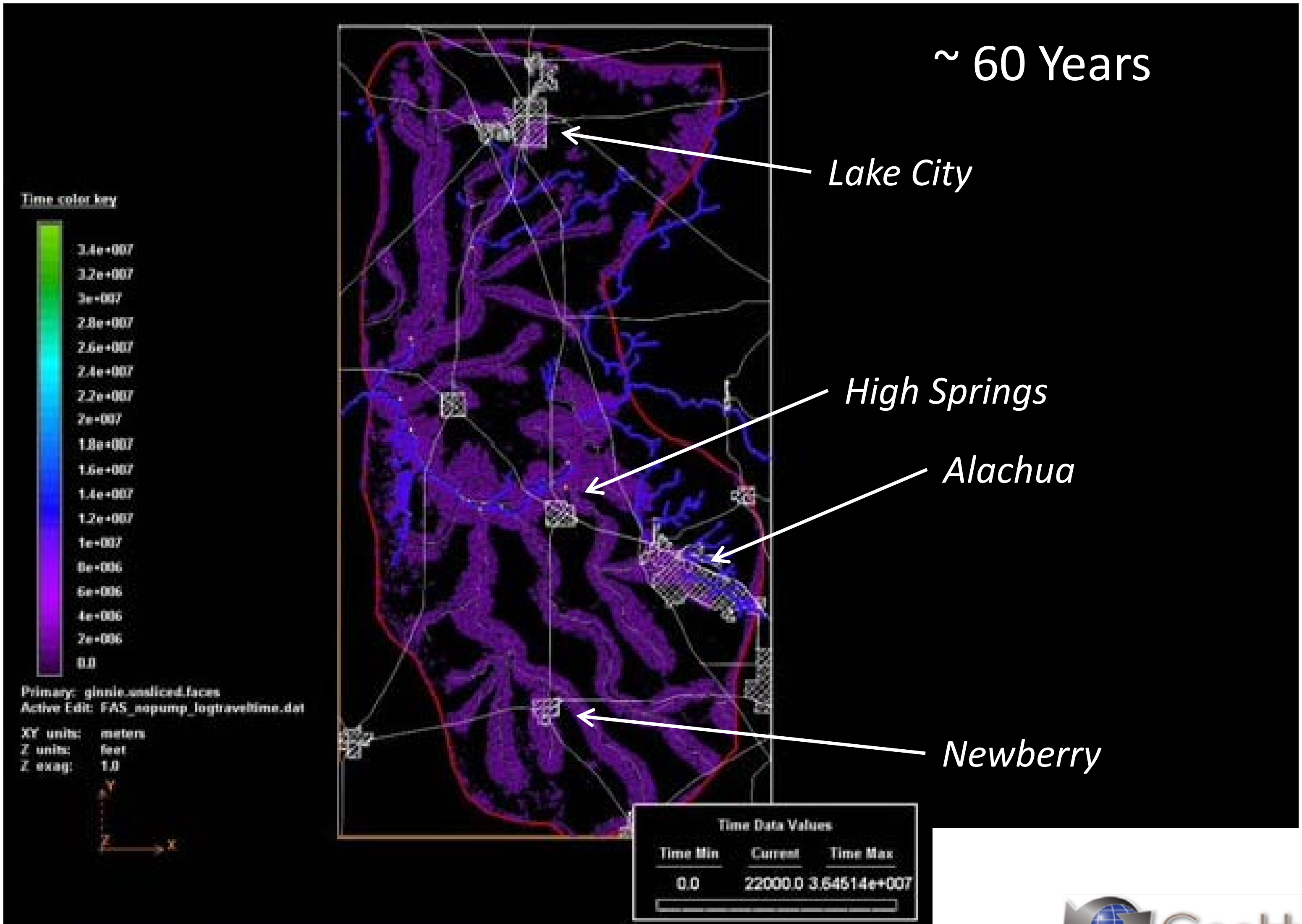

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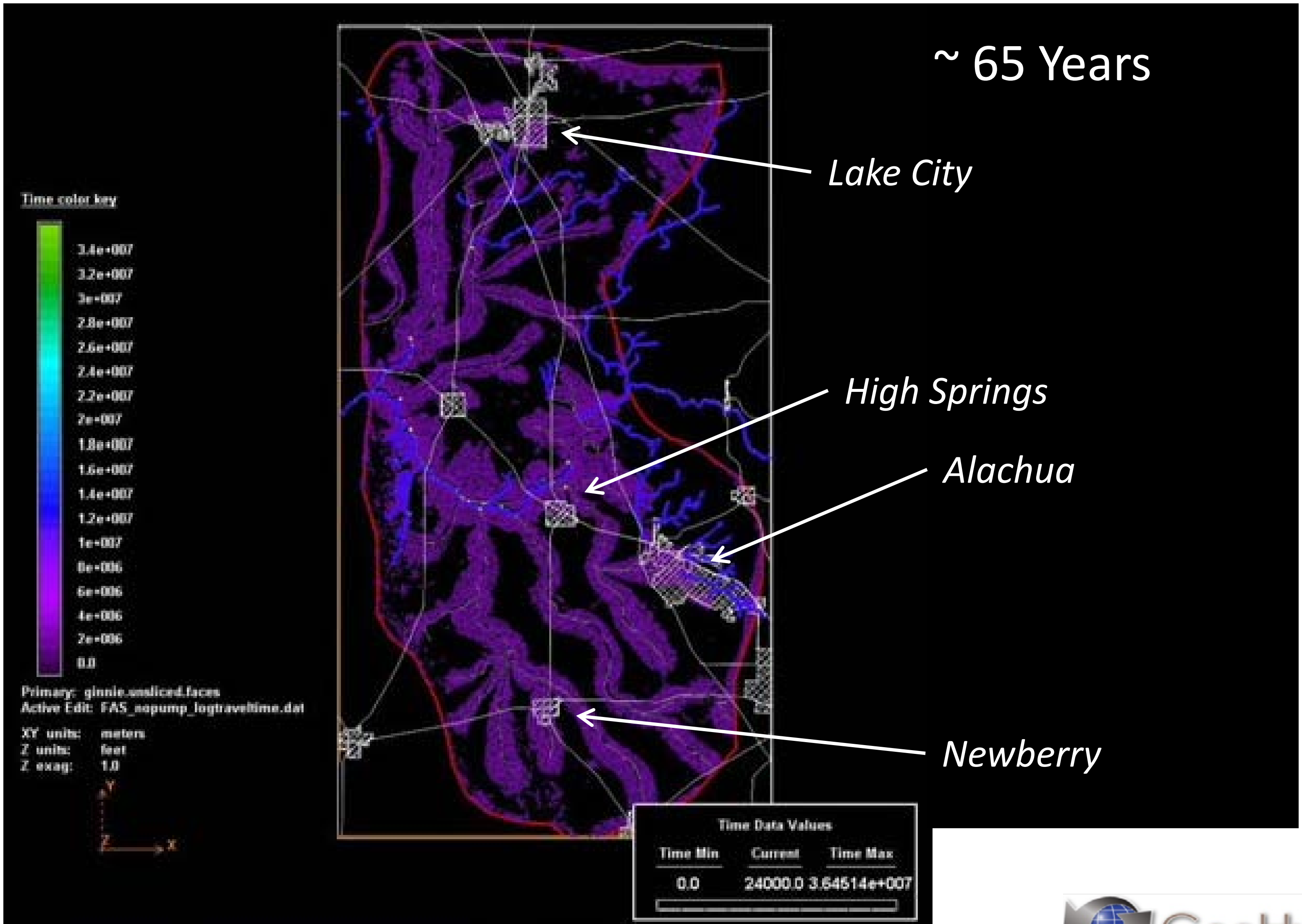

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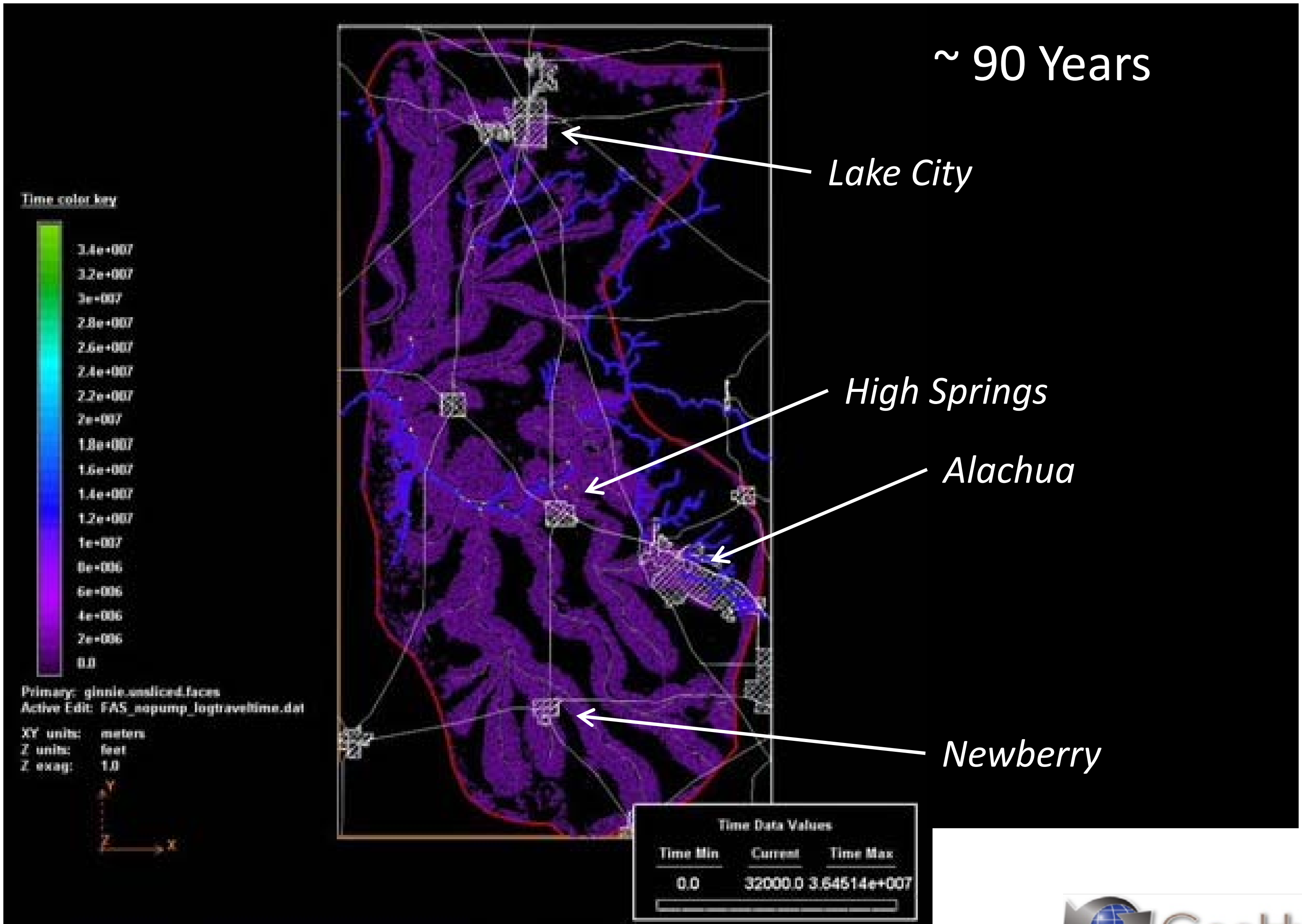

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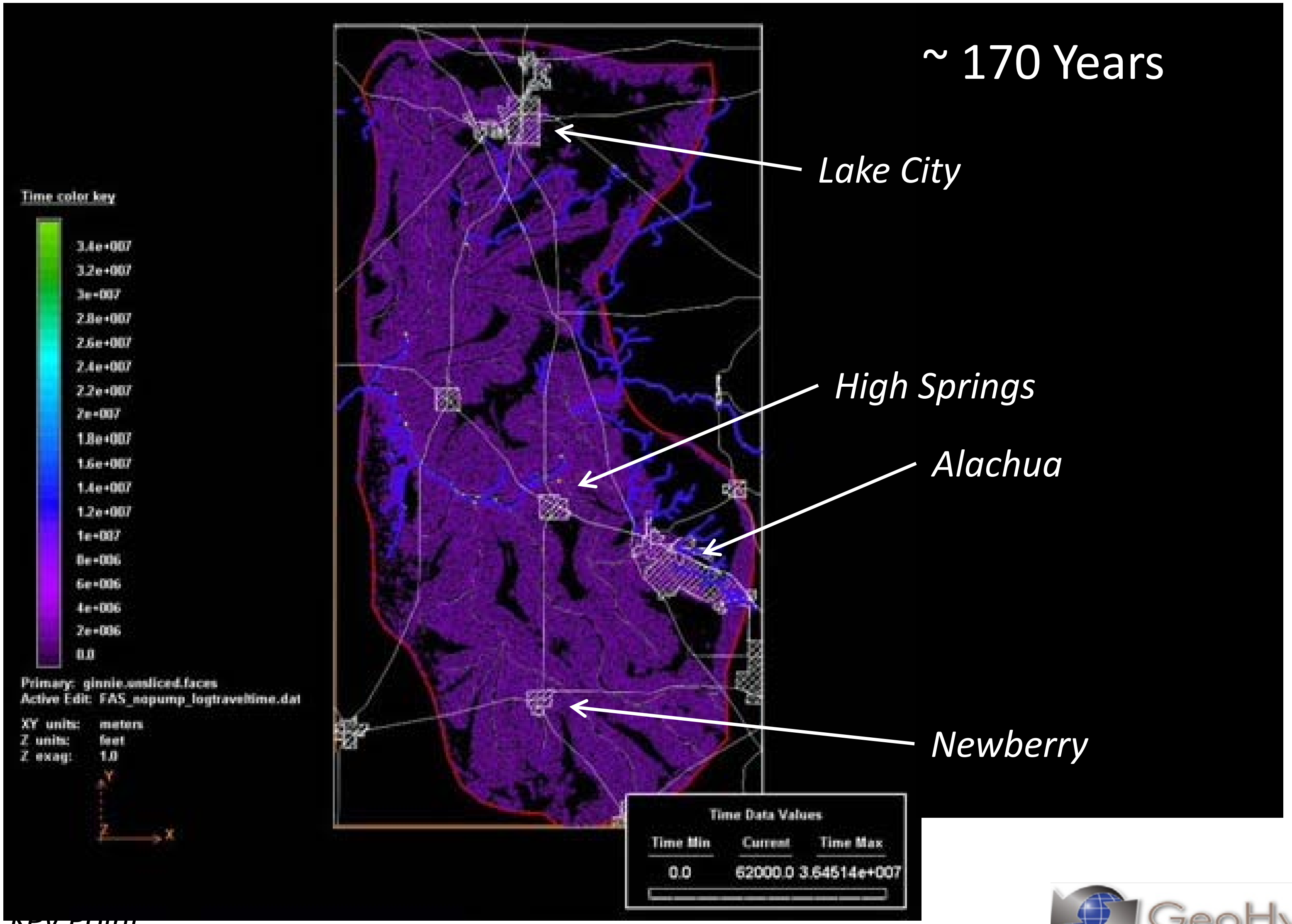

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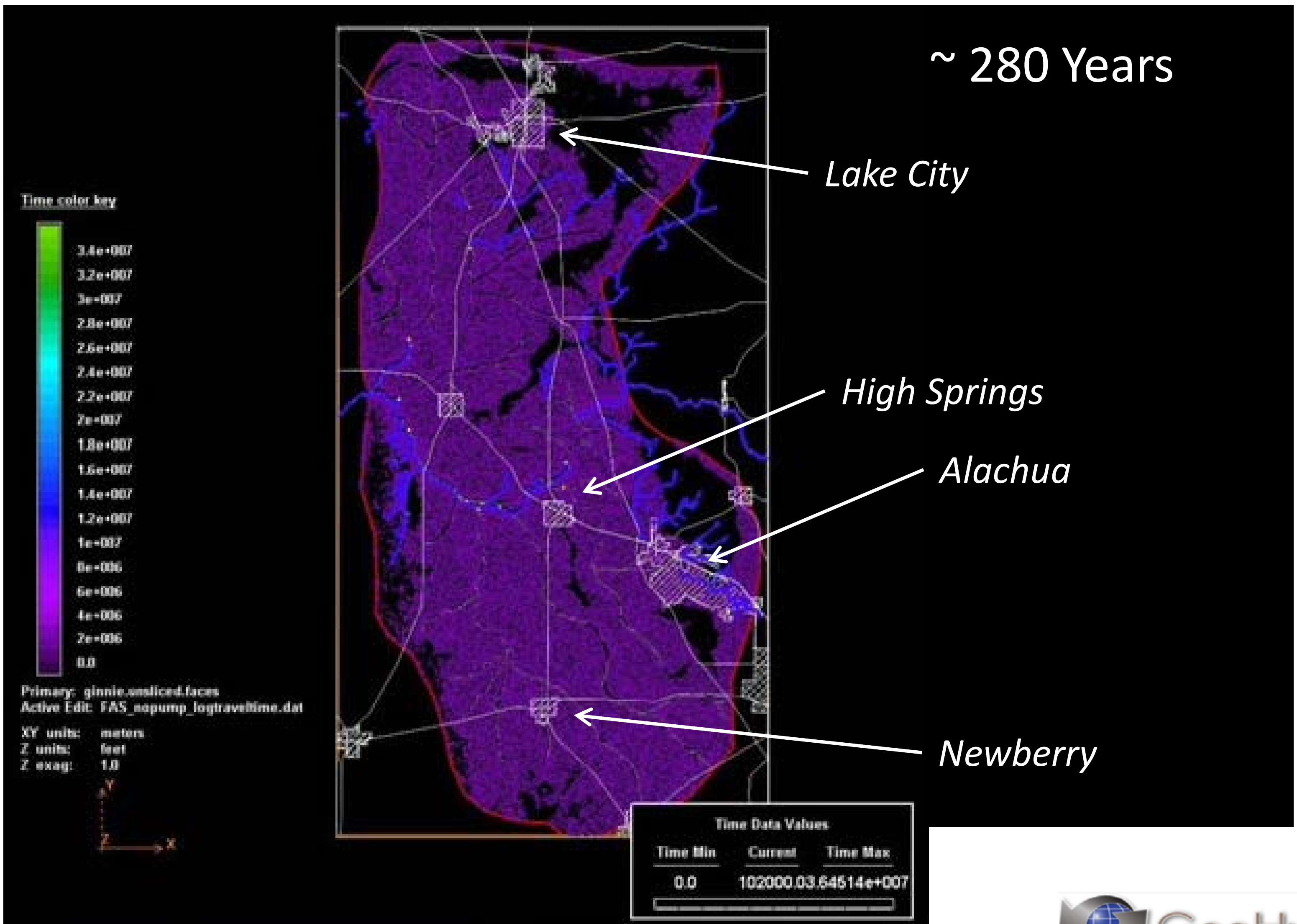


Key Point:

Future Model Applications

- Scenario analyses
  - Development proposals
    - Municipality growth & expansion
    - Land-use changes (agriculture – residential)
    - Mining
  - Flood / drought >> already have those
- Groundwater pumping impact analysis
- Fate & Transport
  - Management level
    - Point source
    - Non-point source
  - Applicant level
    - Independent model development
    - Existing model analysis
- Transient Analyses
  - Event specific predictions
  - Higher resolution time-scale predictions

Key Point: Existing model can be adapted for several applications

DISCUSSION

Data Synthesis & Model Setup

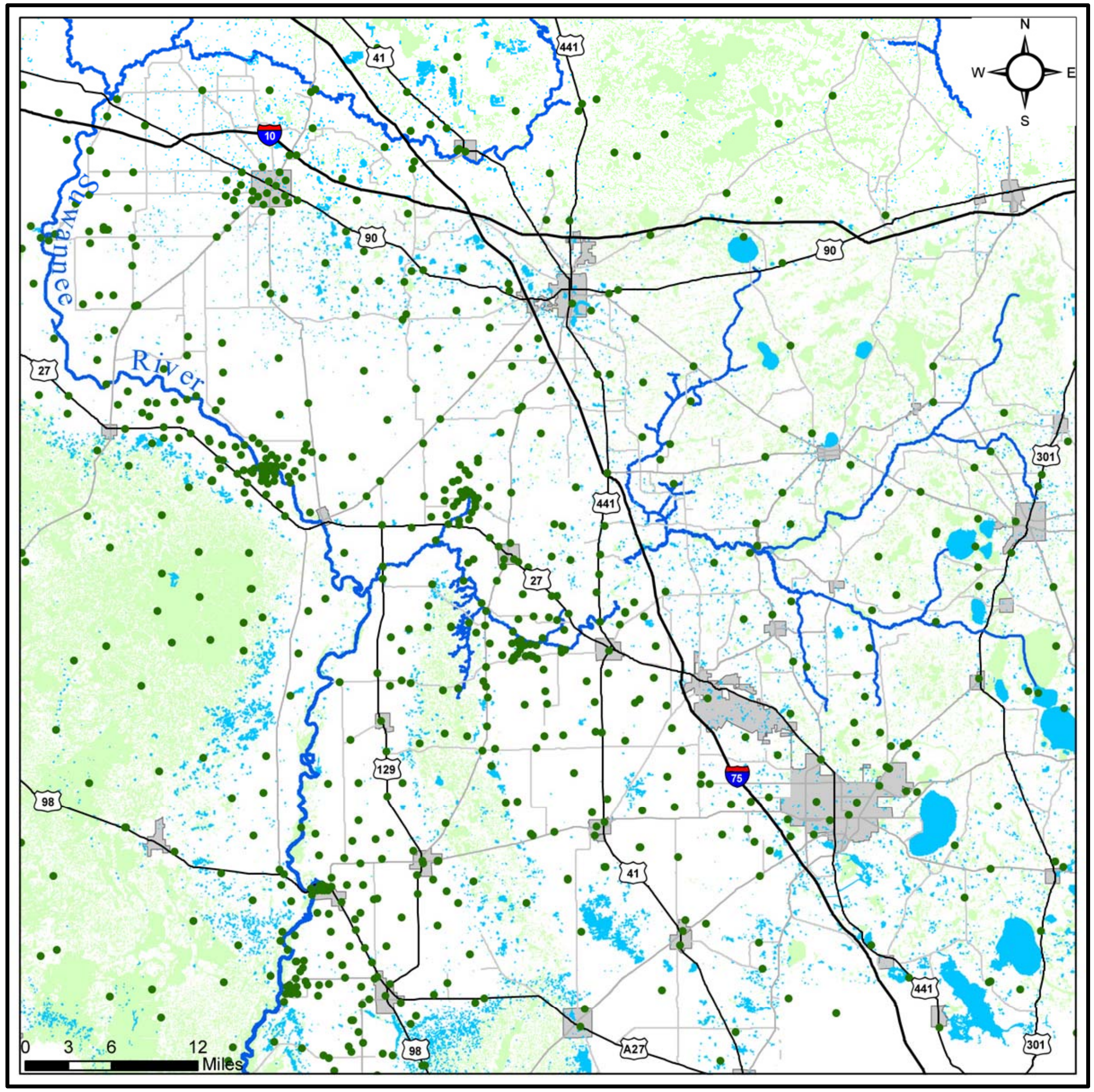
Brent Meyer, M.S.
GeoHydros, LLC
Reno, NV

M.S. – Univ. of Nevada, Reno
Hydrogeology & Geochemistry
Modeler @ H2H for 5 years

- Groundwater levels (high water & low water conditions)
- Geologic framework
  - Borehole logs
  - Geologic maps
- Hydraulic conductivity
  - Geologic basis
  - Calibrated assignments
- Conduit assignments
  - Caves
  - Tracer tests
  - Potentiometric surface

Compilation of Groundwater Level Data

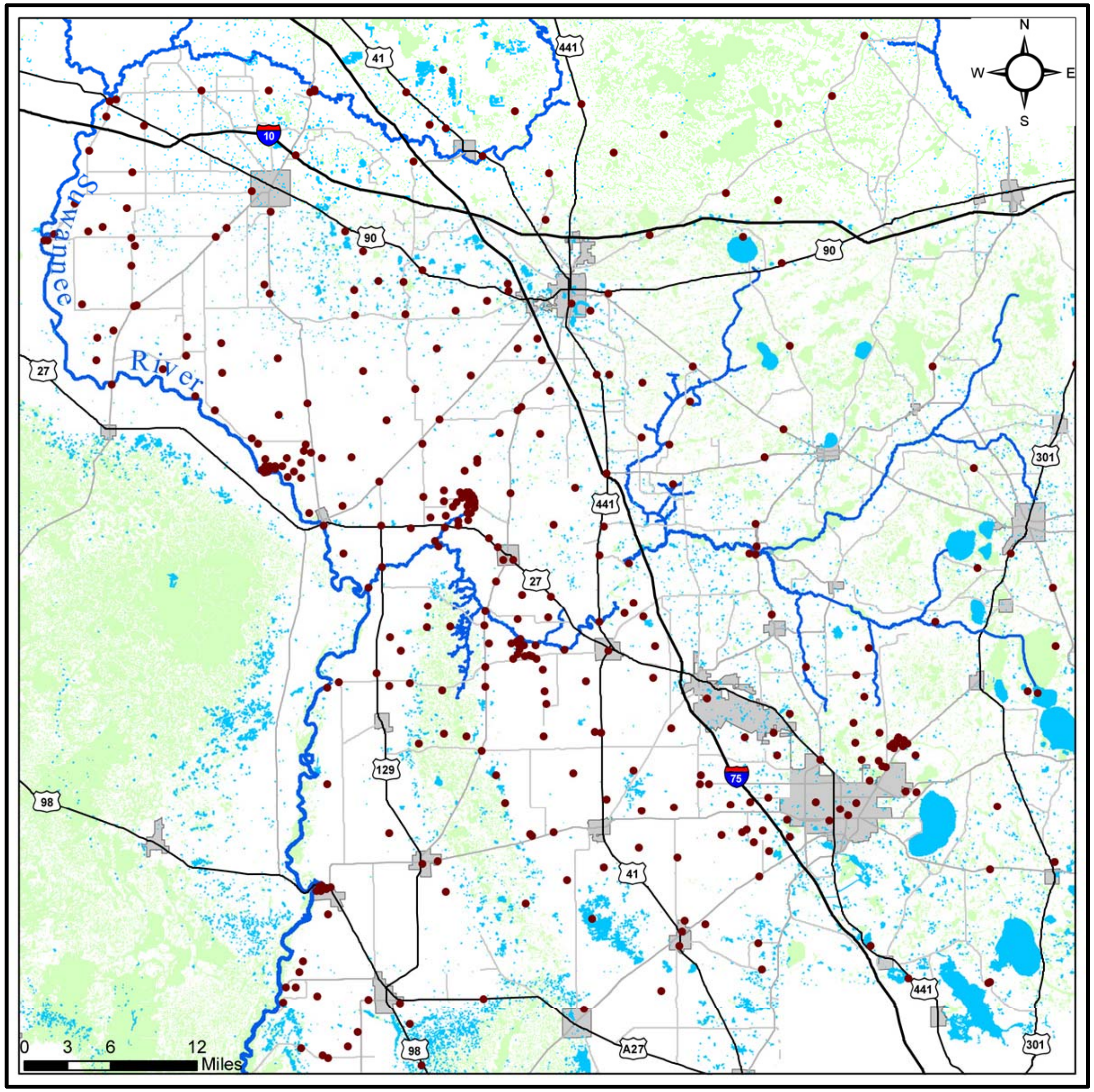
- Total wells east of Suwannee River = 691
- SWRWM = 484
- ACEPD = 174
- KES = 21
- SRWMD & ACEPD = 6
- ACEPD & KES = 6
- Wells in model area = 250



Key Point: Data compiled from area much broader than model area

Synthesis of High Water Dataset

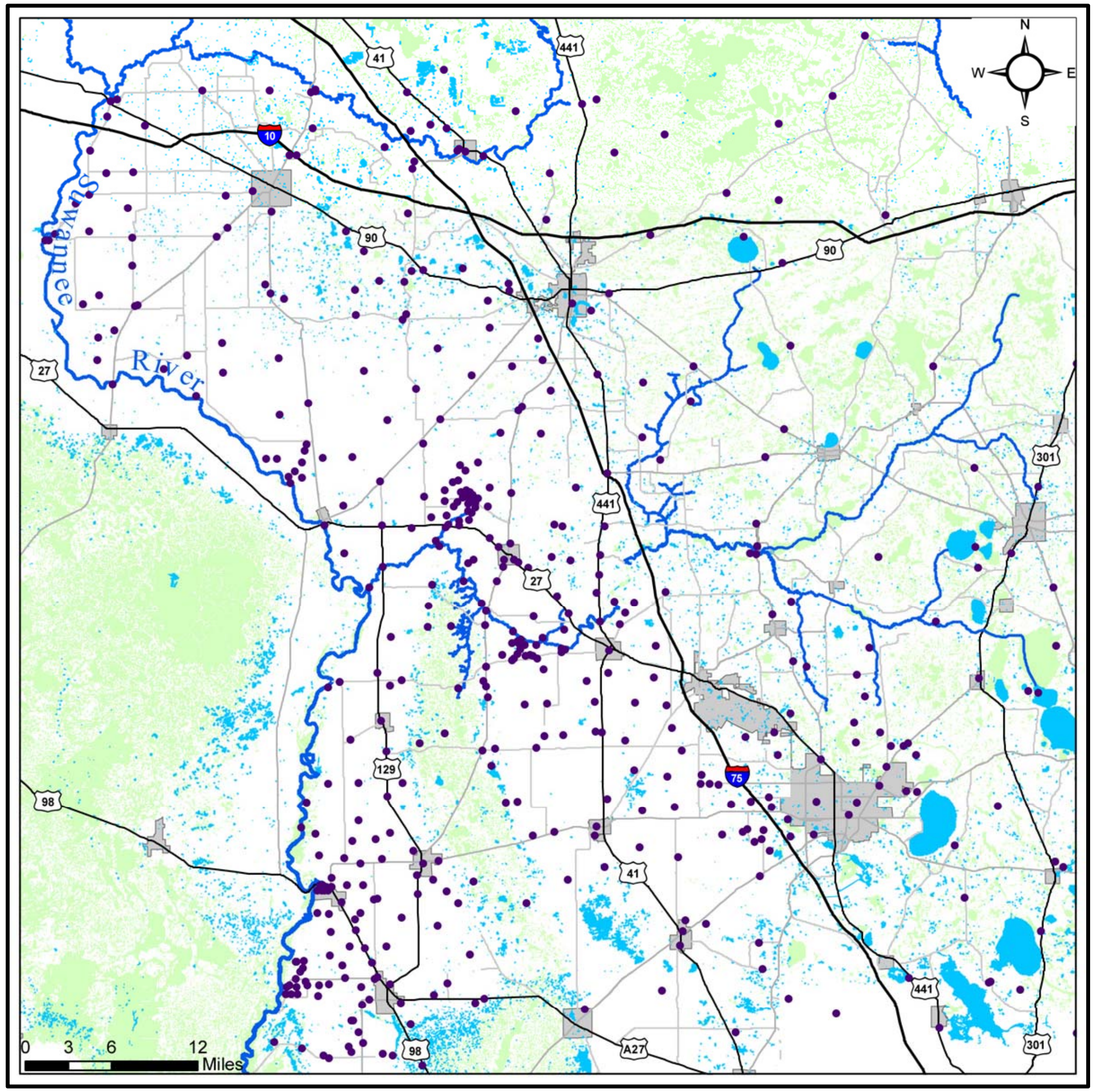
- Evaluated all available head data
- Identified highest water periods as:
  - Jan 1998 – May 1999
  - Oct 2004 – Dec 2005
- Total wells with data for those periods = 396



Key Point: Calibration dataset is compilation of high water records

Synthesis of Low Water Dataset

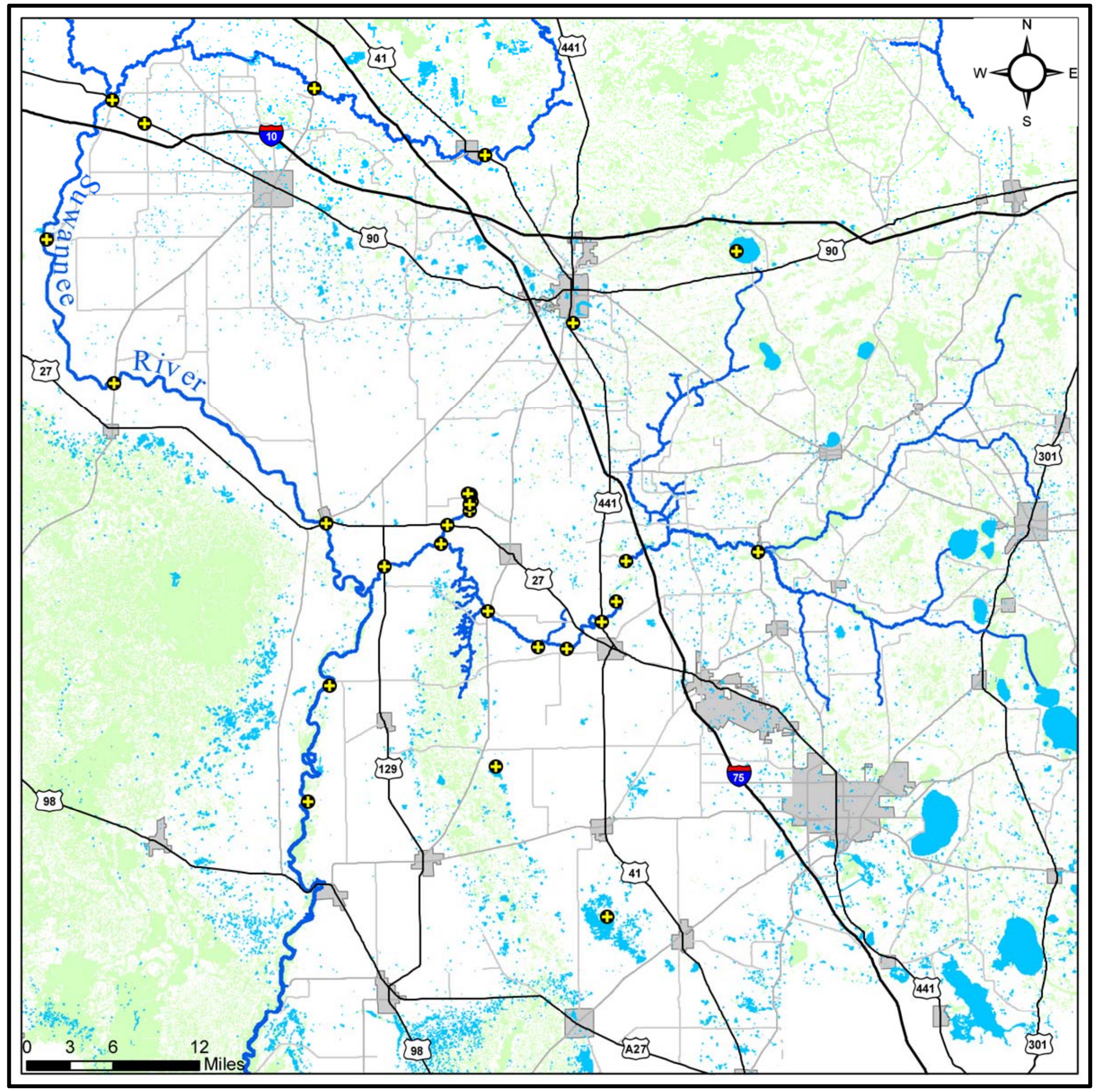
- Identified lowest water periods as:
  - Jan 2001 – Dec 2002
  - May 2007 – Oct 2007
- Total wells with data for those periods = 571



Key Point: Calibration dataset is compilation of low water records

River, Lake, and Spring Stage Data

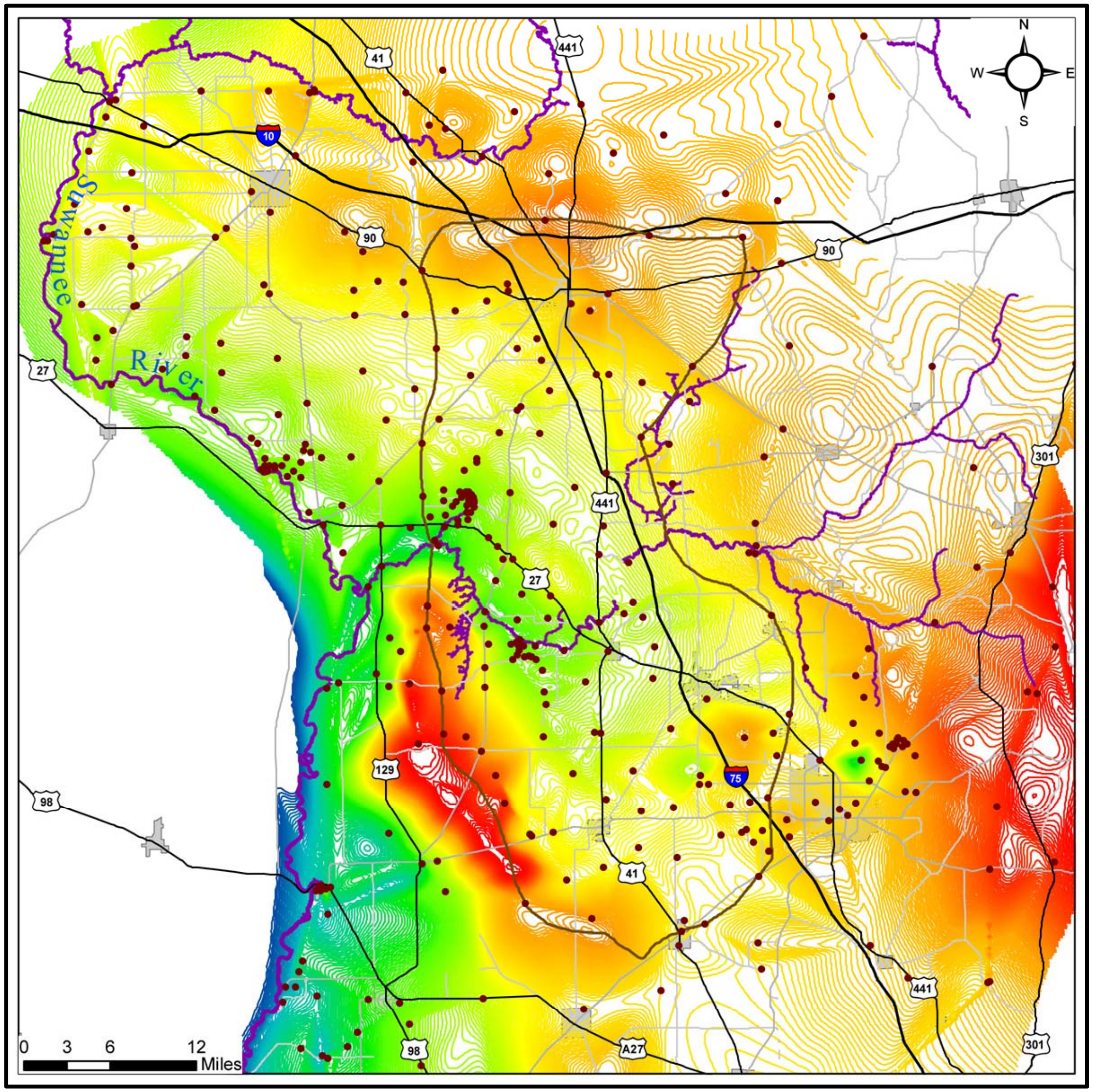
- Total stations = 30
  - Lakes: 4
  - Rivers: 14
  - Springs: 12
- Data sources
  - SRWMD
  - USGS
  - ACEPD



 Key Point: Stage data used to constrain head fields

High Water Potentiometric Surface Map

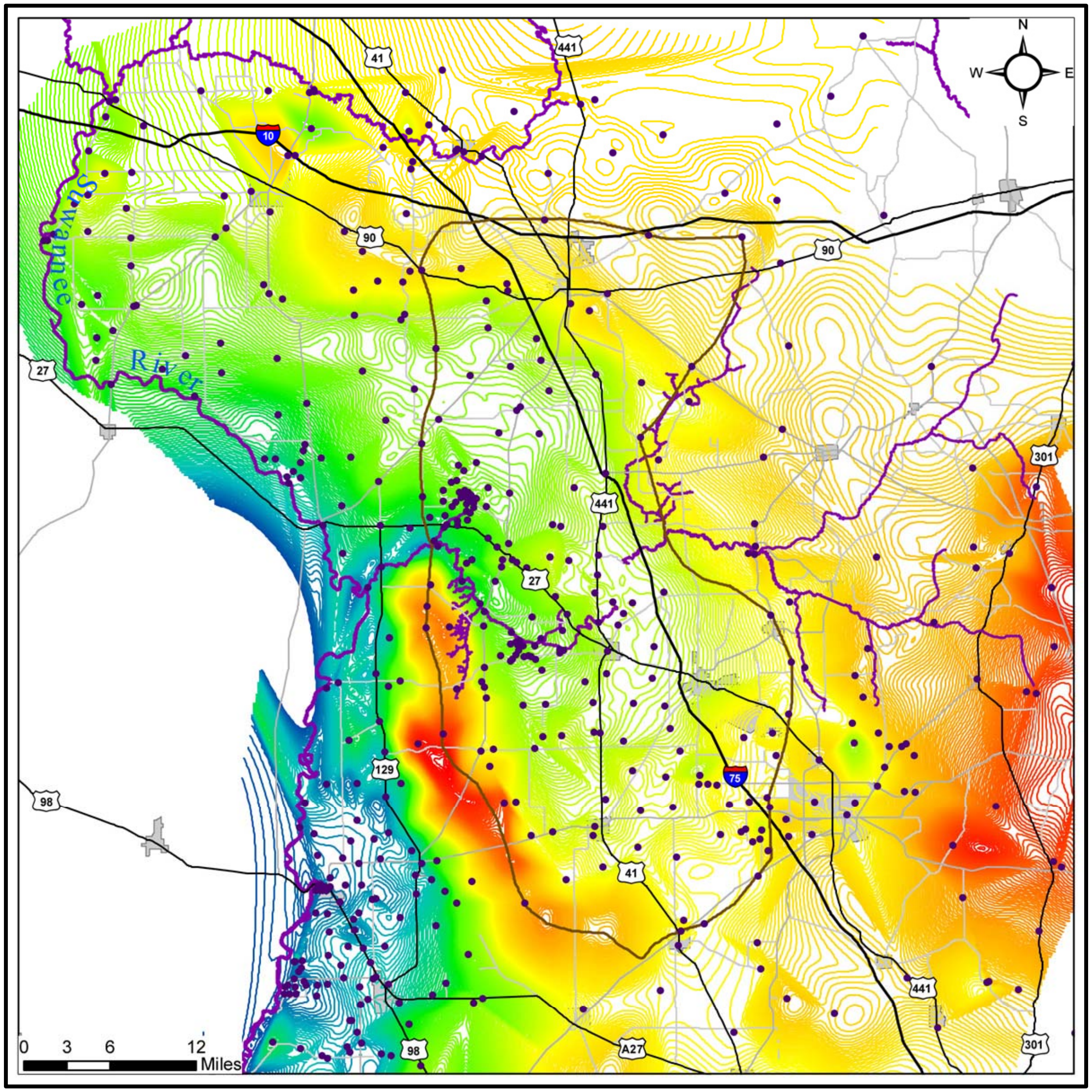
- Developed contour map using all high water data.
- Mapped area larger than target model region.
- Used map to help define outer model boundaries.
  - No-flow ideal
  - Political constraints to east (Gainesville)
- Used map to assign boundary conditions.
- 145 wells within model boundary for calibration.



Key Point: Model boundaries defined by divides as much as possible

Low Water Potentiometric Surface Map

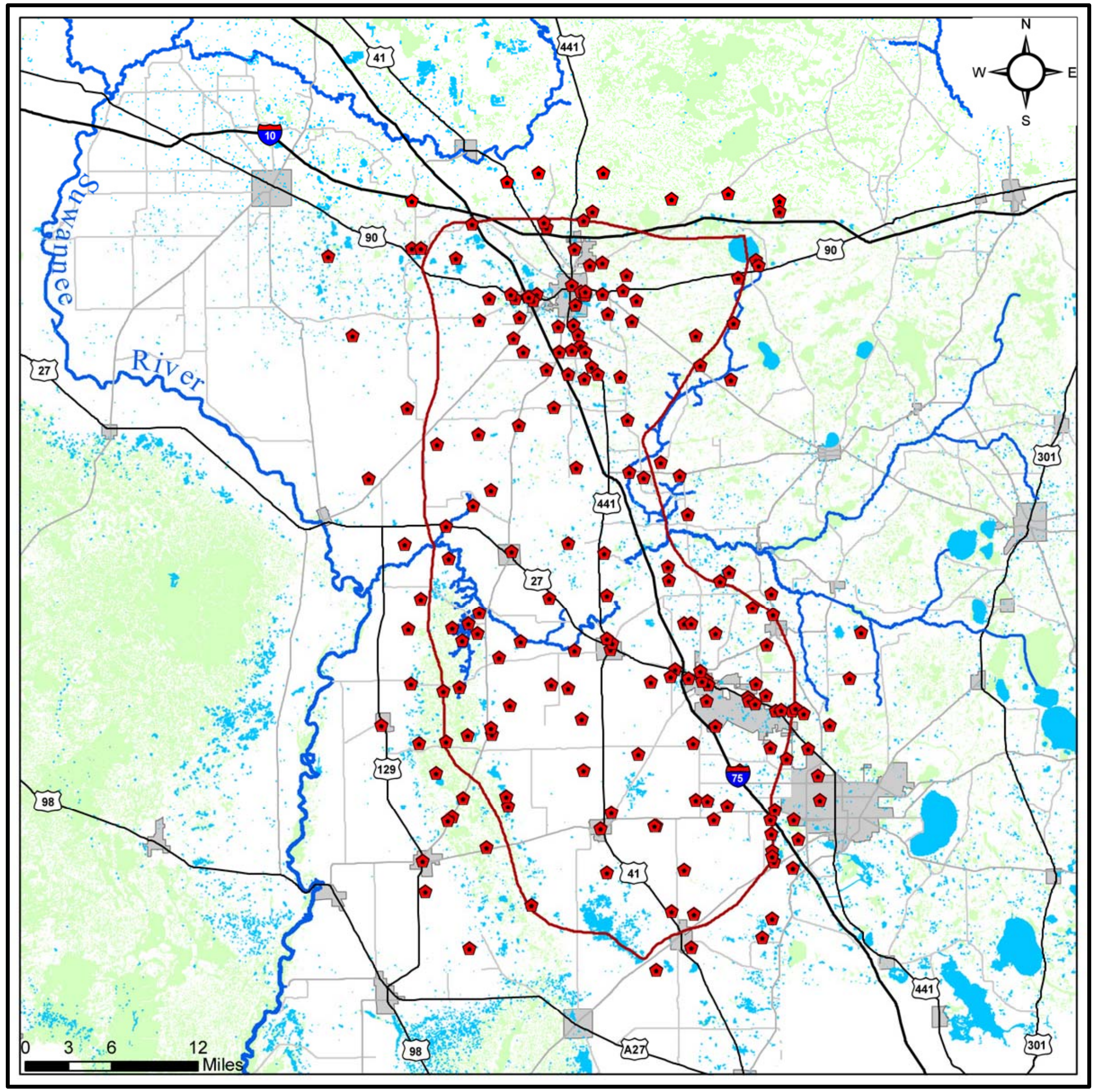
- Developed to constrain model calibration.
- Same framework should be valid for both high water and low water conditions.
- Outer boundaries valid.
- Used map to assign boundary conditions.
- 188 wells within model boundary for calibration.



Key Point: Developed two calibration datasets to increase reliability

Geology: Borehole Data Synthesis

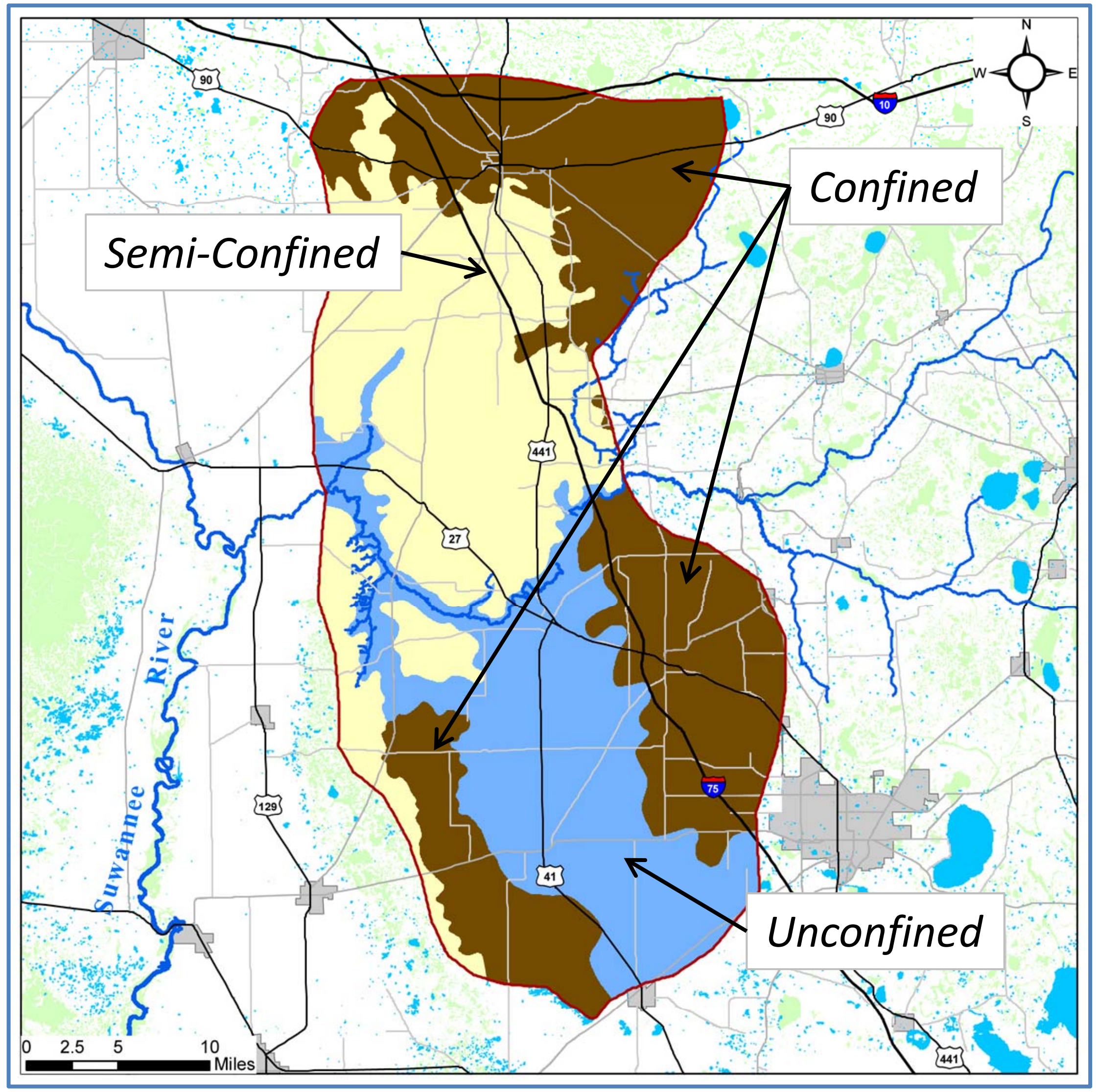
- Relevant hydrostratigraphy
  - Surficial aquifer
  - Confining unit – sand in clay matrix, clay
  - Upper Floridan Aquifer
- Borehole data used to define layer thicknesses & top of FAS
  - Surficial aquifer - unconsolidated sands
  - Confining unit – sand in clay matrix, clay
- Total bore logs: 198
- Source: FGS lithprog database



Key Point: Model hydrostratigraphy defined from borelogs

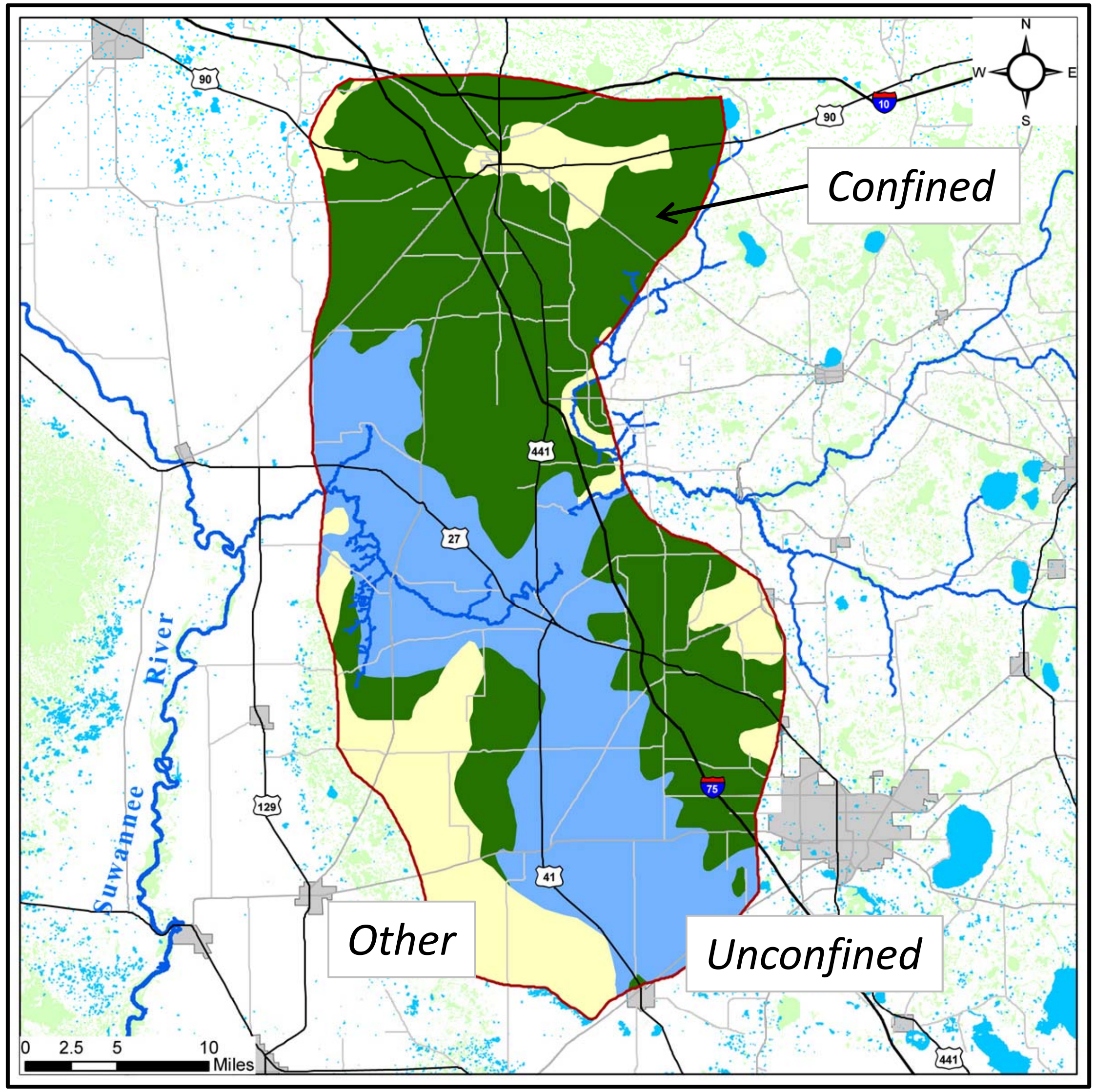
Geology: Geologic Map Synthesis

- Geologic Map of Florida FGS, 2001
- Confining unit : Miocene Hawthorn Formation
- 1st unit within 20 feet of land surface
- Three units
  - Confined = Hawthorn
  - Semi-confined = undifferentiated sand & clay
  - Unconfined = Ocala Limestone



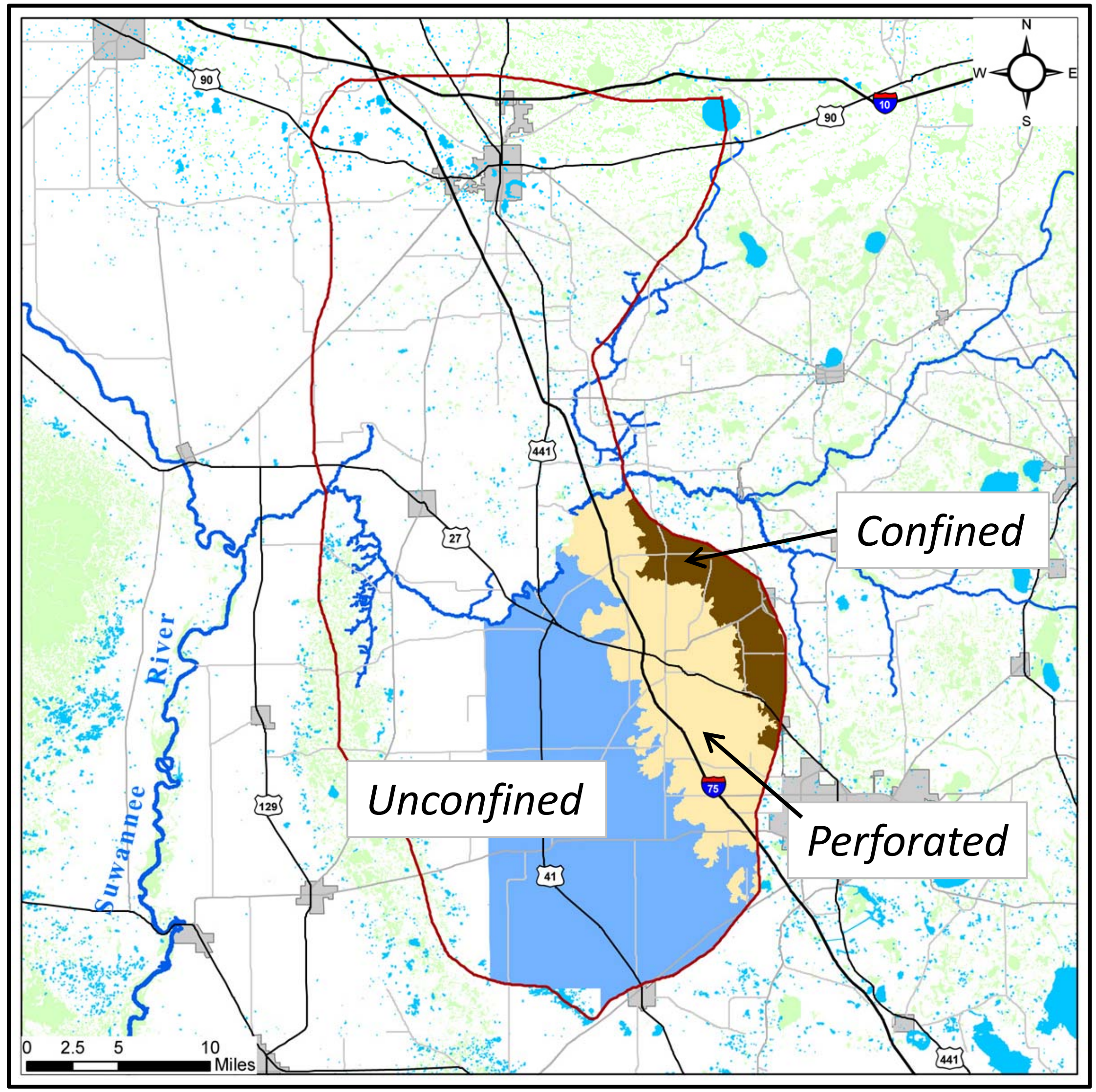
Geology: Geologic Map Synthesis

- Env. Geology of Florida FGS, 2001
- Distribution of rock & sediment by type within 10 feet of land surface
- Confined – semi-confined: clayey sand
- Unconfined: limestone
- Other: medium to fine sand & silt



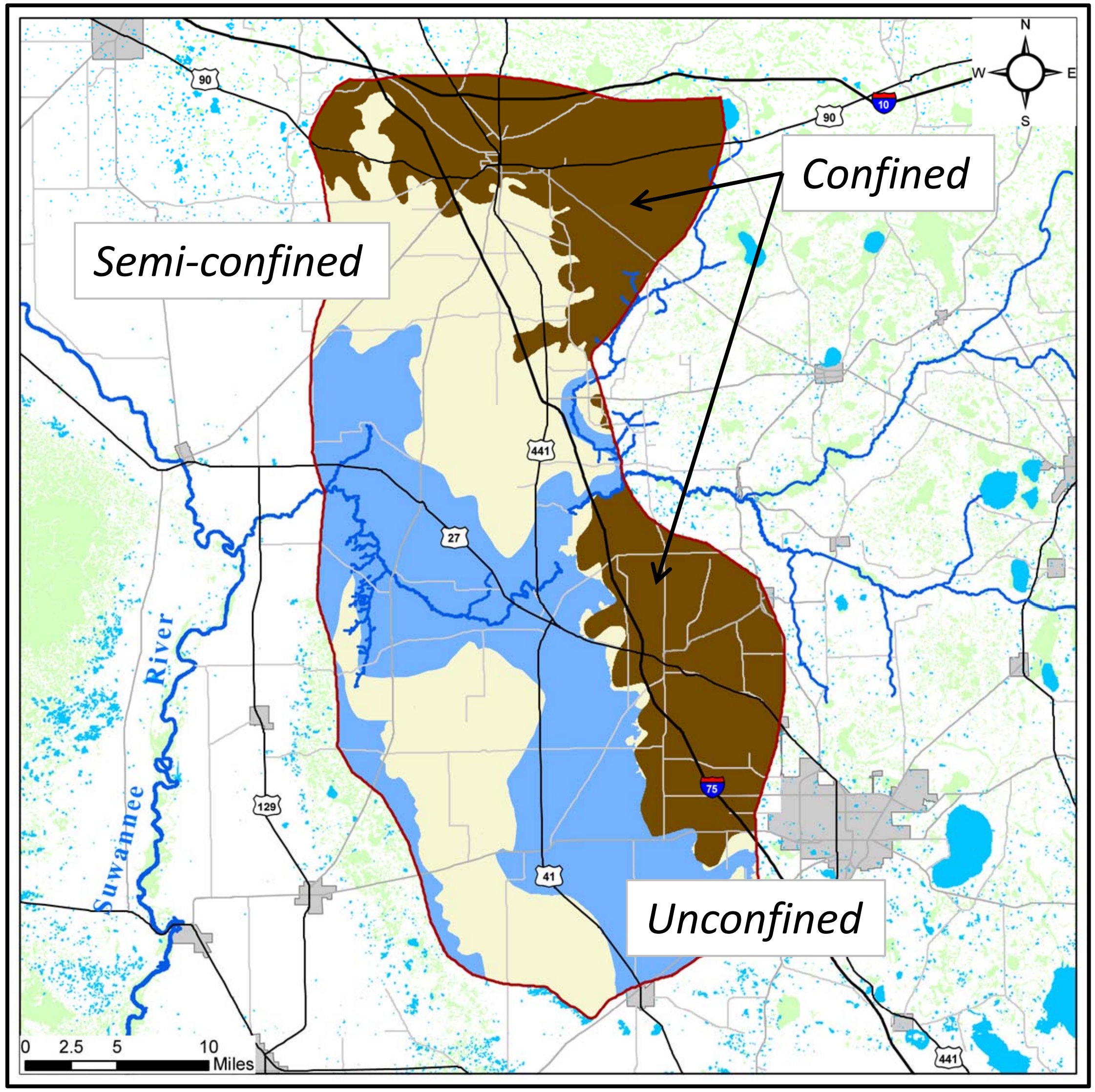
Geology: Geologic Map Synthesis

- Alachua County: aquifer confinement FGS, 1998
- Based on land surface elevations & confining unit thickness from borehole logs
- Confined: well confined
- Perforated: semi-confined
- Unconfined: no confining material



Geology: Hydrostratigraphic Delineation

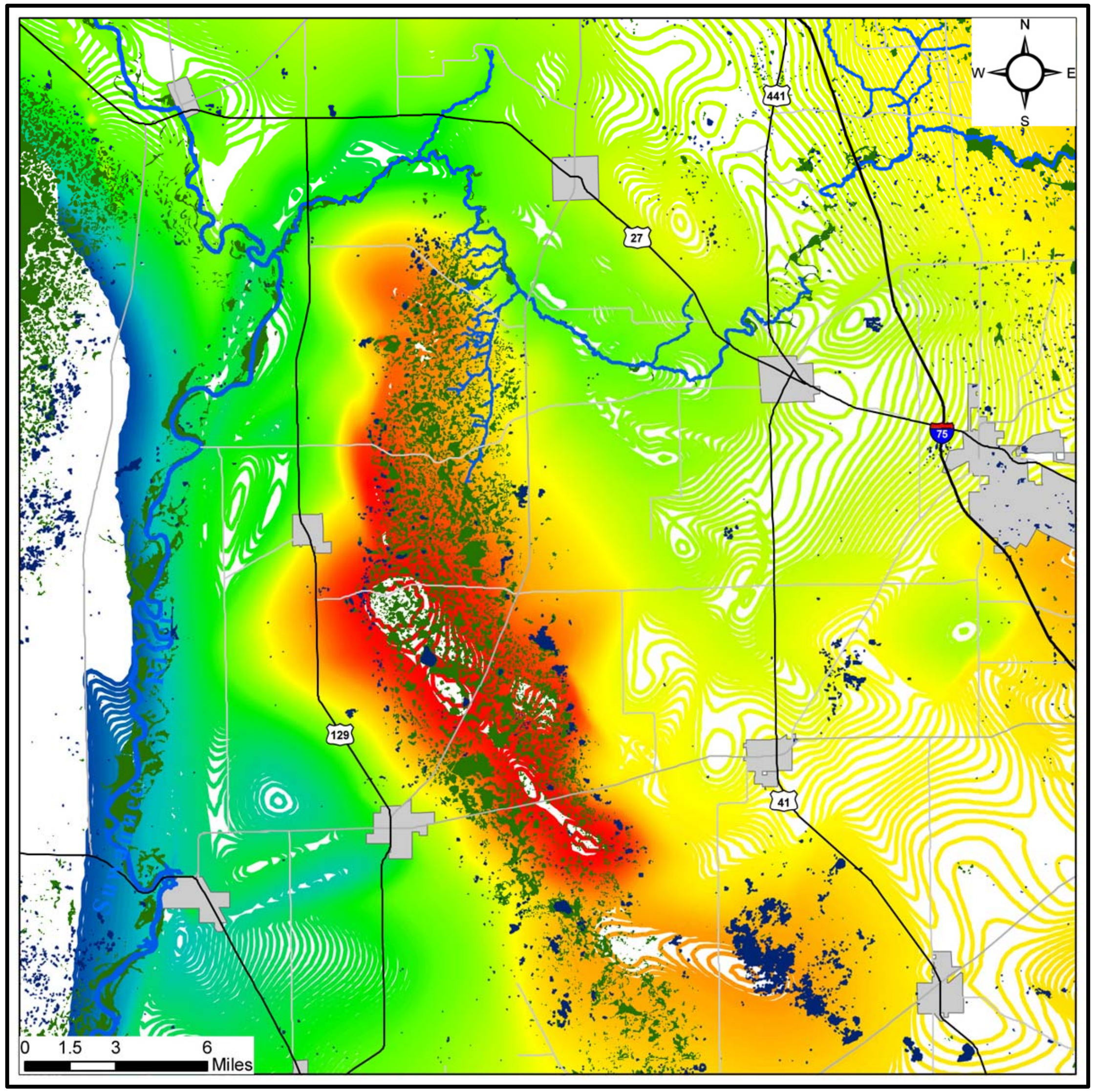
- Compilation of map delineations and unit thicknesses from borehole logs.
- Confining unit
  - Clay K
  - Overlain by surficial aquifer with sand K
- Semi-confining unit
  - Mixed silt & clay K
  - Overlain by surficial aquifer with sand K
- Unconfined
  - Sand K
  - Surficial aquifer merges with FAS



Key Point: Framework is compilation of multiple data & interpretations

Floridan Aquifer Conductivity

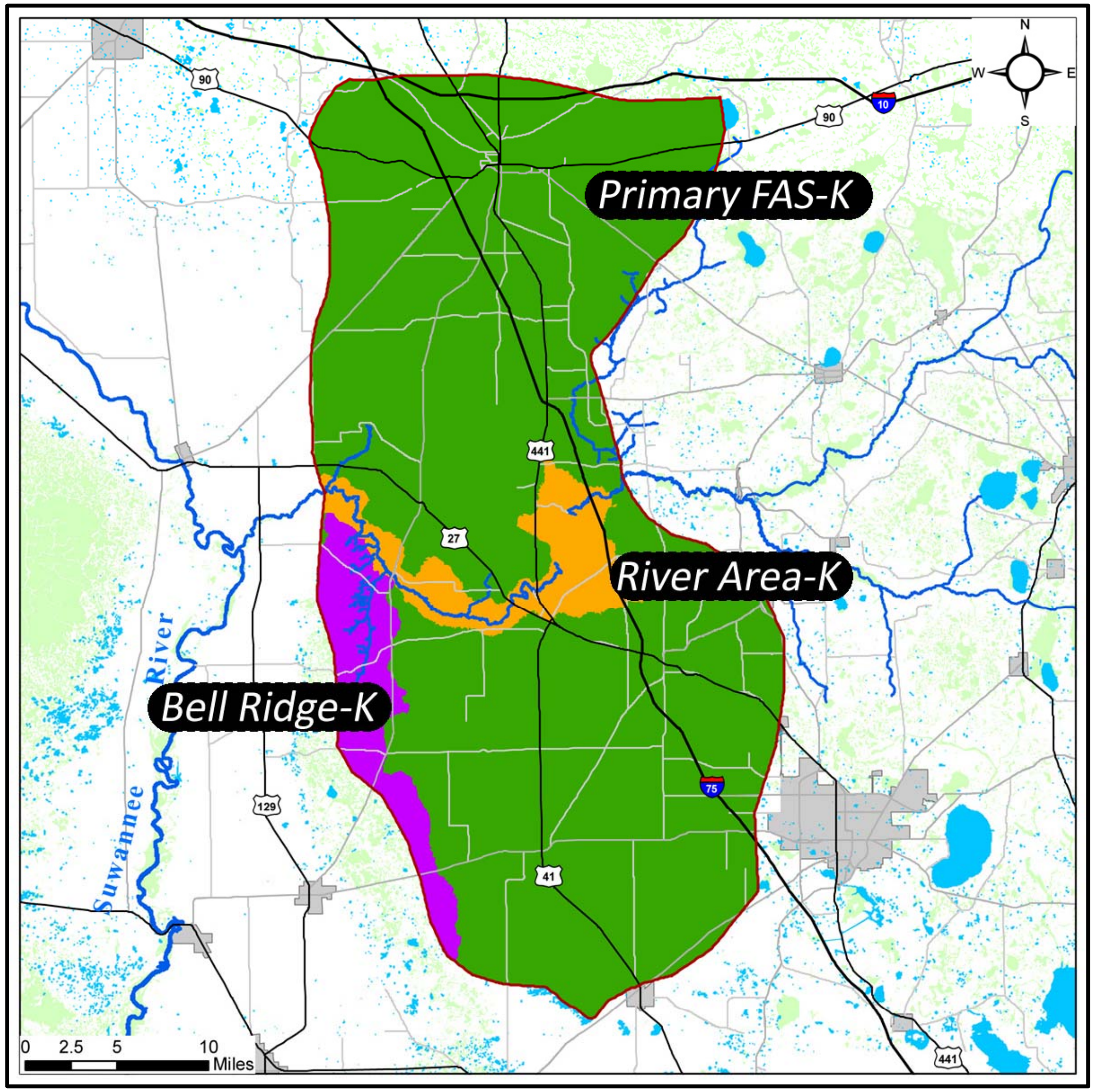
- Assumed uniform K in upper Floridan aquifer except under Bell Ridge.
- Bell Ridge characteristics
  - Different depositional environment
  - Many perched lakes & wetlands
  - Not confined
  - Headwaters of Cow creek
  - Head mound under both high and low water conditions
- Assumed to be region of significantly lower K than rest of Floridan aquifer in model region.



Key Point: Established geologic basis for K variations

Floridan Aquifer Conductivity

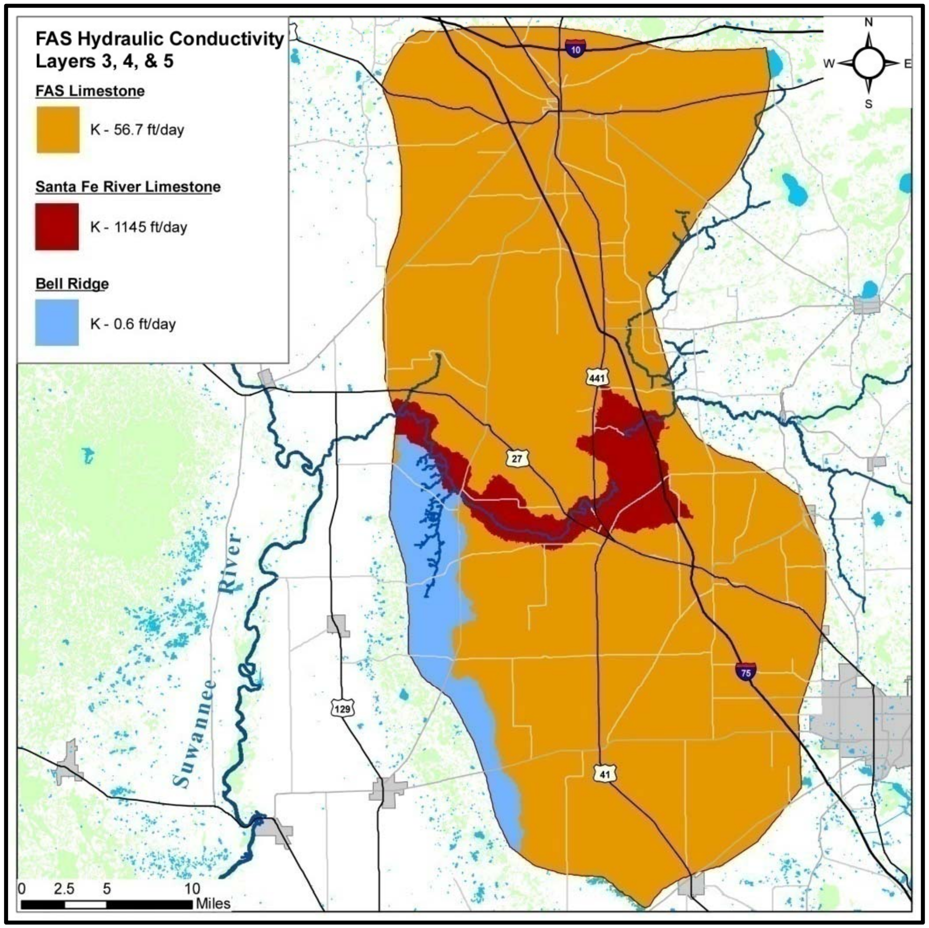
- Primary FAS
  - Relatively high K
  - Similar to high end of range for medium to fine sand.
  - K = 0.0002 m/sec
    2 E-4 m/sec
- FAS under Bell Ridge
  - 2 orders of magnitude lower K
  - Similar to low end of range for fine sand with considerable silt.
  - K = 0.000002 m/sec
    2 E-6 m/sec
- FAS near river
  - Developed a buffer around known caves to establish a high K zone near the river.
  - More fracturing and caves
  - K = 0.004 m/sec
    4 E-3 m/sec



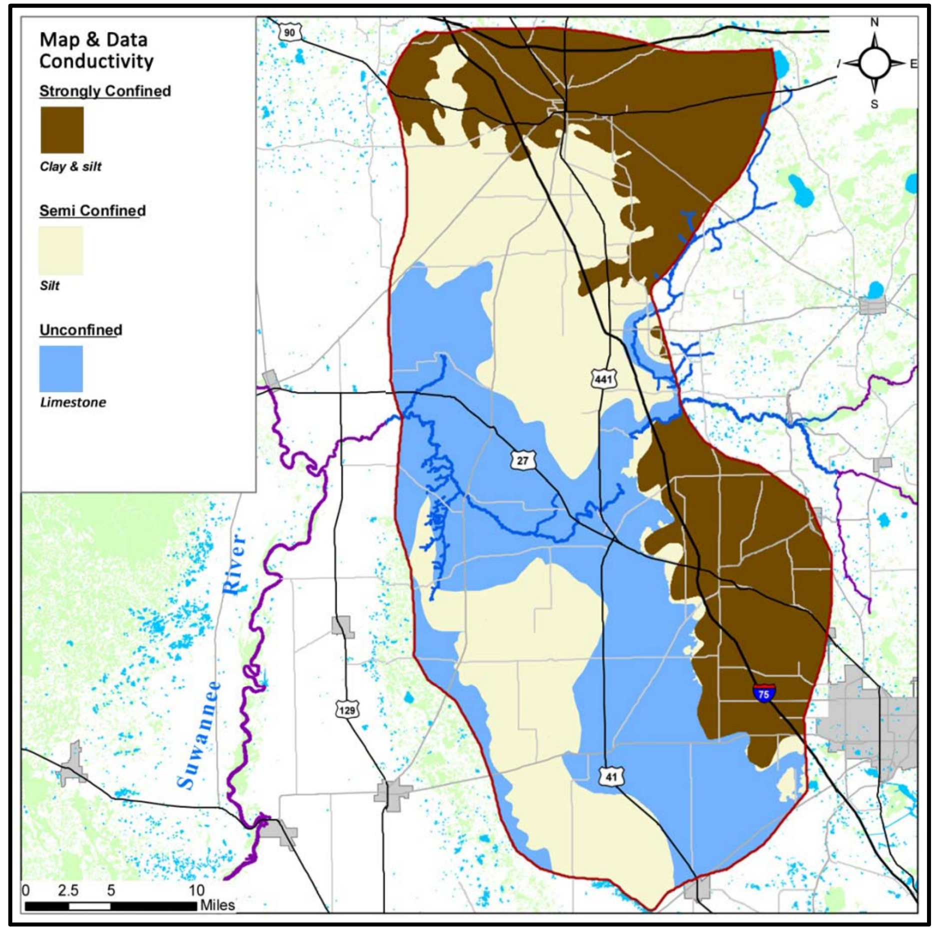
Key Point: FAS-K essentially constant except for Bell Ridge & River

Final Calibrated Conductivities

Upper Floridan Aquifer Layers



Overlying Unit Layers (Confining Unit)

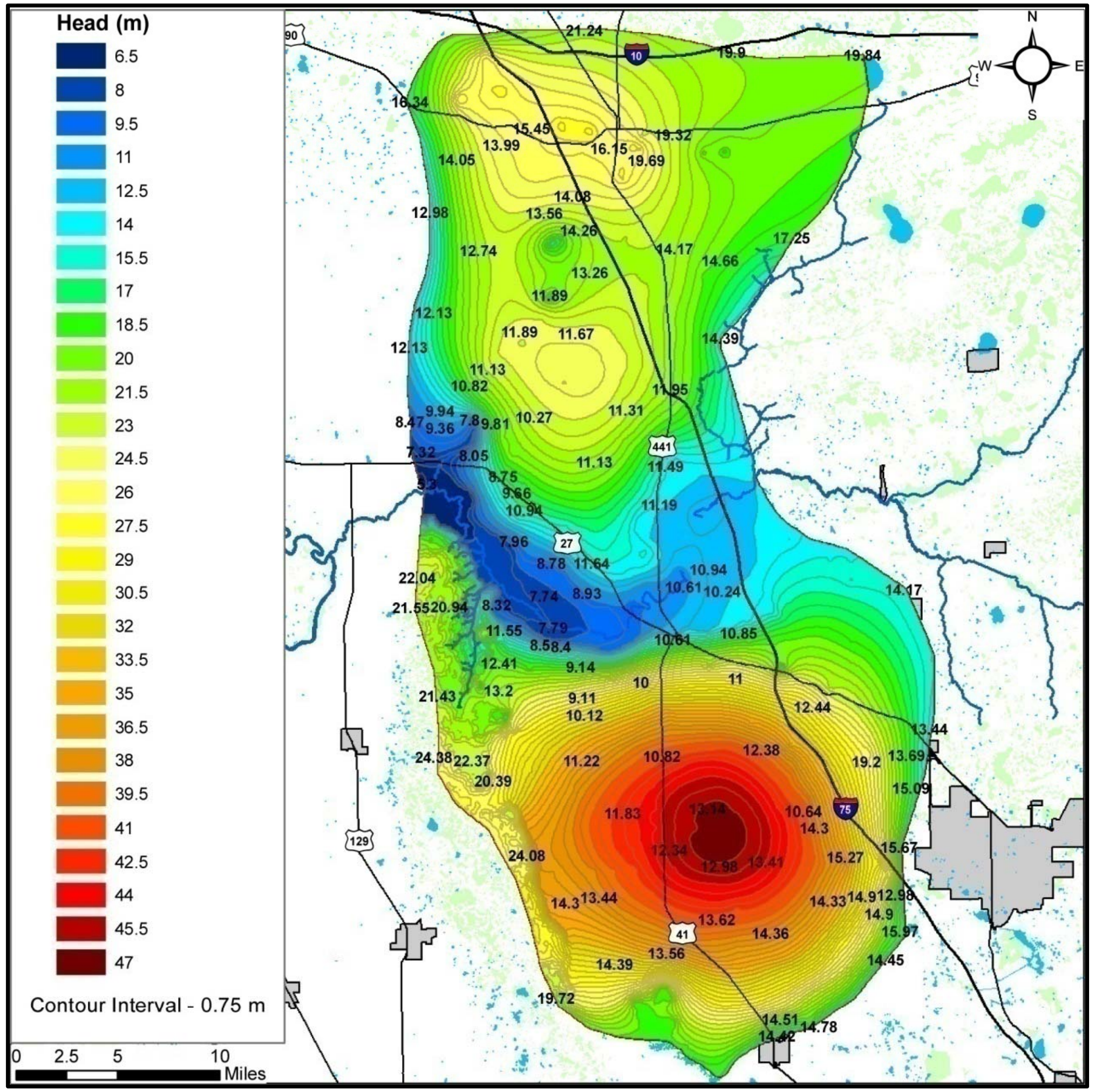


Key Point: Final K zones and magnitudes derived from calibration

Modeling Conduit Flow: *Significance*

<u>The model without conduits</u>

- Same parameter settings
  - High water conditions
  - K, recharge, boundary conditions, springs, rivers, wetlands, lakes
  - Conduits removed
- Water cannot move to discharge locations
  - Springs & rivers
  - External boundaries
- Internal mounding 20+ meters above land surface
- Spring flux too low
  - Ginnie = 0 cfs (58)
  - Gilchrist Blue = 3 cfs (80)
  - Hornsby = 10 cfs (250-350)
  - Poe = 2.5 cfs (90)
  - Blue Hole = 1.5 cfs (295)
  - July = 1 cfs (117)



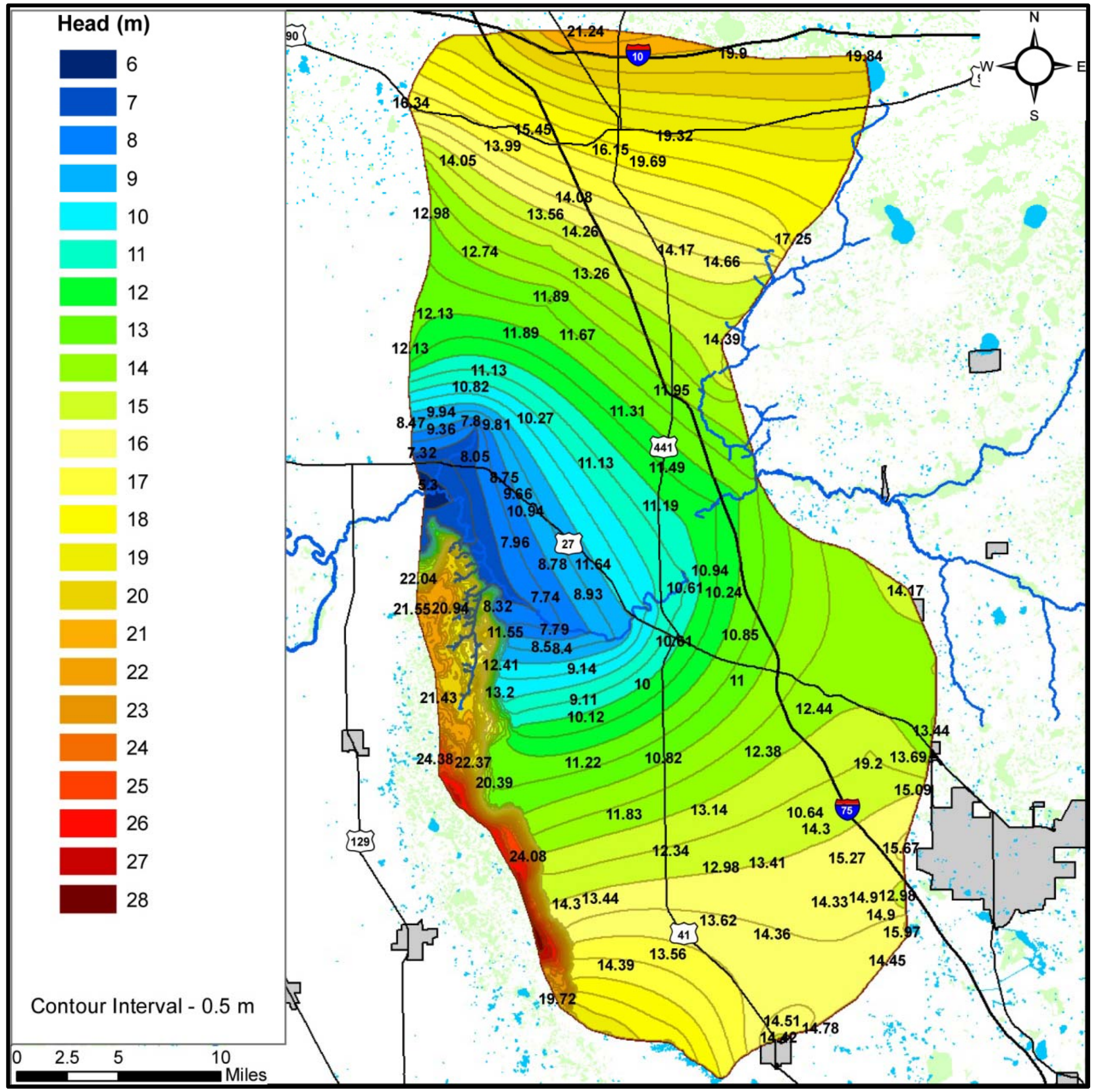
Key Point: Conduits carry the bulk of the flow through a karst aquifer

GeoHydros LLC

Modeling Conduit Flow: *Significance*

<u>Non-conduit approach</u>

- o Raise K in matrix to accommodate flux
- o Raise to highest reasonable value: 0.03 m/sec
  - gravel: 0.03 m/sec
  - karst (reef): 0.02 m/sec
  - coarse sand: 0.006 m/sec
  - medium sand: 0.0005 m/sec
- o Maintain Bell Ridge: 2E-6 m/sec
- o Modeled head flattens
  - Within +/- 2 m of observed
  - Still >= 1m above target
- o Spring fluxes increase slightly
  - Ginnie = 0 cfs (58)
  - Gilchrist Blue = 7 cfs (80)
  - Hornsby = 39 cfs (250-350)
  - Poe = 17.5 cfs (90)
  - Blue Hole = 0-12 cfs (295)
  - July = 7.5 cfs (117)
- o Poorly calibrated heads
- o Springs will not calibrate

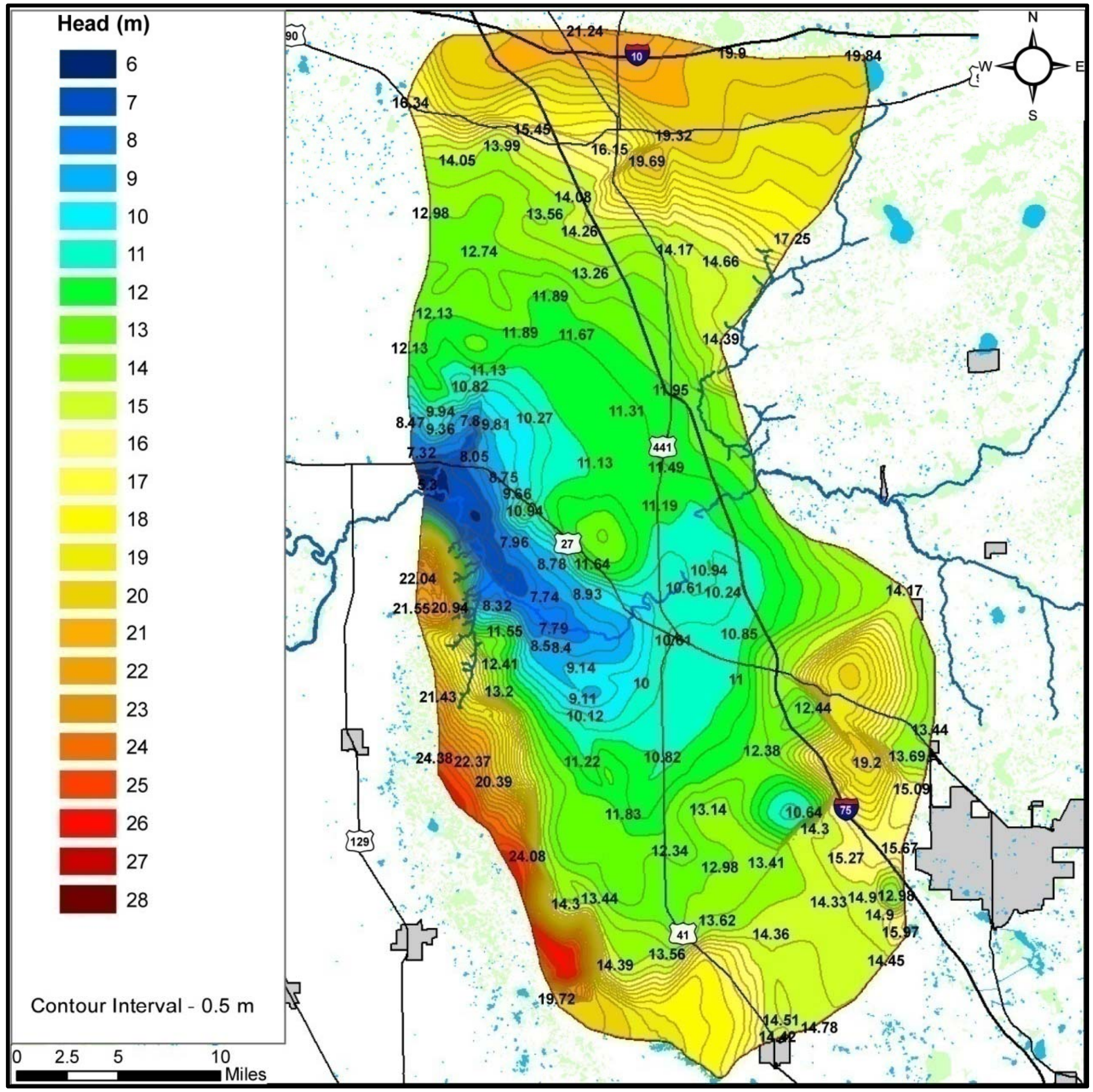


Key Point: Non-conduit models will not calibrate well

Modeling Conduit Flow: *Significance*

<u>*Actual conditions*</u>

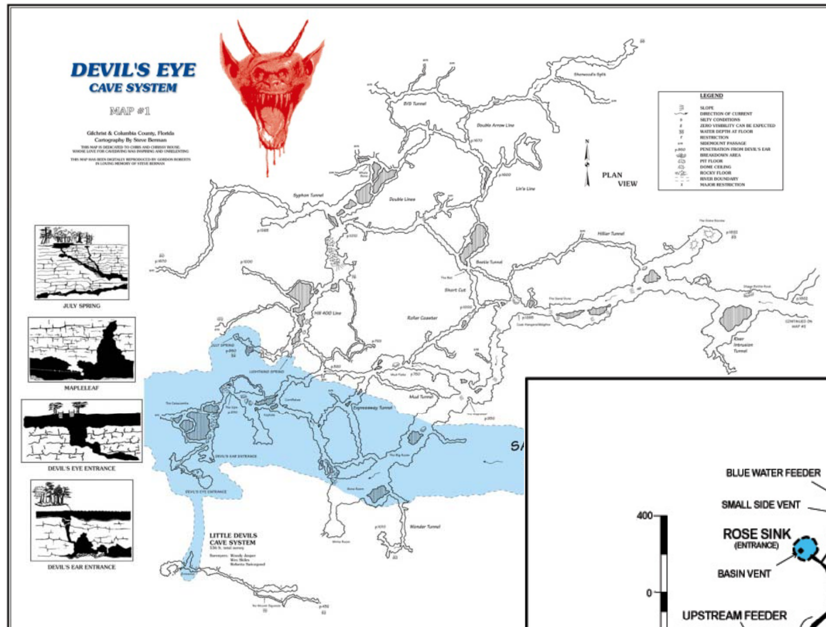
- FAS head field is not a smooth surface from boundaries to river.
- Must have preferential flow paths to create ridges & valleys
- High K zones or conduits?

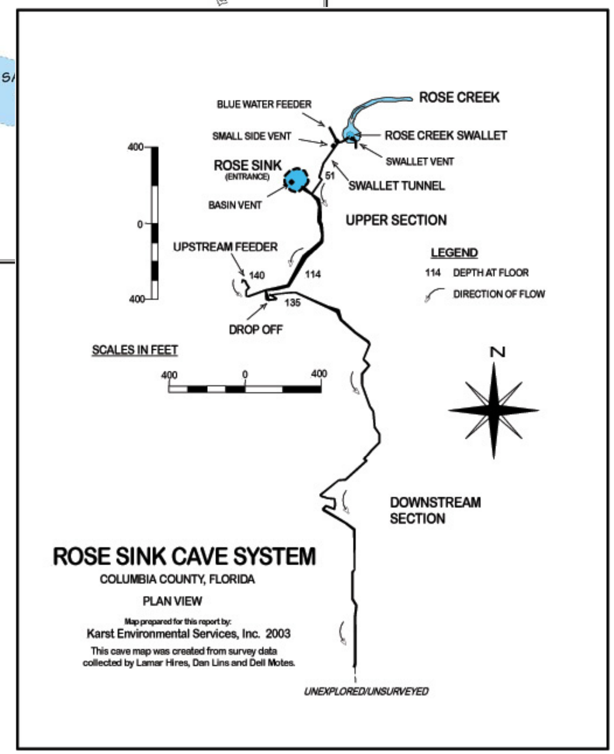


Key Point: Measured head field indicates conduits

Why Conduits? *Known Caves in Area*

- Prevalence of known caves indicates pervasive conduit development.
- Spring Caves
  - Devil's Ear / Devil's Eye / July
  - Ginnie
  - Hornsby
  - Blue Hole
- Swallet Caves
  - Mill Creek Sink
  - Rose Creek Sink

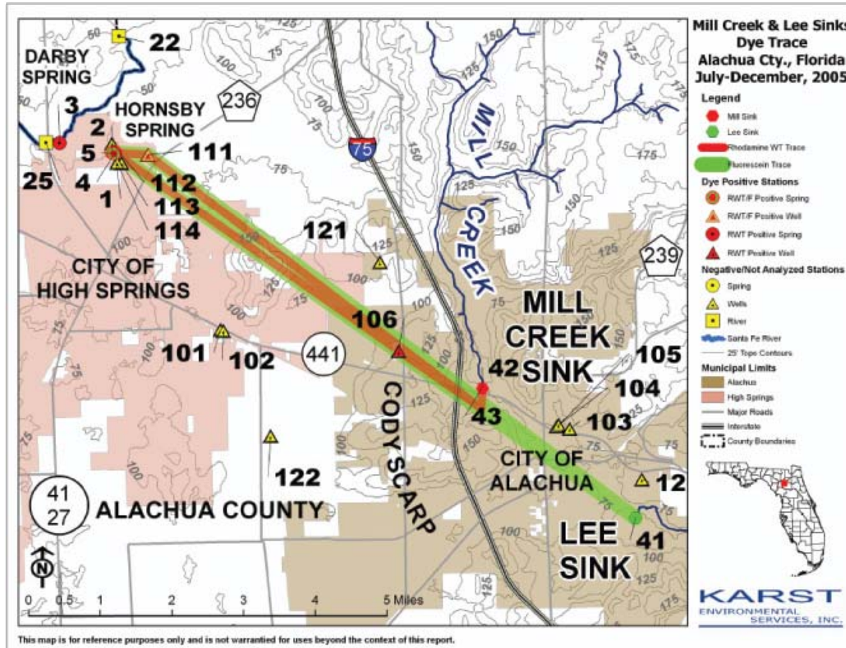


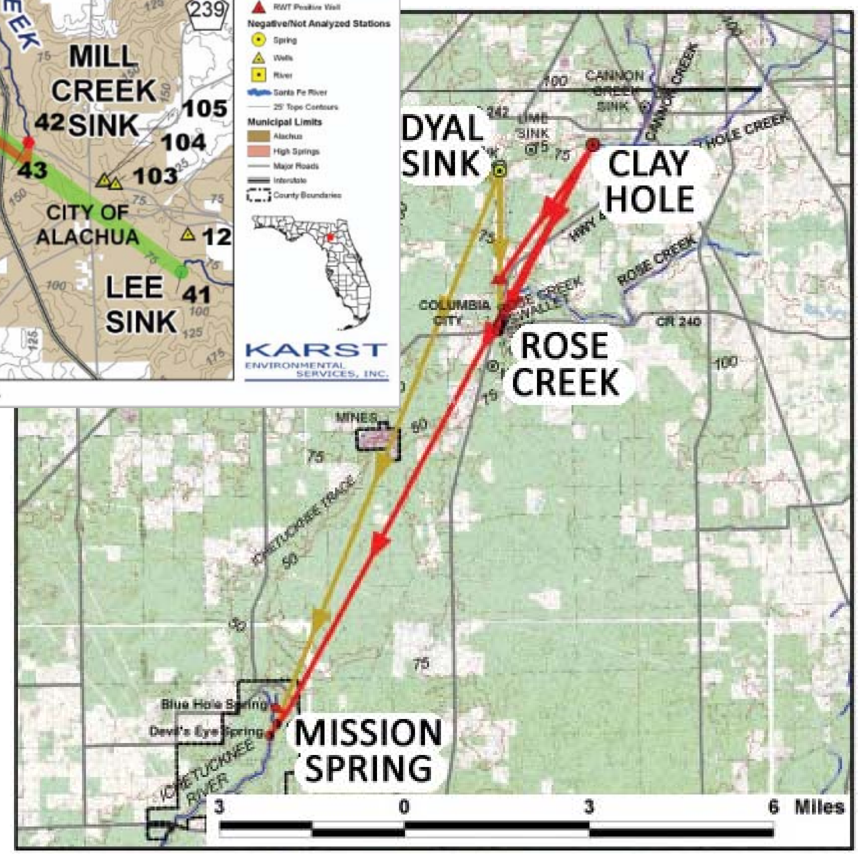


Key Point: Non-standard data & observations critical to model

Why Conduits? *Groundwater Tracing*

- Clay Hole - Mission
  - Inj. 5/15/03
  - Dry conditions
  - Rainfall fills sink on 6/4/03
  - Dye arrives at Blue Hole & Mission
    - 1st detect: 7/31
    - Peak arrival: 8/14
  - Distance: >= 50,000 ft
  - Travel time: 46 – 72 days
  - Velocity: 690 – 1090 ft/day (210-330 m/day)
- Mill Creek – Hornsby
  - Inj. 7/26/05: wet conditions
  - Velocity: 1400 – 2400 ft/day (430-730 m/day)



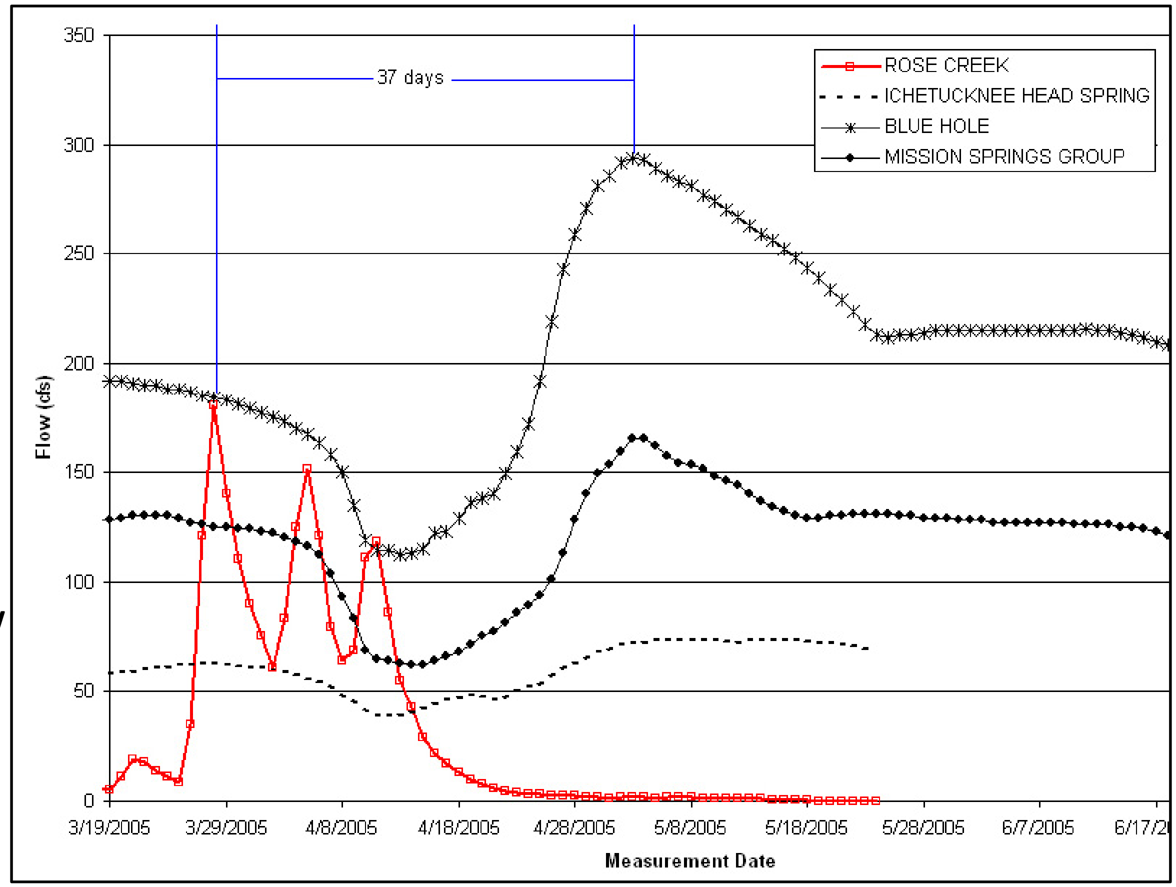


Key Point: Non-standard data & observations critical to model

Why Conduits? *Hydrograph Analysis*

- Storm event fills Rose Sink Swallet *March 2005*
- Flow surges at Blue Hole & Mission Springs
  - Peaks ~ 37 days after
  - Shows connection btw Rose & Blue Hole / Mission
  - Shows flow velocity rises under high water to as much as 410 m/day
- No surge in flow at Ichetucknee Spring
  - Shows no connection btw Rose & Ichetucknee
  - Requires preferential flow paths (conduits)

Measured Flow After March 2005 Storm



Key Point: Non-standard data & observations critical to model

Incorporating Conduits in the Model

- Objectives for modeling preferential flow paths
  - deliver large volumes of water to springs creating high discharge rates (200+ cfs)
  - move water at high velocities (200 to 700 m/day)
  - Two method options
    - 100% Matrix flow with high-K pathways defined in mesh
    - Dual permeability (matrix/conduits)

- Matrix flow design
  - Assumes Darcian flow across entire model region
  - Preferential flow paths created by localized changes in hydraulic conductivity (K), element dimensions, and porosity
  - *Problems*
    - unrealistically high K, extremely small element sizes, and/or unrealistically low porosity are usually needed to achieve flux and velocity calibration
    - High velocities in preferential flow paths almost assuredly create turbulent flow conditions that invalidate the use of Darcy's equation
    - Very difficult to define and modify mesh or grid thus reducing calibration options

Incorporating Conduits in the Model

- Dual permeability method
  - Use Darcian flow to simulate flow in bulk of the aquifer where velocities are low and flux is small
  - Use pipe flow equation (Manning-Strickler) to simulate flow through discrete conduits where flux needs to be greatly increased and velocities are high
  - *Advantages*
    - Very easy to define and modify preferential flow paths
    - High velocities and turbulent flow do not invalidate use of Manning-Strickler equation

WASY Software FEFLOW WASY

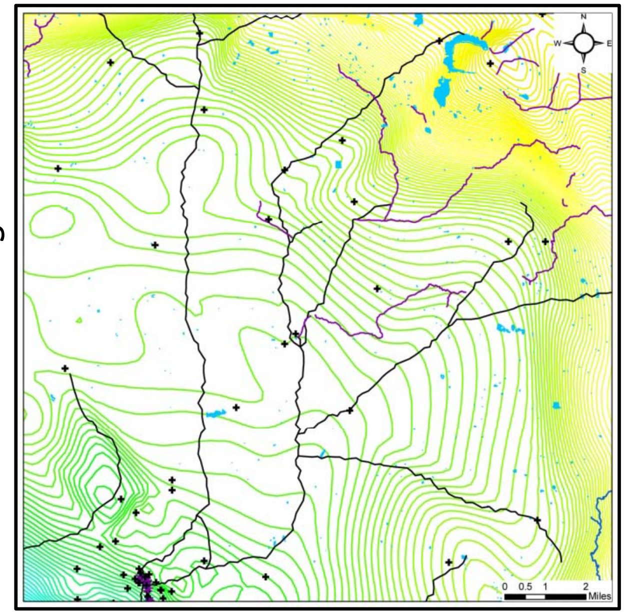
http://www.feflow.info/

Key Point: Dual permeability approach is best for simulating conduits

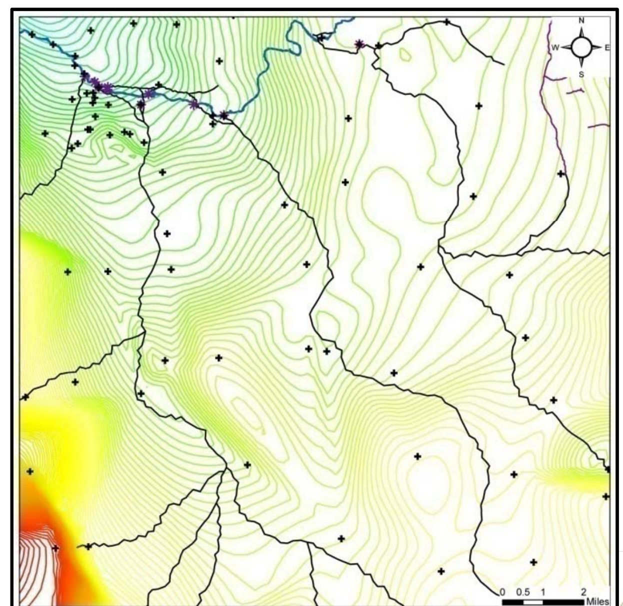
Assigning Conduit Locations

- Based on low water potentiometric surface
- Step-1: Connect known sources to discharges
  - Rose & Clay Hole to Blue Hole & Mission
  - Mill Creek & Lee Sinks to Hornsby
  - O'leno Sink to River Rise
- Step-2: Conduits follow potentiometric valleys
  - Between known connected points
  - Up-gradient from springs
  - Down-gradient from swallets
- Step-3: Connect unexplained closed depressions
  - Cannot be explained by pumping or discharge
  - Connect to known or strongly inferred conduits
  - Fit path to best conform to potentiometric surface
- Modifications & additional assignments
  - Conduit locations integral to calibration
  - Conduits added where head needed to be reduced
  - Initial placement moved if needed for calibration

Northern Region



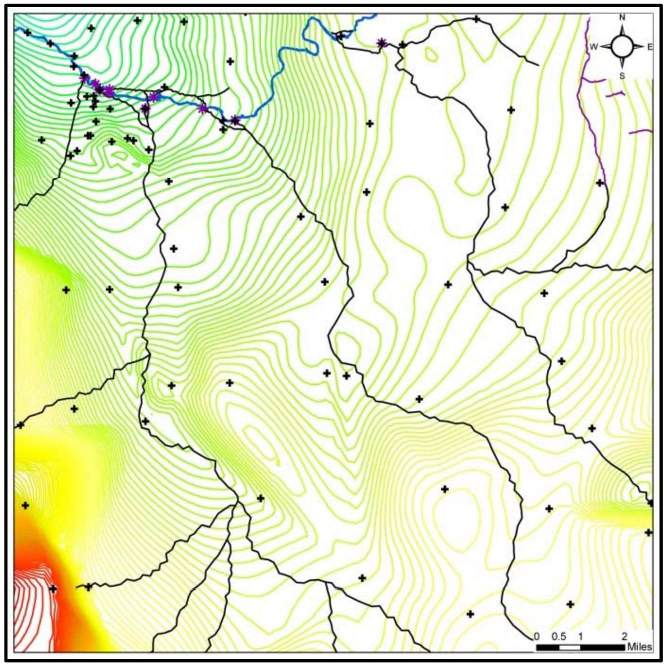
Southern Region



Key Point: Conduits placed to follow pot surf troughs

Assigning Conduit Parameters

- Two Parameters
  - Area (*A*)
    - Controls conduit flux: *Q=VA*
    - Strongly effects head in surrounding matrix
  - Roughness Coefficient
    - Controls velocity (*V*)
    - Represents conduit consolidation
      - Single open conduit with *A = x* will have low friction effects on flow
      - Many small conduits with total *A = x* will have much greater friction effects on flow
- Parameters adjusted manually until model calibrates to head, flux, and velocities



Key Point: Two conduit parameters: Area & Roughness

DISCUSSION

Water Budget: Model Sources & Sinks

- Fundamental objectives
- Springs
- Rivers
  - Stage
  - Flux
- Swallet Inflows
  - Total Flux
  - Individual inflows
- Swallet Seeps
- Lakes & wetlands
- Recharge from precipitation
  - Total flux
  - Distribution
    - Land use
    - ET

Fundamental Constraints

Flow In = Flow Out

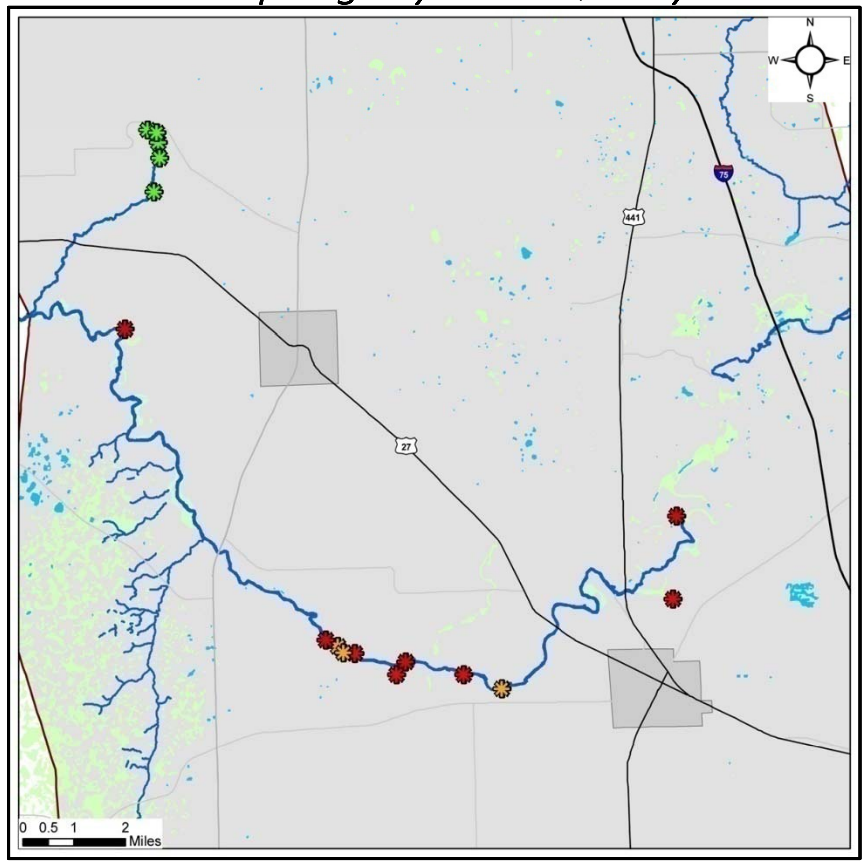
- External boundaries
  - Defined to minimize flow into or out of the model region.
  - Boundaries follow hydrologic divides or are perpendicular to estimated flow direction wherever possible.
  - Highest expected flow out of model is through boundary near Gainesville.
- In-flux
  - Precipitation recharge
    - rainfall - (evapotranspiration + runoff)
  - Santa Fe River at O'leno Sink
    - Drains large area outside model to the east
    - equal to flux at gauge near sink
  - Internal sinking stream & swallet systems
    - accounts for precipitation runoff over confined region
- Out-flux
  - Flux in Santa Fe River downstream from river rise
    - Assumed equal to flux measurement at gauge near Hildreth
  - Pumping wells
  - Spring Discharges

Key Point: Model designed to minimize non-constrainable flows

Water Budget – Flux Out: *Springs*

- Springs assigned at single model nodes as constant head boundaries
  - Head = measured stage
  - Spring node connected to discrete conduit feature
  - Flux out calibrated by varying stage (within measured range) and conduit parameters *(A & Roughness)*
- All springs have at least one flux measurement for high water period
  - Best data for Ichetucknee springs: 328 measurements in 2002
  - Ginnie & Dogwood: 5 in 2001, 2002, & 2007
  - Poe (1), Hornsby (2), River Rise (1) in 2001 and/or 2002
  - Gilchrist Blue, July, Lilly, Rum Island, Sunbeam, Twin – no low water measurements
- All spring nodes assigned in all model layers

Springs by Data Quality



most data

fewer data

little to no data

Key Point: Springs set such that flux can vary

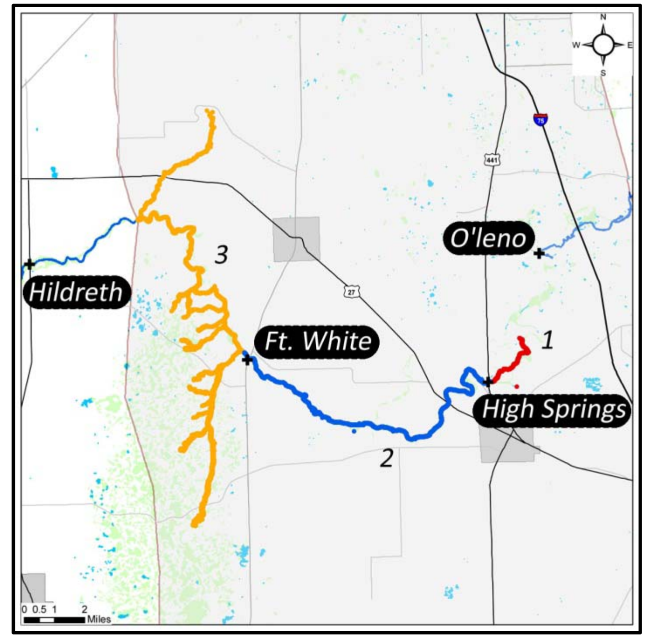
Water Budget – Flux Out: *River Stage*

- Santa Fe & Ichetucknee Rivers
  - Width and length assigned as constant head boundary nodes
    - constant head = stage (high and low water conditions)
      - Santa Fe River stage defined by six gauges and three springs
        - Gauges - Worthington Springs, O'leno SP, High Springs, Fort White, Point Park 3 Rivers Estate, and Hildreth
        - Springs - Poe, Gilchrist Blue, and Ginnie
      - Ichetucknee River stage defined by one gauge and all six springs
    - Stage between measurement points was linearly interpolated
  - River boundary nodes assigned in Surficial Aquifer (Layer 1) and Top 15m of FAS Aquifer (Layer 3)
- Cow Creek & all sinking streams
  - Cow Creek constant head boundary nodes assigned only in top layer of model
    - Head = elevation of creek from topographic map
    - Creek allowed to gain and lose in high water model
    - Creek constrained as gaining or turned off in low water model
  - All sinking streams constant head boundary nodes assigned only in top layer of model
    - Assumed that flow due to discharge from surficial aquifer or surface runoff
    - Head assignment and constraints same as for Cow Creek

Key Point: River stage defined for all rivers & streams (data or topo)

Water Budget: River Fluxes

- Santa Fe River
  - Flux measurements for high and low water periods
    - High water period - April through November 2005
    - Low water period - January 2000 through October 2002
  - Flux data from four river stations
    - O'leno State Park station
      - Highly transient and sporadic data
      - Used as calibration estimate for O'leno Sink
    - High Springs station
      - Sporadic data
      - assumed to represent discharge from River Rise and Hornsby Spring
    - Fort White station
      - Excellent data set
      - Difference between Fort White and High Springs flow used to calibrate combined river & spring discharge in model
    - Hildreth
      - Limited but consistent data set
      - Difference between Hildreth and Fort White flow used to constrain discharge from Santa Fe River nodes plus Cow Creek and Ichetucknee River nodes
      - Difference between O'leno and Hildreth flow used to define recharge into model



Key Point: Santa Fe fluxes constrained by 4 gauging stations

Water Budget: River Fluxes

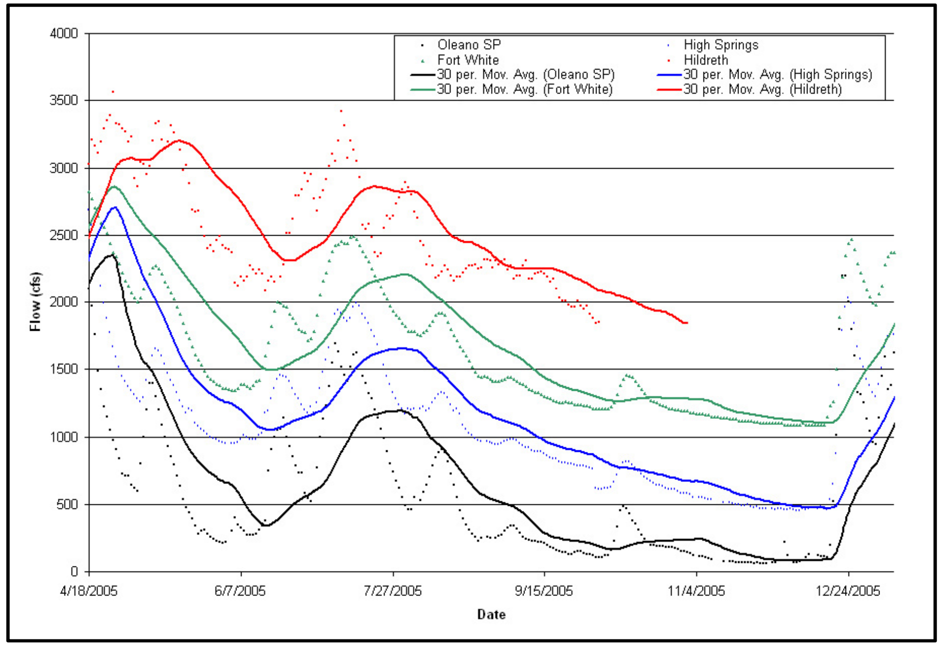
- Ichetucknee River
  - flux assumed to be same as total from six Ichetucknee springs
- Cow Creek and sinking streams
  - Model not calibrated to flux along Cow Creek - no data
  - Model not calibrated to flux along sinking streams
    - Very limited data
    - Available data used to estimate swallet flux

Key Point: Ichetucknee constrained by springs, swallets estimated

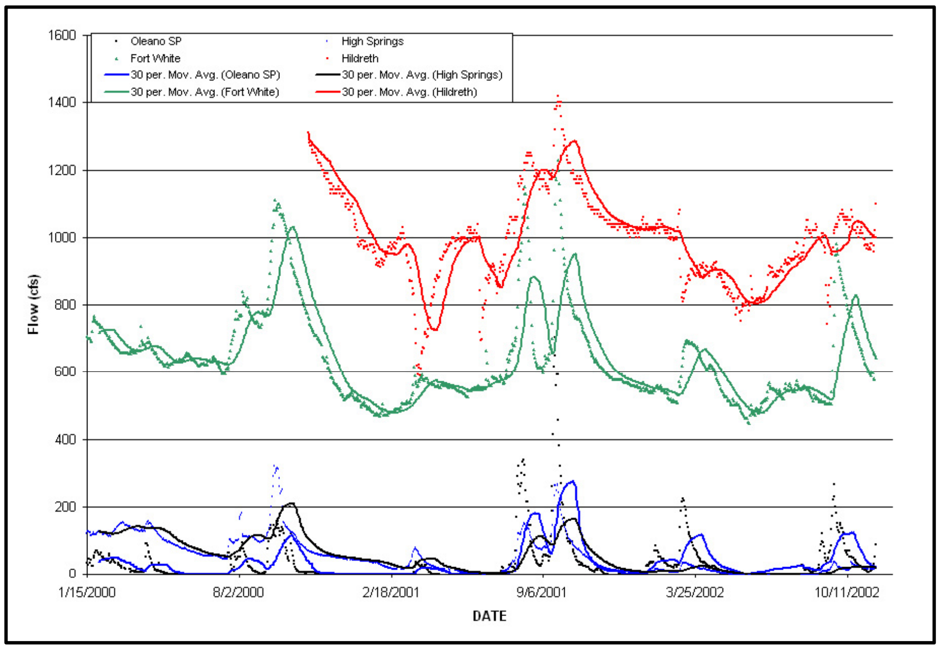
Water Budget: *Defining River Values*

- Applied 30-day running average to river flow data.
- Calculated difference between running average lines for each station set.

High Water Datasets



Low Water Datasets



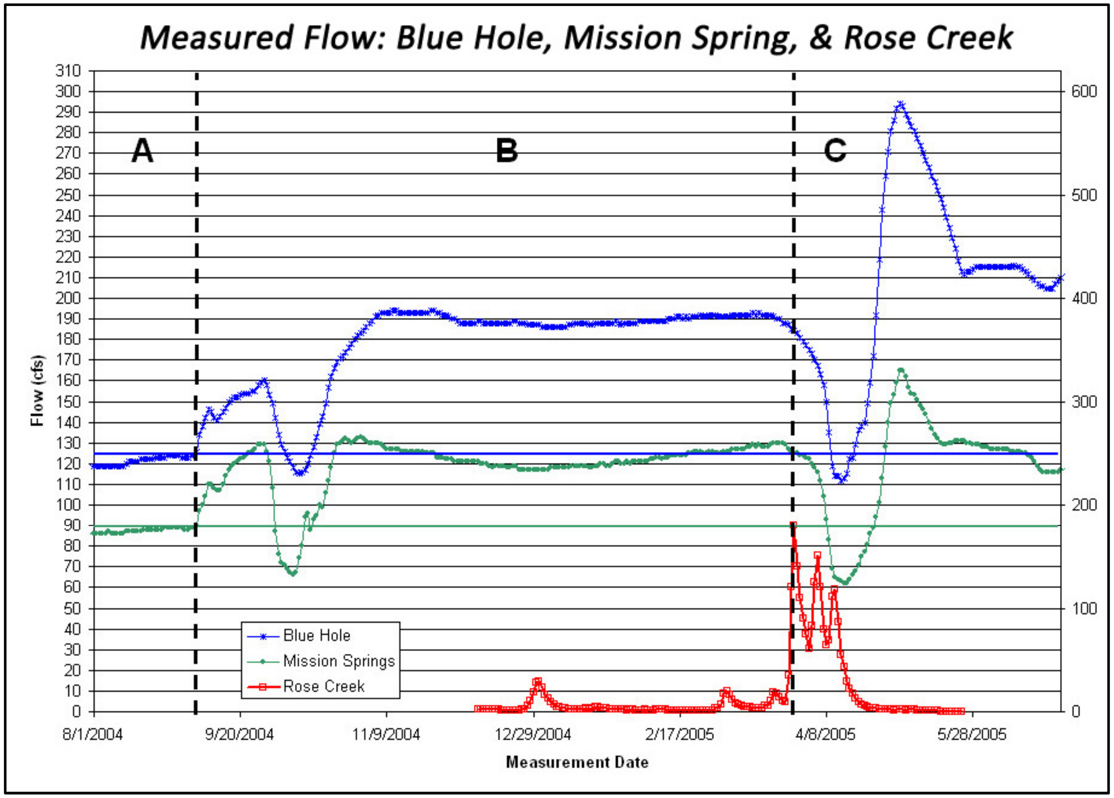
- Calibration ranges and targets calculated from min, max, & ave of the differences.

Key Point: River flux targets calculated from smoothed gauging data

Estimating Total Swallet Inflows

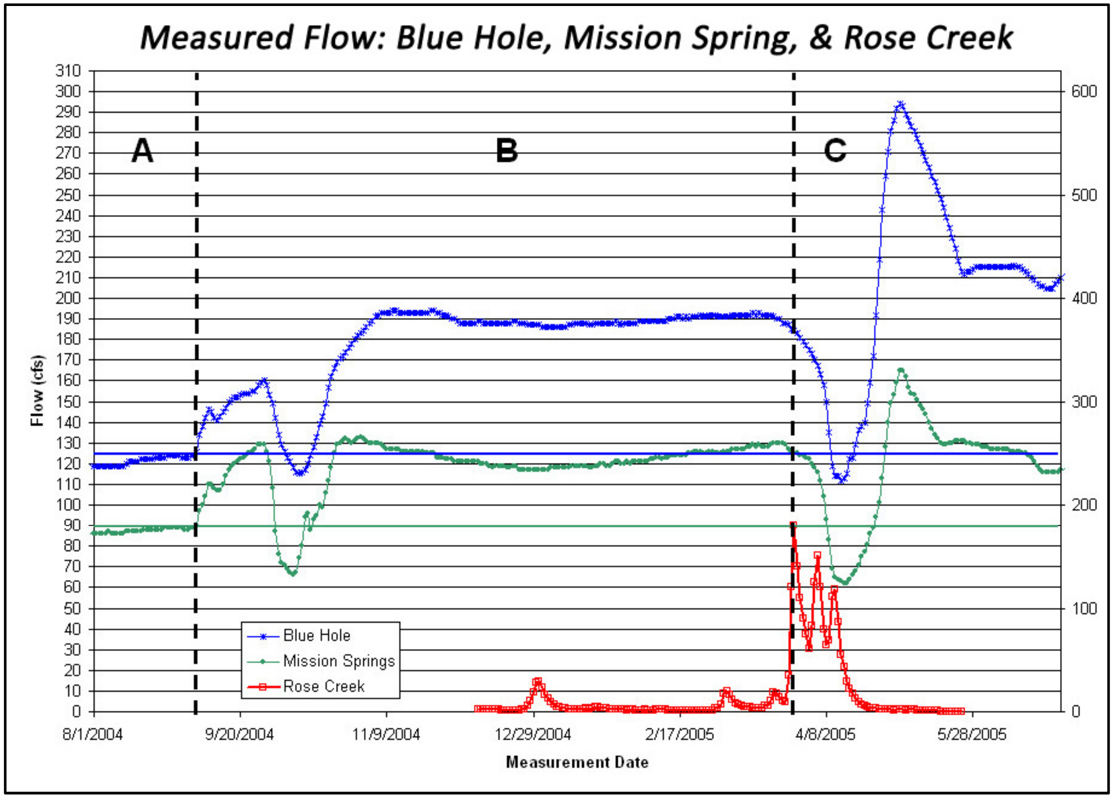
- Swallets were assigned into the model as constant head boundary nodes
  - Swallet nodes were assigned in all layers of the model
  - Swallet nodes were connected to discrete conduit features
  - No available data for swallet stages
  - Assigned head = topographic elevation of swallet from USGS quads

- Constraining fluxes
  swallet & spring flow data
  - Before Sep. 2004 Rose & Clay Hole swallets assumed to be uncharged **(A)**
  - Late 2004 hurricanes fill (charge) swallets **(B)**
  - Flux into FAS reaches steady-state with swallet stage & conduit capacity
  - Further rainfall events increase the stage in swallets **(C)**
  - Swallet stage peaks
  - Flux into FAS and springs peaks
  - Assume that May 2005 flux reaches conduit max capacity



Estimating Swallet Inflows

- Swallet in-flux calculation
  - During time **(A)**, conduit carries primarily groundwater
  - Time **(C)** represents conduit carrying groundwater plus maximum surface water input from Rose and Clay Hole Creek swallets
  - The sum of the flux differences btw time **(A)** and **(C)** in Blue Hole and Mission Springs equals maximum high water swallet in-flux
    - Blue Hole:
      295 - 125 = 170 cfs
    - Mission Springs:
      165 - 90 = 75 cfs
    - Total swallet in-flux =
      245 cfs

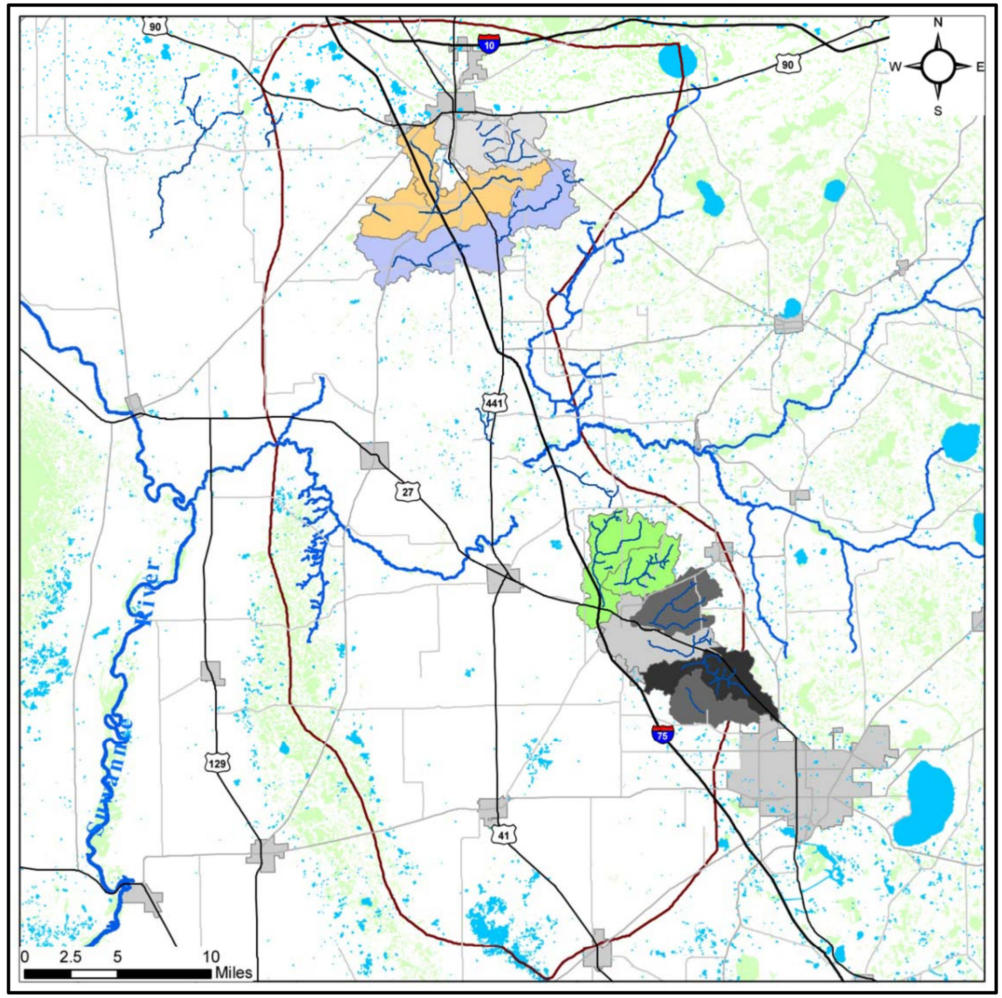


Key Point: Conduit capacities estimated from swallet stage change

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

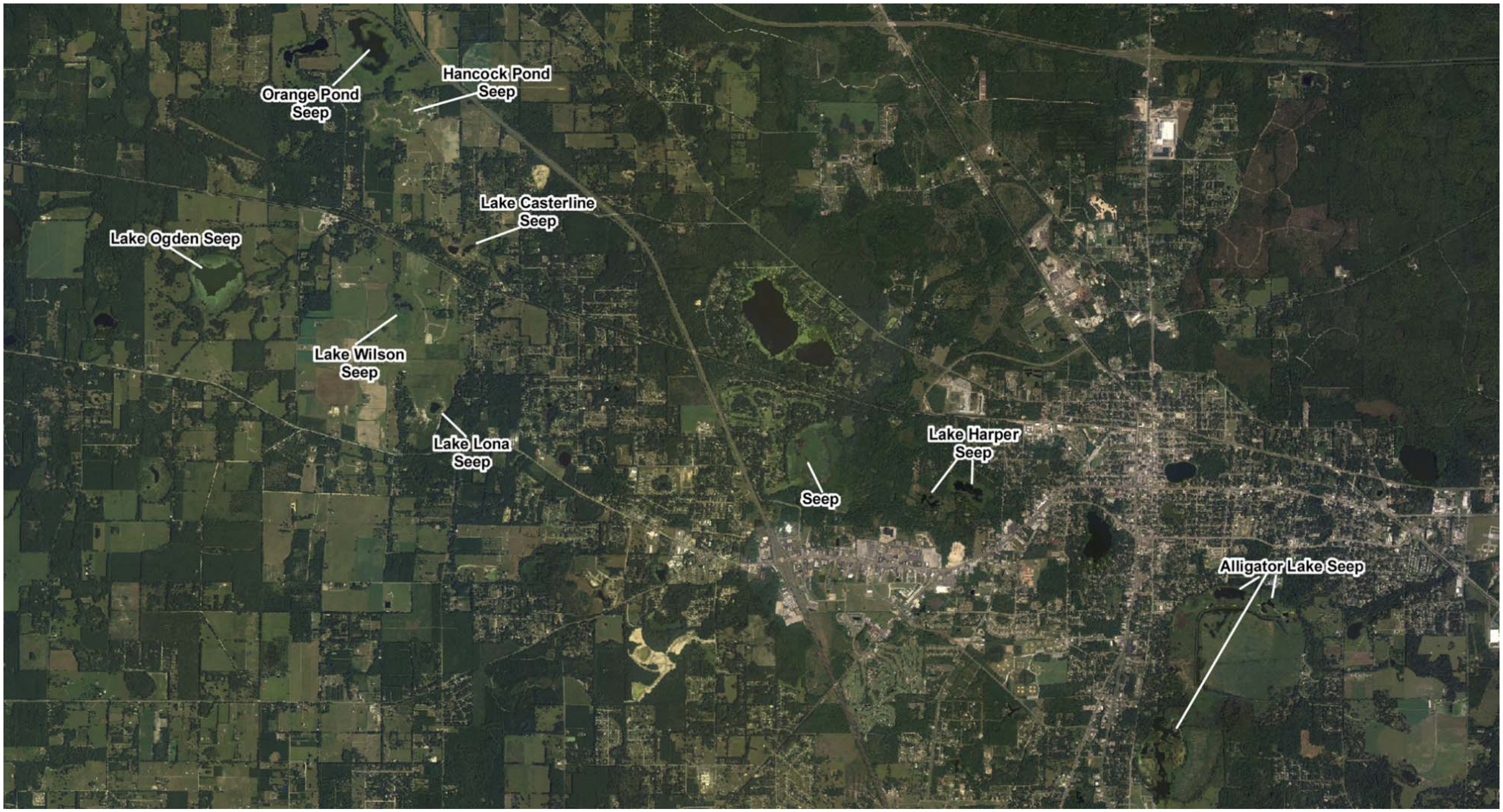
Swallet Watersheds



Key Point: Swallet watersheds used to constrain individual inflows

Swallet-Seeps: *FAS Recharge Mounds*

Low Water Conditions



Key Point: Disappearing lakes are psuedo swallets – high recharge

Swallet-Seeps: *FAS Recharge Mounds*

- Assigned as constant head boundary nodes in the surficial layer only
- Confining unit conductivity (Layer 2) was modified under the seeps to allow restricted recharge into the FAS
  - Conduits terminate near location of swallet seep nodes but are not connected
  - Assigned head at seep nodes taken from topo maps
- Model is not calibrated to flux from swallet seeps because no flux data exists
  - Watershed relationship not valid because water collects in lakes or ponds and seeps through confining unit
  - Flux rate unknown
- Flux at three swallet seeps is constrained by stage and or nearby FAS head measurements
  - Alligator Lake (best constrained seep flux)
    - High and low lake level measurements available
    - FAS head measurement station located nearby
  - San Felasco
    - No stage data for Turkey and Blues Creeks
    - Nearby FAS head measurements
  - Lake Ogden
    - No lake level data
    - Nearby FAS head measurements

Key Point: Model accounts for high recharge from swallet-seeps

Lakes & Wetlands

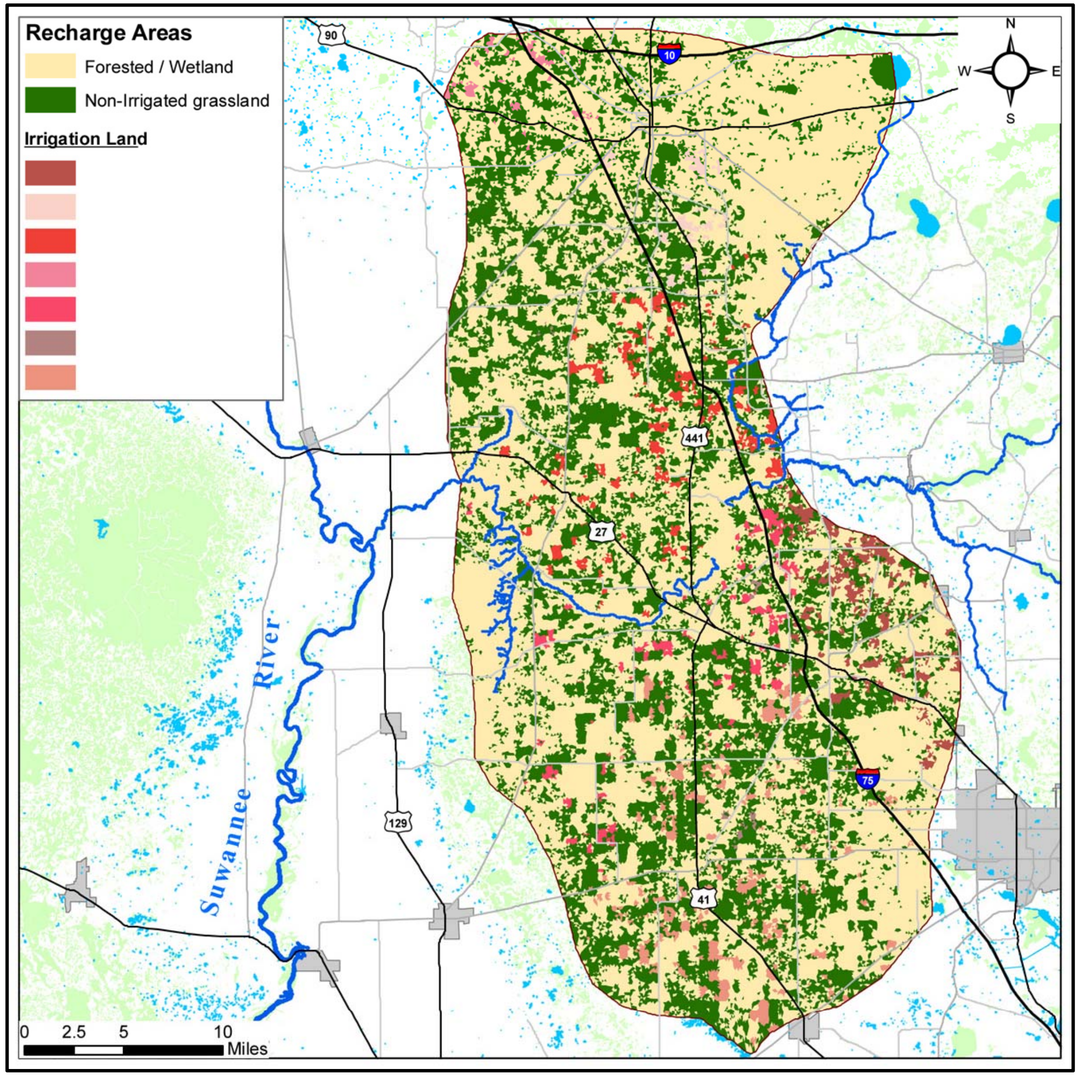
- All other lakes and wetlands are assigned to the surficial model layer as constant head boundary nodes
  - Assigned head = topo elevation
  - Boundary nodes are constrained to only allow aquifer discharge

Recharge from Precipitation: *Total Flux*

- Total recharge was assumed to equal the difference between flux at O'Leno Sink and the flux of the Santa Fe River at Hildreth
  - High water condition flux difference
    - December 2004 through September 2005
    - Average flux = 1680 cfs
    - Min flux = 352 cfs
    - Max flux = 2510 cfs
  - Low water condition flux difference
    - Average flux = 960 cfs
    - Min flux = 720 cfs
    - Max flux = 1215 cfs
- High water model assigned total recharge = 1677 cfs
- Low water model assigned total recharge = 1144 cfs

Recharge from Precipitation: *Distribution*

- Recharge was distributed based on land use maps for model area
- Land use was grouped into three major categories
  - wetlands and forested land
  - irrigated agriculture
  - Non-irrigated grass and scrubland
- Irrigated land was grouped into six subdivisions based on extraction rates from irrigation wells
- Wetlands / forested lands & non-irrigated lands were assumed to get recharge from rainfall only
- Recharge on irrigated land was increased above rainfall based on the volume extracted from irrigation wells
- High Water precipitation assumed to be 71 inches per 12 month period
- Low Water precipitation assumed to be 39 inches per 12 month period



Key Point: Distribution of recharge based on land use maps & ET

Recharge from Precipitation: *Distribution*

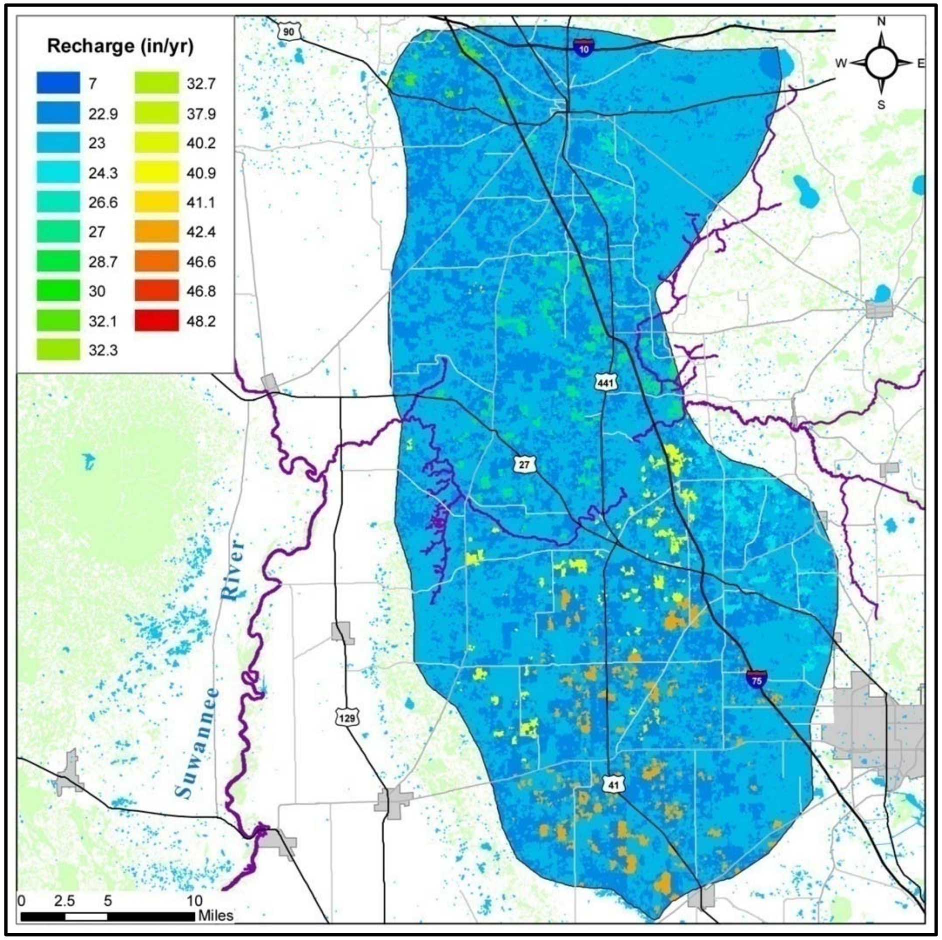
- Evapotranspiration (ET) was then estimated for each land type and subtracted from rainfall or rainfall plus irrigation
  - Assumed that ET was highest where:
    - Water table above land surface
      - High water conditions wetland and lake areas
    - Vegetation is dense and has deep root zone
      - Forested areas (high & low water conditions)
    - Evaporation is increased due to irrigation
      - Irrigated agriculture (high & low water conditions)
  - Assumed ET was lowest where:
    - Water table is significantly below land surface and root zone is shallow
      - Wetland & swallet seep areas (low water conditions)
    - Vegetation consists of grasses and scrubs and land is not irrigated
      - Non-irrigated grass land and fallow agriculture (high and low water conditions)
  - Each recharge zone was ranked from high to low ET, and recharge was varied in each zone until total model recharge matched target recharge for each water condition (high & low)

- Once the recharge distribution was established for each water condition, it was not modified as a calibration parameter

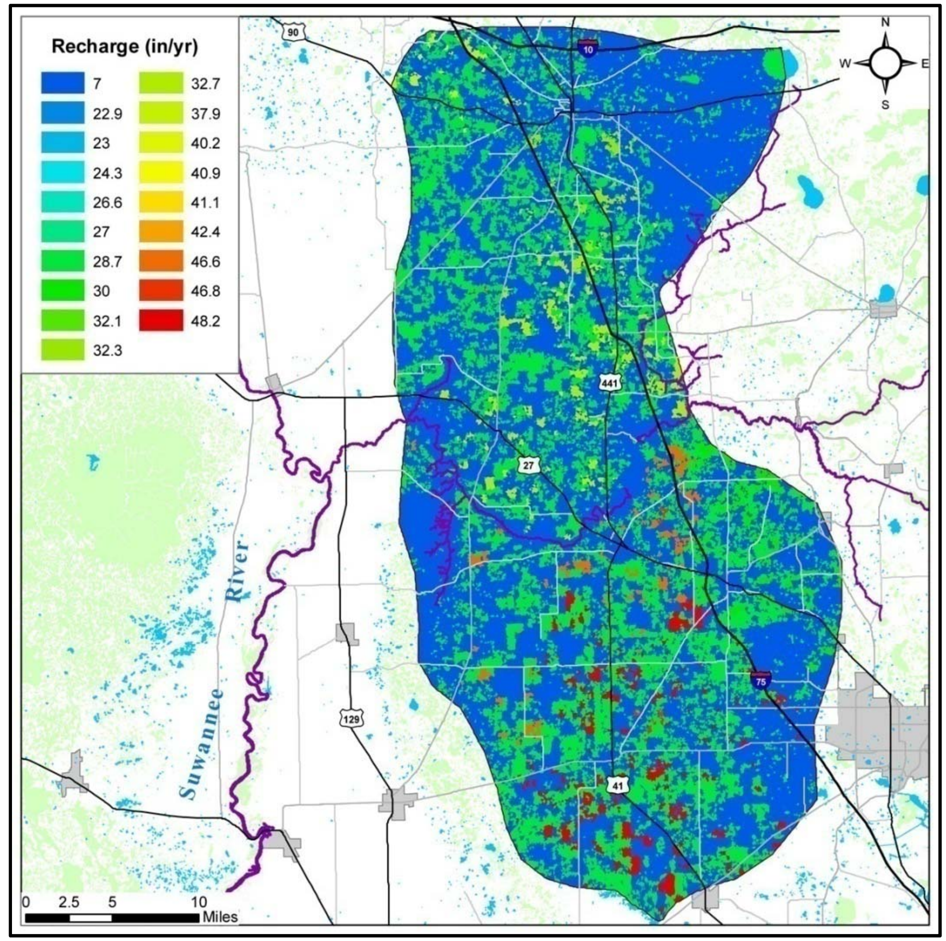
Key Point: Distribution of recharge based on land use maps & ET

Recharge – High & Low Conditions

High Water Conditions



Low Water Conditions



DISCUSSION

1500

Confidence Assessment

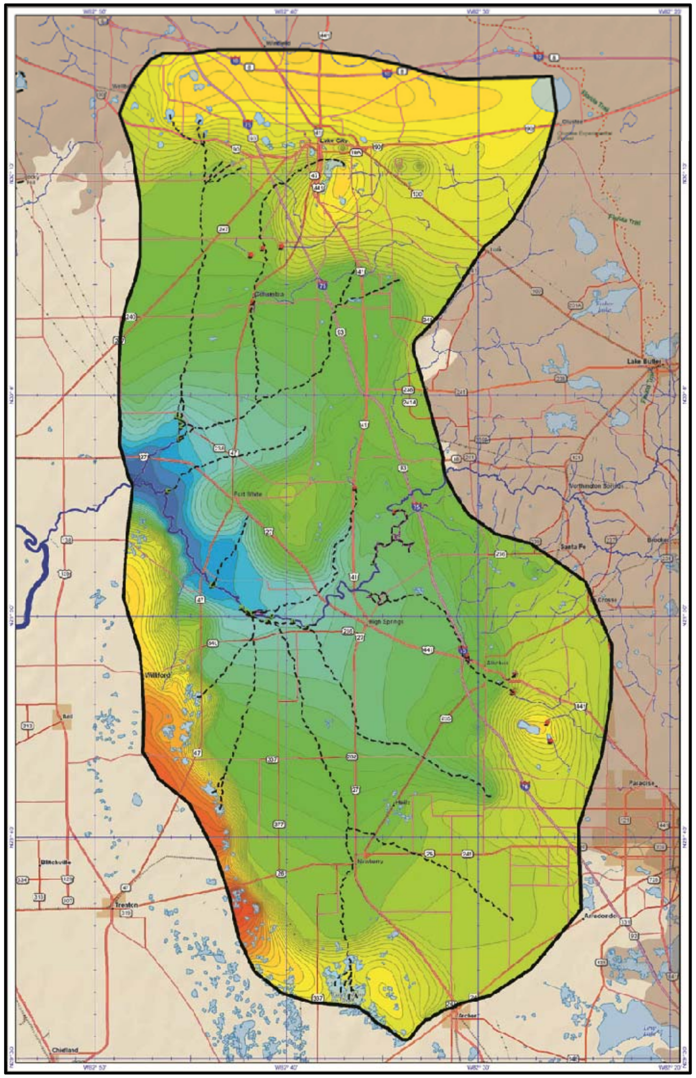
- Confidence in the model predictions stems from:
  - the applicability of the underlying assumptions;
  - the amount and accuracy of the data on which it is based; and
  - the ability of the model to accurately simulate observed conditions, i.e. how well the model calibrates.
- Our fundamental underlying assumptions
  - 3D two-aquifer system separated by a variably thick (present) confining layer.
  - Circulation in the FAS is in the upper ~400 feet, which roughly corresponds to the observed depth of conduit development + 200 ft.
  - There is no significant circulation between the upper and lower Floridan aquifer in the model region.
  - The permeability structure is comprised of dendritic groups of variably sized conduits that converge down-gradient to springs embedded in a variably permeable porous matrix.
  - Flow in the conduits can be described by the Manning-Strickler pipe-flow equation.
  - Flow in the matrix can be described by the Darcy equation.

Confidence Assessment

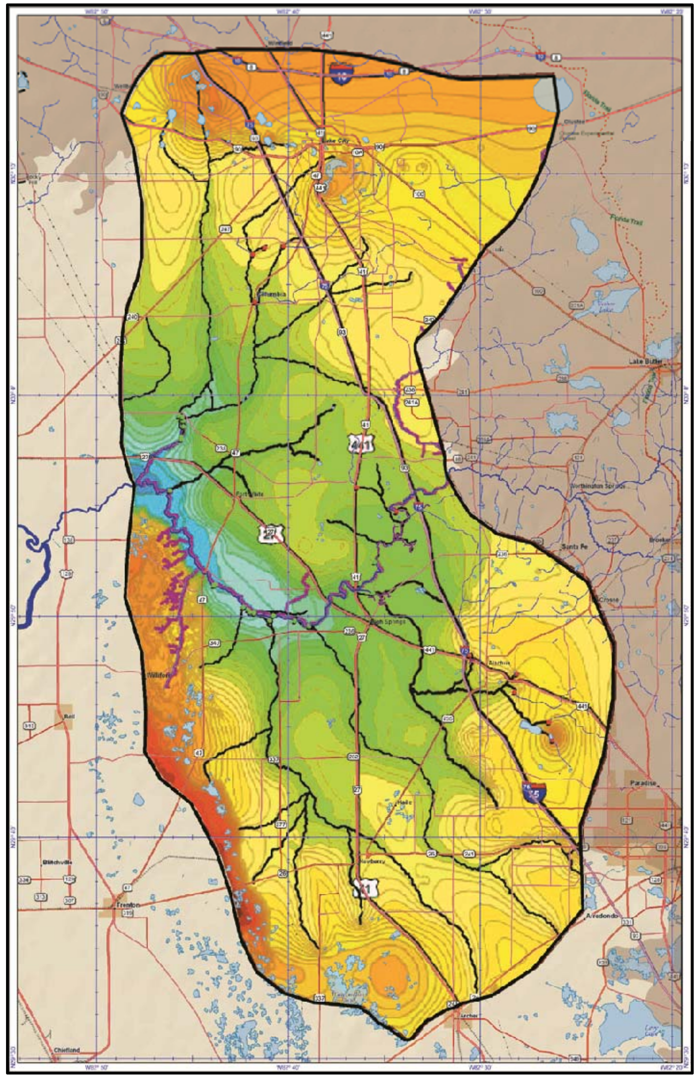
- Our model incorporates a robust dataset of heads, stages, flows, velocities, geologic conditions, and anecdotal observations.
  - Most comprehensive dataset that we've ever had for model construction & calibration.
  - Six-fold calibration: heads, flows, velocities under two sets of conditions – dramatically limits degrees of freedom.
  - Still some holes.
- Model calibrates well to each of the target sets for both high water and low water conditions.
- How can we assess confidence?
  - Validation
  - Professional judgment
  - Some of both

Confidence Assessment: Model Evolution

v08-High Water Calibration



v09-High & Low Water Calibration



v08
- cal to HW to define conduit capacities
- strong data in north
- "well calibrated"

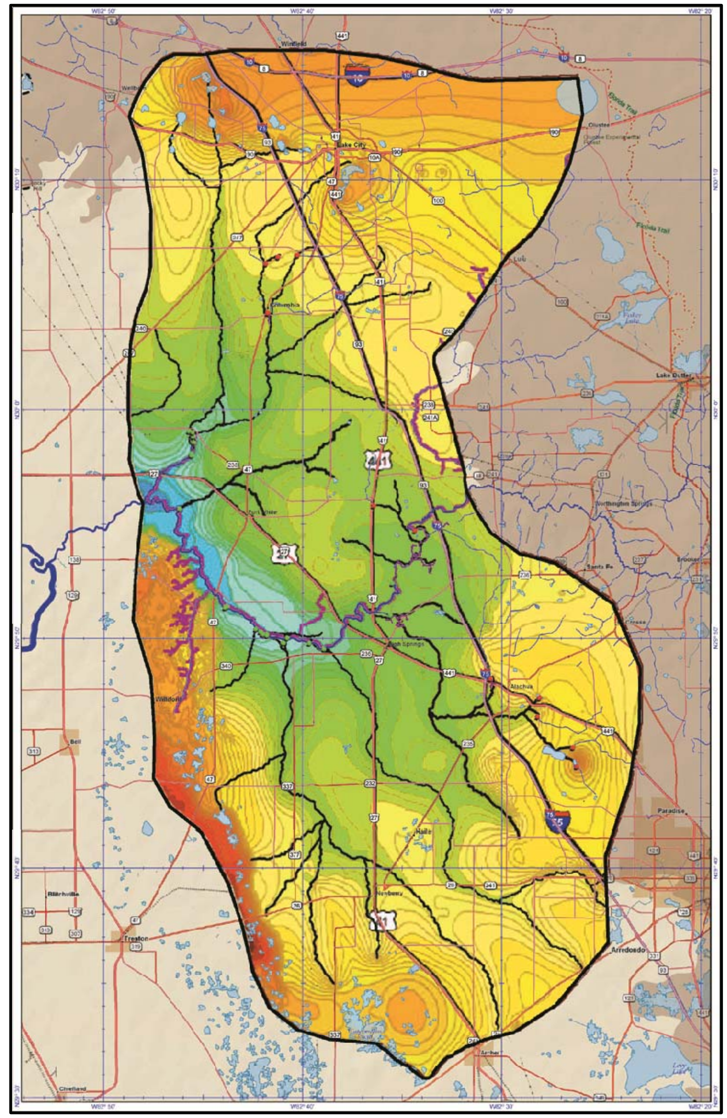
v09
- received sig. more data from ACEPD for southern part model
- low water condition
- decided to expand calibration to address both datasets

Result
- different conduits
- different FAS K
- primarily in south

Key Point: More data = better model

Confidence Assessment: Model Evolution

- Data differences
  - Good, dense data for both conditions in north
  - Much fewer head measurements in south for high water condition
  - Low water head dataset dense in south
- Effect of double calibration
  - Conduits
    - Similar in north
    - Significant changes in south to fit dense dataset
    - Better resolution in conduit placement under low water conditions
    - Identified more detailed conduit patterns
  - FAS-K
    - High water calibration based on higher overall K
    - Head mounds & ridges present in both high & low water datasets
    - High K could not simulate them under low water conditions & calibrate to spring flows
    - Needed to reduce FAS-K to achieve calibration to low water conditions
    - Needed to rework recharge distribution (not magnitudes) to achieve calibration to high water conditions



Key Point: More data = better model

Confidence Assessment: Data

Two basic types of data that determine model accuracy

- Water levels
  - Overall good >> we feel that our two calibration head datasets are sufficiently good (dense) to constrain potentiometric surface in FAS.
  - Issues to consider
    - Data distribution & frequency in Alachua & Gilchrist Counties is strong
    - Not very strong in Columbia County thus FAS north of Santa Fe not as well defined
    - Historical record not that great (poor consistency in time & space)
      - 1998 high water has few data points
      - 2001-2002 low water has more points but still sparse
      - 2004-2005 high water has good coverage north of the river but poor coverage south of the river
      - 2007 low water period has good coverage south of the river but not as good coverage north of the river
    - Steady-state models depend on reliable averages (long data records)

Key Point: Continue & expand head data collection as much as possible

Confidence Assessment: Data

Two basic types of data that determine model accuracy

- Water budget
  - Outputs (discharges)
    - Springs: calibrating to spring fluxes impacts overall flow patterns
      - Ichetucknee Group: excellent coverage - high & low water
      - Santa Fe River springs: poor coverage
        - 1 or 2 measurements for high & low
          - Ginnie, Dogwood, Hornsby, Poe, Gilchrist Blue
        - 1 or 2 measurements for high or low water
          - July, Rum Island, Lilly, Twin
    - Rivers: ensures that overall gains or losses are honored
      - Santa Fe River: good coverage for both stage & flow
      - Cow Creek: no available data
      - Sinking Streams:
        - data needed to calibrate model to surficial aquifer head & flux
        - Very transient: hard to incorporate into steady-state model
        - Limited flow data for few streams
          - Rose Creek, Blues Creek, Pareners Branch

Key Point: Flow data is sparse but critical to model

Confidence Assessment: Data

Two basic types of data that determine model accuracy

- Water budget
  - Inputs (Recharge)
    - Swallets
      - No stage, flow, or dimension data available
      - Stages estimated from topo maps
      - Flows estimated from Rose Creek hydrograph analysis and watershed delineations from topo map (GIS)
      - Lack of data renders this a source of error/reduced confidence
    - Swallet-Seeps
      - No stage, flow, or dimension data available for all but Alligator Lake
      - Only stage data available for Alligator Lake
      - Flux from swallet-seeps very poorly constrained
      - Used constant head nodes in surficial zone for all seeps
      - Adjusted K in confining unit to attain calibration to underlying FAS head
    - Recharge from precipitation
      - Good precipitation data
      - ET data for various land uses under different water level conditions not available
      - Total model recharge constrained by Santa Fe River flow data
      - Recharge distribution could be improved if better ET data becomes available

Key Point: Swallet inflows are most poorly constrained data values

Confidence Assessment: Summary

Confidence much higher for outflows than for inflows

- Major benefit of multiple calibration variables (head, flow, velocity) is that the effect of one poor dataset is offset by the other two .
- Good head & spring discharge datasets minimizes the range of acceptable values for poorly constrained inflows.
- Primary impact on confidence in predictions centers on simulated conduit flow to springs.
  - Example
    - One dataset for Ichetucknee shows max flow at Ichetucknee of 40 cfs and 105 cfs for Blue Hole.
    - 2nd dataset for Ichetucknee (more complete) shows max flow at Ichetucknee of 80 cfs and 295 cfs for Blue Hole.
    - Without 2nd dataset, we would have under-estimated the conduit capacities for Ichetucknee (1/2) & Blue Hole (2/3).
  - Areas of lowest confidence therefore are the springsheds with least flow data:
    - Hornsby, Lilly, Rum Island, Gilchrist Blue, July, Twin, Sunbeam
    - Hard to constrain spring relationships, i.e. Poe, Lilly, Rum Island under low water conditions.

Key Point: Lowest confidence in springsheds with least flow data

Summary & Conclusions

- Model successfully simulates realistic groundwater flow to springs in the WSFRB by specifically addressing karst conduit flow.
- Model delineates 10 individual springsheds that shift between low water and high water conditions: *Ichetucknee, Blue Hole, Sunbeam, River Rise, Rum Island, July, Hornsby, Poe/Lilly, Ginnie, & Twin*
- Model can be used to evaluate both water quantity and quality issues and concerns relative to springs protection.
- Model is now publically available.
- Provided technical presentation to SRWMD, SJRWMD, & FLDEP.
- CCNA wants local governments to use this model to support water resource protection in the WSFRB.

- www.geohydros.com/CCNA/

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