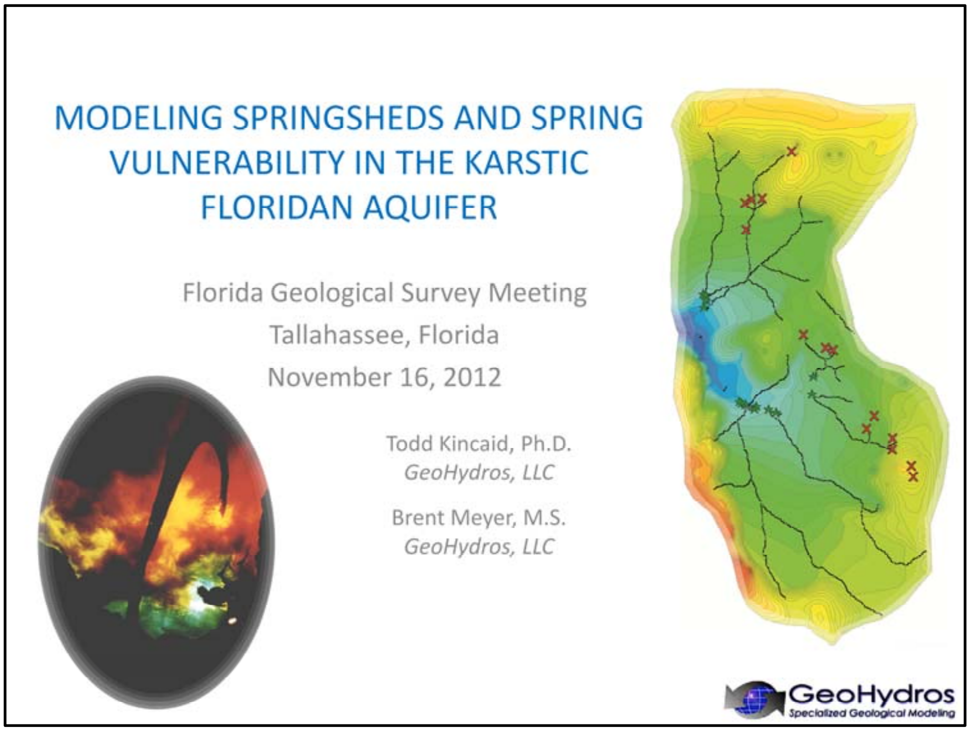
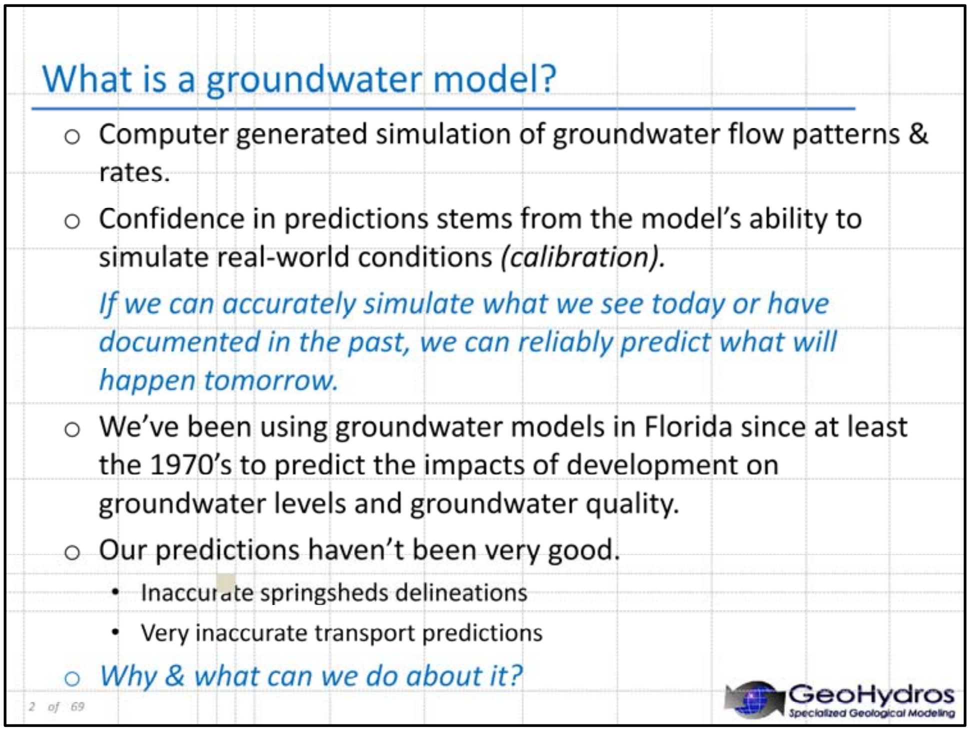


The purpose of this presentation is to provide an overview of the karst modeling research that the FGS and GeoHydros have been engaged in for the past 10 years. The fundamental problem is the veracity of groundwater models constructed for karst regions of the Floridan aquifer. It is widely recognized that traditional groundwater flow models fail to adequately simulate groundwater flow patterns and velocities in karst. The purpose of this research has been to improve upon the traditional modeling methodologies and produce a test-case model that adequately simulates karstic hydrologic complexities: large magnitude discrete spring flow, large magnitude discrete swallet recharge, conduit flow, and very fast groundwater velocities. We have accomplished this goal through our work in the Woodville Karst Plain on Wakulla Springs and through work that GeoHydros performed in the western Santa Fe River Basin with the Coca-Cola Company.

This presentation focuses first on a model developed for the western Santa Fe River Basin. We will compare the results of our new modeling method to the traditional groundwater flow model that is being used by the Suwannee River Water Management District. We will show that where the traditional model fails to adequately simulate observable karstic groundwater flow, the new model does so very well. We'll show why the traditional model fails and how the new model can be applied to address springshed delineations, spring and aquifer vulnerability assessments, the impacts of groundwater withdrawals, and the transport and fate of groundwater contamination.

The focus of the presentation will then shift to the status of a larger regional groundwater flow model that is being developed using the new methodology for the region in north Florida and south Georgia that contributes water to Wakulla, Spring Creek, St. Marks, and Wacissa springs. Finally, we'll show how the new methodology could be applied to address MFL and TMDL work being performed throughout Florida's karst belt (the region of Florida that extends from Tallahassee, across the western half of the peninsula to Tampa).



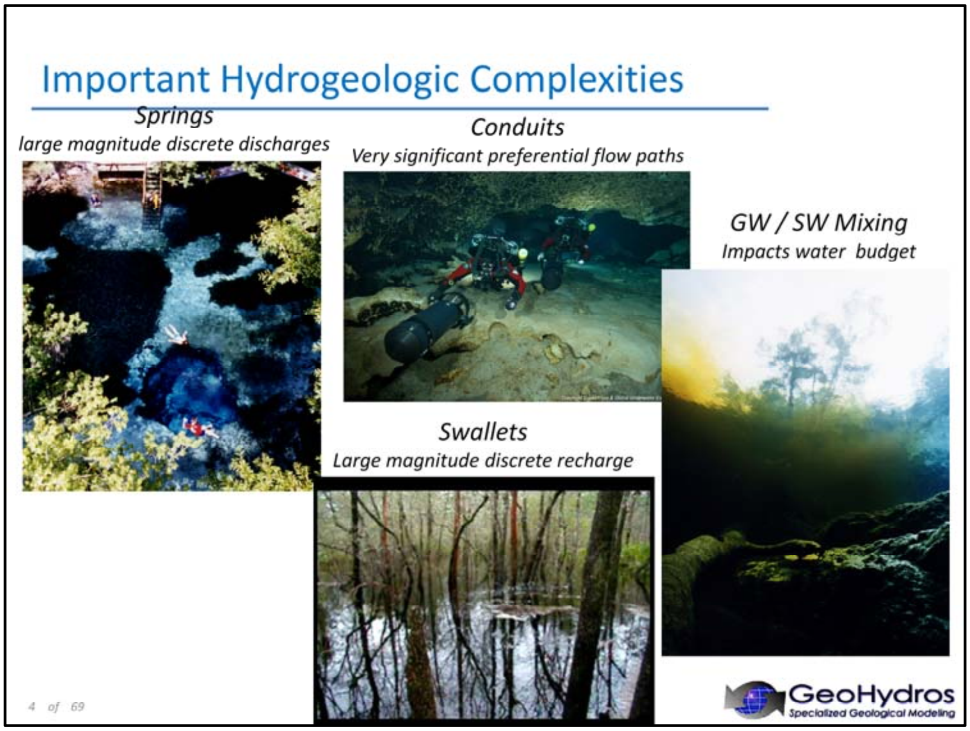
The term "groundwater flow model" typically describes a computer generated simulation of groundwater flow patterns and velocities that can be used to predict the impact of changing conditions (climatic changes, sea level changes, increased groundwater pumping, contamination, etc) on groundwater resources including aquifer water levels, spring discharge, wetland discharge, etc.

Confidence in a model's predictions stems from its ability to match (calibrate to) a set of real-world present-day or recent hydrologic conditions such as groundwater levels in the aquifer, spring flows, river gains or losses, etc. The fundamental assumption underlying groundwater models is that matching these will result in reliable predictions of future conditions . In order to assess confidence in any particular model or the modeling methodology, it is therefore crucial that we make sure that the models we use match as much of the observable present-day conditions as possible where the more we match, the more confident we can be in the predictions.

In karstic aquifers, like much of the Floridan aquifer, this means matching discrete spring flows, observed groundwater velocities through conduits, and swallet recharge as well as groundwater levels. Traditional modeling methods, those that have been employed for nearly all models in Florida, have failed to match these conditions and the predictions have therefore proven to be wrong, particularly with respect to contaminant transport but also to springshed delineations and the impacts of groundwater pumping.

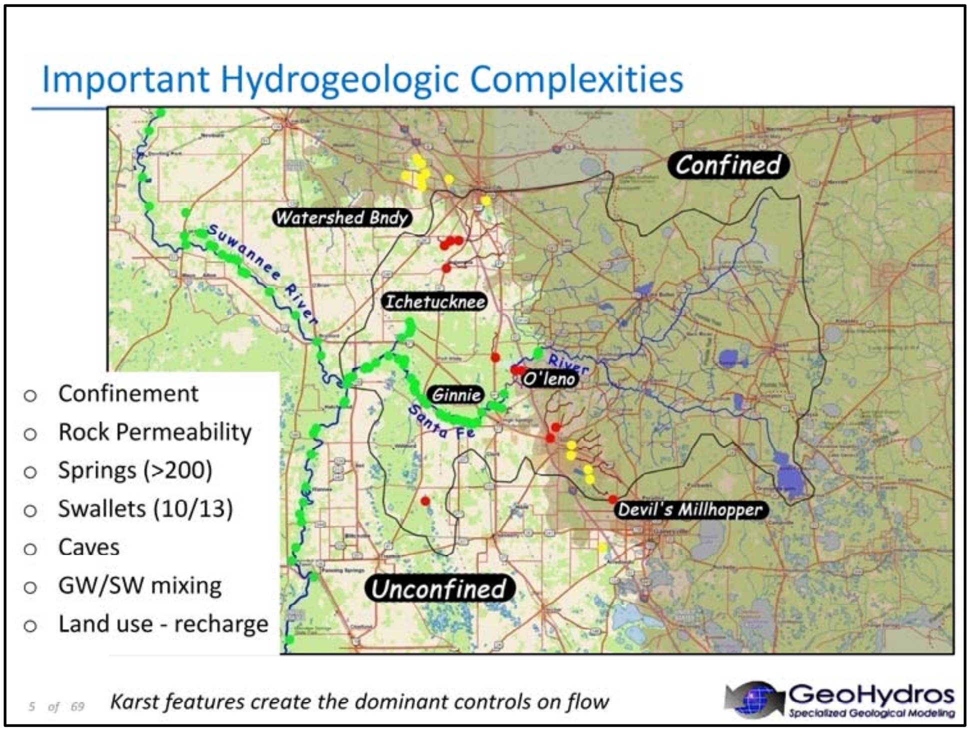
Section – 1
Western Santa Fe River Basin
and
The Suwannee River Water Management District Model

GeoHydros
Specialized Geological Modeling



The most significant hydrogeologic complexities characteristic of karstic aquifers include:

- springs, which are discrete points of (sometimes very large magnitude) groundwater discharge;
- conduits, which are voids in the aquifer rocks (sometimes large enough for people to swim through) that are organized to convey groundwater rapidly down-gradient;
- swallets, which are sinkholes that receive stream flow from the land surface and convey it rapidly into conduits in the aquifer; and
- groundwater / surface water mixing, which is a process by which groundwater and river water are mixed over local scales such as what occurs in the Santa Fe and Suwannee rivers where river water sinks into the aquifer only to reemerge shortly downriver after mixing with groundwater.

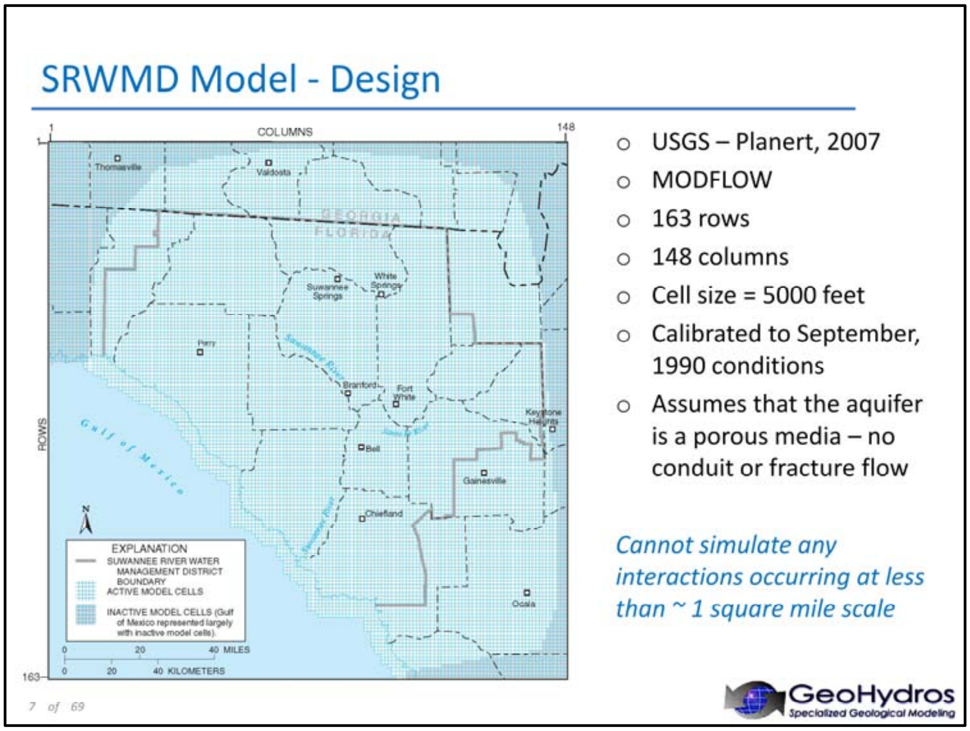


- Springs
  - More than 200 SRWMD
    - 1st Mag (>= 100 cfs): 18
    - 2nd Mag (10-100 cfs): 81
    - 3rd Mag (1-10 cfs): 60
    - 4th Mag (.1-1 cfs): 37
  - 81 in the Santa Fe River Basin
    - 1st Mag: 9
    - 2nd Mag: 36
    - 3rd Mag: 23
    - 4th Mag: 8
- Swallets: disappearing streams that fully 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
- Caves
  - Explored & mapped caves
    - Old Bellamy, Hornsby, Devil's Ear, Mill Creek, Rose Sink, Ginnie, etc.
    - Depths trend 75 – 150 ft
    - Diameters: ~3 – 30 ft
  - Tracer-defined caves
    - Rose Creek, Clay Hole, Mill Creek, San Felasco, Ichetucknee, Ginnie
    - ~650 – 2500 ft/day groundwater velocities
- Groundwater / surface water mixing
  - Extensive along river
  - e.g. ~50% Devil's Ear flow is recycled river water

Desirable Modeling Applications

- Predict impacts of groundwater extraction on spring flows
  - Simulate springshed boundaries and how they interact
  - Simulate specific spring discharges
  - Simulate magnitude and spatial location of pumping
  - Simulate specific groundwater extractions
- Predict impacts of changing recharge conditions on spring flows
  - Simulate land use and land use changes
  - Simulate 3D hydrostratigraphic framework
- Map spring and well vulnerability to contamination
  - Simulate groundwater flow patterns to springs
  - Simulate groundwater velocities
- Identify sources of contamination to springs

GeoHydros
Specialized Geological Modeling



Consider the SRWMD model as an example of standard modeling techniques applied to karstic aquifers. The base model was constructed by the U.S. Geological Survey who published a paper on it's development in 2007.

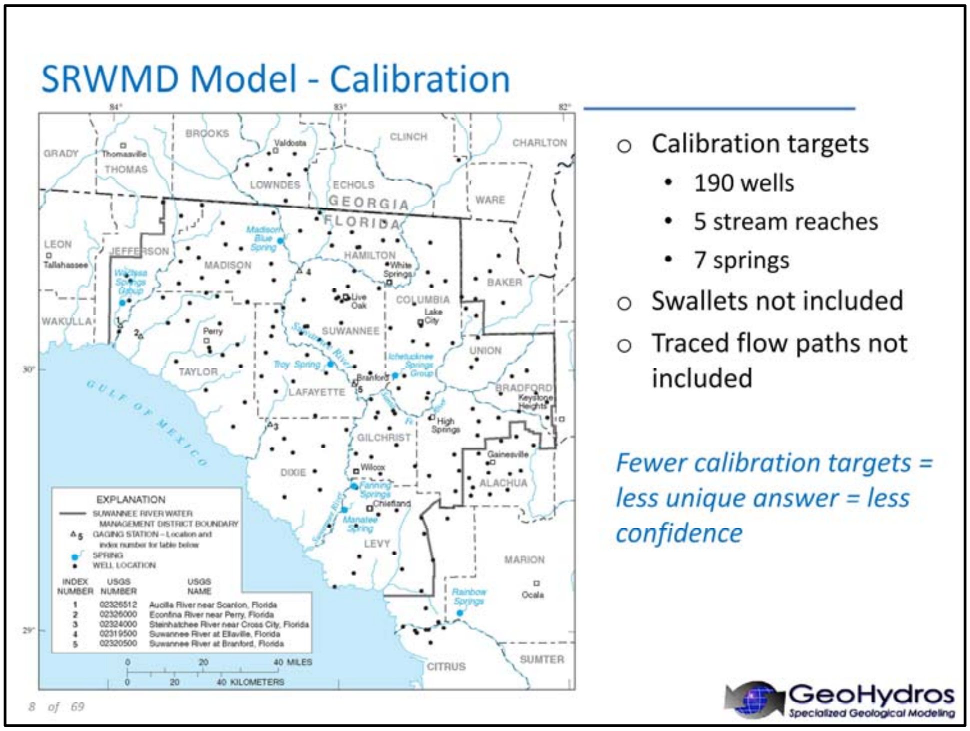
The model was constructed using the software MODFLOW. It is based on a conceptualization of the Floridan Aquifer System being a porous media through which groundwater flows diffusively. The model domain encompasses the entire Suwannee River basin and is designed as a finite difference grid consisting of 163 rows and 148 columns wherein each cell measures 5000 x 5000 feet.

The cell size precludes any legitimate analysis of interactions that take place over an area smaller than approximately one square mile. The porous media conceptualization precludes simulation of conduit flow.

The model was calibrated to September 1990 conditions. The single calibration limits the model's applicability to the wide range of flow conditions that characterize this basin.

<u>Reference</u>

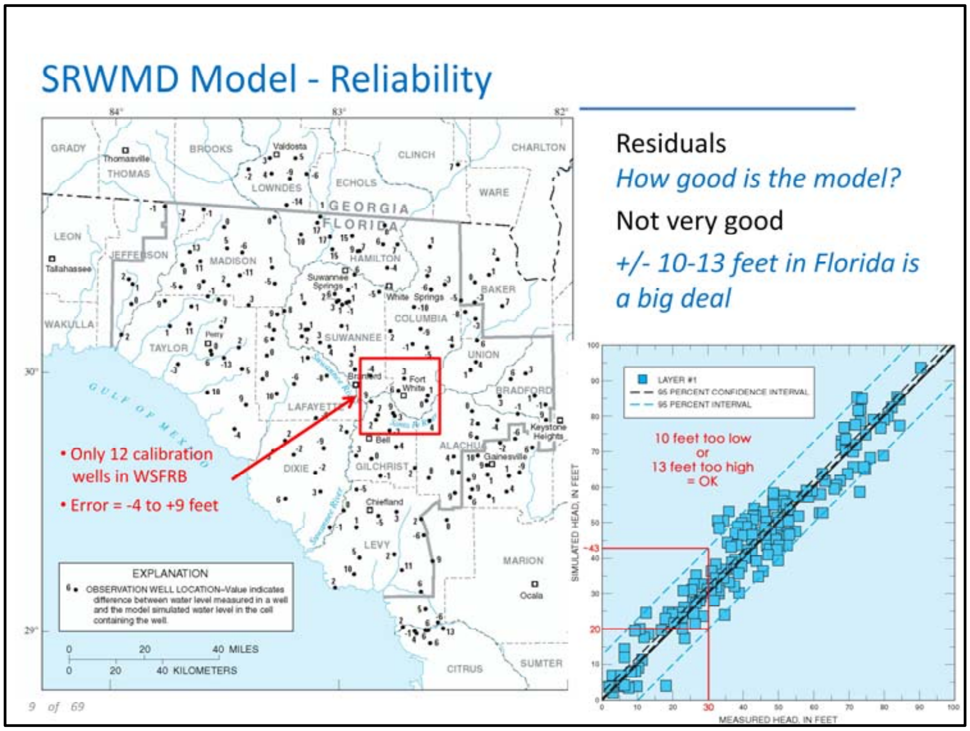
Planert, M., 2007. Simulation of Tegional Ground-Water Flow in the Suwannee River Basin, Northern Florida and Southern Georgia, Scientific Investigations Report 2007-5031, U.S. Geological Survey, 50 p.



Calibration is the process of matching the model to observed conditions. Generally, a calibration dataset is compiled before or near the beginning of model construction. It should include heads and flows. An acceptable “fit” to the data should also be defined prior to model construction. More data types and locations included in the calibration process yields a more unique simulation, which generally equates to a better, more reliable model.

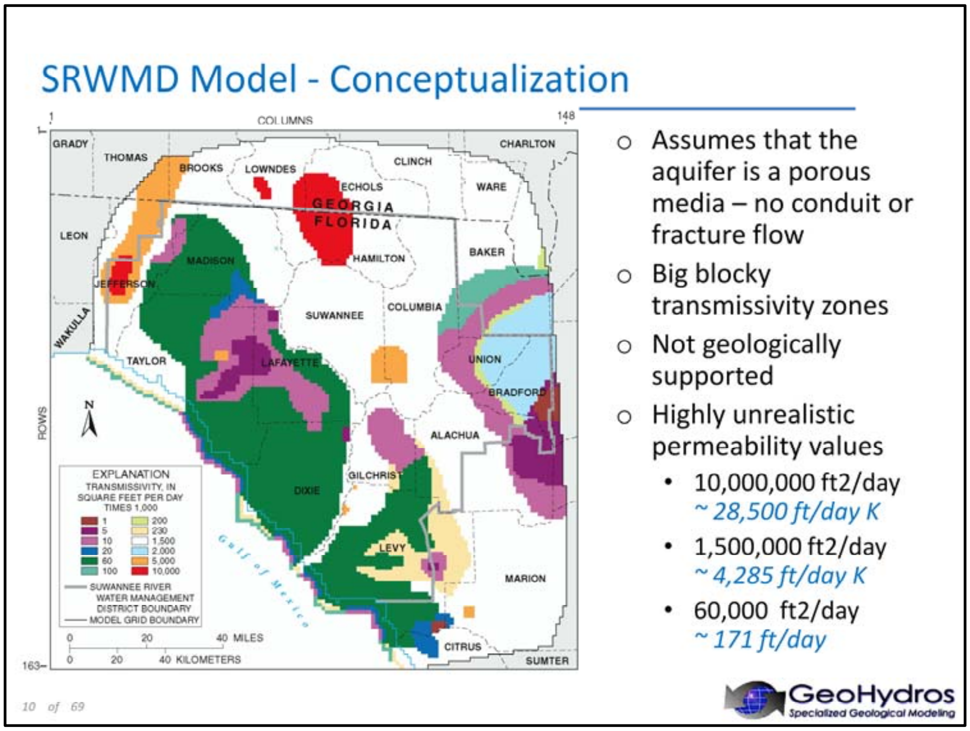
The SRWMD model was calibrated to 190 wells, 5 stream reaches and 7 springs located within the model domain (the Suwannee River Basin).

Swallets were not included. Caves were not included. Tracer-defined flow paths and velocities were not included. The vast majority of spring discharges were not included.



The USGS reported that nearly all points fall close to the 95% confidence interval based on linear regression. If we look more closely at the plot however, we find that the 95% lines equate to an error of 10 feet below the observed value to 13 feet above the observed value. If we look at the map of residuals (model error), we see that within the western Santa Fe River Basin the error ranges between -4 and positive 9 feet and that directly to the north of that region (near Lake City), the model under predicts head by 9 feet.

+- 9 feet is a lot of error given that the potentiometric surface of the Floridan aquifer is so flat. The error basically means that the model is not doing a very good job of simulating the local hydraulic gradients and therefore is unlikely to adequately simulate flow patterns or velocities.



Now lets look at what had to be done to the model design to achieve the level of calibration that was reported.

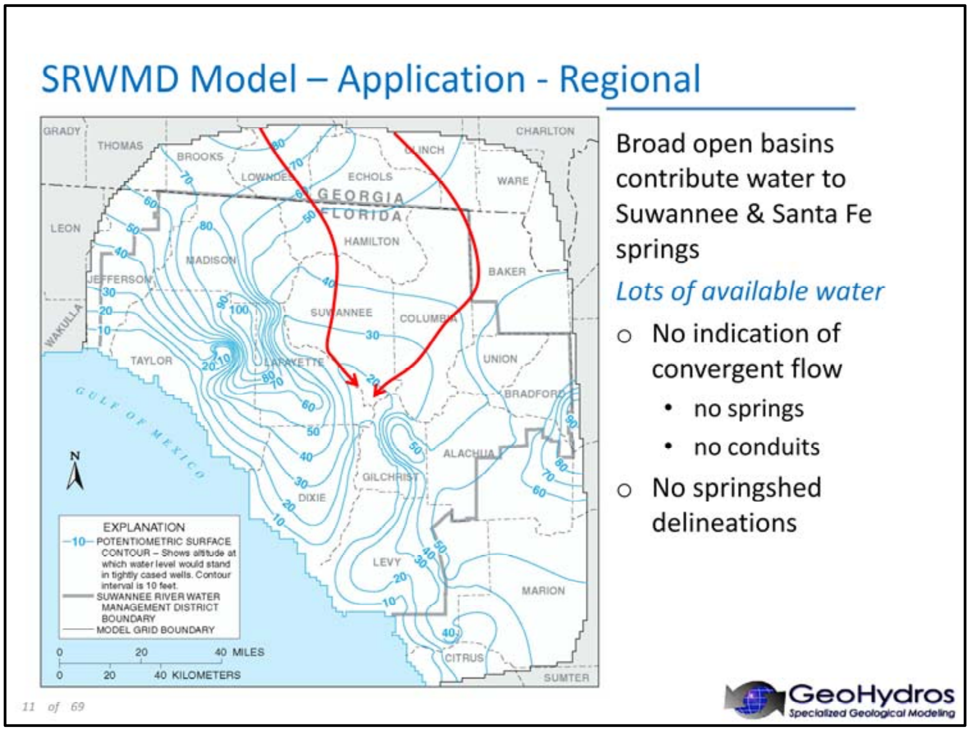
Basically, groundwater models are constructed by plugging in what is known or can be surmised (boundary condition heads, source and sink flows, etc) and then tweaking what is not known (rock properties and recharge) within reasonable limits such that the resulting model simulation matches the observed conditions. Transmissivity is typically the primary rock property knob that is turned to achieve calibration.

This is a map of the aquifer transmissivity (ability of the rock to transmit water) that was derived through the calibration process. Notice first that the distribution is blocky and then that the highest value equates to 28,500 feet per day conductivity and that large low-permeable green zone equates to 171 feet per day conductivity.

The blocky nature is not geologic in nature meaning that the distribution of rock types (rocks of differing permeability) do not correspond to differing geologic conditions. In fact most of the domain consists of the unconfined region of the Floridan aquifer system where the rocks are ubiquitously Ocala or Suwannee limestones. The magnitude of the transmissivities are far higher than values derived by testing actual rocks and beyond the limits of values indicative of porous media flow.

The distribution and magnitude of the transmissivity zones were established only to match the heads and flows. The fact that the resulting pattern and values do not make sense geologically indicates that the underlying conceptualization is wrong.

Inaccurate conceptualizations result in inaccurate predictions. For instance, the size and shape of a cone-of-depression are heavily determined by the transmissivity of the rocks. Over-estimating transmissivity will under-estimate the size and depth of the cone-of-depression. That, in turn, undermines the model's ability to simulate the impacts of pumping.

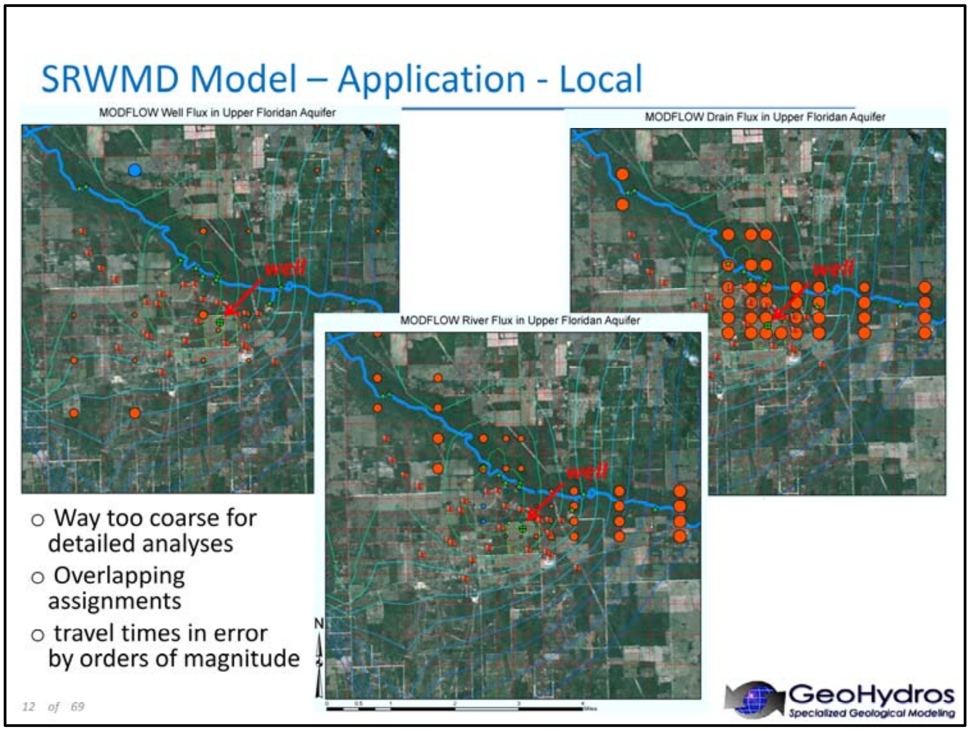


The design and calibration are critical to the application of the model for both water supply and water quality problems.

This slide shows the simulated potentiometric surface of the Floridan aquifer system. Water flows from high to low regions on the map. The red lines denote simulated flow paths into the western Santa Fe River basin. The modeled potentiometric surface does not reveal convergent flow patterns indicative of conduit flow in karst and observable in the Suwannee river basin. It doesn't indicate the presences of discrete spring discharges.

The implications of these failings in terms of water supply planning and management are:

- an inability to define springshed boundaries
- the belief that the western Santa Fe River basin receives flow from as far north as south Georgia



These maps show a real-world example of the model being used to assess of the impact pumping from a well on spring flows. *Note that despite the design limitations and even the express written guidance from model authors, regional models almost always end up being applied to real-world site specific problems.* The well in question is marked on each of the three maps by a green dot with a black plus inside. The orange flags are monitor wells. The green stars are springs. The dark blue line is the Santa Fe River.

The left map shows the distribution of wells that were simulated in the model. Each orange dot is a well in the model that is extracting water from the aquifer. The large blue dot is a well that is injecting water into the aquifer. Note that the well in question is simulated by the small orange dot just below its actual position that is centered in a box that represents model cells that have been refined to a smaller size (~0.25 miles on square).

The center map shows how the model simulates the Santa Fe River. In this map, the orange dots represent cells that are assigned in the model as river meaning that they either receive or inject water depending on the simulated potentiometric surface, the assigned elevation of the river bed, and a conductance terms describing the ability of the river bottom to transmit water. Note that the same cell that was assigned as a well is also assigned as a river.

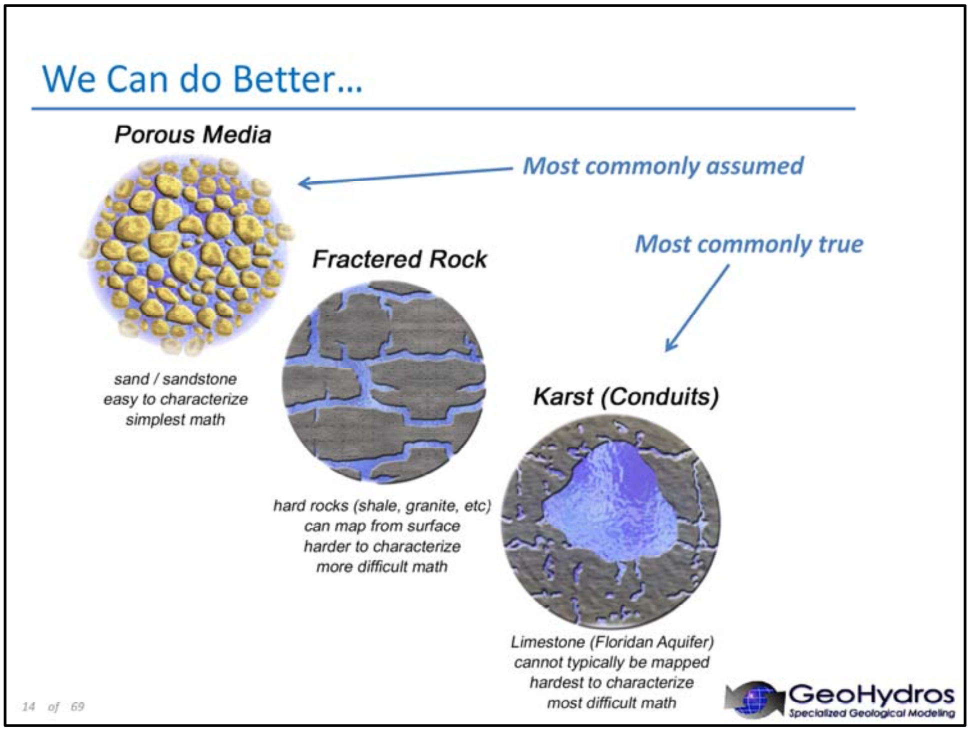
The right map shows how the model attempts to simulate springs. This time, each orange dot marks a model cell that is assigned as a drain meaning that it will discharge water if the potentiometric surface is higher than an elevation assigned to represent the spring vent. Note that the same cell that was assigned as a well and a river is also assigned as a drain.

The model is clearly being used to simulate conditions that it wasn't designed to handle: interactions taking place over less than a square mile, and large-magnitude discrete spring flows. The distribution of cells assigned as river and drains reflects the fact that model cannot simulate real-world conduit flows i.e. more area is needed to transmit the observed flow.

Section – 2

Western Santa Fe River Basin
and
The Hybrid Karst Model

GeoHydros
Specialized Geological Modeling



Finding a better modeling methodology, one that achieves better simulations of real-world conditions, was the purpose of the 10+ year Woodville Karst Plain research effort.

As it turns out, we do not believe the limitations are necessary. The first step is to abandon the overly simplistic conceptualization of the Floridan aquifer system as a simple porous media in favor of one that views the aquifer as a porous media with networks of embedded caves organized to deliver groundwater flow to discrete spring discharges. This is not a unique approach and the modeling literature describes the design as a hybrid model.

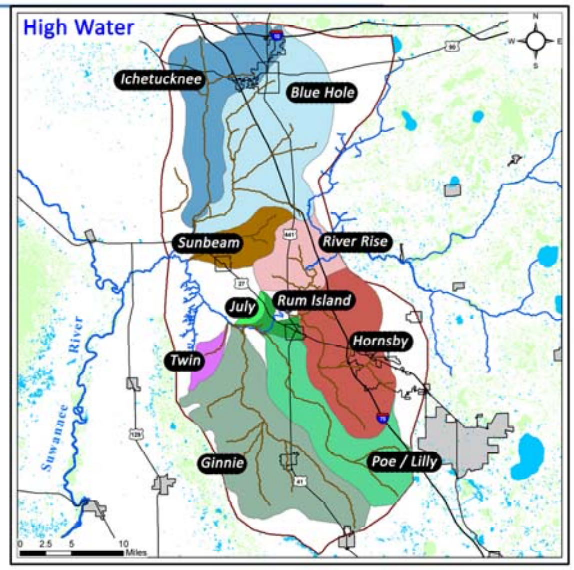
In application, this simply means shifting away from MODFLOW in favor of a finite-element software package that provides for a hybrid articulation of flow. Our choice was to use a well-documented and widely used software package called FEFLOW.

For more information of FEFLOW see:
http://www.feflow.info/

We Can Delineate Reasonable *Springsheds*

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

Spring Group	High (km^2)	Low (km^2)
Ginnie / Blue	395	414
Blue Hole Group	377	488
Hornsby	274	210
Ichetucknee	248	222
Poe / Lilly	237	241
River Rise	116	134
Sunbeam	80	103
Twin	29	49
Rum Island	24	26
July	12	11



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GeoHydros
Specialized Geological Modeling

Changing the conceptualization permits far more realistic predictions and simulations.

This slide shows the model-simulated springsheds for the major 1st and 2nd magnitude springs along the western Santa Fe River. The shape and size of these springsheds closely follows those that have been defined by detailed potentiometric surface mapping, groundwater tracing, and geochemical analysis of spring discharges and groundwater from wells.

The brown line marks the domain of a hybrid numerical groundwater flow model that was used to define the springsheds. The springshed boundaries were drawn from forward particle tracks. The table at the left shows the simulated size of the springsheds under high-water and low-water conditions.

Toggling back and forth between this slide and the next slide will illustrate how the springsheds likely change under different hydrologic conditions.

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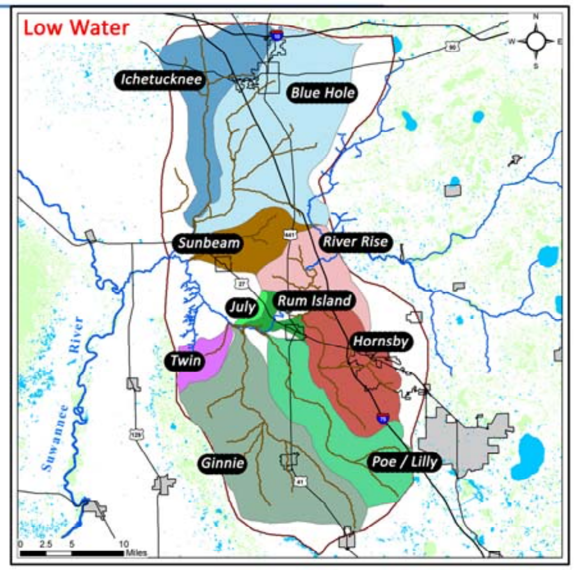

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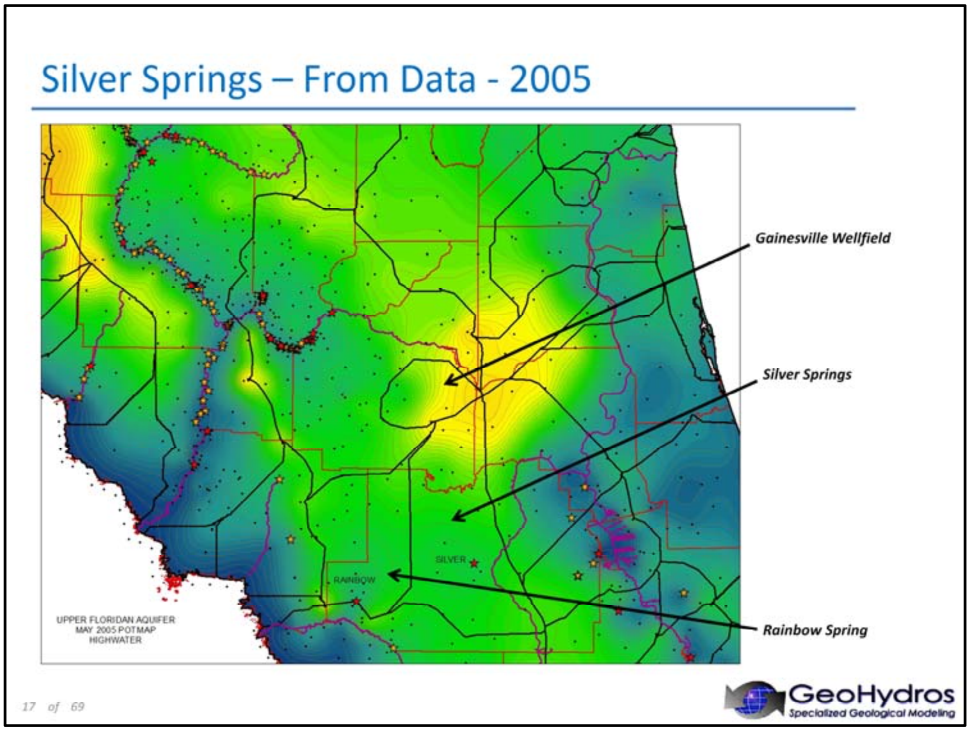
GeoHydros
Specialized Geological Modeling

This slide shows the model-defined springsheds under low-water conditions.

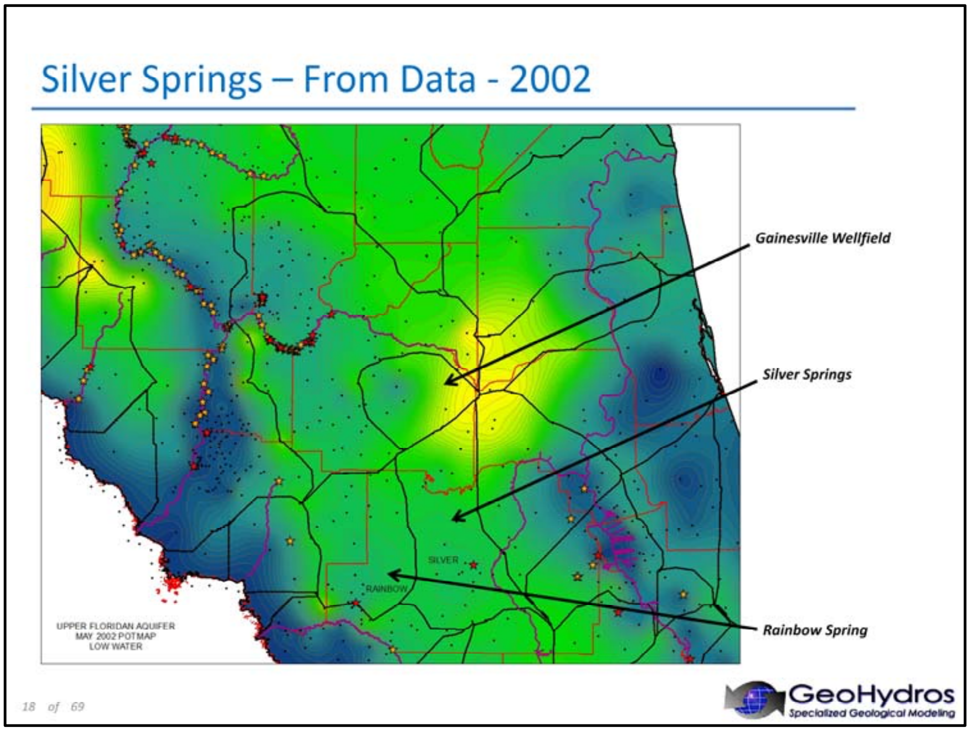
Toggling back and forth between this slide and the previous slide will illustrate how the springsheds likely change under different hydrologic conditions.



This map and the map on the next slide are intended to show that changing springshed boundaries in response to different hydrologic conditions is shown by raw data and is thus the expectation.

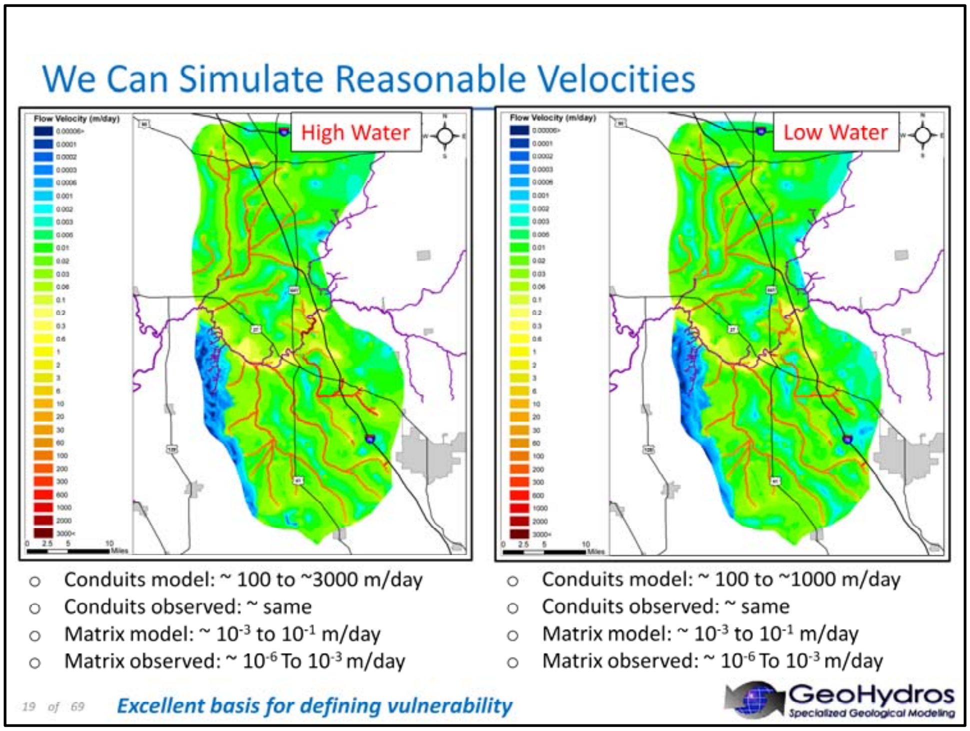
This map shows the springsheds and well capture zones in the Silver springs region of Florida under high-water hydrologic conditions (marked by May 2005 potentiometric surface data).

Toggling back and forth between this slide and the next slide will illustrate how the springsheds actually change under different hydrologic conditions.



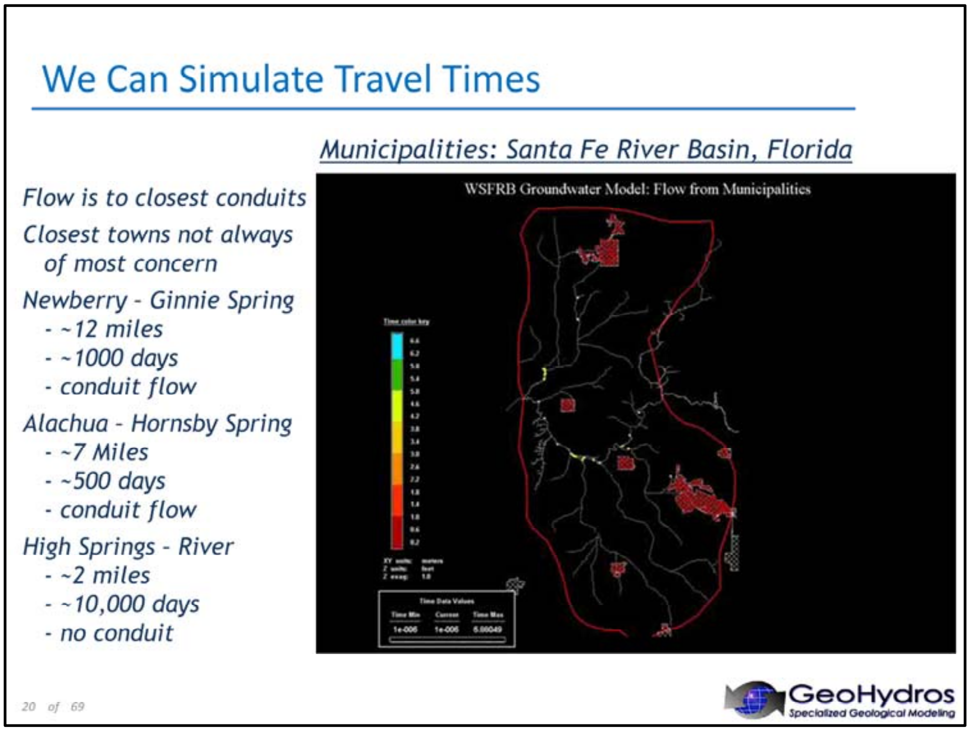
This map shows the springsheds and well capture zones in the Silver springs region of Florida under low-water hydrologic conditions (marked by May 2002 potentiometric surface data).

Toggling back and forth between this slide and the previous slide will illustrate how the springsheds actually change under different hydrologic conditions.



A commonly observed characteristic of karst aquifers is a several order of magnitude difference between matrix and conduit groundwater velocities.

This slide shows how changing the conceptualization of the aquifer and the modeling methodology results in a more realistic simulation of groundwater velocities. The model-simulated flow field entails up to a six order of magnitude difference between matrix and conduit velocities. Note that the model matches tracer-defined conduit velocities and also generally matches velocities estimated for the rock types that typify the Floridan aquifer system.



The hybrid model yields a more realistic simulation of flow paths and travel-times – ones that are supported by groundwater tracer tests.

The next five slides show snapshots from an animation of forward particle tracks by travel-time. The particles were started at points contained within each of the municipality boundaries within the hybrid model domain: Lake City, Fort white, High Springs, Alachua, Newberry, and Archer (generally from north to south).

The colors represent travel-time. The pathways will show that the travel-time to springs, and thus spring vulnerability, is determined by proximity of the source to the closest conduit – not the proximity of the source to the spring.

In this case, it was assumed that Ginnie spring is vulnerable to contamination emanating from High Springs because of its proximity but the model indicates that it is significantly more vulnerable to contamination from Newberry despite the fact that it is much farther away.

Simulating Travel Times - Municipalities

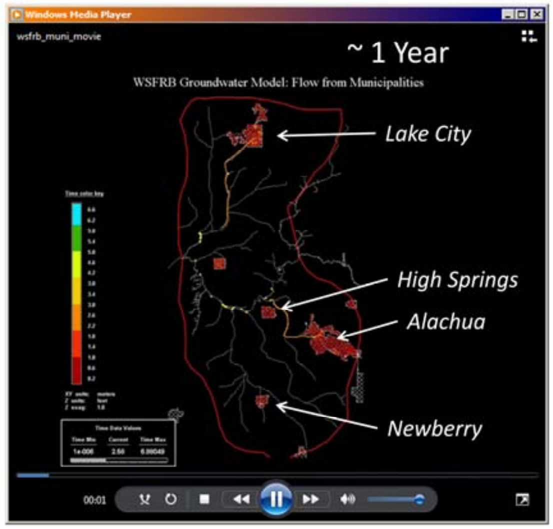
Flow is to closest conduits

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
Specialized Geological Modeling

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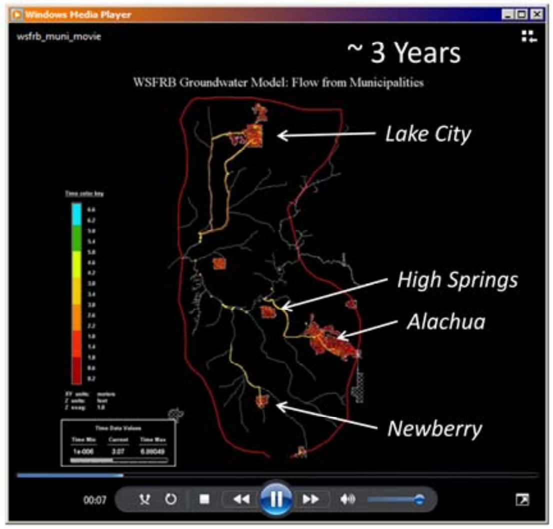

GeoHydros
Specialized Geological Modeling

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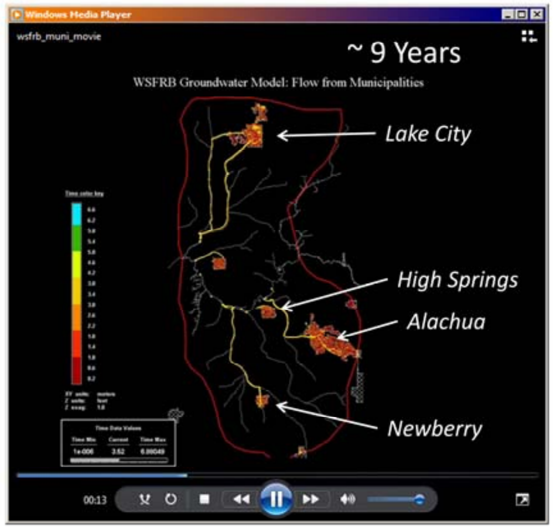

GeoHydros
Specialized Geological Modeling

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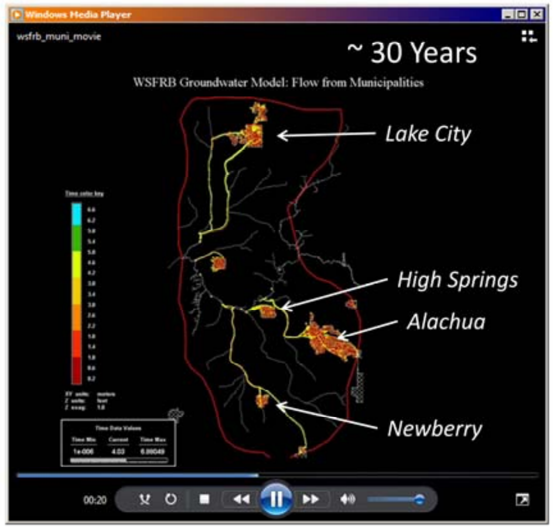

GeoHydros
Specialized Geological Modeling

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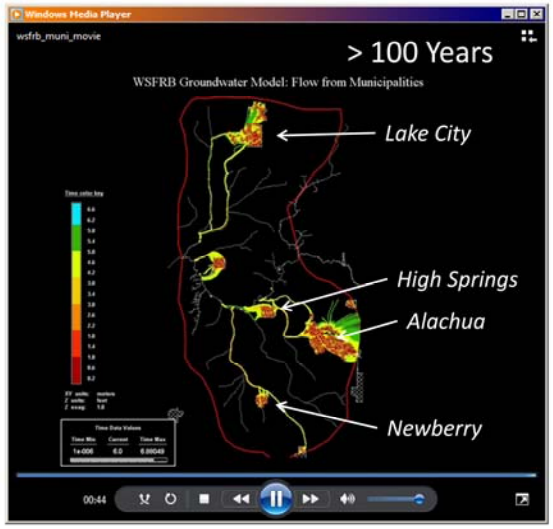
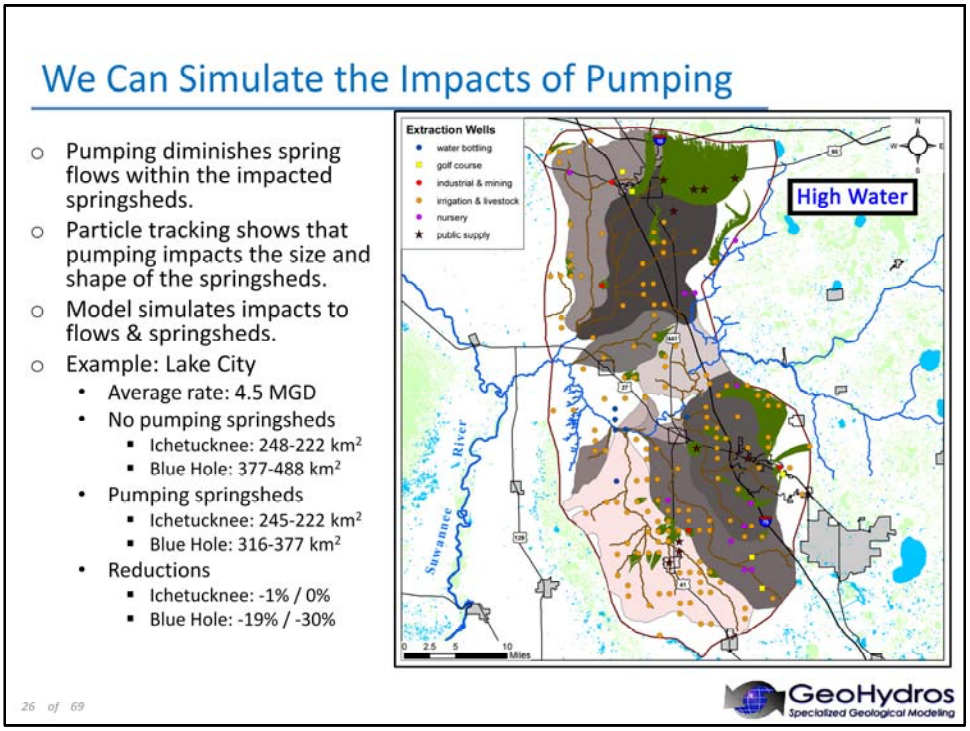


GeoHydros
Specialized Geological Modeling

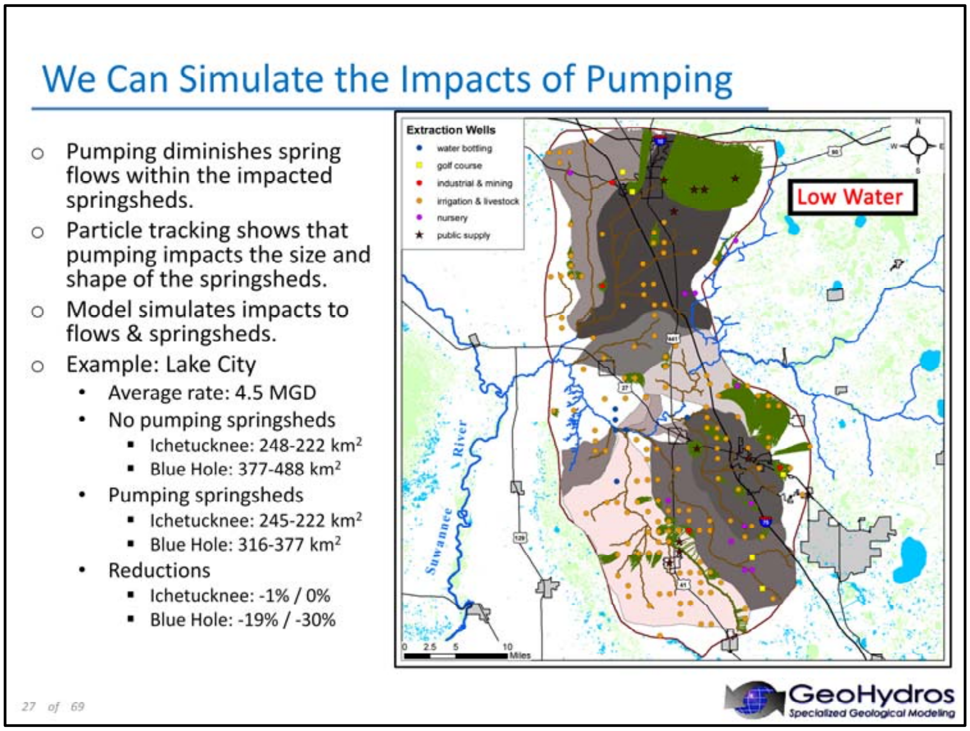


The hybrid model can also be used to more confidently predict the impact of groundwater pumping on spring flows.

This map shows model-simulated capture zones (green) for all of the major pumping wells in the model domain relative to the model-defined springsheds (grays and pink) under high-water conditions. The springshed sizes can be easily estimated using GIS under both pumping and no-pumping conditions and the difference is indicative of the impact that the specified pumping has on spring discharge.

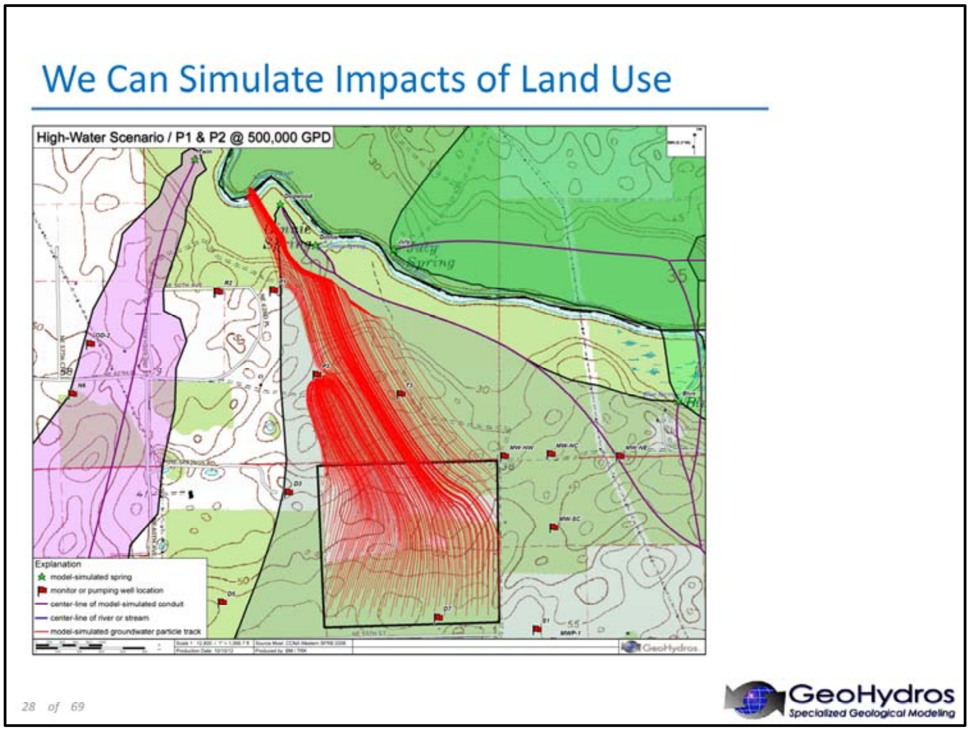
The example shown is for Lake City (the largest well capture zone shown). In that case, pumping can be expected to reduce the size of the Blue Hole springshed (one of the springs contributing flow to the Ichetucknee River) by 19% under high-water conditions and 30% under low-water conditions. The model also shows that Blue Hole will be significantly more impacted than the Icetucknee head spring.

Toggling back and forth between this slide and the next slide will illustrate how the springsheds and capture zones likely change under different hydrologic conditions.



This map shows model-simulated capture zones (green) for all of the major pumping wells in the model domain relative to the model-defined springsheds (grays and pink) under low-water conditions.

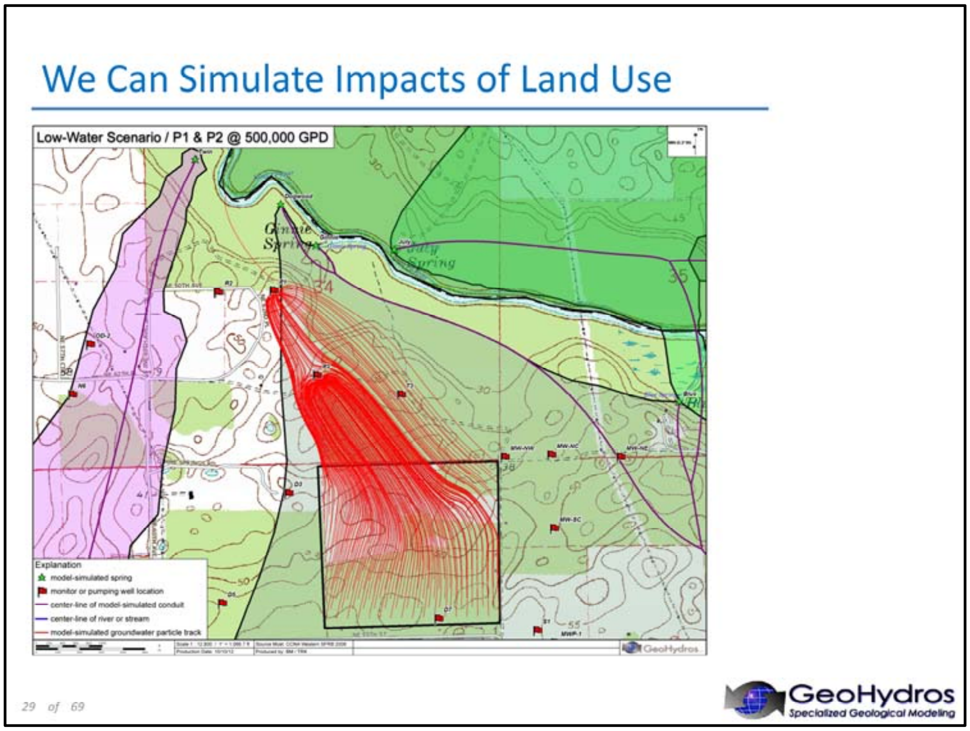
Toggling back and forth between this slide and the previous slide will illustrate how the springsheds and capture zones likely change under different hydrologic conditions.



Using the hybrid model, we can more reasonably simulate probable contaminant transport pathways, even at very local scales.

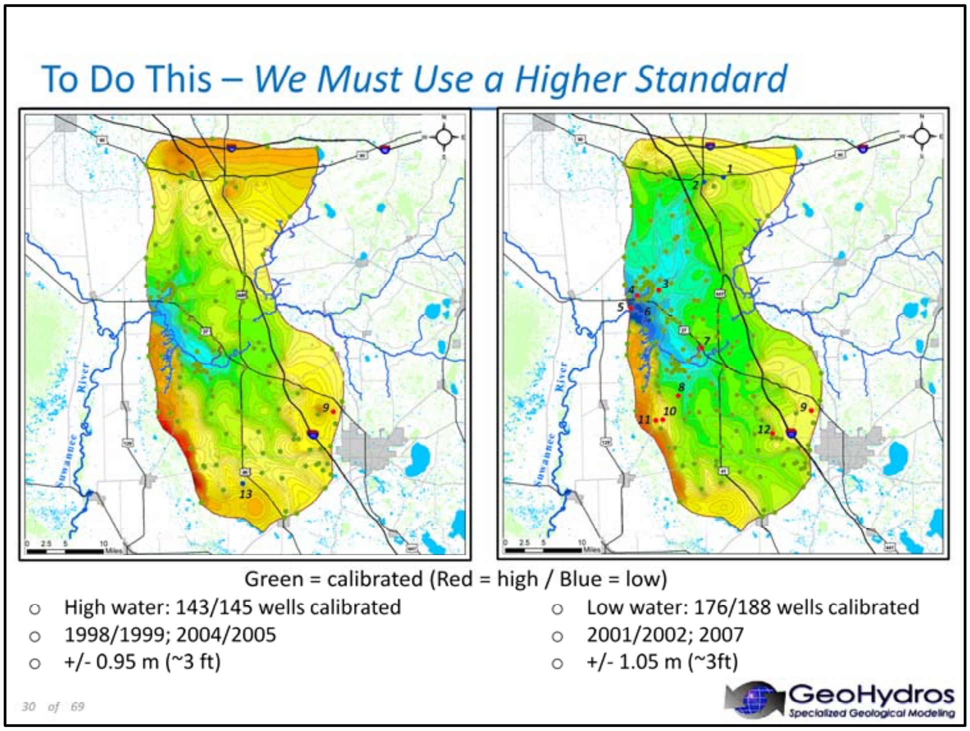
In this slide and the next slide, we show particle tracks showing the model-simulated path and fate of water entering a plot of agricultural land. This simulations shows the flow paths under high-water conditions and groundwater pumping at two water supply wells located between the plot of land and the Santa Fe River. Each well is pumping at 500,000 gallons per day. The closest well intercepts a large part of the flow. Some of the remaining flow is intercepted by the farther well but a large part of the flow makes it to the river near Dogwood spring.

Toggling back and forth between this slide and the next slide will illustrate how the flow paths likely change under different hydrologic conditions.



This simulations shows the flow paths under low-water conditions and groundwater pumping at two water supply wells located between the plot of land and the Santa Fe River. Each well is pumping at 500,000 gallons per day. In this case, all of the flow is intercepted by the two wells and none makes it to the river or the springs.

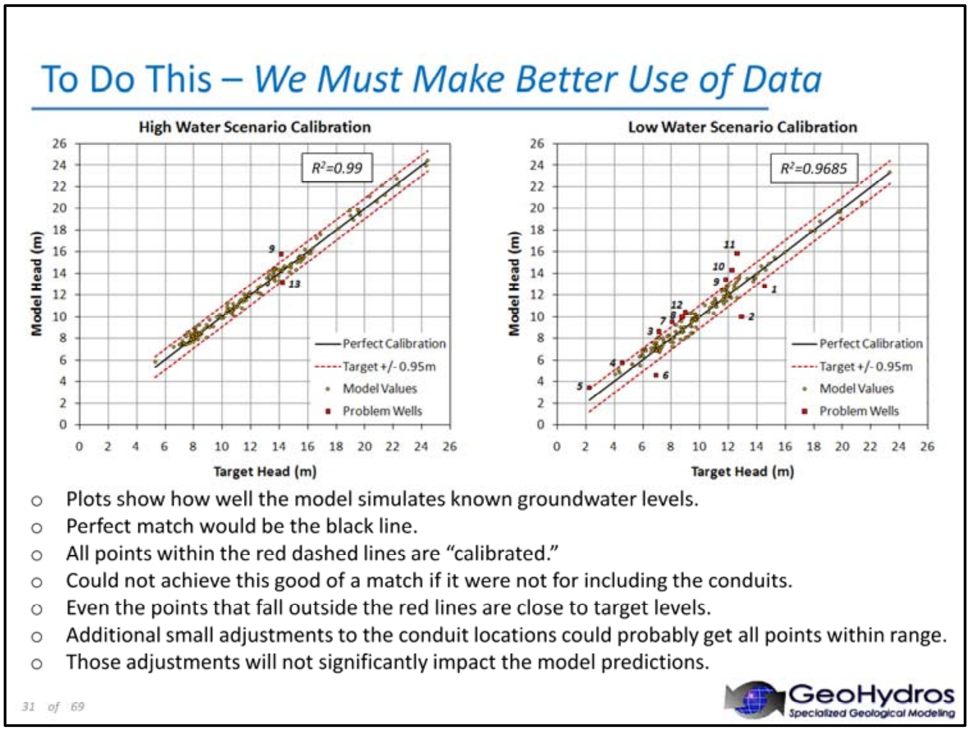
Toggling back and forth between this slide and the previous slide will illustrate how the flow paths likely change under different hydrologic conditions.



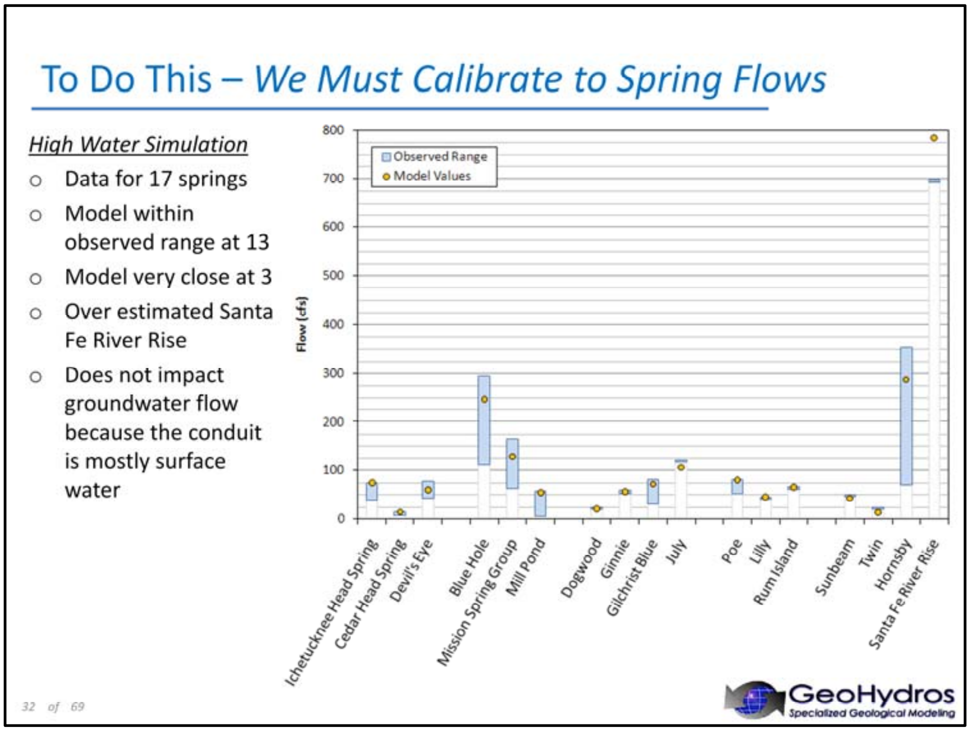
In order to produce better, more reliable, and more useful groundwater flow models in karst aquifers, we need to modify and improve on six aspects of the model development process.

1. Denser groundwater level calibration datasets need to be developed and used. Typically, these datasets are compiled from a single time period (i.e. September 1990). This approach rarely yields enough data to discern probable conduit patterns (i.e. troughs in the potentiometric surface). For the western Santa Fe hybrid model, we performed statistical analyses on all available historical head, precipitation, spring flow, and river stage data. From those analyses, we developed two comprehensive datasets: one reflecting high-water conditions, and one reflecting low-water conditions. By doing this, we were able to establish a much denser distribution of groundwater levels to which the model could be calibrated (*145 and 188 wells respectively compared to 190 wells used for the entire District model*).

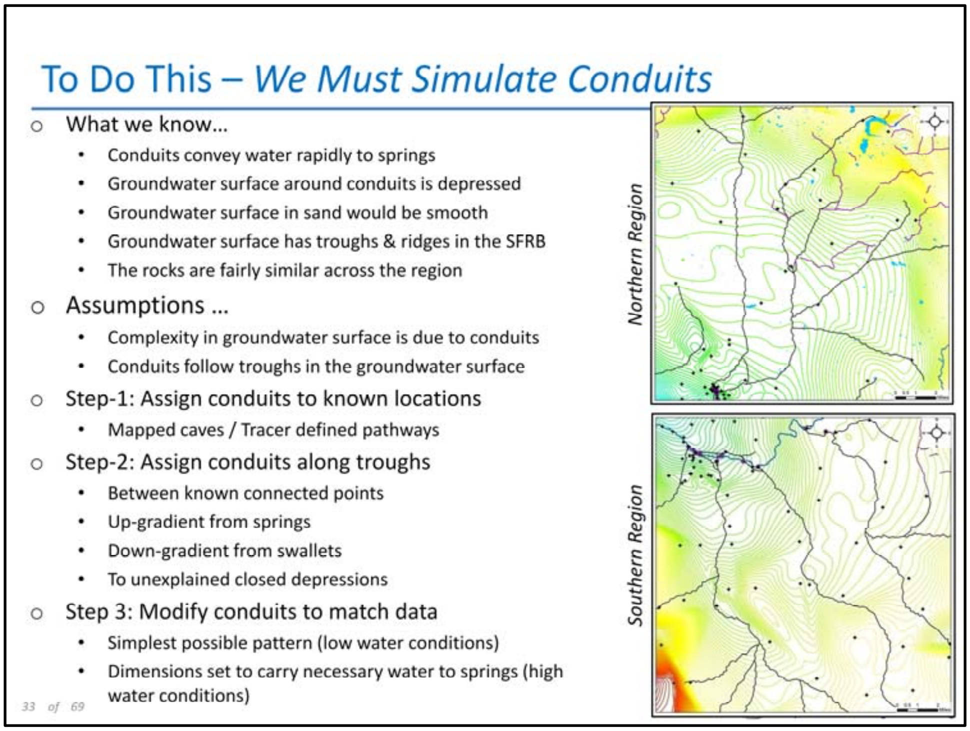
2. More rigorous calibration targets need to be identified and used. Typically, a value of 5% of the total head change across a model domain is used as a calibration target but that can allow large errors in regions where the gradient is variable and does not address the distribution of the error. Here, we used the average observed range in head for the respective periods as a target, and more significantly identified the location of all errors and addressed any problems in regions that would likely significantly impact the results on a one-by-one basis (i.e. near the northern boundary where a divide is observable in the potentiometric surface data separating flow to the Suwannee River from flow to the Santa Fe River.



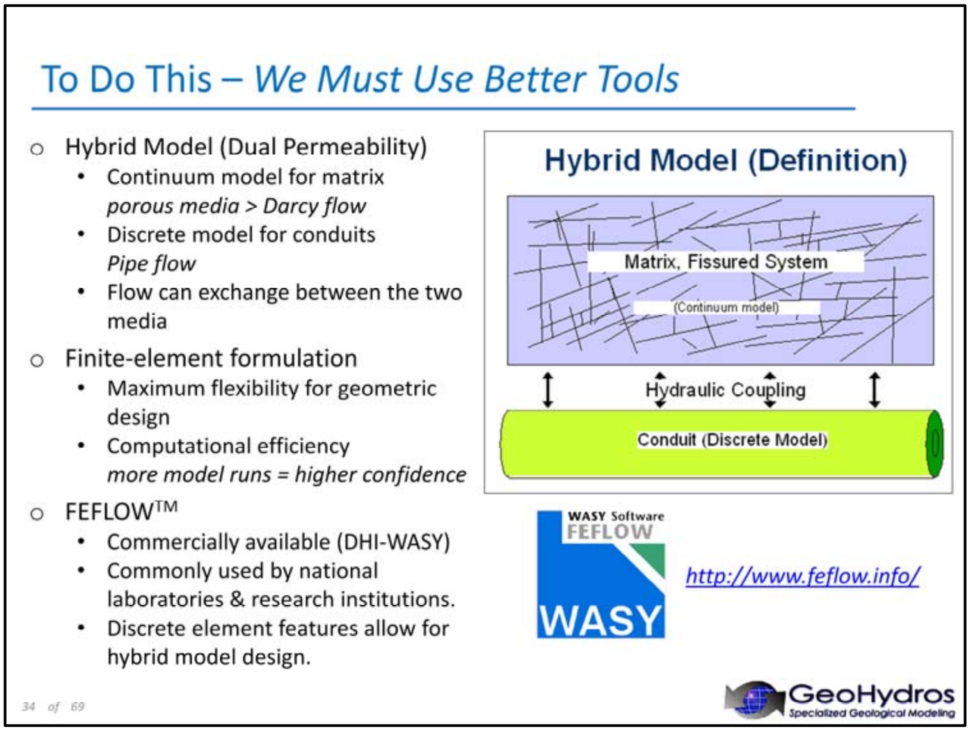
3. Calibration needs to be performed against end-member hydrologic conditions (or conditions near the end-members). This is because, in karst aquifers, there is rarely an "average" condition. Instead, the systems tend toward the end-members: high-flow during rainy seasons, and low-flow during droughts and dry seasons. The western Santa Fe hybrid model was therefore calibrated to two datasets: one representing average high-water conditions, and the other representing average low-water conditions. The process involves iterating adjustments to the variable sets until one set of hydraulic conductivity values, conduit placements, and conduit properties results in an acceptable calibration to both low-water and high-water recharge conditions.



4. The models must be calibrated to discrete spring flows rather than aggregate river gains. This is the key to ensuring that the simulated groundwater flow patterns will adequately discriminate between flow to different springs or spring groups. For the hybrid model, sufficient low-water and high-water data was available for 17 springs to include as calibration targets. Rather than specific target values, the objective was to simulate flows that fell within the observed range for both the high-water and low-water datasets. These targets were then evaluated after every model iteration, along with the groundwater levels at the wells, and the model iteration process continued until the simulation acceptably matched both heads and spring flows. Ultimately, the hybrid model was able to match or very nearly match all the spring flows except the flow from the Santa Fe River Rise under high-water conditions.

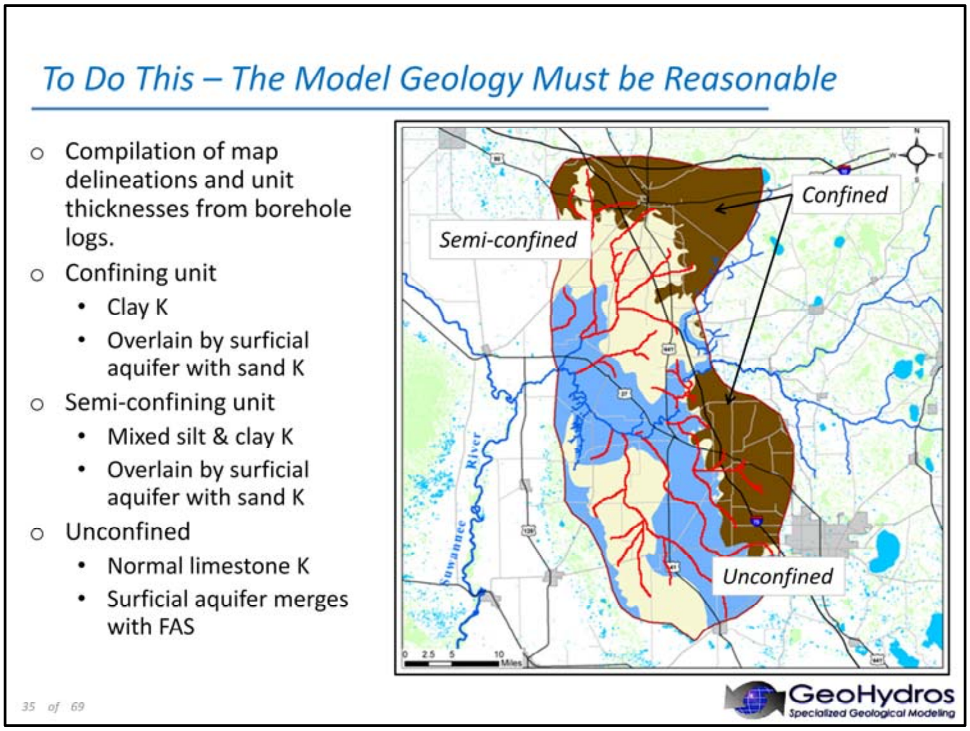


5. Conduits must be explicitly represented in the model. This is critical feature of the model that allows for a realistic simulation of groundwater velocities, and groundwater flow patterns – *ones that honor groundwater tracing results*. Conduits can be included in several different ways. The hybrid modeling approach coupled with a finite-element numerical design allows them to be represented explicitly as 1-D linear features through which flow is simulated by the Manning-Strickler equation. The placement of the conduits can then be readily changed during the calibration process to achieve the best possible match to observed heads and flows. In the western Santa Fe model, caves were initially assigned according to available cave maps and tracer-defined flow paths where in the latter case the hey were placed in troughs visible in potentiometric surface maps generated from the calibration data located between the points of tracer injection and detection. The conduits were subsequently moved and/or extended as needed to achieve the desired level of calibration.

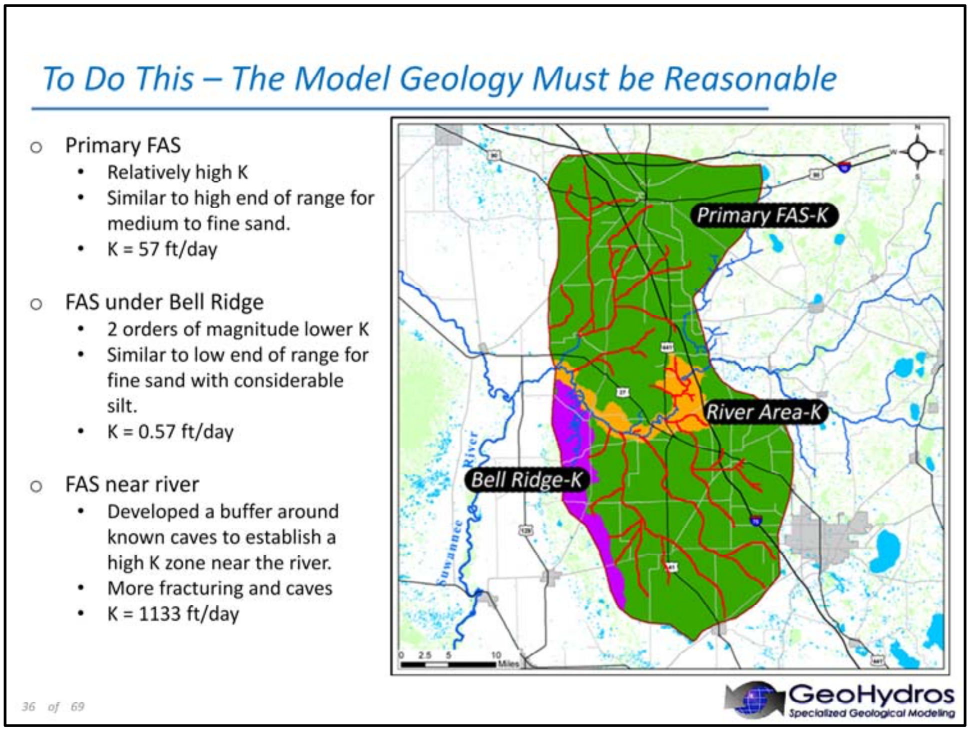


FEFLOW is widely used internationally with results from a multitude of research and real-world applications described in the scientific literature. The DHI-WASY website lists 165 peer-reviewed publications where FEFLOW was used to evaluate groundwater flow and heat and mass transport problems. The software is not as widely used as MODFLOW in the United States but is commonly used by a number of government, academic, and private organizations including:

- the US Geological Survey;
- the US Nuclear Regulatory Agency;
- the US Navy Public Works Center;
- the US Office of Surface Mining;
- Battelle National Laboratories;
- Lawrence Livermore National Laboratories;
- the California Department of Toxic Substance Control;
- the California Water Resources Control Board;
- the South Florida Water Management District;
- Penn State University;
- Texas A&M University;
- the Massachusetts Institute of Technology;
- the University of California;
- the Desert Research Institute; and
- the Southwest Research Institute.

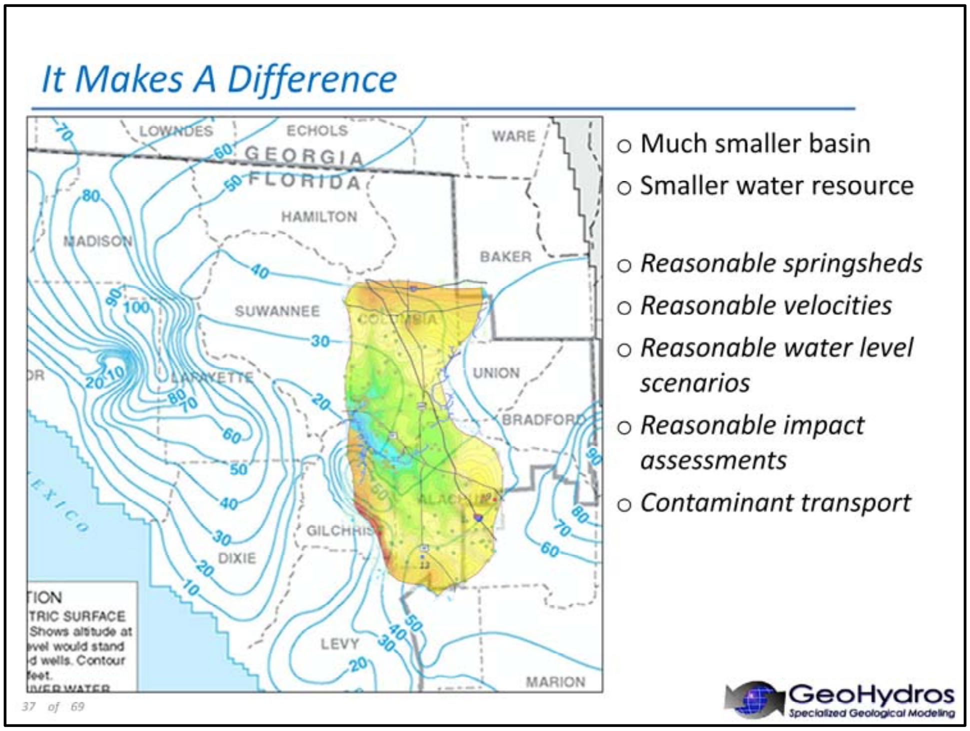


6. The model must be constructed such that the distribution of rock permeabilities (transmissivities or hydraulic conductivities) reflects real-world geologic variation. This slide and the next slide show how the western Santa Fe model was conceptualized vertically and horizontally. This slide shows the distribution of confining material over the model domain, which significantly influences recharge into the Floridan aquifer system. The next slide shows the manner in which hydraulic conductivity was assigned in the model for the Floridan aquifer system layers. As opposed to the blocky distribution of transmissivities used in the District model to achieve calibration, this approach allowed for relatively uniform assignments except where variation was indicated by the geology and groundwater levels. The result is realistic hydraulic conductivity values that allow for a realistic simulation of well capture zones and more intricate head variation driven by the location, size, and roughness of the conduits.



This slide shows the distribution and magnitude of hydraulic conductivities in the western Santa Fe model. The bulk of the domain was assigned a homogeneous value of about 60 feet/day, which is a typical value for medium-grained sands and non-diagenetically altered limestones. A low value of about 0.5 feet/day was assigned to the region underlying the Bell Ridge, which is supported both by borehole logs, groundwater level data, and perched water overlying barren limestone surfaces. A very high value of about 1100 feet/day was assigned along the Santa Fe River corresponding to our conceptualization of this region as being more broadly karstified. Calibration was achieved primarily by changing the location, configuration and properties of the conduits assigned in the Floridan aquifer system model layer.

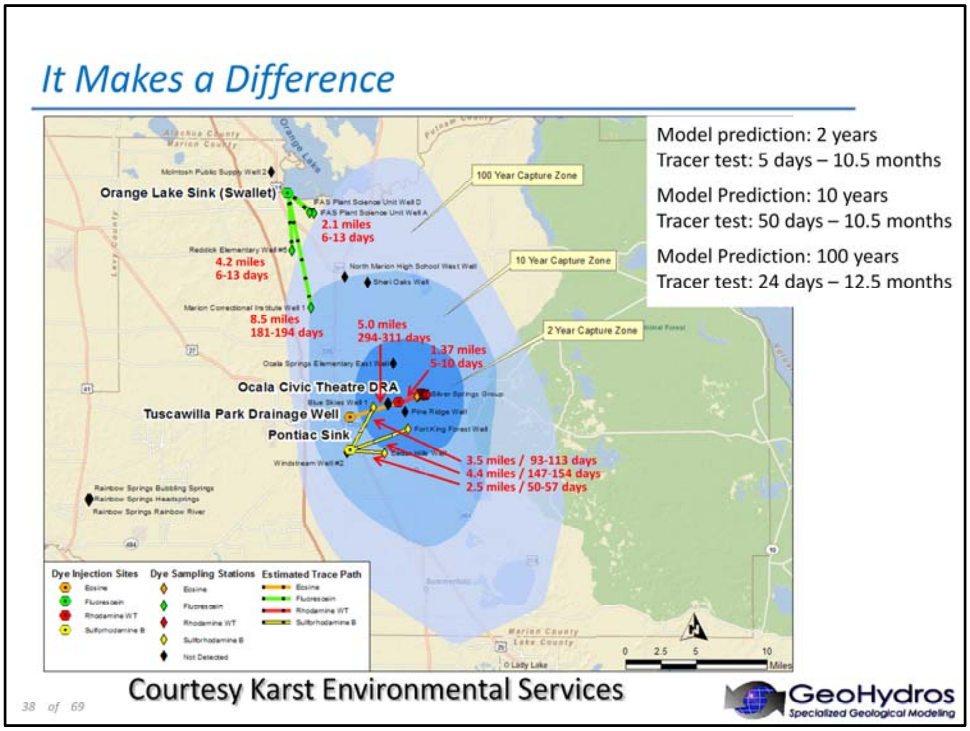
These values differ significantly from those used in the district model: about 4,300 feet/day through most of this domain, ~30 feet/day in a blocky area in the southeastern part of this domain, and ~14,000 feet/day in a blocky area in the northern part of this domain.



The differences between the two modeling approaches cannot be understated. Take for instance that the District model shows that the combined springsheds for the western Santa Fe River extend well into Georgia whereas the hybrid model *(and the potentiometric surface data)* show that they are closed at about the latitude of Lake City. The difference between the two is therefore a very different prediction of groundwater availability to the springs and therefore impacts to flows associated with pumping.

The larger hydraulic conductivity values used in the District model equate to significantly smaller predictions of capture zones, an issue that is particularly topical now in the northern Suwannee River basin. The use of conduits, discrete spring discharges, and swallets in the hybrid model allows for defensible springshed delineations and defensible contaminant transport assessments.

Each of these improvements is achieved through the use of a modeling approach that is tailored to karst environments but is ostensibly the same, and it produces a more defensible model because it is significantly better calibrated.



This slide provides another example of the benefits of the hybrid modeling approach. The underlying map shows zones of roughly equal travel-time to Silver Springs as predicted by a porous media groundwater flow model. The colored lines depict actual groundwater flow paths and travel-times that were measured in the field through groundwater tracing.

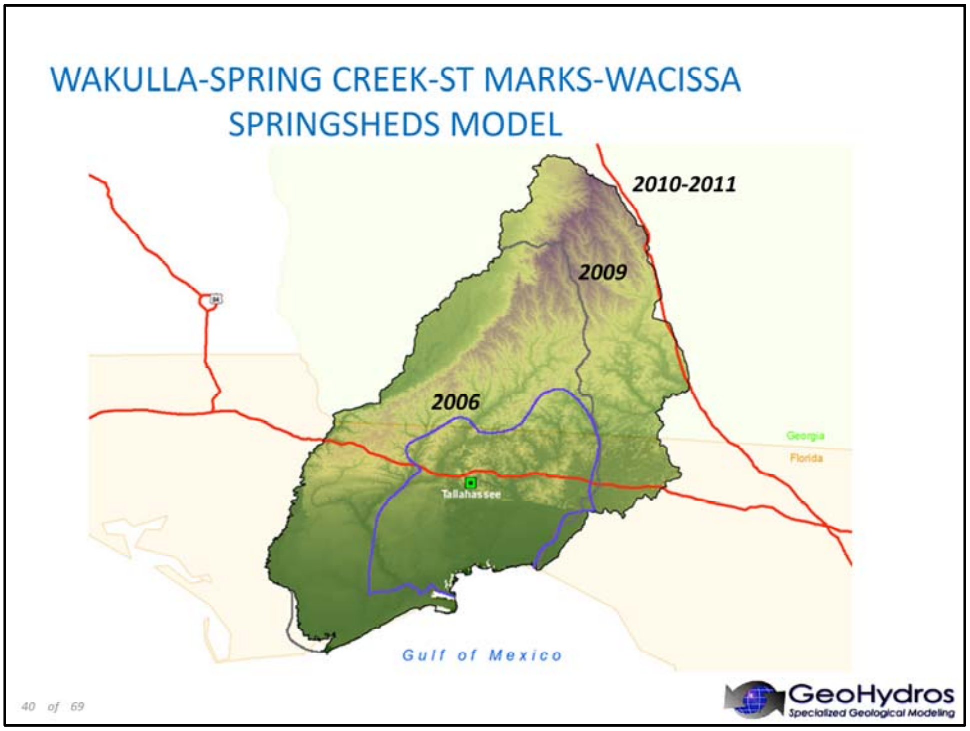
The data clearly shows that the model is under-estimating travel time to the Silver Springs by as much as 2 orders of magnitude (100x). It also suggests that the model has significantly under-estimated the size of the springshed. As was the case with in the western Santa Fe River basin, these errors are most likely due to the absence of conduits in the model design and the use of unrealistically high transmissivity or hydraulic conductivity values, which in turn, equate to under-estimation of well capture zones.

Taken together, the groundwater tracing results negate the veracity of model predictions for both contaminant transport and water supply applications.

It is clear that there is a pressing need for better models both for TMDL and for MFL applications. The hybrid approach would serve that need and both of those applications.

Section – 3
The North Florida Hybrid Karst Model

GeoHydros
Specialized Geological Modeling



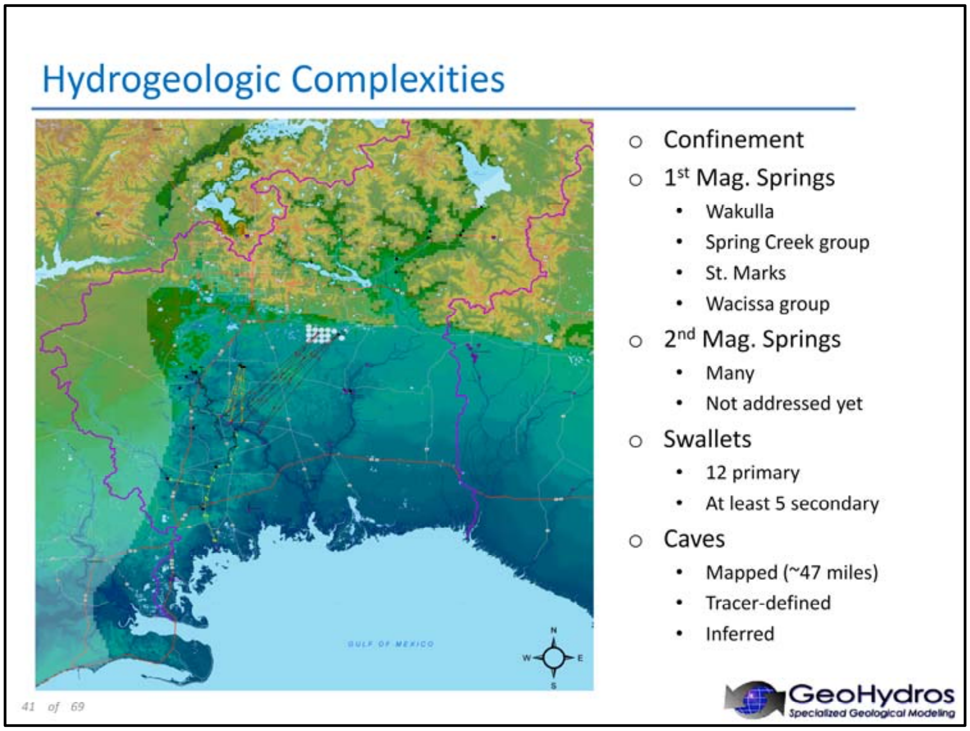
The remainder of this presentation will focus on the status of a larger-scale hybrid model that we have been developing for north Florida to simulate groundwater flow through the Wakulla, Spring Creek, St. Marks, and Wacissa springsheds. Developing this model has been the fundamental goal of the Woodville Karst Plain hydrogeologic research project that we and the FGS have been engaged in since 2002. Three major versions of the model have been released: 2006, 2009, and 2010. Each version reflects lessons learned about how to most effectively simulate karstic groundwater flow. The three progressively larger boundaries reflect our evolving understanding that the model domain needs to be large enough to capture pertinent geologic complexities and to all for a confident internal delineation of springshed boundaries.

The 2010-2011 boundary reflects the final interpretation of a region large enough to encompass and reliably simulate the springshed boundaries for Wakulla, Spring Creek, St. Marks, and Wacissa springs, where simulating all of these is deemed necessary in order to reliably simulate any of them.

A well-calibrated version of the model was completed and submitted to the FGS in 2010. Modeling work in 2011 was intended to focus on scenario analyses using the calibrated model. However, additional groundwater pumping data was uncovered, particularly in Georgia, that forced our team to revise the model structure.

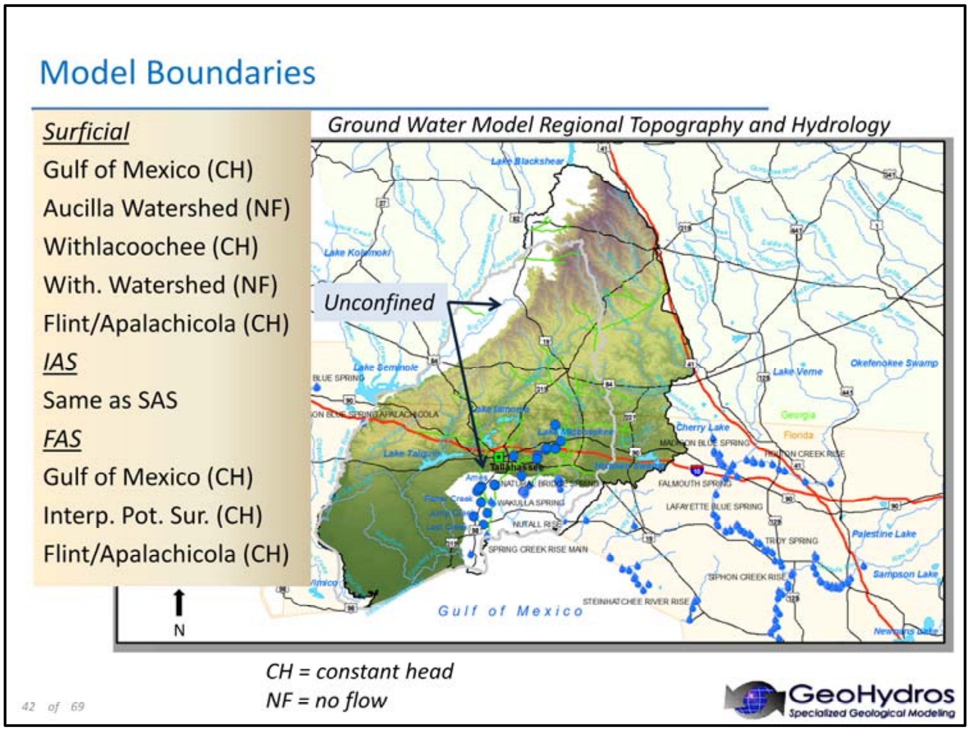
At present, the geologic framework, calibration datasets, and groundwater extraction datasets have all been revised but the model has not been recalibrated and thus remains unfinished.

The following slides will describe the construction and results of the 2010 model, which will be followed by slides that describe the status of the revisions.



The Woodville Karst Plain was chosen as the focus area for this research and modeling effort because it is extensively karstified and contains well-documented features representative broadly representative of karst hydrology and other karst basins in Florida. These include: more than 50 miles of mapped caves, the Wakulla-Leon Sinks cave system being the longest in North America; at least 12 swallets and 5 more swallet seeps that receive water from major streams (Lost Creek, Fisher Creek, Munson Slough, etc); 4 of the largest 1st magnitude springs in Florida (Wakulla, Spring Creek, St. Marks, Wacissa) and many more 2nd and 3rd magnitude springs; and long tracer-defined conduit groundwater flow pathways (12-mile pathway between the City of Tallahassee sprayfield, 6-mile pathway between Ames Sink and Wakulla Spring, 7-mile pathway between Lost Creek and Spring Creek springs, and an 8-mile pathway between Lost Creek and Wakulla Spring.

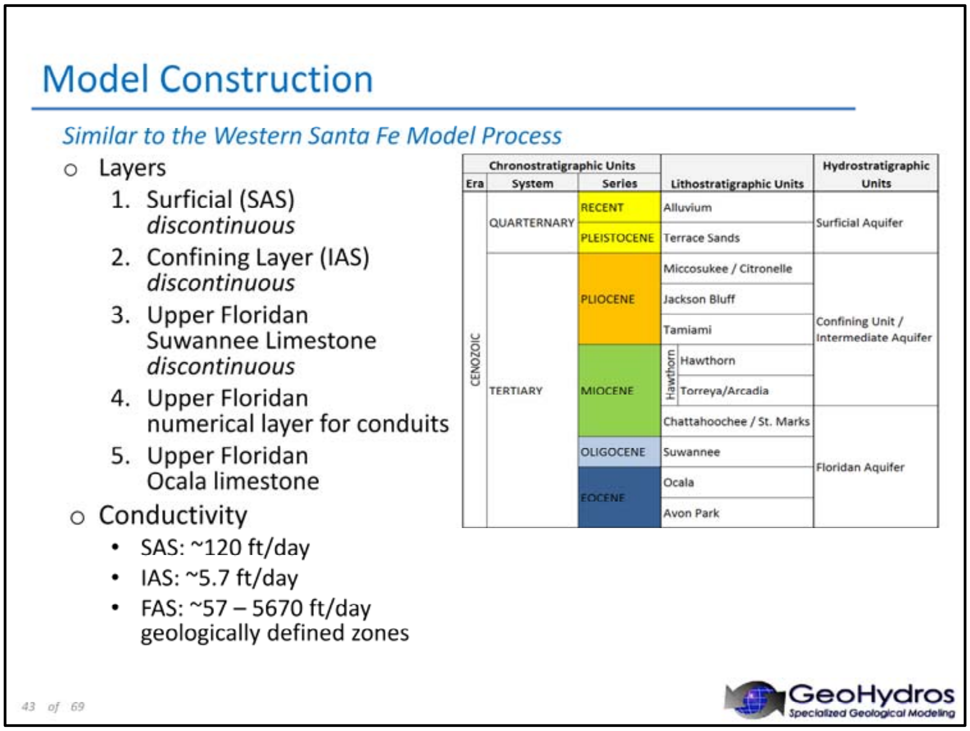
These are all the same complexities that were present and were modeled in the western Santa Fe River basin.



The model boundaries extend from the Gulf of Mexico in the south to Warwick / Lake Blackshear Georgia in the north, and from the Flint/Apalachicola River in the west to the groundwater divide between the Woodville Karst Plain and Suwannee River basins in the east. The eastern boundary essentially follows I-75 to Valdosta and then trends southwest to the mouth of the Econfina River.

The specific boundaries were chosen such that they correspond with natural hydrologic boundaries as much as possible. The model area is so large because the intent is to simulate the springshed boundaries, which are effected by the eastern and western hydrologic boundaries and groundwater pumping that occurs in Georgia, potentially as far north as Albany and Warwick. The boundary expansions that occurred in 2009 and 2010 were performed to address these issues.

The upper boundary of the model is the land surface and the lower boundary of the model is the top of the Avon Park Limestone.



The model is intended to simulate flow through the upper Floridan aquifer system. The 2010 model included 5 layers: 2 representing the Surficial aquifer and the Intermediate aquifer, which we simulate as a confining layer; and 3 representing the upper Floridan aquifer.

Conductivities for the three layers were derived through model calibration but bracketed according to geologically reasonable values: about 120 feet/day for the Surficial aquifer; about 6 feet/day for the confining layer; and between 60 and 5700 feet/day for the Floridan aquifer layers.

Model Construction

- Swallets: *~260 cfs total*
  Lost Creek, Jump Creek, Black Creek, Fisher Creek, Ames, St. Marks River, Natural Bridge, Still Creek, Lake Drain Creek, Lloyd Creek, and Burnt Mill Creek
- Swallet-Seeps: all major lake basins in north Florida section of the domain
- Springs: *target ~5,050 cfs total*
  Wakulla, Spring Creek, St Marks, Wacissa
  Cray's Rise, Natural Bridge, Rhodes, and Horn
- Caves & Traced Pathways
- 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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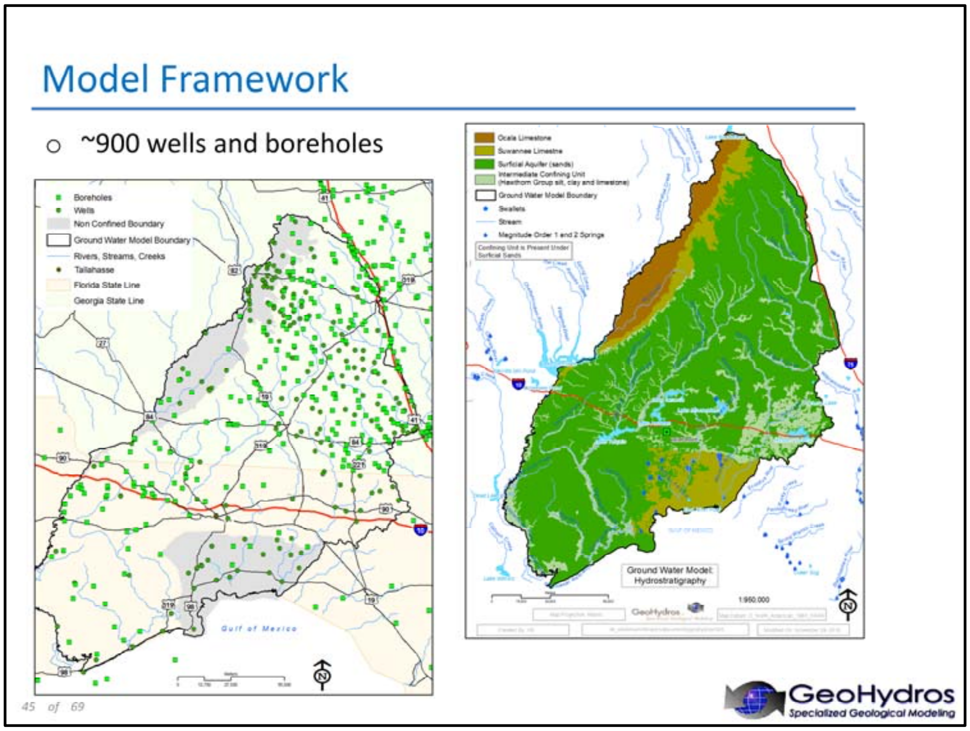
Specialized Geological Modeling

The 2010 model included the 4 major springs plus Cray's Rise, Natural Bridge, Rhodes, and Horn springs; 12 swallets, 5 swallet-seeps, and all of the traced pathways shown on the previous map.

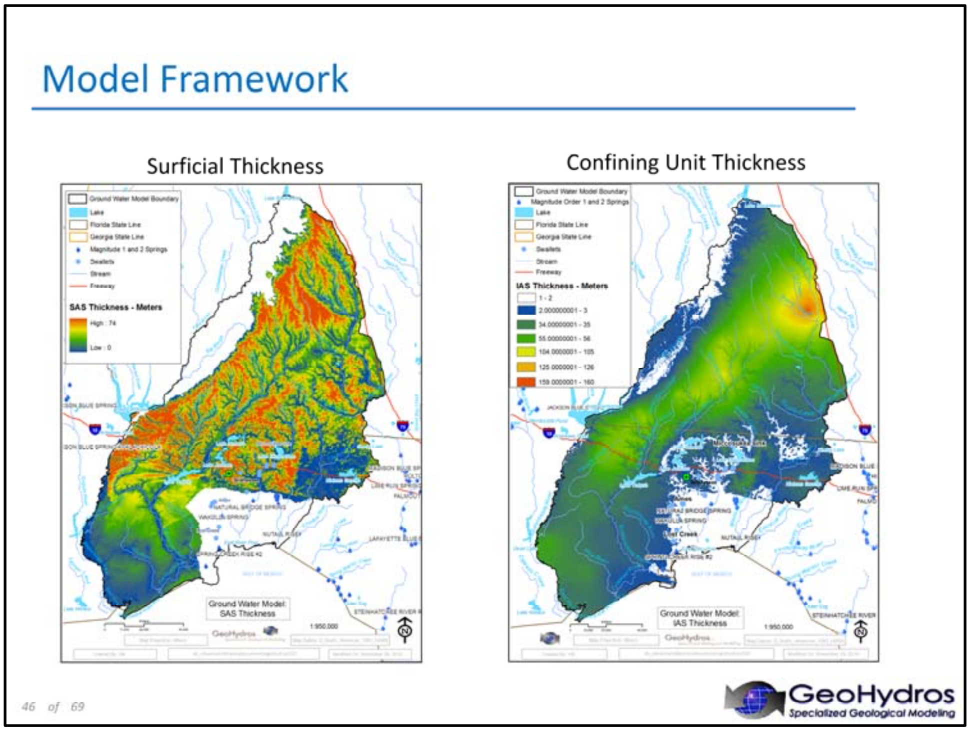
Pumping data was compiled for Florida and Georgia (NWFWMD permit data for Florida, and County compilations for Georgia). The Georgia data was not explicitly included because pumping locations could not be assigned and the initial survey indicated that it was not large enough in magnitude to significantly effect flow and calibration.



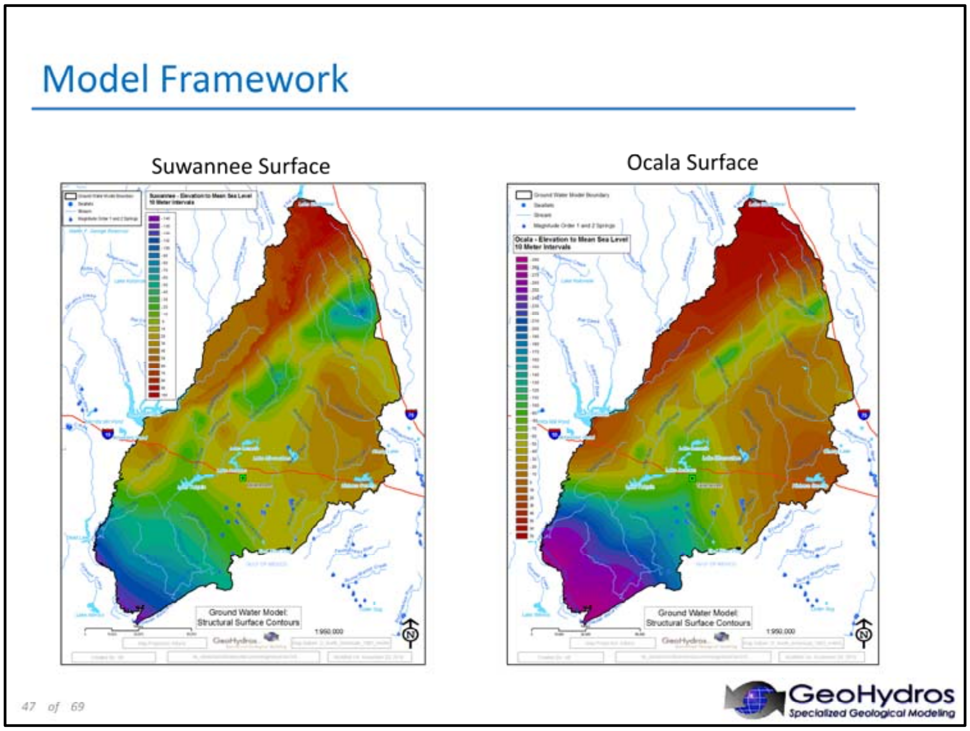
The geologic framework for the 2010 model was constructed from geologic maps and data derived from 900 wells and boreholes predominantly published or provided by the U.S. Geological Survey. The model surfaces were ultimately derived from maps published by the USGS – Miller (1986).

Hydrogeologic Framework of the Floridan Aquifer System in Florida and in Parts of Georgia, Alabama, and South Carolina, James A. Miller, USGS Professional Paper 1403-B, 1986

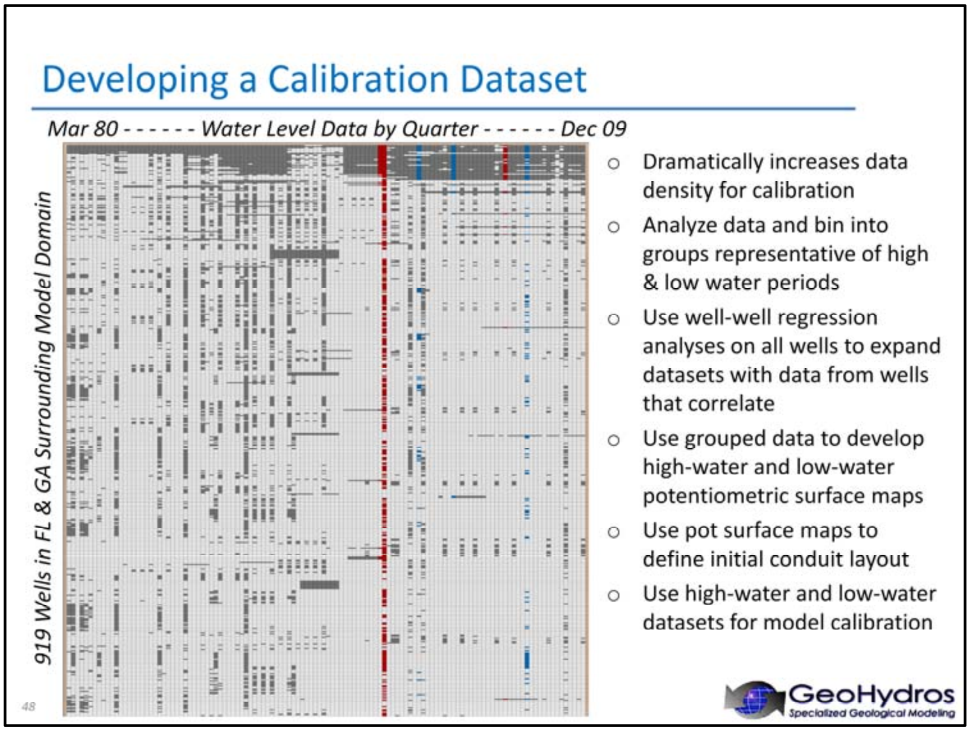
The geologic structure was fairly uniform and layered except for the Surficial aquifer, which was highly variable in terms of thickness, and for a trough of thicker confining unit sediments and depressed limestone elevations corresponding to the Gulf Trough. Generally, the Surficial aquifer and confined conditions in the Floridan aquifer system were present through the central part of the model while unconfined conditions marked the northwestern and southern parts of the model domain.



These maps show the simulated variability in the Surficial aquifer thickness and the generally trend thick confining unit following the central part of the model proximal to the Gulf Trough.



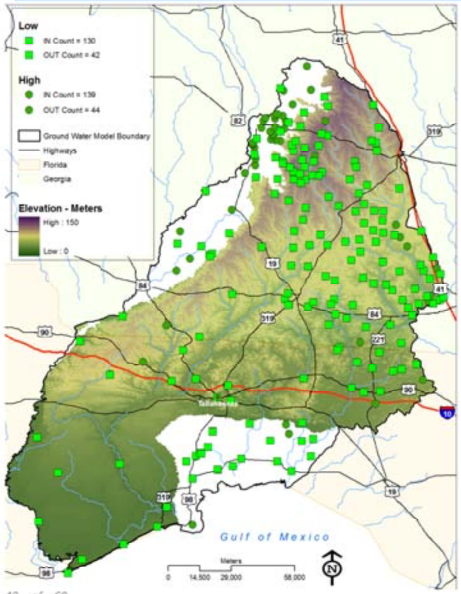
These maps show the generally depressed elevations of the Ocala and Suwannee Limestones along the central part of the model proximal to the Gulf Trough.



Calibration datasets were compiled from historical groundwater level data derived from 919 wells in Florida and Georgia following the same process as described for the western Santa Fe River basin model. The Georgia data was derived from the U.S. Geological Survey. The Florida data was primarily derived from the NW Florida Water Management District and Suwannee River Water Management District, and augmented with data from the U.S. Geological Survey.

We performed statistical analyses on all available historical (1980-2009) head, precipitation, spring flow, and river stage data. From those analyses, we developed two comprehensive datasets: one reflecting high-water conditions, and one reflecting low-water conditions. Both datasets were subsequently used in the model calibration process but the 2010 model was primarily calibrated only to the high-water dataset.

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
- *Boxes are low-water data points*
- *Circles are high-water data points*
- *Shared points are not distinguished.*

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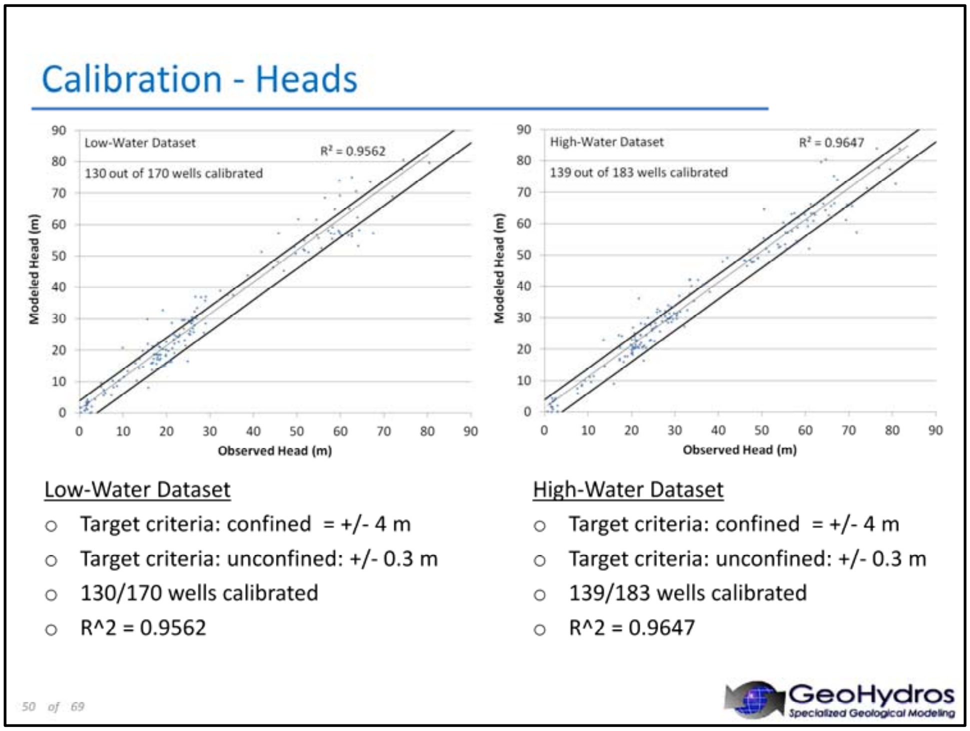
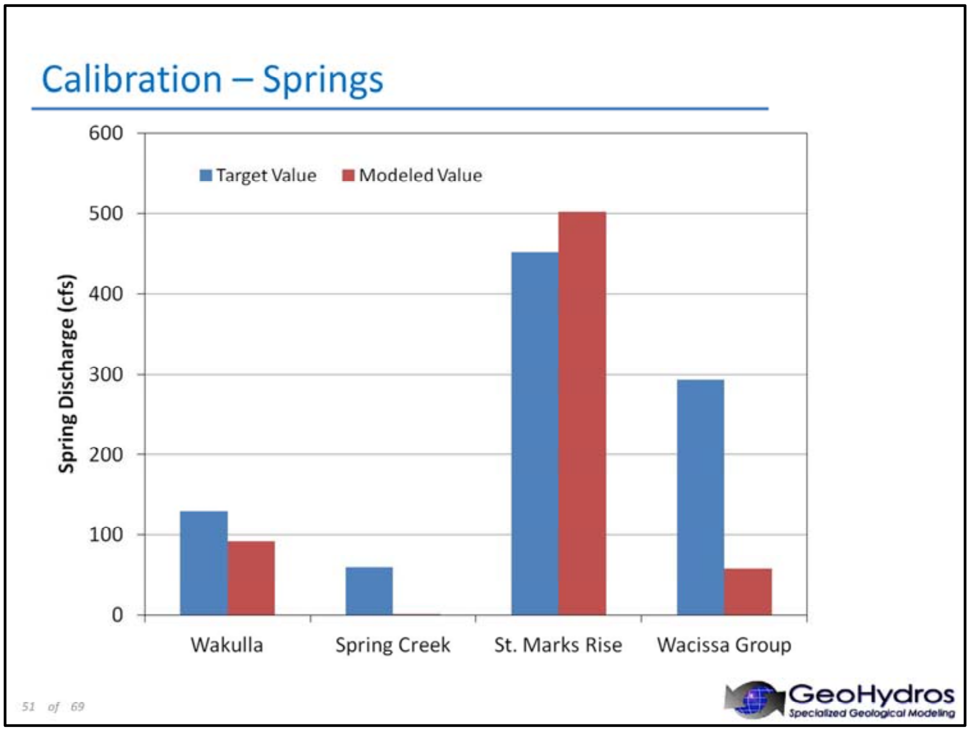
Specialized Geological Modeling

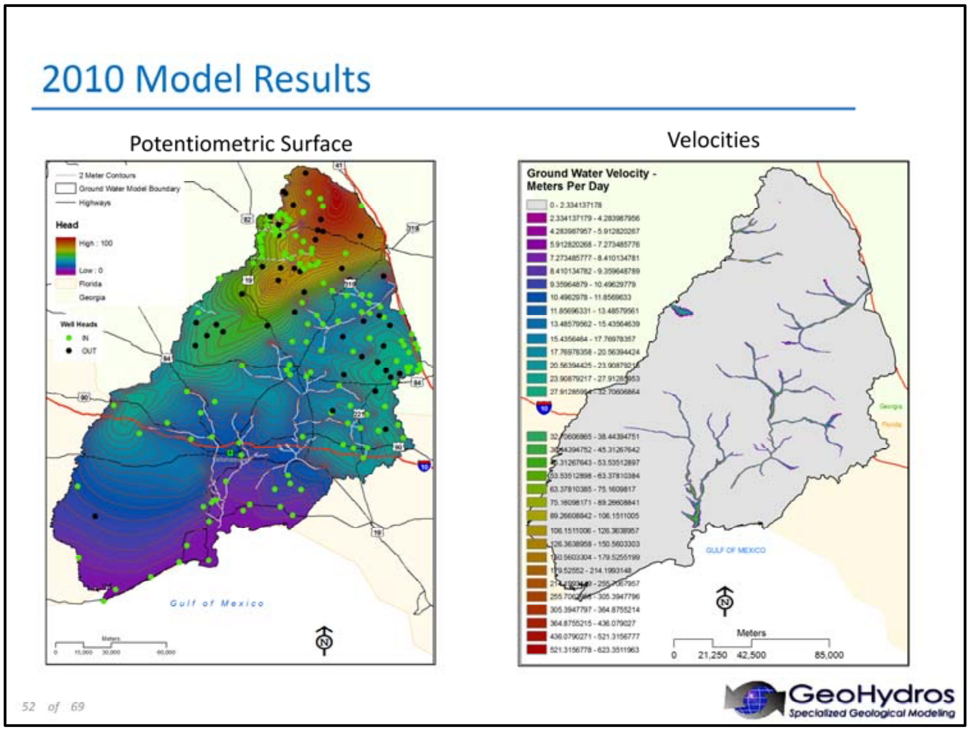
This map shows the distribution of wells used to develop the high-water and low-water calibration datasets.



These plots show the results of the calibration process for the 2010 model where both the high-water and low-water versions calibrated reasonably well to the head datasets. Target criteria was +/- 4m (12 feet) in the confined regions and +/- 0.3 m (~1 foot) in the unconfined regions.



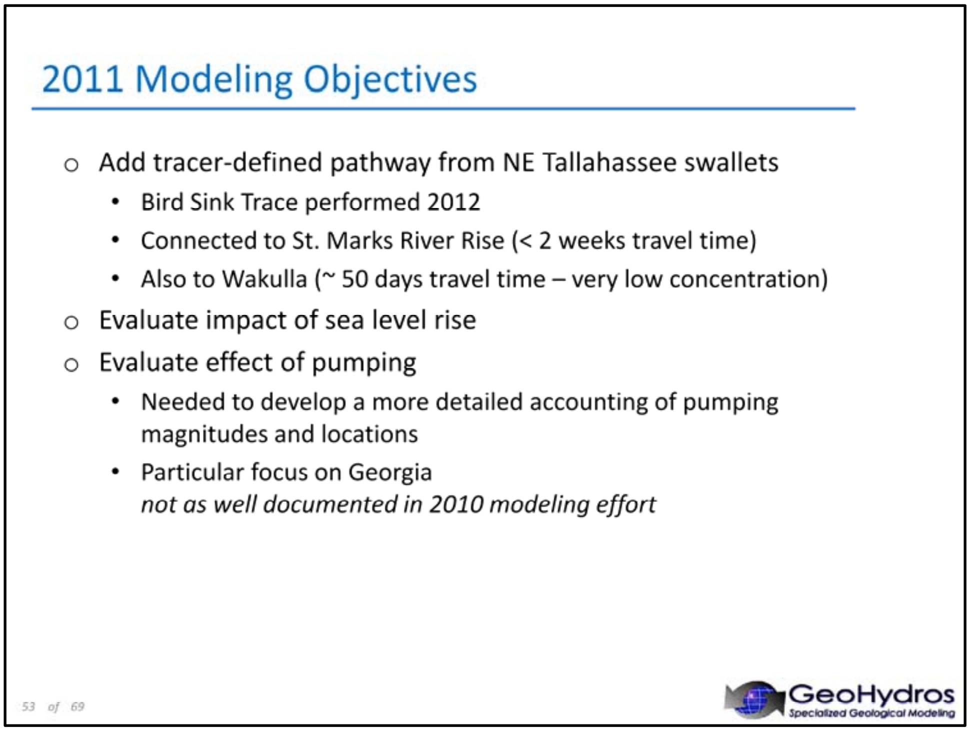
This plot shows the status of the 2010 spring flow simulation relative to observed (target) flows that were derived from the only available published values - FGS Bulletin #66.



These plots show the potentiometric surface of the Floridan aquifer and the distribution of groundwater velocities simulated by the 2010 calibrated model.

Conduits were extended well north of the mapped caves and traced flow paths in order to calibrate to low heads throughout the central part of the model domain in Georgia that were present in both the low-water and the high-water calibration datasets.

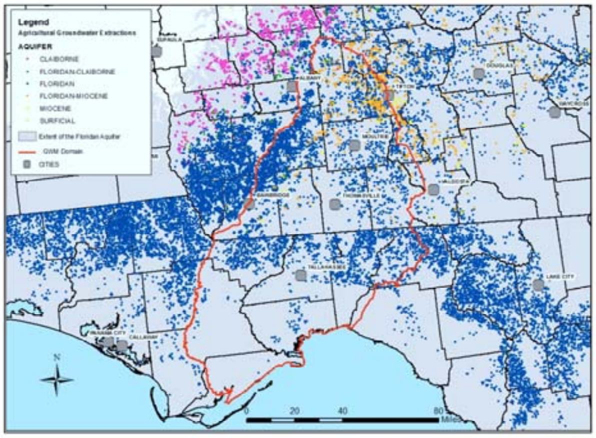
As with the western Santa Fe model, the distribution of heads and velocities simulated by the regional hybrid model are consistent with expected patterns in a karst aquifer.



Moving into 2011, our focus for the modeling effort shifted from construction and calibration to scenario analyses. Two types of analyses were planned: one focused on the probable impacts of sea-level rise of coastal (or near coastal) spring discharges; and the other focused on the impact of groundwater pumping on spring discharges.

We focused first of the pumping analysis because that data had not yet been fully incorporated into the model design and the thought was to have existing pumping conditions included in the sea-level rise analyses.

Agricultural Pumping



- National Environmentally Sound Production Agriculture Laboratory (NESPAL) - University of Georgia's College of Agricultural and Environmental Sciences
- Georgia EPD
- NWFWMD
- SRWMD

GA: 183 MGD – Contributing Counties / 93 MGD Model Domain
FL: 29 MGD – Contributing Counties / 21 MGD Model Domain

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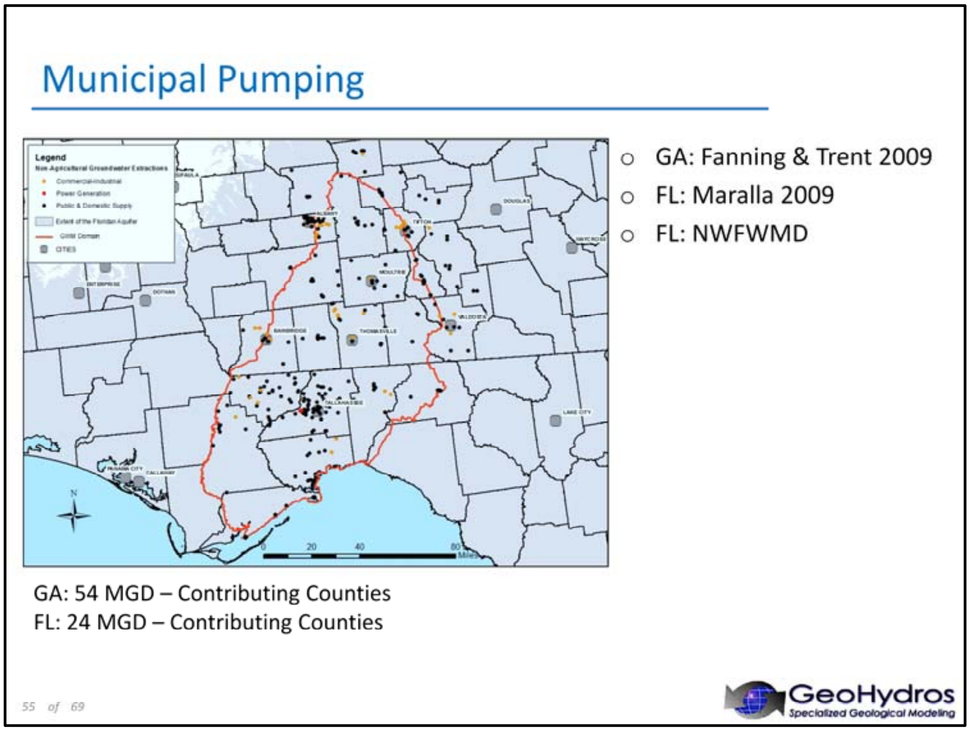
The first task was to further research the Georgia pumping to identify or estimate agricultural pumping locations and the distribution of the magnitudes reported for each County. In doing this we uncovered substantially more detailed accountings of pumpage both for agricultural and municipal/industrial usage. Ultimately we compiled all new pumping datasets both for Georgia and Florida that were based on the more in depth estimations. The total pumpage was substantially larger than was previously estimated and the new data pointed to Georgia as the larger groundwater consumer in the region likely to contribute to Florida spring flows – by 4x-6x for agricultural extractions.

The data shows that total agricultural extractions in the parts of Georgia within the model domain are 93 MGD, which by comparison is more than 10 MGD larger than the low flow at Wakulla Spring.

The primary source of data for the location and magnitude of Georgia extractions was the National Environmentally Sound Production Agriculture Laboratory (NEPSAL), which is part of the University of Georgia’s College of Agricultural and Environmental Sciences.

The primary sources of data for agricultural pumping in Florida were the NW Florida Water Management District and the Suwannee River Water Management District.



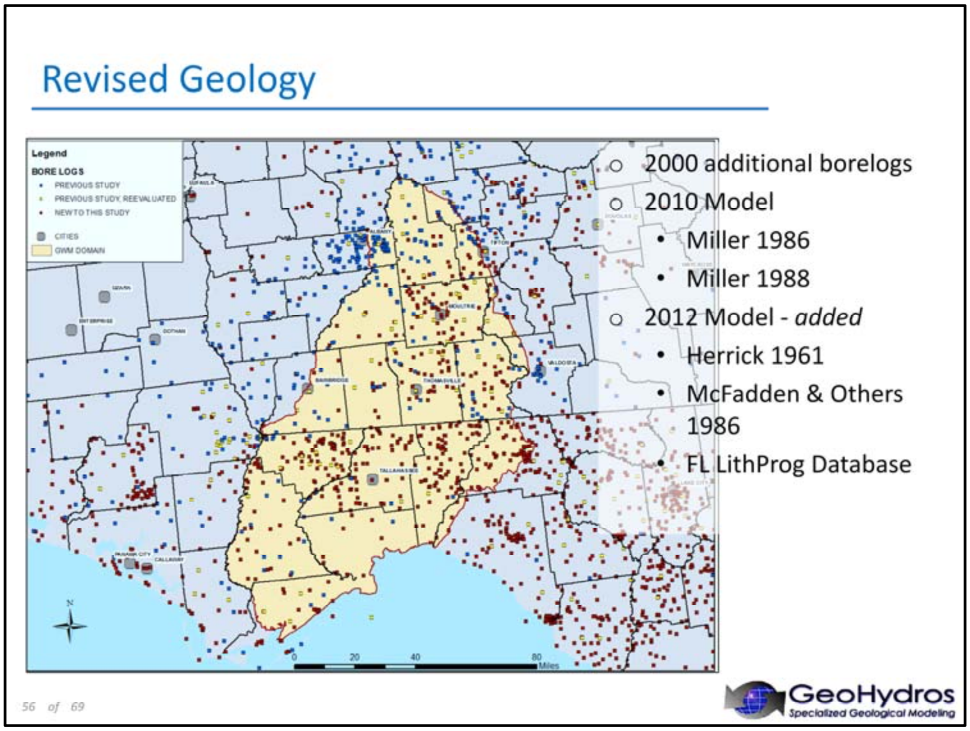
Again, the data search revealed that municipal extractions from the Floridan aquifer in Georgia are more than double those in Florida.

The primary data source for Georgia was:

Fanning, J.L. and Trent, V.P., 2009, Water Use in Georgia by County for 2005; and Water-Use Trends, 1980–2005:U.S. Geological Survey Scientific Investigations Report 2009–5002, 186 p., Web-only publication available at http://pubs.usgs.gov/sir/2009/5002/.

The primary data sources for Florida were the NW Florida Water Management District and

Marella, R.L., 2009, Water withdrawals, use, and trends in Florida, 2005: U.S. Geological Survey Scientific Investigations Report 2009-5125, 49 p.



As a consequence of incorporating the larger magnitude pumping, it became clear that the geologic framework would have to be revised. This included removal of conduits from a large part of the Georgia section of the model domain and refining the delineation of the confining unit and the lower permeability material that constitutes the Gulf Trough / Apalachicola Embayment.

To achieve the geologic framework revisions, geologic and lithologic picks from 2000 additional borelogs were compiled and integrated into the model surface delineations. The data was compiled for the majority of the Floridan aquifer system because that is how it was compiled in the source documents and because doing do will facilitate application in adjacent Florida basins.

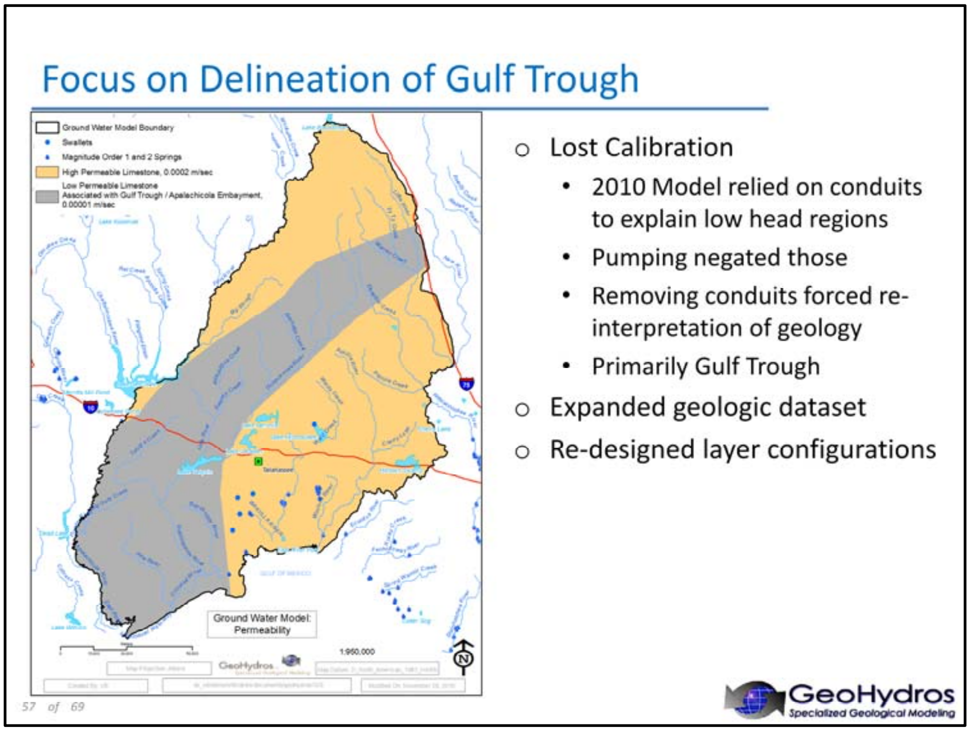
All data sources now include:

Herrick, S.M., 1961, Well logs of the Coastal Plain of Georgia: Georgia Geologic Survey Bulletin 70, 462 p.

McFadden, S.S., Hetrick, J.H., Kellam, M.F., Rodenbeck, S.A., and Huddlestun, P.F., 1986, Geologic data of the Gulf Trough area, Georgia: Georgia Geologic Survey Information Circular 56, 345 p.

Miller, J.A., 1986. Hydrogeologic Framework of the Floridan Aquifer System in Florida and in Parts of Georgia, Alabama, and South Carolina, James A. Miller, USGS Professional Paper 1403-B.

Miller, J.A., 1988, Geohydrologic data from the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Open-File Report 88–86, 678 p.



The primary focus was directed at revising the interpretation of the Gulf Trough area.

Revised Hydrostratigraphic Framework

- Expanded Model to bottom of Oldsmar or equivalent
- 9 model layers (expanded from 5)
- Divisions set to describe lateral and vertical heterogeneity in Floridan aquifer system units

GWM LAYER	AGE	HIGH PERM	LOW PERM	NOTE
1	Post Miocene	Undif. sand & clay		Continuous, vertical K will define where Hawthorn present
	Miocene	Altamaha	Hawthorne	
2	Miocene	Chattahoochee / Tampa / St. Marks		Discontinuous, all Miocene limestones where present
3	Upper Oligocene	Suwannee		Discontinuous, all Suwannee where present
4	Lower Oligocene		Marianna / Undif.	Discontinuous, all Marianna where present
5	Upper Late Eocene	Ocala	Cooper Marl	Discontinuous, all Ocala where present
6	Lower Late Eocene	Wilson	Undif. / Barnwell	Discontinuous, horizontal K will define Wilson / Undifferentiated division
7	Upper Middle Eocene	Avon Park	Lisbon	Continuous, horizontal K will define Avon Park / Lisbon division
8	Lower Middle Eocene	Lake City	Tallahatta	Continuous, horizontal K will define Lake City / Tallahatta division
9	Early Eocene	Oldsmar	HTGB	Continuous, horizontal K will define Oldsmar / HTGB division
-	Paleocene	Cedar Key	Cedar Key	Top of the layer is bottom slice of model

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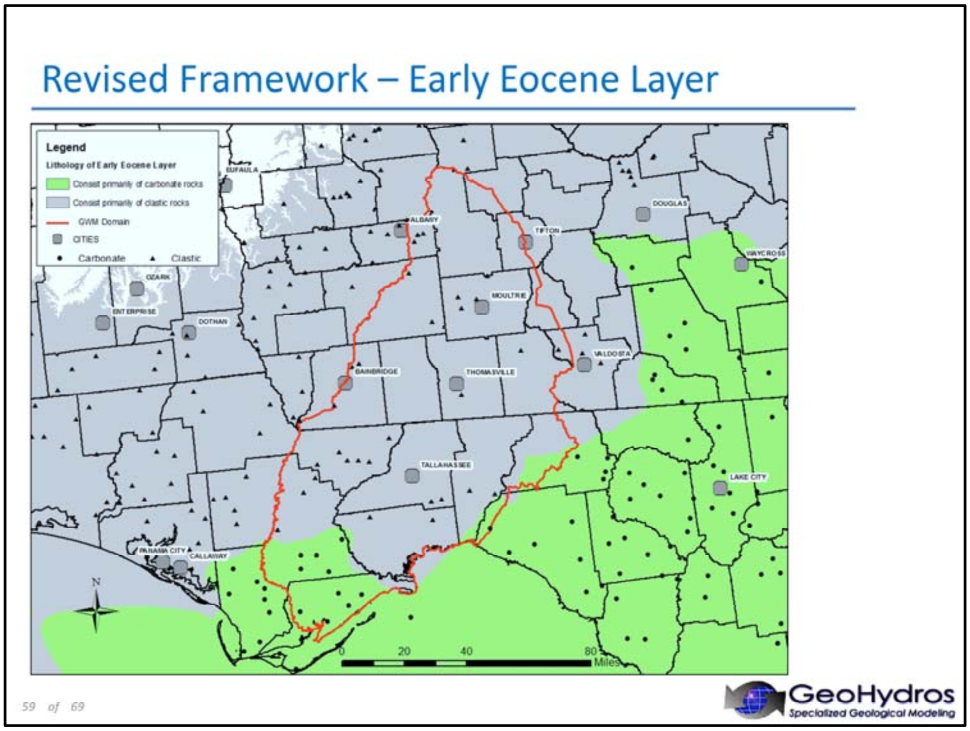
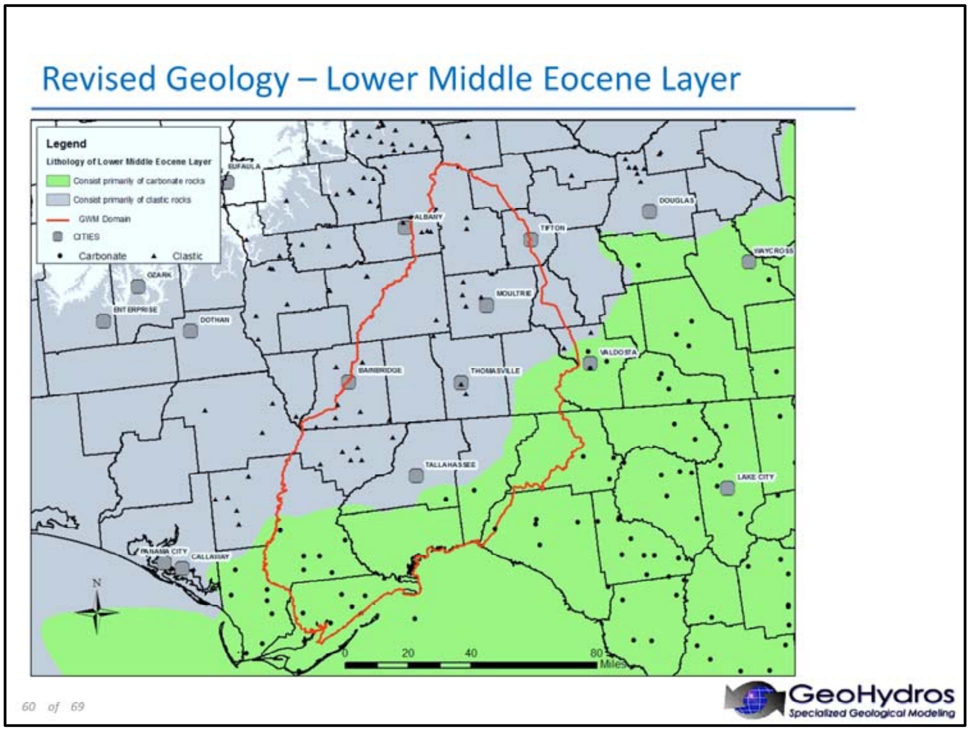
The model was expanded vertically to include all of the upper Floridan aquifer and much of the lower Floridan aquifer (down to the bottom of the Oldsmar Limestone or equivalent). The layer configuration was expanded from 5 layers to 9 layers such that the lateral and horizontal heterogeneity in the Floridan aquifer systems limestones could be adequately represented. The result is a much more detailed and defensible delineation of the confining unit and the Gulf Trough materials.

The subsequent 8 slides will depict the distribution of relatively low and high permeability material within the respective model layers – going from lowest (model layer 9) to highest (model layer 3). Each colored zone will be modeled as a homogeneous unit with respect to hydraulic conductivity where the value (in the horizontal and vertical directions) will be established through model calibration but bracketed by values appropriate for the rock type.



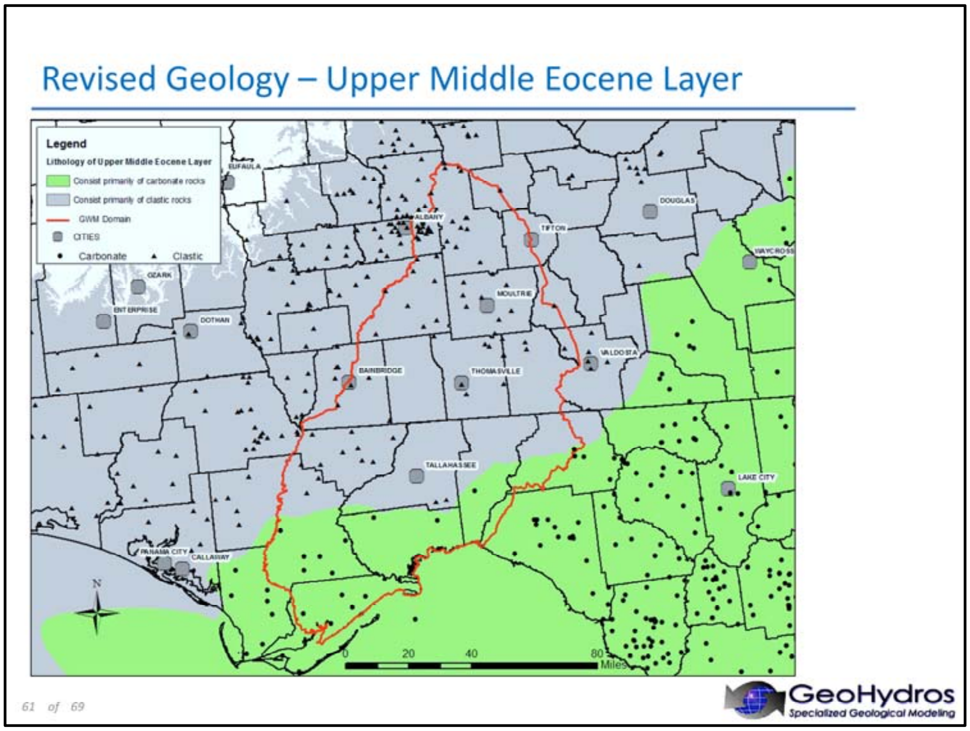
Model layer 9

Early Eocene / green = carbonate rocks / gray = siliciclastic rocks



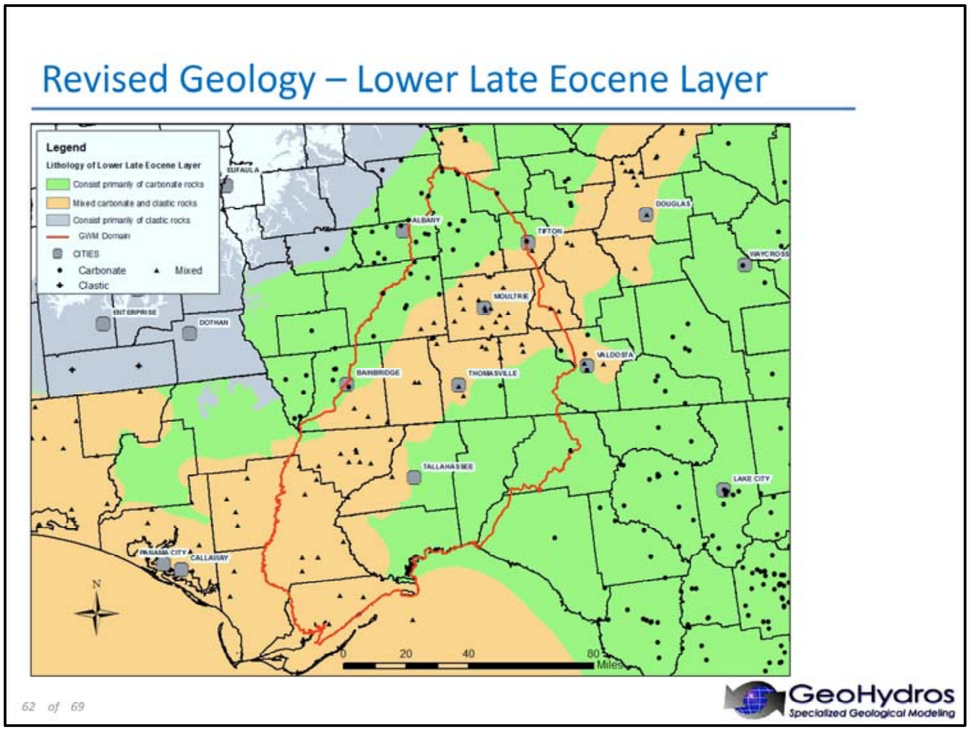
Model layer 8

Lower Middle Eocene / green = carbonate rocks / gray = siliciclastic rocks



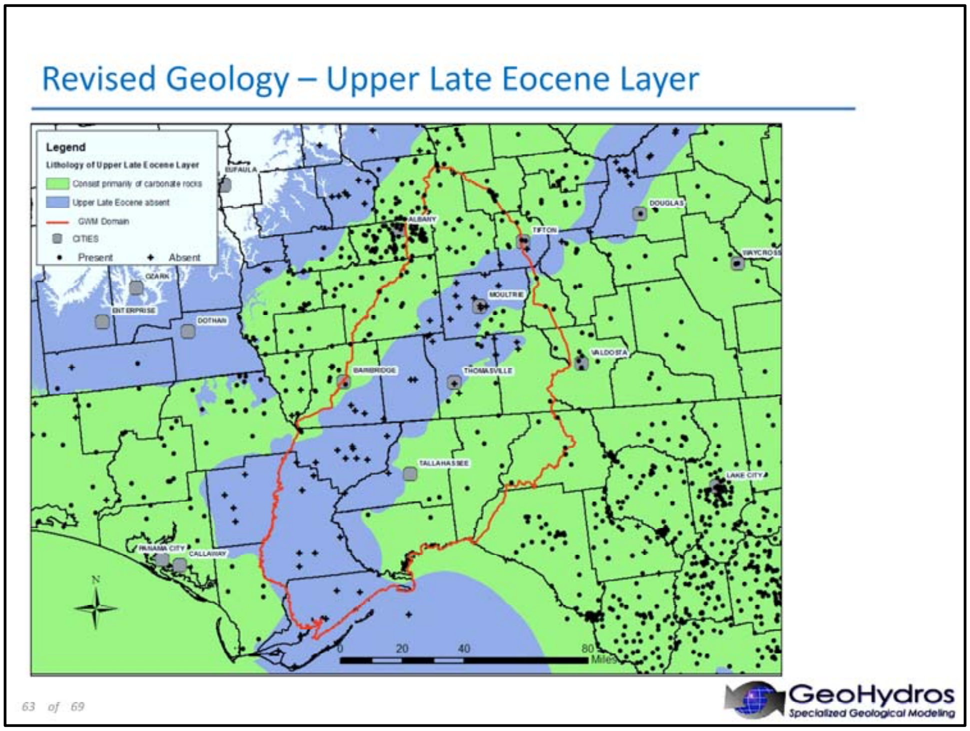
Model layer 7

Upper Middle Eocene / green = carbonate rocks / gray = siliciclastic rocks



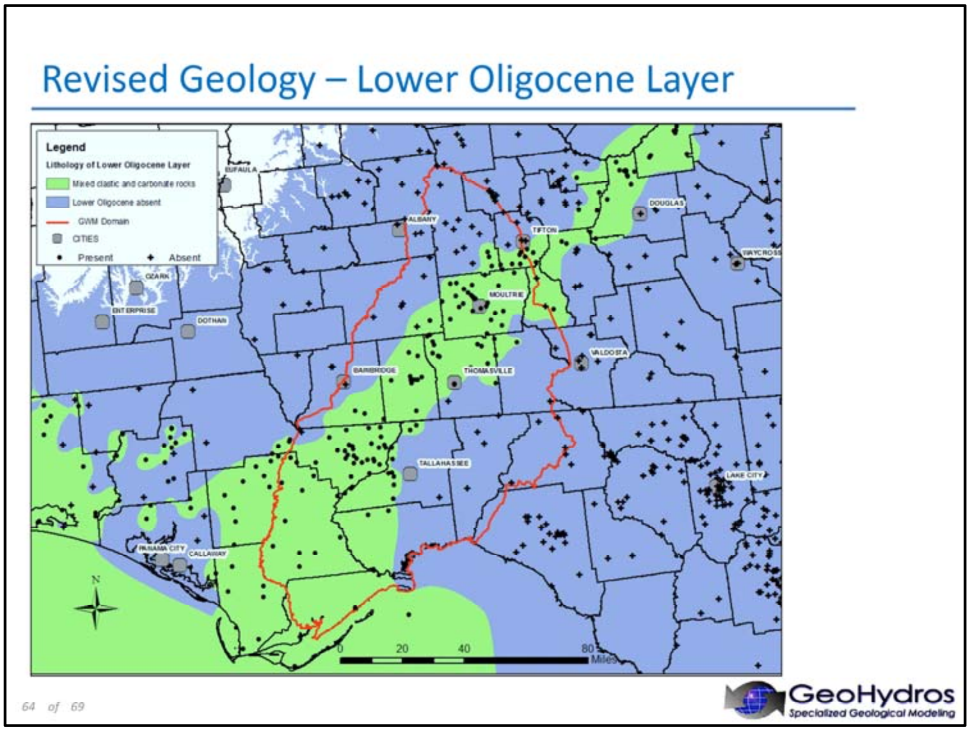
Model layer 6

Lower Late Eocene / green = carbonate rocks / gray = siliciclastic rocks / tan = mixed carbonates and clastics



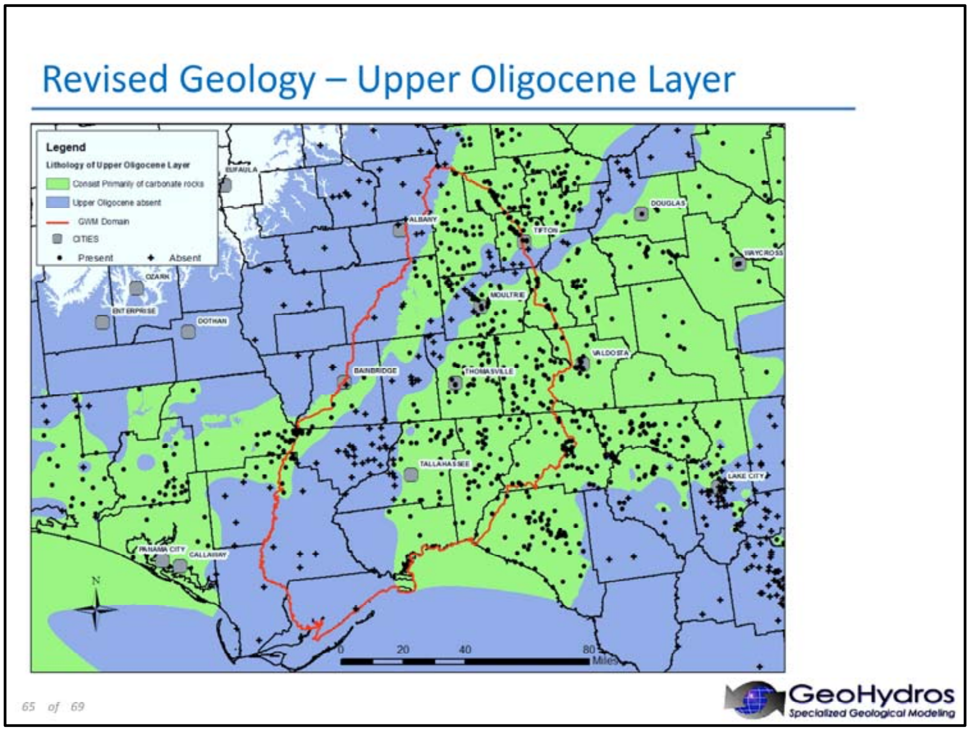
Model layer 5

Upper Late Eocene / green = carbonate rocks / blue = Unit is absent (Gulf Trough & Apalachicola Embayment)



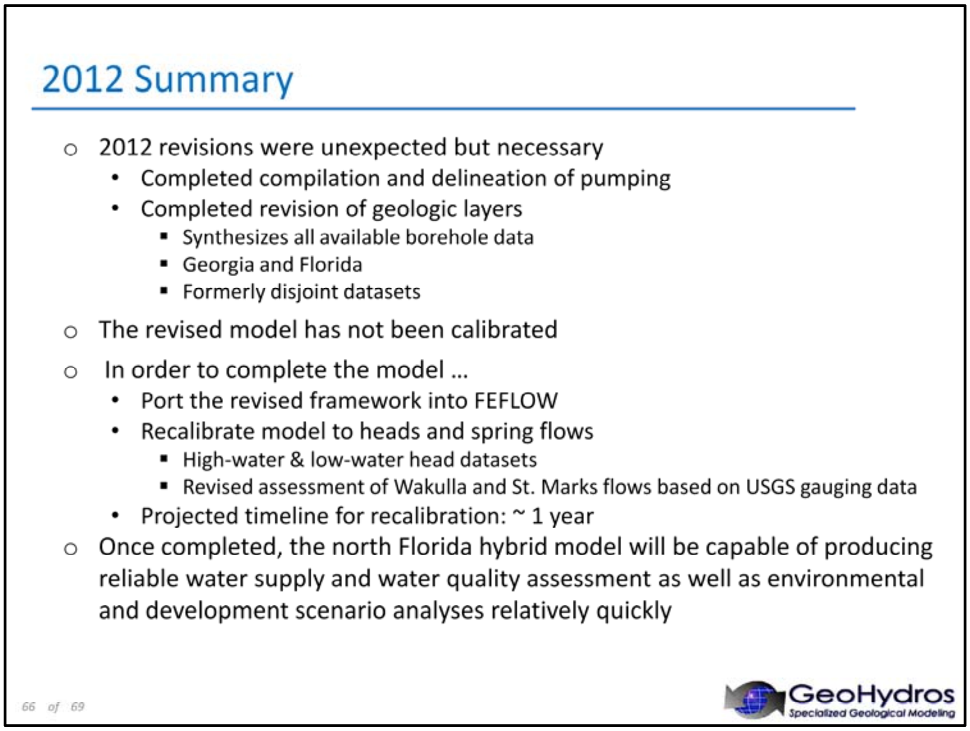
Model layer 4

Lower Oligocene / green = mixed clastic and carbonate rocks (associated with Gulf Trough and Apalachicola Embayment deposition) / blue = Unit is absent (outside of Gulf Trough & Apalachicola Embayment)



Model layer 3

Upper Oligocene / green = carbonate rocks / blue = Unit is absent



In summary …

- The revisions performed in 2011 to the geologic and pumping delineations in the model were unexpected but necessary to maintain model calibration.
- A comprehensive delineation of pumping and pumping locations over the entire model domain has been completed and is available independently for use in other studies.
- Comprehensive datasets have been compiled showing the distribution, elevation, and thickness of all units comprising the Floridan aquifer system in Florida, Georgia, and South Carolina. These datasets are available independently for use in other studies.
- The hydrostratigraphic framework of the north Florida hybrid model has been preliminarily revised.
- The model has not been recalibrated and thus remains unfinished.
- Completing the model will require
  - Porting the revised framework into FEFLOW
  - Calibrating the revised model to the high-water and low-water datasets
  - We will be using revised and more accurate estimates for high-water and low-water flows from Wakulla and St Marks springs based on USGS stream gauging data
  - Projected timeframe for recalibration is about 1 year
- The completed model will be able to deliver reliable water supply and water quality assessments contributing to MFL and TMDL applications

Program Applications

- MFL
  - Delineate springsheds and boundary fluctuations
  - Define water budget for high and low water conditions
  - Quantify impacts of pumping
  - Quantify impacts of reuse and return flows
- TMDL
  - Delineate springsheds and boundary fluctuations
  - Define groundwater flow patterns and travel times
  - Define vulnerability zones
  - Define contaminant loading and breakthrough profiles

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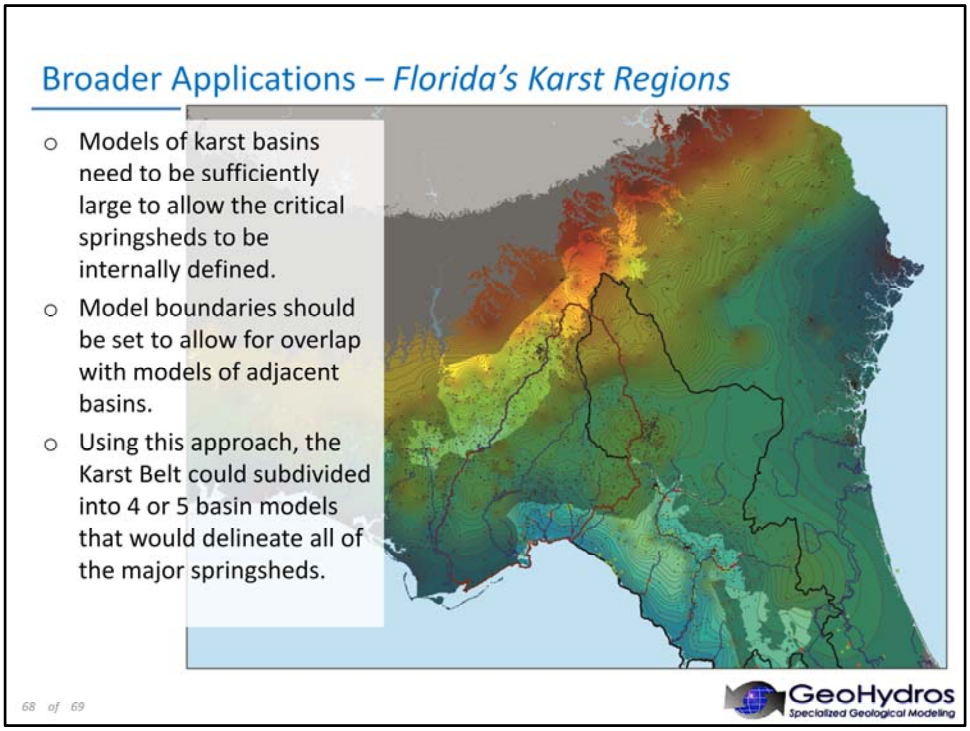

Another fundamental problem facing Florida groundwater resource management is the lack of a single comprehensive way of assessing groundwater quantity and quality that is consistent with District-scale models. We believe the hybrid modeling approach can contribute to solving this problem as well.

By constructing groundwater basin-scale models using the combined high-water and low-water approach to calibration, it is possible to construct overlapping models that both cover the entire karstic portion of the State and deliver simulations and predictions that are consistent across the model boundaries.

Our preliminary assessment indicates that such an approach would involve constructing 4-5 models at scales similar to or somewhat larger than the north Florida hybrid model. These models would be immediately applicable to both MFL and TMDL application efforts.

Thanks for Listening

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  - Rodney DeHan, Jon Arthur, Scott Dyer, Tom Greenhalgh, Harley Means
  - FGS Staff
  - Applied research to solve problems
  - www.geohydros.com/FGS/

- *The Coca-Cola Company*
  - Vested interest in sustained clean freshwater discharge to the Western Santa Fe River
  - "Diminished water quality & quantity diminishes our business and their brand"
  - *www.geohydros.com/CCNA/*

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