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

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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.
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)

2006: Turf Pond – Wakulla Spring
10.9 miles / 56 days (980 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
Hydrogeologic Complexities

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

Porous Media

- Sand / sandstone
- Easy to characterize
- Simplest math

Fractured 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
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/
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.
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

**Surficial**
- Gulf of Mexico (CH)
- Aucilla Watershed (NF)
- Withlacoochee (CH)
- Withlacoochee Watershed (NF)
- Flint/Apalachicola (CH)

**IAS**
- Same as SAS

**FAS**
- Gulf of Mexico (CH)
- Interp. Pot. Sur. (CH)
- Flint/Apalachicola (CH)

*CH = constant head
*NF = no flow*
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

Mar 80 - Water Level Data by Quarter - Dec 09

919 Wells in FL & GA Surrounding Model Domain
Calibration Datasets

- **High Water**
  - 1998 2\textsuperscript{nd} quarter - GA & NFWMD
  - 2005 2\textsuperscript{nd} quarter – SRWMD

- **Low water**
  - 2002 2\textsuperscript{nd} quarter – SRWMD
  - 2000 2\textsuperscript{nd} quarter – NFWMD
  - 2006 3\textsuperscript{rd} 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.**
Calibration

- Total head range: 80 m
- Target criteria = +/- 5% = 4 m
- Tighter in unconfined: +/- 0.3 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
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
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
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)
Modeling Conduits ...

Wakulla Conduit System

St. Marks Conduit System
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 conduits can be brought into calibration through continued manipulation of conduit locations and parameter settings.
Model Results: Groundwater Velocities

- Conduits model: ~ 10 to ~620 m/day
- Conduits observed: ~ 100 – 2400 m/day
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.
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
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.
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/
**Applications: Springshed Delineations**

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

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<thead>
<tr>
<th>Spring Group</th>
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<th>Low (km²)</th>
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<td>395</td>
<td>414</td>
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<td>Blue Hole Group</td>
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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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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
Applications: Source Water Protection

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Applications: Springs Vulnerability

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

~ 0 Years

Lake City
High Springs
Alachua
Newberry
Applications: Springs Vulnerability

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

~ 30 Years

Lake City
High Springs
Alachua
Newberry
Applications: Springs Vulnerability

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

~ 40 Years
Applications: Springs Vulnerability

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

~ 60 Years
Applications: Springs Vulnerability

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

~ 65 Years

Lake City
High Springs
Alachua
Newberry
Applications: Springs Vulnerability
Travel-time to discharge from points within the Santa Fe River Basin, Florida

~ 90 Years

Lake City
High Springs
Alachua
Newberry
Applications: Springs Vulnerability

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

~ 170 Years

Lake City

High Springs

Alachua

Newberry
Applications: Springs Vulnerability

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

~ 280 Years

Lake City

High Springs

Alachua

Newberry