2023 Joint Regulatory Plan Review

Stakeholder Meeting Executive Summary

NAME OF MEETING: Stakeholder Meeting 5
DATE: December 14, 2021
LOCATION: Virtual

On Tuesday, December 14, 2021 at 2:00 pm, the Harris-Galveston and Fort Bend Subsidence Districts (the Districts) held their fifth Joint Regulatory Plan Review Stakeholder Meeting. This meeting was held as a virtual meeting. Numerous board members, elected officials, regional water authorities, and representatives from local, State and Federal agencies joined the meeting, with more than 70 panelists and attendees participating. A full list of meeting participants is included in **Attachment A**.

The purpose of this meeting was to provide project element updates from the Joint Regulatory Plan Review. Mr. Jason Afinowicz of Freese and Nichols welcomed the stakeholders to the Districts' fifth virtual stakeholder meeting and introduced the Joint Regulatory Plan Review project team and collaborators, including speakers Cindy Ridgeway (Texas Water Development Board - Manager of Groundwater Availability Modeling Program), and John Ellis (U.S. Geological Survey (USGS) - Supervisory Hydrologist. Additionally, Michelle Sneed (USGS – Groundwater and Land Subsidence Specialist, California Water Science Center, Jake Knight (USGS - Hydrologist), and Jeremy White (Principal Hydrogeologist with INTERA, formerly with the USGS) attended as panelists.

They provided a presentation of the following topics:

- Project Status Update
- Groundwater Availability Modeling Overview
- GULF 2023 Model Preliminary Findings

The formal presentation concluded with a review of the overall project schedule and upcoming milestones. A copy of the meeting presentation is provided in **Attachment B.**

A question and answer session was held after the presentation. A summary of the questions and responses is provided in **Attachment C.**

ATTACHMENT A – MEETING ATTENDANCE

FIRST	LAST	AFFILIATION
Jason	Afinowicz	Freese and Nichols
Emily	Anderson	Halff Associates, Inc.
Delilah	Arolfo	
Mohamed	Bagha	Michael Baker International, Inc.
Susan	Baird	HGSD Board Member
Matt	Barrett	San Jacinto River Authority
James	Beach	Advanced Groundwater Solutions, LLC
Radu	Boghici	Texas Water Development Board
Christopher	Braun	U.S. Geological Survey
John	Burke	John E Burke & Assoc. LLC
Kandice	Cabets	Quadvest
Michael	Campbell	I2M Consulting, LLC
Kippy	Caraway	
Ki	Cha	Texas Water Development Board
Jun	Chang	North Harris County Regional Water Authority
Katie	Clayton	City of Sugar Land
Bruce	Cunningham	
Katie	Dahlberg	Texas Water Development Board
Betty	Daugherty	MUD 60
Rene	Derewetzky	Texas Stream Team
Chris	Drabek	Advanced Groundwater Solutions, LLC
John	Dupnik	Texas Water Development Board
John	Ellis	U.S. Geological Survey
Gregory	Ellis	GM Ellis Law Firm PC
Mark	Evans	North Harris County Regional Water Authority
Tina	Felkai	San Jacinto River Authority
Pamela	Fontenot	Pamela K. Fontenot Consulting, LL
Julia	Frankovich	BGE, Inc.
Larry	French	Texas Water Development Board
Jessica	Fritsche	Brown and Caldwell
Matthew	Froehlich	BGE, Inc.
Nayeli	Gallardo	Invenergy
Yassin	Gallardo	Lower Neches Valley Authority
Neil	Gaynor	Montgomery County Municipal Utility District (MUD) 6
Stephanie	Glenn	Houston Advanced Research Center (HARC)
Lauren	Gonzalez	Black & Veatch

FIRST	LAST	AFFILIATION
Rohit	Goswami	
Ashley	Greuter	Harris-Galveston Subsidence District
Sarah	Gruen	
Charles	Hall	Raba Kistner
Bob	Harden	Harden Hydrology & Engineering, PLLC
Daryn	Hardwick	Texas Water Development Board
Samantha	Haritos	
Ryan	Harmon	INTERA Inc.
Linda	Harnist	FBSD Board Member
Zach	Holland	Bluebonnet Groundwater Conservation District
Beverly	Hopkins	Brazoria County Ground Water Conservation District
Jace	Houston	San Jacinto River Authority
Bill	Hutchison	Consultant
Megan	Ingram - TWDB	Texas Water Development Board
Kyle	Jones	BGE, Inc.
Mike	Keester	LRE Water, LLC
Naushad	Kermally	
Marcel	Khouw	CHCRWA
Jake	Knight	U.S. Geological Survey
Sunil	Kommineni	KIT Professionals, Inc.
Wendi	Lacki	
Melissa	Lanclos	Houston Advanced Research Center (HARC)
Ivan	Langford	Galveston County WCID#1
Lisa	Lattu	Lockwood, Andrews & Newnam
Michael	Lee	U.S. Geological Survey
Bob	Lux	The Woodlands Water Agency
John	Martin	Southeast Texas Groundwater Conservation District
Wilson	McCoy	
Temple	McKinnon	Texas Water Development Board
Christina	Miller	ABHR
Douglas	Miller	HMW SUD
Brad	Moon	Geologist
Gary	Moore	Brazoria County Ground Water Conservation District
Keir	Murray	KLM Public Affairs, LLC
Matt	Nelson	Texas Water Development Board
Paul	Nelson	
George	Newsman	Woodlands Water Agency
Merritt	Nolte-Roth	City of Sugar Land
Laura	Norton	Montgomery County MUD Director

FIRST	LAST	AFFILIATION
Patrick	O'Day	O'Day Drilling Co Inc
Wade	Oliver	INTERA Inc.
Andrew	Osborne	INTERA Inc.
Veronica	Osegueda	Houston Public Works
Wayne	Owen	San Jacinto River Authority
Tina	Petersen	Harris-Galveston Subsidence District
Jon	Polley	Radcliffe Bobbitt Adams Polley PLLC
Jason	Ramage	U.S. Geological Survey
Rick	Ramirez	City of Sugar Land
Mitchell	Ramon	City of Houston
Mackrena	Ramos	Lockwood, Andrews, and Newnam, Inc.
Stacey	Reese	Stacey Reese Law, PLLC
Samantha	Reiter	Lone Star Groundwater Conservation District
Cindy	Ridgeway	Texas Water Development Board
Kathy	Rogers	Harris-Galveston Subsidence District (HGSD) Board Member
Robert	Schoenewe	Raba Kistner
William	Seifert	Ground Water Consultants, LLC
Shelley	Sekula-Gibbs	Woodlands Township
Charles	Shumate	Lockwood, Andrews & Newnam, Inc.
Michelle	Sneed	U.S. Geological Survey
Russell	Smith	
Brent	Spier	City of Clear Lake Shores TX
James	Stinson	Woodlands Water Agency
Richard	Stolleis	Kaluza, Inc. / Village of Pleak
William	Stromatt	AWBD - Montgomery County MUD-60
Philip	Taucer	Freese and Nichols
Jennifer	Thayer	Lone Star Groundwater Conservation District
Shaun	Theriot-Smith	HGSD Board Member
Janice	Thigpen	Lone Star Groundwater Conservation District
Robert	Thompson	Harris-Galveston Subsidence District
Michael	Thornhill	Thornhill Group, Inc.
Mike	Turco	Harris-Galveston Subsidence District
Talan	Tyminski	
Mark	Unland	
Sharon	Valiante	City of Fulshear
Alia	Vinson	Allen Boone Humphries Robinson LLP
Shirley	Wade	Texas Water Development Board
William	Wallace	Fort Bend Subsidence District (FBSD) Board Member
Gene	Walton	FBSD Board Member

FIRST	LAST	AFFILIATION
Suzanne	Whatley	City of Sugar Land
Jeremy	White	U.S. Geological Survey
Michael	White	Brazoria County Groundwater Conservation District
William	Wilson	Strata Geological Services
Joe	Zimmerman	City of Sugar Land

ATTACHMENT B – MEETING PRESENTATION

Thank you for joining us today for the **Joint Regulatory Plan Review Stakeholder Meeting**

All participants have been joined in “listen only” mode.

For meeting audio, you can use your microphone and speakers (VoIP) or call in using your telephone at **877-309-2074.**
Access code: **802-557-536**

If you are having technical difficulty, please send a message to staff in the chat or email *HgGoToMeetings@subsidence.org*

Before we Begin

This webinar is scheduled for two hours. We have left time for questions.

All participants will be muted during the presentation

Questions can be submitted via the Go To Webinar "Questions" screen at any time.

This webinar is being recorded

We will post slides on our website after the meeting today

2023 Joint Regulatory Plan Review

Stakeholder Meeting 5

14 December 2021

Keys Stakeholder Engagement Opportunities

Meeting attendance and project awareness

Providing data for technical analyses

Providing feedback on draft material

Participate in targeted outreach efforts

1 Develop Population and Demand Projections

Develop projections of population and water demand over a ten-county area through the year 2100.

2 Conduct Alternative Water Supply Assessment

Review alternative water supplies for the capability of reducing future groundwater demand.

3 Develop the Gulf Coast Land Subsidence and Groundwater Flow Model

Development of the GULF-2023 model for simulating regional groundwater flow and subsidence in the Gulf Coast Aquifer.

4 Evaluate Regulatory Scenarios

Evaluate the performance of the HGSD and FBSD regulatory plans and consider refinements to the regulatory plan framework to accommodate future growth, alternative water supplies, and the most recent aquifer science.

Cindy Ridgeway

- TWDB

John Ellis

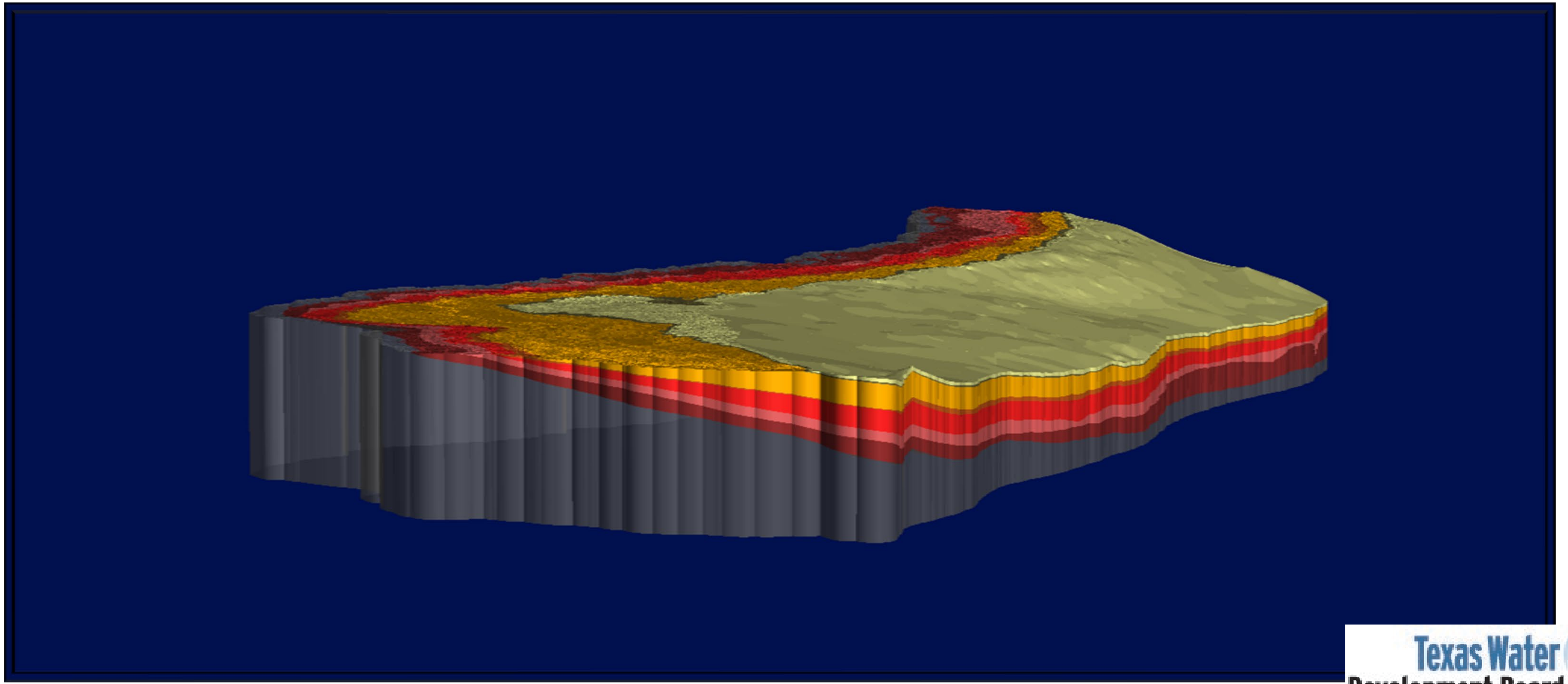
- USGS

Project Elements

Groundwater Availability Modeling

GULF 2023 Model Preliminary Findings

Groundwater Availability Modeling



Groundwater Availability Modeling

In Statute: Develop groundwater flow models for the major and minor aquifers of Texas.

Purpose: Tools that can be used to aid in groundwater resources management by stakeholders.

Public process: Stakeholder involvement during model development process.

Models: Freely available, standardized, thoroughly documented. Reports available over the internet.

Living tools: Periodically updated.

Purpose of Stakeholder Meetings

- Opportunity for input and data to help with model development
- Updates on model progress
- Providing feedback on draft material
- Learn how to best use model & model limitations

Groundwater Availability Modeling

Cindy Ridgeway, P.G.

Manager of Groundwater Availability Modeling Section

512-936-2386

Cindy.ridgeway@twdb.texas.gov

Texas Water Development Board

P.O. Box 13231

Austin, Texas 78711-3231

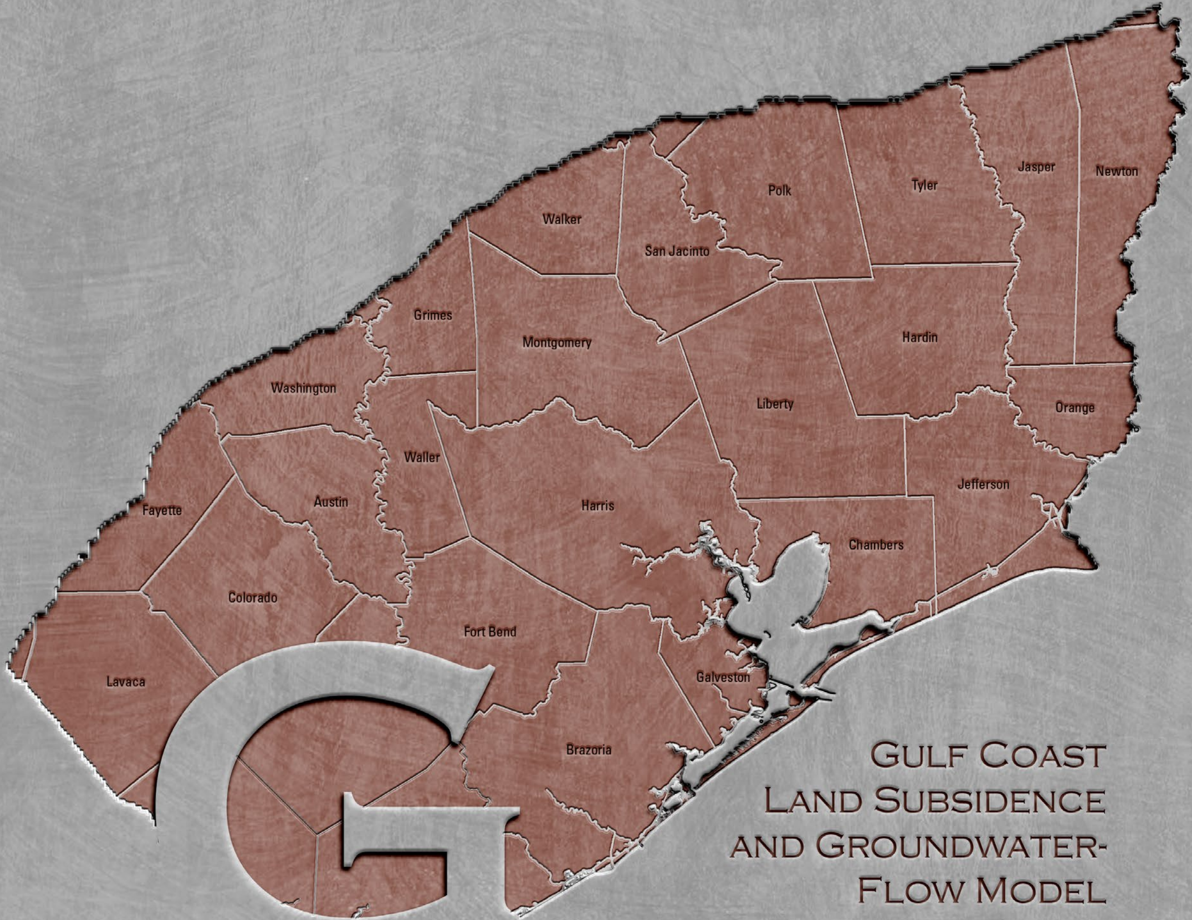
Web information:

www.twdb.texas.gov/groundwater/models/gam/

Project Elements

Groundwater Availability Modeling

GULF 2023 Model Preliminary Findings



Gulf Coast Land Subsidence and Groundwater-Flow Model

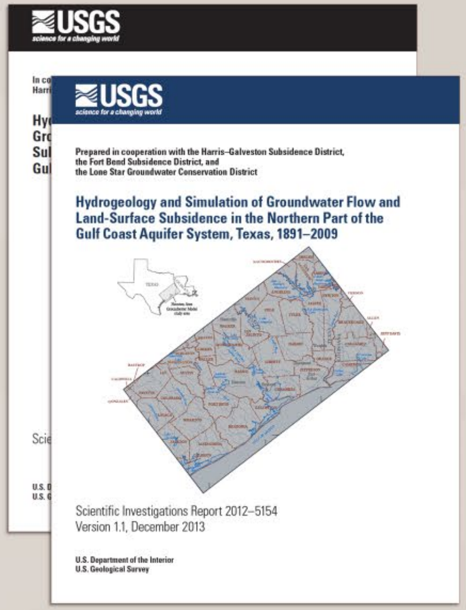
GULF 2023

Joint Regulatory Plan Review

John Ellis
jellis@usgs.gov

In cooperation with the Harris-Galveston and Fort Bend Subsidence Districts

Overview

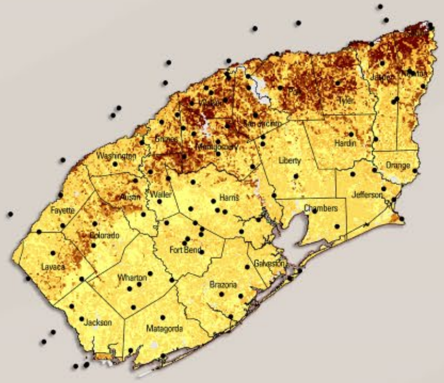

USGS
science for a changing world

Prepared in cooperation with the Harris–Galveston Subsidence District, the Fort Bend Subsidence District, and the Lone Star Groundwater Conservation District

Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas, 1891–2009

Scientific Investigations Report 2012–5154
Version 1.1, December 2013

U.S. Department of the Interior
U.S. Geological Survey

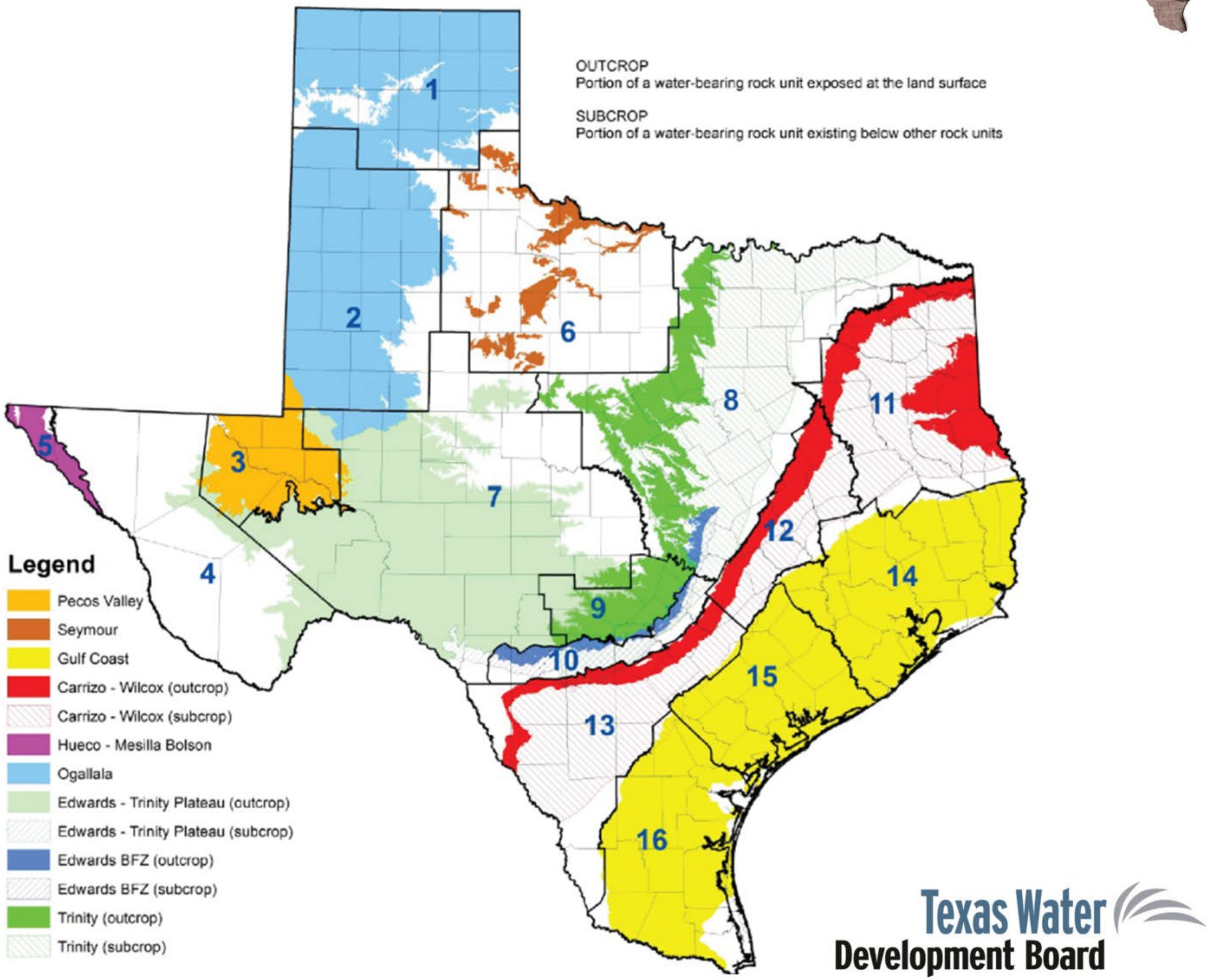


Cooperators	Purpose: HAGM update	CLAS model refinement	Modeling advances

Overview

Groundwater-flow definitions

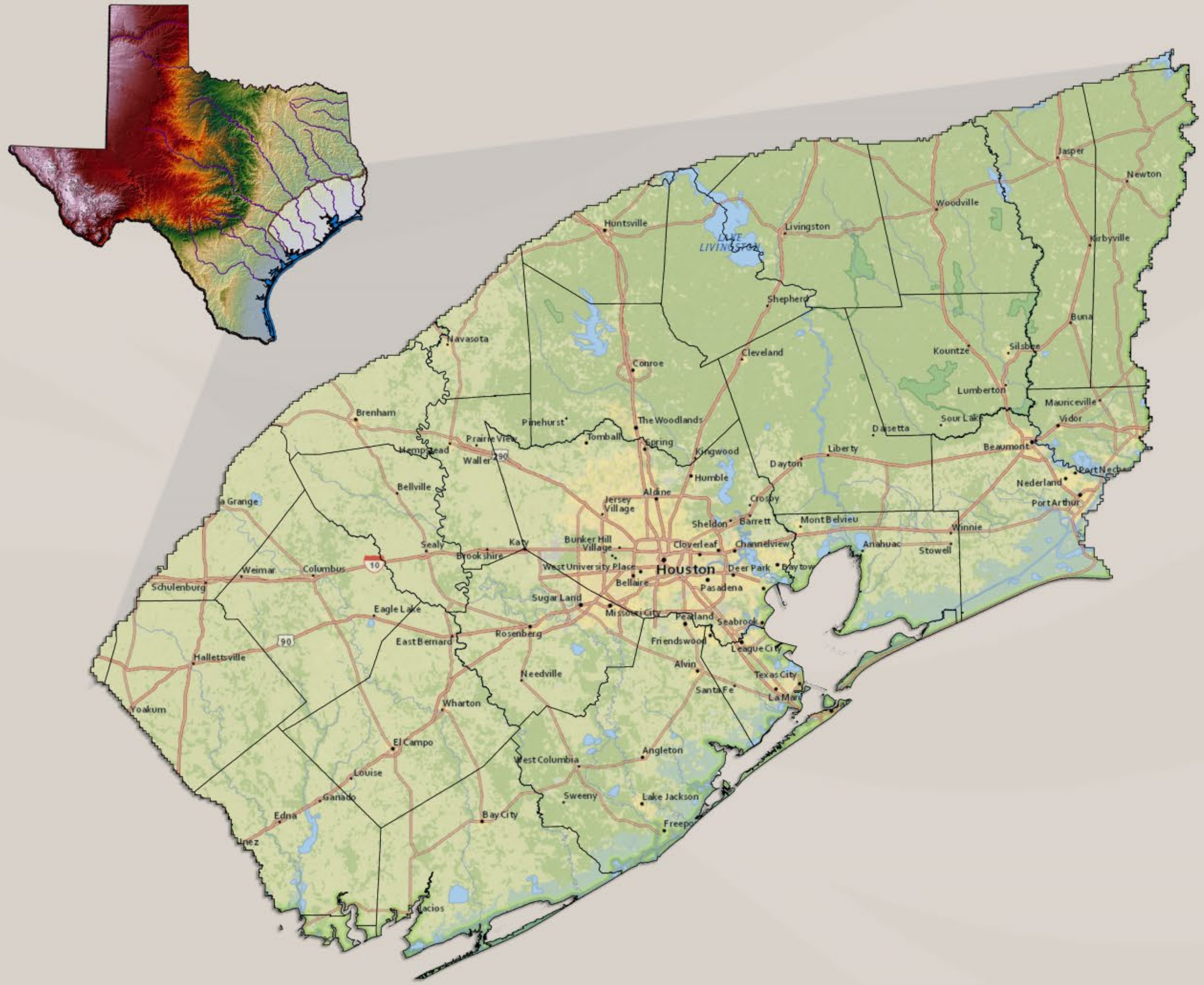
- Aquifer: Water saturated permeable geologic unit that can transmit significant quantities of water
- Water table: The level at which water stands in a shallow screened well in an unconfined aquifer
- Recharge: The entry of water to the saturated zone at the water table
- The primary observable quantity describing groundwater flow is the water level as measured in a well



Study Area

Spatial extent

- Northern boundary corresponds with the upgradient extent of the Catahoula outcrop
- Eastern extent is the TX—LA border (Sabine River)
- Western extent is Lavaca and Jackson Counties
- Southern boundary is nearshore area (to 10 miles offshore—not shown)
- Barrier islands removed in model (shown here and subsequent slides)



Hydrogeology

Geologic classification[1]			Published geologic and hydrogeologic units									Units from this report[2]	
System	Series	Geologic unit	Rose (1943)	White and others (1944)	Lang and others (1950)	Wood and Gabrysch (1965)	Turcan and others (1966)	Jorgensen (1975)	Baker (1979)	Carr and others (1985)	Kasmarek and Strom (2002)	Hydrogeologic	Geologic
Quaternary	Holocene	Alluvium				Confining layer, Alta Loma Sand[3]	Chicot aquifer	Chicot aquifer (upper part)	Chicot aquifer	Chicot aquifer	Chicot aquifer	Chicot aquifer	Alluvium
	Pleistocene	Beaumont Formation		Zone 6	Beaumont Formation								Beaumont Formation
		Lissie Formation: Montgomery Formation			Alta Loma Sand			Chicot aquifer (lower part)					Lissie Formation
		Lissie Formation: Bentley Formation											
		Willis Sand	Zones 6–7[4]		Zones 6–7[4]								Willis Sand
Tertiary	Pliocene	Goliad Sand	Zones 3–5	Zones 3 and 5	Zones 3–5	Heavily pumped layer	Evangeline aquifer	Evangeline aquifer	Evangeline aquifer	Evangeline aquifer	Evangeline aquifer	Evangeline aquifer	Goliad Sand (upper part)
													Goliad Sand (lower part)
	Miocene	Fleming Formation / Lagarto Clay	Zone 2	Zone 2	Zone 2	Zone 2	Burkeville confining unit	Burkeville confining unit	Burkeville confining unit	Burkeville confining unit	Burkeville confining unit		Lagarto Clay (upper part)
												Burkeville confining unit	Lagarto Clay (middle part)
							Jasper aquifer					Jasper aquifer	Lagarto Clay (lower part)
		Oakville Sandstone	Zone 1	Zone 1[5]	Zone 1	--[6]		Jasper aquifer (upper part); Jasper aquifer (upper part)	Jasper aquifer	--[7]	Jasper aquifer		Oakville Sandstone
	Oligocene	Frio Formation			Catahoula Formation		Unnamed aquiclude[8]	--[9]	Catahoula confining system	--[7]	--[10]	Catahoula confining unit	Frio Formation
		Vicksburg Formation											Vicksburg Formation

Model Configuration

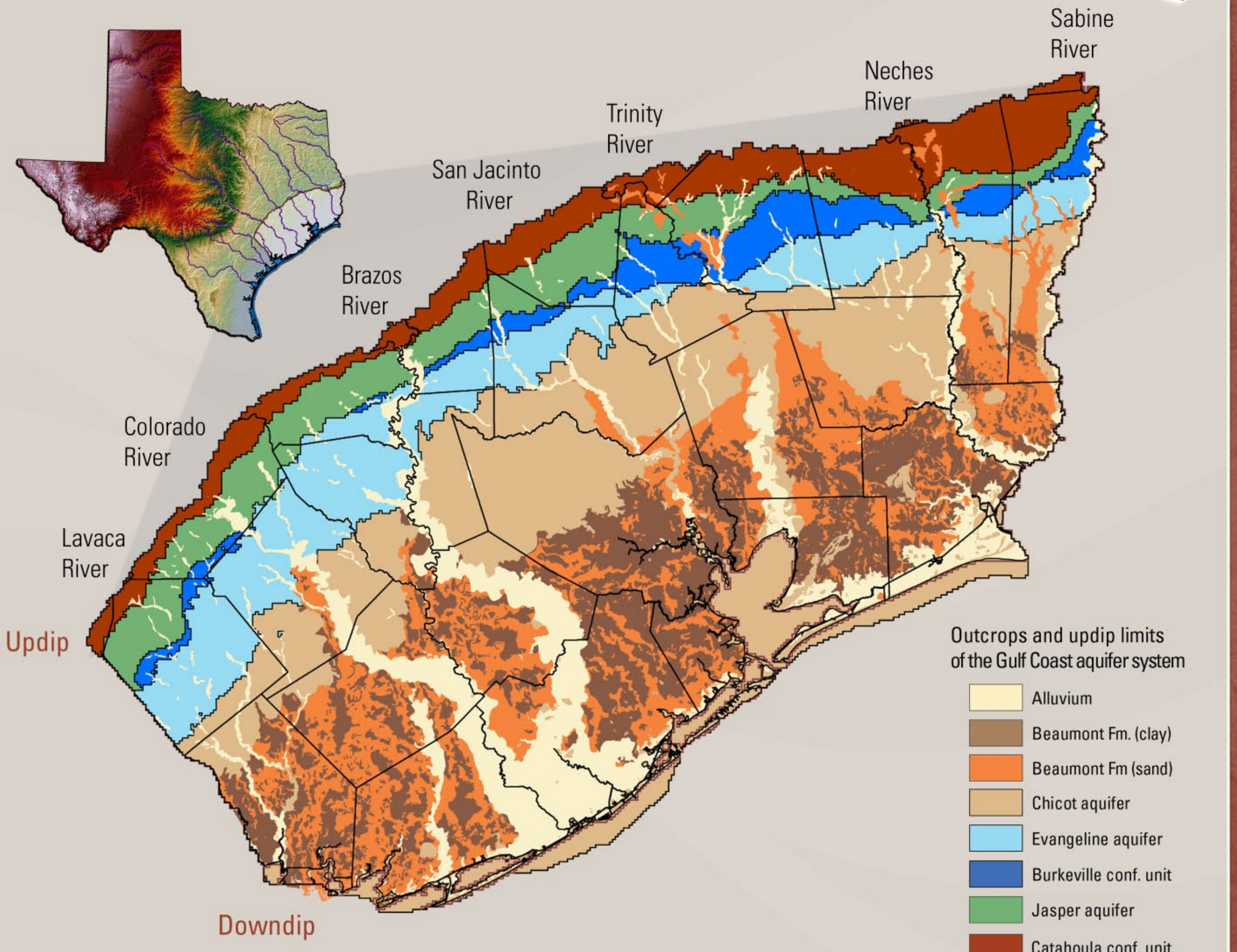
Model layering

- Layer 1: Alluvium and Beaumont Clay
- Layer 2: Chicot Aquifer
- Layer 3: Evangeline Aquifer
- Layer 4: Burkeville Confining Unit
- Layer 5: Jasper Aquifer
- Layer 6: Catahoula Formation

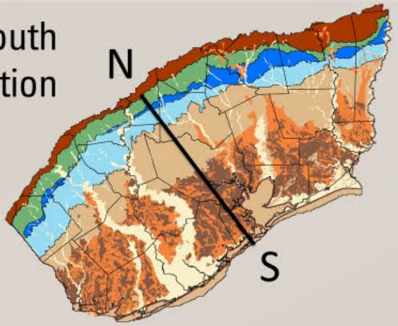
Model time discretization

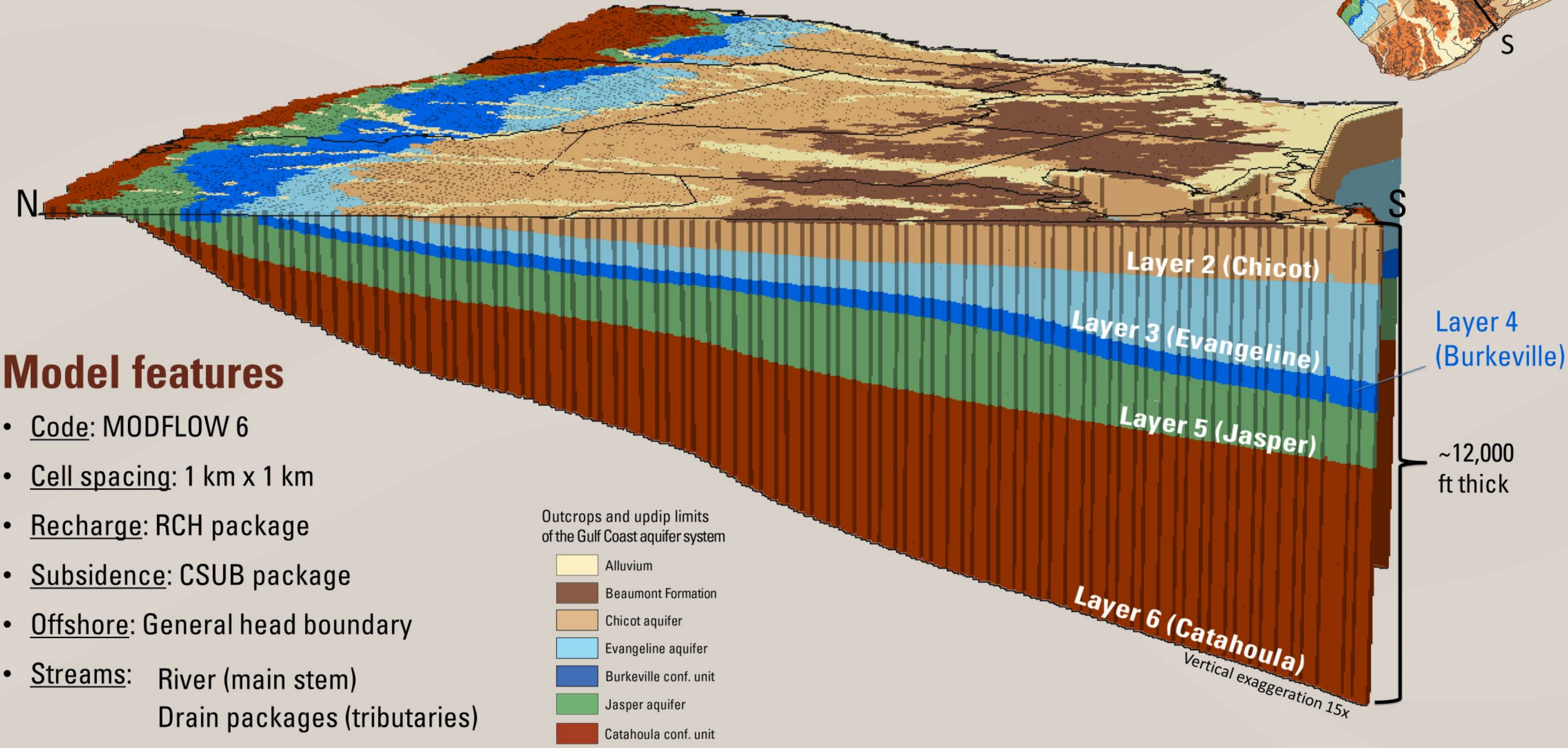
- 1896: 1 (Predevelopment)
- 1897–1939: 3 (about 14 years each)
- 1940–1969: 6 (5 years each)
- 1970–1999: 30 (annual)
- 2000–2018: 228 (monthly)

268 total



Model Configuration





Model features

- Code: MODFLOW 6
- Cell spacing: 1 km x 1 km
- Recharge: RCH package
- Subsidence: CSUB package
- Offshore: General head boundary
- Streams: River (main stem)
  Drain packages (tributaries)

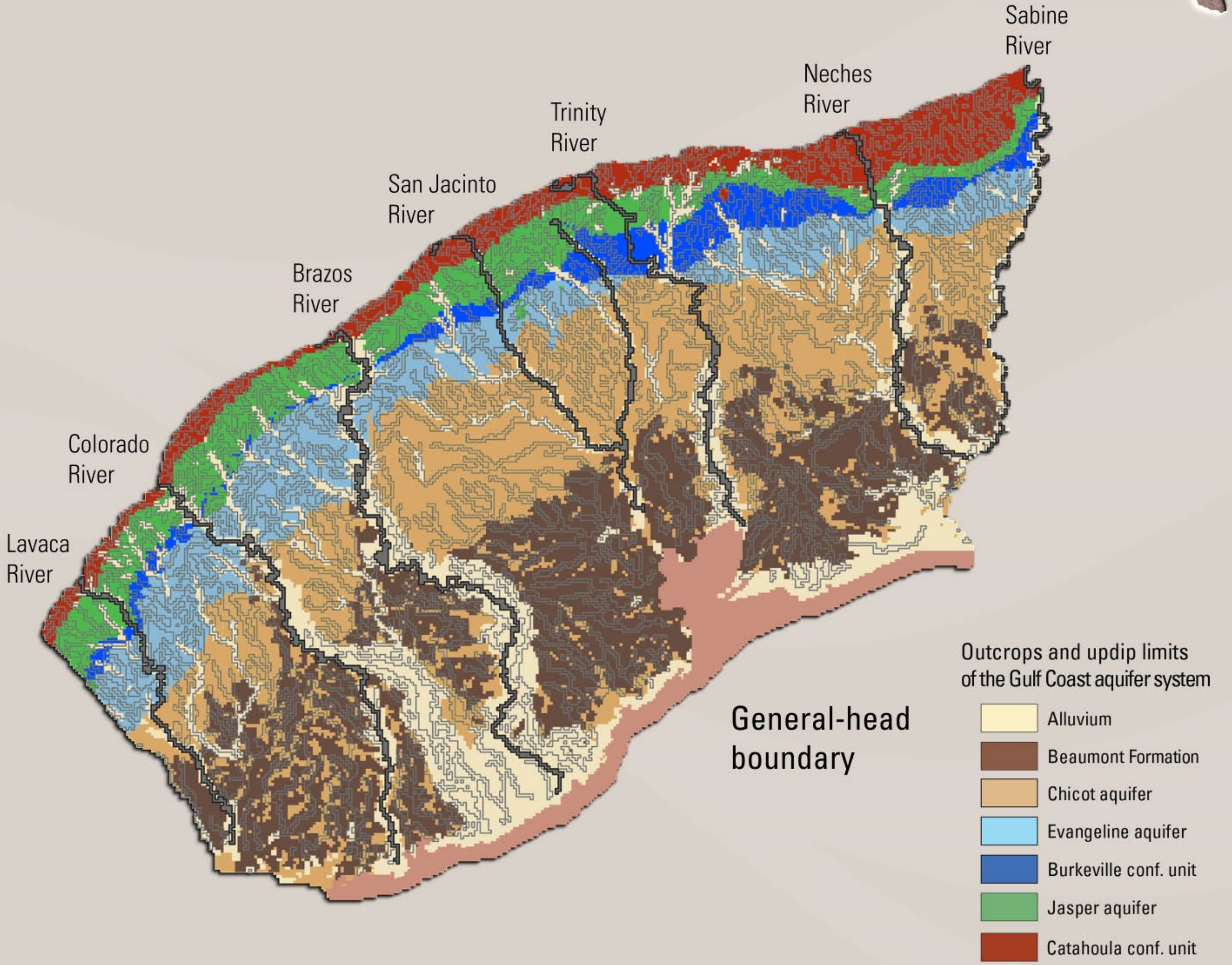
Model Features

Model-area rivers

- Used to route surficial recharge that does not enter the deep system
- River package[1]: used for 7 major rivers (dark shading)
- Drain package[1]: used for named tributary streams (light shading)

General-head boundary

- Simulates offshore area in layer 1 of the model
- GHB cells at downdip model limit in each layer

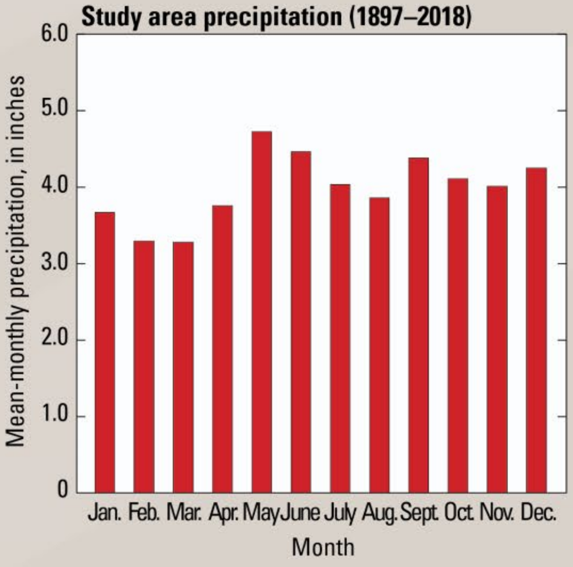


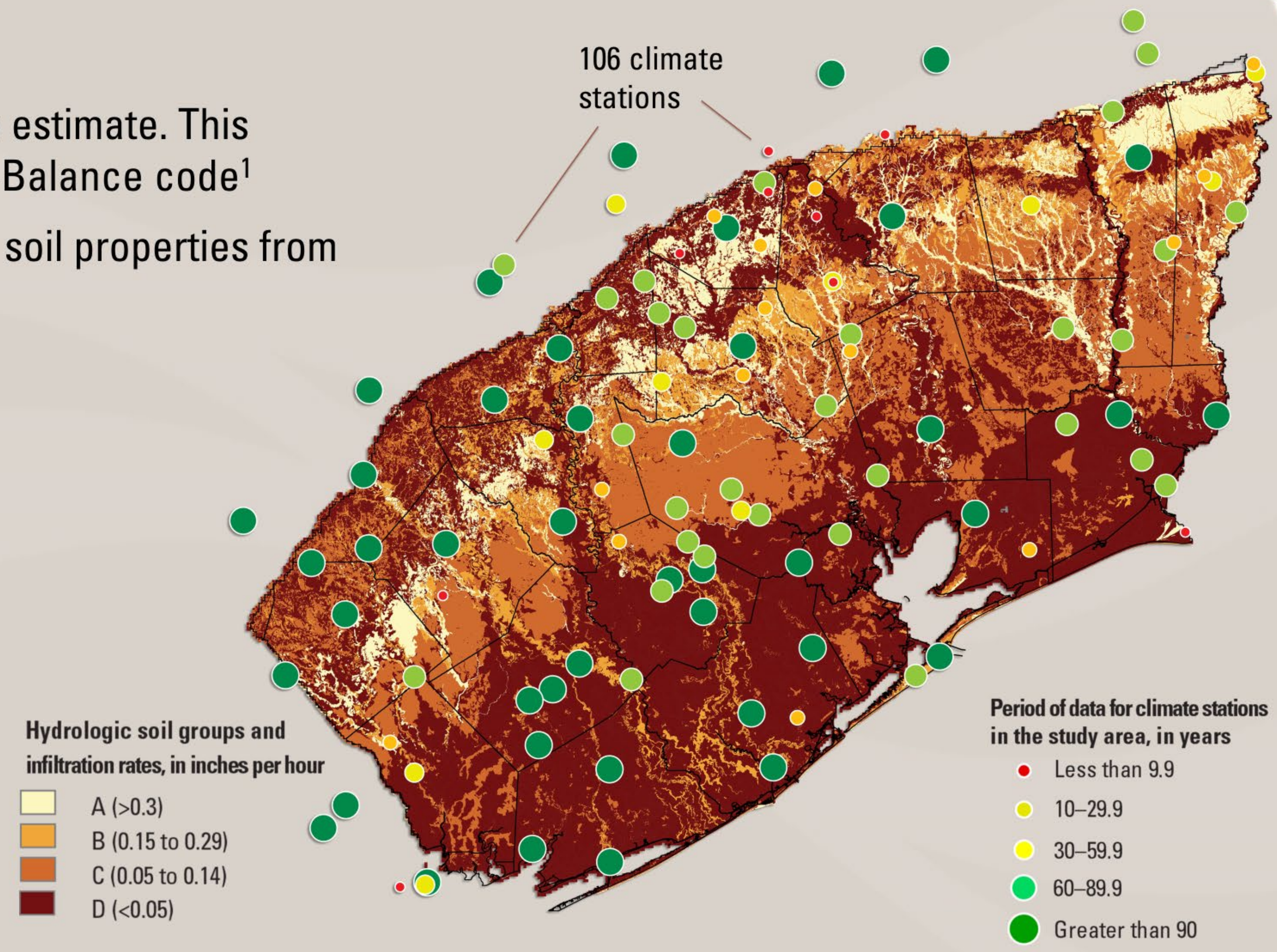
[1]Langevin and others, 2017

Model Features

Recharge

- Can use many different methods to estimate. This project used the USGS Soil-Water-Balance code[1]
- Climate data obtained from NOAA, soil properties from NRCS.



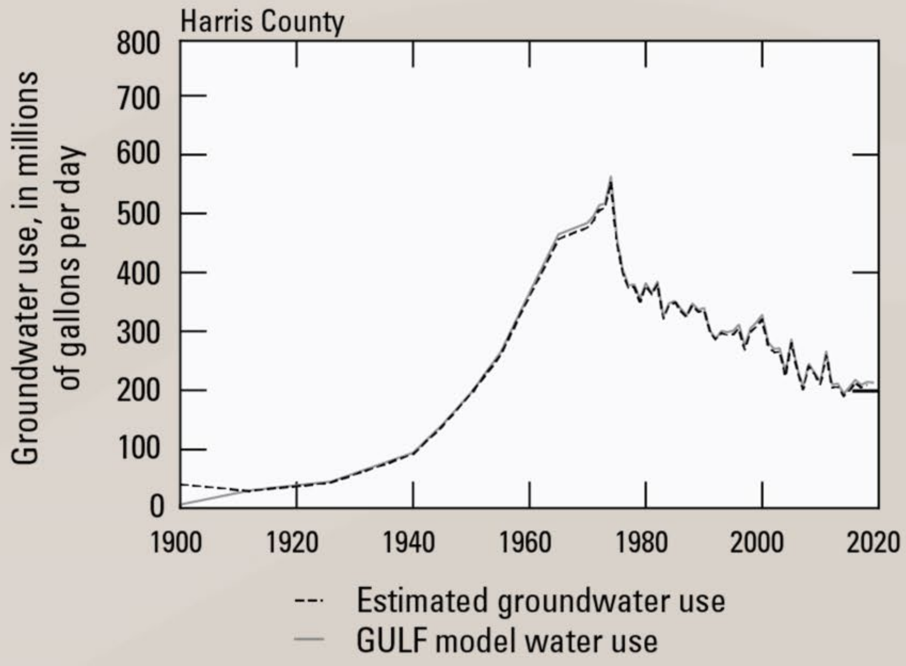


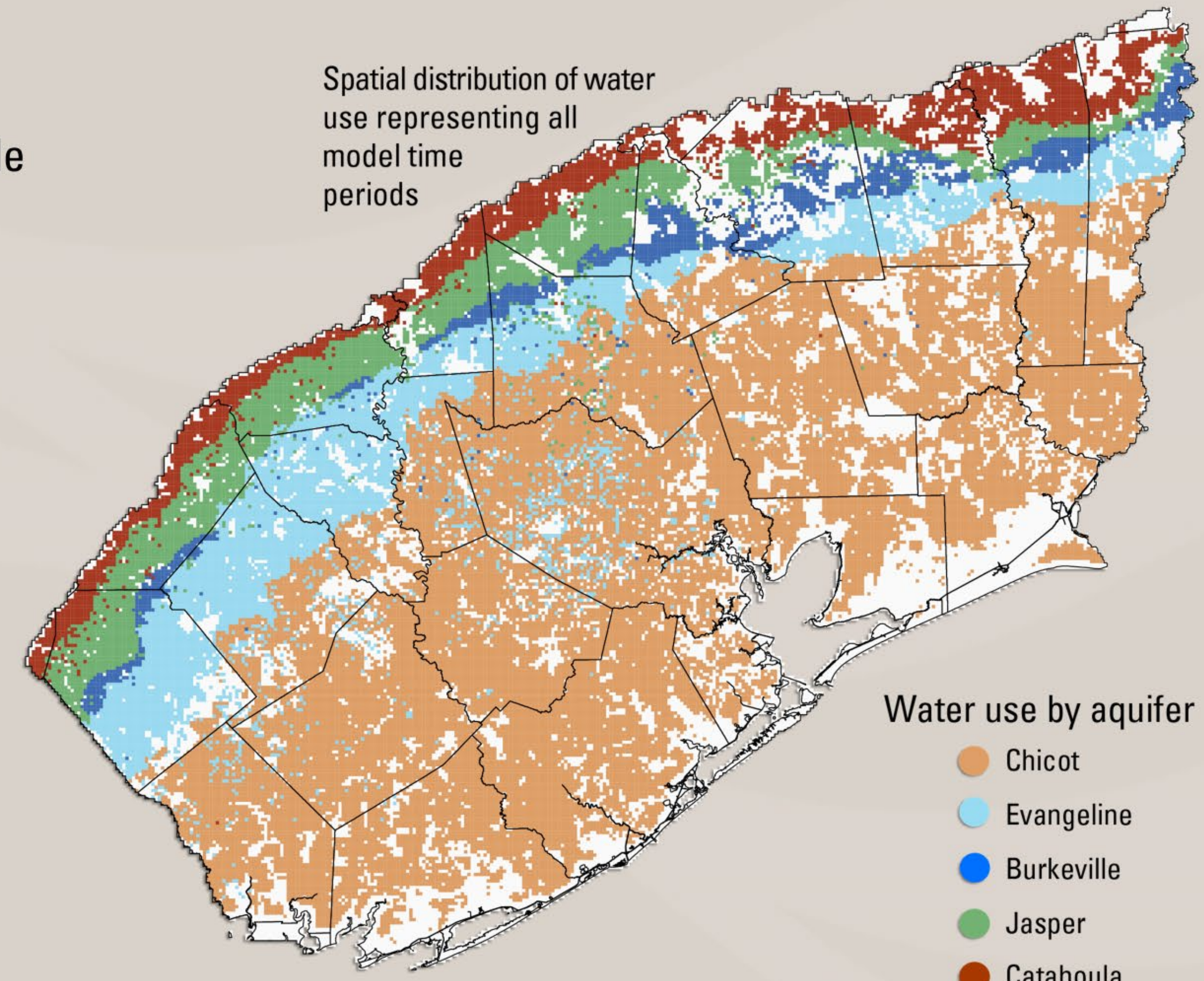
[1]Westenbroek and others, 2010

Model Features

Groundwater use

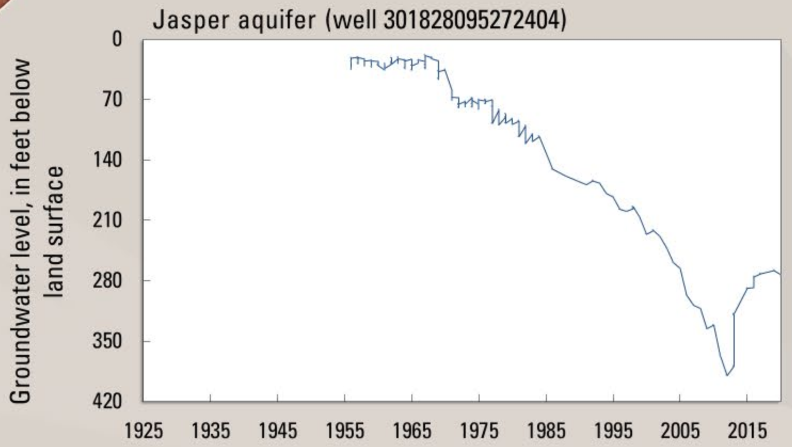
- Groundwater use from Oliver and Harmon (2021)
- To account for uncertainty in estimates, an adjustable range is used during model calibration

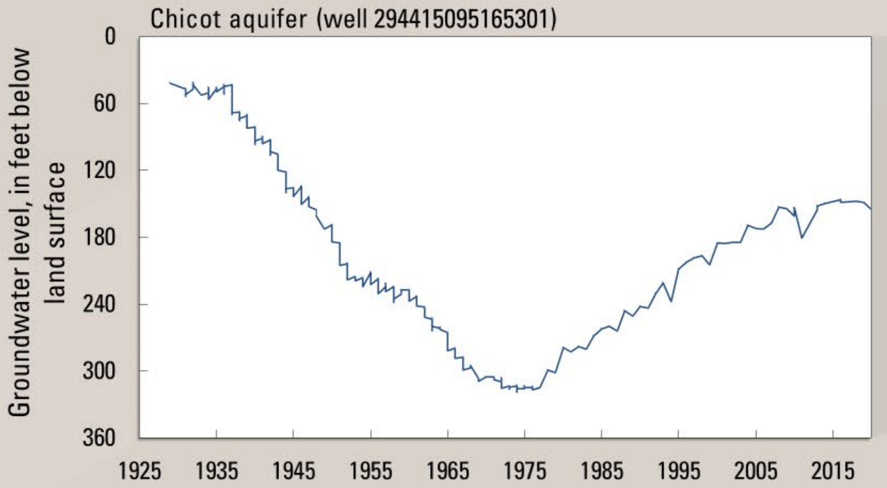


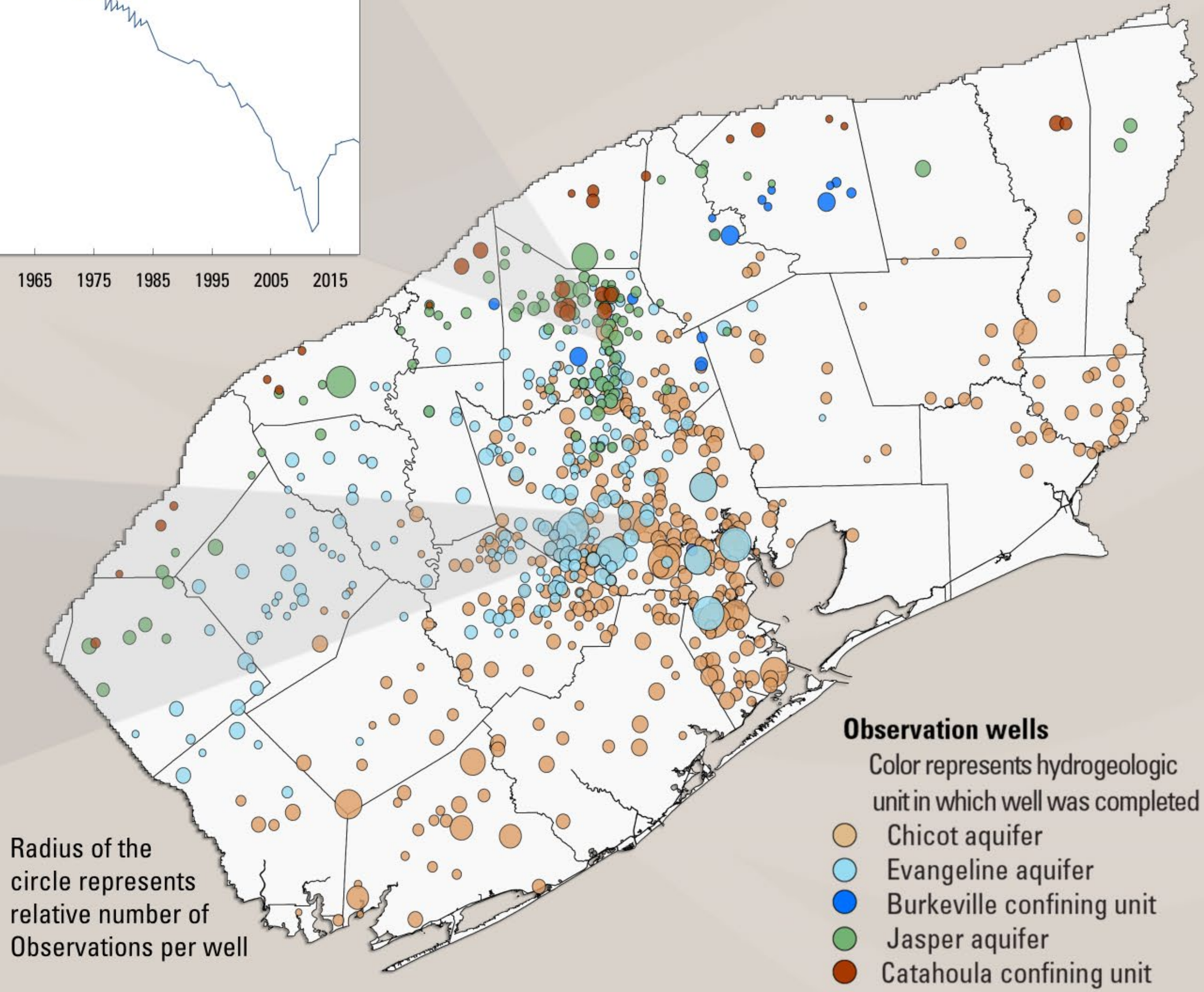


Groundwater Levels

- Changes in groundwater levels occur because of changes in the volume of water stored in the aquifer
- The U.S. Geological Survey, the Texas Water Development Board, and others monitor groundwater levels in the study area



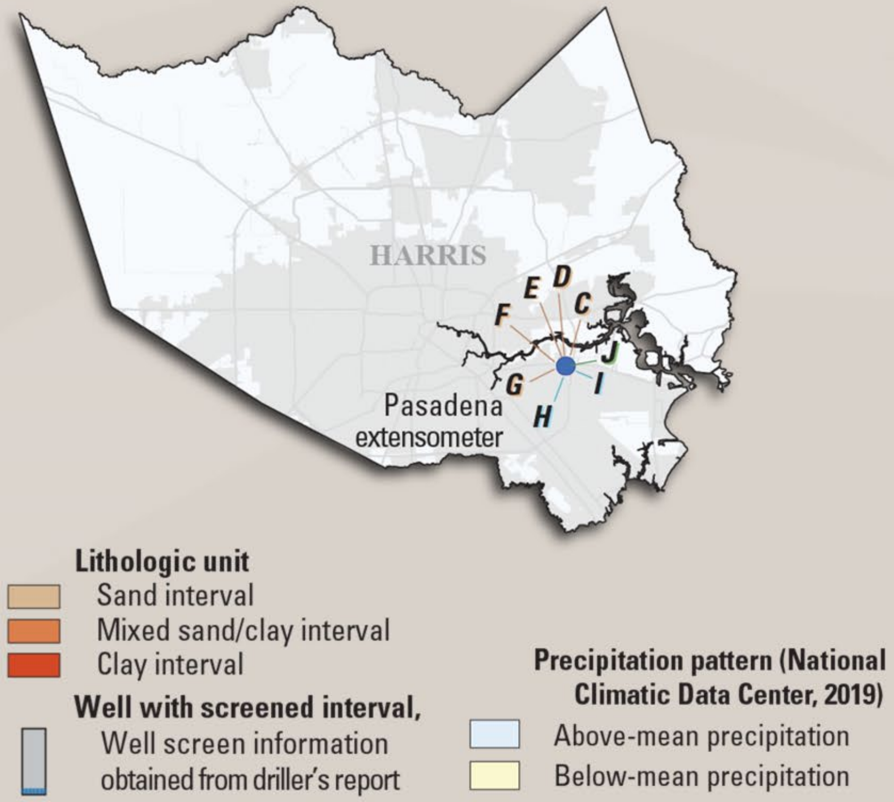


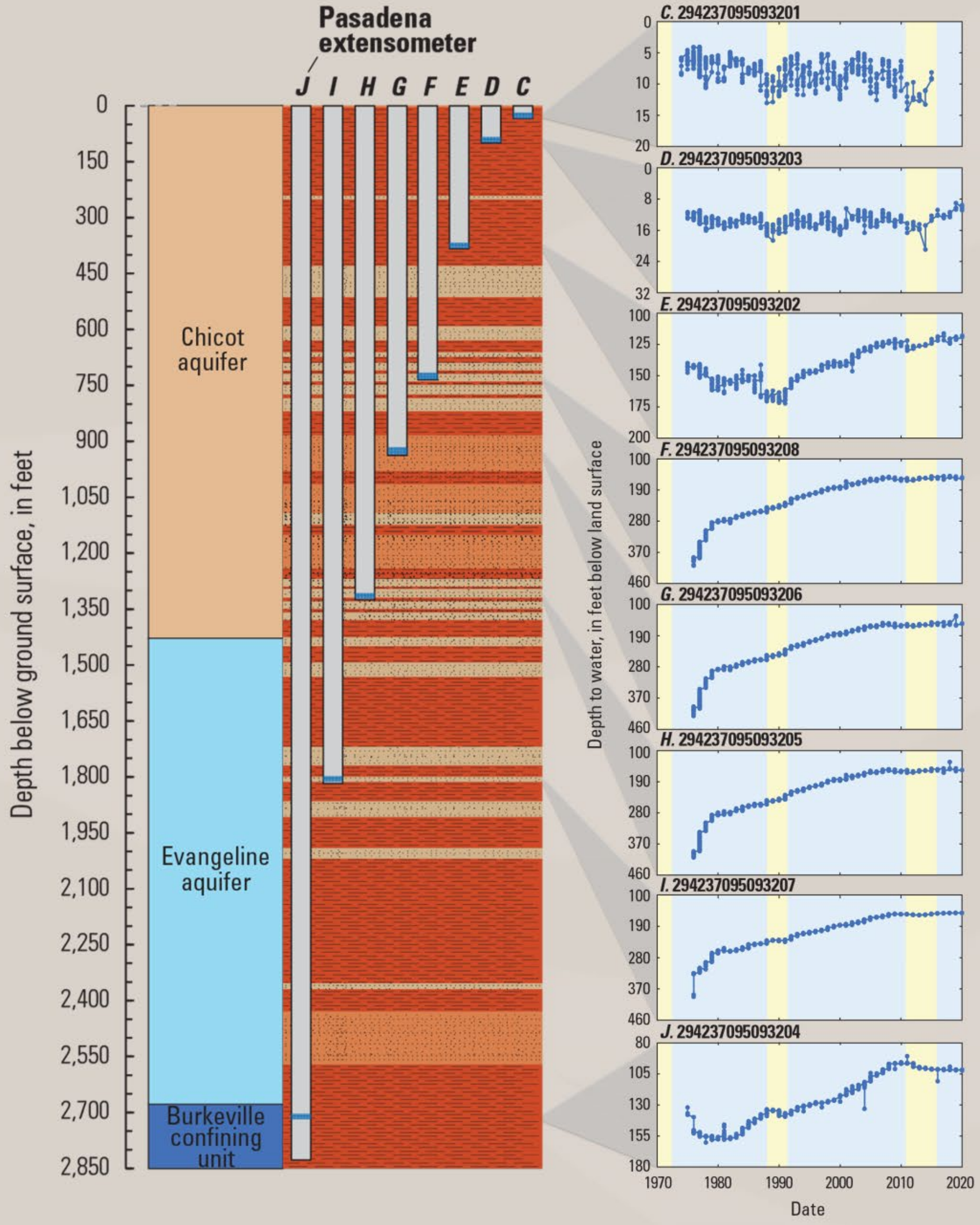


Co-located Groundwater Levels

Pasadena extensometer

- Substantial degree of similarity between groundwater levels across 1,400 feet vertically
- Similarity of groundwater levels at different depth intervals observed as far back as 1937

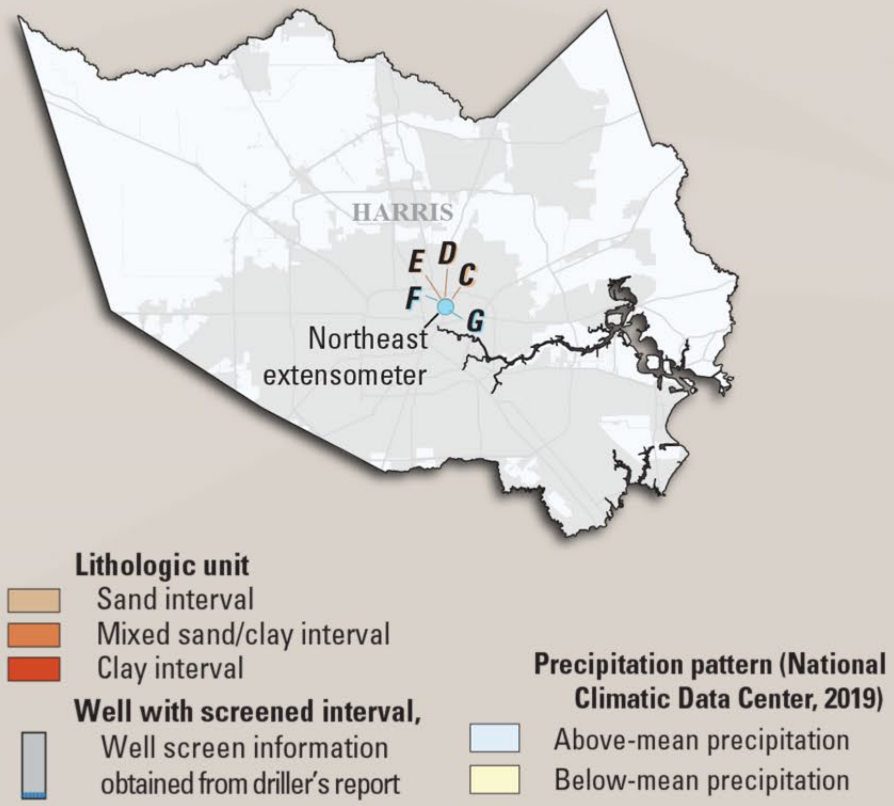


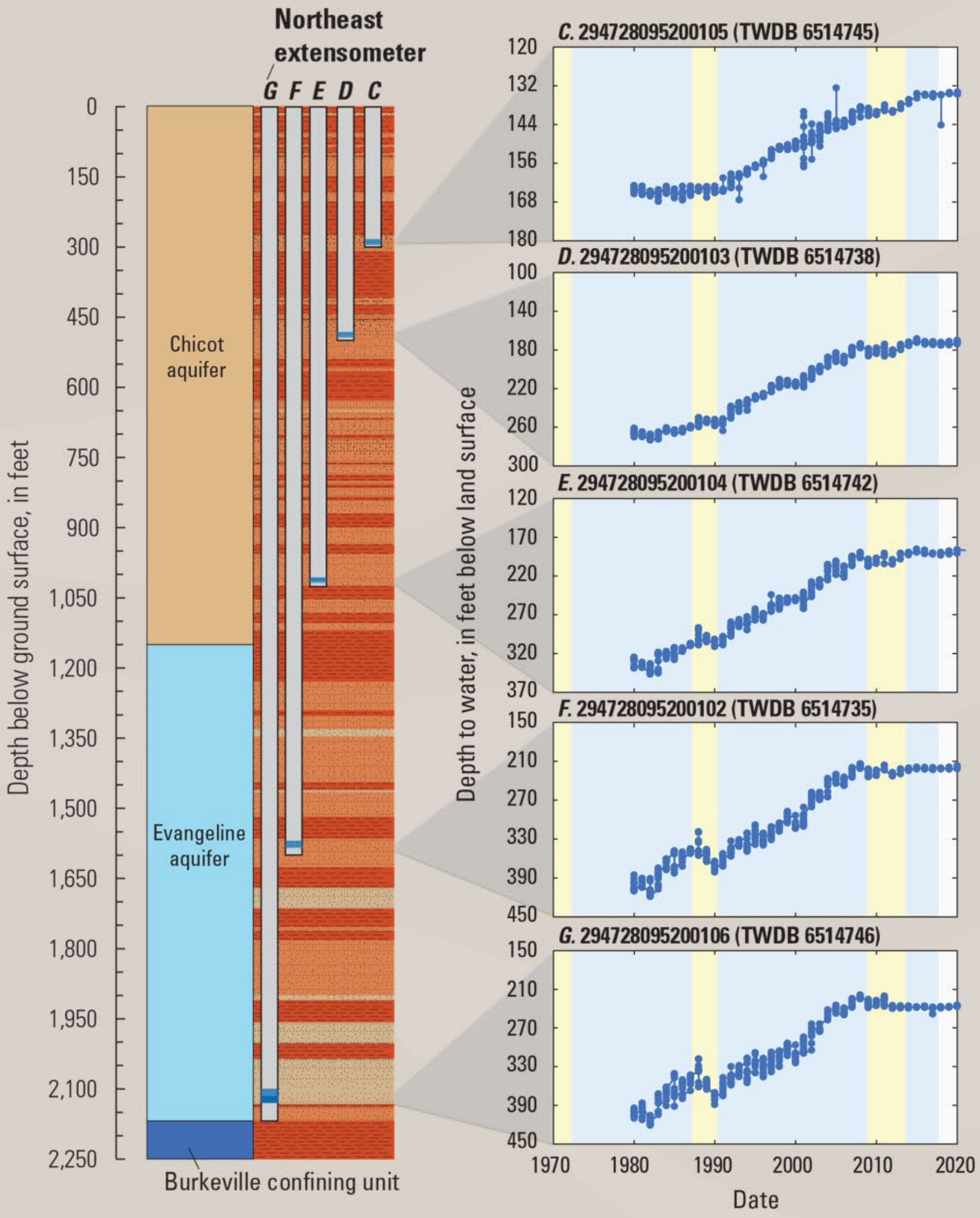


Co-located Groundwater Levels

Northeast extensometer

- Substantial degree of similarity between groundwater levels across 1,800 feet vertically
- Recovery of groundwater levels after a reduction in groundwater use, but not to predevelopment levels

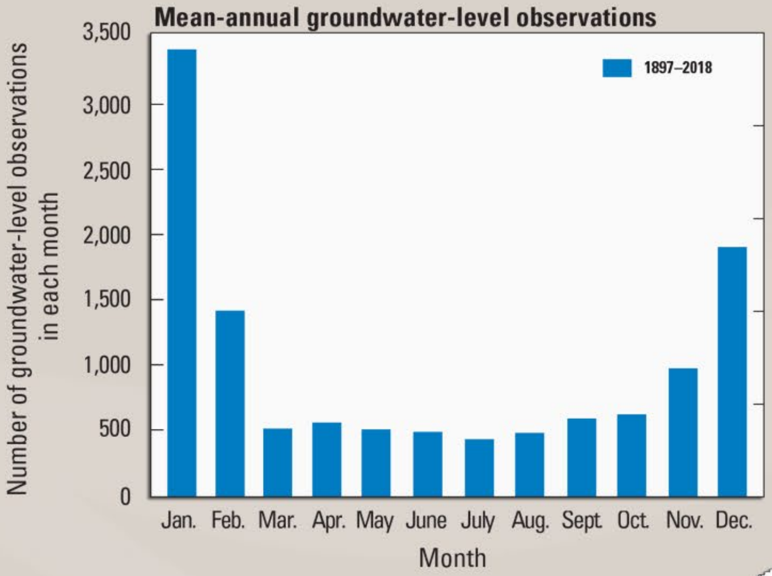


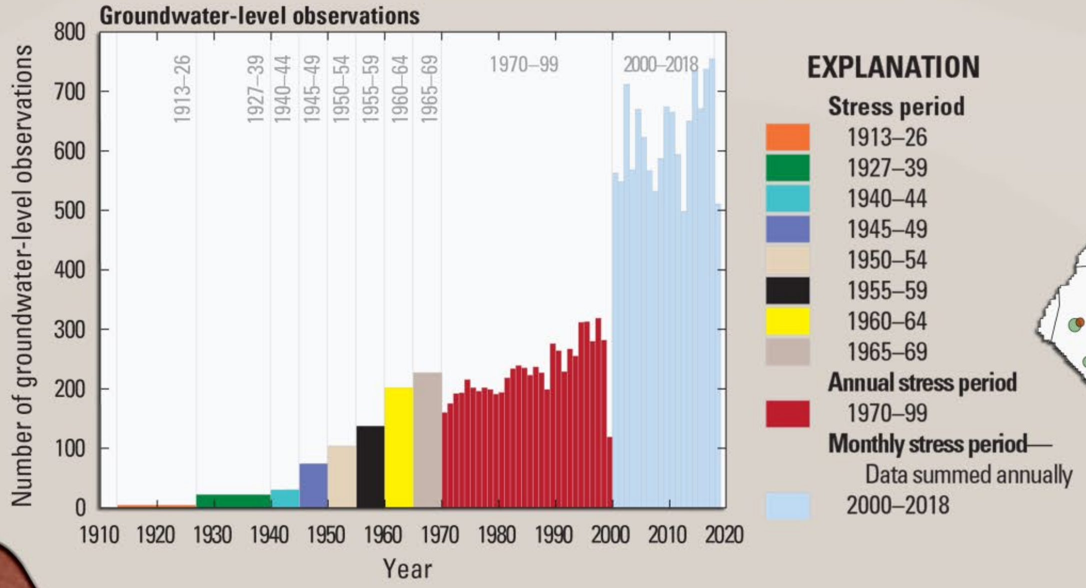


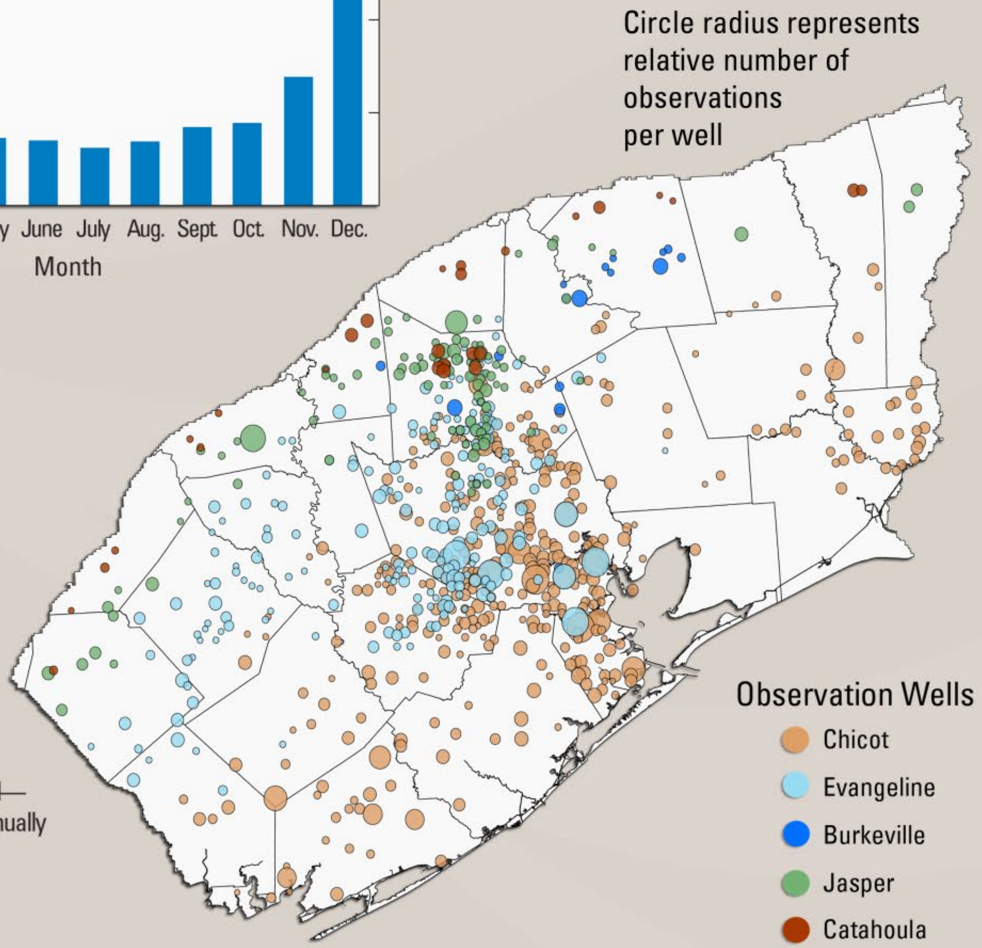
Model Features

Groundwater levels

- Greater number of groundwater levels through time as monitoring in the study area has increased
- Most groundwater levels taken from December–February each year
- A programmatic approach was used to prepare groundwater levels used in the model

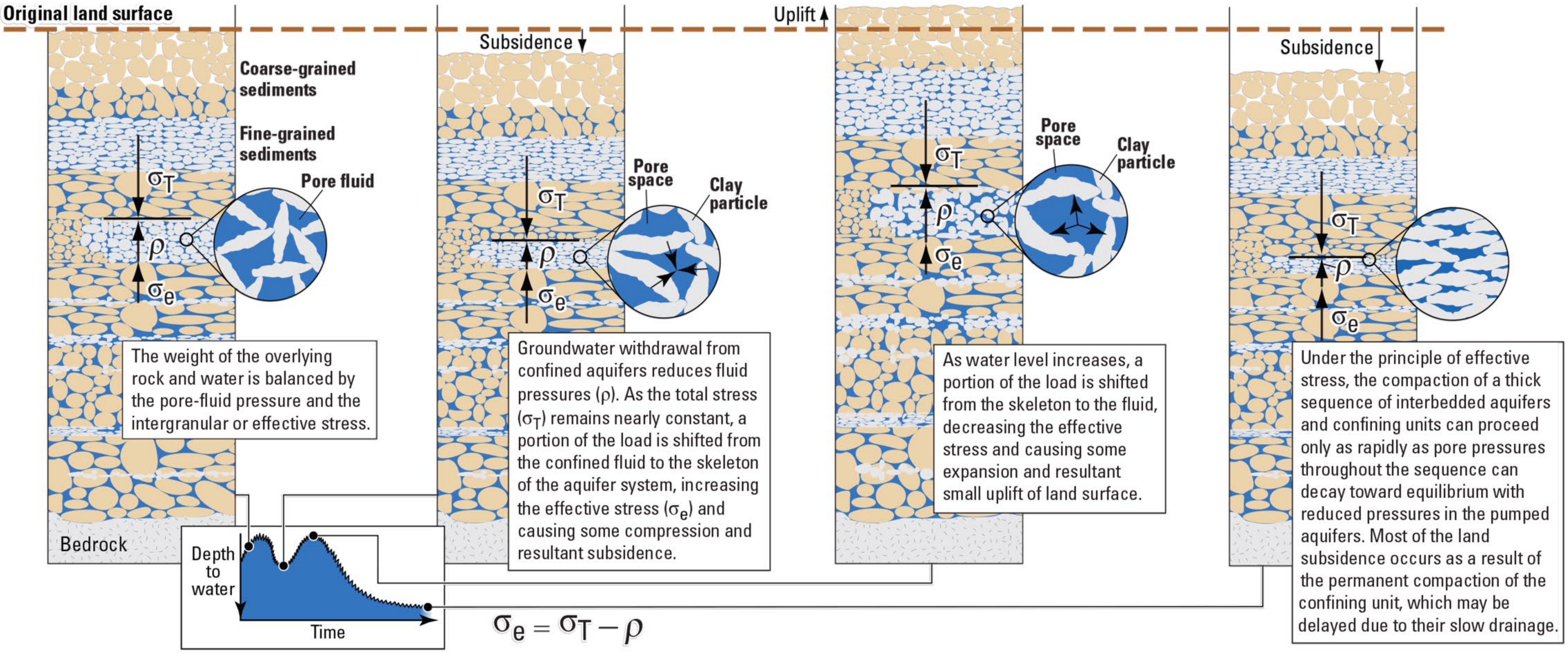






Subsidence

Effective stress and compaction



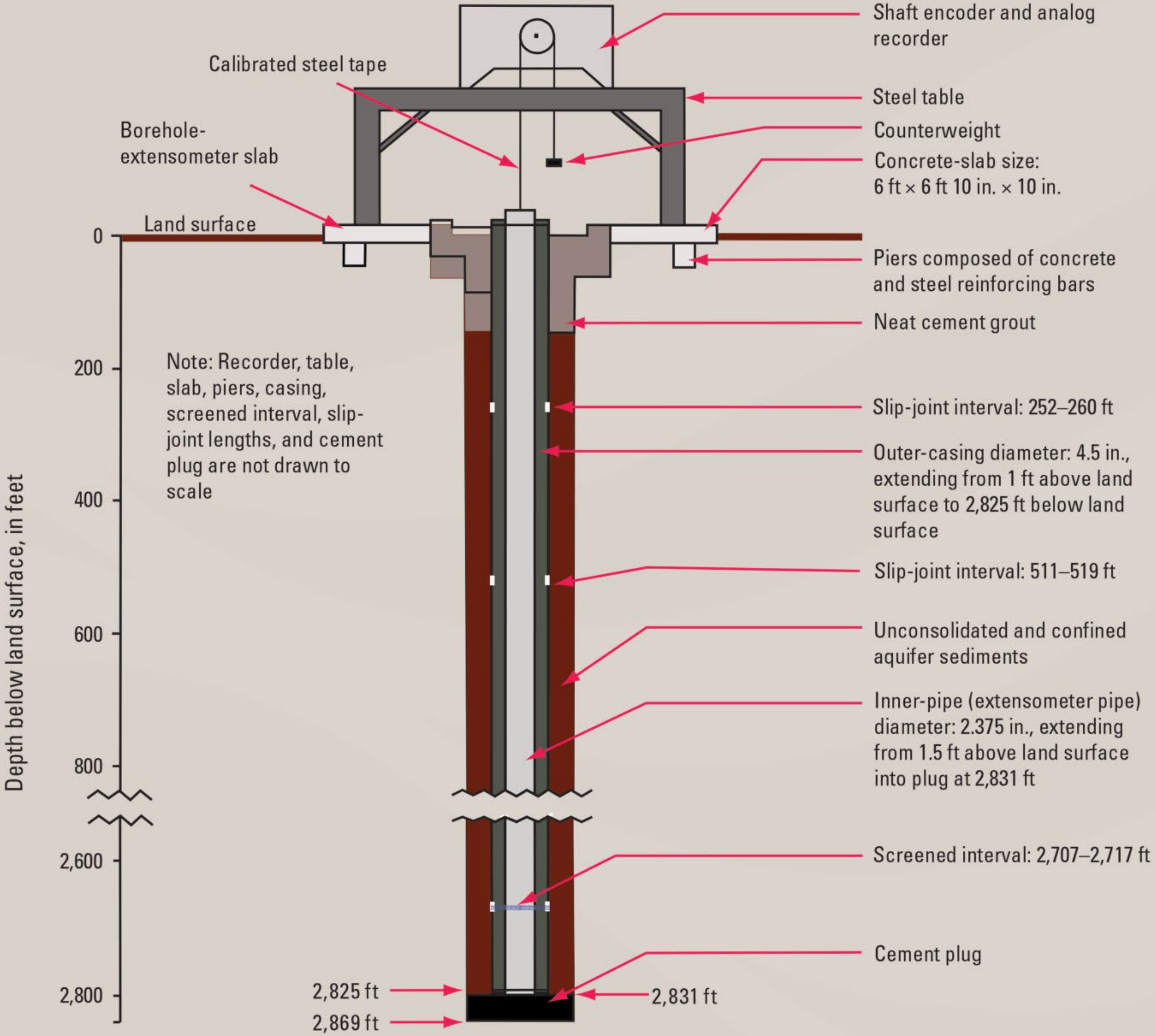
Subsidence

Borehole extensometers

- Basically, a deeply-anchored benchmark in the earth
- During installation, a hole is drilled to a depth where the sediment is stable
- Then, an inner pipe is installed and situated on a cement plug at the bottom
- The distance between the inner pipe and land surface, recorded by the shaft encoder or f-recorder, is the amount of compaction

East End extensometer

Clear Lake (shallow) extensometer



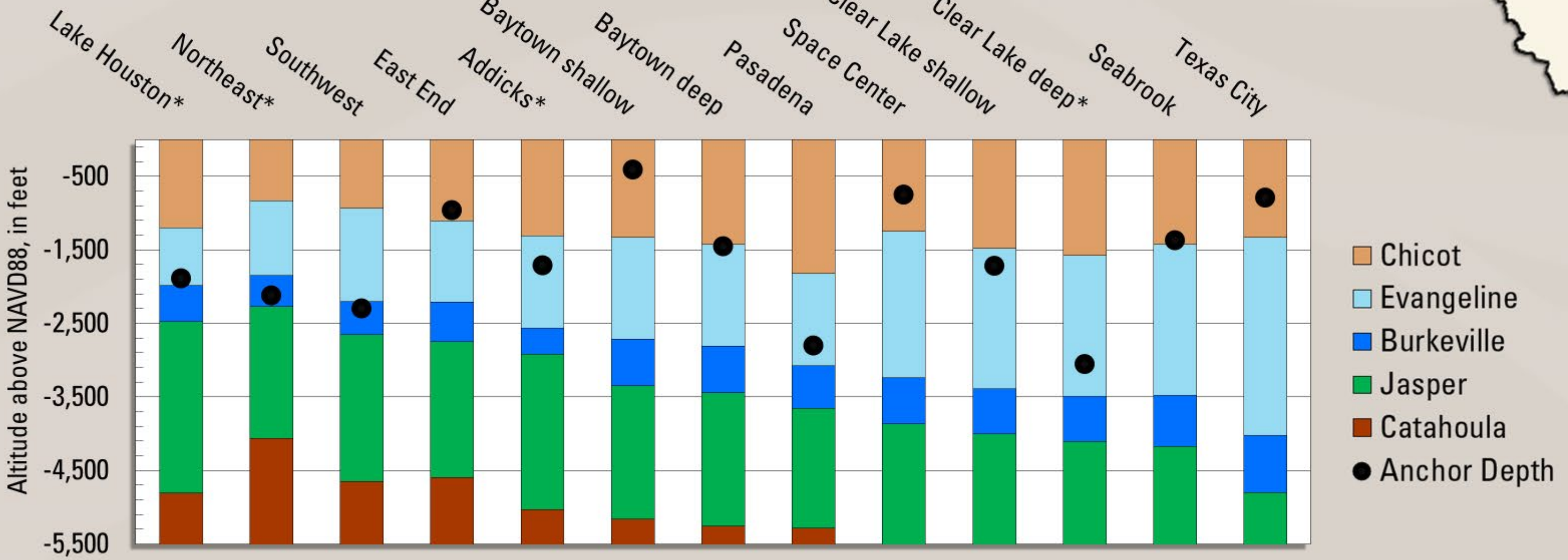
Note: All depths are referenced to land-surface elevation

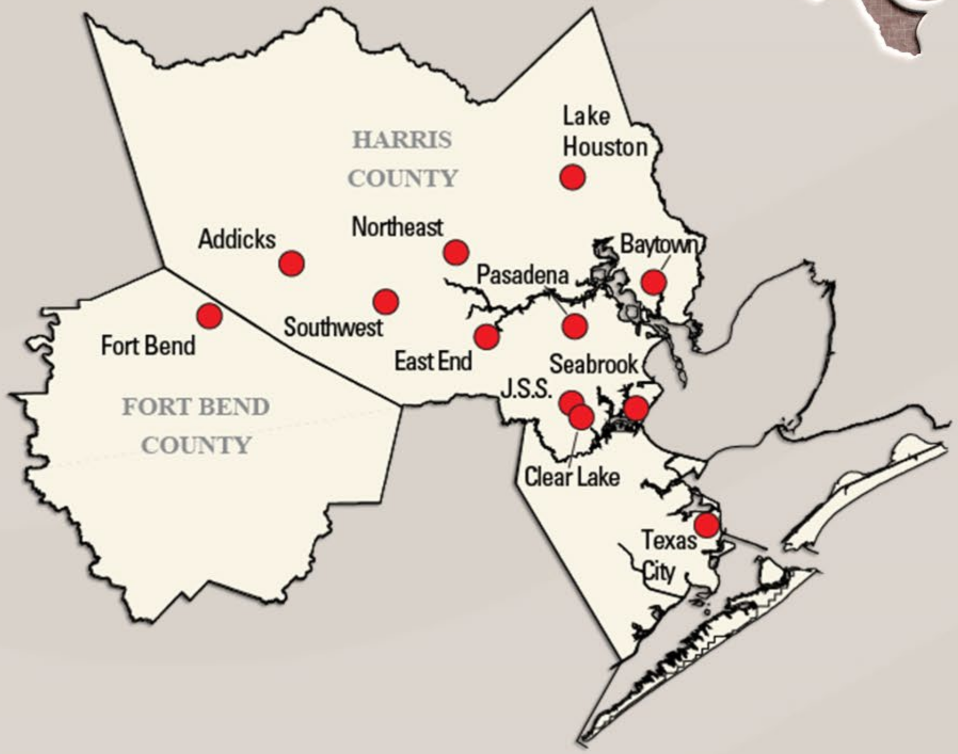
Shown: Pasadena extensometer

Subsidence

Model subsidence datasets

- Extensometers: measure compaction in the aquifer system. Fourteen extensometers at 12 sites (13 in the GULF model).
  - Seven measure compaction in Chicot aquifer, six in Chicot + Evangeline aquifers.
  - 13 extensometers installed between 1958 and 1980





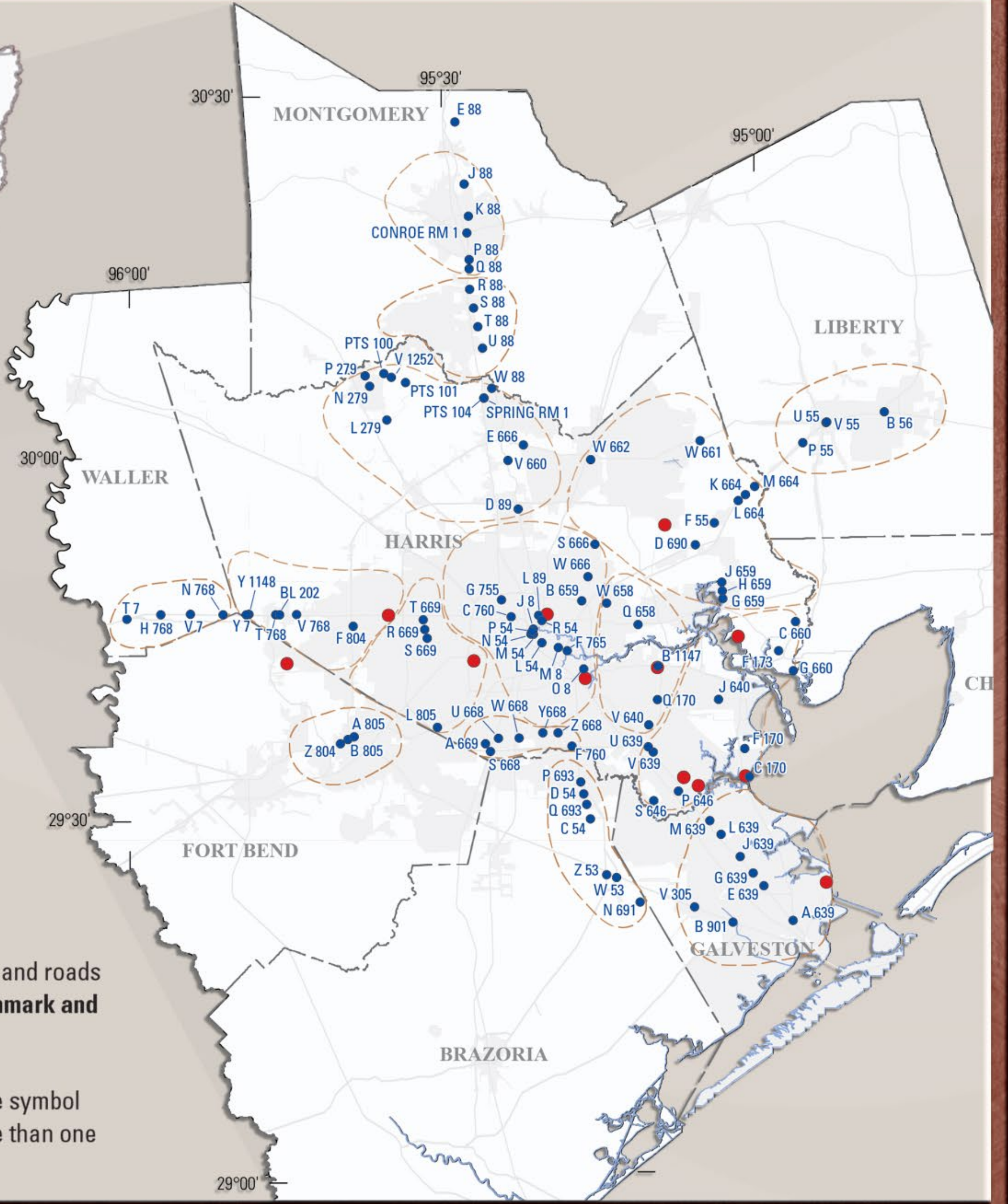
Pasadena extensometer

Lake Houston extensometer

NAVD; North American Vertical Datum of 1988
*CORS site
Ft Bend extensometer not shown

Subsidence

- Benchmarks: The GULF model was calibrated to leveling data at 105 benchmarks
  - 20 benchmarks: Occupations in 1906 or 1918 through 1987 or later
  - 39 benchmarks: Occupations in 1932–33 through 1987 or later
  - 97 benchmarks: Occupations in 1942–43 through 1987 or later
  - 18 benchmarks: Reoccupied in 2019–21. A total of 10 of these benchmarks have data from 1932–33 through 2019–21



Urban area—Cities and roads

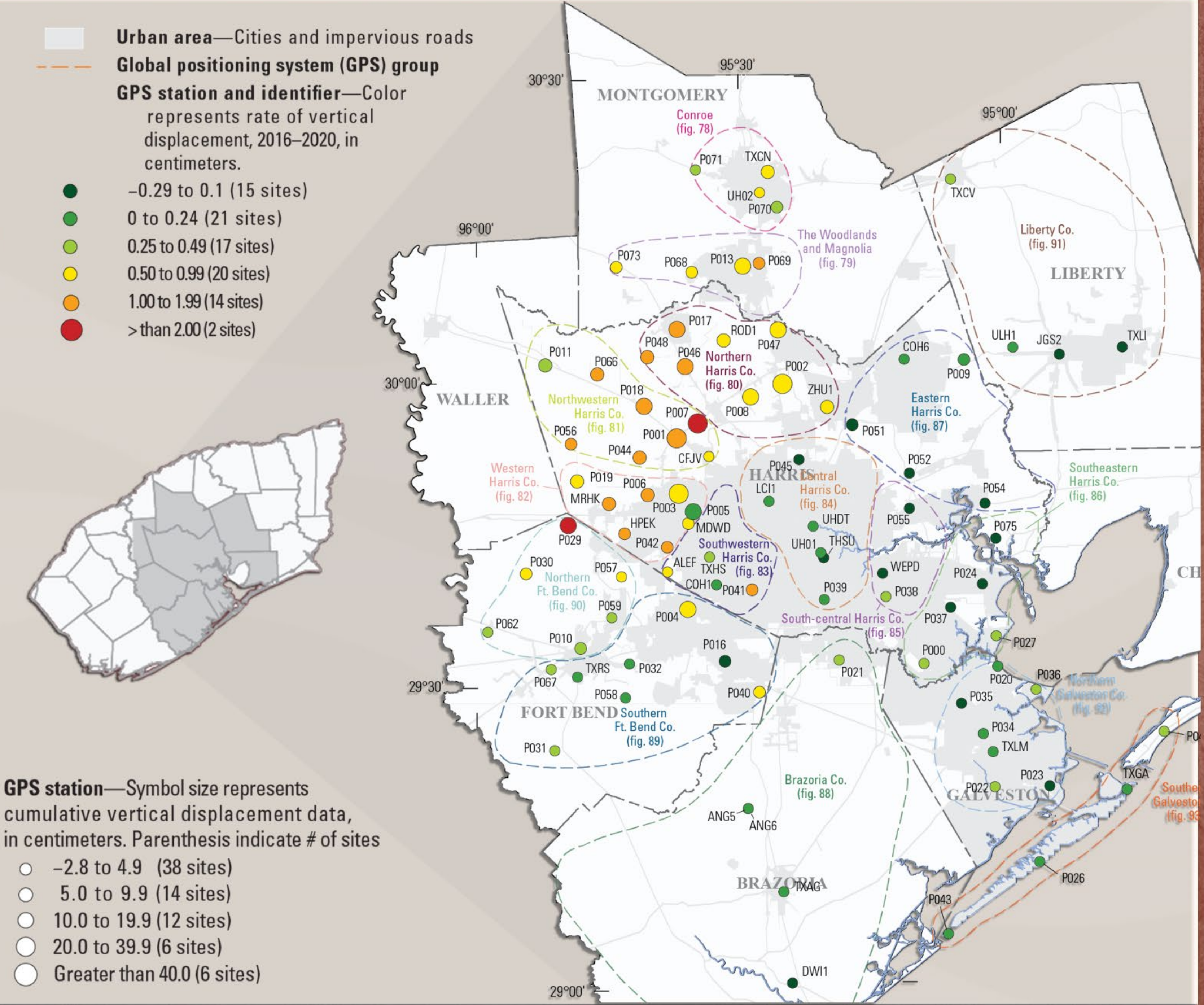
V 55 **Monumented benchmark and benchmark name**

Benchmark group

Extensometer—one symbol may represent more than one extensometer

Subsidence

- The GULF model was calibrated to vertical-displacement data at 178 GPS stations, 80 of which are in the greater Houston area
- Each report GPS group contains sites geographically clustered to describe vertical-displacement trends
- The same geographic groupings are used for the benchmark, GPS, and groundwater wells for comparability.

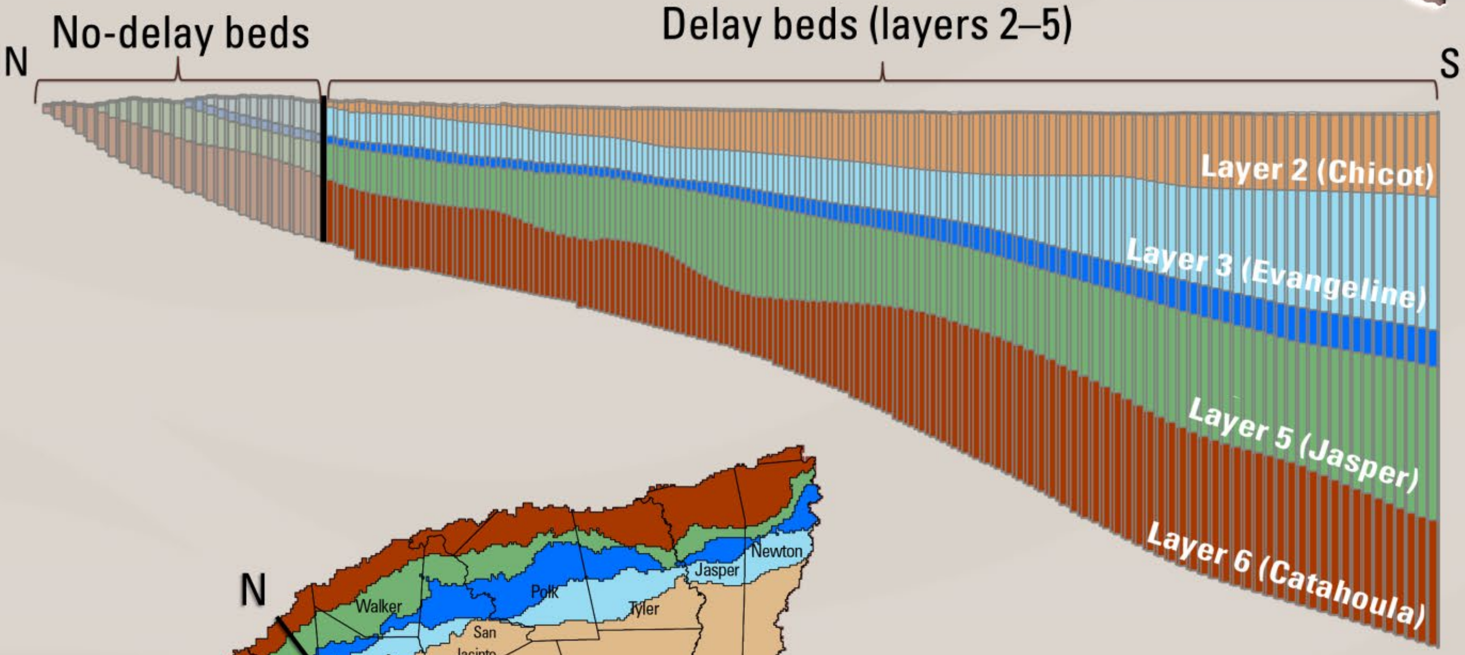


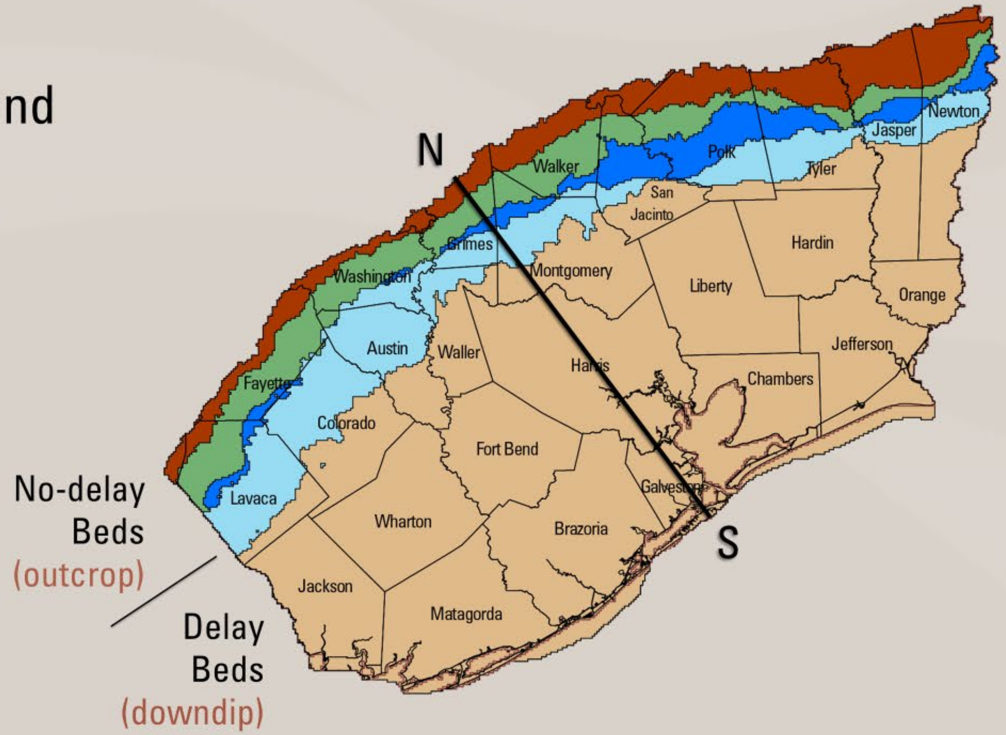
Subsidence

Subsidence package

- Newly formulated subsidence package (CSUB)[1] for the MODFLOW 6 model code
- Simulates groundwater-storage changes and compaction
- Using delay beds in subcrop area, and no-delay beds in outcrop area
- Compaction relation

  $\Delta b = \Delta h S_s b$ Head based



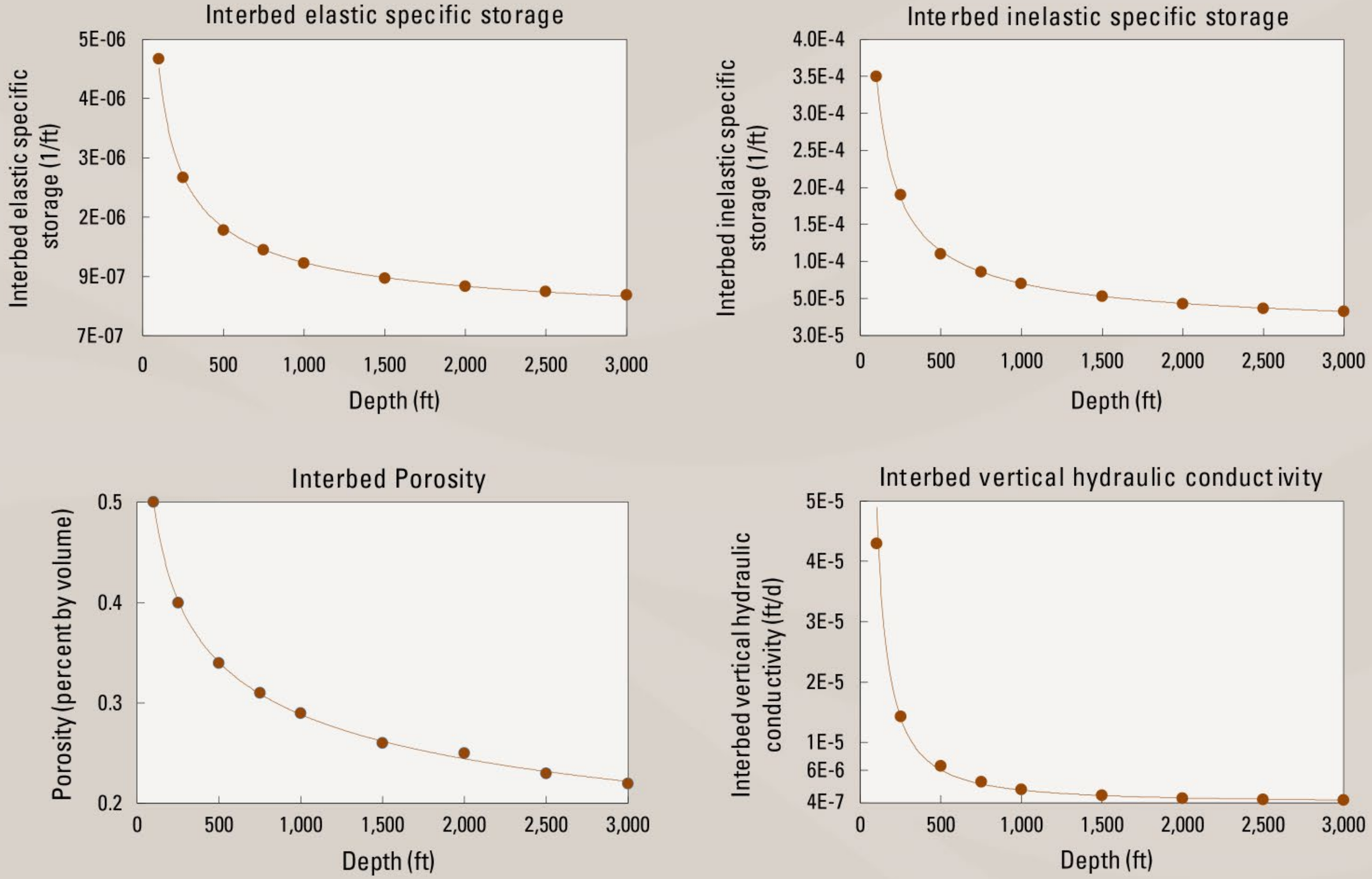


[1]Hughes and others, *in press*

Subsidence

Subsidence package parameters

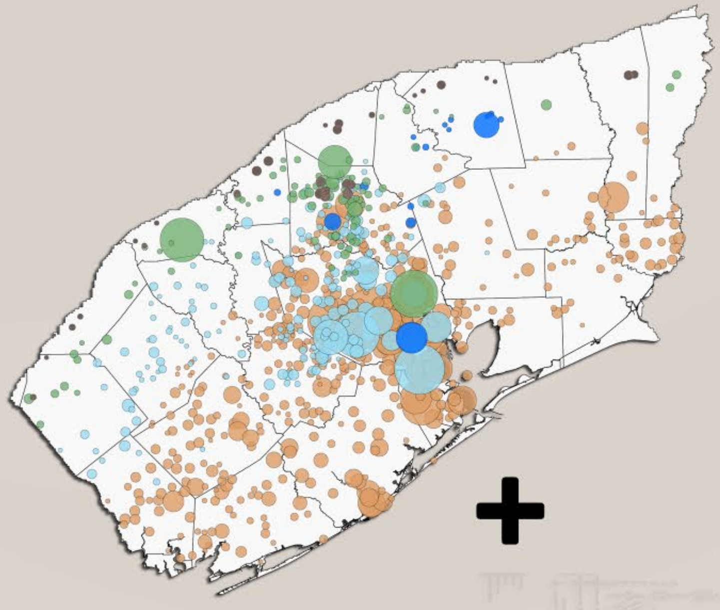
- Fine grained (interbeds)
  - Specific storage (elastic, inelastic)
  - Porosity
  - Vertical hydraulic conductivity
  - Interbed thickness
  - Number of interbeds
- Coarse grained (sand units)
  - Specific storage (elastic)
  - Porosity
- Drawdown at preconsolidation stress



Best fit lines through data from Kelley and others (2018), tables 2-1, 2-2

Model history matching and uncertainty

- Process of changing initial model inputs (parameters) to reduce residuals. Residuals = simulated – observed (or estimated)
- Using PEST++ IES[1] software to history match an ensemble, not just one model
- Use probabilistic approach to assess uncertainty in model results



+

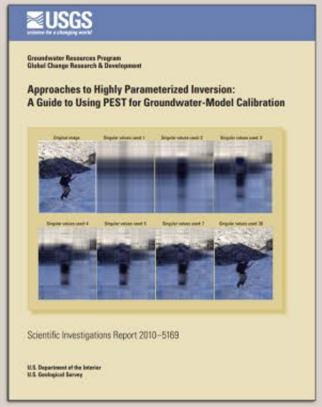
PEST++

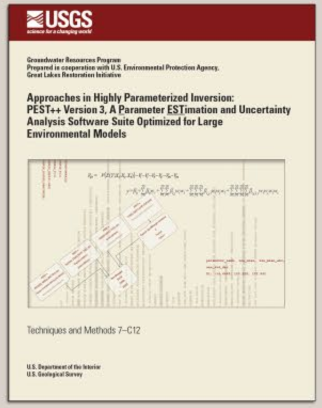
Software Suite for Parameter Estimation, Uncertainty Quantification, Management Optimization, and Sensitivity Analysis

+

HTCondor

High Throughput Computing



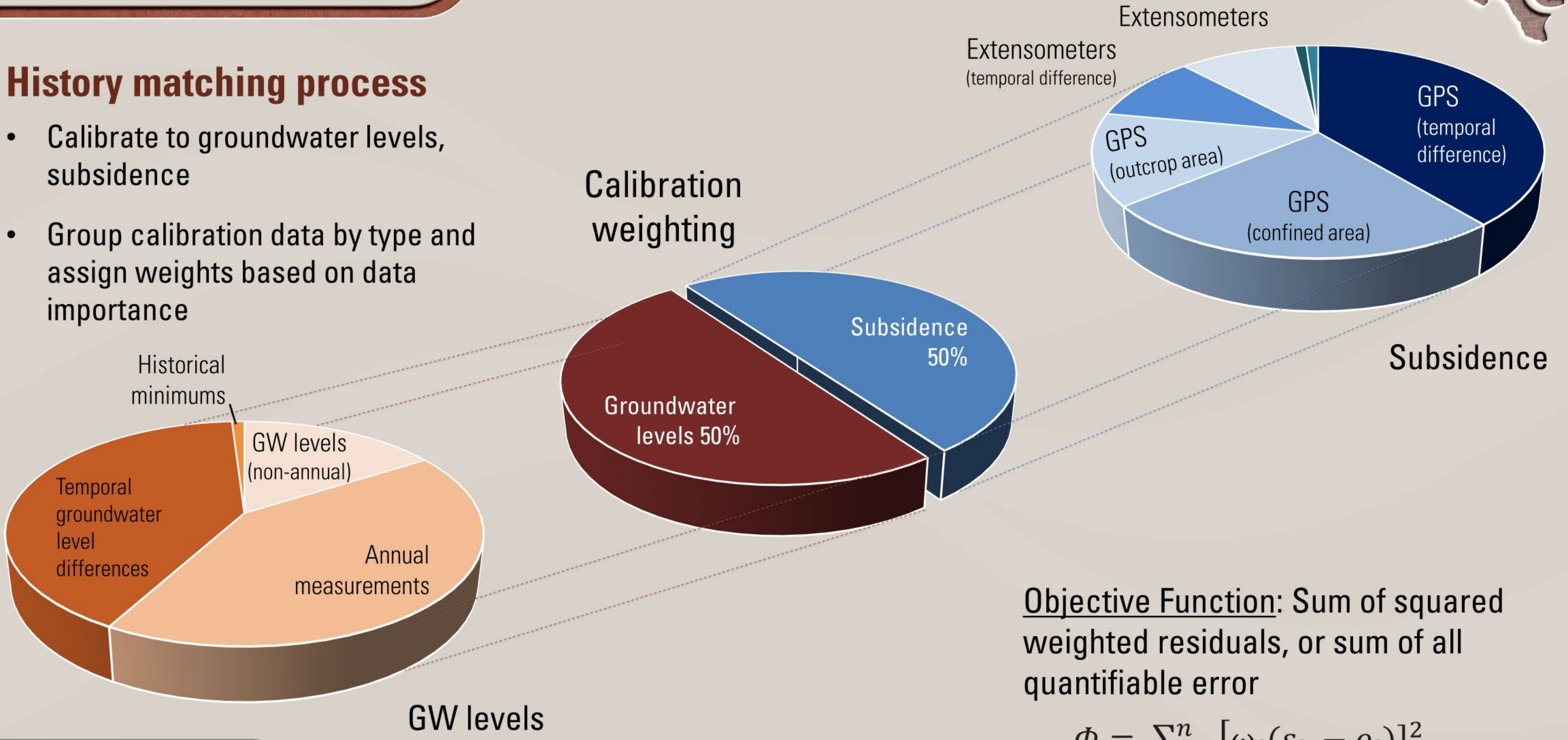


[1]White, 2018

Calibration & Uncertainty

History matching process

- Calibrate to groundwater levels, subsidence
- Group calibration data by type and assign weights based on data importance



Objective Function: Sum of squared weighted residuals, or sum of all quantifiable error

$$\Phi = \sum_{i=1}^{n}[\omega_i(s_i - o_i)]^2$$

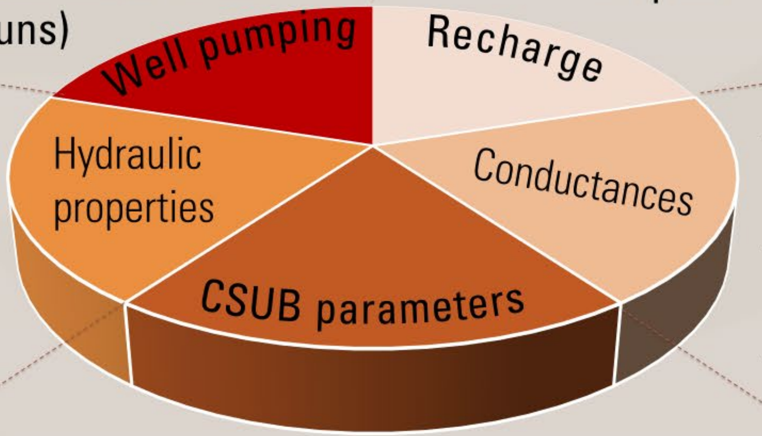
Model Parameters

- Thanks to advances in history matching using PEST-IES, currently using 183,207 adjustable parameters.
- Include entire-layer, geostatistical (pilot point), and individual cell parameters

Parameter groups and parameters

From water-use estimates (initial runs)

From SWB outputs



– River conductance
– Drain conductance
– GHB conductance

– Horizonal hydraulic conductivity
– Vertical hydraulic conductivity
– Specific Yield

1.7 million parameters

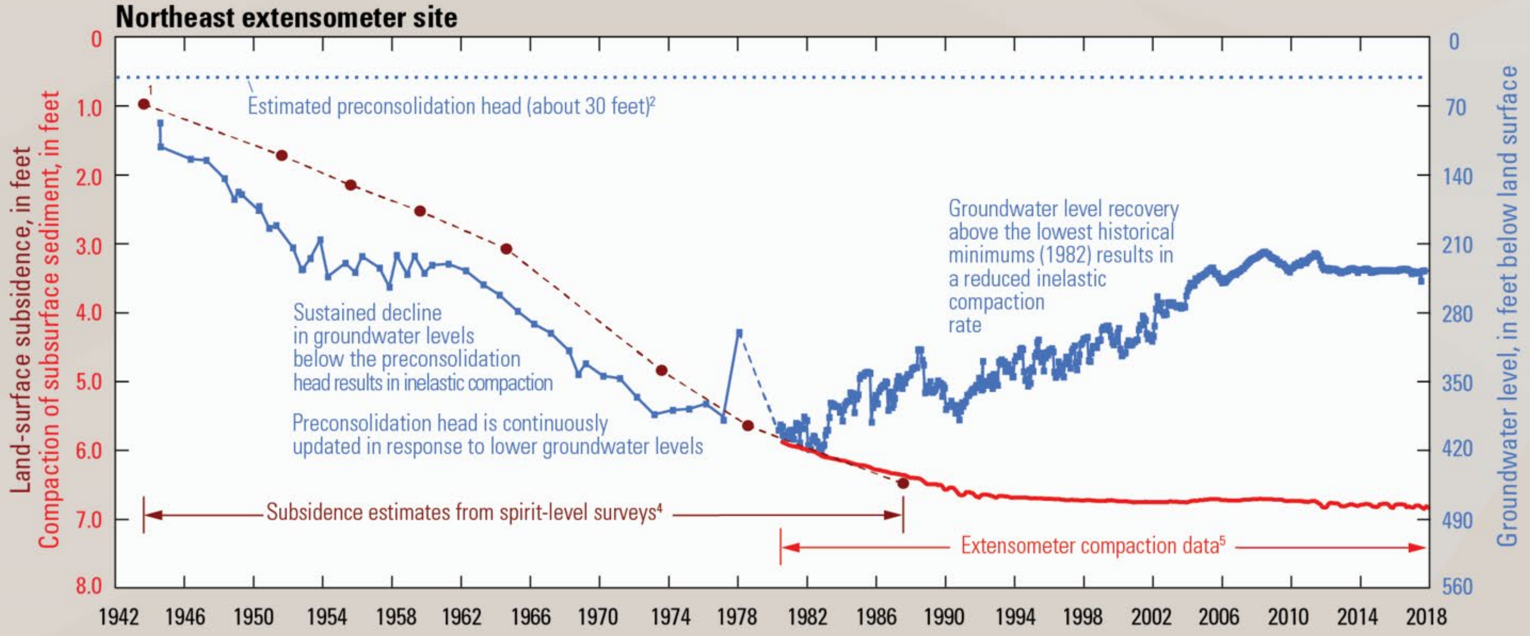
Fine grained
- – Elastic specific storage
- – Inelastic specific storage
- – Porosity
- – Vertical hydraulic conductivity

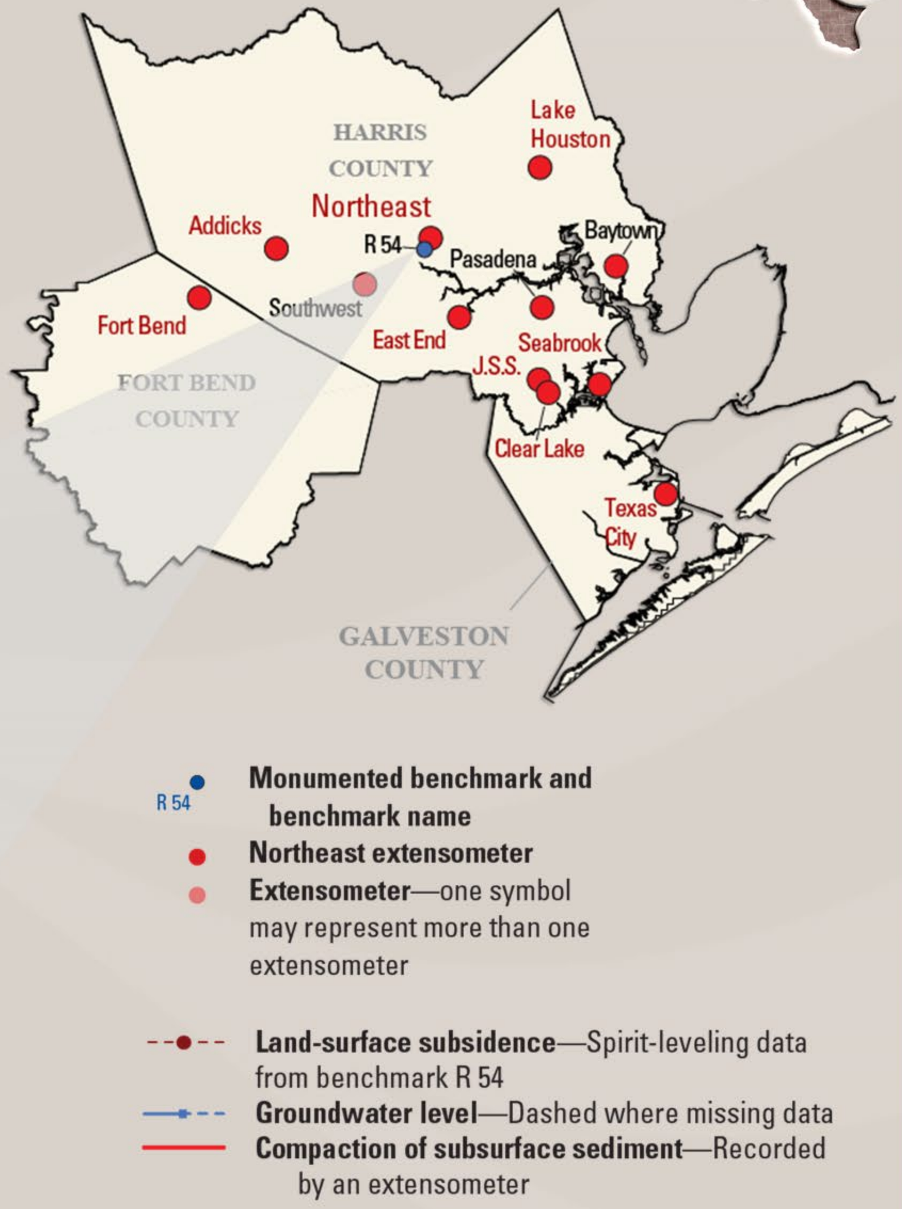
Coarse grained
- – Specific storage (elastic)
- – Porosity

Cumulative subsidence

PRELIMINARY RESULTS

- Northeast extensometer: About 6.8 feet of subsidence through 2018
  - By 1943, groundwater levels were about 100 feet below land surface, and subsidence was about 0.9 feet.
  - As groundwater levels continued to decline, the aquifer system reached a continually greater level of effective stress, resulting in inelastic compaction.



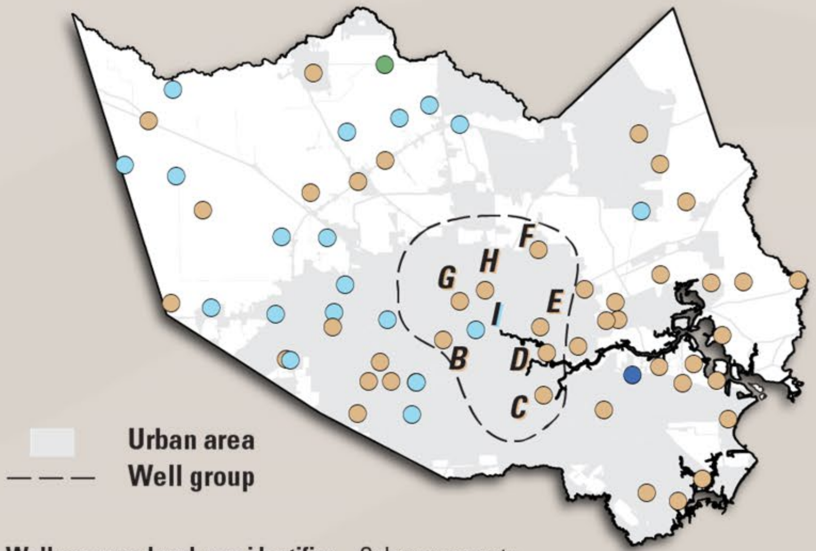


Groundwater Levels

PRELIMINARY RESULTS

Observed and simulated results

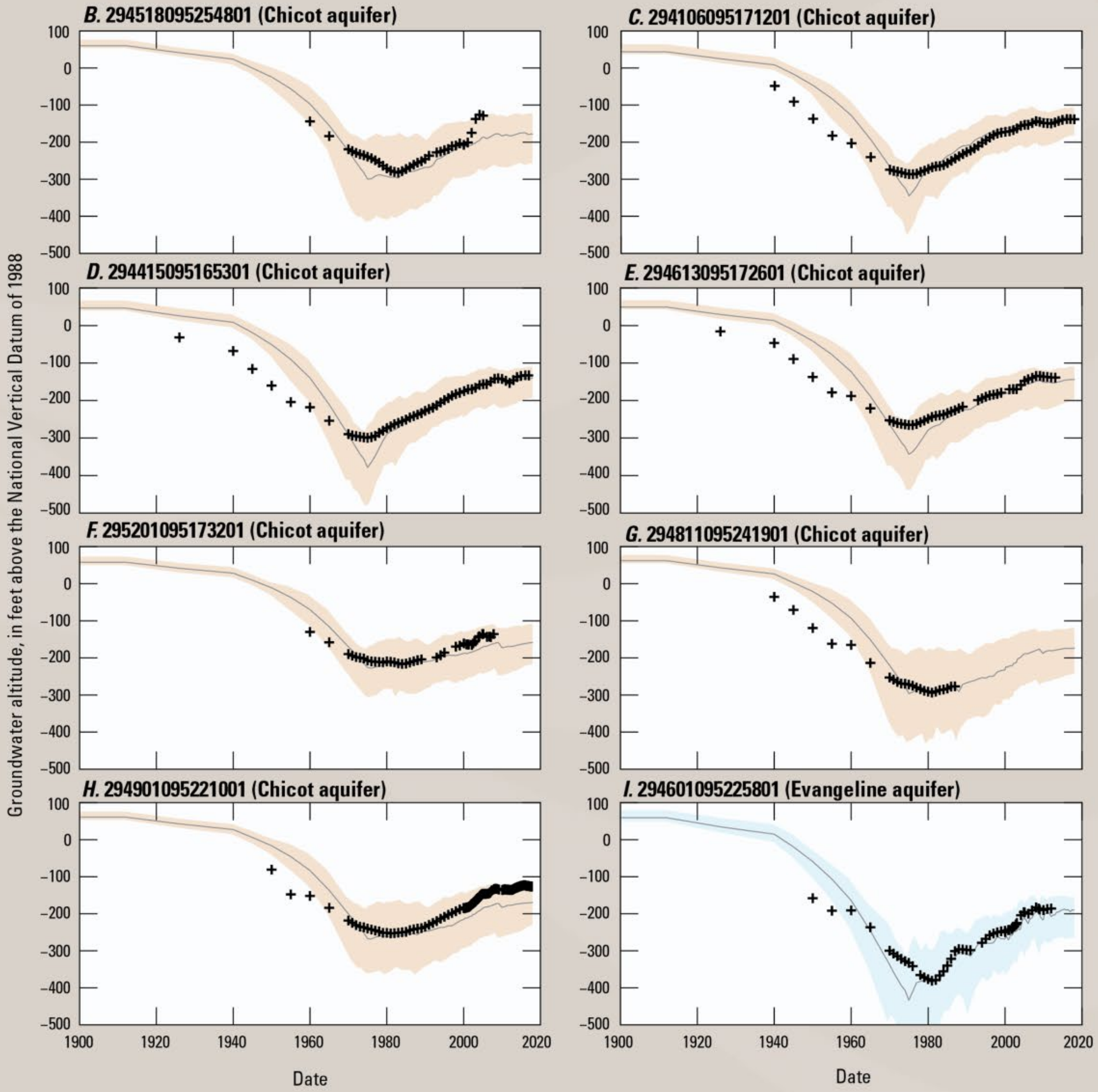
- The range of simulated groundwater levels generally bracket the historical observations
- Historical minimums not fully simulated in some areas



Well measured and map identifier—Color represents hydrogeologic unit in which well was completed. Identifier shown for wells with hydrographs

D Chicot aquifer (model layer 2)

I Evangeline aquifer (model layer 3)



Observed and simulated groundwater levels

+ Historical observation

— GULF model

GULF model ensemble

Chicot aquifer (model layer 2)

Evangeline aquifer (model layer 3)

Groundwater Levels

PRELIMINARY RESULTS

Observed and simulated results

- The range of simulated groundwater levels generally bracket the historical observations
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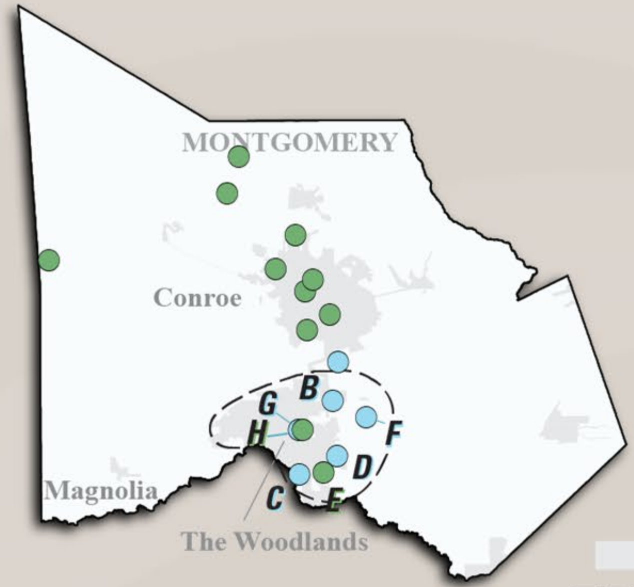


Urban area

Well group

Well simulated and map identifier—Color represents hydrogeologic unit in which well was completed. Identifier shown for wells with hydrographs

D Evangeline aquifer (model layer 3)

E Jasper aquifer (model layer 5)

Observed and simulated groundwater levels

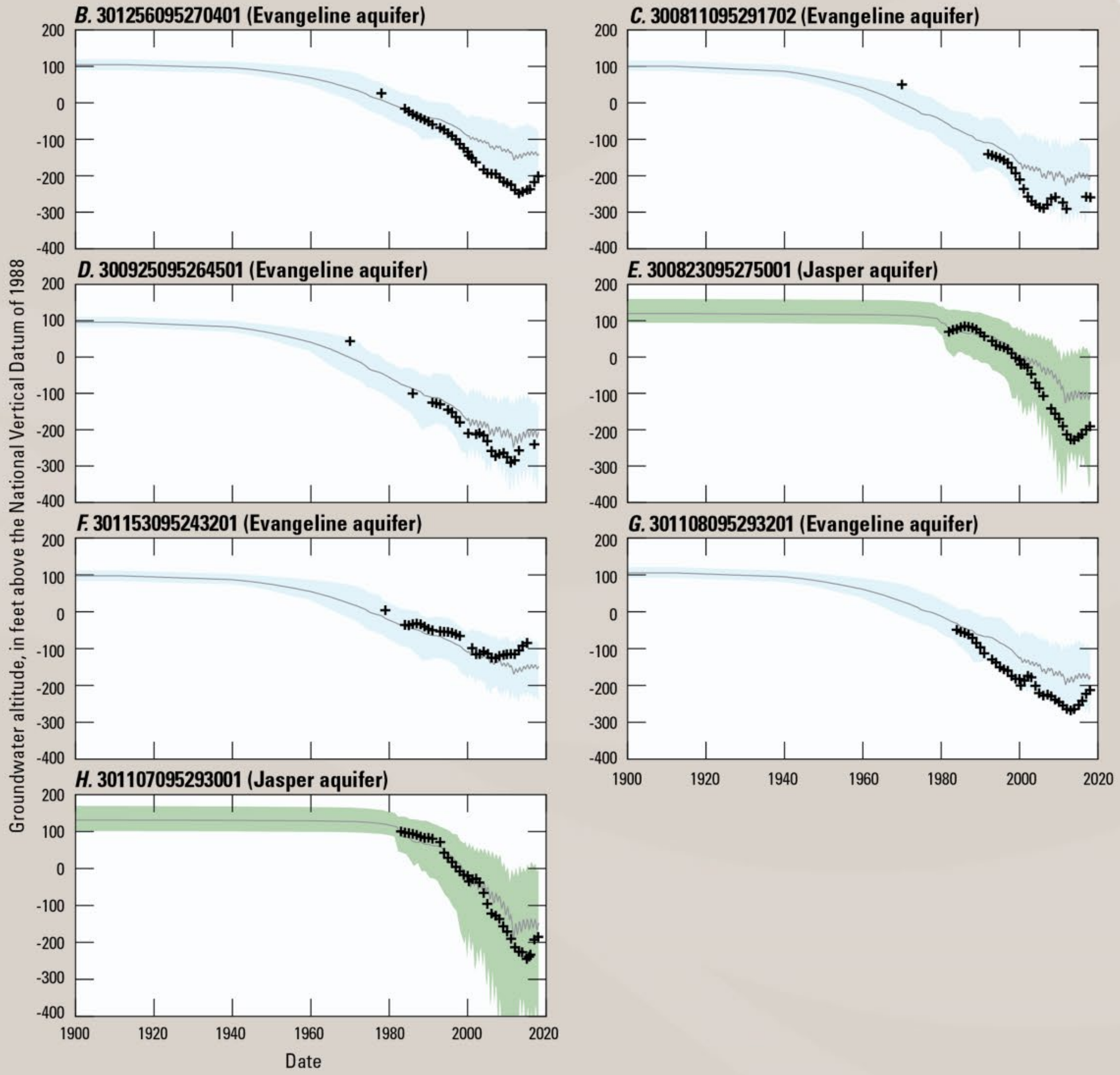
+ Historical observation

GULF model

GULF model ensemble

Chicot aquifer (model layer 2)

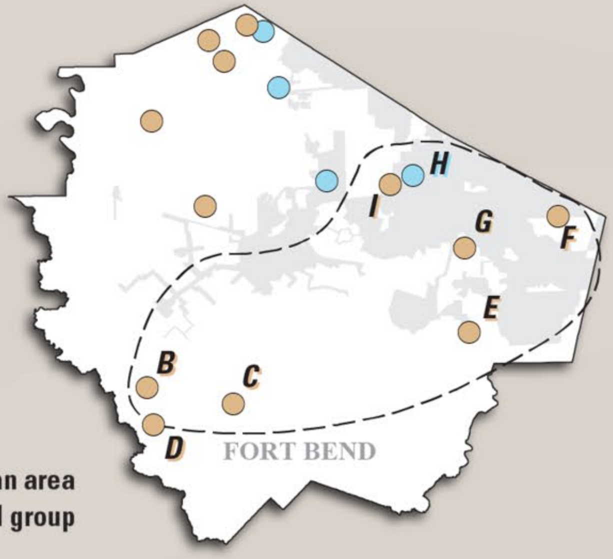
Evangeline aquifer (model layer 3)



Groundwater Levels

Observed and simulated results

- The range of simulated groundwater levels generally bracket the historical observations
- Historical minimums not fully simulated in some areas



Urban area

Well group

Well measured and map identifier—Color represents hydrogeologic unit in which well was completed. Identifier shown for wells with hydrographs

D Chicot aquifer (model layer 2)

H Evangeline aquifer (model layer 3)

Observed and simulated groundwater levels

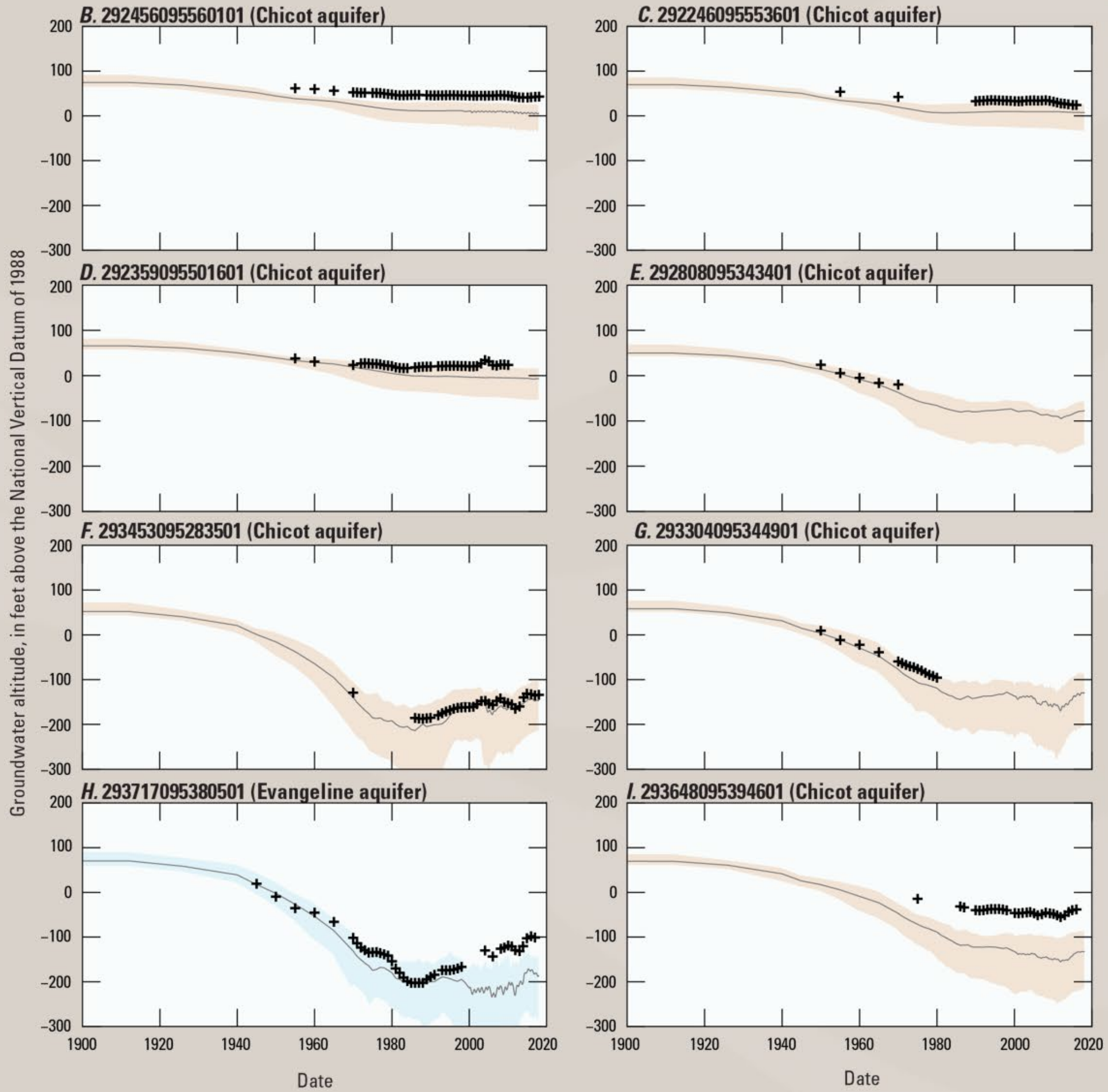
+ Historical observation

GULF model

GULF model ensemble

Chicot aquifer (model layer 2)

Evangeline aquifer (model layer 3)



Groundwater Levels

PRELIMINARY RESULTS

Observed and simulated results

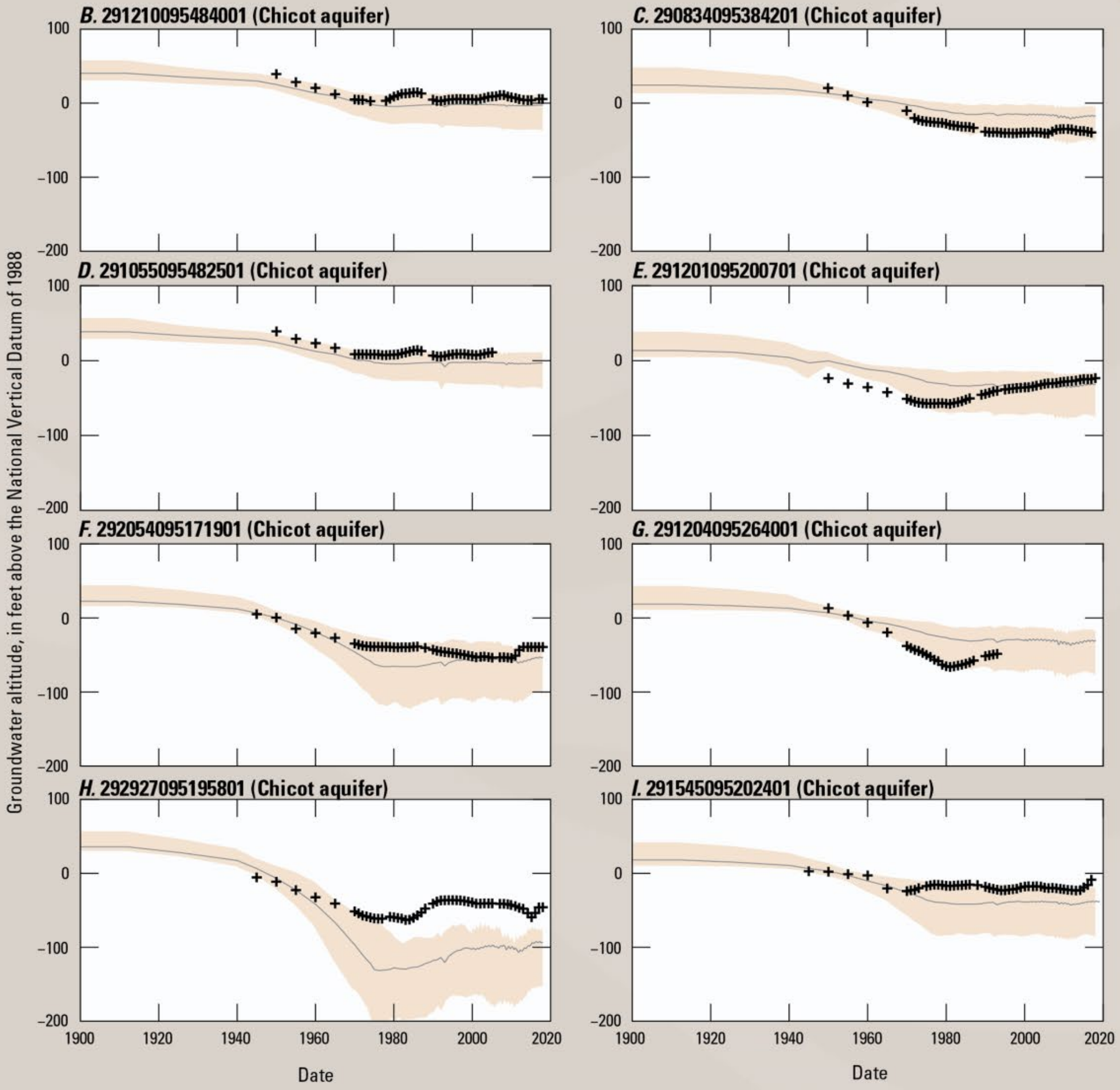
- The range of simulated groundwater levels generally bracket the historical observations
- Historical minimums not fully simulated in some areas

Observed and simulated groundwater levels

- \+ Historical observation
- GULF model
- GULF model ensemble
  - Chicot aquifer (model layer 2)

Well simulated and map identifier—Color represents hydrogeologic unit in which well was completed. Identifier shown for wells with hydrographs

D Chicot aquifer (model layer 2)

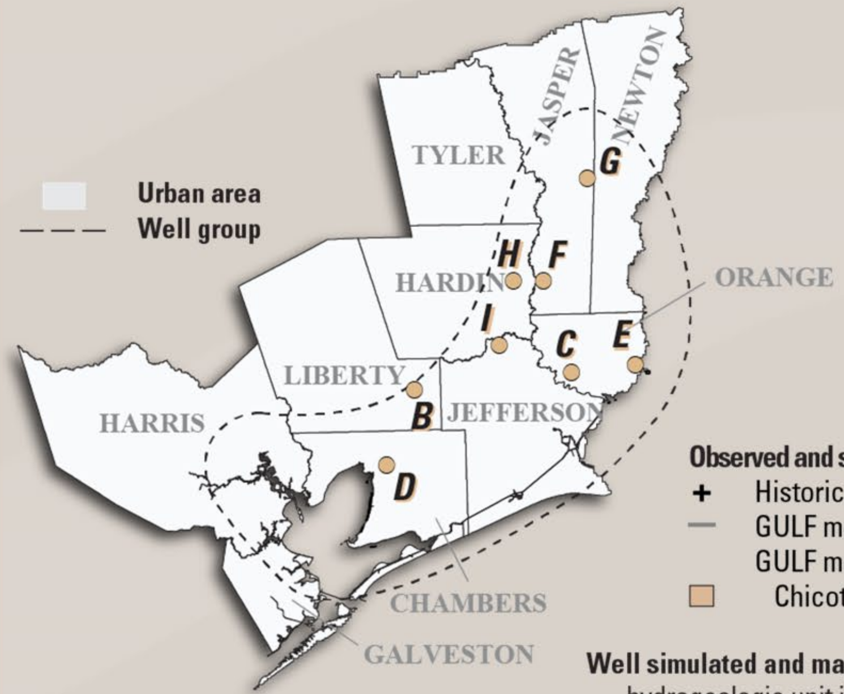


Groundwater Levels

PRELIMINARY RESULTS

Observed and simulated results

- The range of simulated groundwater levels generally bracket the historical observations
- Historical minimums not fully simulated in some areas



Observed and simulated groundwater levels

+ Historical observation

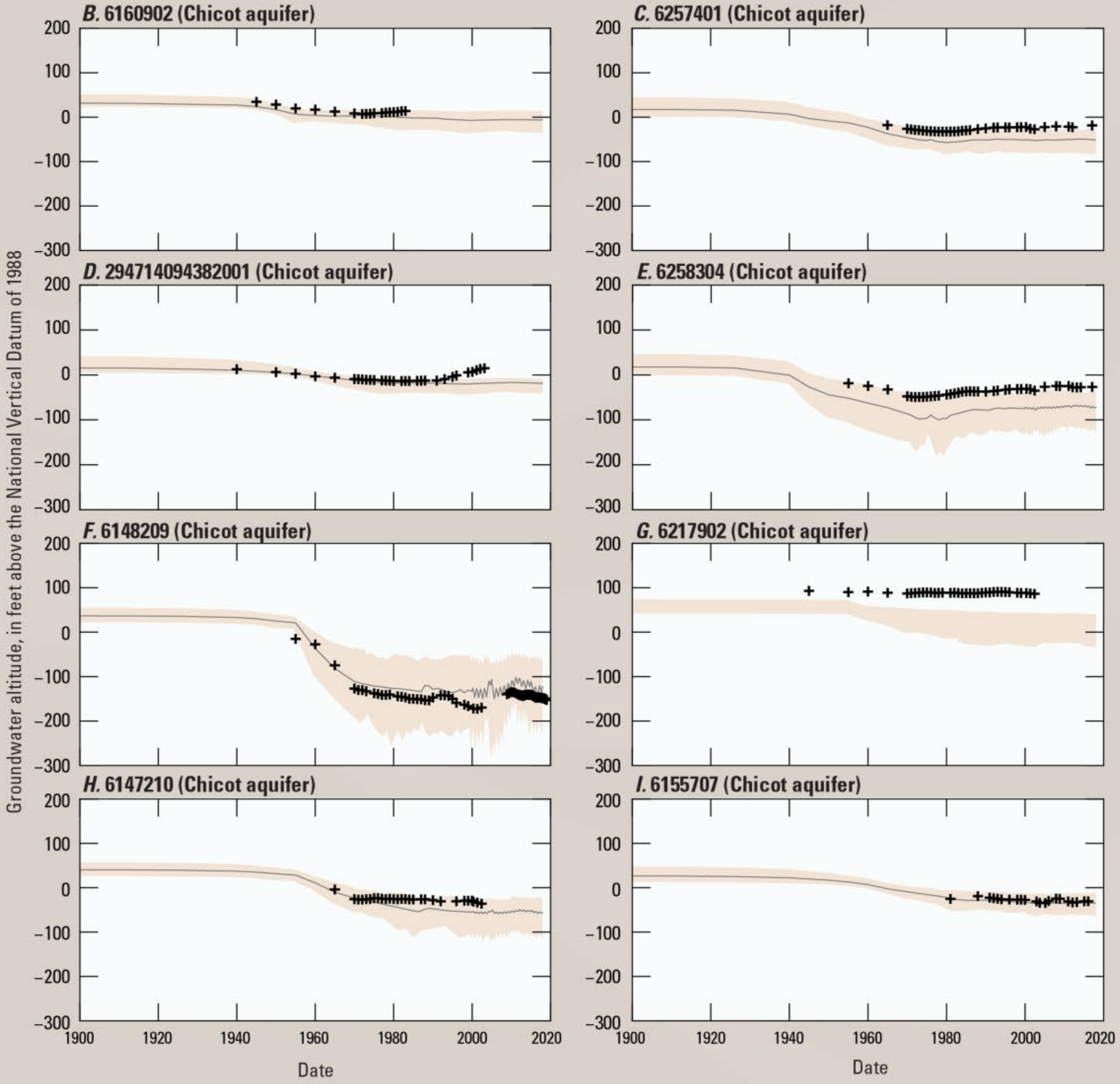
— GULF model

GULF model ensemble

Chicot aquifer (model layer 2)

Well simulated and map identifier—Color represents hydrogeologic unit in which well was completed. Identifier shown for wells with hydrographs

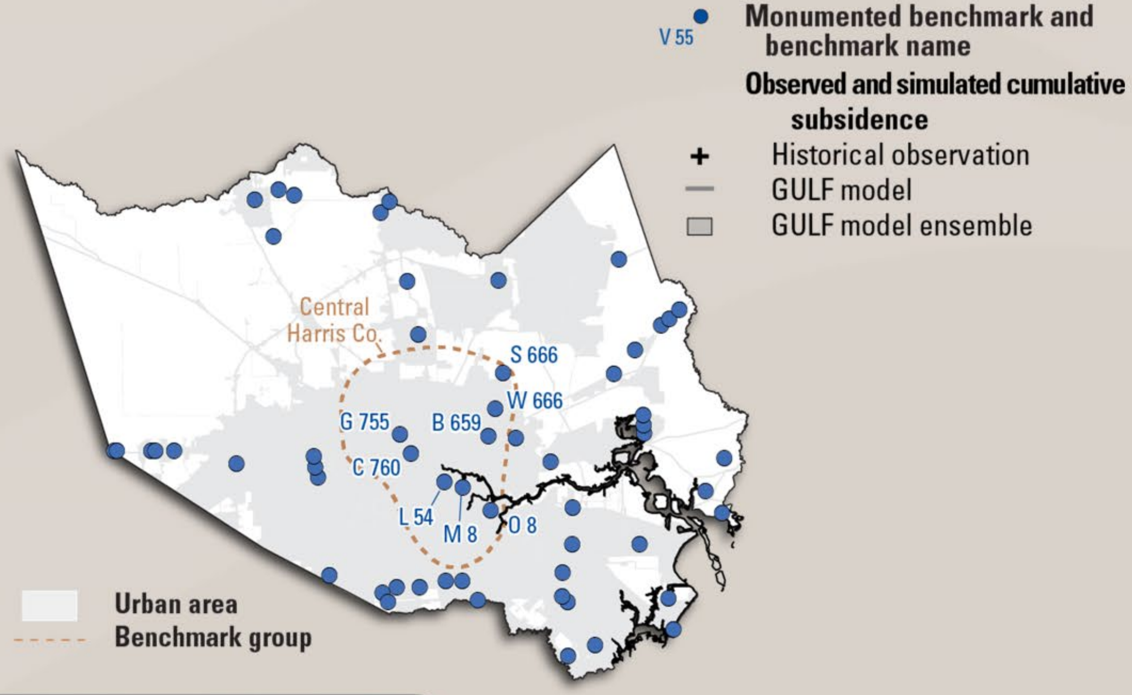
D Chicot aquifer (model layer 2)

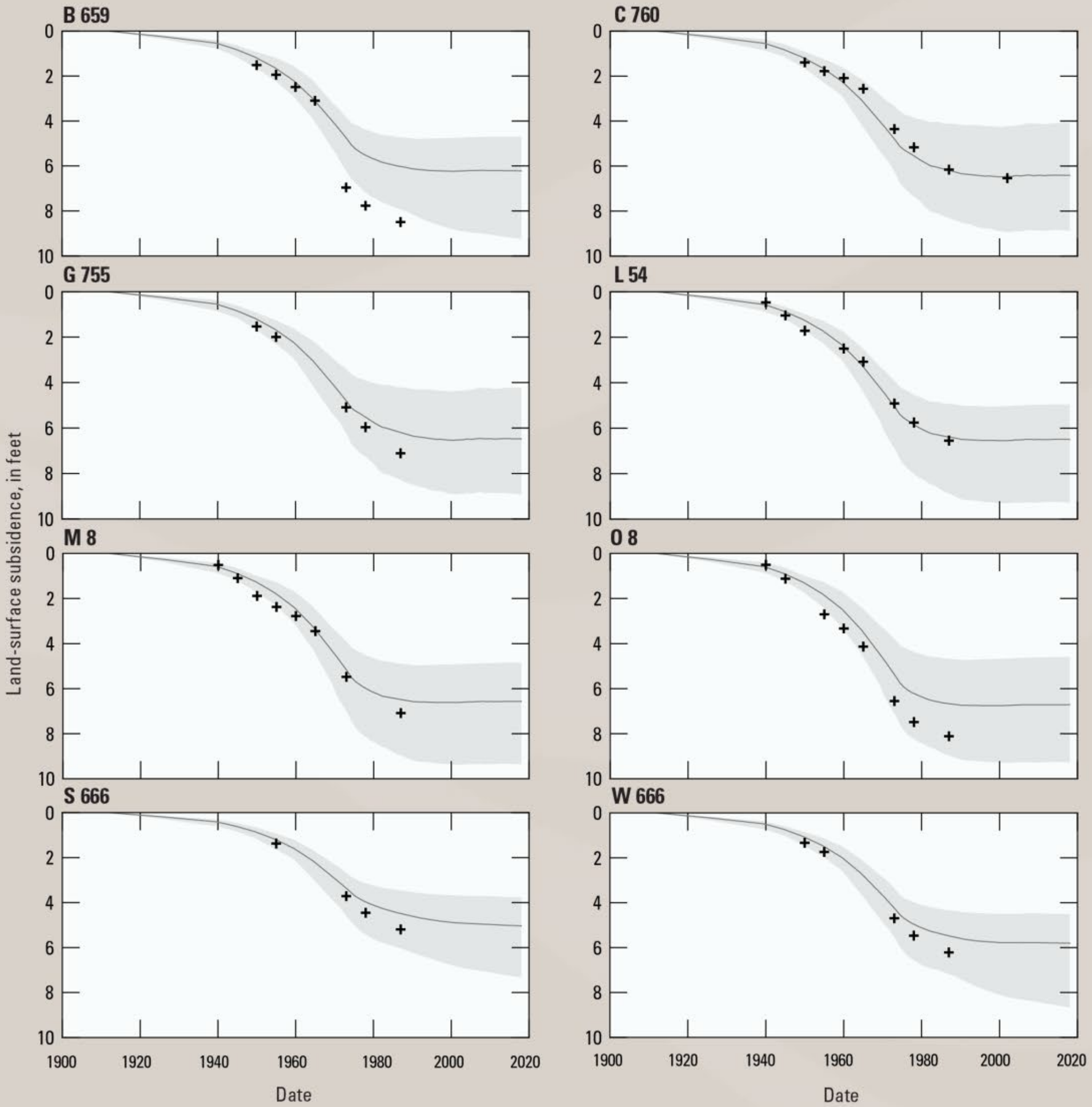


Subsidence

Observed and simulated results

- The range of simulated subsidence generally brackets the historical observations

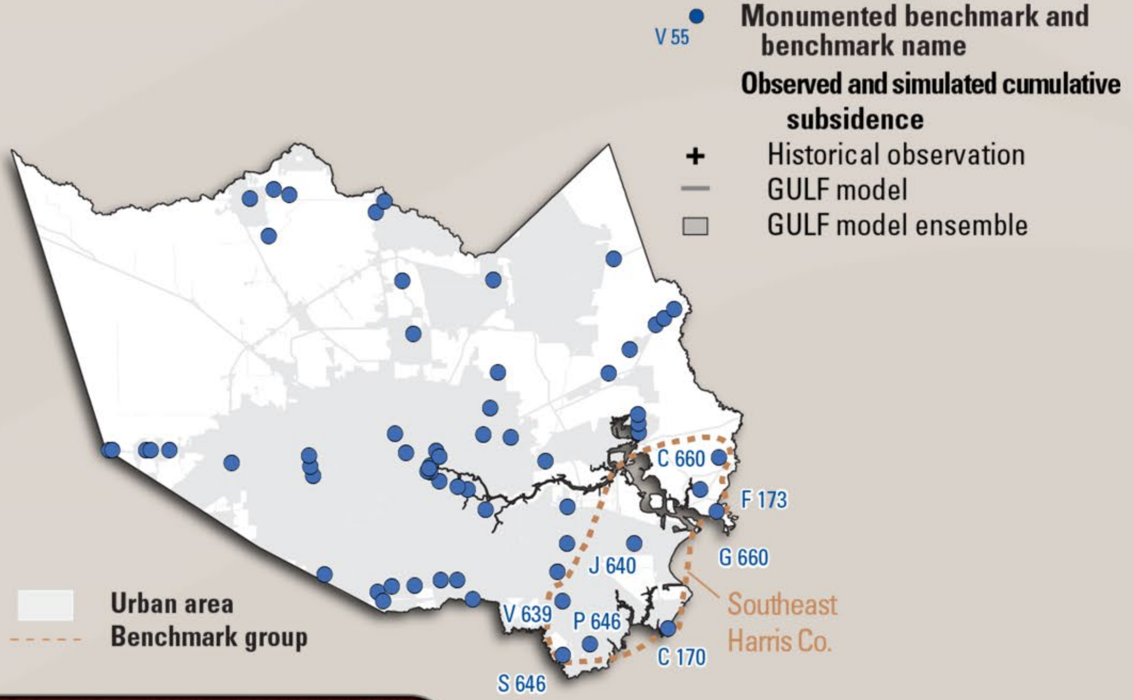


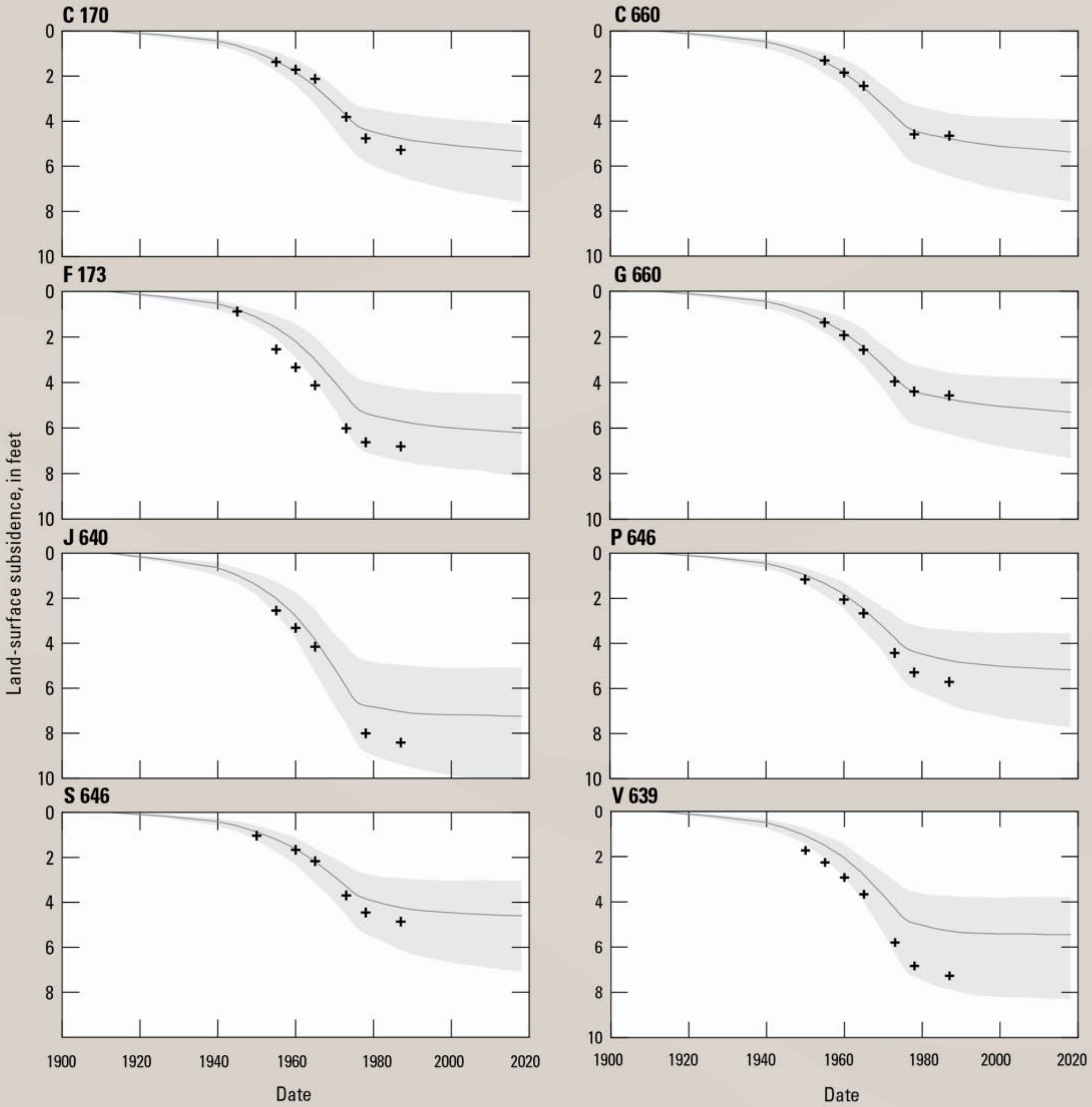


Subsidence

Observed and simulated results

- The range of simulated subsidence generally brackets the historical observations
- In southeast Harris County, some subsidence occurred prior to installation of benchmarks



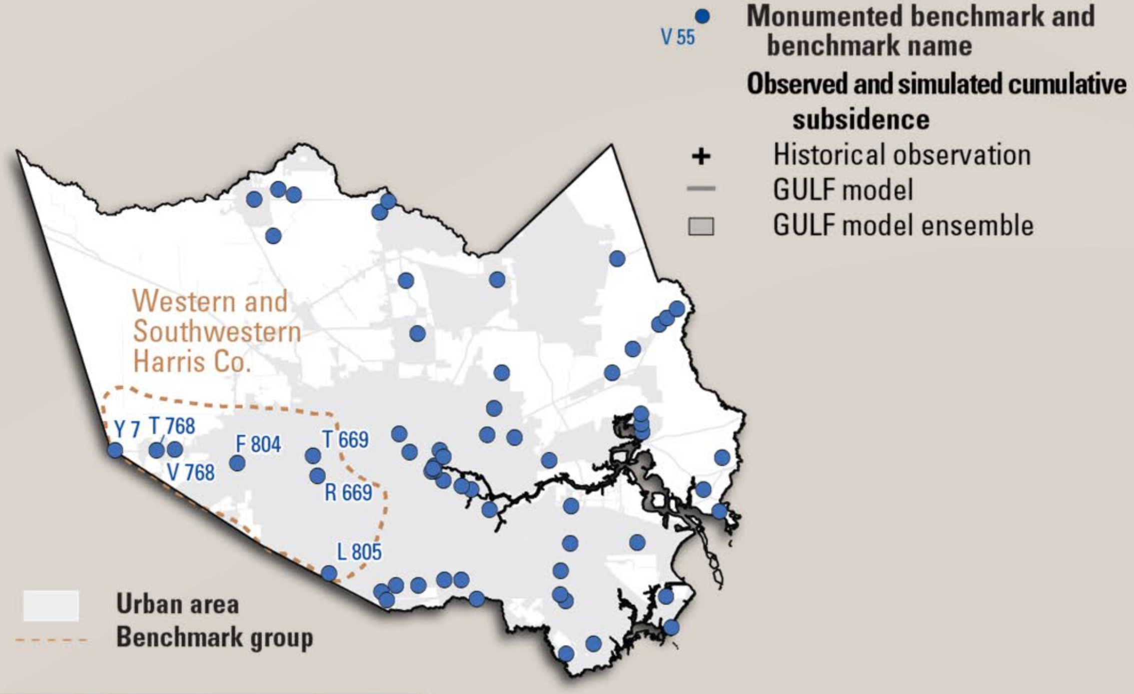


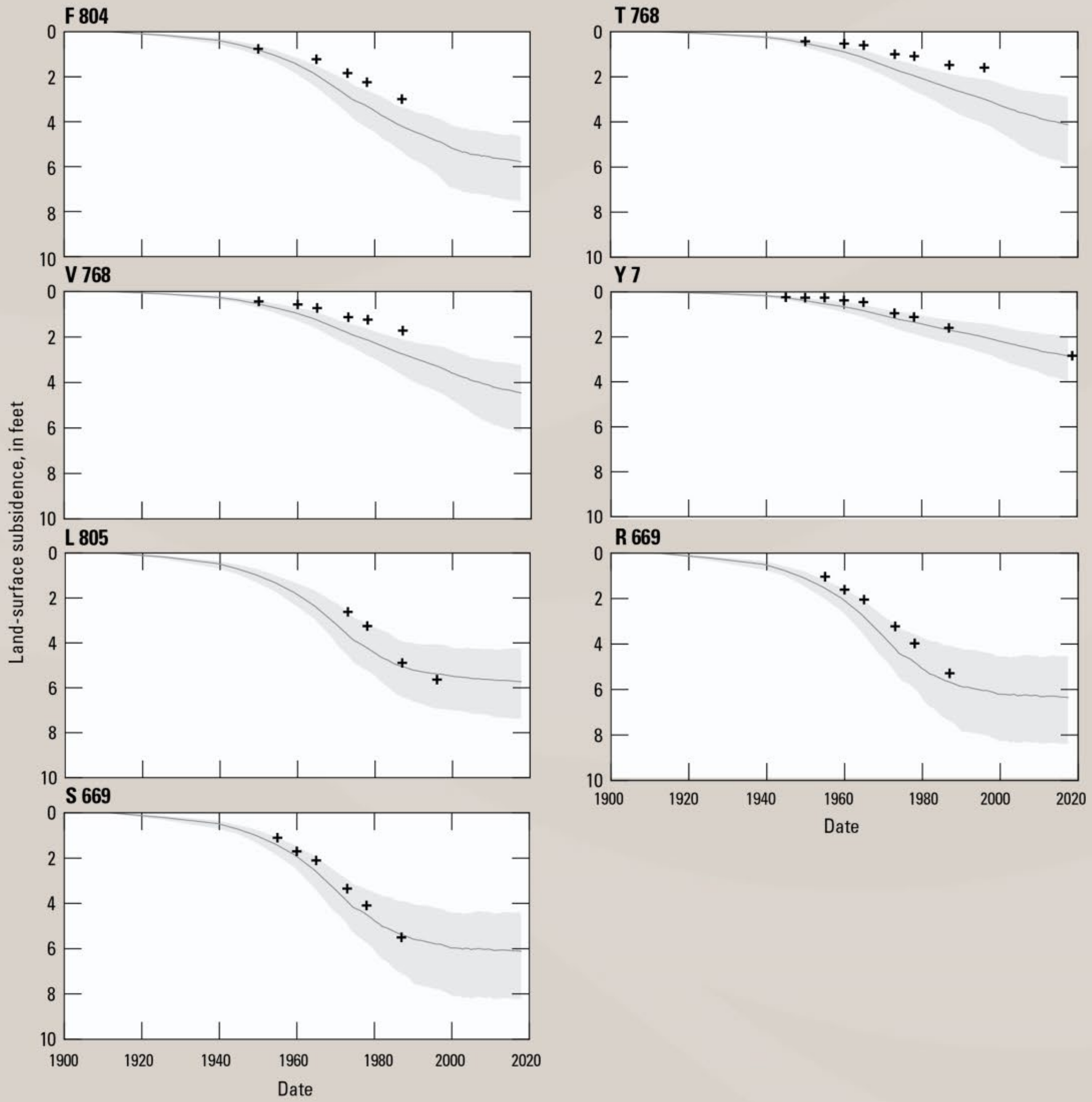
Subsidence

PRELIMINARY RESULTS

Observed and simulated results

- The range of simulated subsidence generally brackets the historical observations

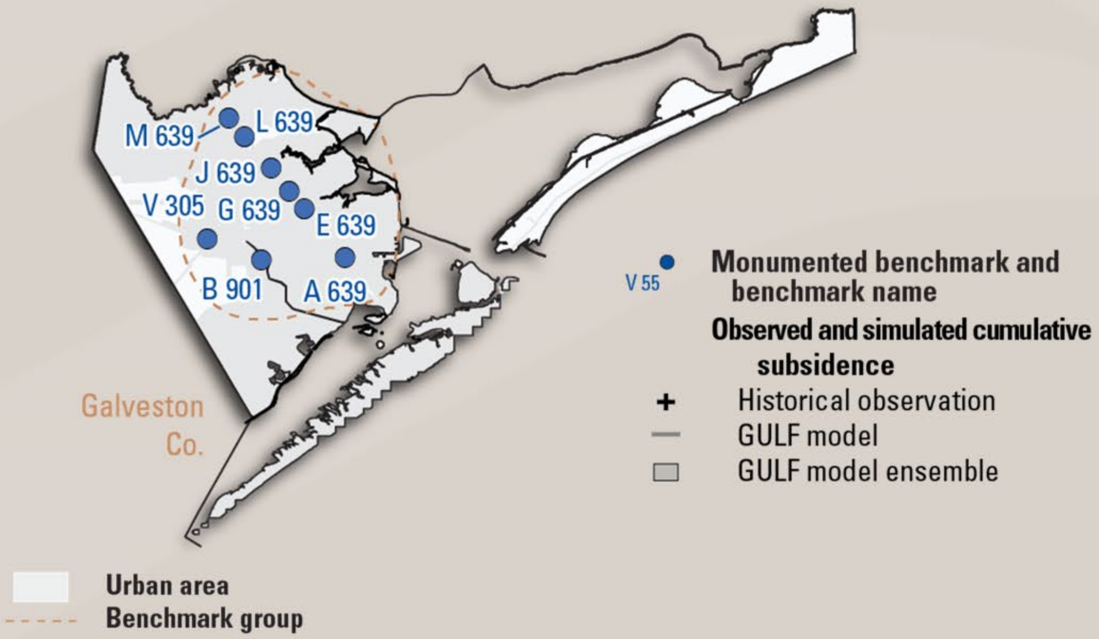


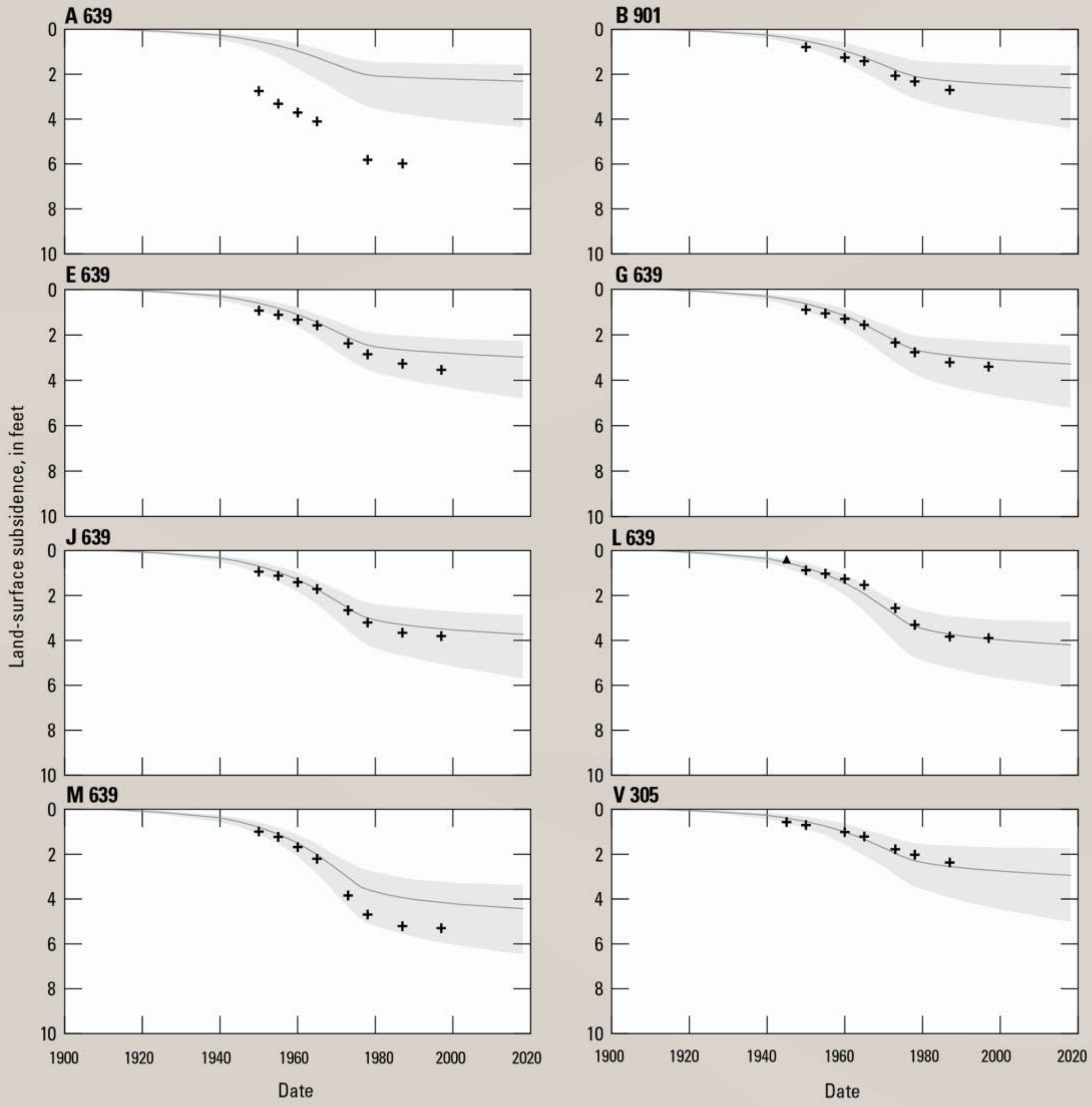


Subsidence

Observed and simulated results

- The range of simulated subsidence generally brackets the historical observations
- Subsidence is undersimulated at benchmark A 639, where subsidence increased substantially over a short distance



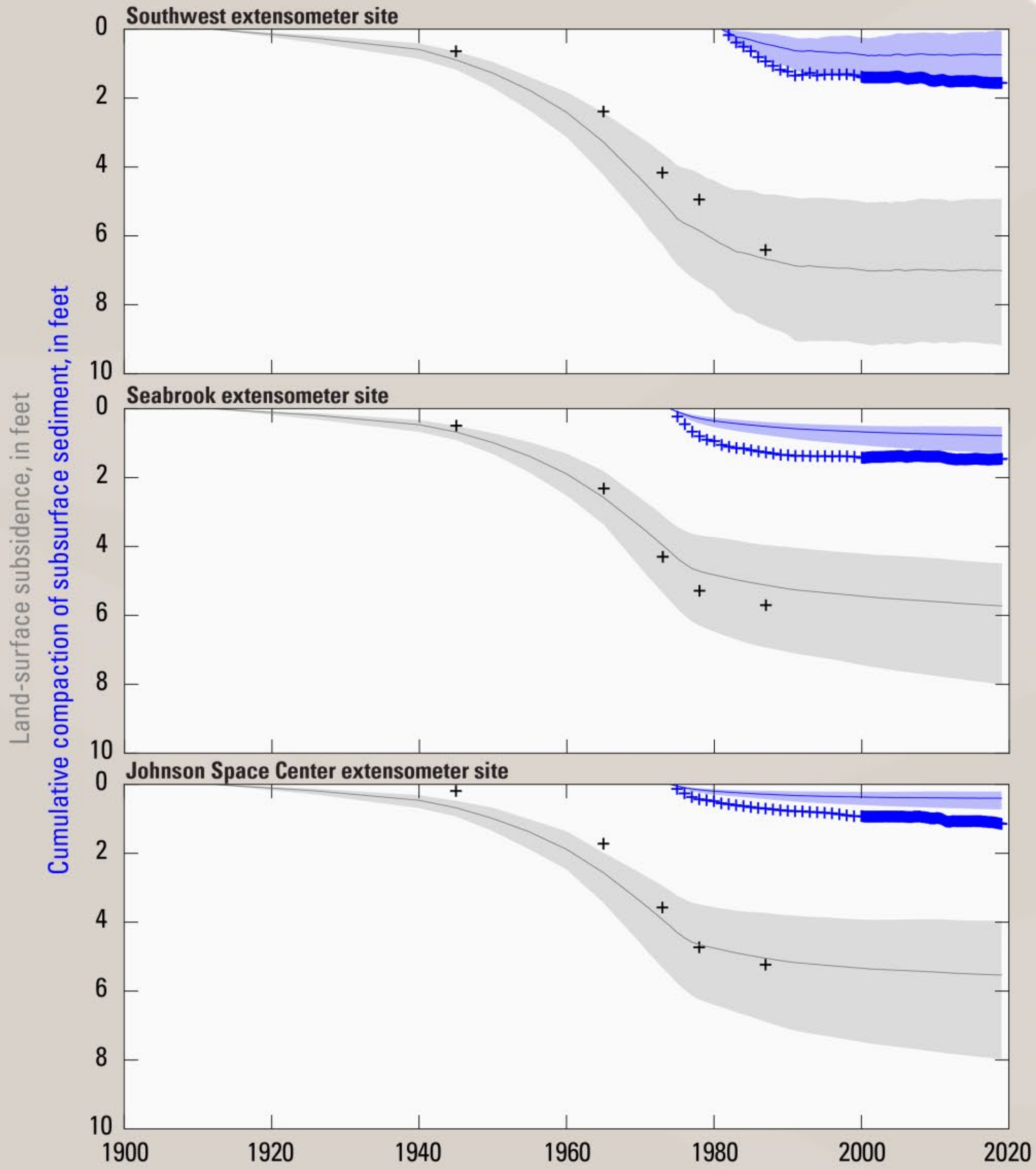


Subsidence

Observed and simulated results

- The range of simulated subsidence and compaction generally brackets the historical observations
- Compaction was undersimulated at some extensometers

Estimated and simulated subsidence, in feet
+ Estimated subsidence
— GULF model
GULF model ensemble
Observed and simulated aquifer-unit compaction, in feet
+ Historical observation
— GULF model
GULF model ensemble

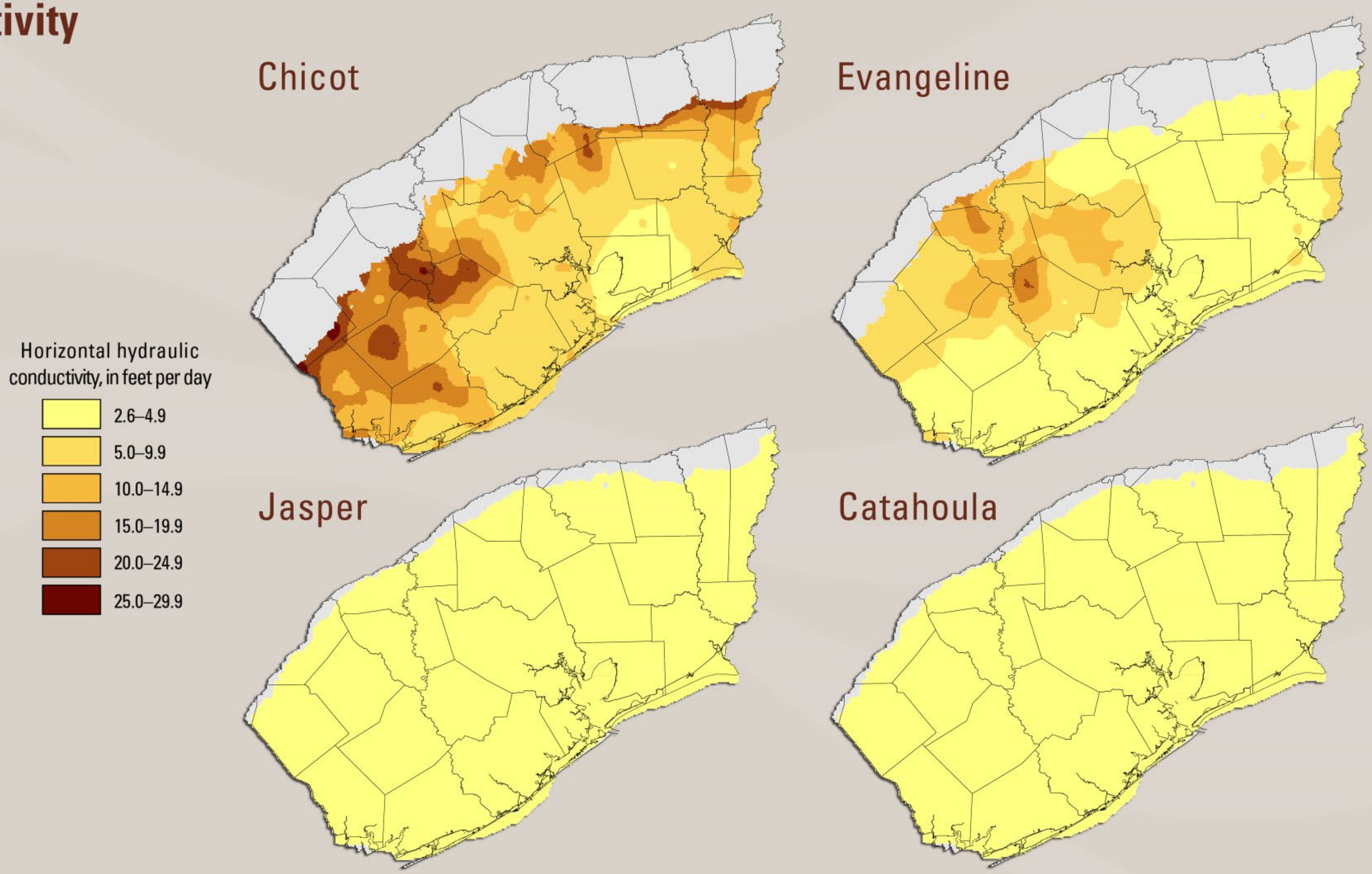


Parameters

PRELIMINARY RESULTS

Horizontal hydraulic conductivity

- Chicot aquifer
  - Mean: 11.1 ft/d
  - 95% range: 4.1–20.0 ft/d
- Evangeline aquifer
  - Mean: 5.4 ft/d
  - 95% range: 2.1–12.9 ft/d
- Jasper aquifer
  - Mean: 0.6 ft/d
  - 95% range: 0.27–1.2 ft/d
- Catahoula confining unit
  - Mean: 1.8 ft/d
  - 95% range: 1.0–3.0 ft/d

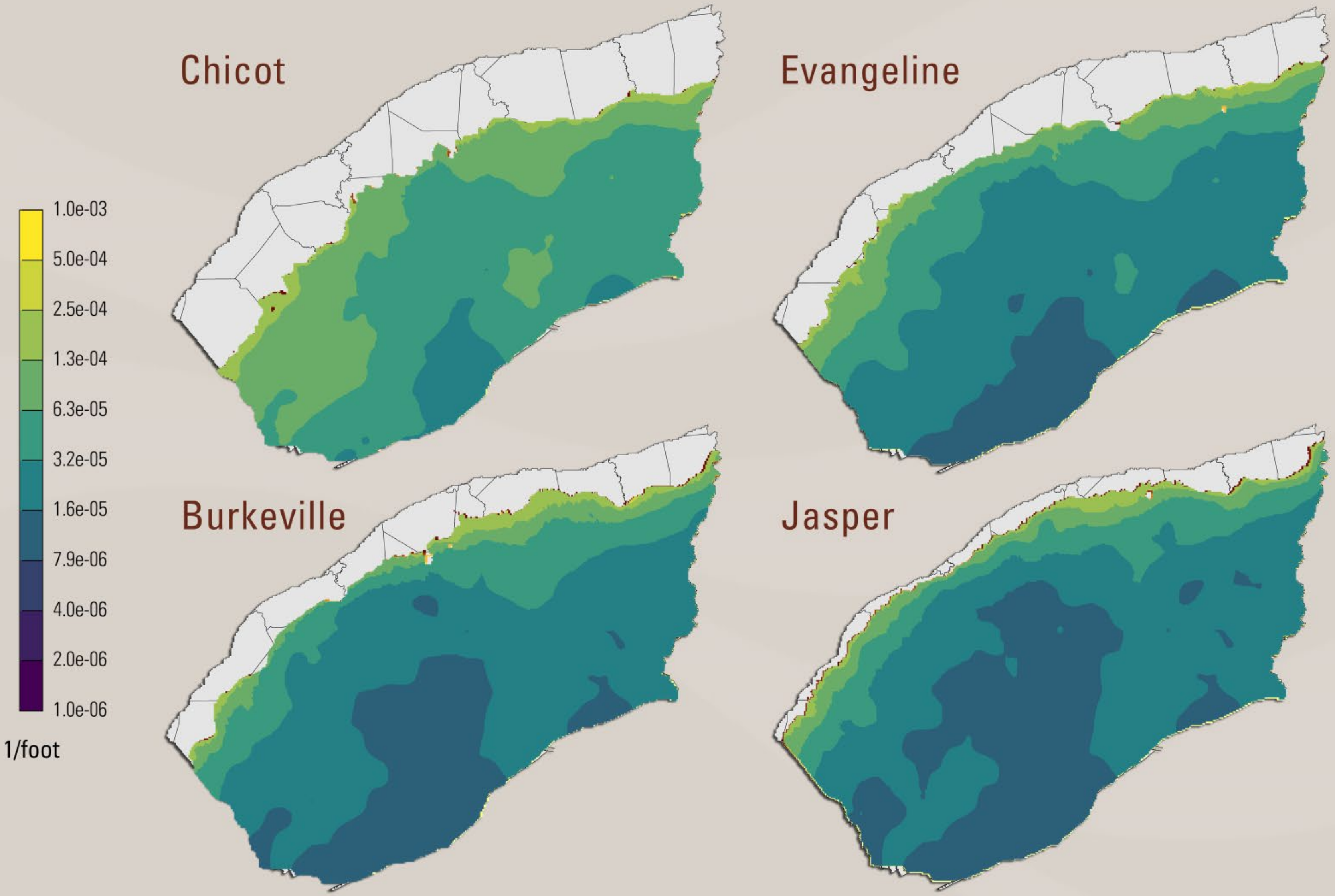


Parameters

PRELIMINARY RESULTS

Interbed inelastic spec. storage

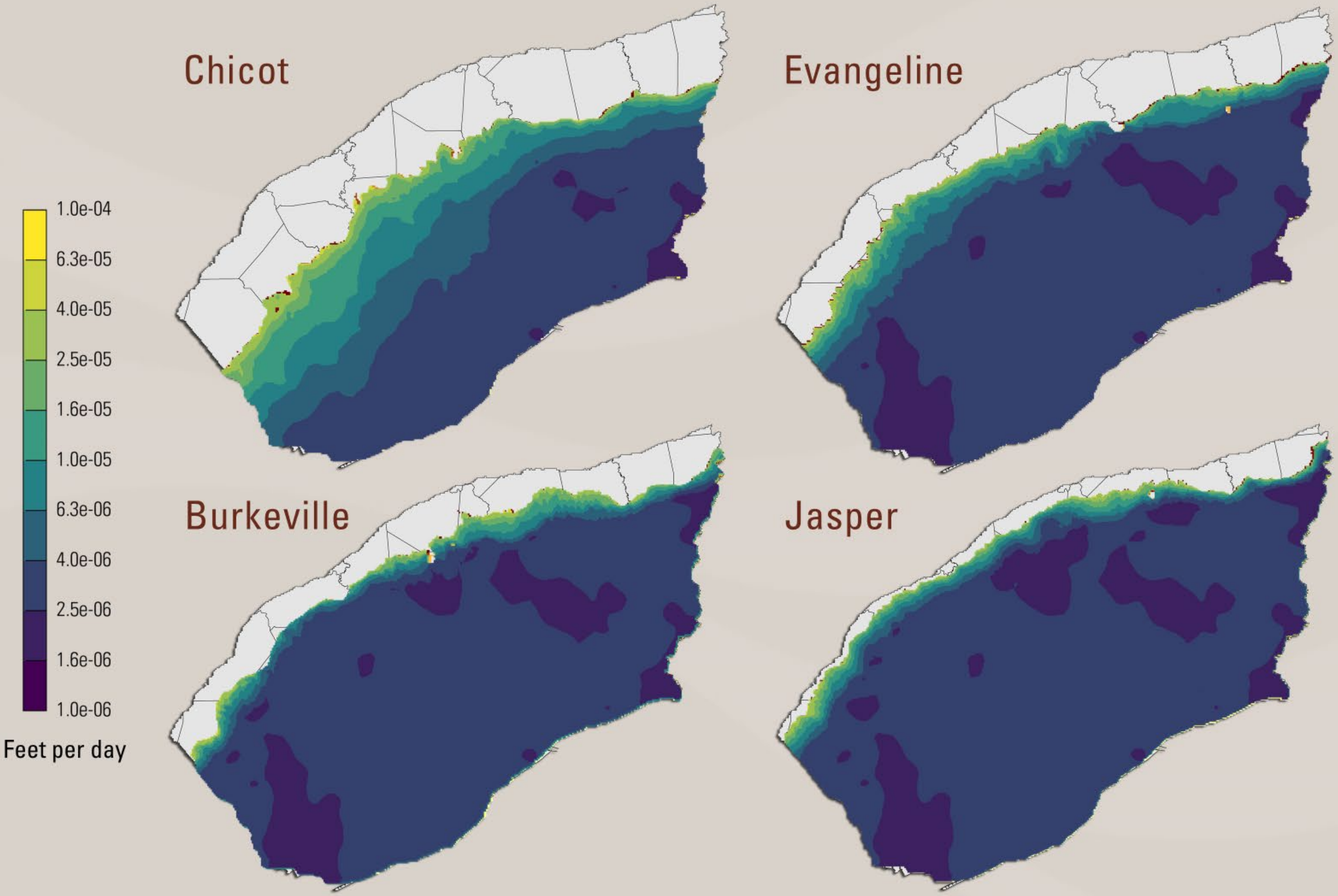
- Chicot aquifer
  - Mean: $6.2E^{-5}$ ft^{-1}
- Evangeline aquifer
  - Mean: $3.7E^{-5}$ ft^{-1}
- Burkeville confining unit
  - Mean: $3.2E^{-5}$ ft^{-1}
- Jasper aquifer
  - Mean: $3.0E^{-5}$ ft^{-1}



Parameters

Interbed vertical hydraulic conductivity

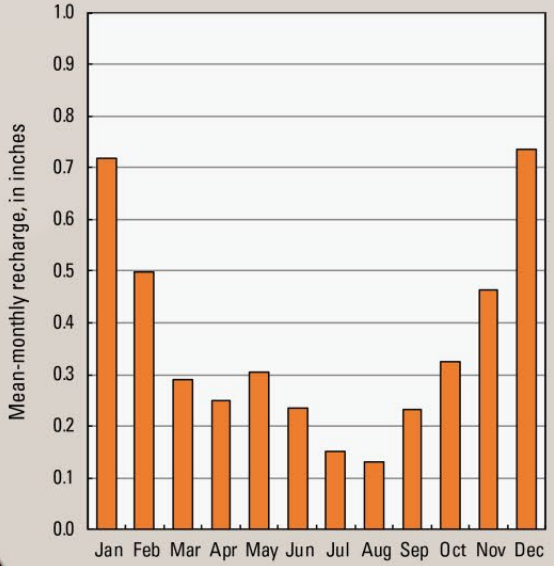
- Chicot aquifer
  - Mean: $6.6E^{-6}$ ft/d
- Evangeline aquifer
  - Mean: $4.3E^{-6}$ ft/d
- Burkeville confining unit
  - Mean: $3.9E^{-6}$ ft/d
- Jasper aquifer
  - Mean: $3.9E^{-6}$ ft/d

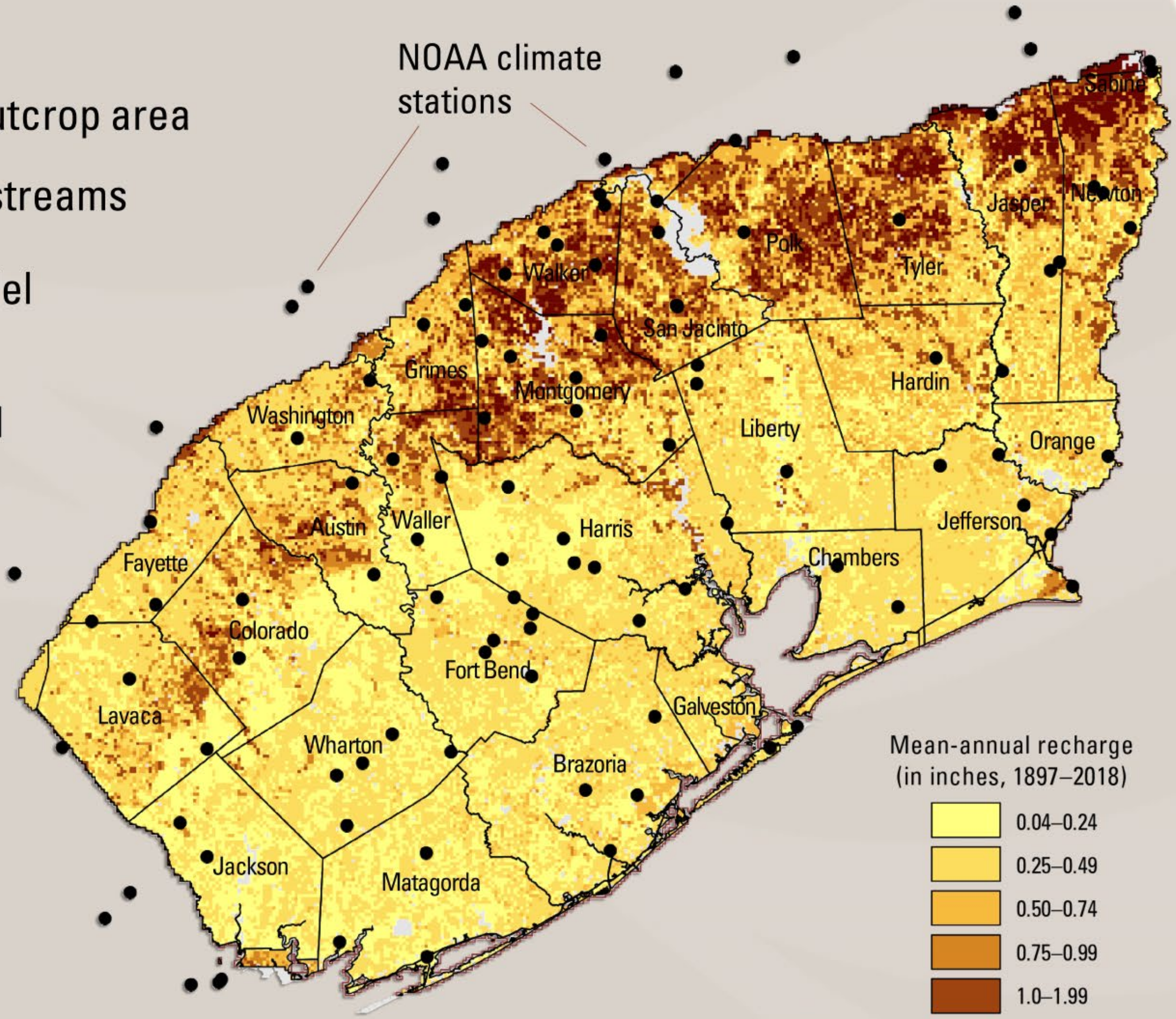


Recharge

Calibrated recharge

- SWB-derived recharge occurs primarily in aquifer outcrop area
- Majority of the estimated recharge is discharged to streams
- Spatially-distributed recharge at right applied to model layer 1.
- Deep recharge (next slide) is net flux between layer 1 and underlying layers





Recharge

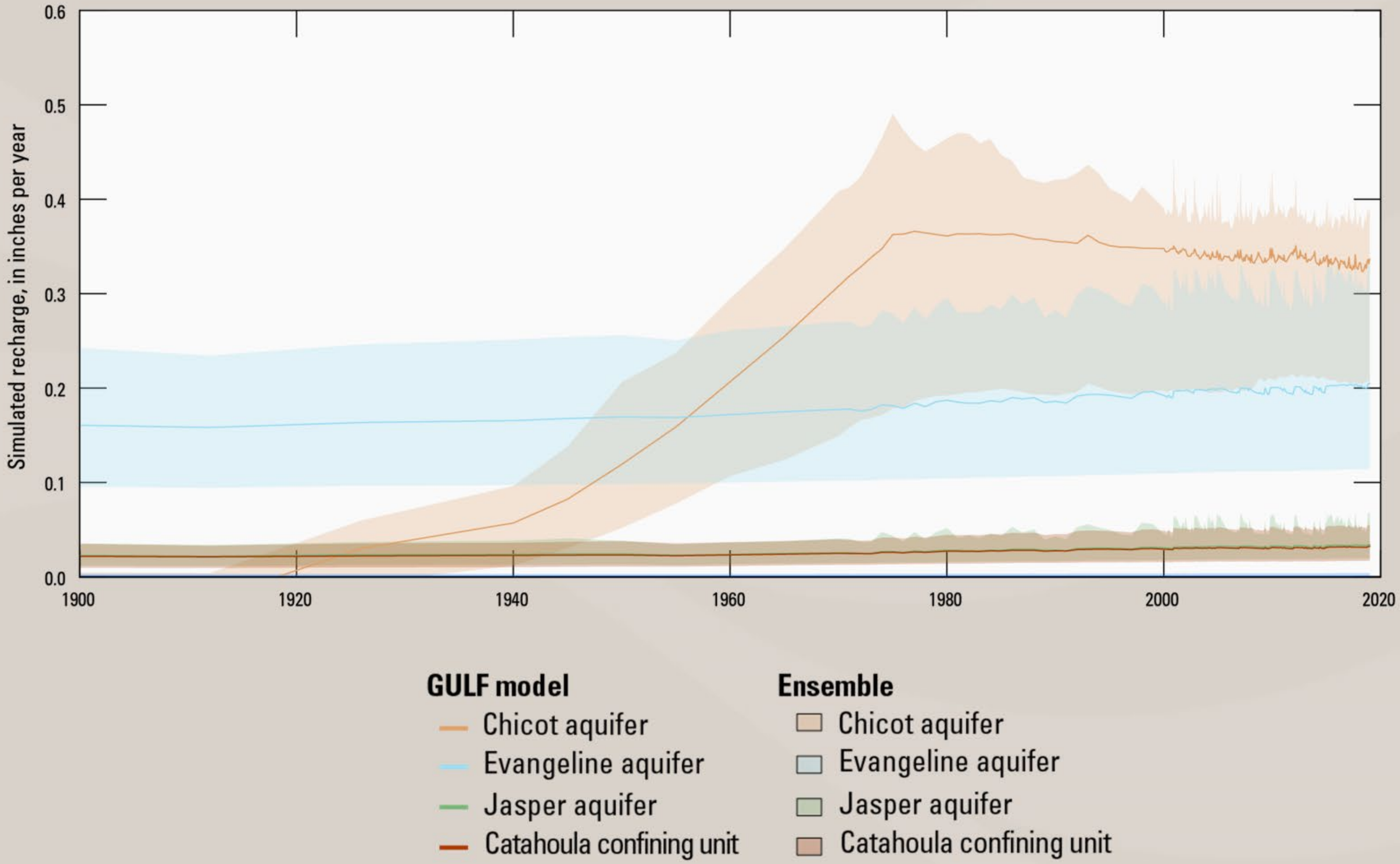
PRELIMINARY RESULTS

Deep recharge (mean annual):

- Chicot: 0.31 inches
- Evangeline: 0.19 inches
- Jasper: 0.03 inches
- Catahoula: 0.03 inches

Comparison:

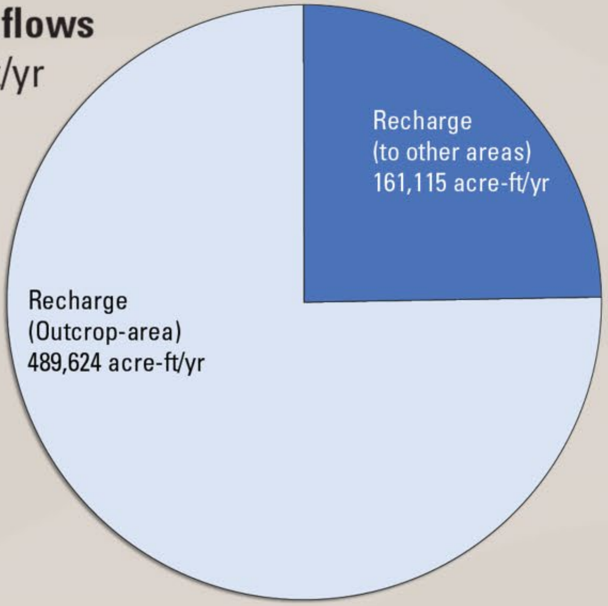
- Chicot:
  - HAGM: 0.56 inches (2009)
  - NGC-GAM: 0.4, 0.55 inches (1977, 2000)
- Evangeline:
  - HAGM: 0.23 inches (2009)
  - NGC-GAM: 0.12, 0.11 inches (1977, 2000)
- Jasper
  - HAGM: 0.07 inches (2009)
  - NGC-GAM: 0.06, 0.07 inches (1977, 2000)



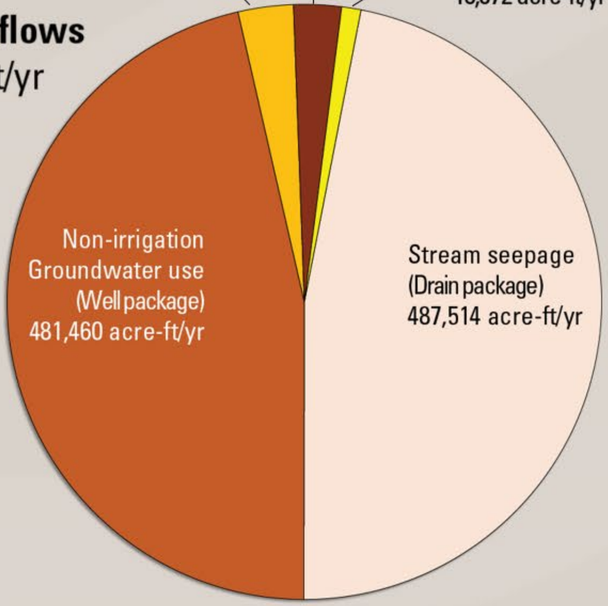
Water Budget

PRELIMINARY RESULTS

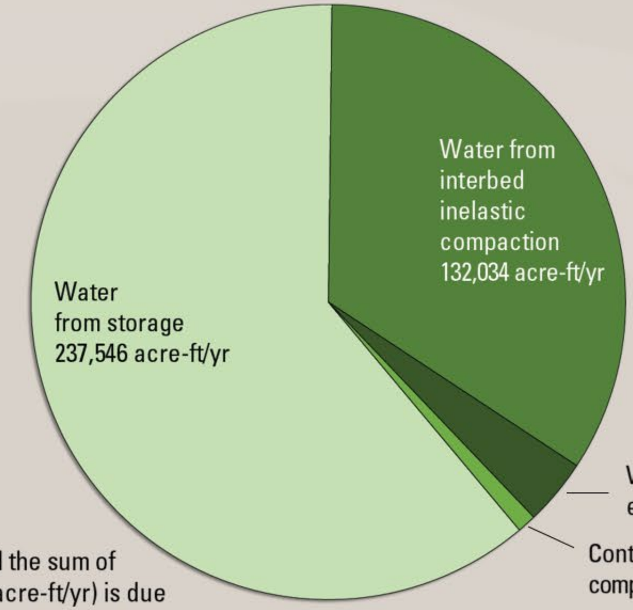
GULF model inflows
650,739 acre-ft/yr



GULF model outflows
1,037,903 acre-ft/yr



GULF model change in storage
Total: 387,501 acre-ft/yr



The difference between the outflows and the sum of the inflows and change in storage (337 acre-ft/yr) is due to water from interbed elastic compaction and solver error

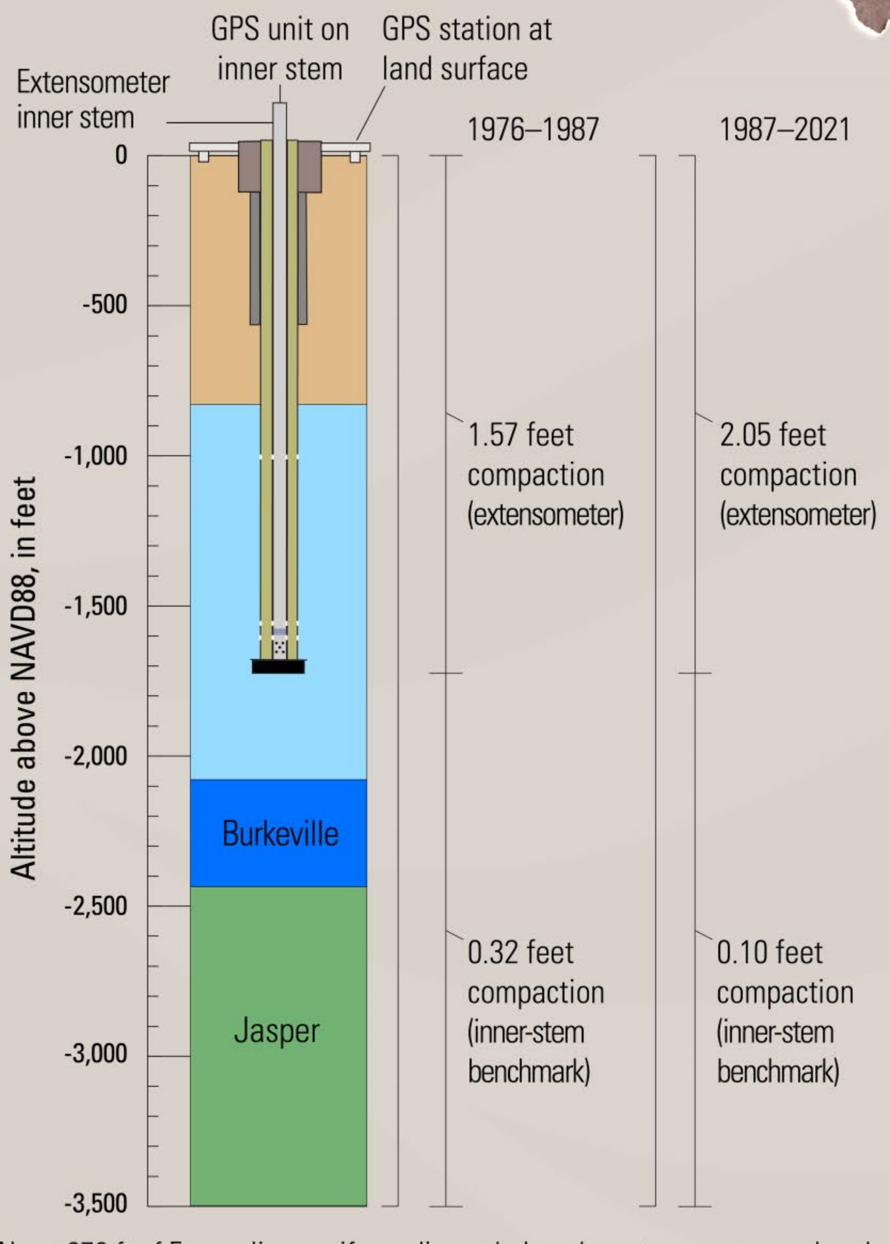
Deep-seated compaction

PRELIMINARY RESULTS

Addicks extensometer

- Cumulative compaction of 0.37–0.42 ft in sediment below the extensometer inner stem between 1978 and 2021.

1976–87		1987–2021	
K 1226:	1.86 ft subsidence	K 1226:	NA ft subsidence
Extensometer:	1.57 ft compaction	Extensometer:	2.05 ft compaction
Inner stem BM:	0.32 ft compaction	Inner Stem BM:	0.10 ft compaction



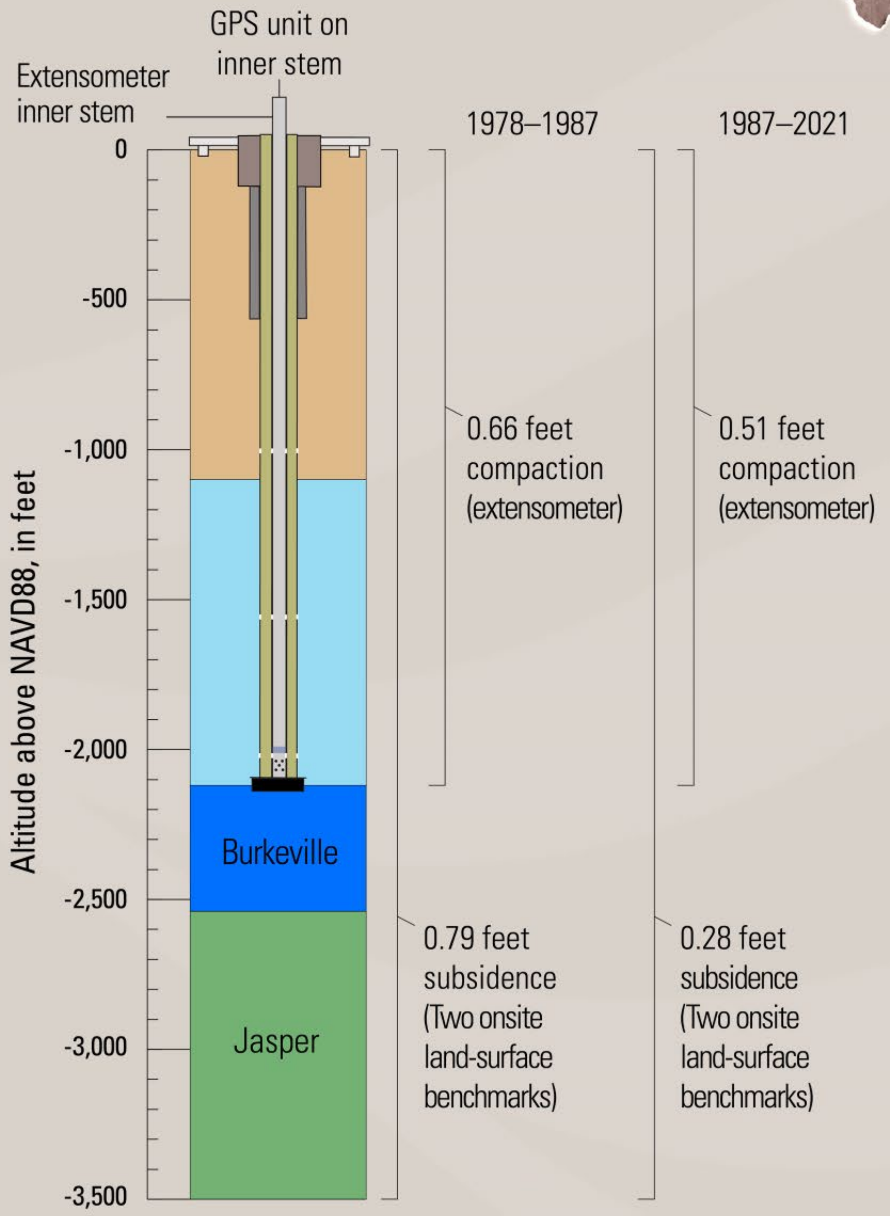
About 370 ft of Evangeline aquifer sediment below the extensometer anchor depth

Deep-seated compaction

Northeast extensometer

- Net compaction of zero in sediment below the extensometer inner stem between 1978 and 2021.

1978–87		1987–2021	
W 1278 | V 1278:	0.79 ft subsidence	W 1278 | V 1278:	0.28 ft subsidence
Extensometer:	0.66 ft compaction	Extensometer:	0.51 ft compaction
Deep interval:	0.13 ft compaction	Inner stem BM:	-0.14 ft compaction

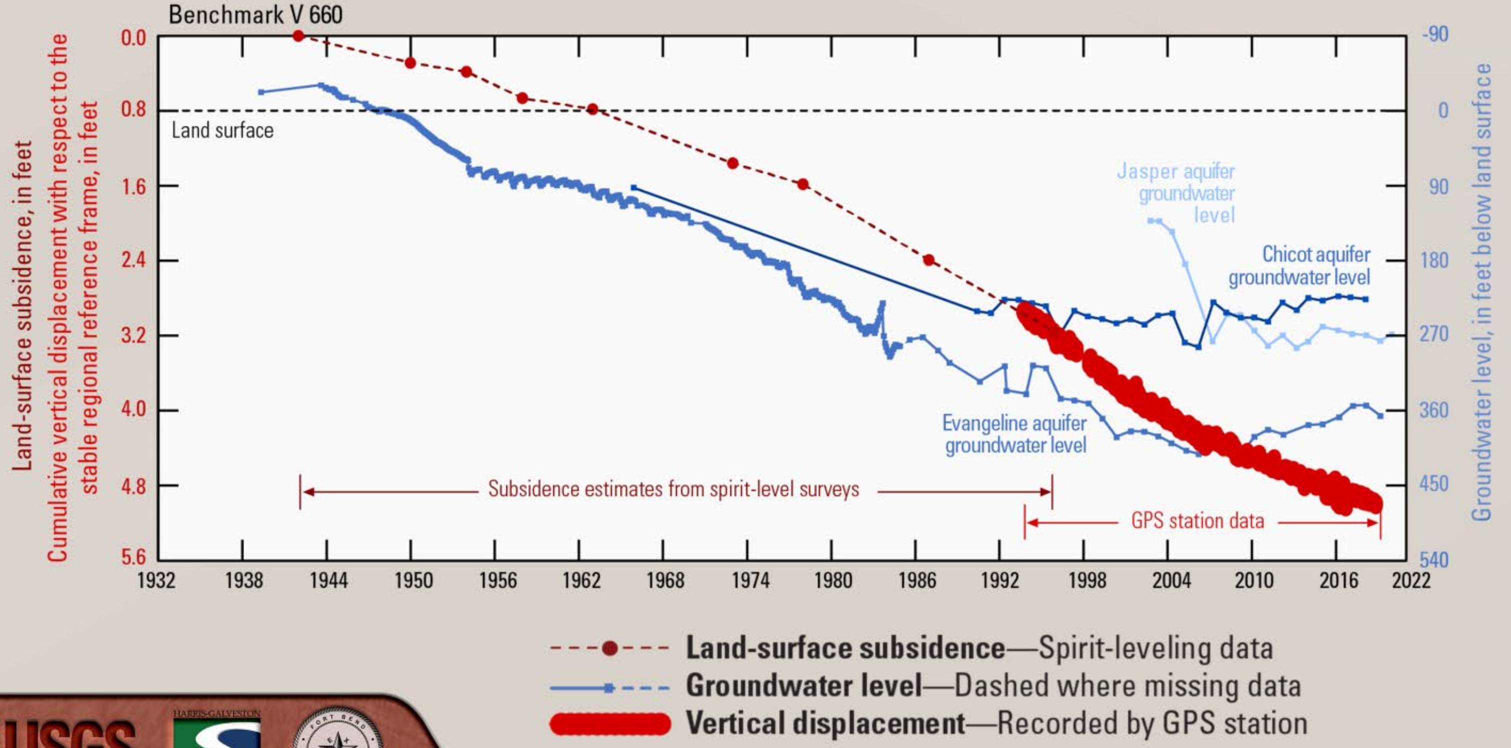


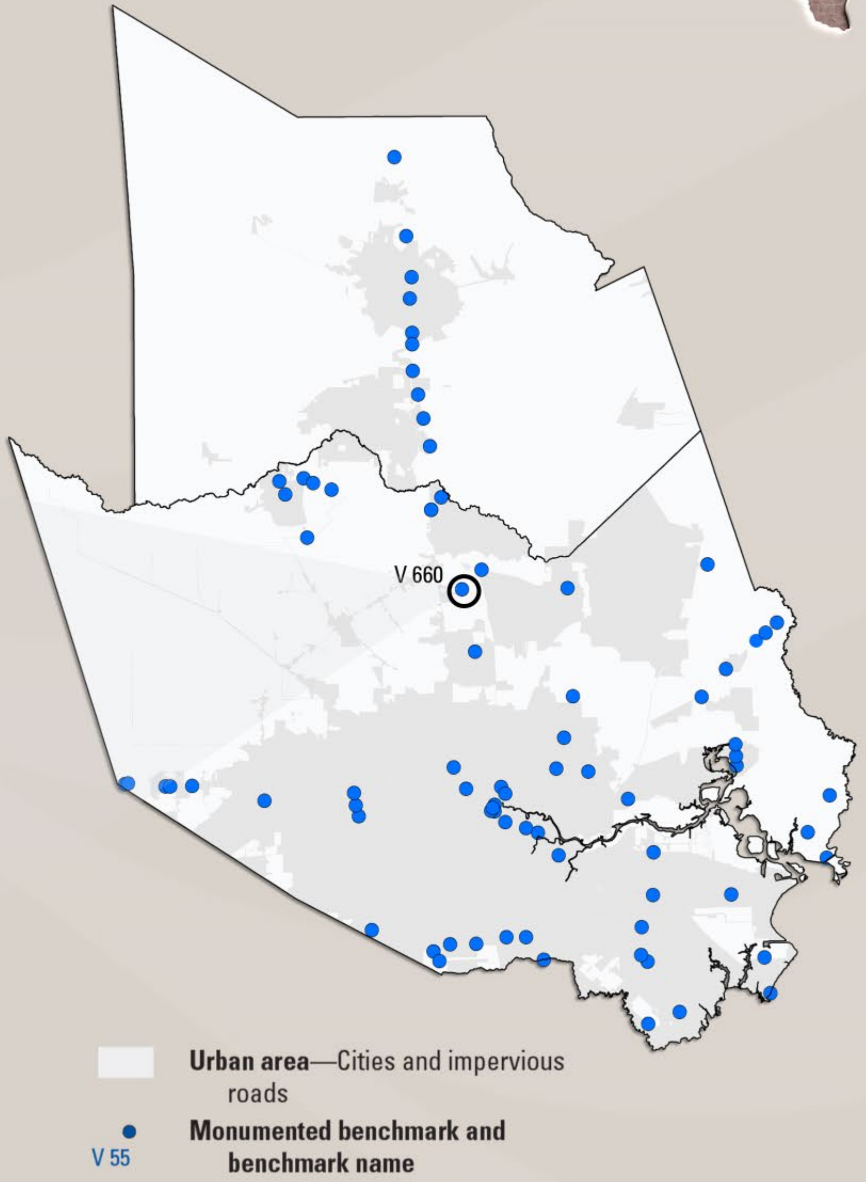
Chicot | Evangeline | Burkeville | Jasper

Cumulative subsidence

PRELIMINARY RESULTS

- Benchmark V 660: 5.2 feet of subsidence through 2021
- Similarities between water level declines and subsidence from 1943 to 1996.
- After 1996, residual compaction occurring due to water levels remaining near historical minimums



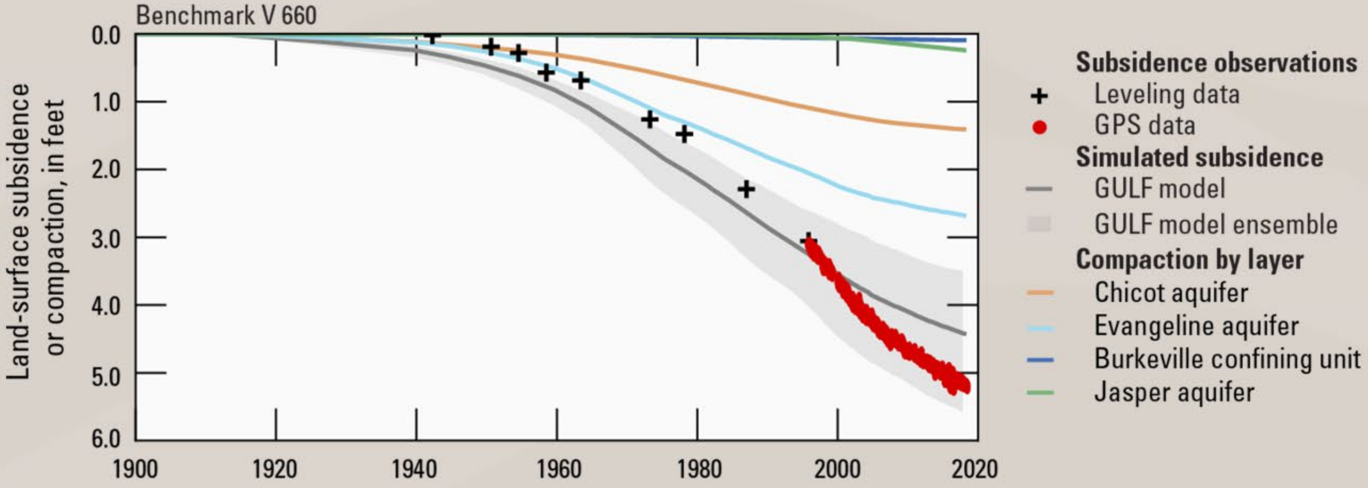


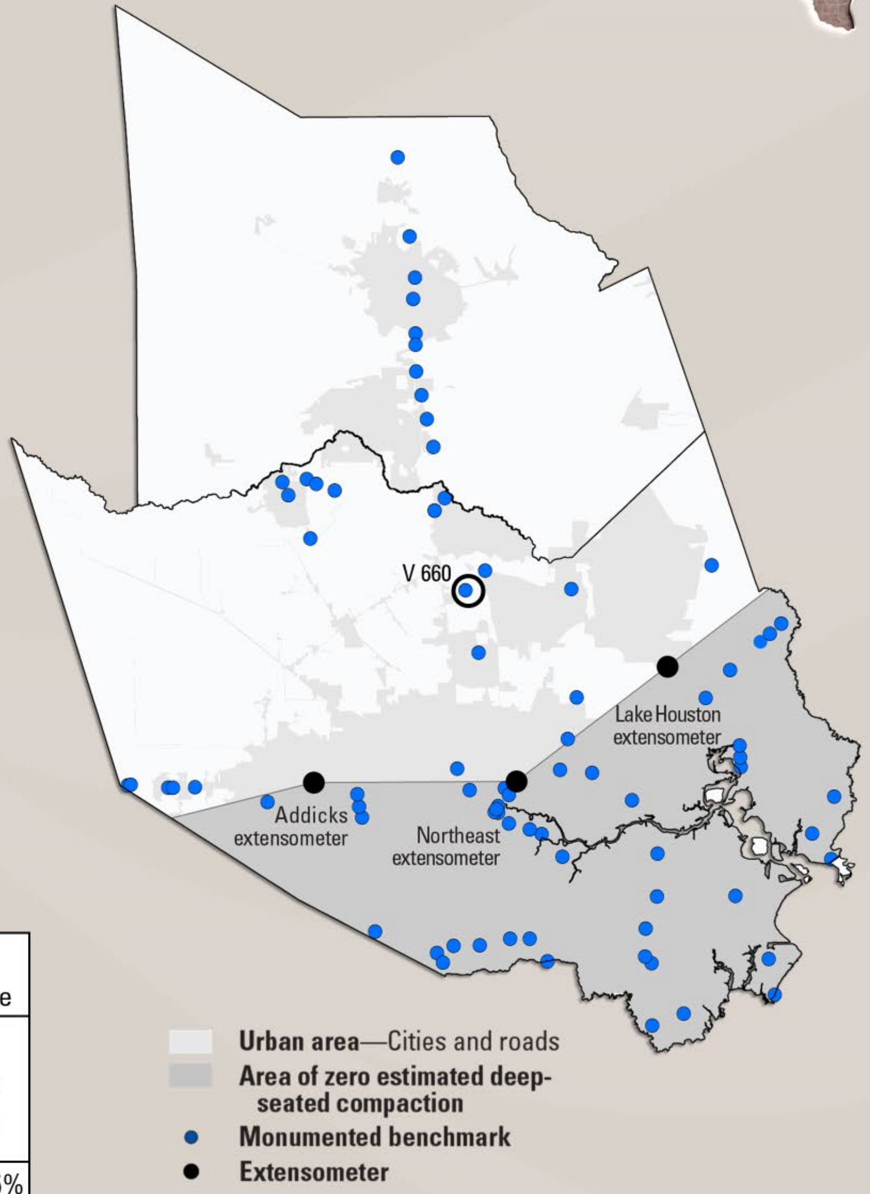
Cumulative compaction

PRELIMINARY RESULTS

Simulated Jasper aquifer compaction – V 660

- 0.2 feet, or 5 percent of simulated subsidence
- The top of the Jasper aquifer in this area is at -1,650 feet above NAVD 88
- Similar to the Clear Lake extensometer, where only 3 percent of compaction occurs below -1,722 feet above NAVD 88



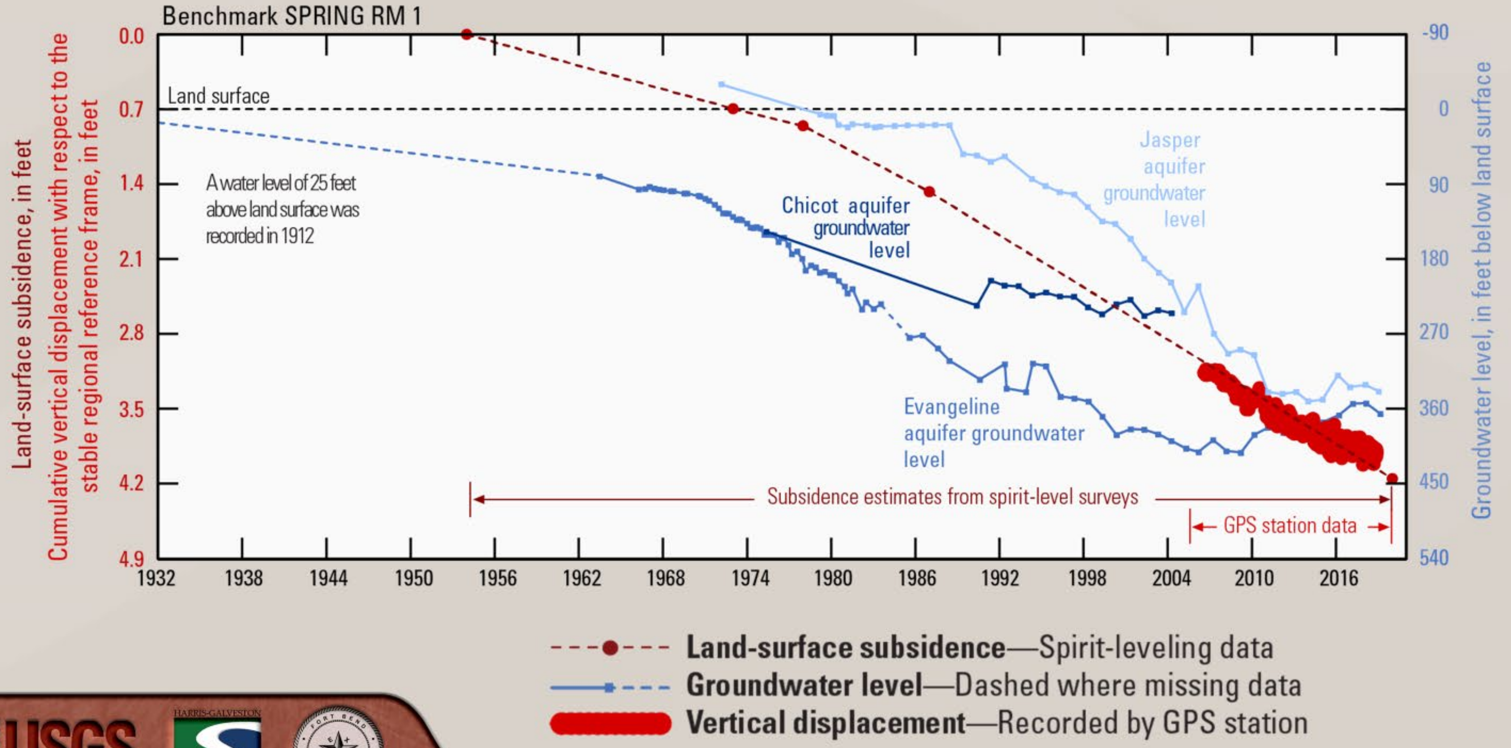


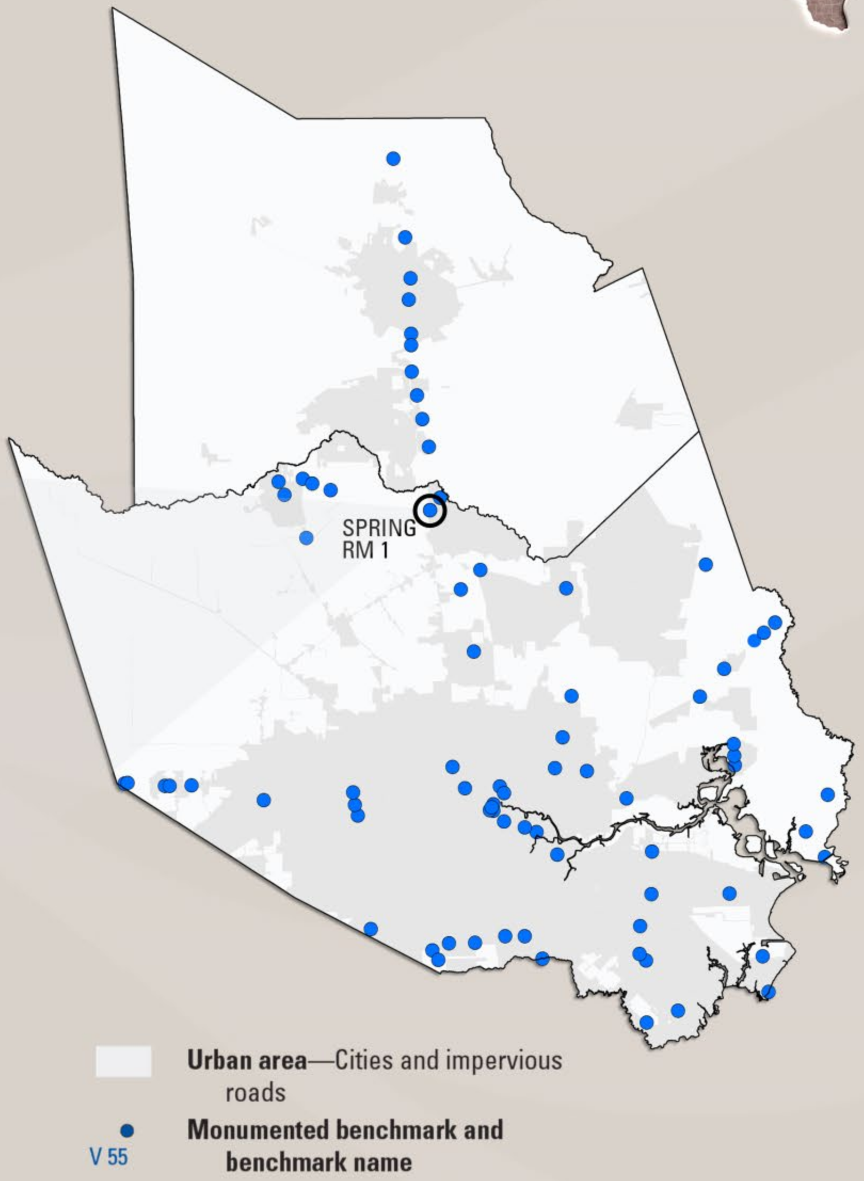
Benchmark	County	Simulated hydrogeologic unit compaction as a percentage of simulated land-surface subsidence			
		Layer 2 (Chicot aquifer)	Layer 3 (Evangeline aquifer)	Layer 4 (Burkeville confining unit)	Layer 5 (Jasper aquifer)
V 660	Harris	32%	61%	2%	5%

Cumulative subsidence

PRELIMINARY RESULTS

- Benchmark SPRING RM 1: 4.2 feet of subsidence through 2021
- Subsidence not expected at this site prior to 1954 based on leveling data at a nearby benchmark
- Greater Jasper aquifer groundwater-level decline compared to benchmark V 660

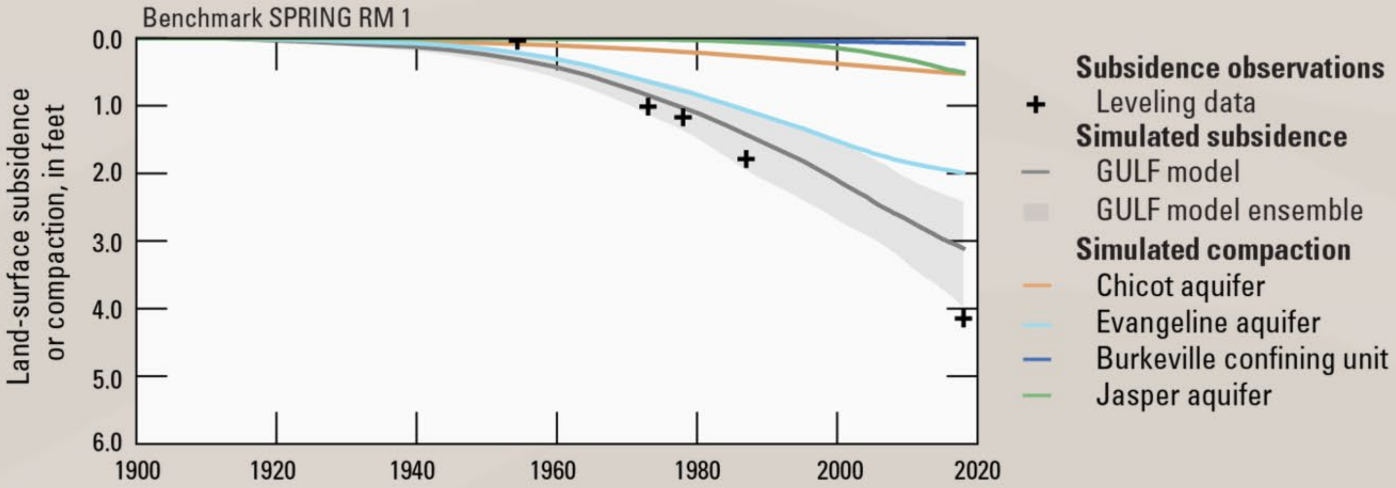


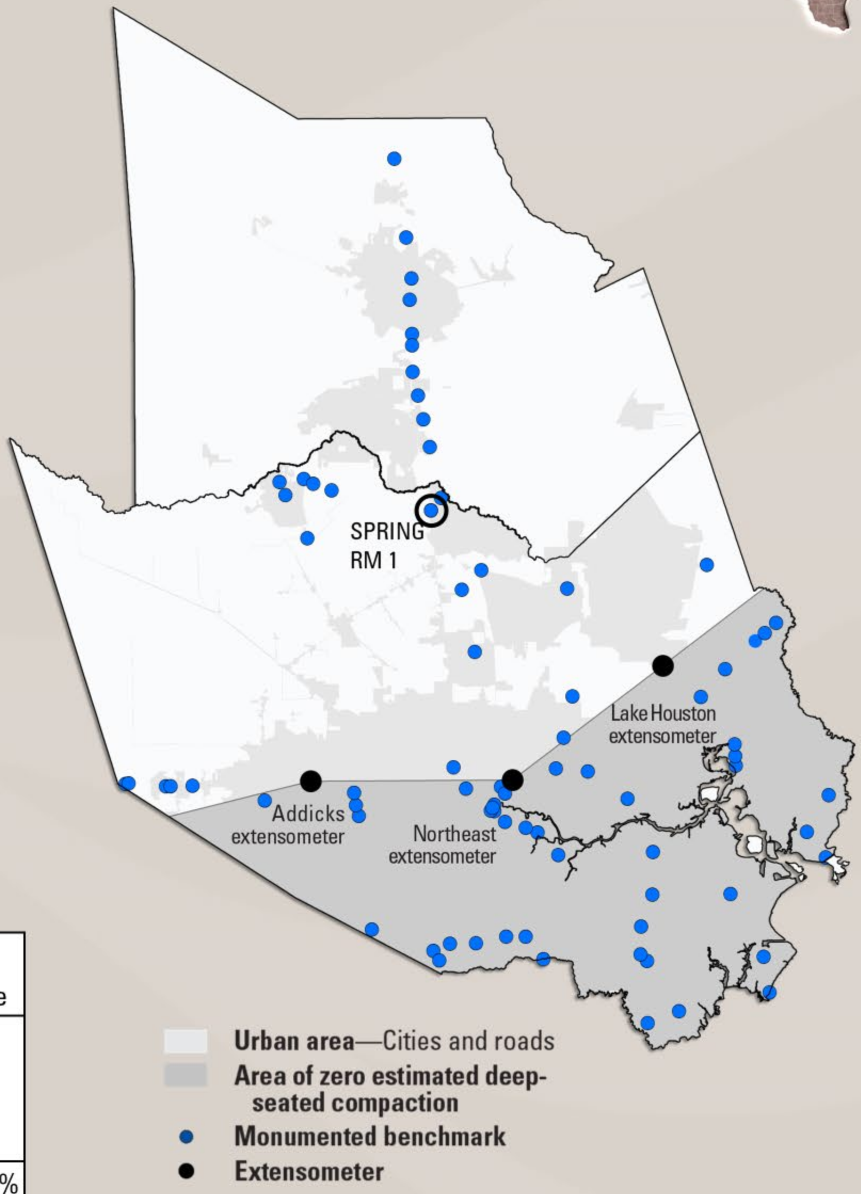


Cumulative compaction

Simulated Jasper aquifer compaction – SPRING RM 1

- 0.5 feet, or 16 percent of simulated subsidence
- The top of the Jasper aquifer in this area is at -1,350 feet above NAVD 88, or 300 feet shallower than at benchmark V 660



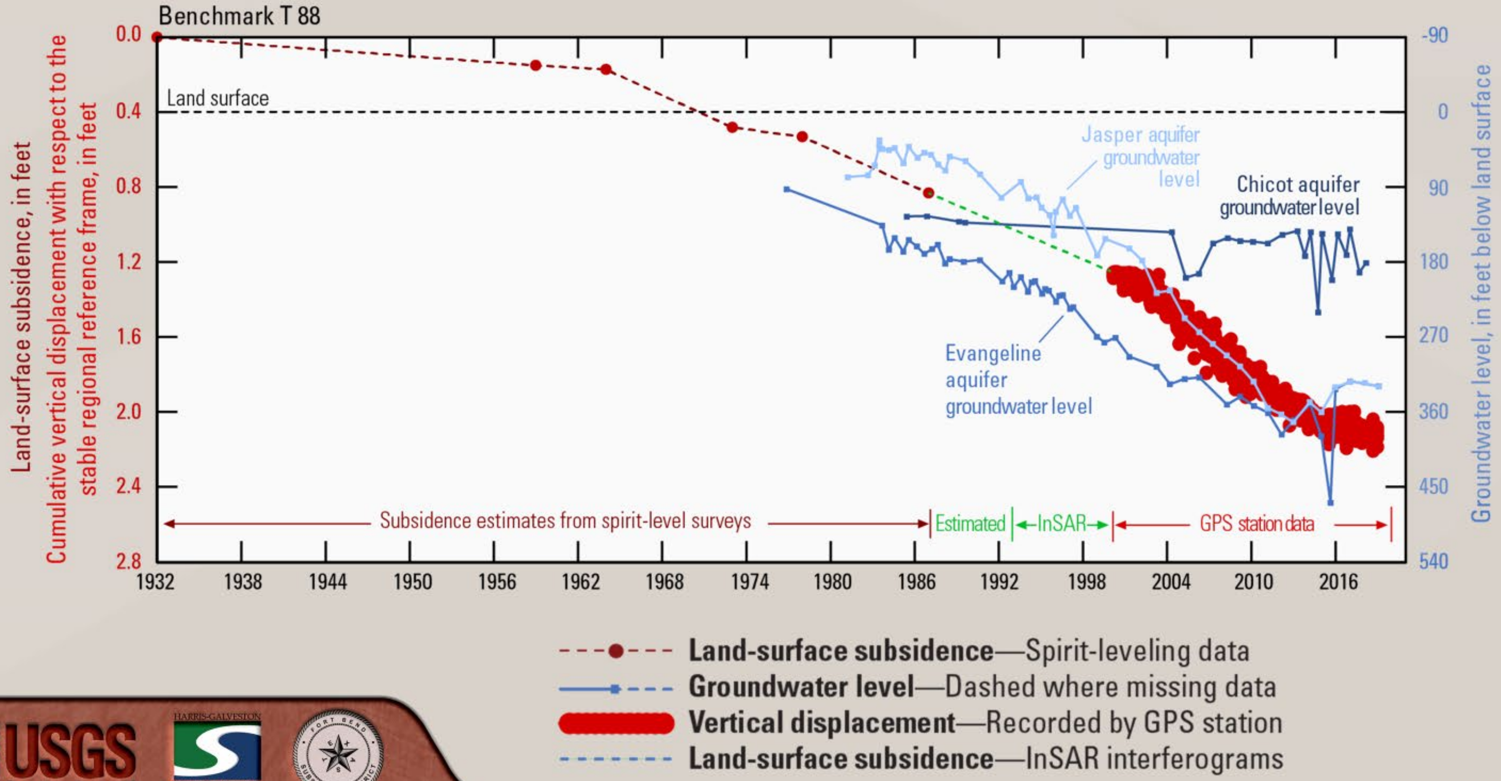


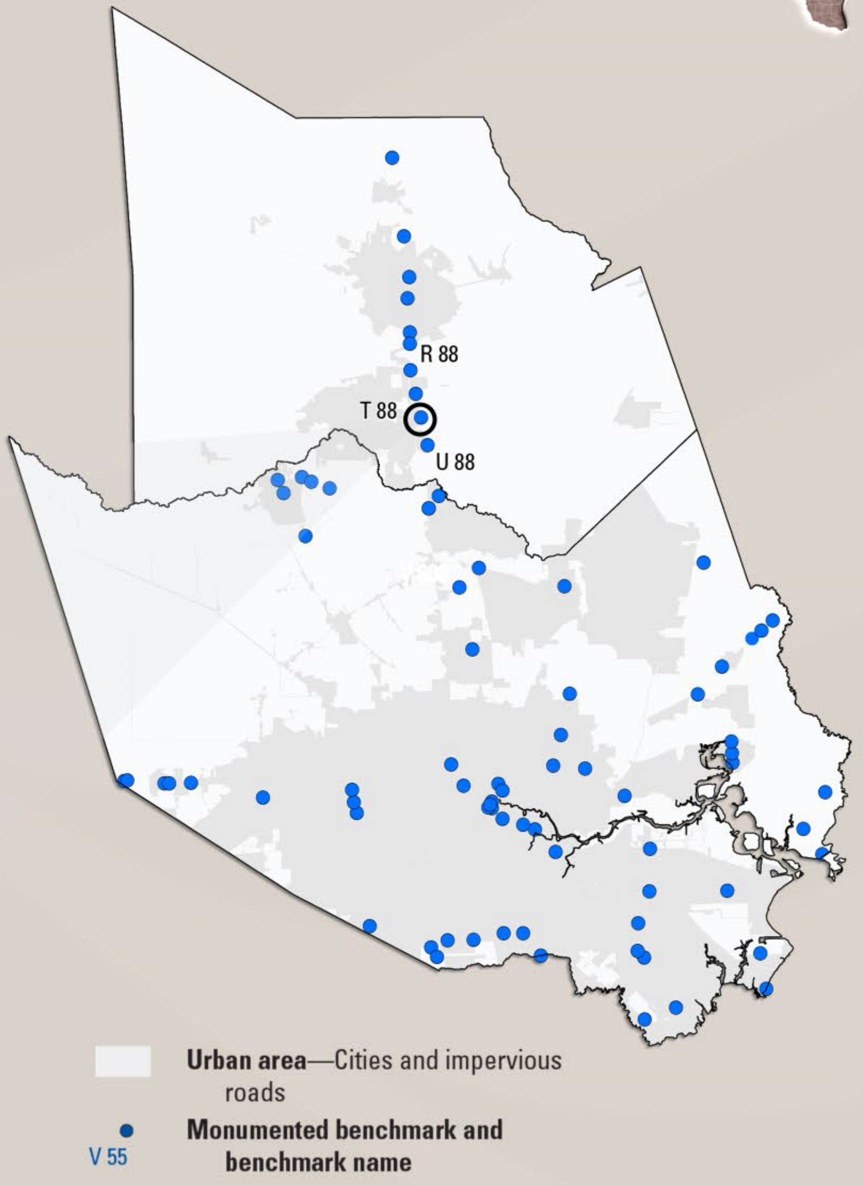
Benchmark	County	Simulated hydrogeologic unit compaction as a percentage of simulated land-surface subsidence			
		Layer 2 (Chicot aquifer)	Layer 3 (Evangeline aquifer)	Layer 4 (Burkeville confining unit)	Layer 5 (Jasper aquifer)
SPRING RM 1	Harris	16%	65%	3%	16%

Cumulative subsidence

PRELIMINARY RESULTS

- Benchmark T 88: 2.2 feet of subsidence through 2021
- Range of estimated subsidence in The Woodlands along I-45:
  - Benchmark R 88: 1.3 feet
  - Benchmark U 88: 2.5 feet
- Similar Jasper aquifer groundwater-level decline compared to benchmark SPRING RM 1

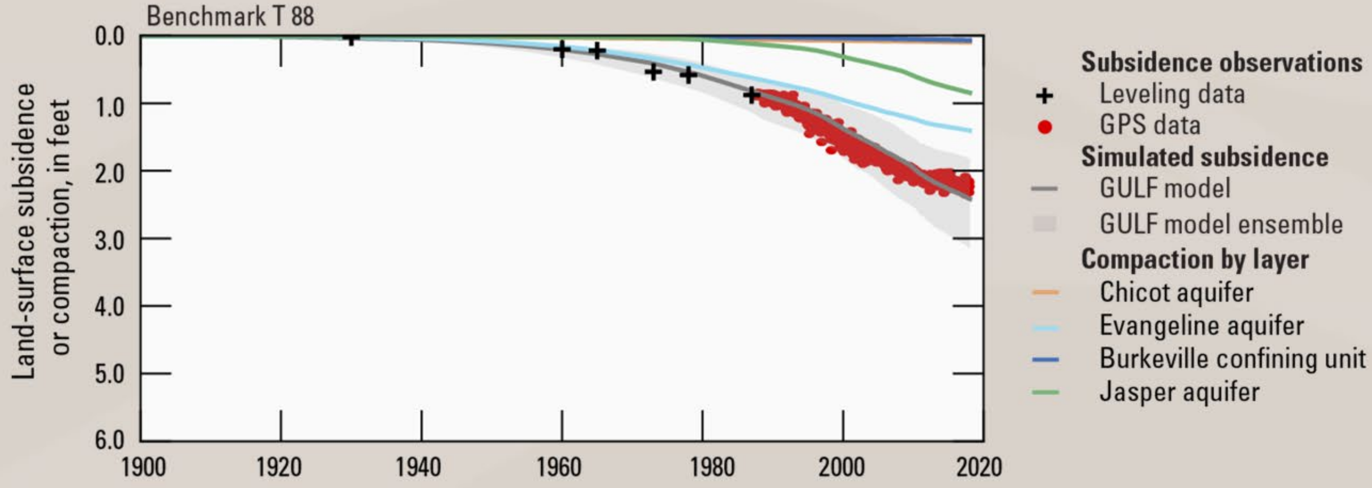


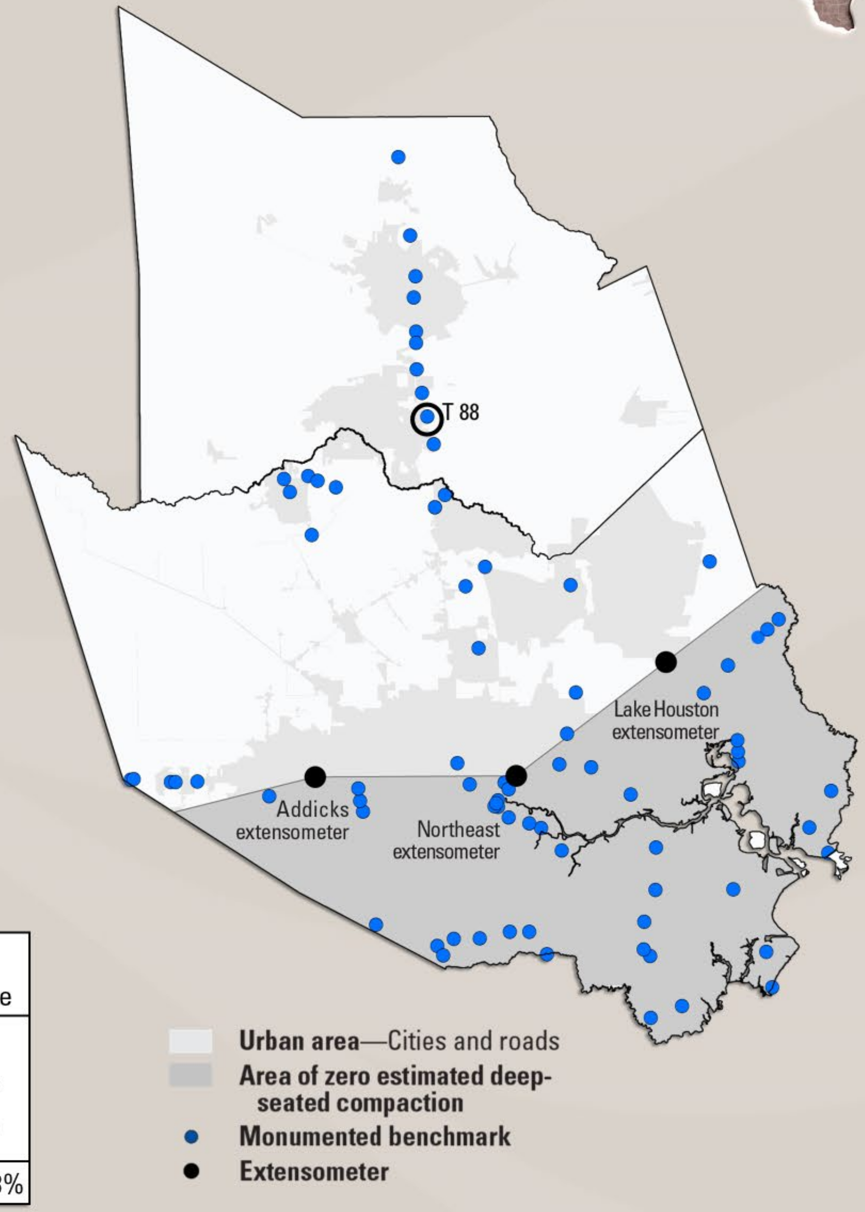


Cumulative compaction

Jasper aquifer compaction – T 88

- 0.8 feet, or 33 percent of simulated subsidence
- The top of the Jasper aquifer in this area is at -1,100 feet above NAVD 88, or about 250 feet shallower than at benchmark SPRING RM 1





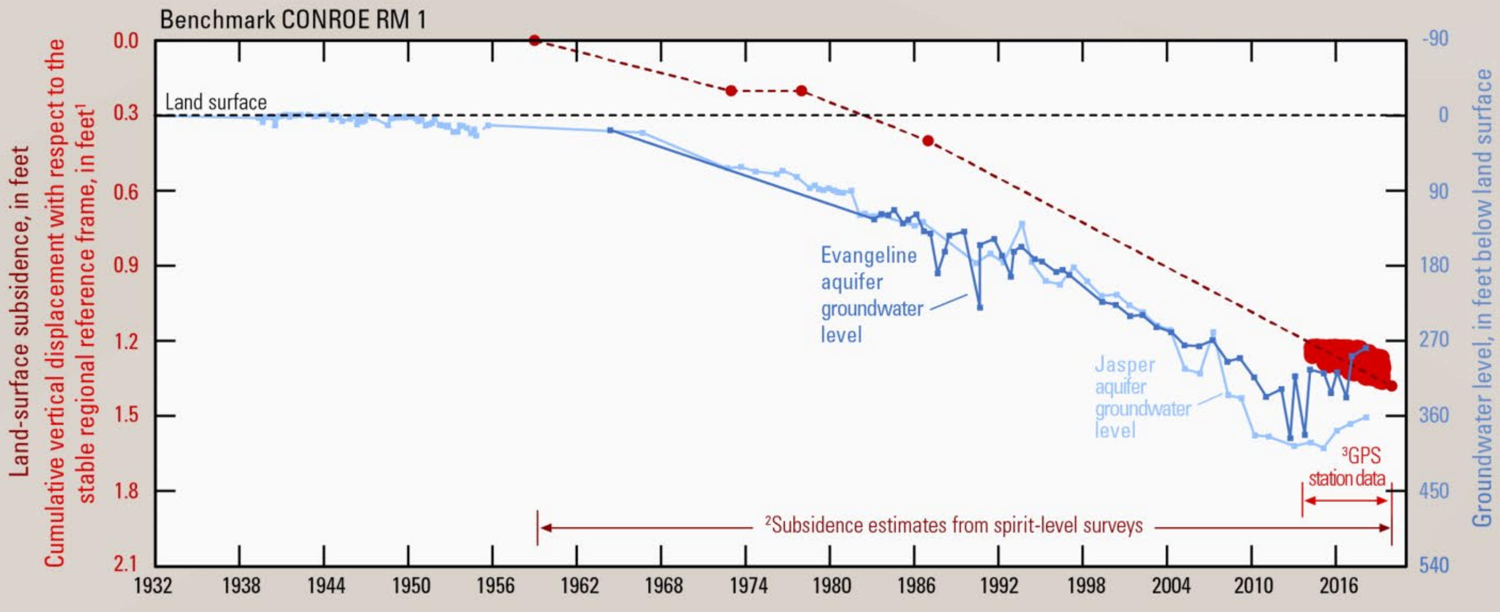
Benchmark	County	Simulated hydrogeologic unit compaction as a percentage of simulated land-surface subsidence			
		Layer 2 (Chicot aquifer)	Layer 3 (Evangeline aquifer)	Layer 4 (Burkeville confining unit)	Layer 5 (Jasper aquifer)
T 88	Montgomery	4%	58%	3%	33%

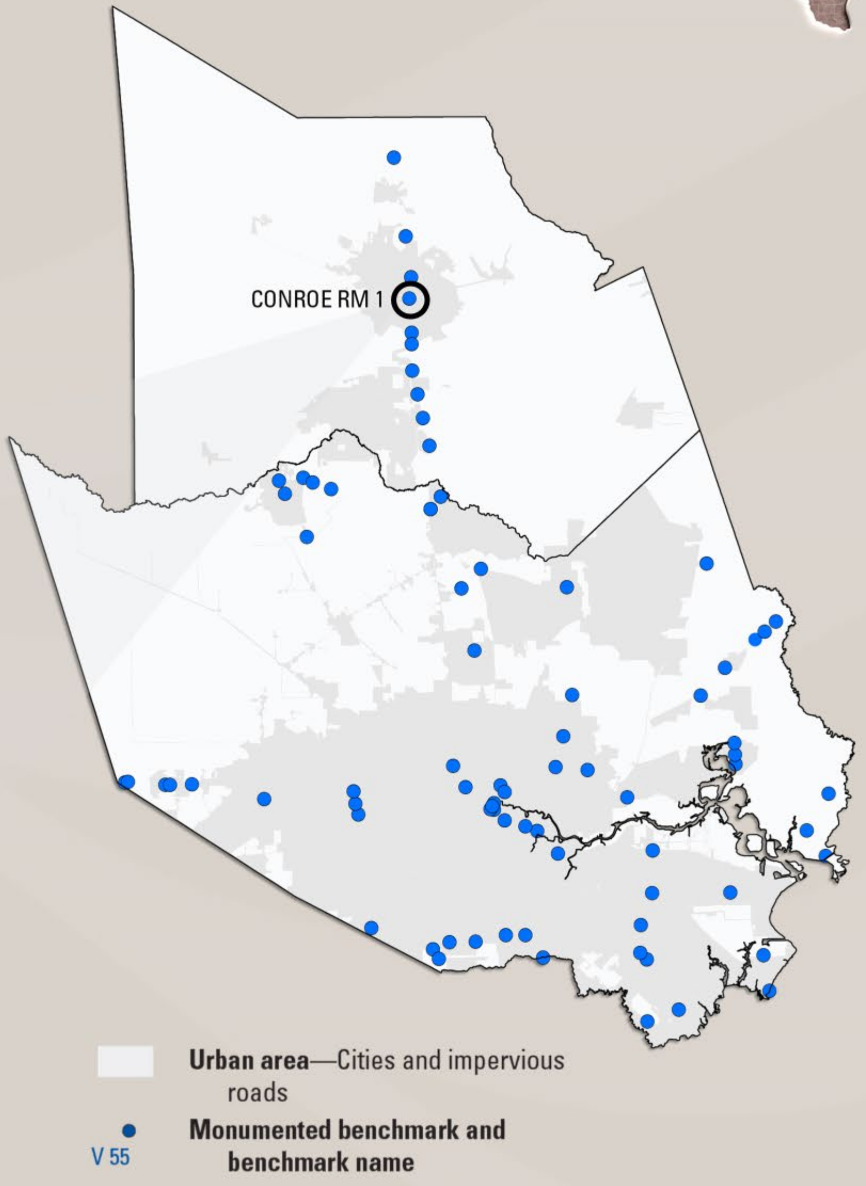
The percentage of compaction by hydrogeologic unit does not sum to 100 percent due to rounding

Cumulative subsidence

PRELIMINARY RESULTS

- Benchmark CONROE RM 1: 1.5 feet of subsidence through 2021
- 1.4 feet of subsidence from benchmark reoccupation, 0.1 feet subsidence occurred prior to 1958 at nearby benchmarks
- Greater Jasper aquifer groundwater-level decline compared to benchmarks T 88, SPRING RM 1, and V 660





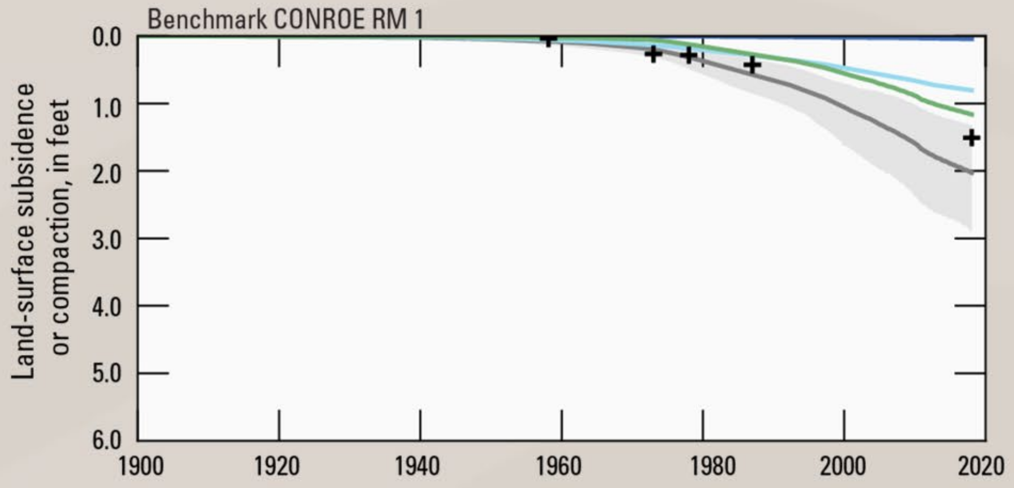
USGS science for a changing world

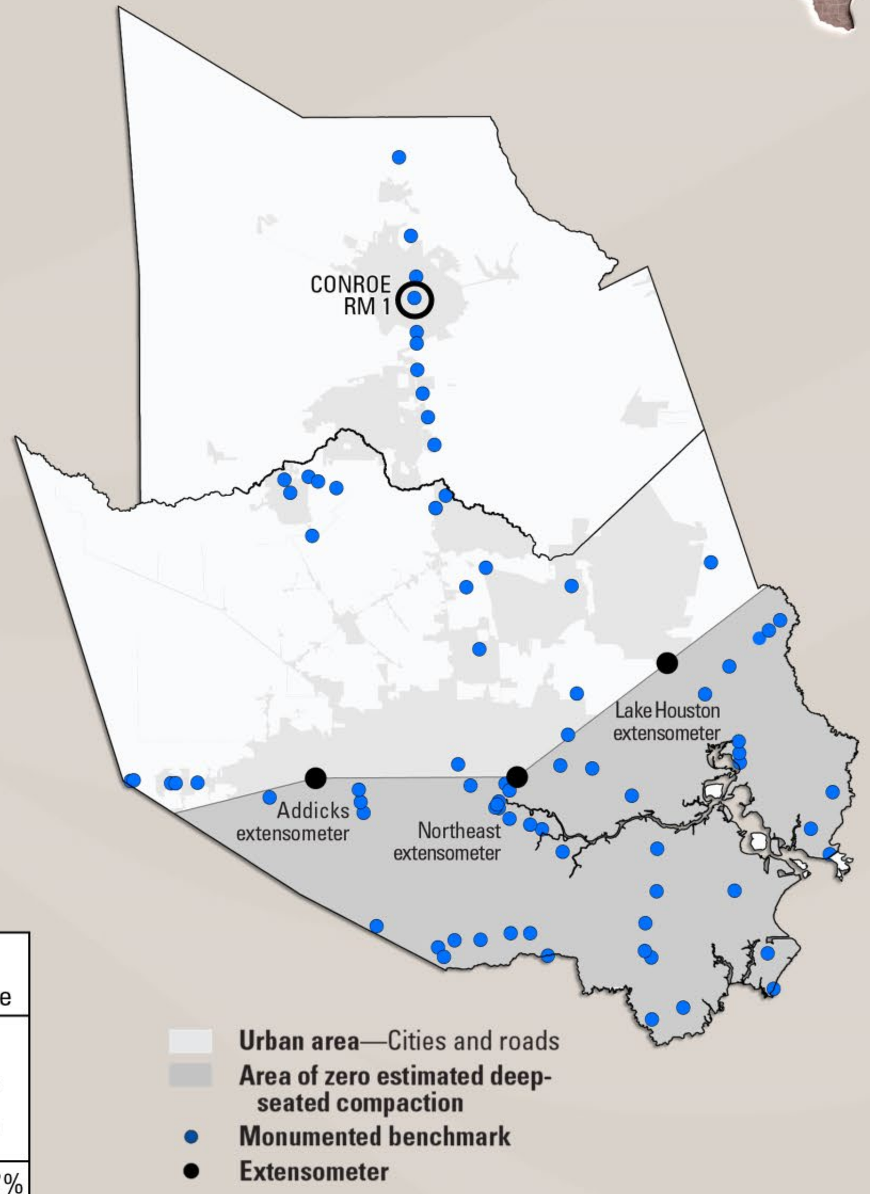
HARRIS-GALVESTON SUBSIDENCE DISTRICT

Cumulative compaction

Jasper aquifer compaction – CONROE RM 1

- 1.1 feet, or 57 percent of simulated subsidence
- The top of the Jasper aquifer in this area is at -700 feet above NAVD 88, or about 400 feet shallower than at benchmark T 88



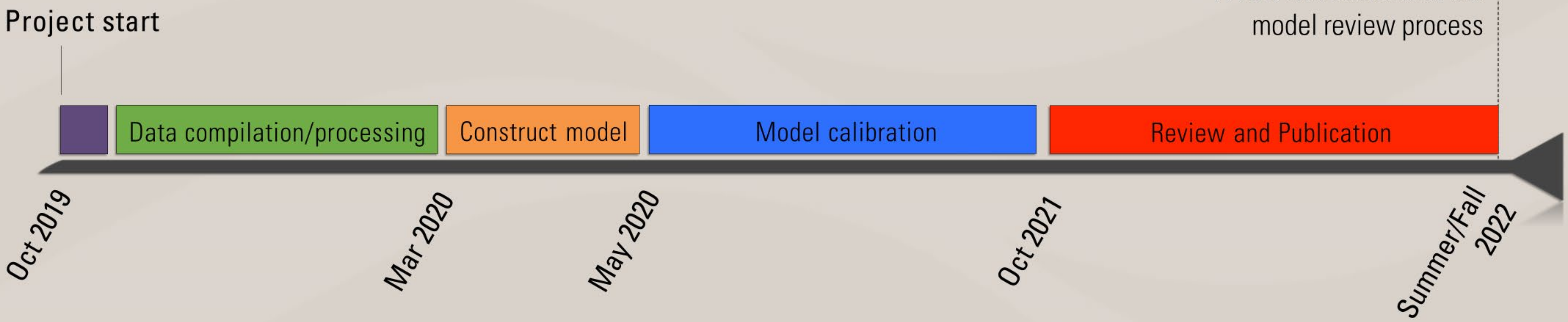


Benchmark	County	Simulated hydrogeologic unit compaction as a percentage of simulated land-surface subsidence			
		Layer 2 (Chicot aquifer)	Layer 3 (Evangeline aquifer)	Layer 4 (Burkeville confining unit)	Layer 5 (Jasper aquifer)
CONROE RM 1	Montgomery	1%	38%	2%	57%

The percentage of compaction by hydrogeologic unit does not sum to 100 percent due to rounding

Timeline

- Report to be released summer/fall 2022
- TWDB will coordinate the model review process



Groundwater Availability Model

GULF

2023

Gulf Coast Land Subsidence and Groundwater Flow Model

In cooperation with the Harris-Galveston Subsidence District
In cooperation with the Fort Bend Subsidence District

John Ellis | jellis@usgs.gov

Schedule and Next Steps

	GULF 2023 Model	Projected Water Needs	Alternative Water Supplies	PRESS Assessment	Water Use Scenarios
2020	Model Conceptual Report	Methodology, Model Updates	Overview of Alternatives	PRESS Model Validation	
2021	Complete Model Update	Population and Demand Projections	Technical Characterization, Final Report		
STATUS					
2022	Complete Model Update	Direct Stakeholder Process, Final Projections			Scenario Development
2023				Scenario Testing	Scenario Testing, Recommendations

Upcoming Milestones

Q2 2022

- Population Projections

Questions and Answers

Thank you for attending the Joint Regulatory Plan Review Stakeholder Meeting

We appreciate your interest and engagement in this meeting.

If you have time, please take a moment to complete the survey at the end of this webinar. We will also include a link to the survey in a follow-up email if you cannot complete the survey now.

ATTACHMENT C – Question and Answer Session

The following summary documents questions that were received during the stakeholder meeting as well as formal responses provided for the record.

QUESTIONS WITH RESPONSES

1. ***Are all wells on a hydrostatic pressure gradient or do some display overpressure?***
   If hydrostatic head is zero at the water table, then, yes hydrostatic pressure will increase with depth below the water table.

   If the term 'overpressure' is referring to a potentiometric water level in a well that exists above the level at which the "water-bearing unit" is first intersected (e.g. confined conditions) then yes, there are many such wells in the study area. If this is referring to a confined well that is flowing (or when the water level is greater than the land surface), then undoubtedly some of these wells still exist. Flowing wells were numerous in the greater Houston area during and prior to the 1920s before substantial groundwater development resulted in the decline of water levels.

2. ***Would you say that the aquifer levels have raised about as much as can be expected? Some compaction cannot be reversed.***
   This depends on the location in the model area. For the more down-dip areas such as central to southwestern and southeastern Harris county, where surface water conversions have been implemented for some time, water levels have recovered considerably with very little annual change in water level from year to year. In other areas it will take time to see to what degree they recover. However, it is unlikely that the water-levels in any area in region will recover to pre-development levels.

3. ***What is the lateral extent of drawdown from well locations?***
   The lateral extent of the drawdown is based on a number of factors, among which include whether the pumping well is screened in a confined or an unconfined hydrogeologic unit. For a confined unit, the drawdown will be more laterally extensive than for an unconfined unit assuming the same values for hydraulic conductivity, aquifer thickness, and transmissivity. These differences relate to the response to pumping in unconfined and confined units. Whereby, physical dewatering of the pore spaces of the sediment occurs in an unconfined aquifer whereas pressure head decline (but no change in saturated thickness) occurs in a confined unit.

4. ***Are the "historic observations" in slide 40 actual data or smoothed/running average data?***
   Those observations, which are the points indicated with black cross mark symbols, are smoothed data. A five-year moving average was applied to groundwater-level observations prior to 2000, and a two-year moving average was used from 2000–2018. In this way, much of the high-frequency noise associated with these observations was removed while retaining the important trends expected to be matched by the model, such as long-term changes in groundwater levels.

5. ***What is the impact of the hydrocarbon production beneath the aquifers through time? How is that accounted for in model?***

The model calibration is based on benchmark data and other datasets, so it is incorporated to the extent that it impacts the available records. There was some early subsidence analysis such as an examination of the Goose Creek oil field in 1926.. The model has been calibrated to all available historical subsidence data in the region.

6. ***Have you calculated calibration statistics for outcrop and downdip areas by layer consistent with TWDB GAM standards?***
   USGS has worked with TWDB to determine what they need in regard to the model results.

7. ***Are you confident that the RCH package accurately accounts for recharge in areas outside of central Houston?***
   The inclusion of the RCH package in this model allows for the incorporation of available soil data throughout the region to be utilized in the analysis. This improvement addresses a limitation in the previous model by reasonably distributing recharge throughout the model domain and produces good results.

8. ***All the parameters and results are reported in this presentation in feet. You mentioned that the grid size is 1 km. Is the model in metric units and have you simply converted model results to English units?***
   The model is in metric units. Outputs have been provided in alternative units for reports and slides as appropriate.

9. ***What is the natural subsidence rate of area? >1 in per year which exceeds your average subsidence rate?***
   Recent reports (Zhou and others, 2021) suggest that natural subsidence rates in the Houston area are one to two millimeters a year.

10. ***Where is the R88 benchmark located?***
    The R88 benchmark is located near The Woodlands in the vicinity of the FM 1488 and IH 45 intersection. Benchmark T88 is located near Research Forest Drive and IH 45.

11. ***USGS has studied subsidence rates related to hydrocarbon production and USGS has studied the natural subsidence of the Gulf Coast. How are these account for in the model?***
    Based on Zhou and others (2021) the natural subsidence is estimated at 1–2 mm/yr; therefore, it is likely a small component of the subsidence observed or estimated in the greater Houston area. The correlation of water-level declines and the onset and continuation of subsidence suggest that most subsidence in the greater Houston area is due depressurization of the aquifer system as a result of wide-spread groundwater development.

    The model is calibrated based on available publications and data such as benchmark information, GPS readings, compaction data, etc. The fit between the observed and simulated groundwater levels and subsidence datasets suggests that the model reasonably simulated subsidence where it is due to water level declines. .

12. ***What type of PEST-IES data will be included in the model submittal?***
    The model submittal will include all PEST-IES data that is referenced in the report.

13. ***Can you describe the USGS review process for this effort?***
    The USGS review process involves technical peer review followed by a report and editorial review prior to publication. The peer review process includes thorough reviews by a

number of personnel with extensive experience in subsidence research, groundwater modeling, aquifer recharge, and GNSS techniques.

14. ***For Cindy (TWBD): Do you have an estimate for the time for stakeholder review? (i.e. one month? 90 days?)***
    Stakeholder review would be a minimum of one month, and usually in the range of 30 to 45 days. If someone was needing additional time, they can contact TWDB to negotiate a longer window.
15. ***It sounds like the model will be approved as the GAM by the TWDB, regardless of questions and comments? If issues are identified with compaction, will that affect the adoption of the GAM?***
    Most issues should be vetted during conceptual modeling process. If there are concerns, it will be negotiated between USGS and TWDB. Clarifications will be recorded. A revision to the USGS report could be issued with additional information if necessary. TWDB would keep stakeholders appraised on timeframe via its website.