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

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GeoHydros, LLC

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Program Objectives

- Choose a karst basin in Florida that is conducive to long-term study and representative of other Florida karst basins.
- Identify and test characterization methods that provide an accurate understanding of karst controls on groundwater flow patterns.
- Deploy these methods to collect the necessary data to fully describe flow through the study basin.
- Identify and test modeling methods that accurately simulate the karstic groundwater flow patterns.
- Deploy these methods to develop a basin-scale model of flow through the study basin that accurately simulates observed conditions.
- Condense the knowledge gained through the long-term study into recommended procedures for characterizing and modeling groundwater flow in Florida's other karst basins.

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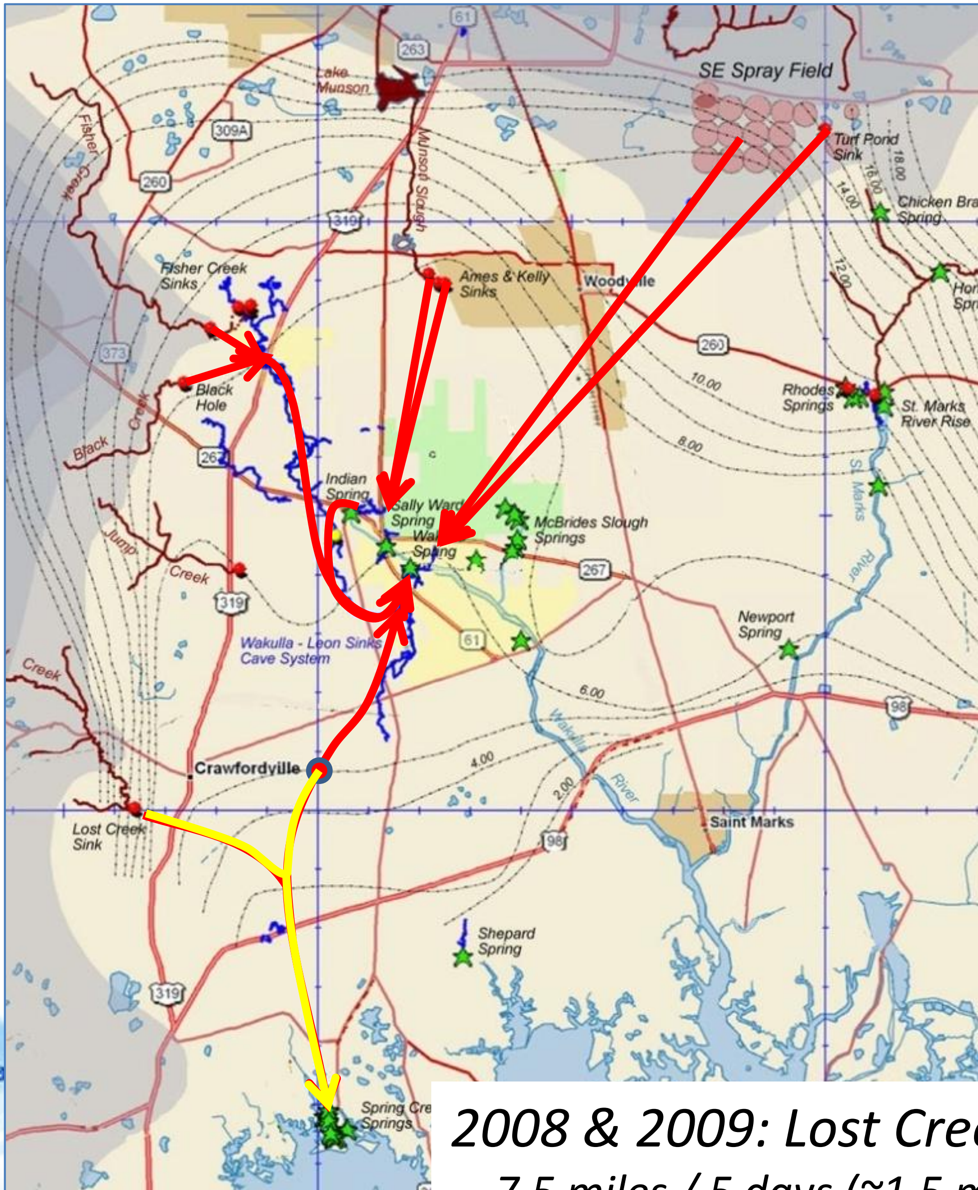
Talk Overview

- Modeling Objectives
- Model status
- Construction Overview
- Calibration Dataset Overview
- Results
  - Calibration
  - Simulated Potentiometric Surface
  - Simulated Velocities
  - Springshed Delineation
- Future Work & Improvements
- Applications

Real-World Groundwater Flow Patterns



2002: Fisher Creek – Emerald Sink
1.7 miles / 1.7 days (3,770 ft/day)

2003: Black Creek – Emerald Sink
1.6 miles / 1.6 days (2,670 ft/day)

2004: Emerald Sink – Wakulla Spring
10.3 miles / 7.1 days (7,650 ft/day)

2005: Kelly Sink – Indian Spring
5.2 miles / 13.5 days (2,040 ft/day)

2005: Ames Sink – Indian Spring
5.2 miles / 17.2 days (1,600 ft/day)

2005: Indian Spring – Wakulla Spring
5.5 miles / 5.9 days (4,890 ft/day)

2006: Wells – Wakulla Spring
10.4 miles / 66.5 days (830 ft/day)
10.4 miles / 56 days (980 ft/day)

2006: Turf Pond – Wakulla Spring
10.9 miles / 56 days (1,030 ft/day)

2008 & 2009: Lost Creek – Spring Creek & Wakulla Spring
7.5 miles / 5 days (~1.5 miles/day) – 7.75 miles / 47 days (~870 ft/day)

Important Hydrogeologic Complexities

Springs

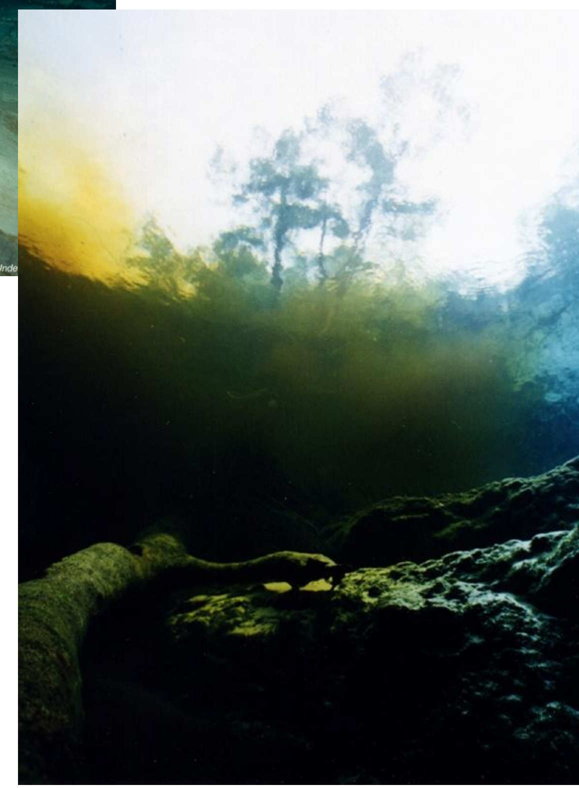
large magnitude discrete discharges

Conduits

Very significant preferential flow paths

GW / SW Mixing

Impacts water budget



Swallets

Large magnitude discrete recharge

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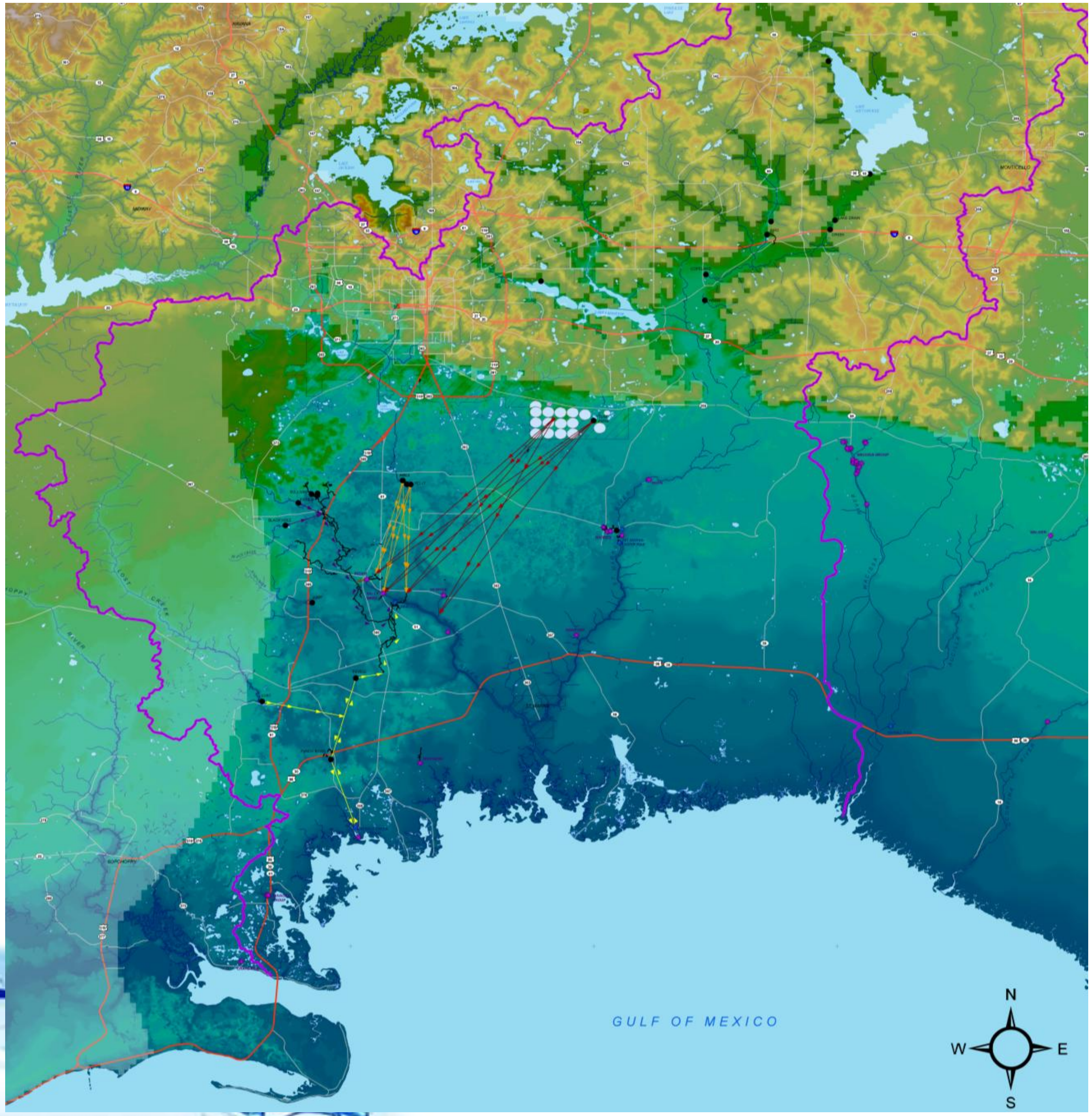
Hydrogeologic Complexities



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

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Model Objectives

- Develop a model that calibrates to high and low water conditions.
  - *Most models only address average conditions*
  - *Thus far, we've only calibrated to high water conditions*
- Define all springsheds that may interact under varying conditions to control water and contribute water flow to Wakulla Spring.
  - *We know that springsheds change and interact under different conditions*
- Develop a model that incorporates karst features and conduit flow patterns.
- Develop a model that will deliver reliable predictions of travel-times.
  - *Use model results to develop spring/aquifer vulnerability maps*
- 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.

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What is a Groundwater Model?

- Computer generated simulation of groundwater flow patterns & rates.
- Used to make predictions about impacts to flow and quality stemming from specific actions or conditions.
  - *Groundwater availability & development*
  - *Contaminant vulnerability & cleanup*
- Confidence in predictions stems from the model's ability to simulate real-world conditions *(calibration).*
  - Models that accurately simulate present or past conditions are deemed to be reliable predictors of future conditions.
- In order to be reliable, modeling assumptions must be valid or applicable to the environment being modeled.
- We've been using groundwater models in Florida since at least the 1970's to predict the impacts of development on groundwater levels and groundwater quality.

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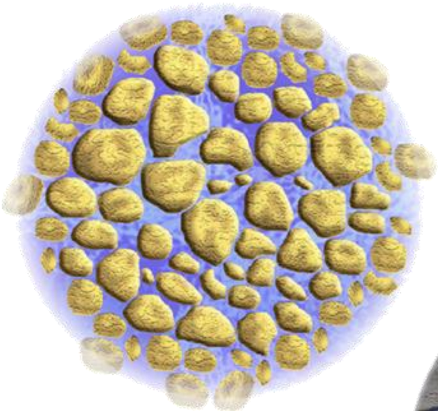
Basic Conceptualization Options

Most commonly assumed

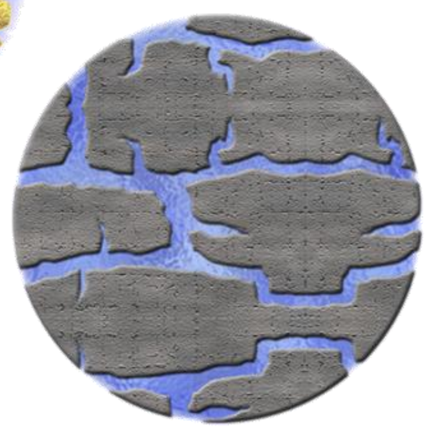
Most commonly true

Porous Media



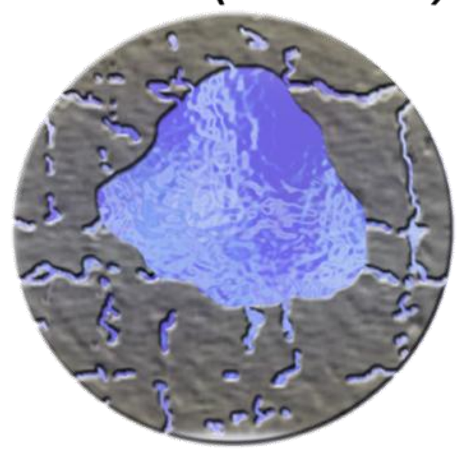
sand / sandstone
easy to characterize
simplest math

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

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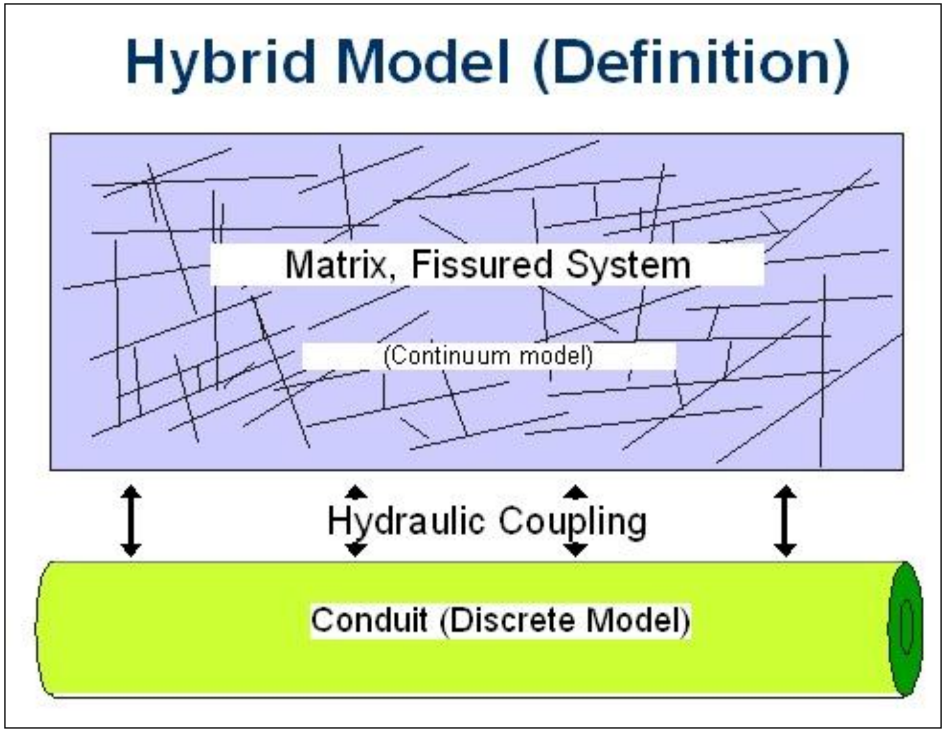
Numerical Approach & Software

- 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/

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Model Status

- Completed the expansion and re-development of the model framework.
- Expanded the boundaries to all for overlap with potential future model of the Suwannee River Basin.
- Analyzed historical groundwater level data and developed composite calibration datasets for high-water and low-water periods.
- Developed representative recharge coverages for high-water and low-water periods.
- Developed conduit assignments for model framework.
- Produced a converged steady-state model that calibrates to the high-water period dataset.

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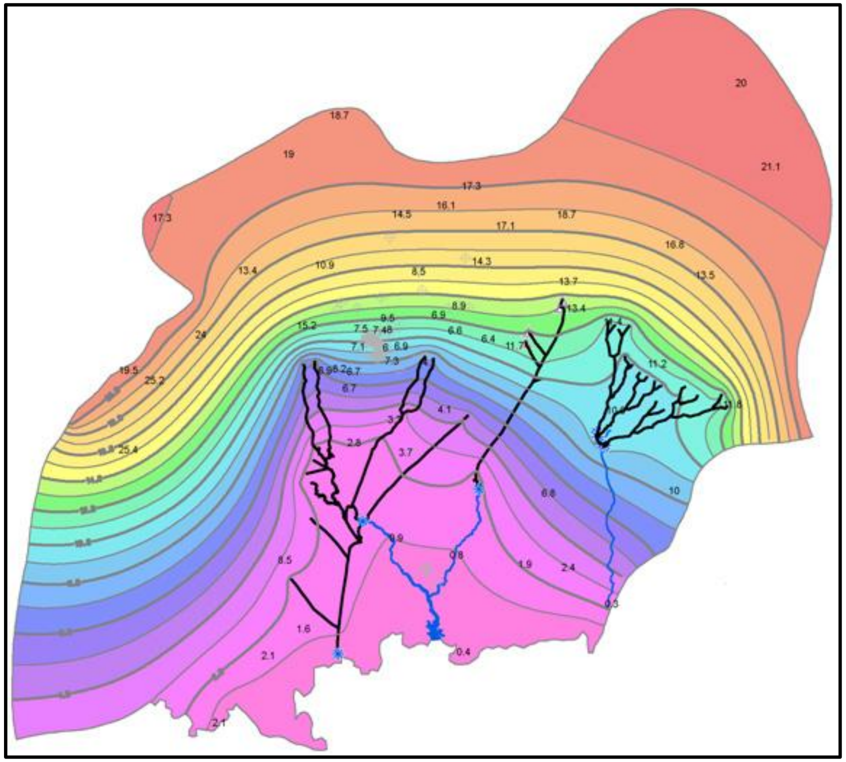
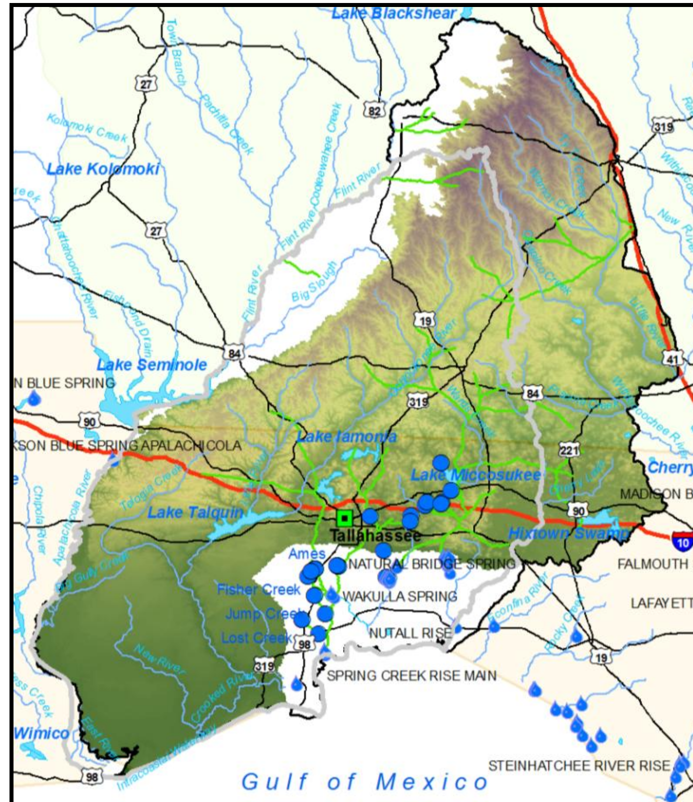
Model Status



- Smaller domain – just into GA based on previous model head potentials
- No surficial aquifer
- No recharge
- Cursory calibration dataset
- No pumping



- Larger domain to allow model to define springshed
- SAS, IAS, FAS framework
- recharge
- Expanded calibration dataset

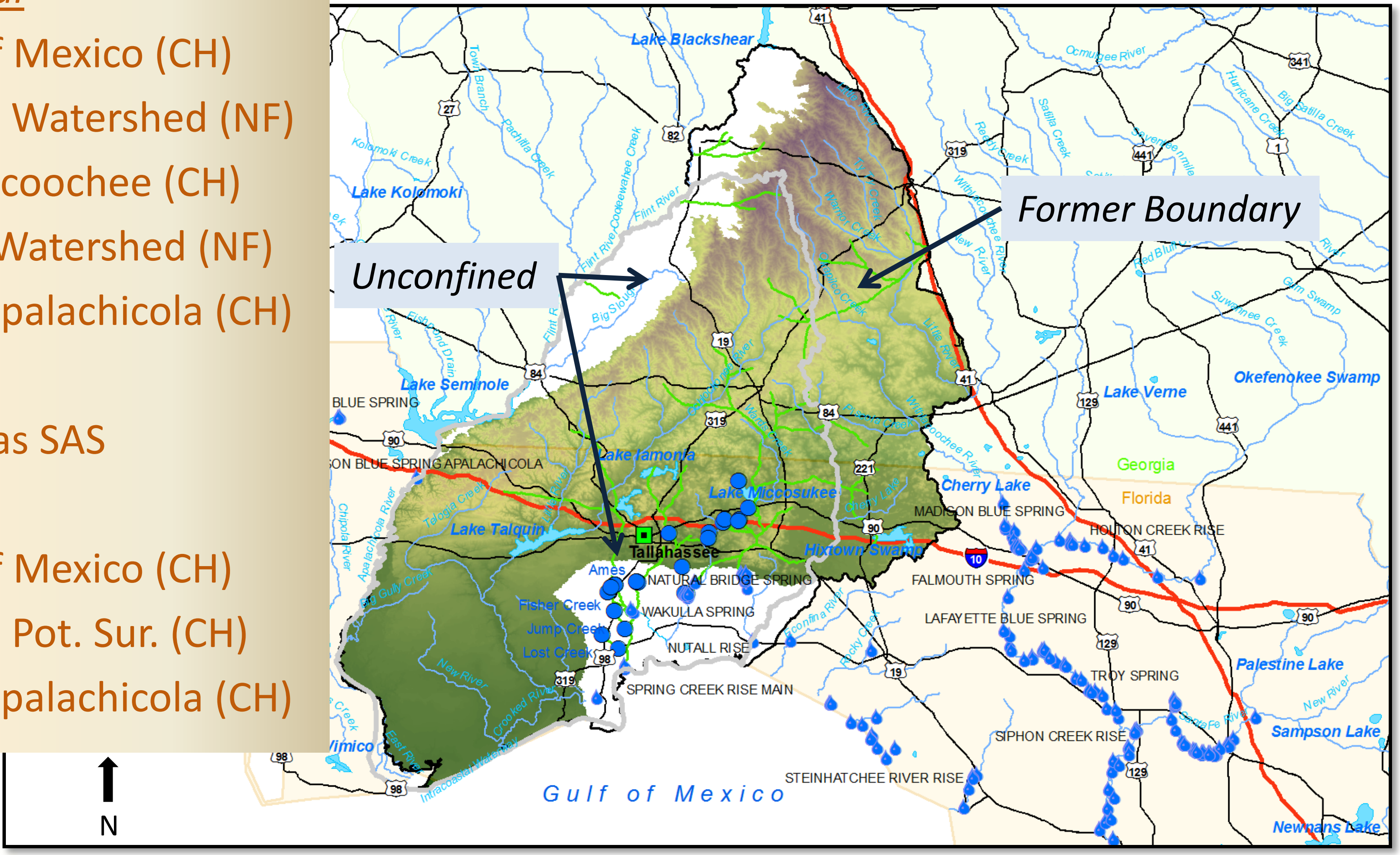
Model Boundaries

<u>*Surficial*</u>
Gulf of Mexico (CH)
Aucilla Watershed (NF)
Withlacoochee (CH)
With. Watershed (NF)
Flint/Apalachicola (CH)

<u>*IAS*</u>
Same as SAS

<u>*FAS*</u>
Gulf of Mexico (CH)
Interp. Pot. Sur. (CH)
Flint/Apalachicola (CH)

Ground Water Model Regional Topography and Hydrology



CH = constant head
NF = no flow

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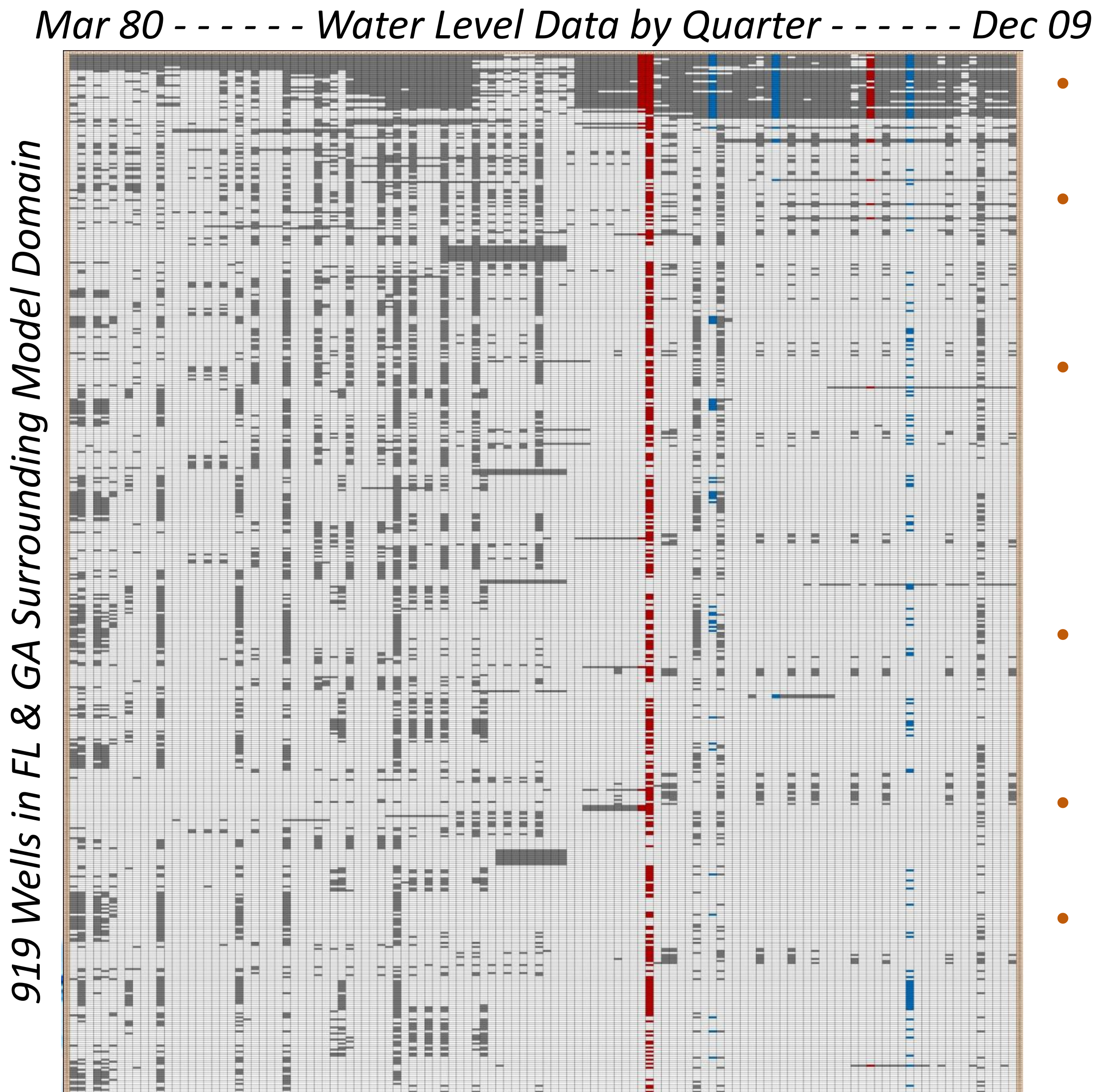
Developing a Calibration Dataset



- 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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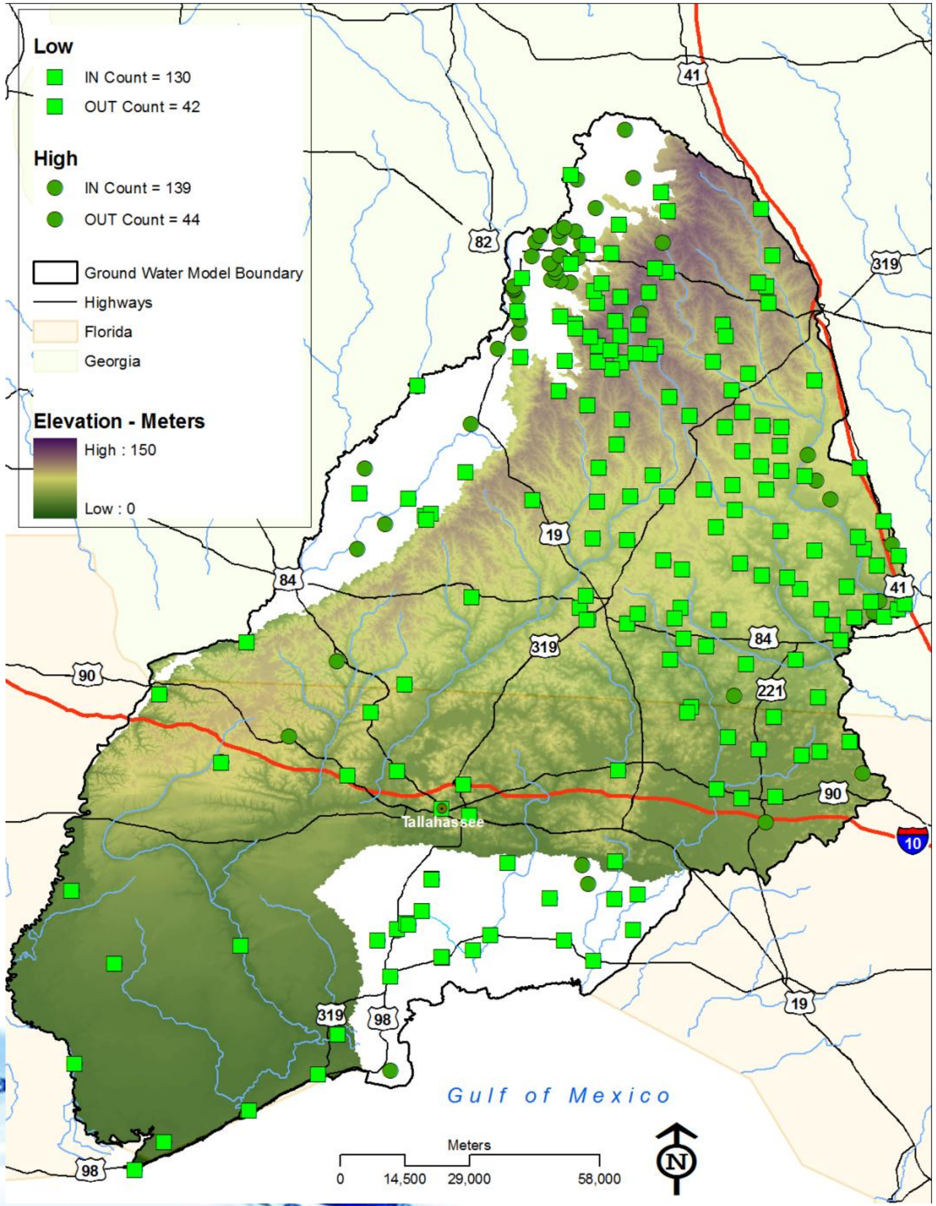
Calibration Datasets



- High Water
  - 1998 2nd quarter - *GA & NFWMD*
  - 2005 2nd quarter – *SRWMD*
- Low water
  - 2002 2nd quarter – *SRWMD*
  - 2000 2nd quarter – NFWMD
  - 2006 3rd quarter – Georgia
- Current model is only calibrated to high water conditions dataset
- *Boxes are low-water data points*
- *Circles are high-water data points*
- *Shared points are not distinguished.*

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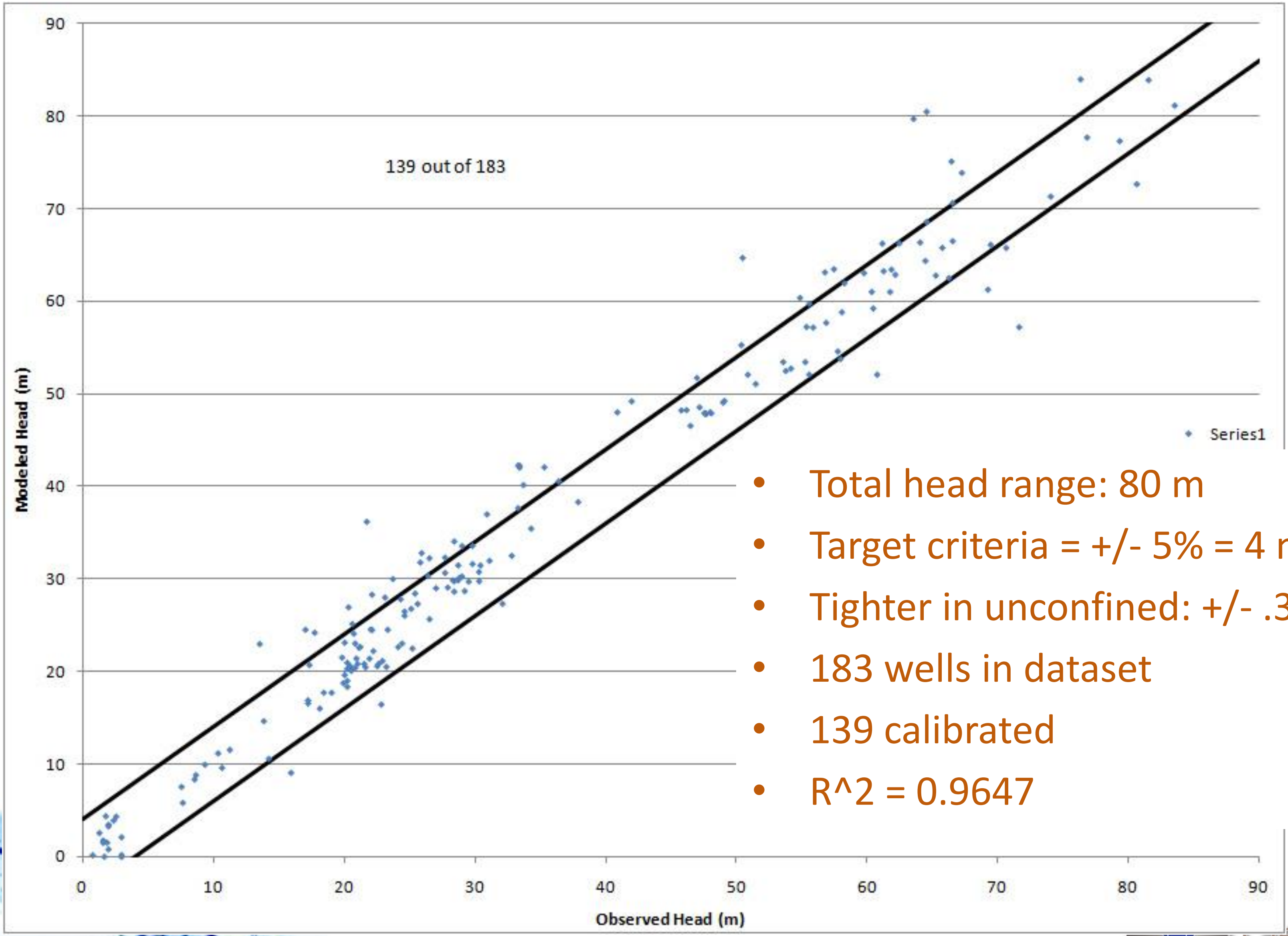
Calibration



- Total head range: 80 m
- Target criteria = +/- 5% = 4 m
- Tighter in unconfined: +/- .3 m
- 183 wells in dataset
- 139 calibrated
- R^2 = 0.9647

Model Construction

- Layers
  1. Surficial (SAS) discontinuous thus the layer 1 contains SAS, IAS, & FAS
  2. Confining Layer (IAS) discontinuous thus layer 2 contains IAS & FAS
  3. Upper Floridan – Suwannee Limestone discontinuous thus layer 3 contains both Suwannee & Ocala
  4. Upper Floridan – numerical layer for cave assignments – same assignments otherwise as layer 3.
  5. Upper Floridan – Ocala limestone with some conduits for theorized Flint River conduits.

Model Construction

- Conductivity Assignments
  - Sand (SAS) = 5E-4 m/s hor. & 5E-5 m/s ver. ~ medium sand
  - IAS = 2E-5 m/s hor. & 5E-9 m/s ver. ~ fine sand or silt hor. & clay ver.
  - Suwannee = 5E-4 m/s hor. & ver.
  - Ocala = 2E-4 m/s hor. & ver.
  - Ocala near Flint River = 2E-2 m/s hor. & ver.
- All layers are homogeneous except for Ocala near Flint River because we don’t know much about caves but know the heads are flat.
- Comparison to Porous Media Approach
  - 24 conductivity zones in FAS
  - Min K = 1E-5 m/s
  - Max K = 0.05 m/s (~2 orders of magnitude higher than conduit model)

Model Construction

- Recharge
  - High water = 15.7 inches / year
  - Low water = 6.4 inches / year
  - Based on flow analysis on GA rivers
    Focused on GA rivers because most of FL rivers receive groundwater whereas GA rivers flow over confined area
- Recharge Distribution
  - Distributed equally over model domain
  - Want to redistribute that based on land use but total target will remain same
  - Recharge to Floridan in confined areas is ~ 2 inches per year where rest of recharge flows through surficial to rivers and streams.

Model Construction

- Swallet Estimates
  - Based on Lost Creek Flow (1999 – 2010 *some gaps*)
  - Max = 3960 cfs, Min = 0 cfs, Ave = 122 cfs, Med = 35 – 178 cfs *(all or upper 1/3)*
  - Assume high water to be ~70 cfs as steady-state target
  - Assume Fisher, Black, ~ ½ Lost Creek = ~ 35 cfs
  - Assume Ames (Munson Slough) ~ 2/3 Lost Creek = 47 cfs
  - Assume Upper St. Marks combined ~ = Lost Creek or more = ~70 cfs
  - Total swallet inflow ~= 260 cfs
  - Assume Lakes not active under high water because of groundwater elevations in GA – become active under low water conditions
- Setup
  - Five layers, 6 slices
  - Elements: 3, 832,155
  - Nodes: 2,312,730

Runtime: ~20 – 25 mins per run

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Model Construction

- Pumping
  - Florida
    - Defined by NFWMD permitted pumping (average)
    - 49 wells
  - Georgia
    - Data not as good / compiled by county
    - Decatur = 32-42 MGD
    - Grady = 5-8 MGD
    - Thomas = 15-20 MGD
    - Mitchell = 30-40 MGD
    - Brooks = 3-5 MGD
    - Colquitt = 9-18 MGD
    - Worth = 7-10

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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 & 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

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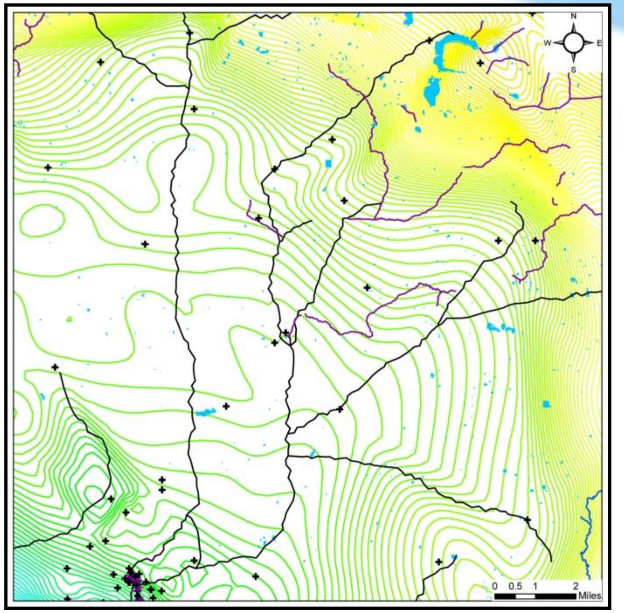
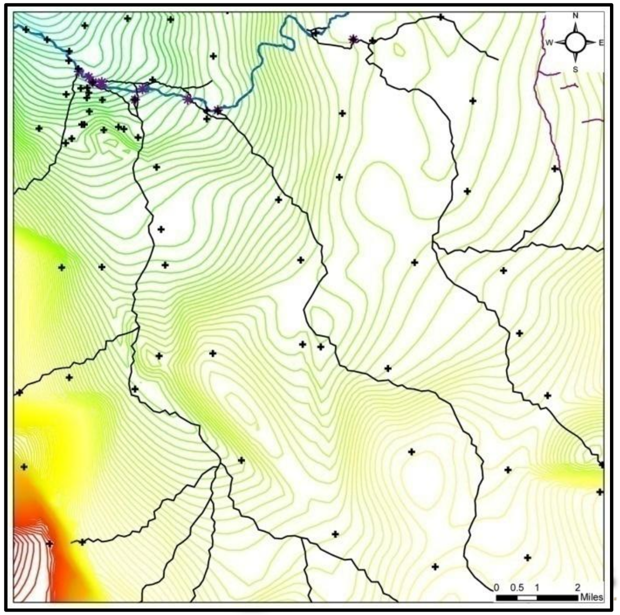
Conduit Locations & Assignments

- 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)

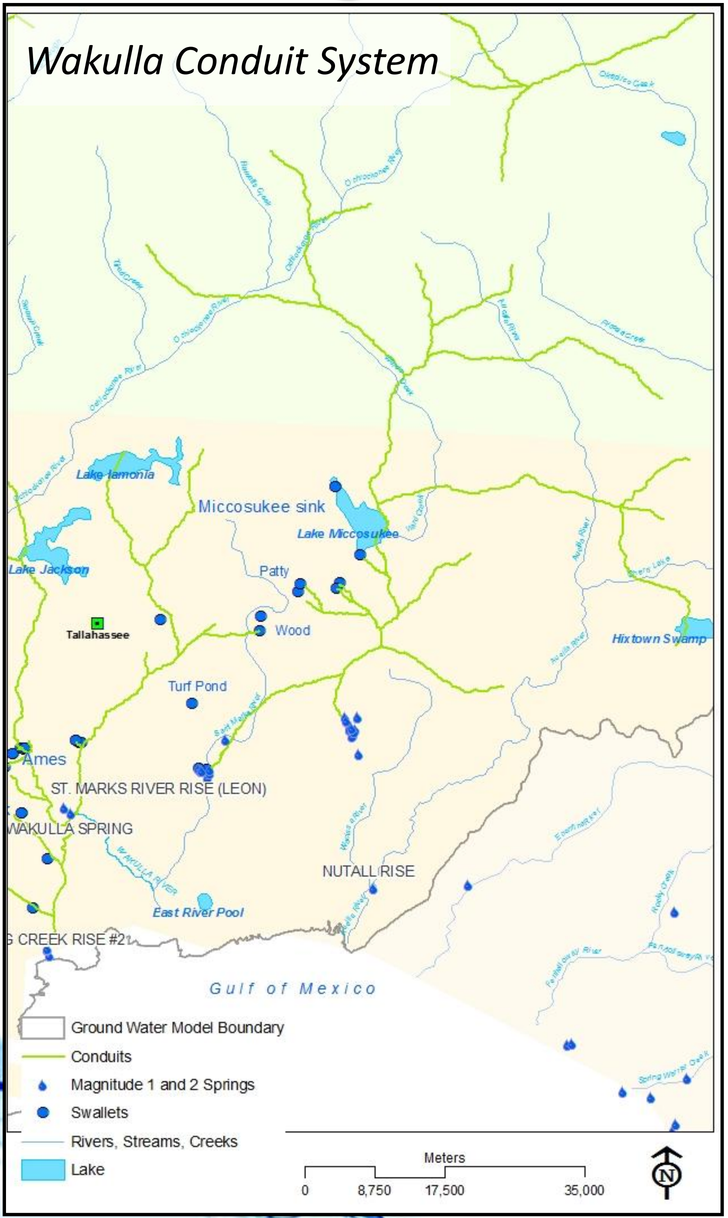
Northern Region

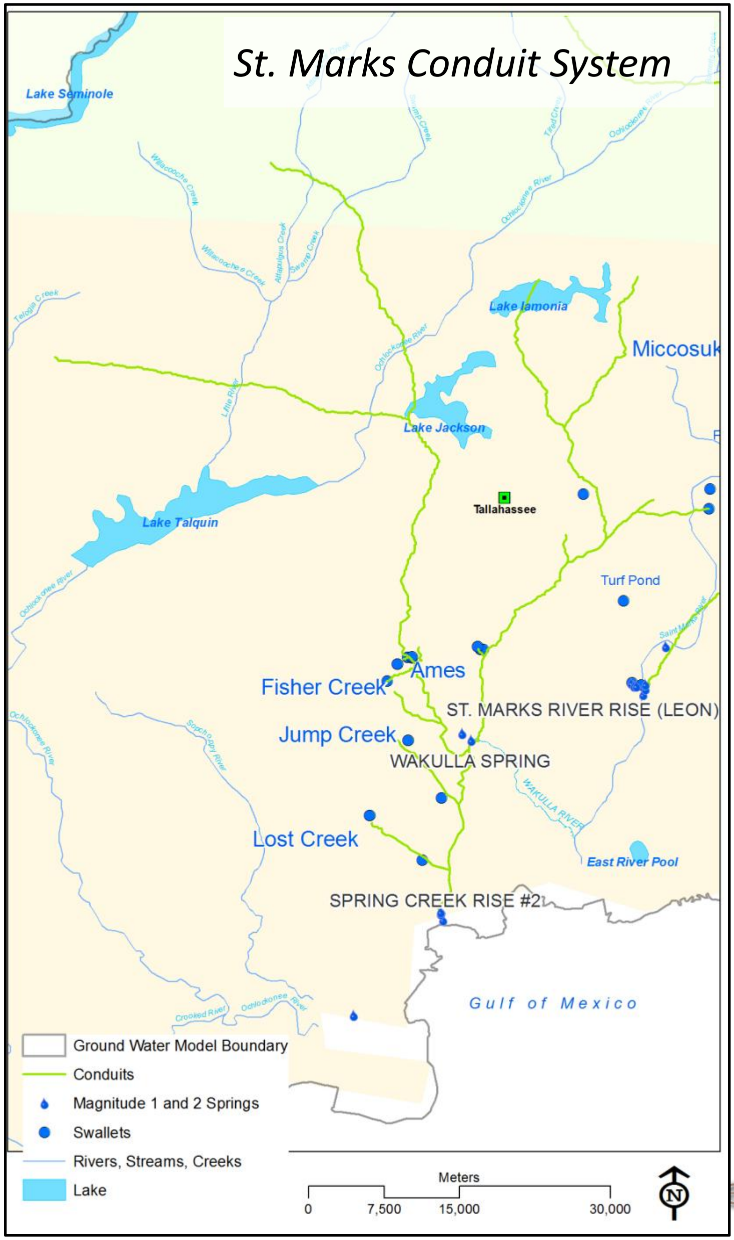


Southern Region



Modeling Conduits …





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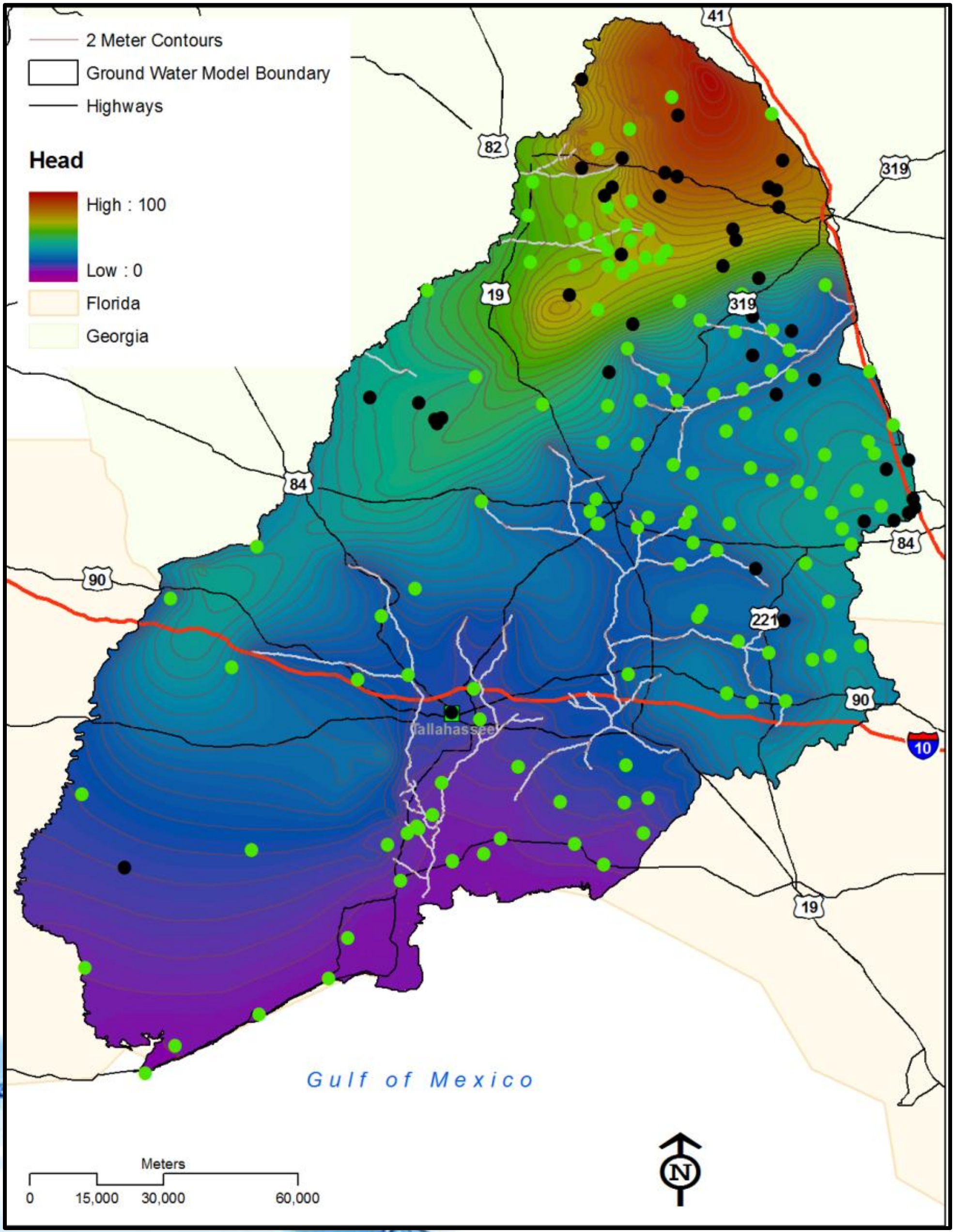
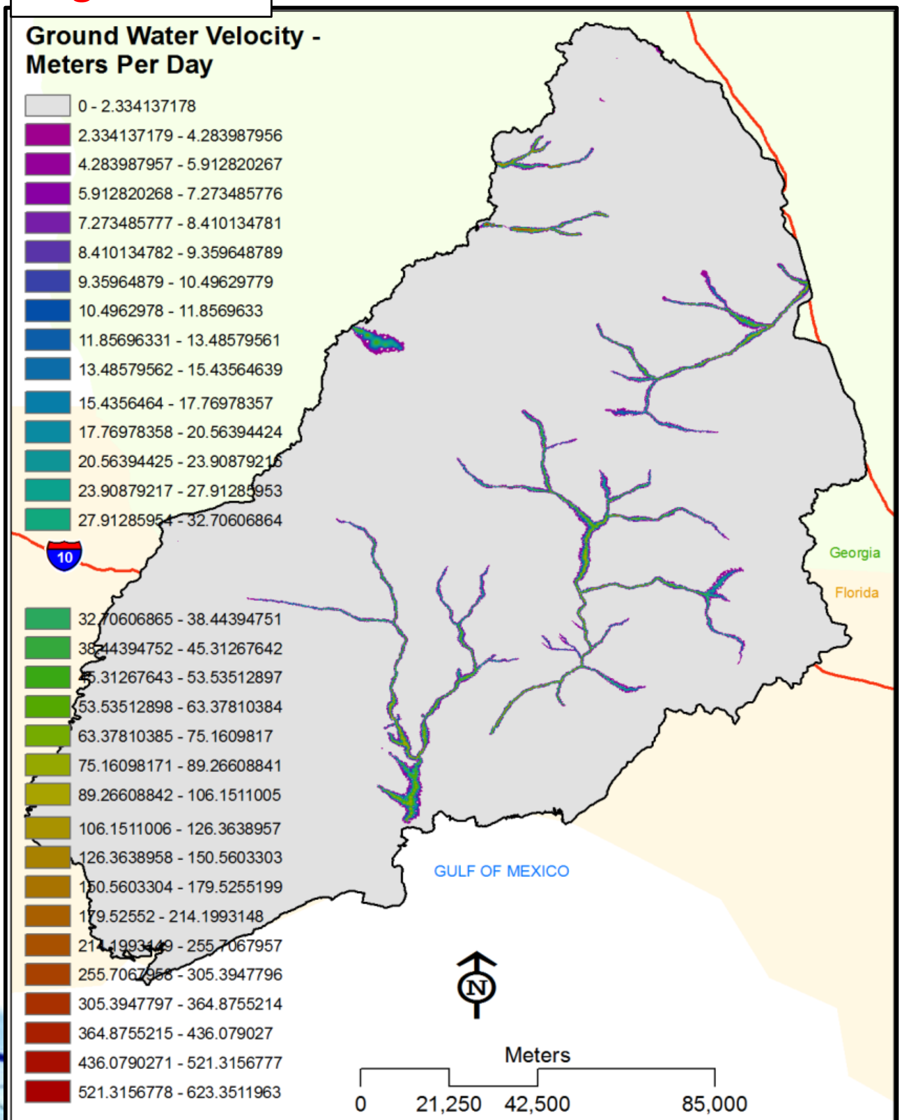
Model Results: Groundwater Levels

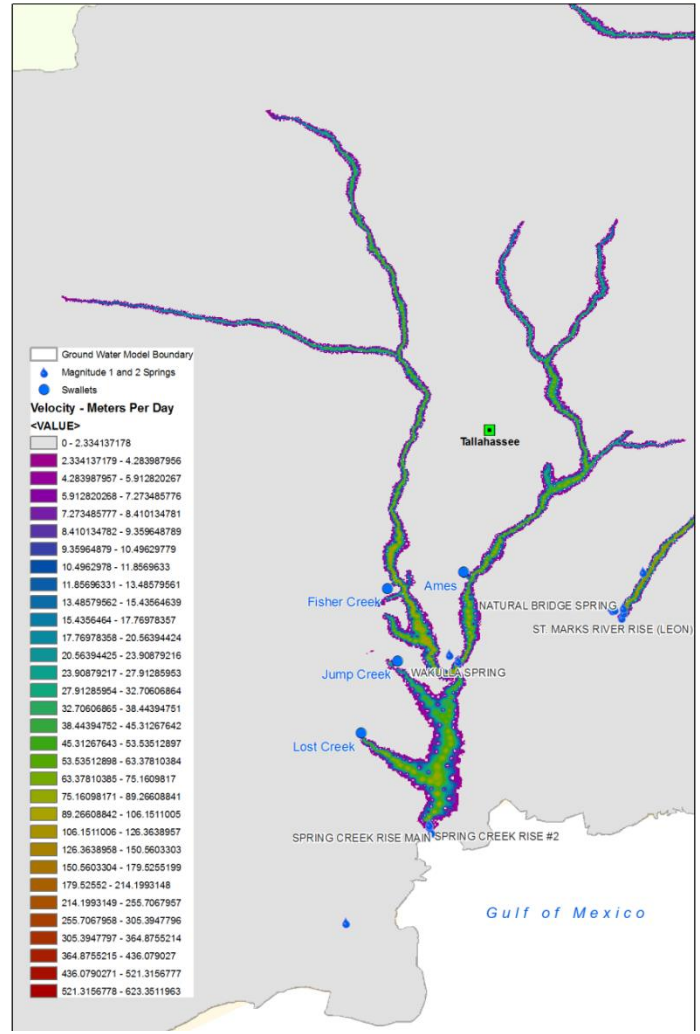


- Green dots mark wells that fall within the calibration range.
- Black dots mark wells that fall outside of the calibration range.
- Black dots near conduts can be brought into calibration through continued manipulation of conduit locations and parameter settings.

Model Results: Groundwater Velocities

High Water





- Conduits model: ~ 10 to ~620 m/day
- Conduits observed: ~ 100 – 2400 m/day

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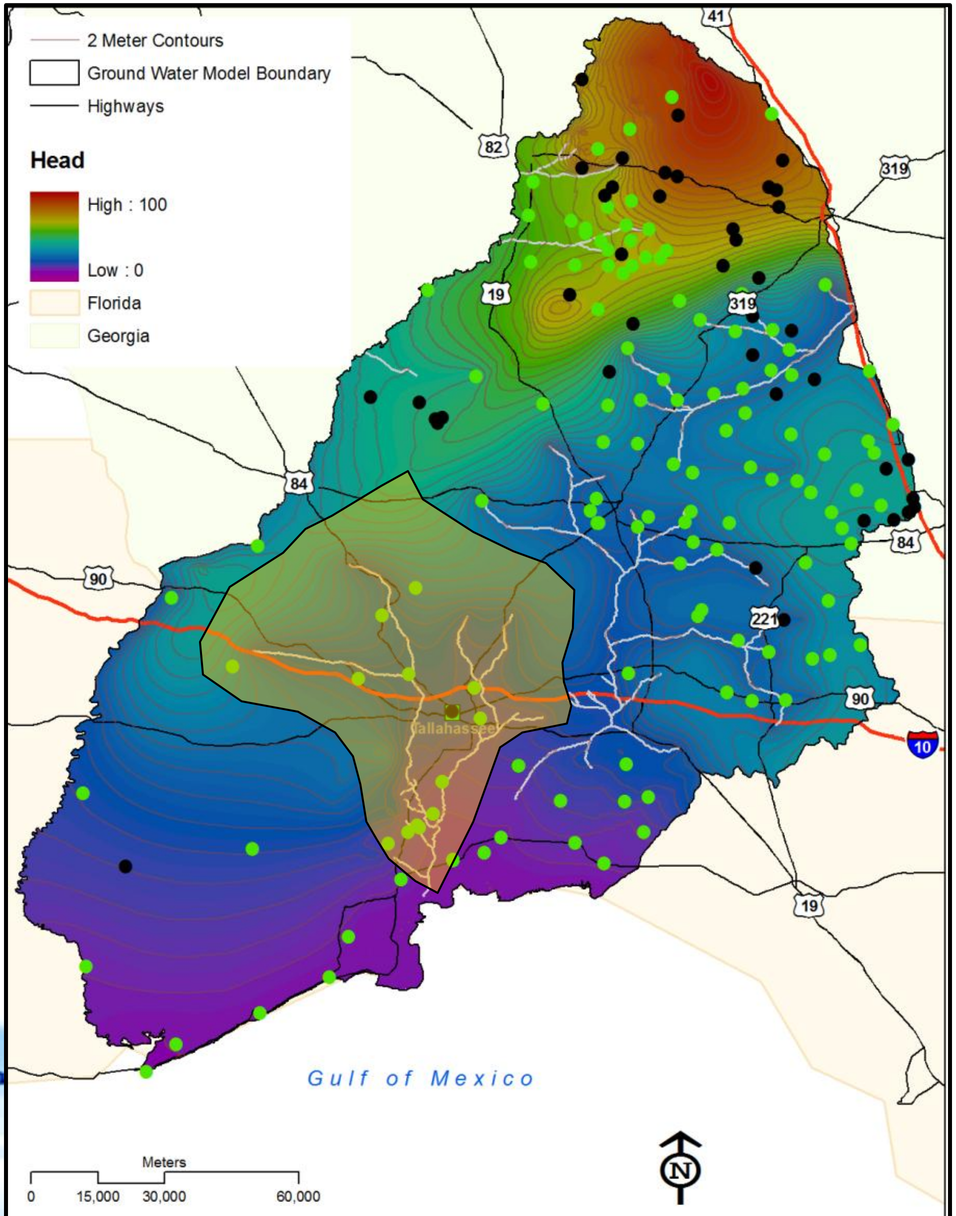
Model Results: Wakulla Springshed



- 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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Where we want to go from here?

- Constrain flow paths and velocities for Upper St. Marks swallets
- Iterate calibration with low water dataset
  - Will improve the delineation of conduit networks
  - Will improve high water calibration as well
  - Makes model much more unique
- Develop vulnerability maps & animations for springsheds
- Develop pumping impact analyses for individual springsheds
  - Add returns – i.e. spray field
  - Will attribute pumping to the springs that are impacted
  - Refine GA data if possible
- Develop recommended procedures for modeling in karst basins
- Expand effort to address other major karst basins
- Establish benchmark models for aquifer assessments

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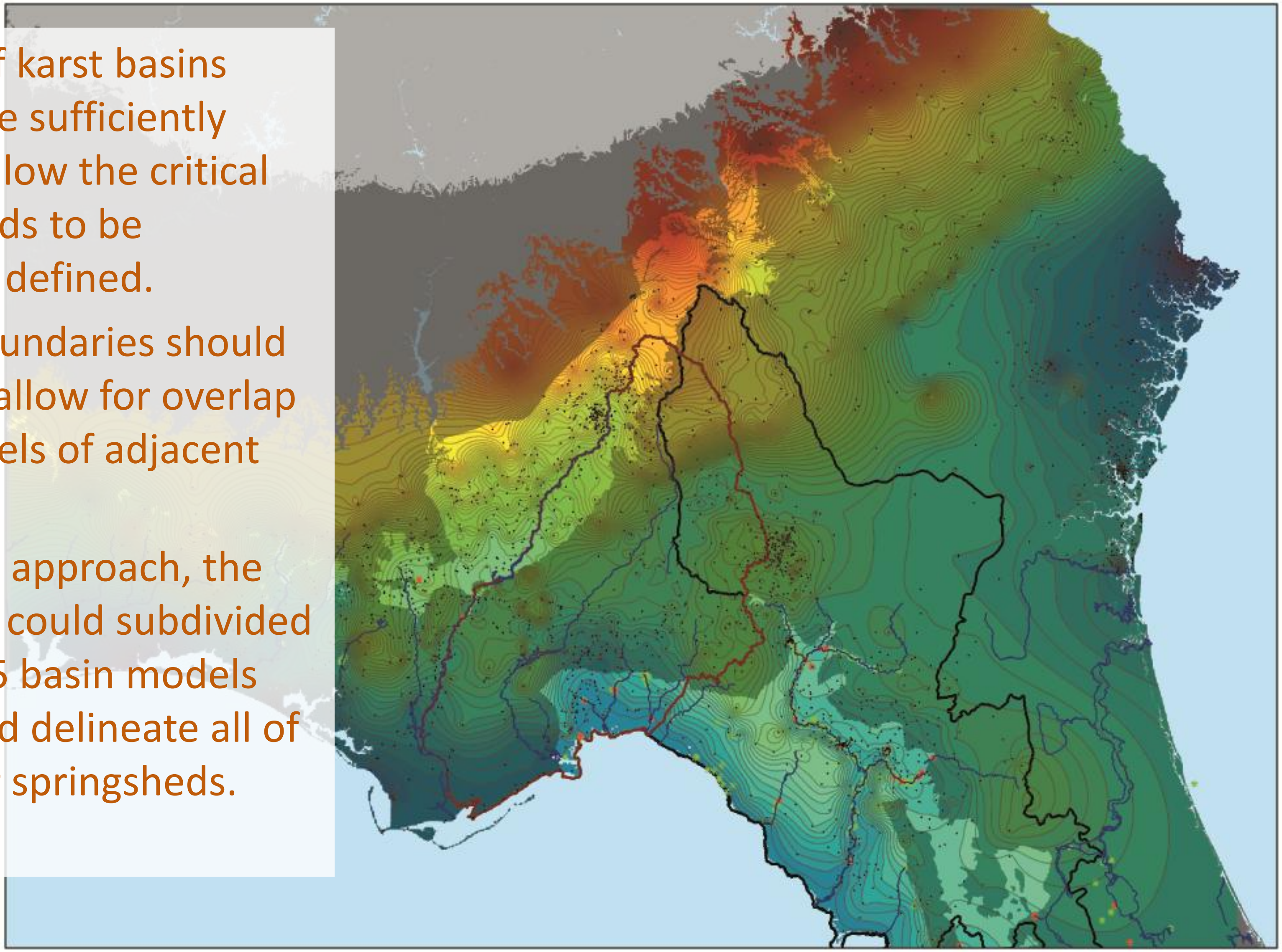
Watershed-Scale Approach to Modeling

- Models of karst basins need to be sufficiently large to allow the critical springsheds to be internally defined.
- Model boundaries should be set to allow for overlap with models of adjacent basins.
- Using this approach, the Karst Belt could subdivided into 4 or 5 basin models that would delineate all of the major springsheds.



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Applications Examples from the Western Santa Fe River Basin Model funded by The Coca-Cola Company

More information on the WSFRB Model is available at:

www.geohydros.com/CCNA/

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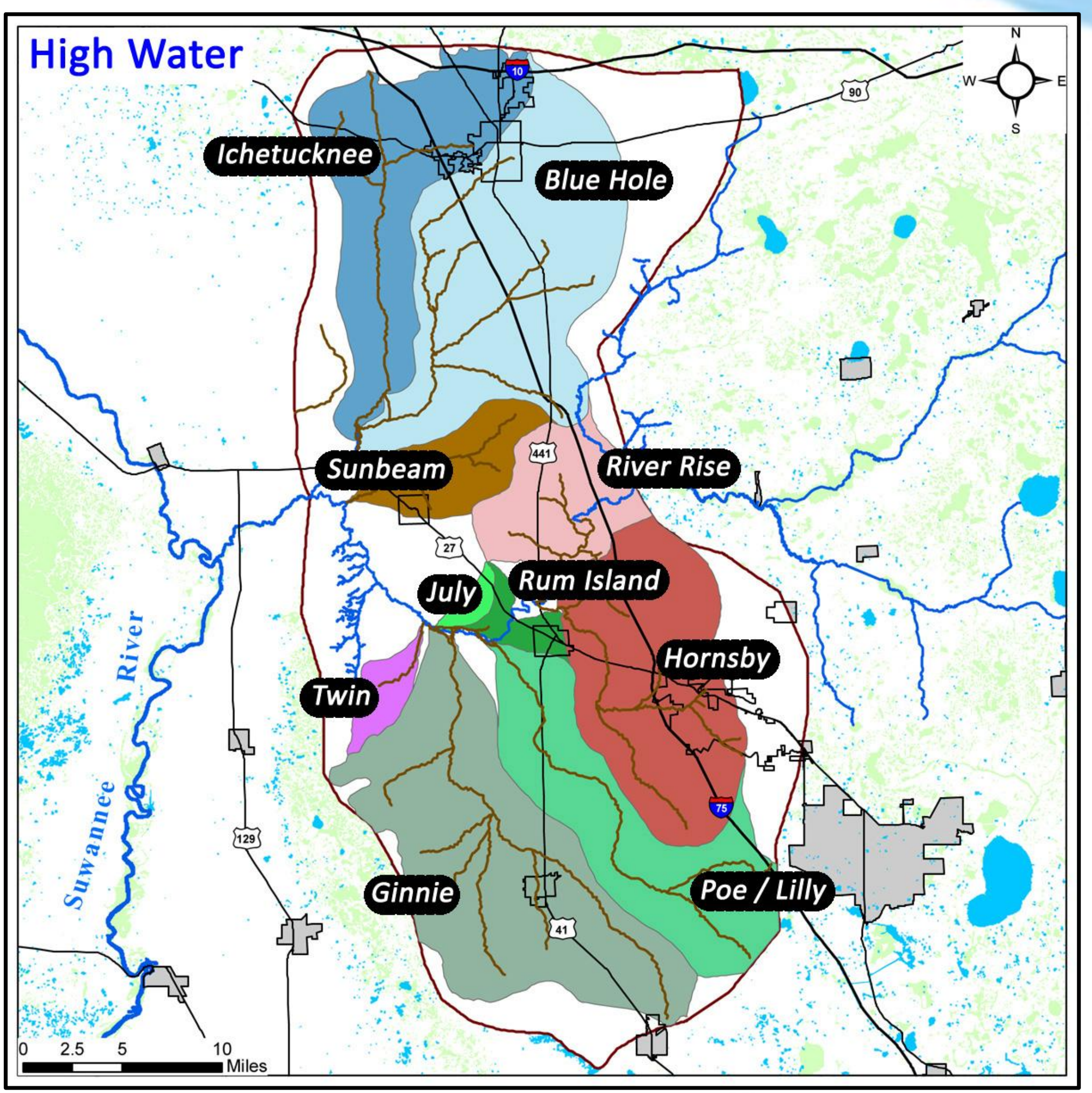
Applications: Springshed Delineations

- 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



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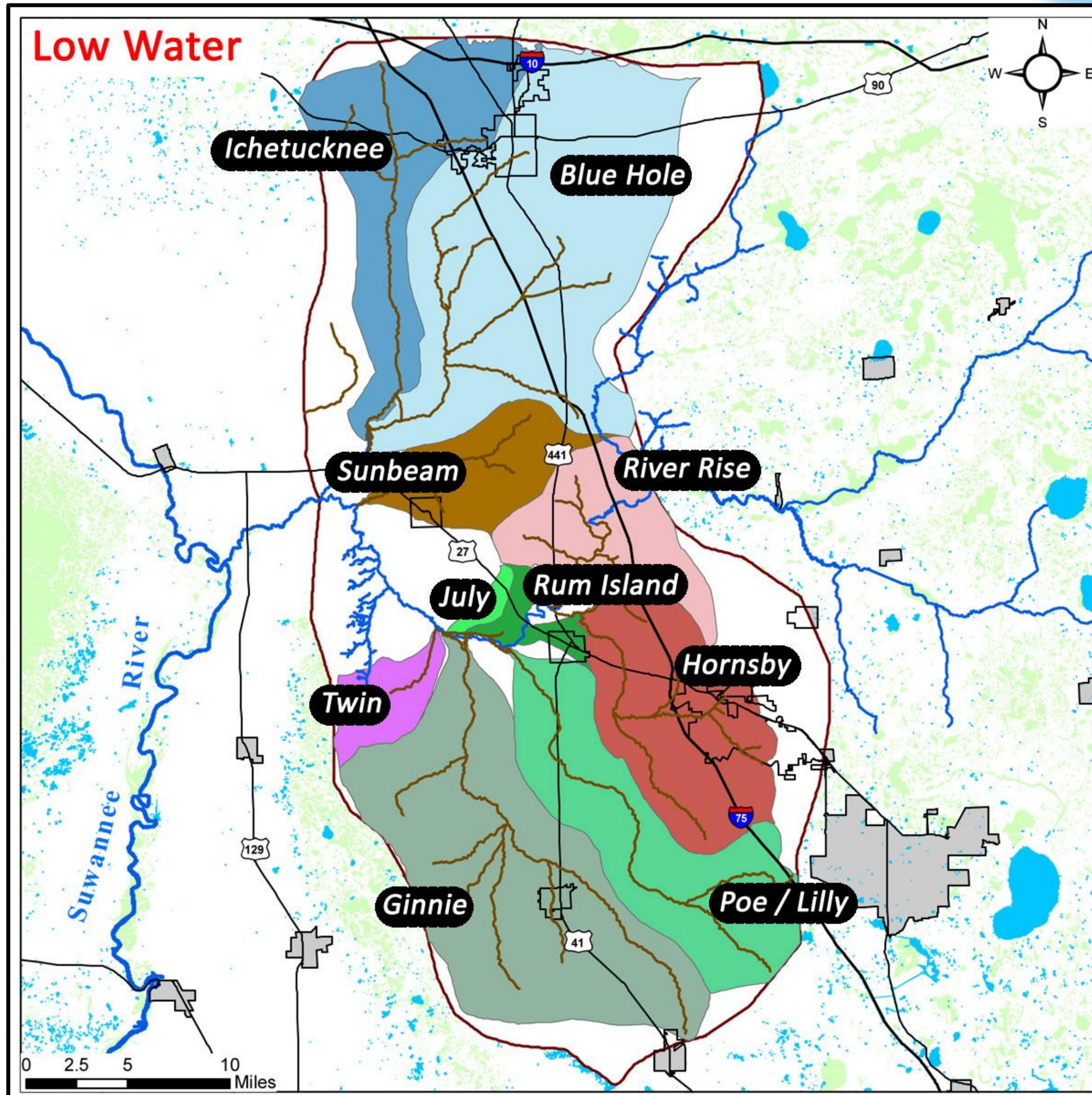

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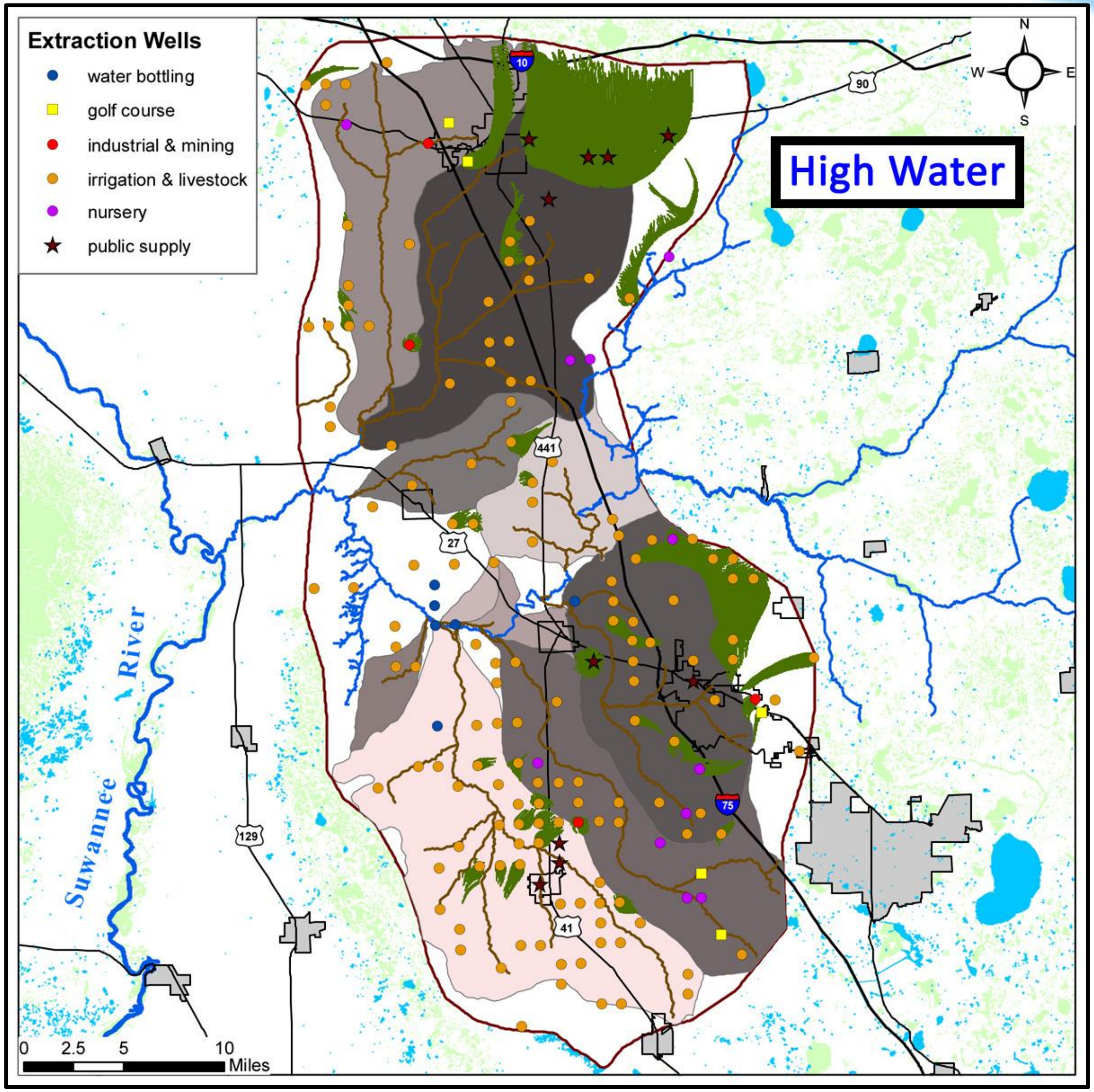
Applications: Pumping Impacts

- 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%



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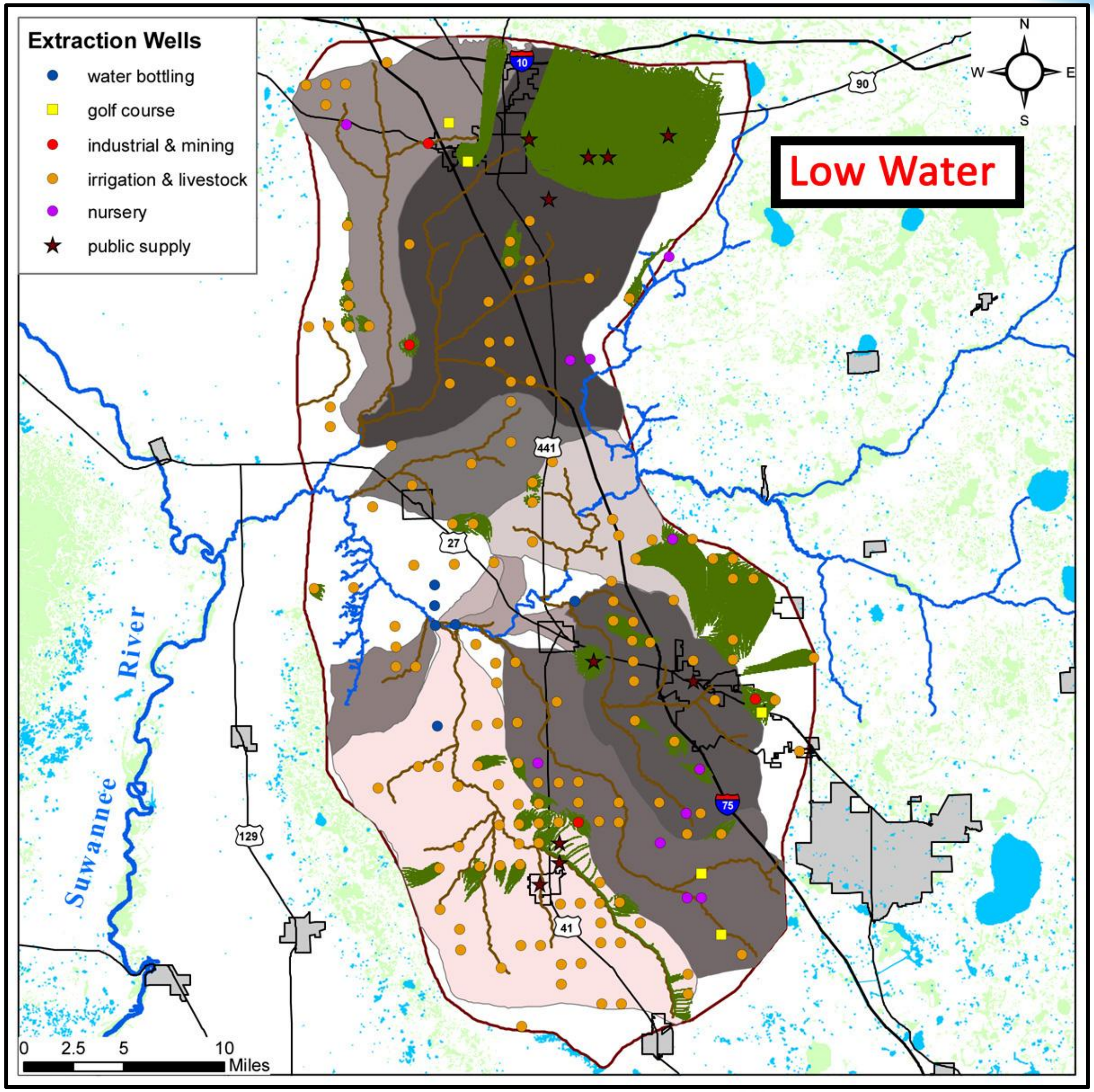

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Applications: Source Water Protection

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

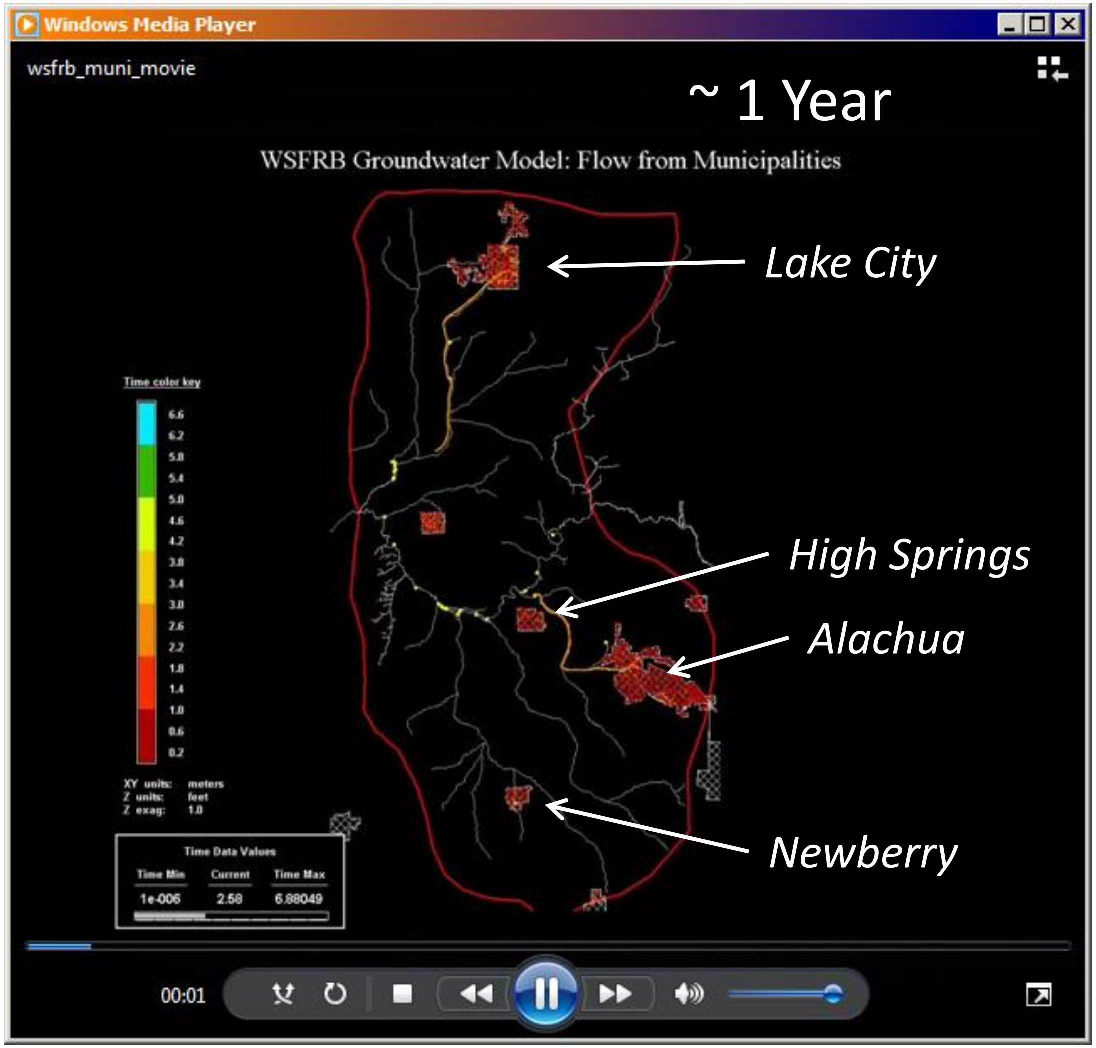
Flow is to closest conduits

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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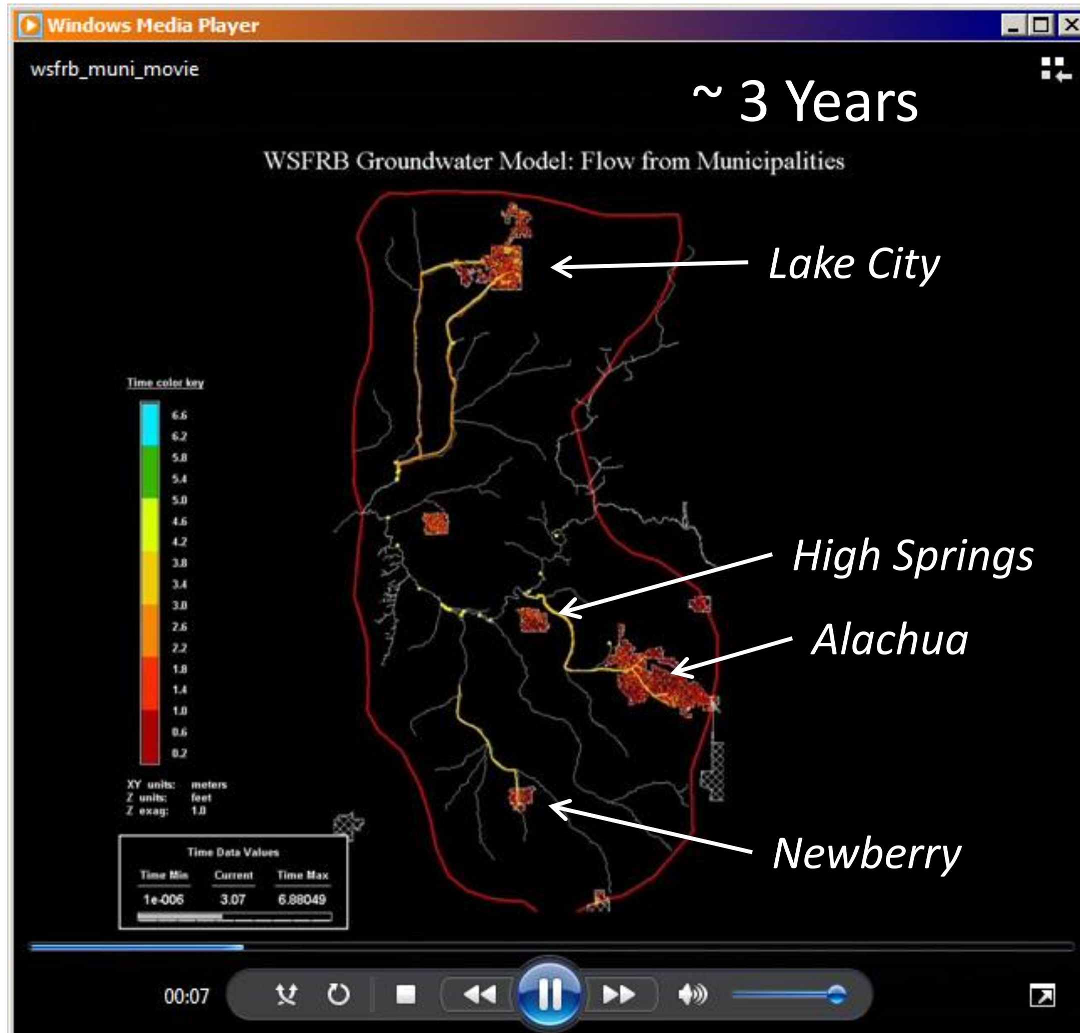

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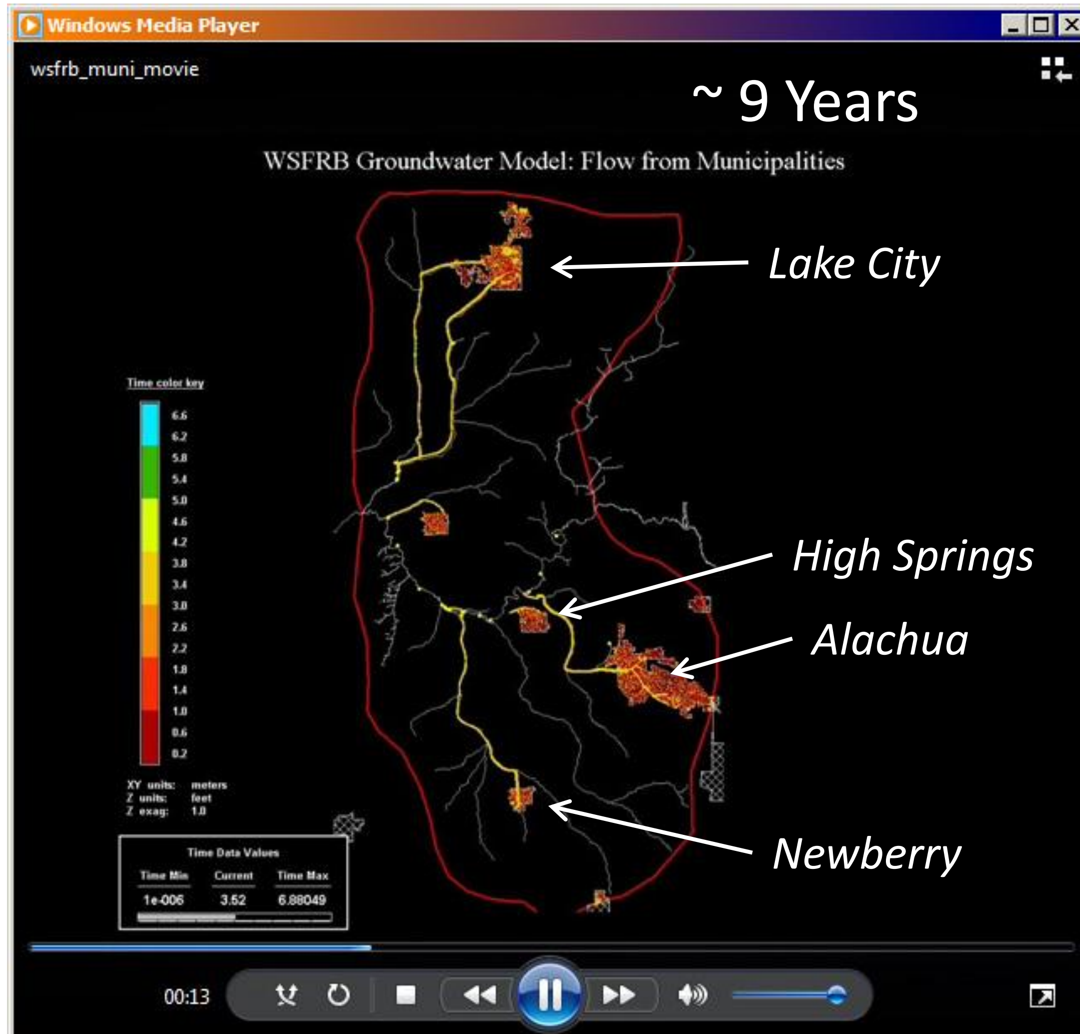

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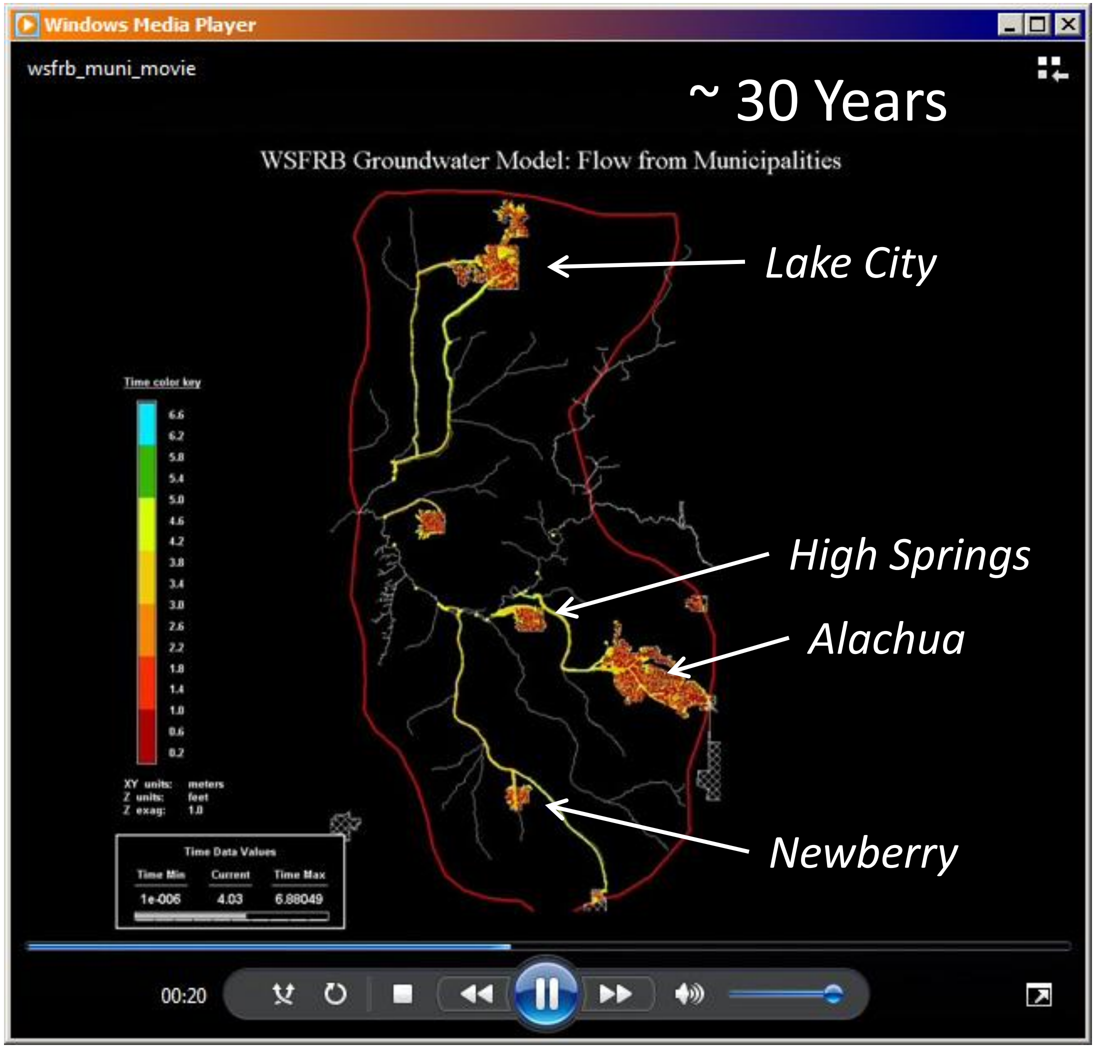
Flow is to closest conduits

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*



GeoHydros

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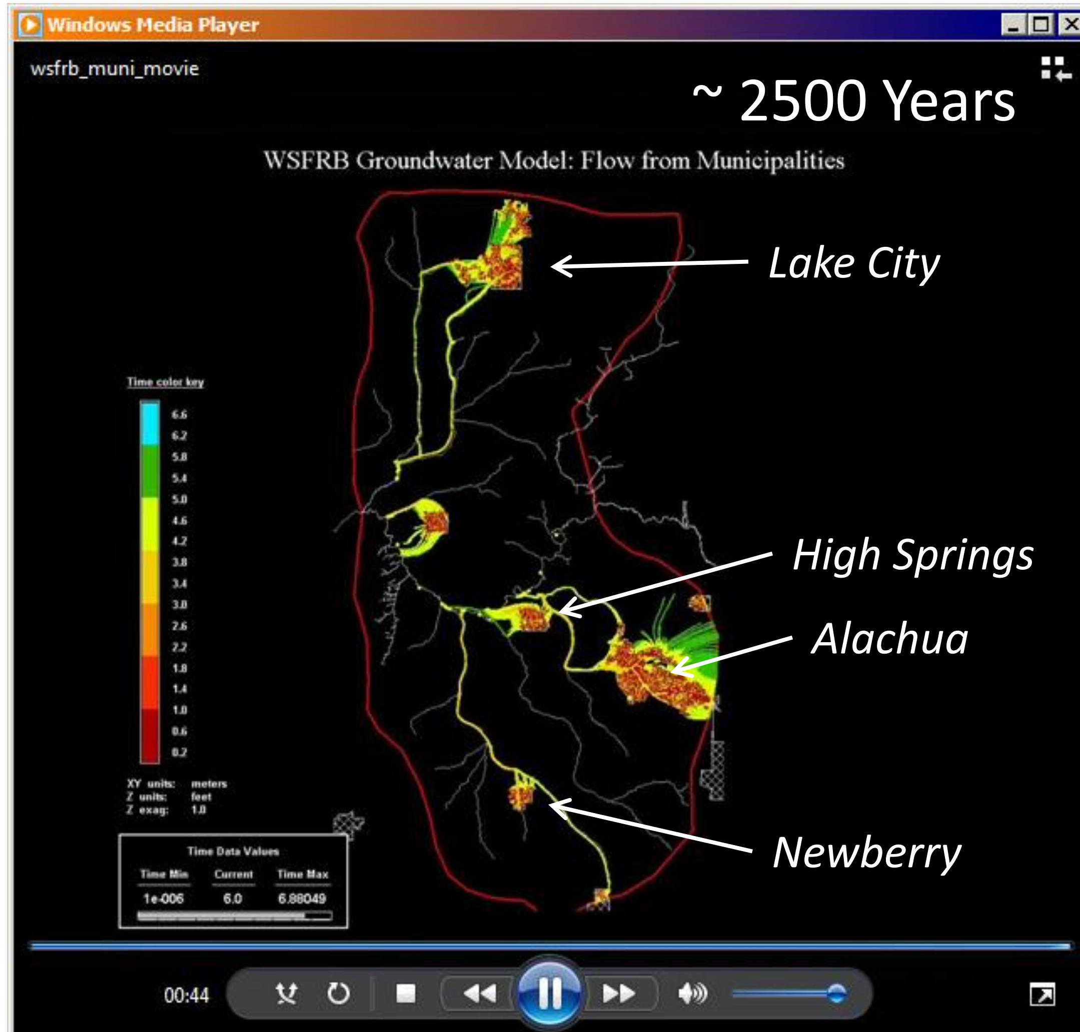
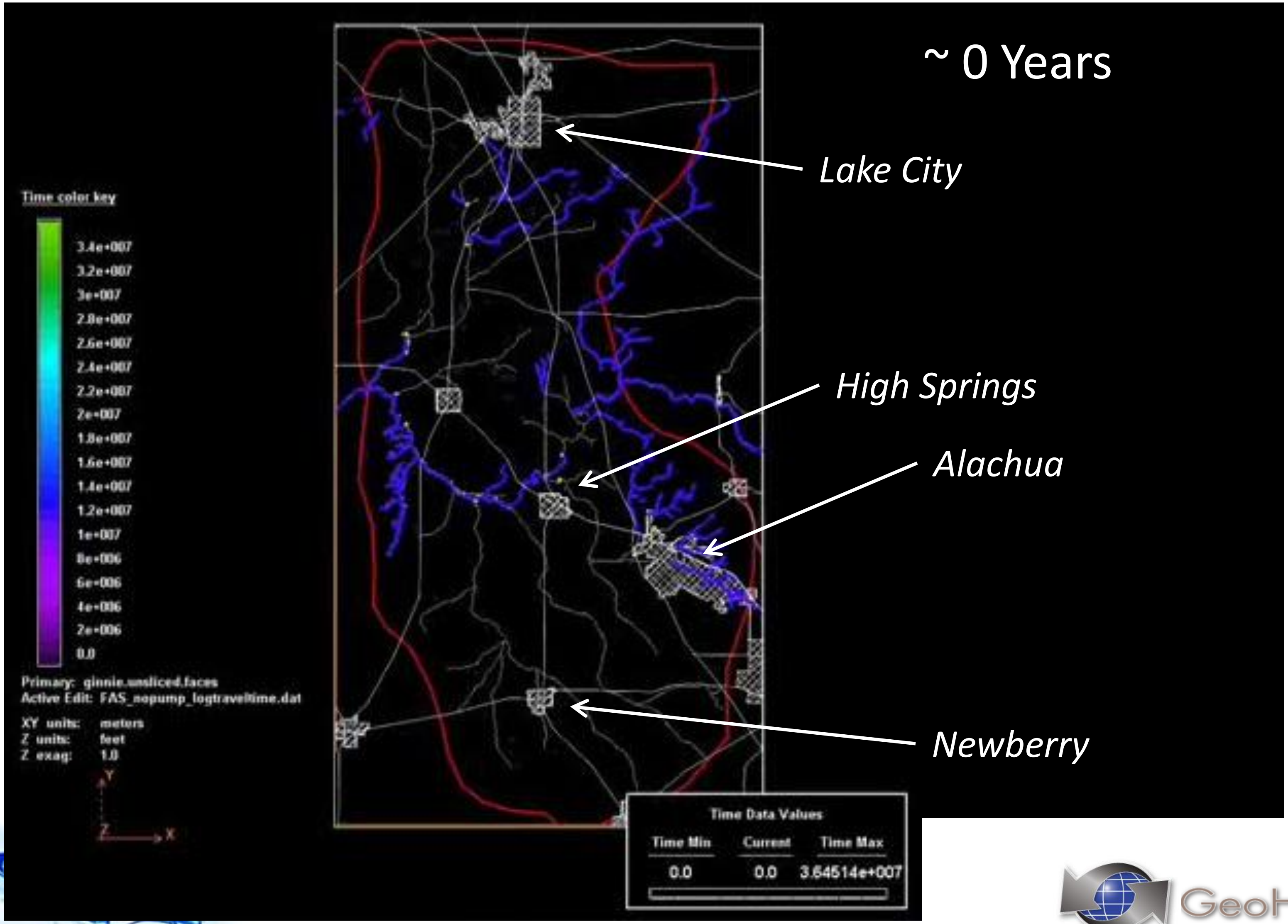


GeoHydros

Applications: Springs Vulnerability

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



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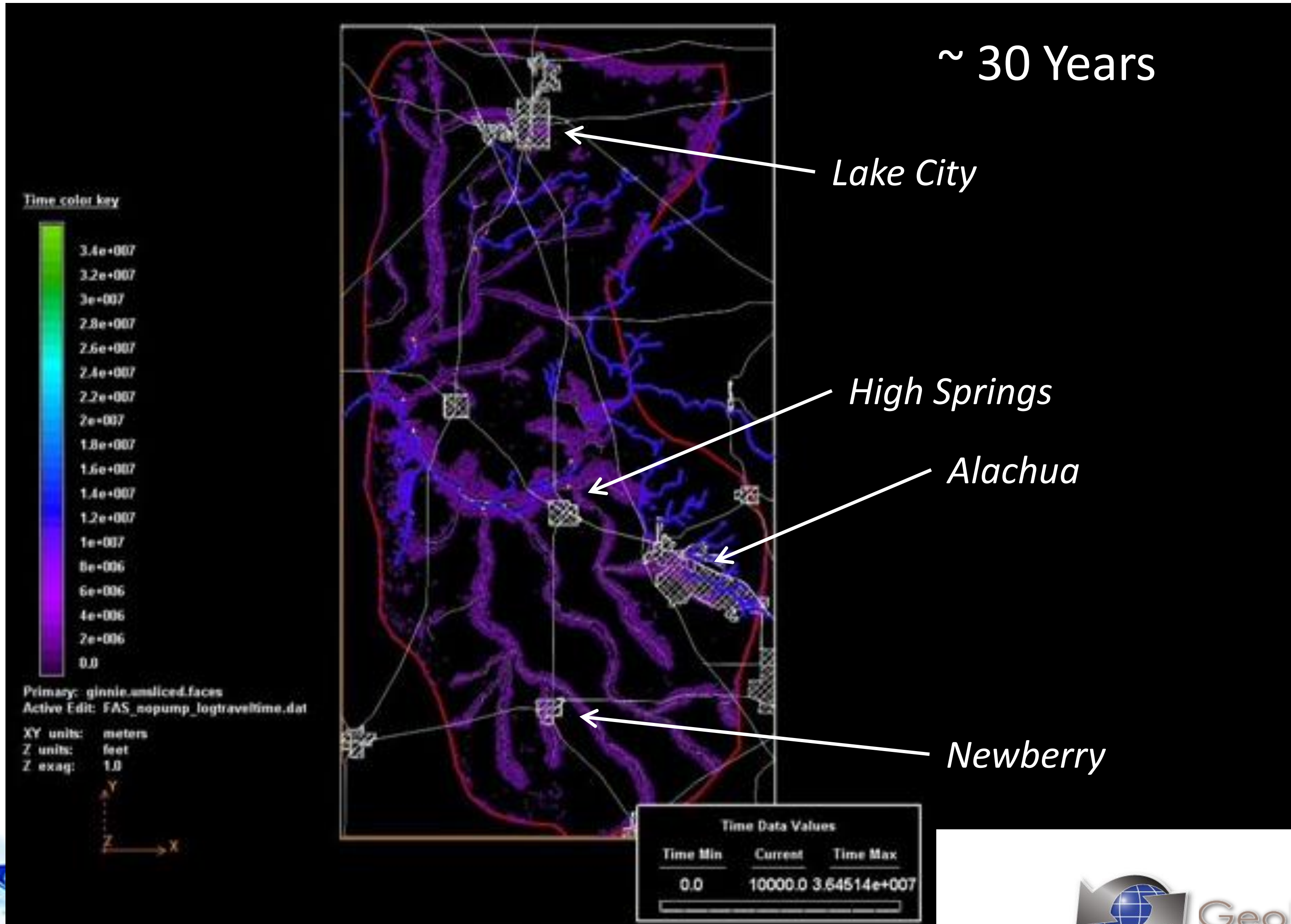

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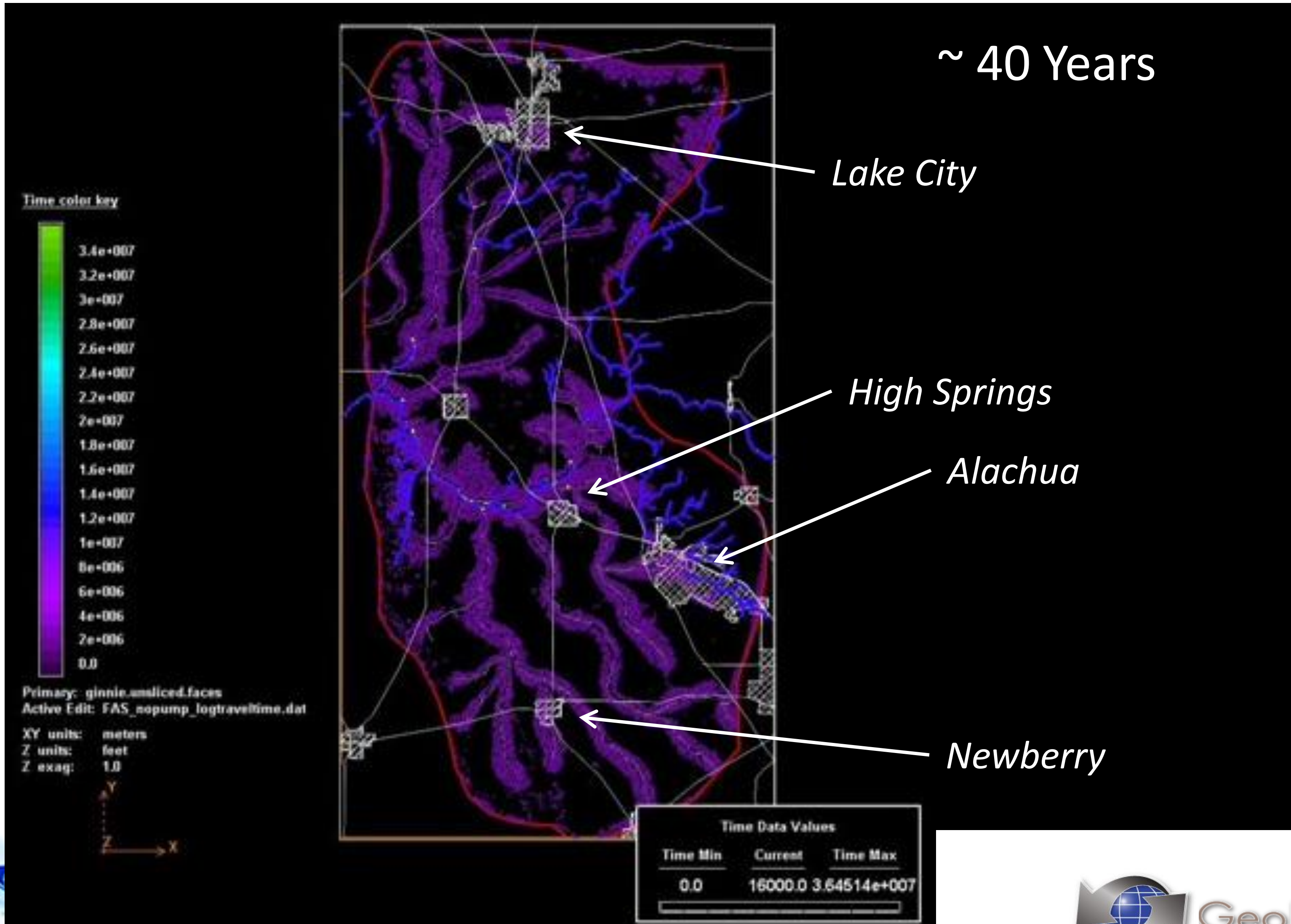

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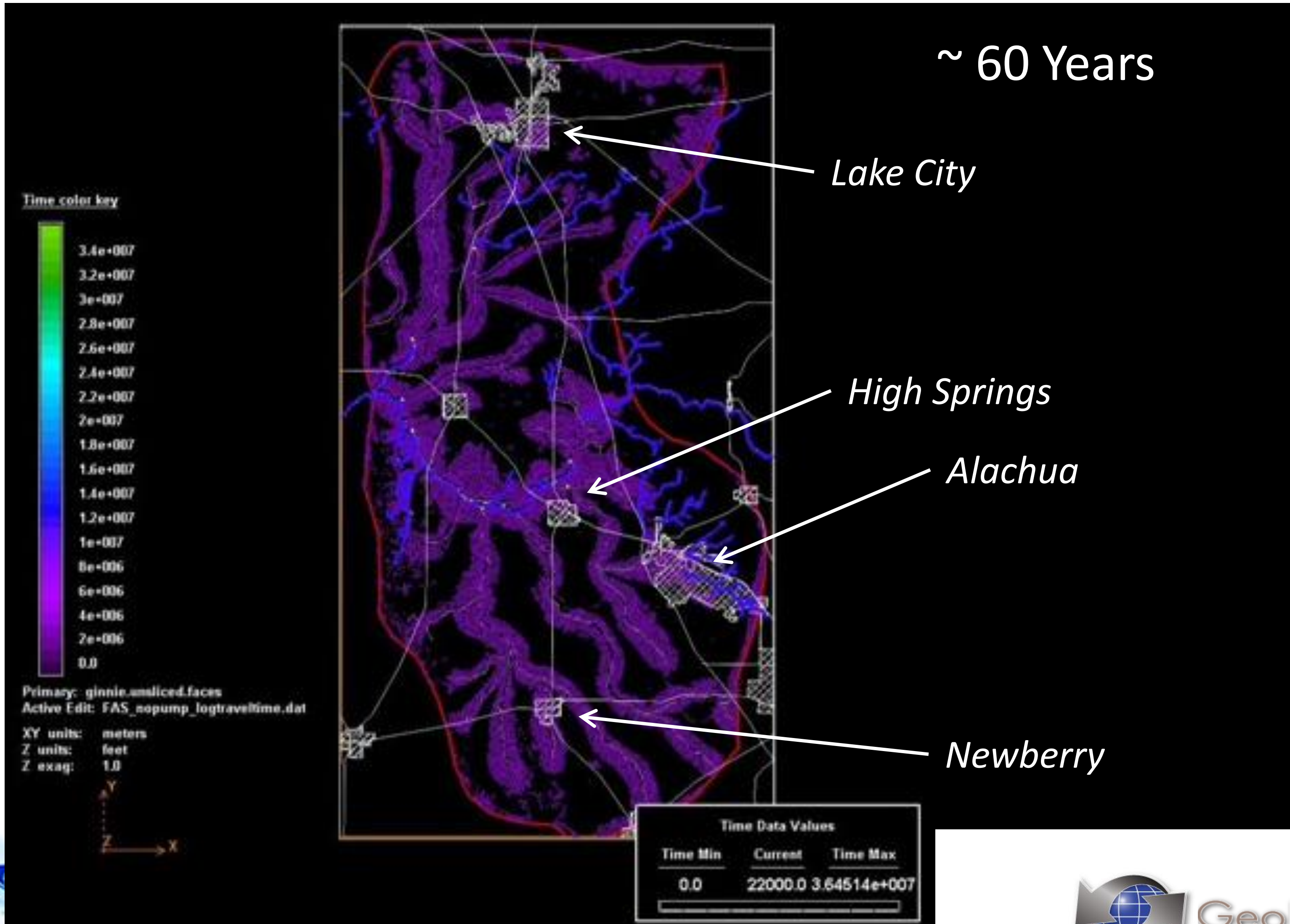

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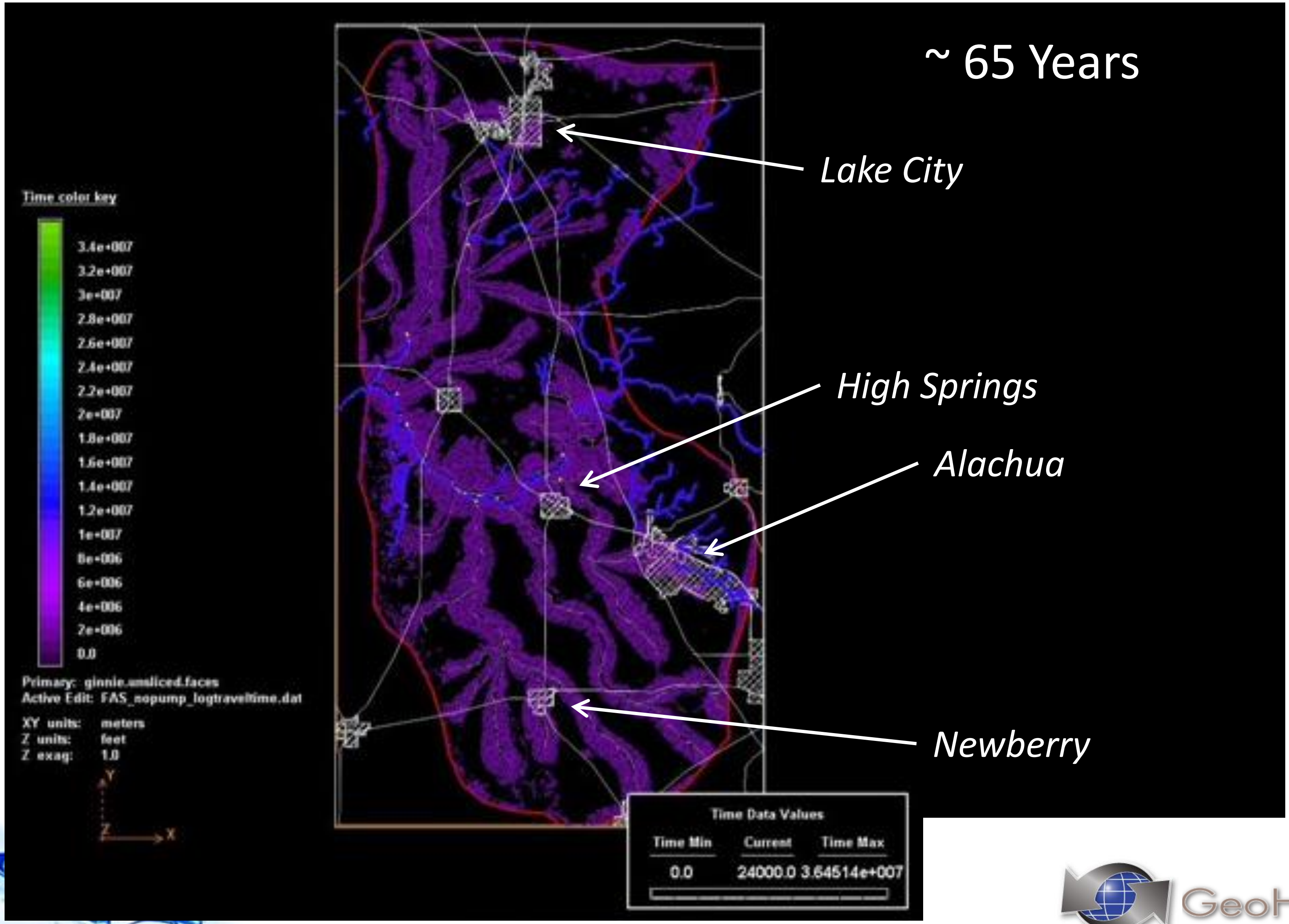

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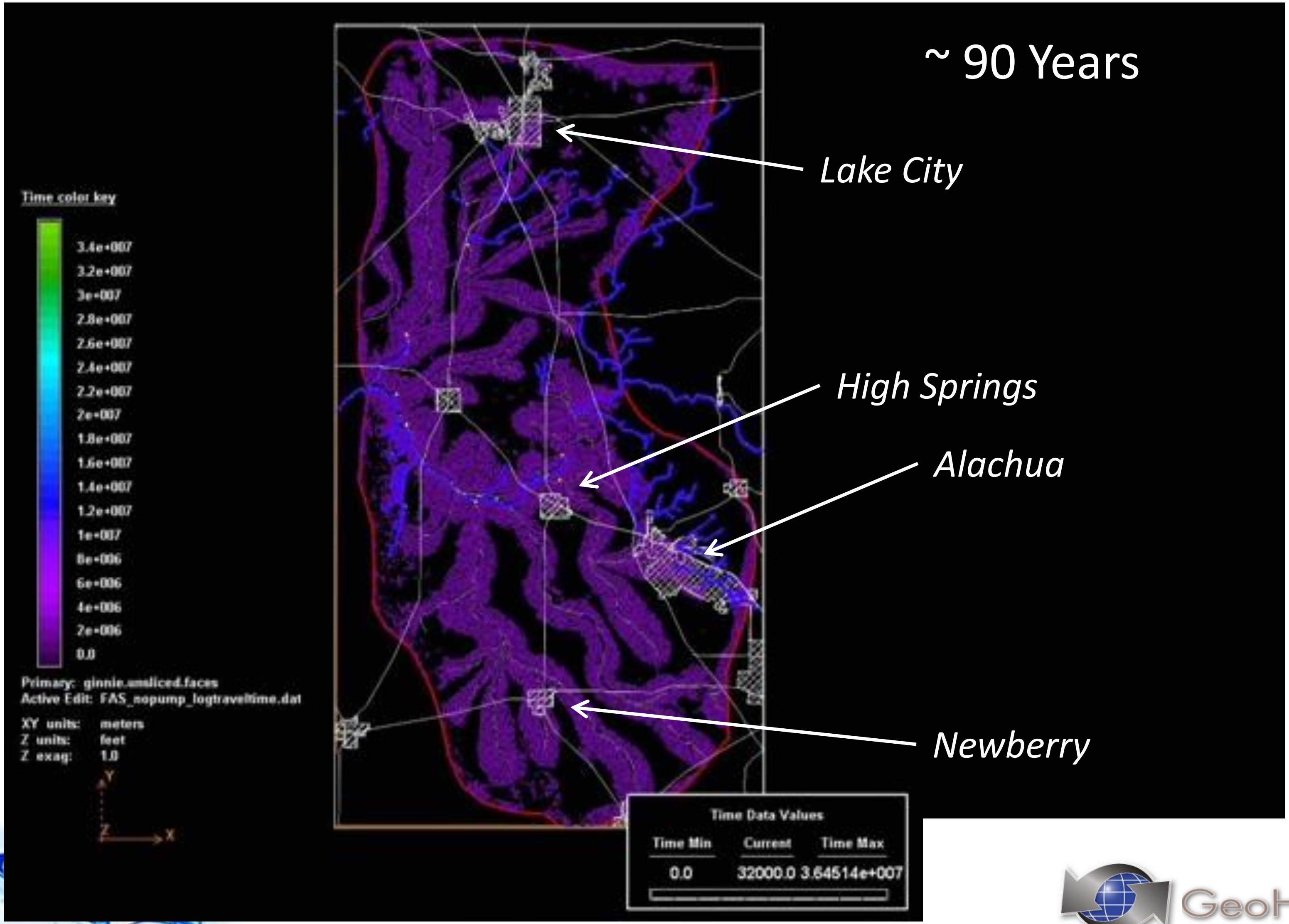

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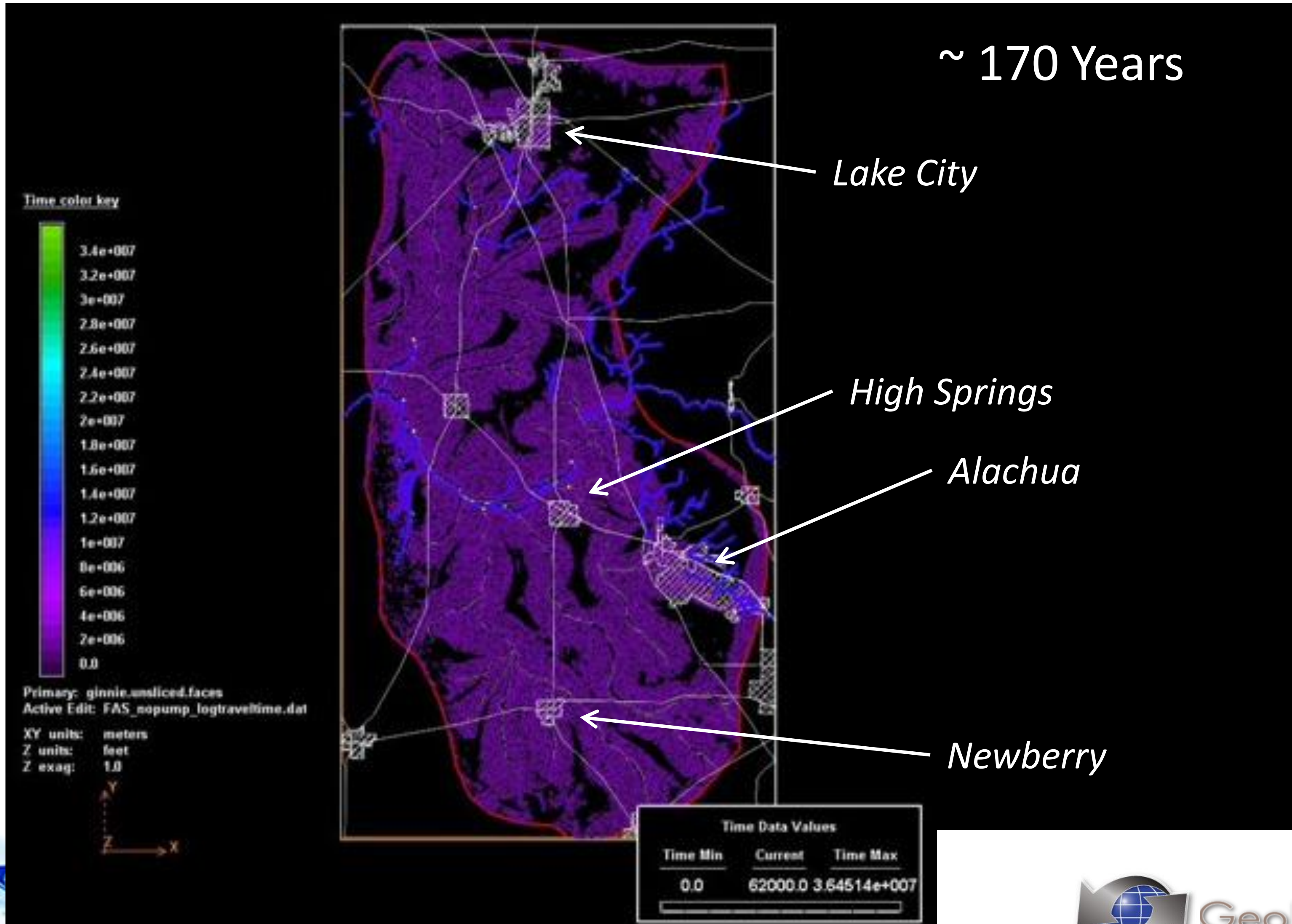

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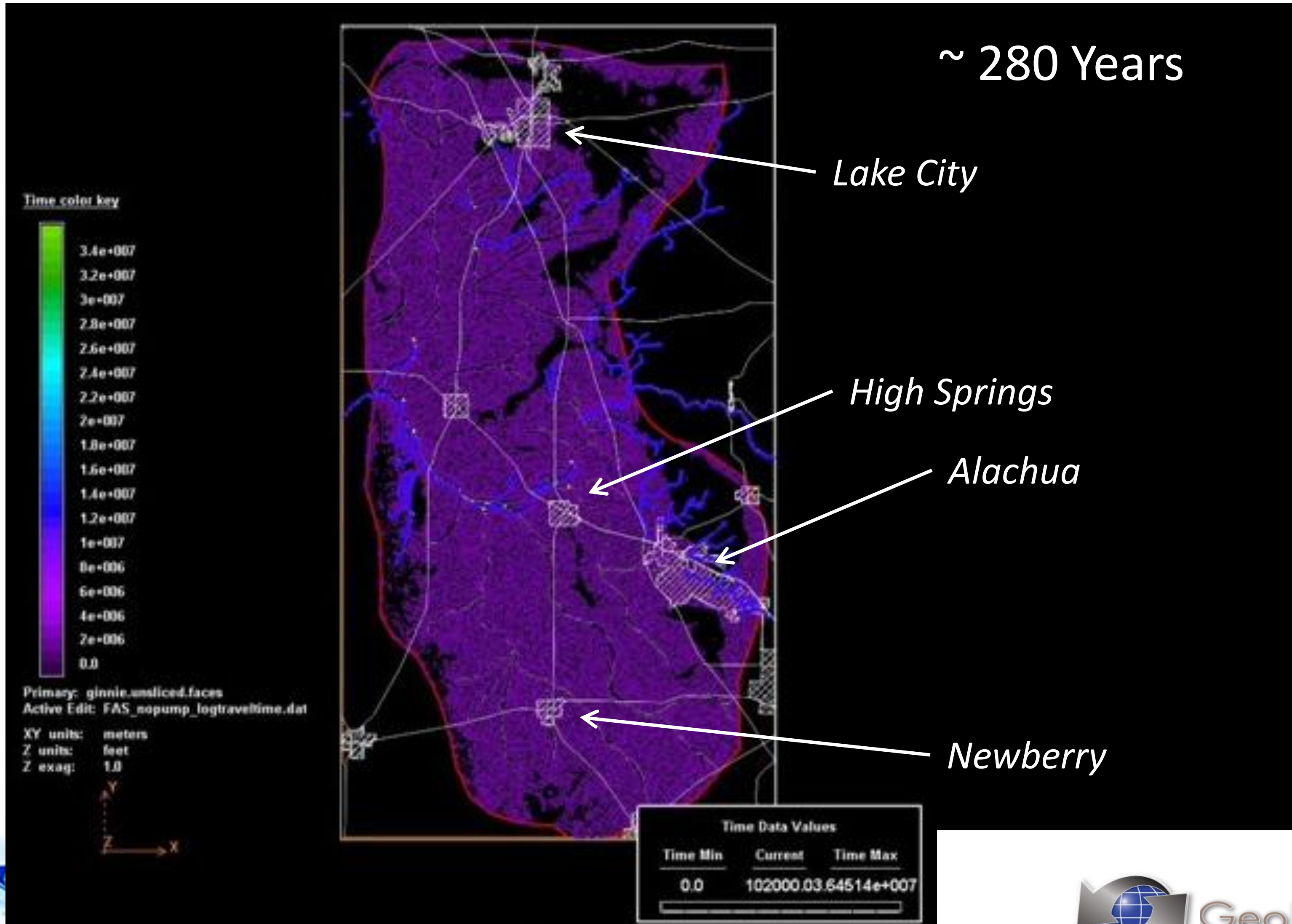

Work Funded by

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