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science for a changing world

Gulf Coast
Land Subsidence
and Groundwater-
Flow Model

GULF-2023

GULF COAST LAND SUBSIDENCE AND PRELIMINARY MODELING RESULTS

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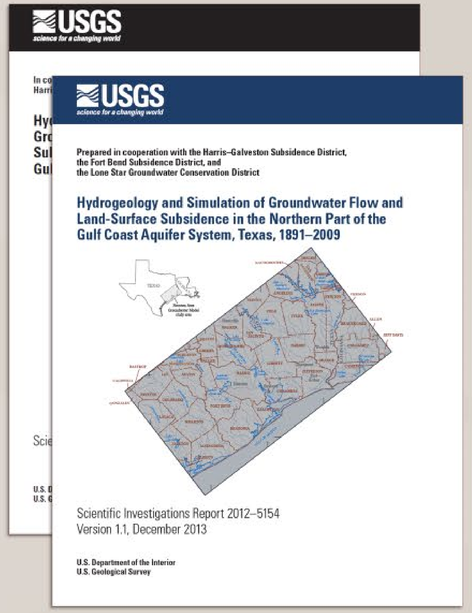
U.S. Geological Survey

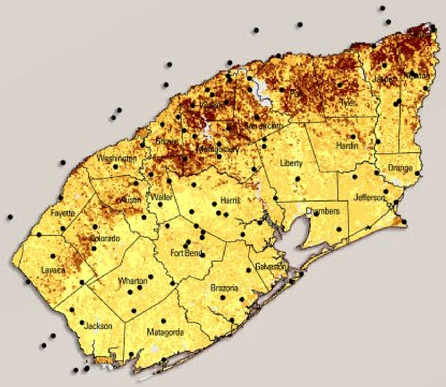
Research in cooperation with
the Harris-Galveston and Fort
Bend Subsidence Districts

Overview

HARRIS-GALVESTON SUBSIDENCE DISTRICT

FORT BEND SUBSIDENCE DISTRICT
FORT BEND COUNTY, TEXAS



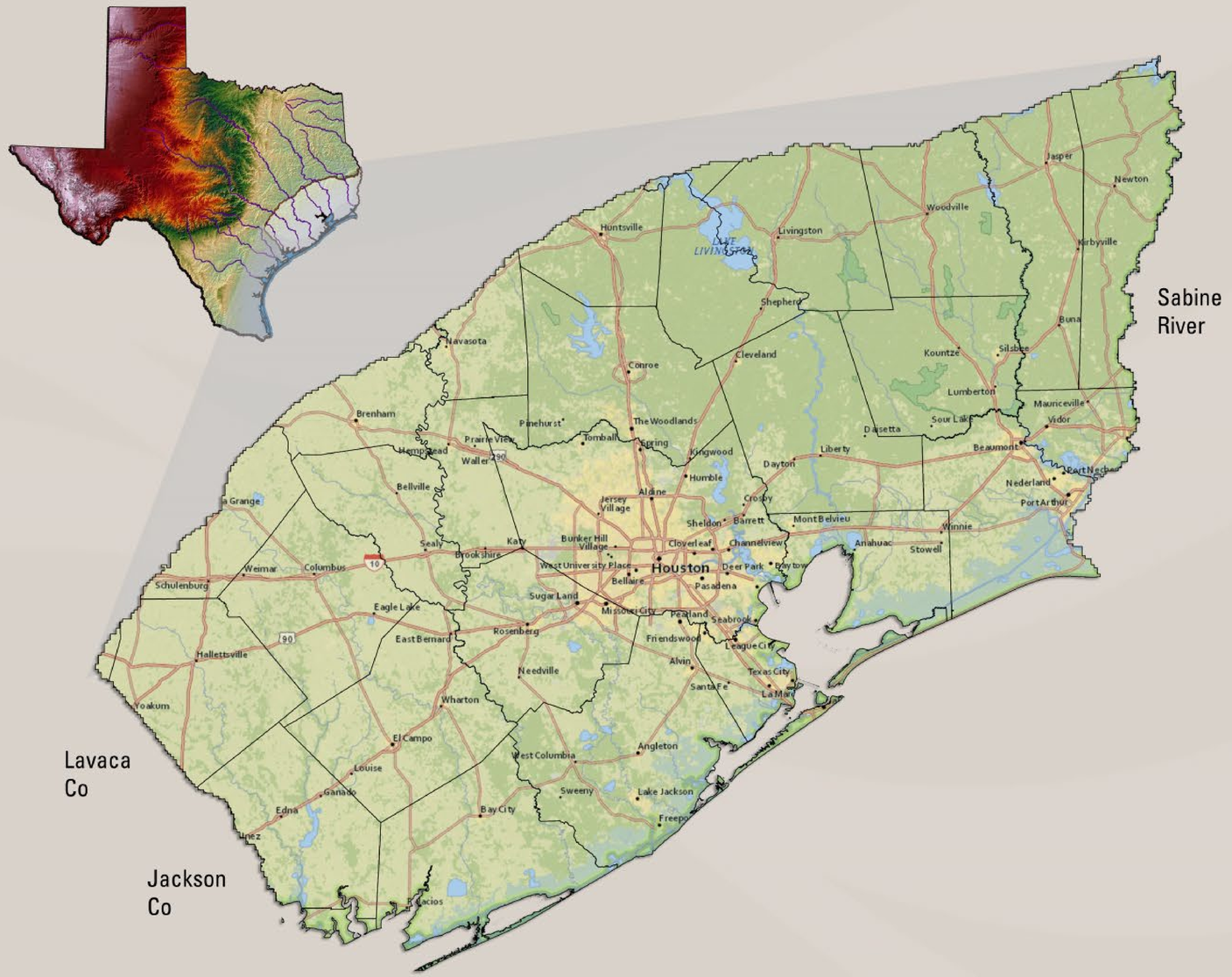


Cooperators	HAGM update + new GAM	CLAS model refinement	Modeling advances

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



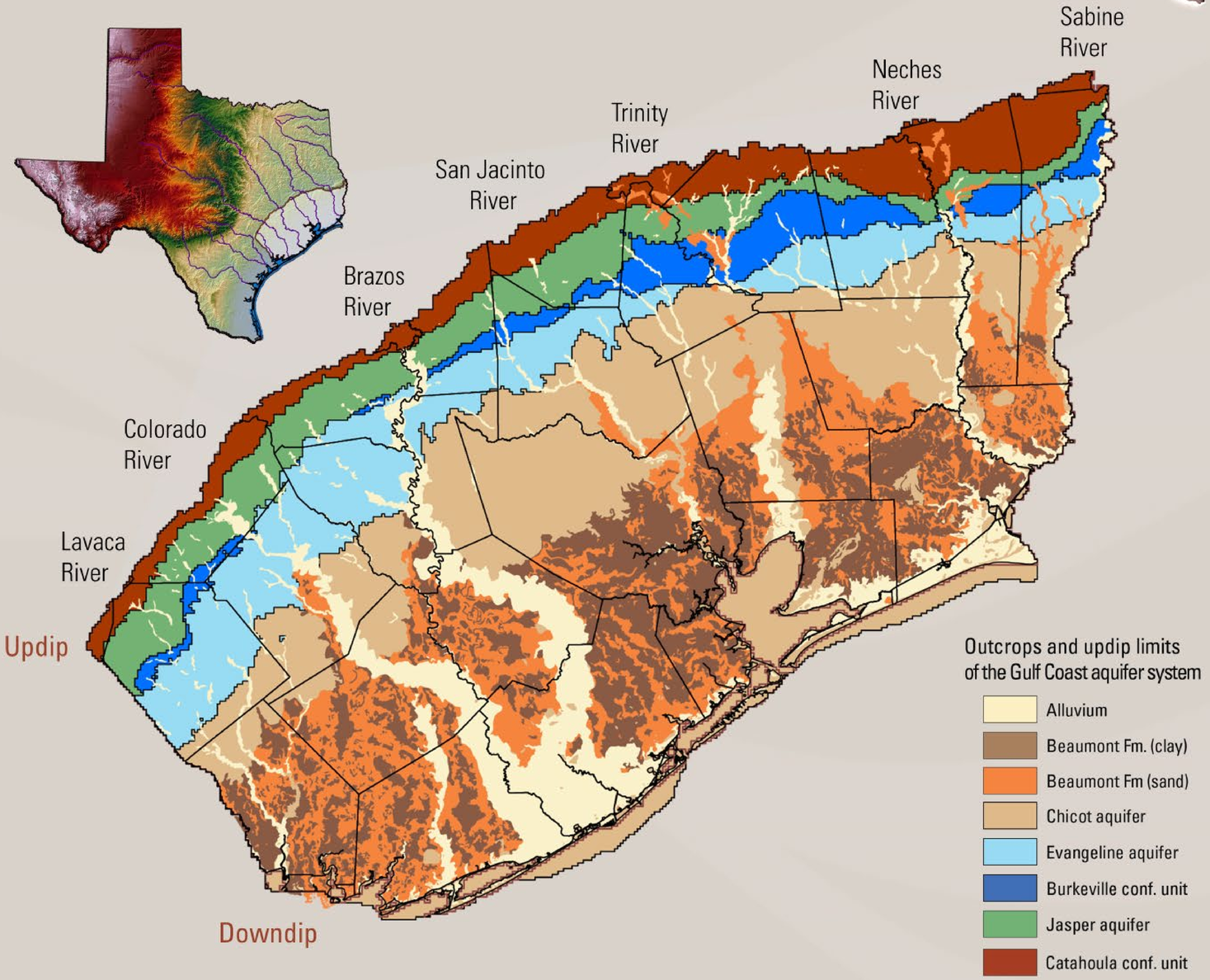
Model Configuration

Model layering

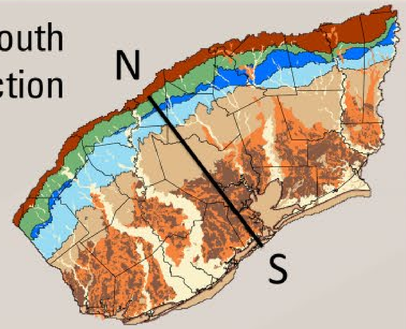
- Layer 1: Alluvium and Beaumont Clay
- Layer 2: Chicot Aquifer
- Layer 3: Evangeline Aquifer
- Layer 4: Burkeville Confining Unit
- Layer 5: Jasper Aquifer
- Layer 6: Catahoula Formation

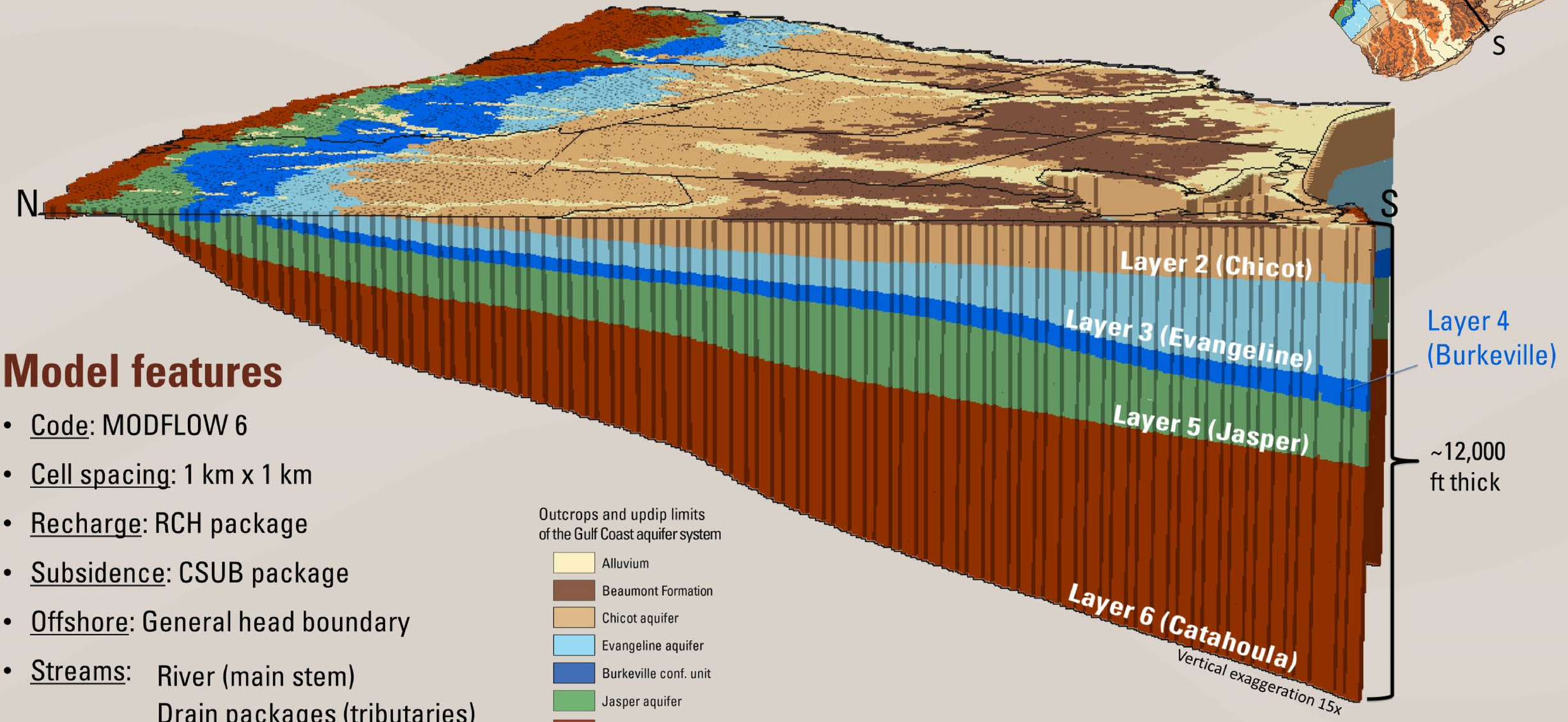
Model time discretization

- 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)

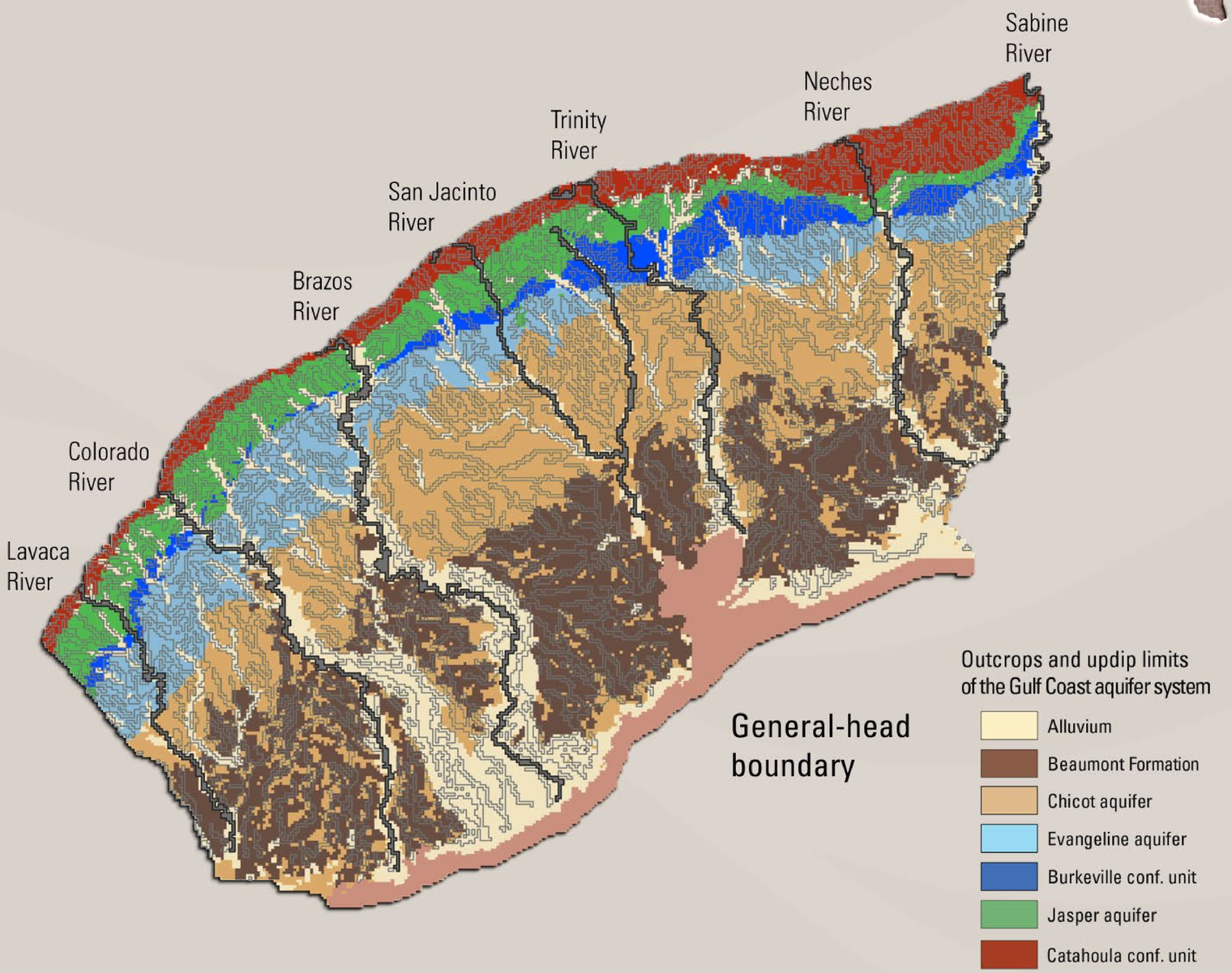
Model Features

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

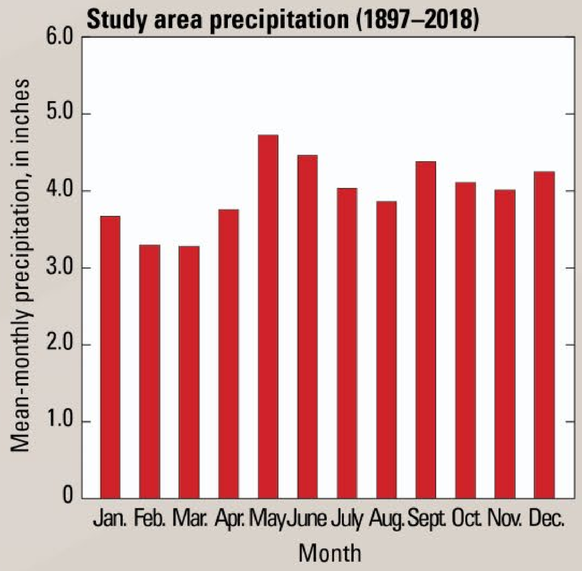


[1]Langevin and others, 2017

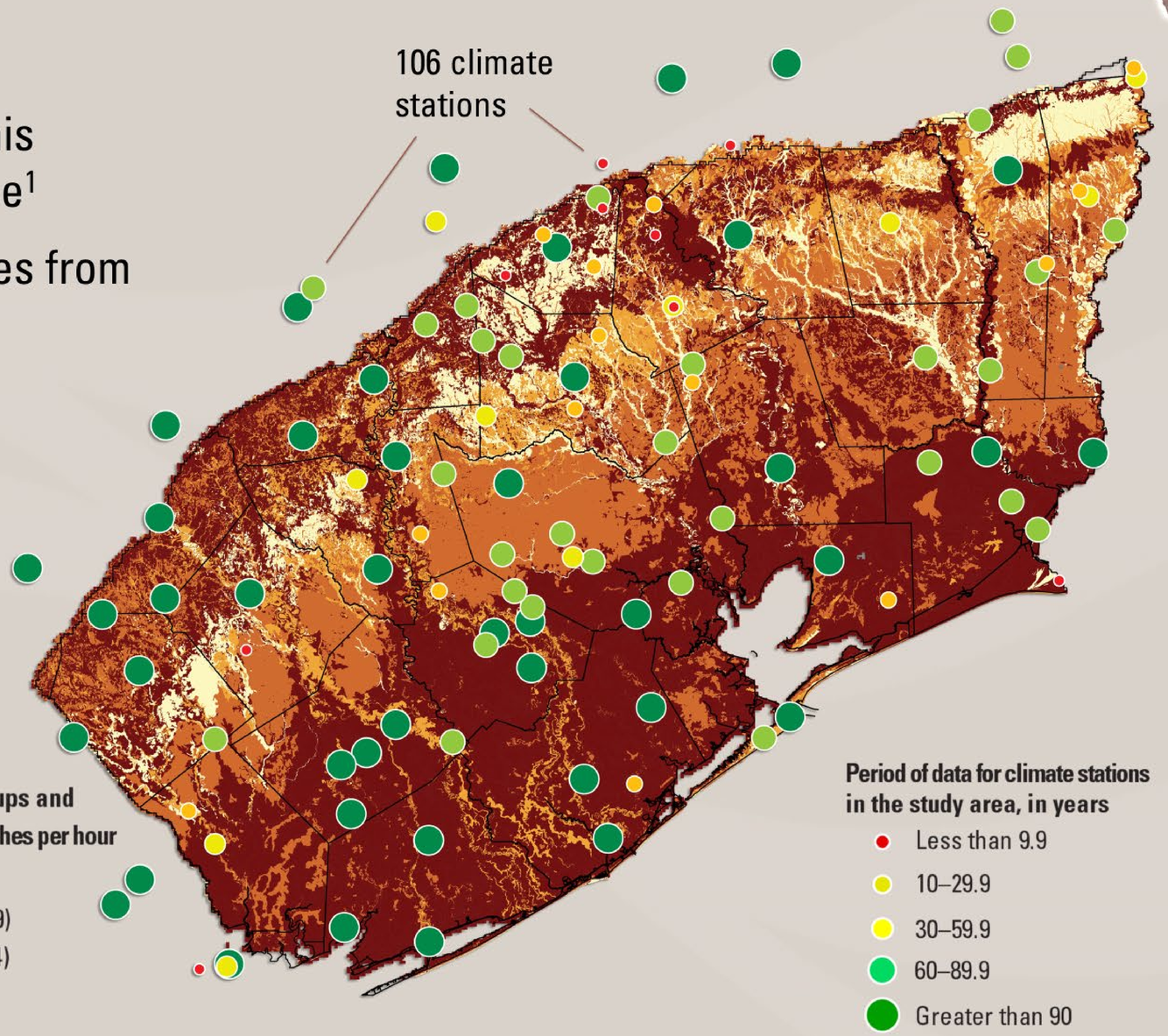
Model Features

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.



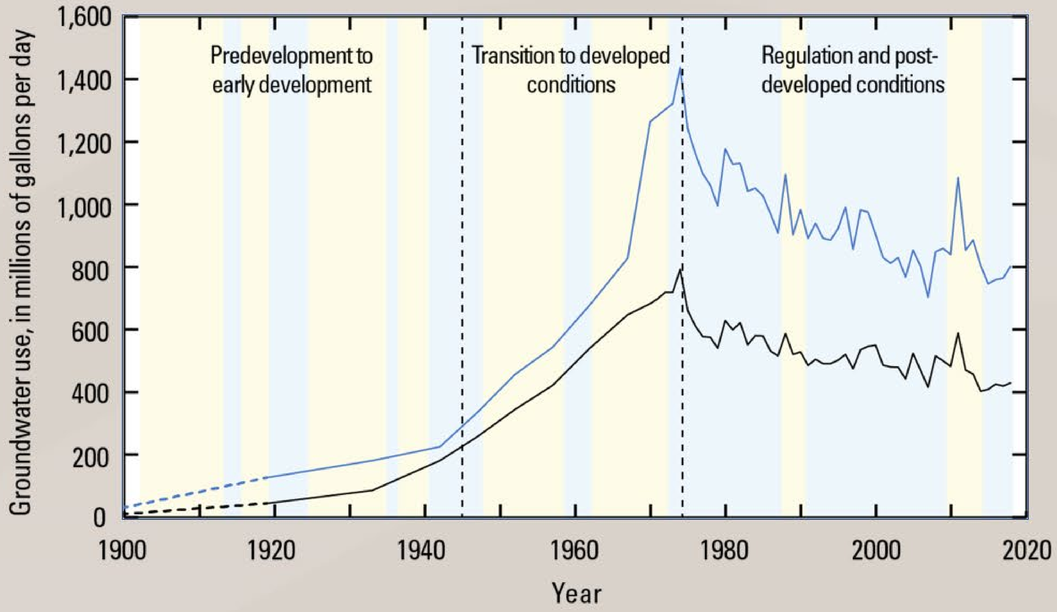
[1]Westenbroek and others, 2010



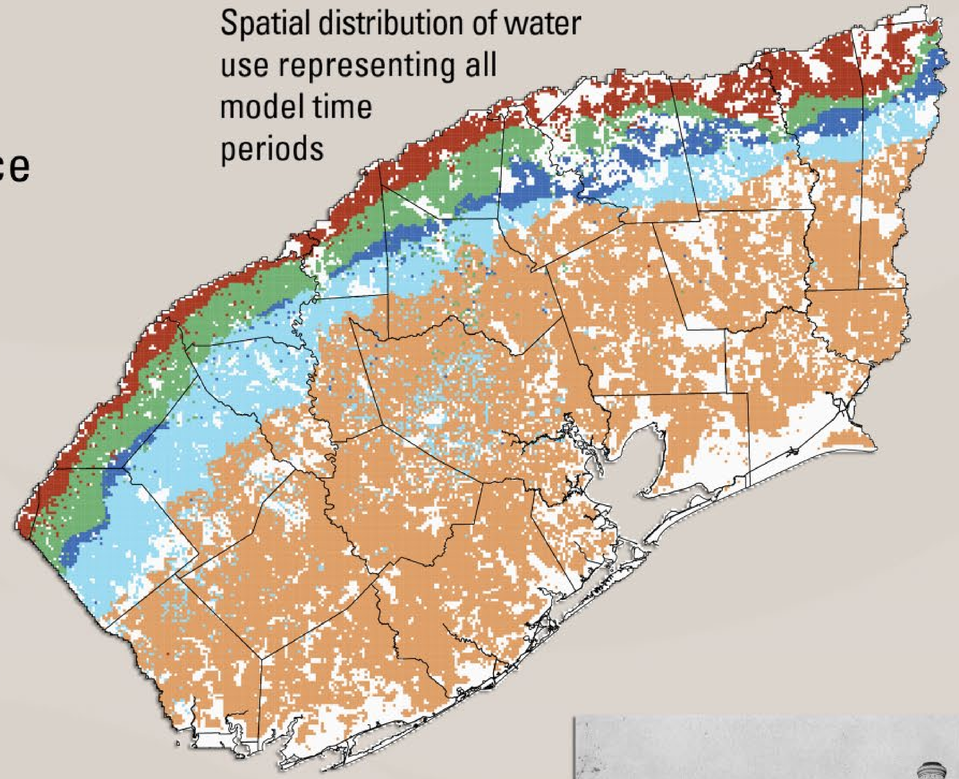
Model Features

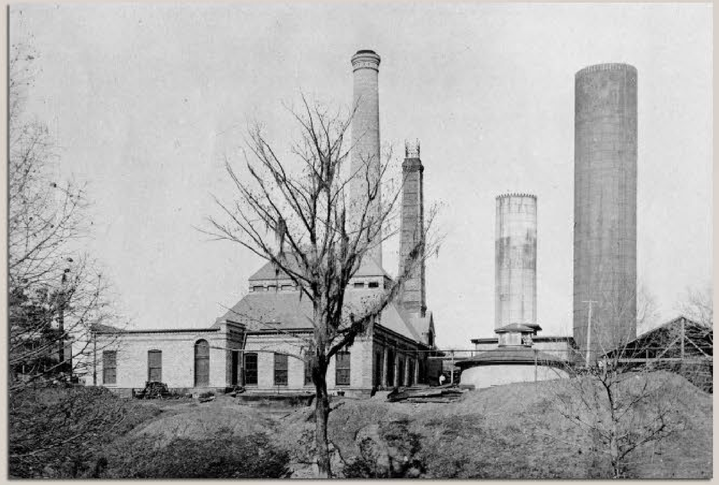
Groundwater use

- Modeled groundwater use prepared by Intera Geoscience
- To account for uncertainty in estimates, an adjustable range was used during model calibration



Spatial distribution of water use representing all model time periods

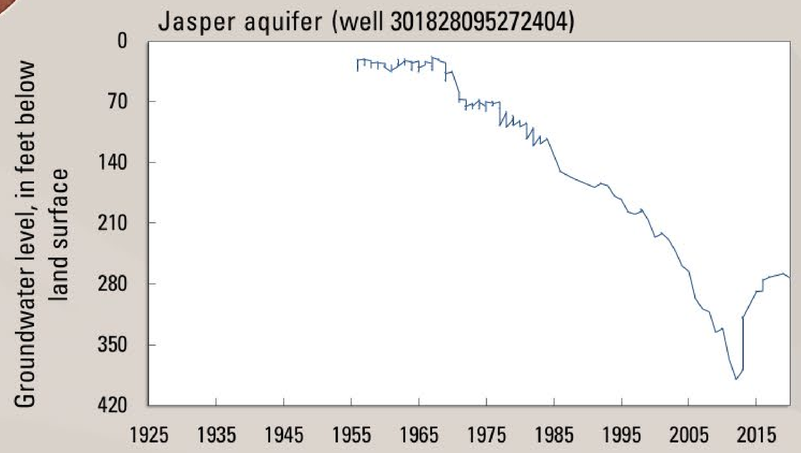


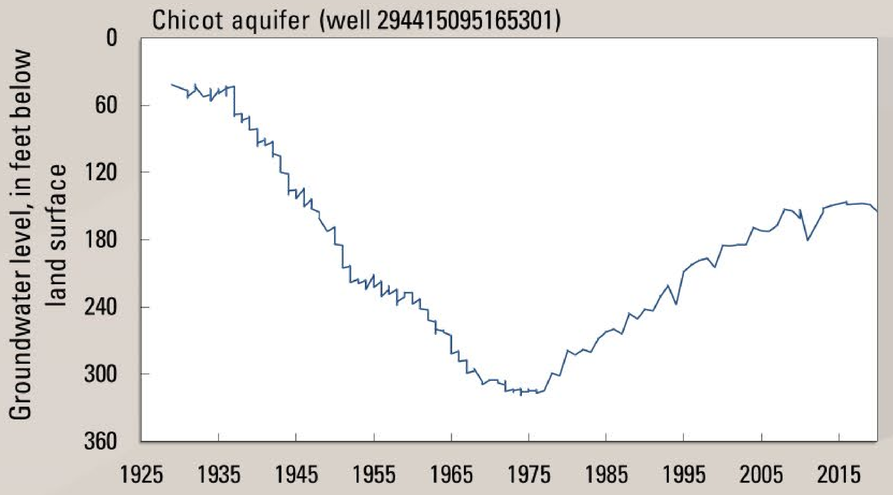


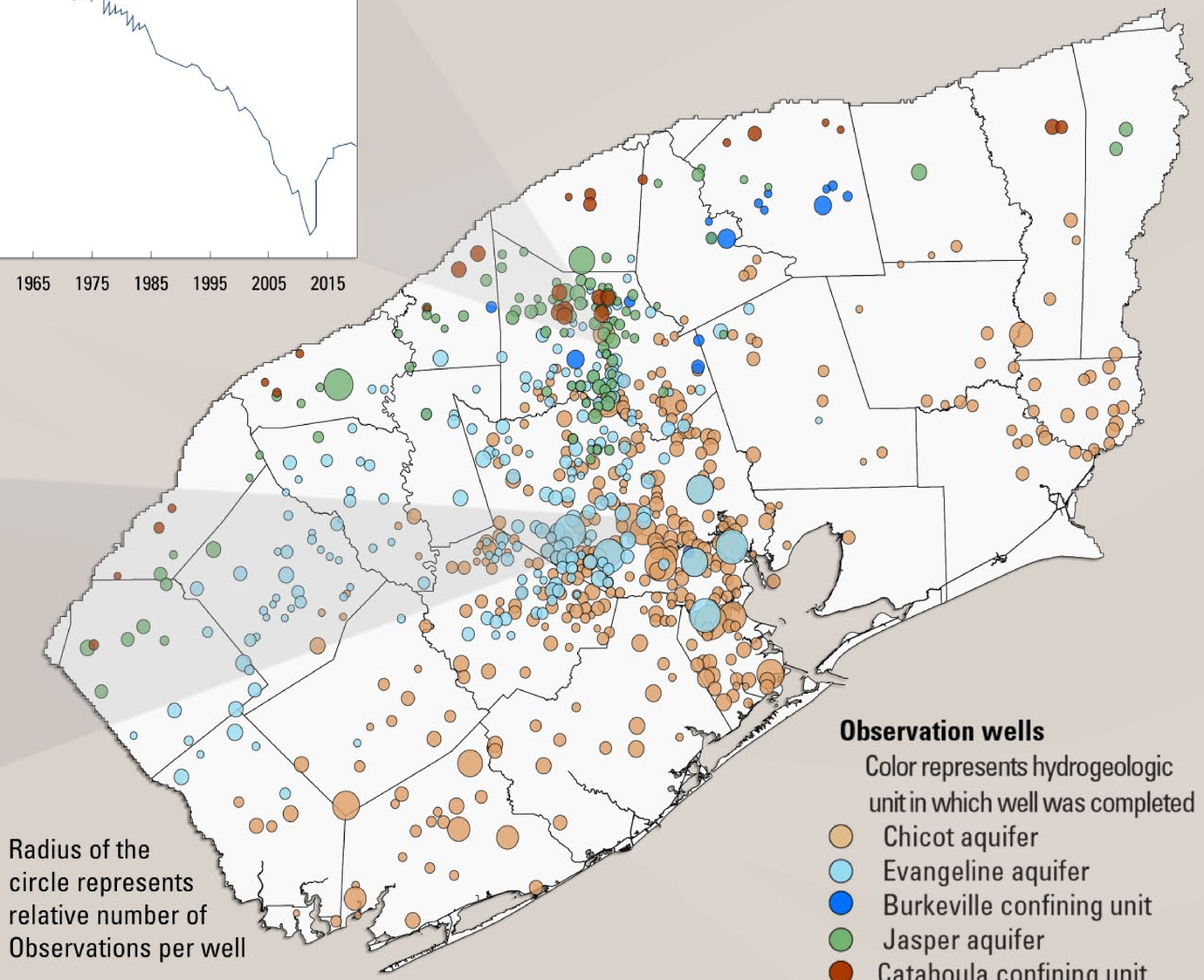
1879 Houston Water Works plant

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







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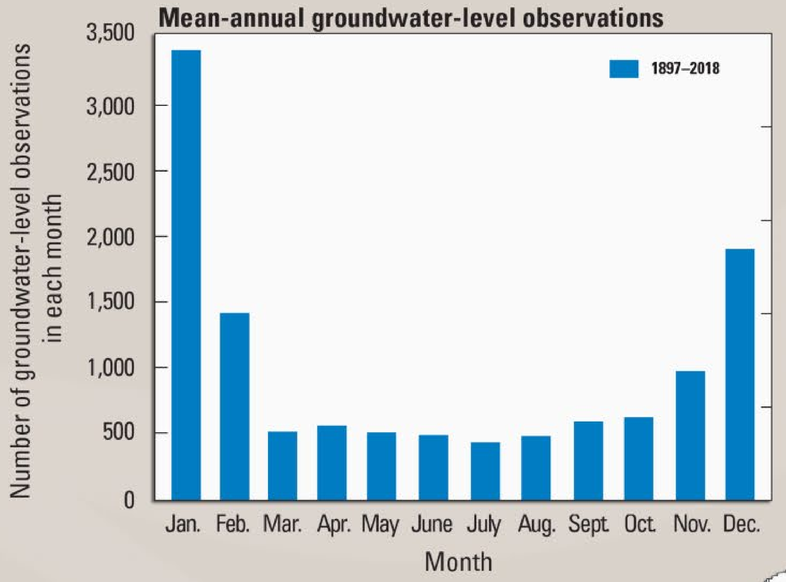
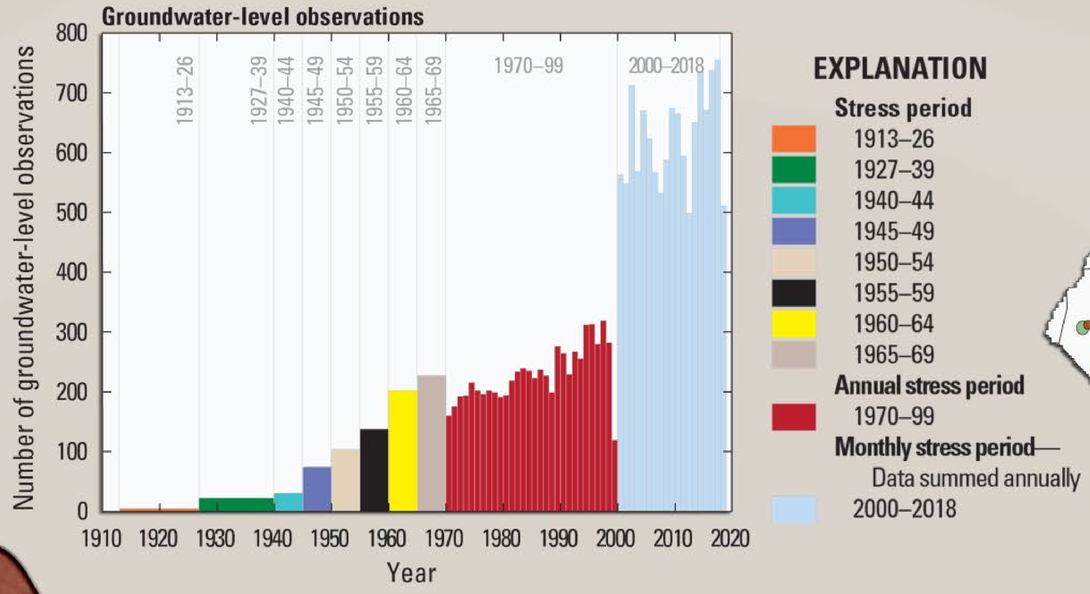
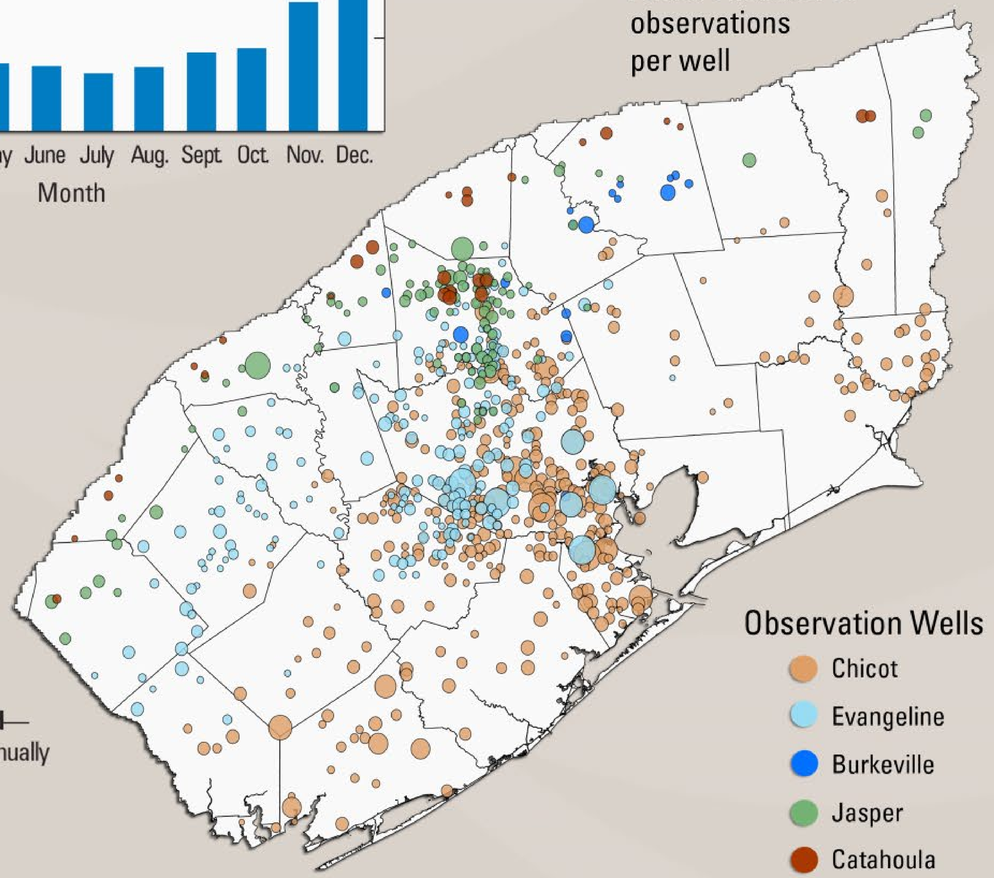
Model Features

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

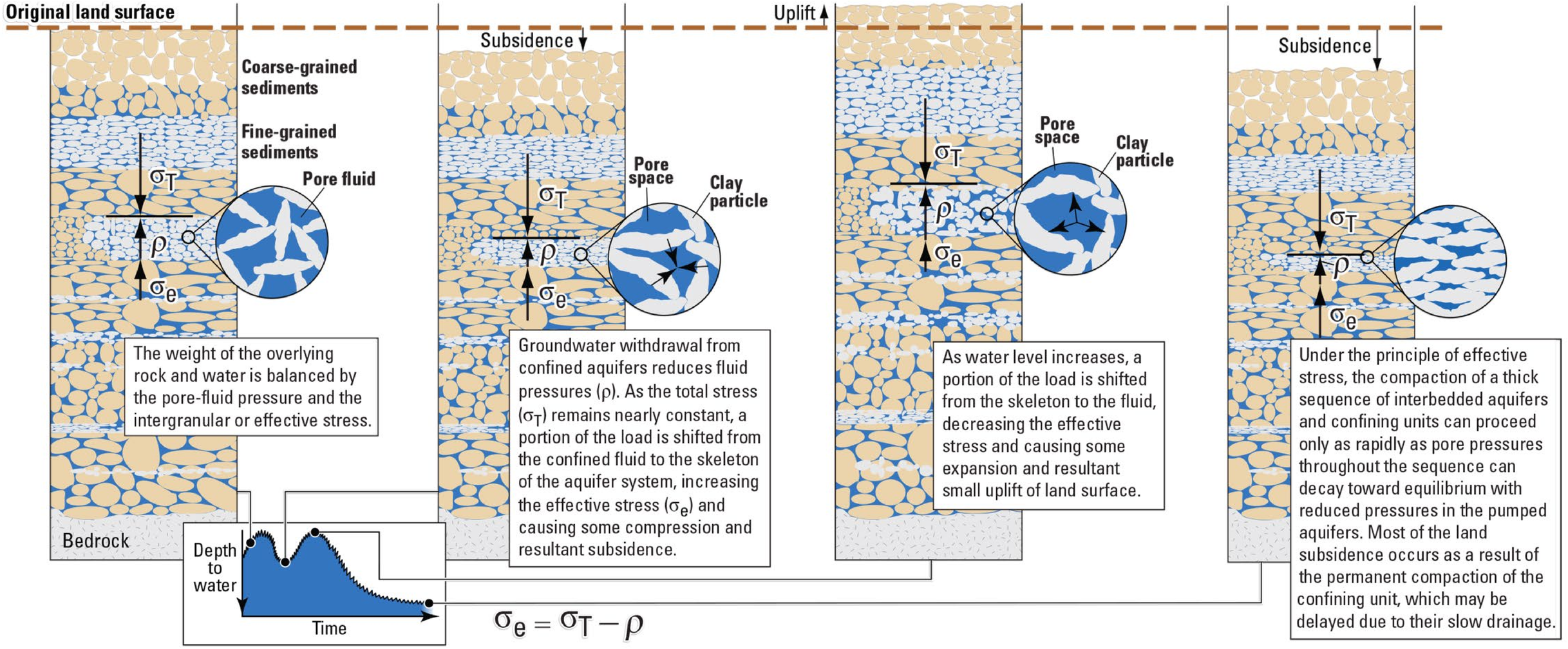






Subsidence

Effective stress and compaction



The weight of the overlying rock and water is balanced by the pore-fluid pressure and the intergranular or effective stress.

Groundwater withdrawal from confined aquifers reduces fluid pressures (ρ). As the total stress (σ_T) remains nearly constant, a portion of the load is shifted from the confined fluid to the skeleton of the aquifer system, increasing the effective stress (σ_e) and causing some compression and resultant subsidence.

As water level increases, a portion of the load is shifted from the skeleton to the fluid, decreasing the effective stress and causing some expansion and resultant small uplift of land surface.

Under the principle of effective stress, the compaction of a thick sequence of interbedded aquifers and confining units can proceed only as rapidly as pore pressures throughout the sequence can decay toward equilibrium with reduced pressures in the pumped aquifers. Most of the land subsidence occurs as a result of the permanent compaction of the confining unit, which may be delayed due to their slow drainage.

$$\sigma_e = \sigma_T - \rho$$

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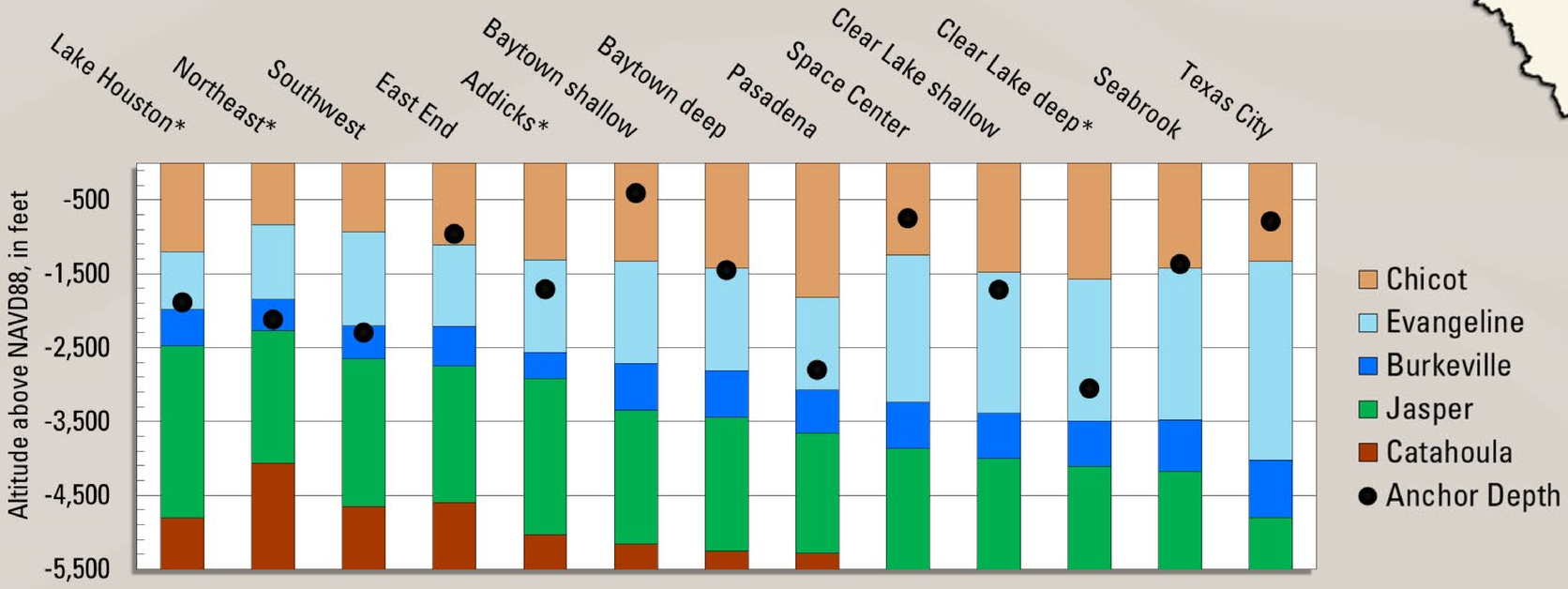
Subsidence

Datasets

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



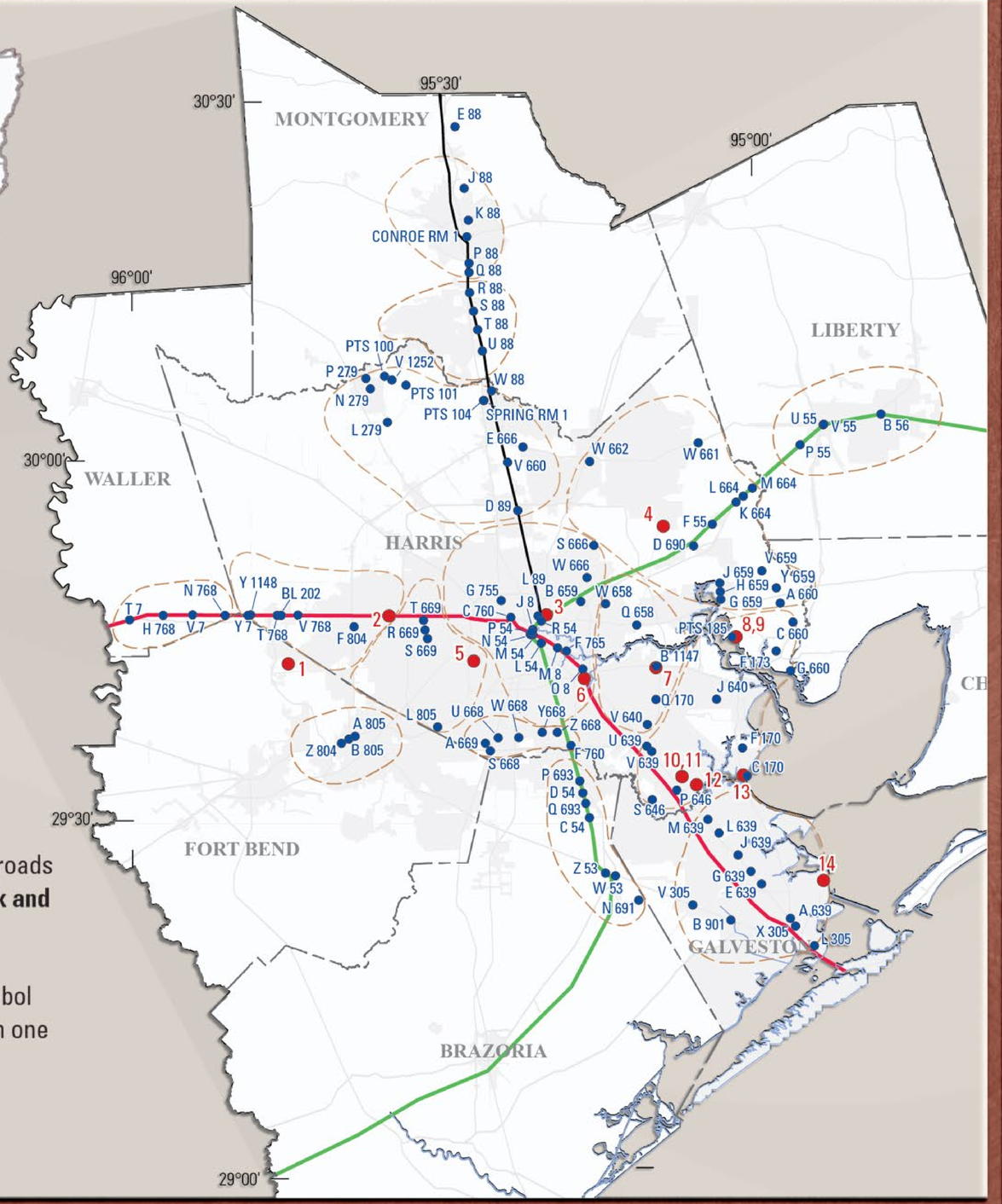

Pasadena extensometer


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 during 1906–1918 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



Subsidence

- The GULF model was calibrated to vertical-displacement data at 178 GPS stations
- Earliest GPS data available beginning in 1994
- Generally greater rates of subsidence in northern, northwestern, and western parts of the greater Houston area

GPS CORS Station LKHU

Urban area—Cities and impervious roads

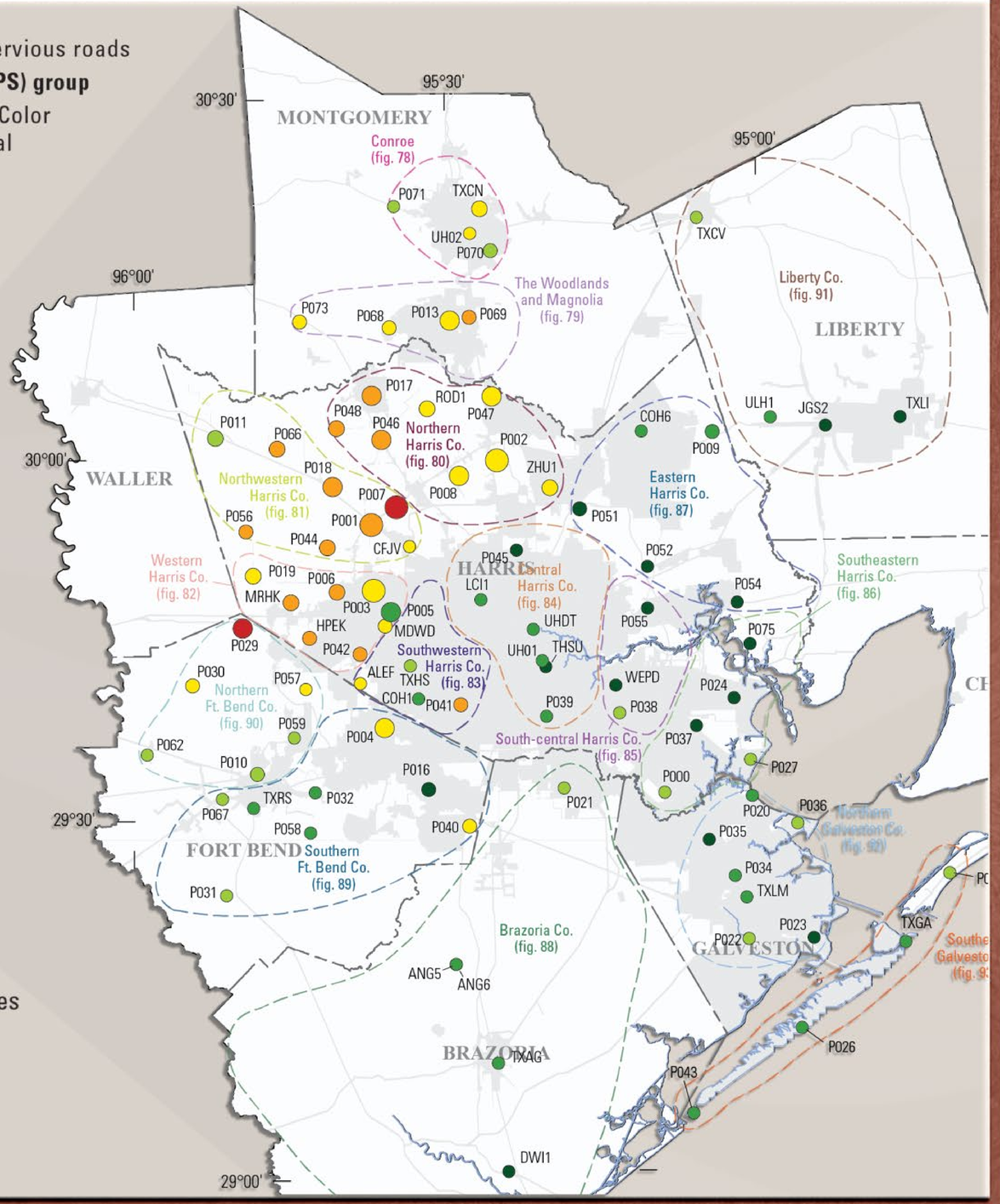
Global positioning system (GPS) group

GPS station and identifier—Color represents rate of vertical displacement, 2016–2020, in centimeters.

- –0.29 to 0.1 (15 sites)
- 0 to 0.24 (21 sites)
- 0.25 to 0.49 (17 sites)
- 0.50 to 0.99 (20 sites)
- 1.00 to 1.99 (14 sites)
- > than 2.00 (2 sites)

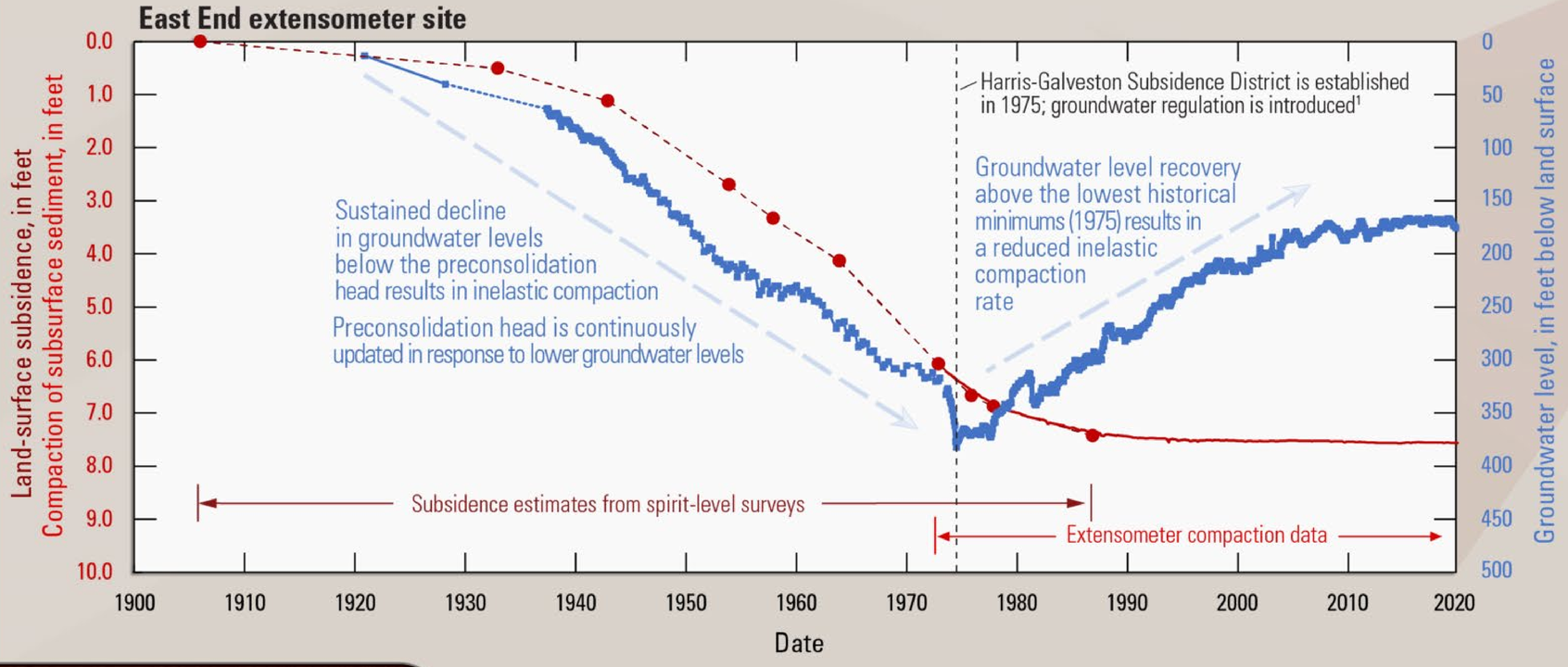
GPS station—Symbol size represents cumulative vertical displacement data, in centimeters. Parenthesis indicate # of sites

- –2.8 to 4.9 (38 sites)
- 5.0 to 9.9 (14 sites)
- 10.0 to 19.9 (12 sites)
- 20.0 to 39.9 (6 sites)
- Greater than 40.0 (6 sites)



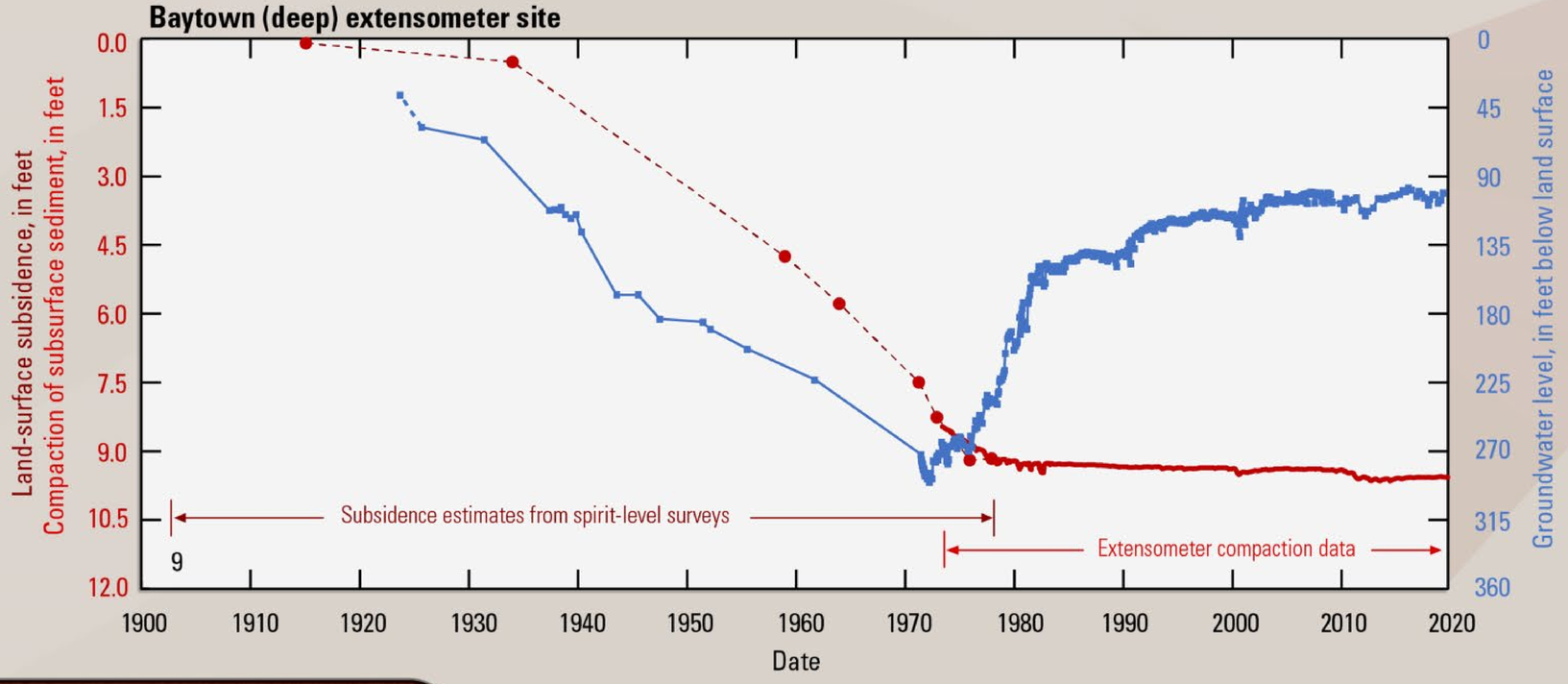
Cumulative subsidence

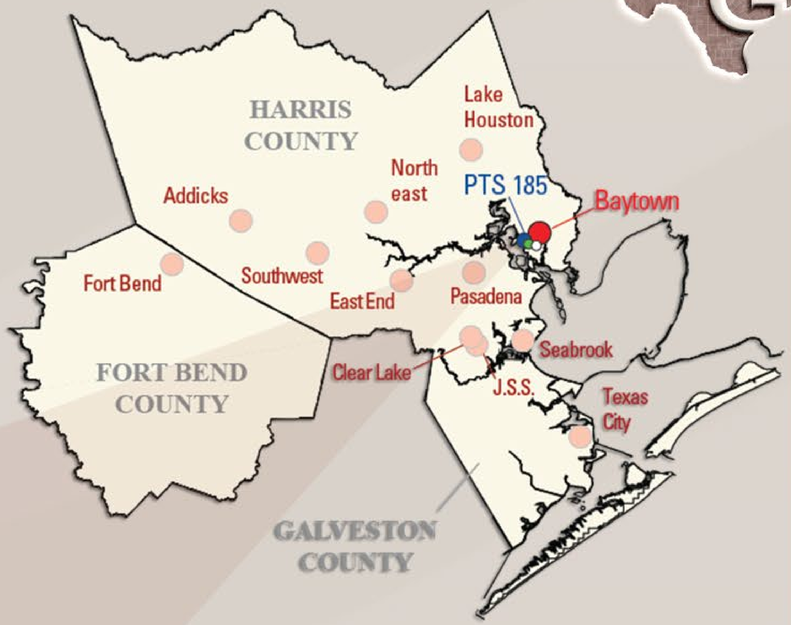
- East End extensometer: About 7.4 feet of subsidence through 2020
  - By 1943, groundwater levels were about 115 feet below land surface, and subsidence was about 1.1 feet.
  - As groundwater levels continued to decline, the aquifer system reached a continually greater level of effective stress, resulting in inelastic compaction.



Cumulative subsidence

- Baytown extensometer: About 9.3 feet of subsidence through 2020
  - During 1971–1973, the area around this extensometer subsided by about 5 inches per year.
  - Subsidence was due to groundwater level declines from groundwater use in Baytown and Pasadena.

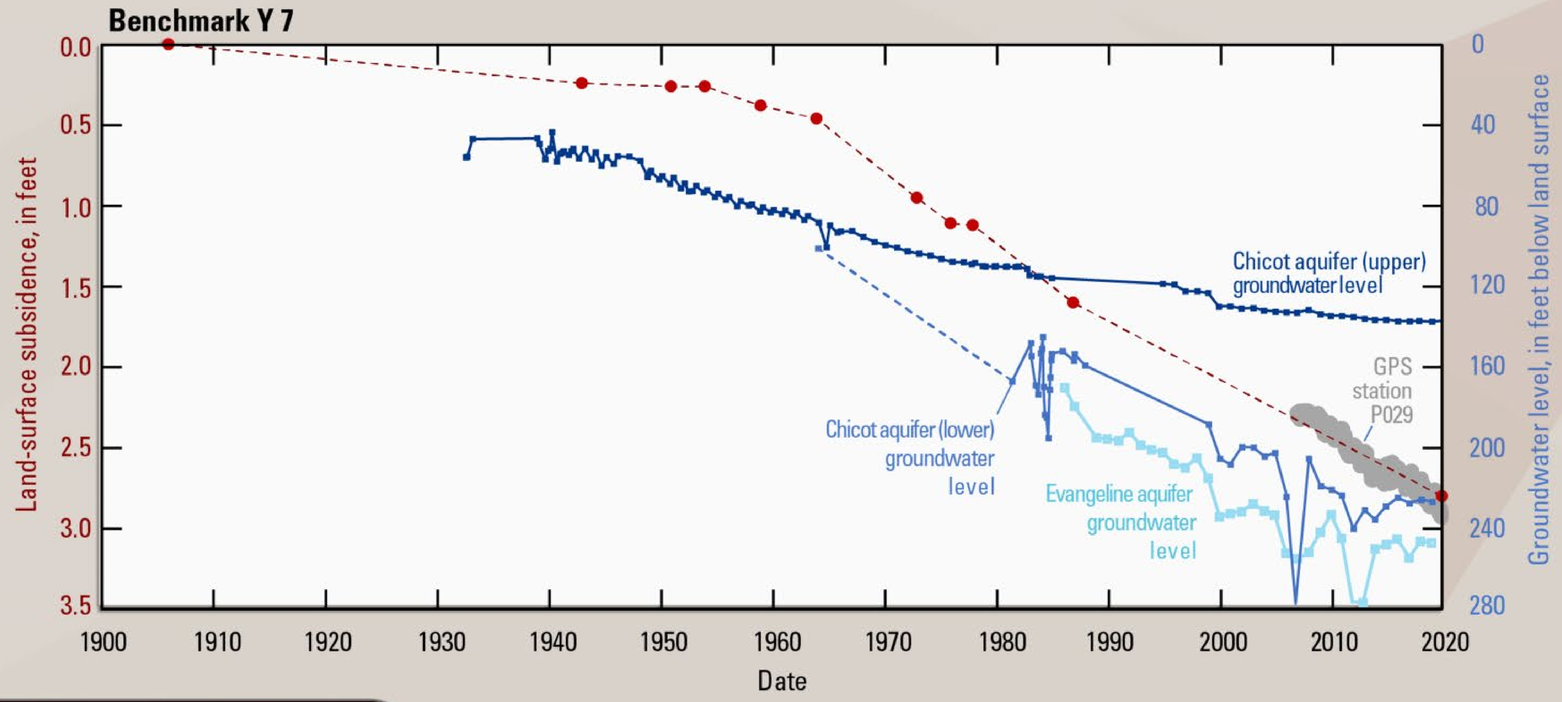




Burnett School well, Baytown, Tex.

Cumulative subsidence

- Area near benchmark Y 7: About 2.8 feet of subsidence through 2020
  - Less subsidence per 100 feet of water level decline compared to central and southeastern Harris County
  - Katy area has the greatest spatial distribution of historical water use, coarser Chicot aquifer sediment, and close proximity to the recharge zone



- Extensometer site—may represent more than one extensometer
- Y 7 — Monumented benchmark and benchmark name
- P019 — GPS station
- Chicot well
- Evangeline well
- Chicot aquifer outcrop area

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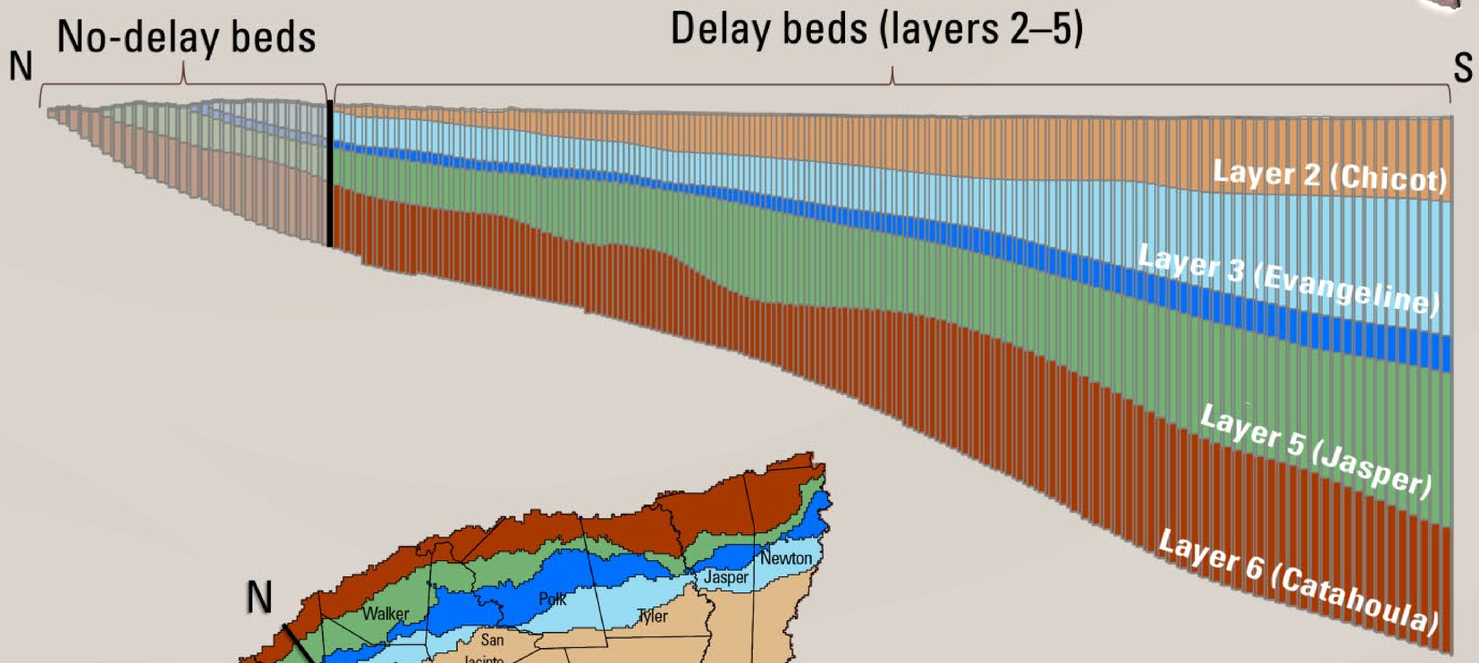
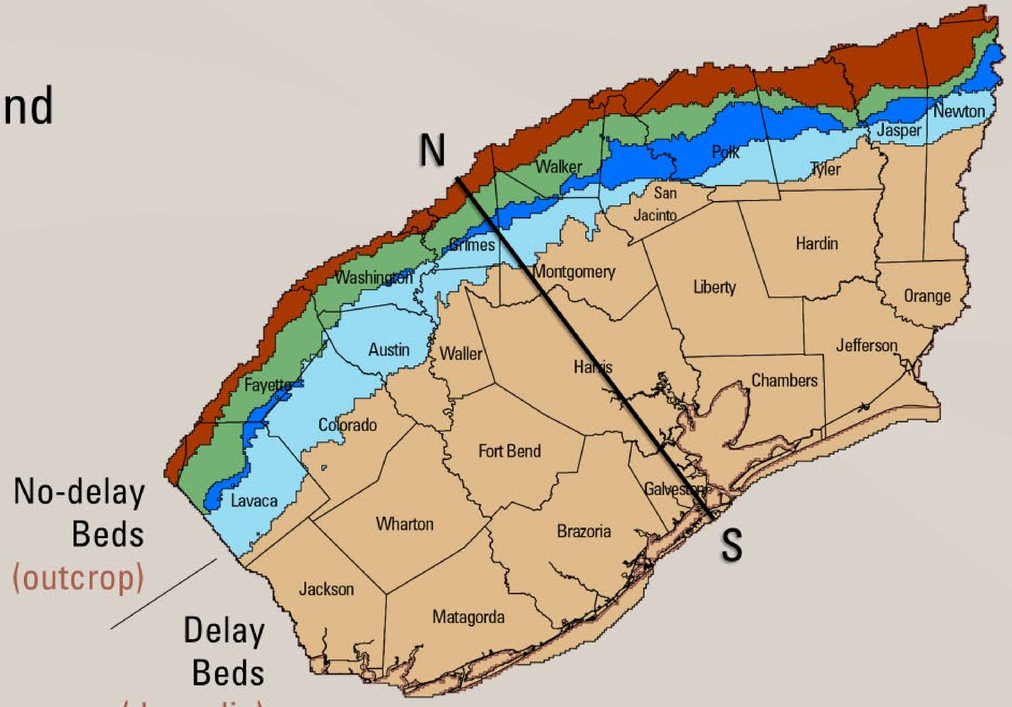
Subsidence

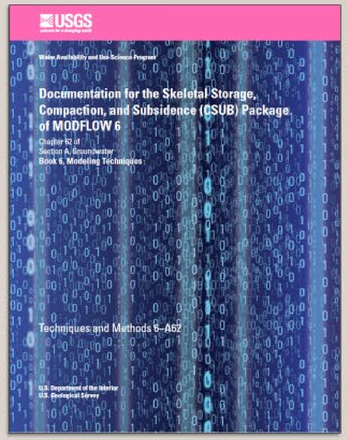
Subsidence package

- 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



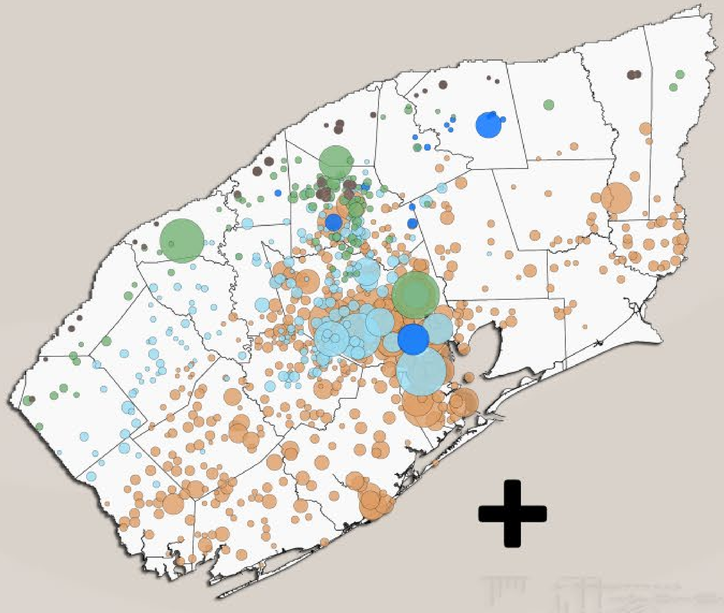




[1]Hughes and others, 2022

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



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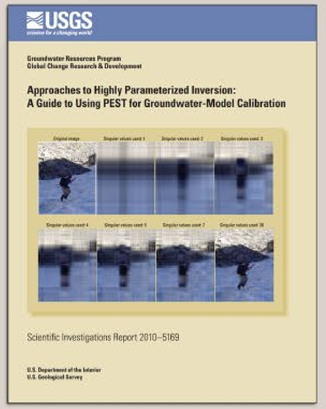
PEST++

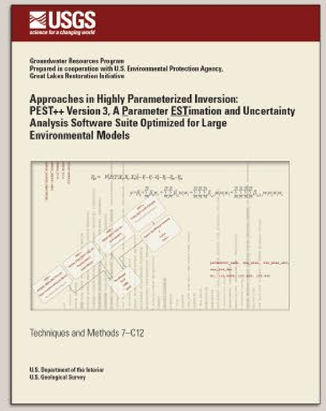
Software Suite for Parameter Estimation, Uncertainty Quantification, Management Optimization, and Sensitivity Analysis

+

HTCondor

High Throughput Computing





[1]White, 2018

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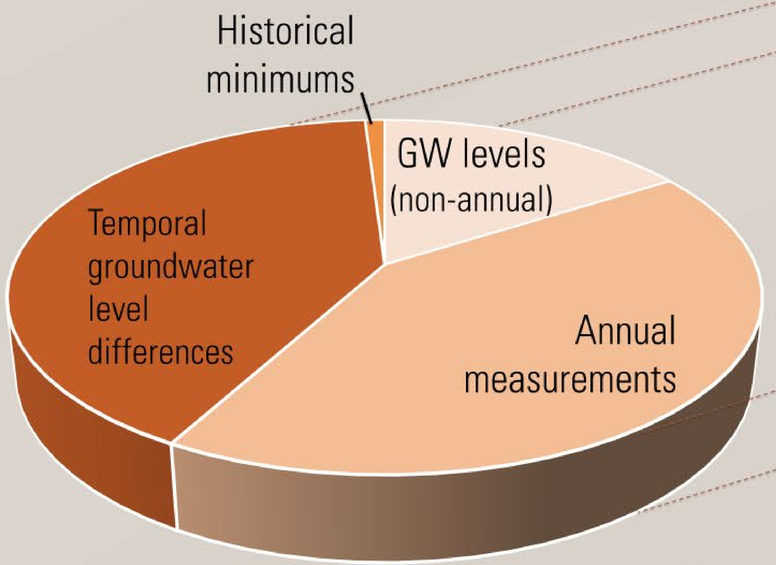
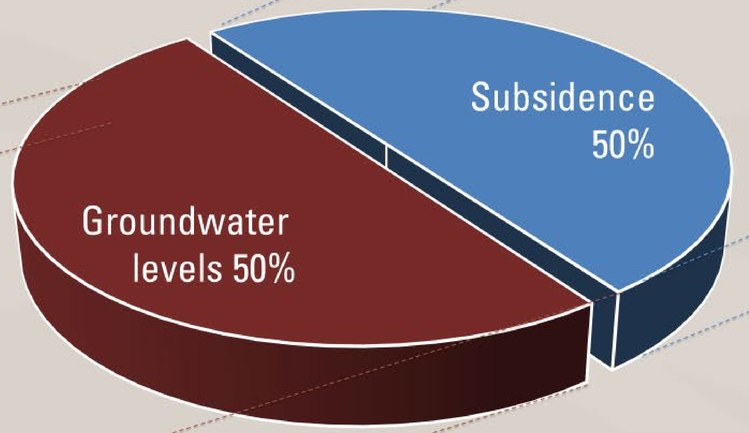
History matching process

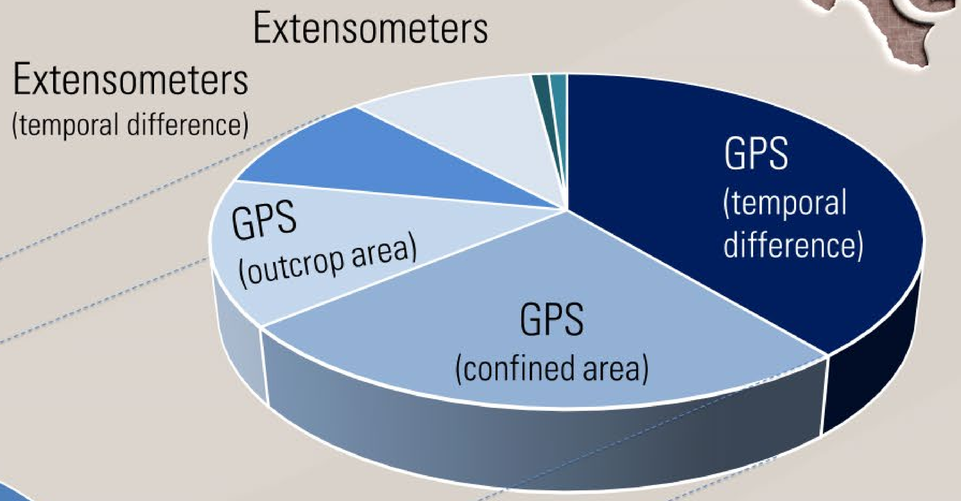
- Calibrate to groundwater levels, subsidence
- Group calibration data by type and assign weights based on data importance

Calibration weighting



GW levels





Subsidence

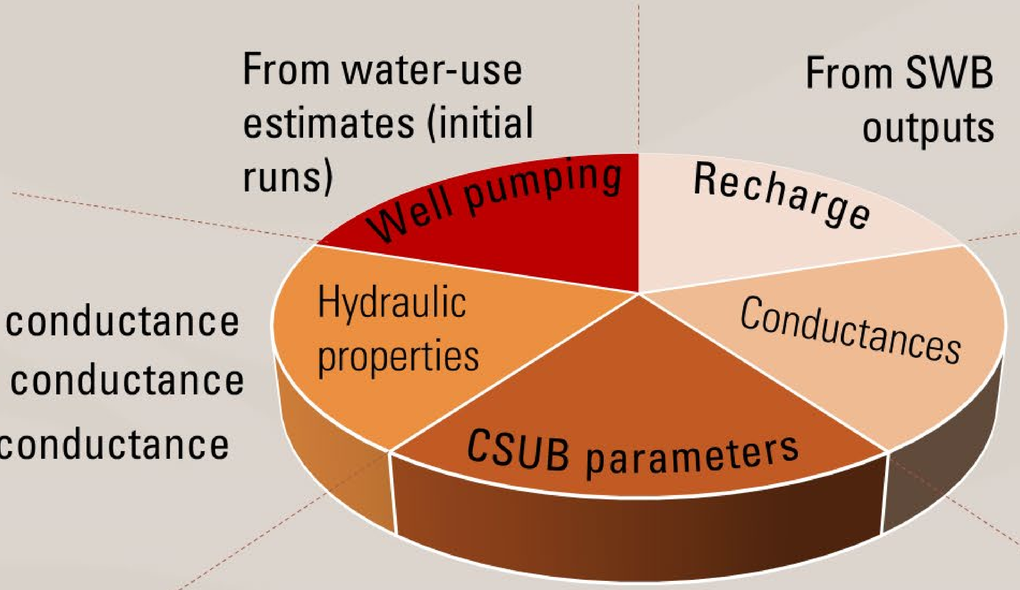
Objective Function: Sum of squared weighted residuals, or sum of all quantifiable error

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

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



Subsidence parameters

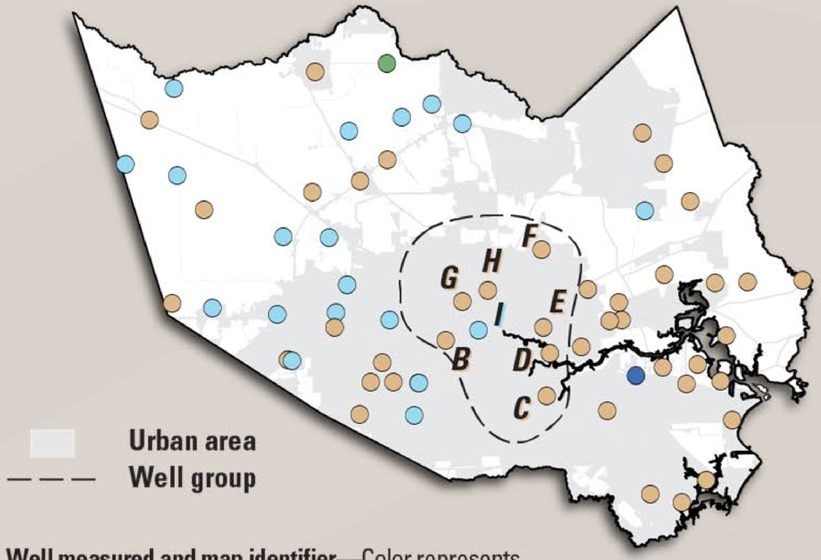
Fine grained
- Elastic specific storage
- Inelastic specific storage
- Porosity
- Vertical hydraulic conductivity

Coarse grained
- Specific storage (elastic)
- Porosity

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



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

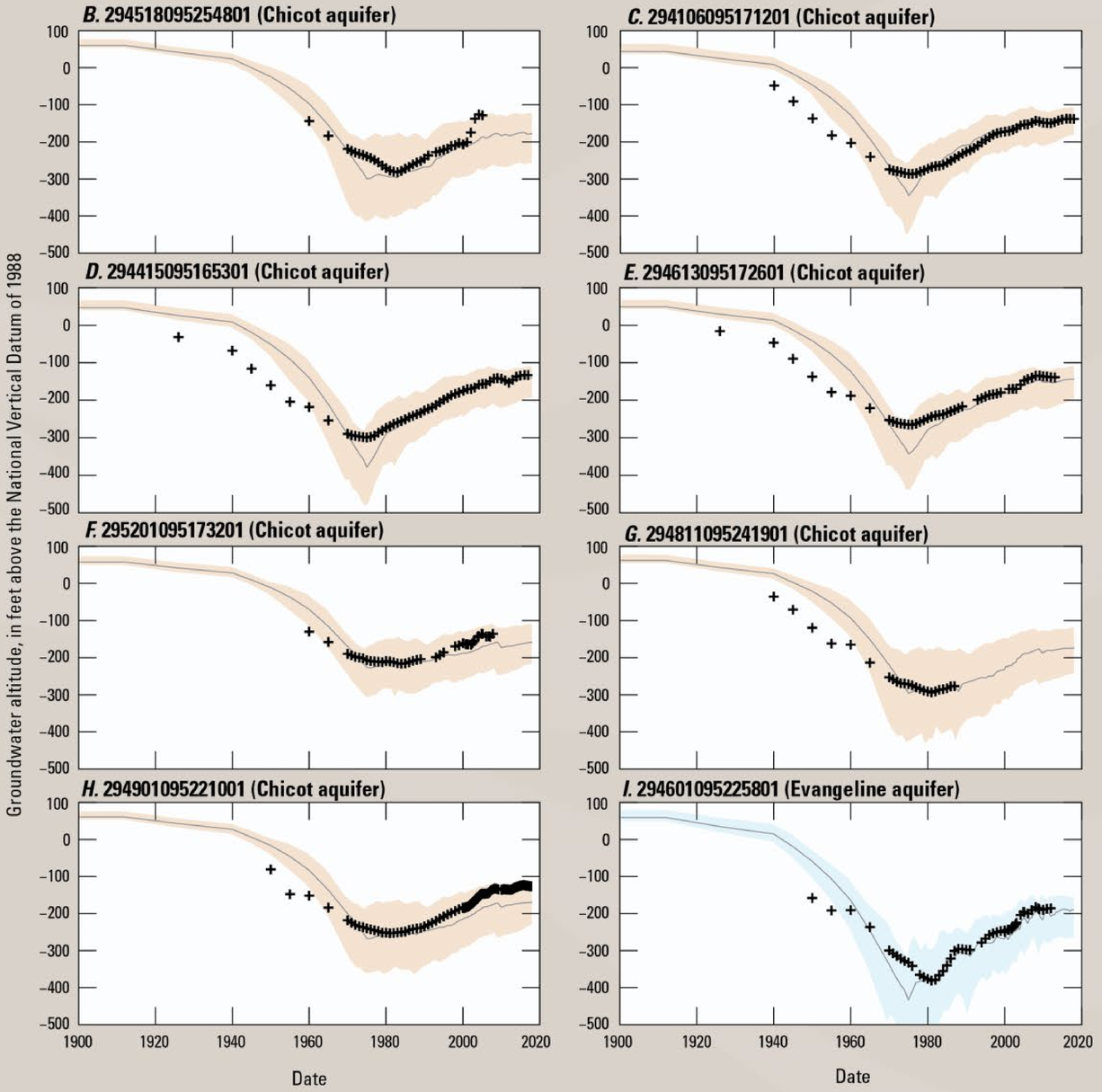
\+ Historical observation

GULF model

GULF model ensemble

Chicot aquifer (model layer 2)

Evangeline aquifer (model layer 3)



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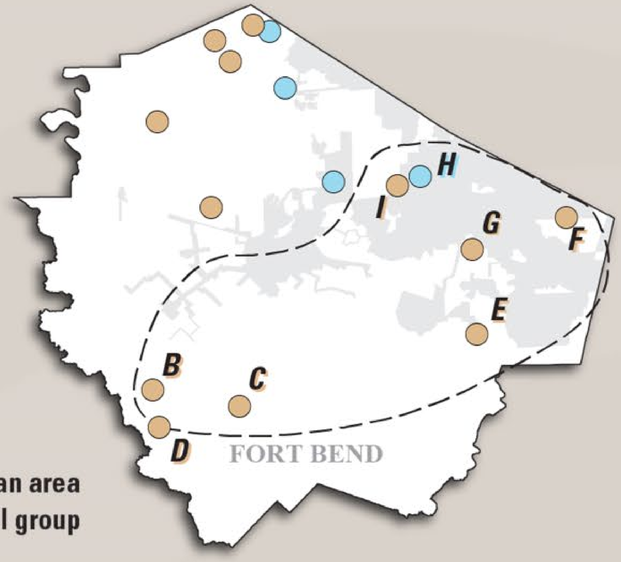

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GULF model

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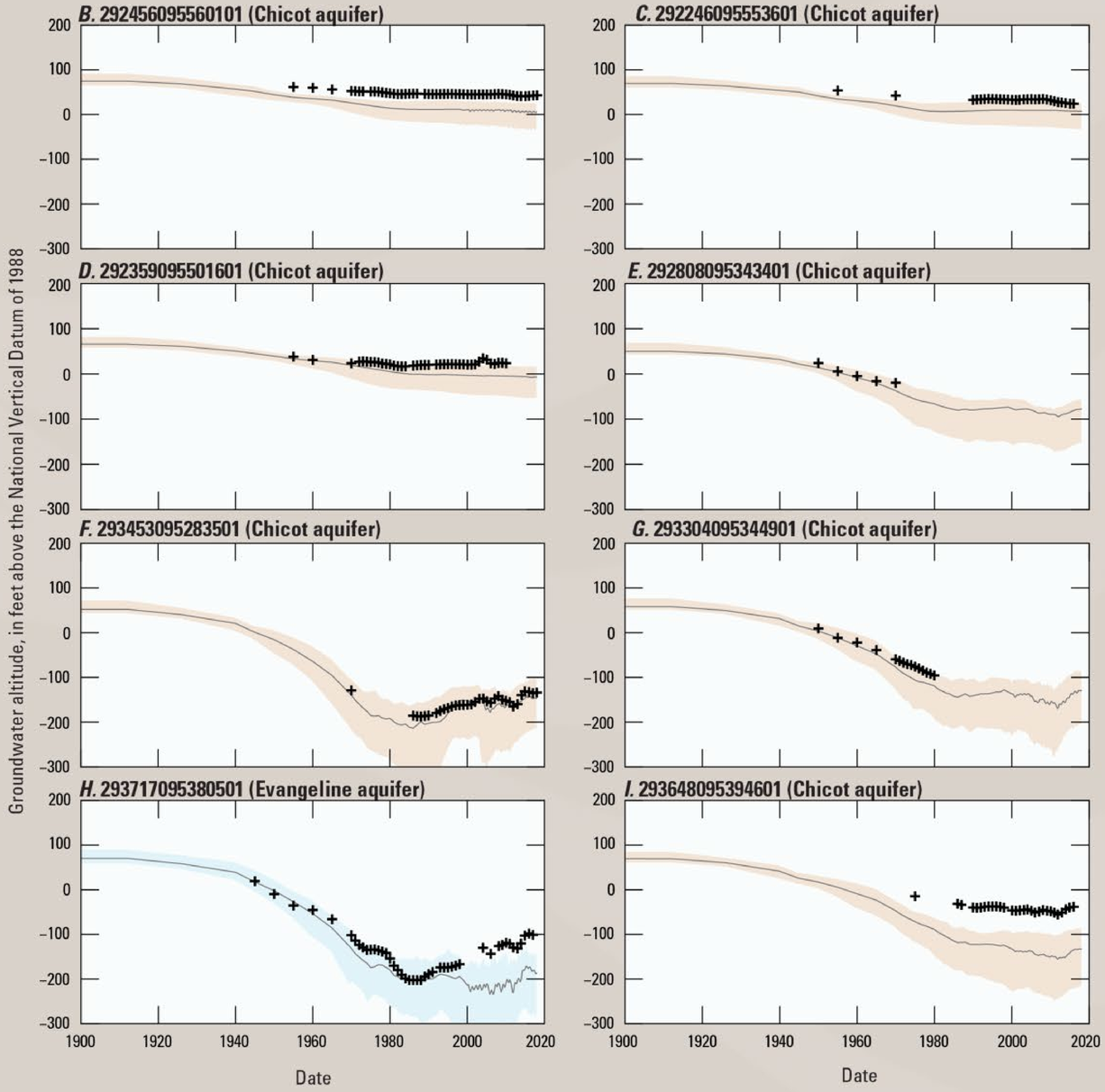

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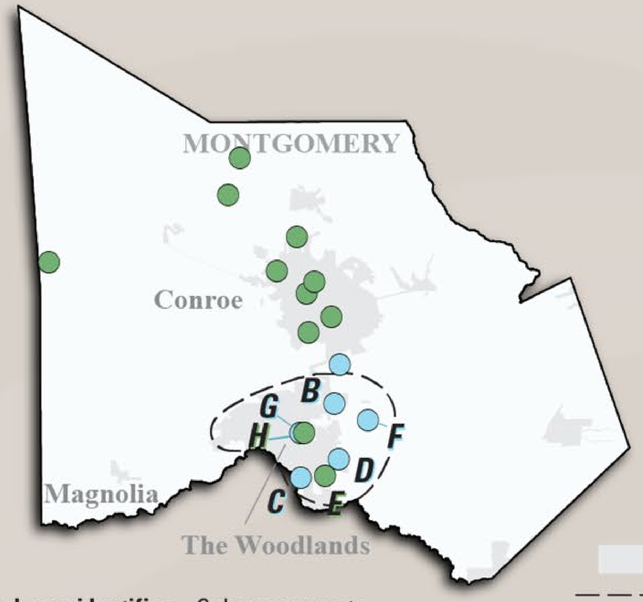


Urban area

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

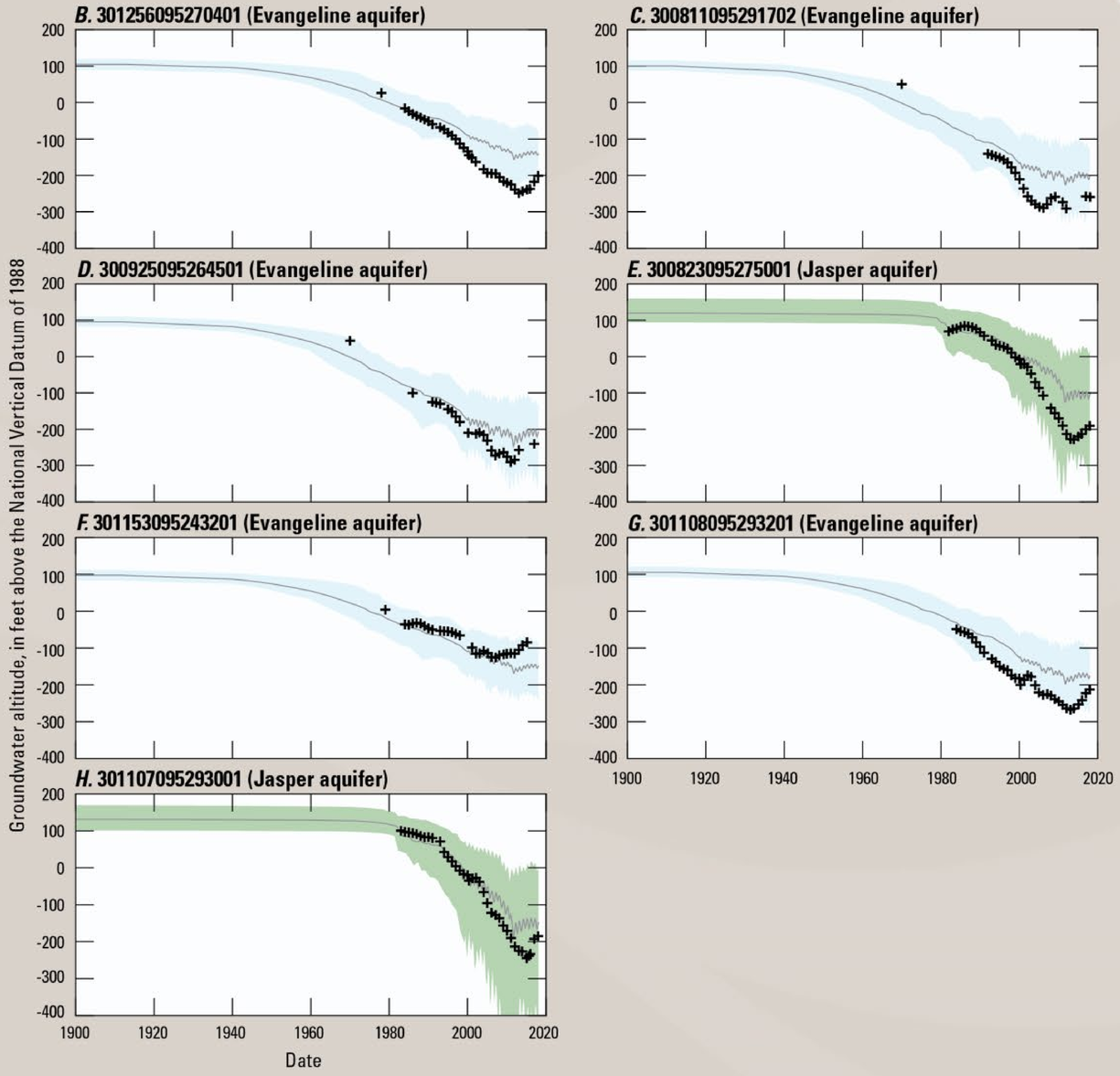
+ Historical observation

GULF model

GULF model ensemble

Chicot aquifer (model layer 2)

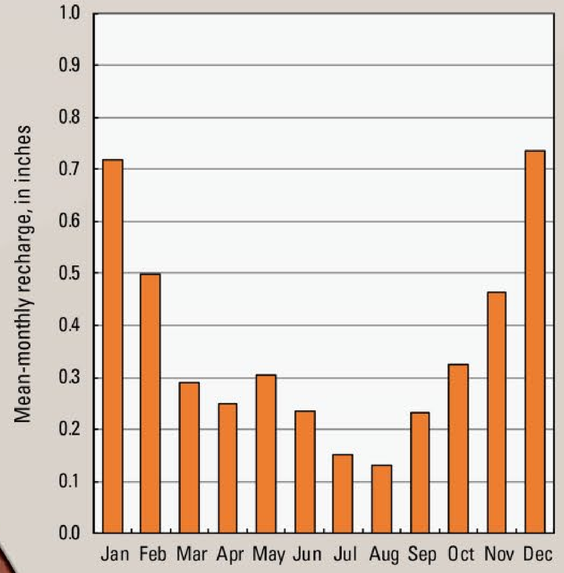
Evangeline aquifer (model layer 3)

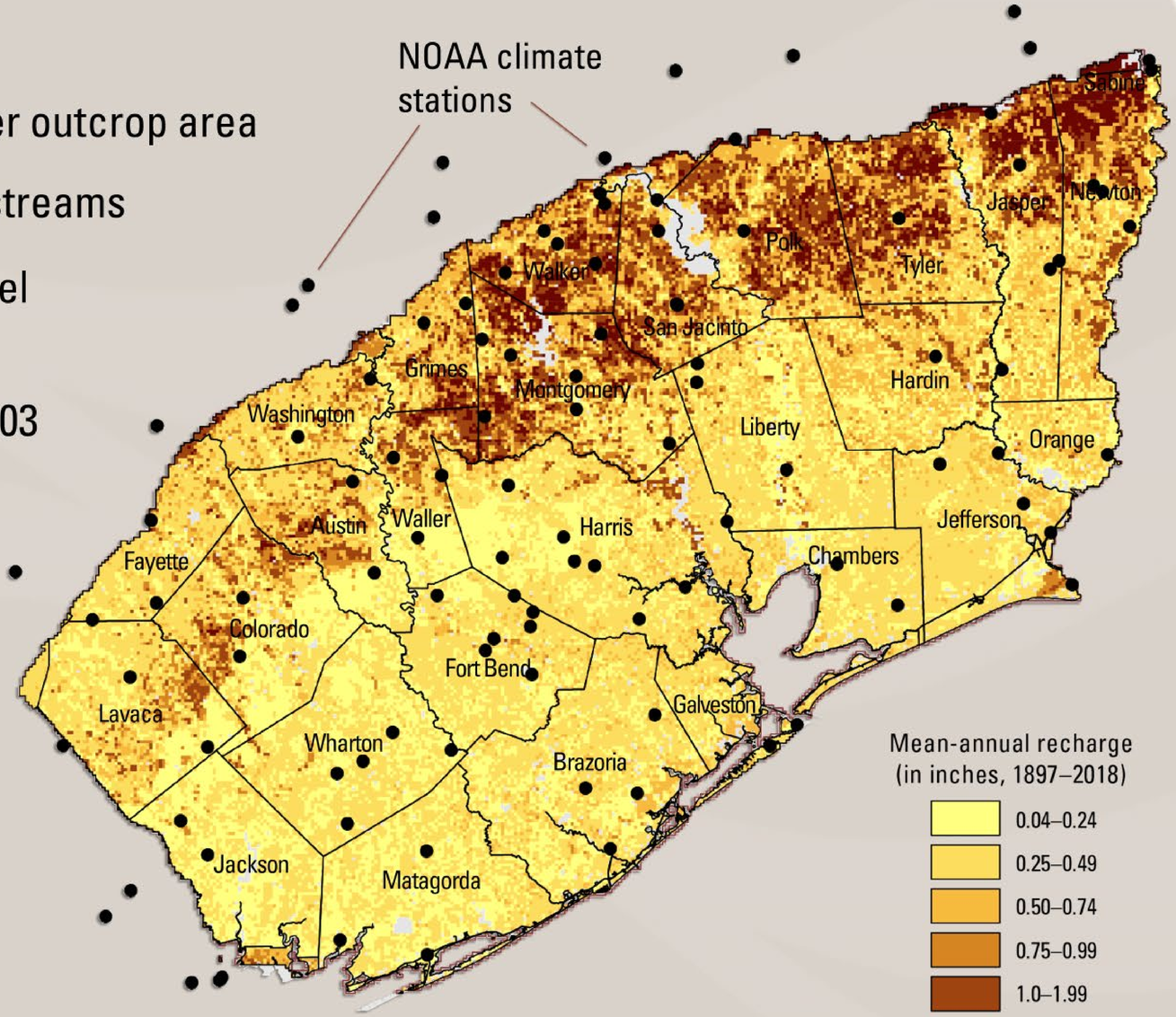


Recharge

Calibrated recharge

- SWB-derived recharge occurs primarily in the aquifer outcrop area
- Majority of the simulated recharge is discharged to streams
- Spatially distributed recharge at right applied to model layer 1.
- Deep recharge: 0.3 in (Chicot), 0.19 in (Evangeline), 0.03 in (Jasper), 0.03 in (Catahoula).





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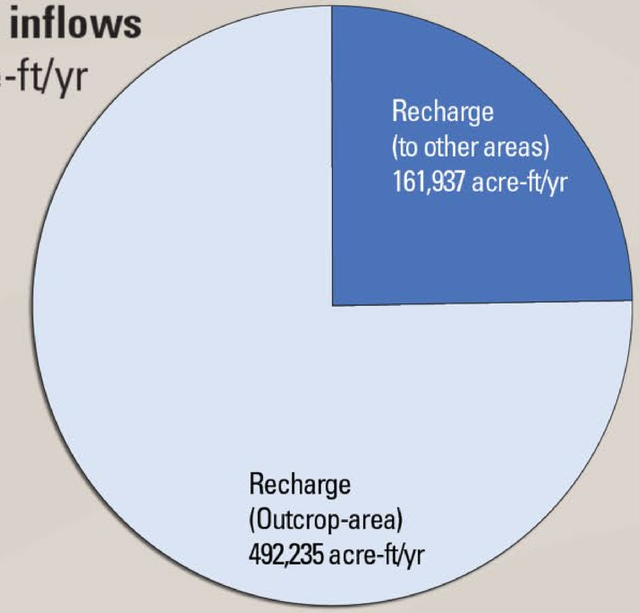
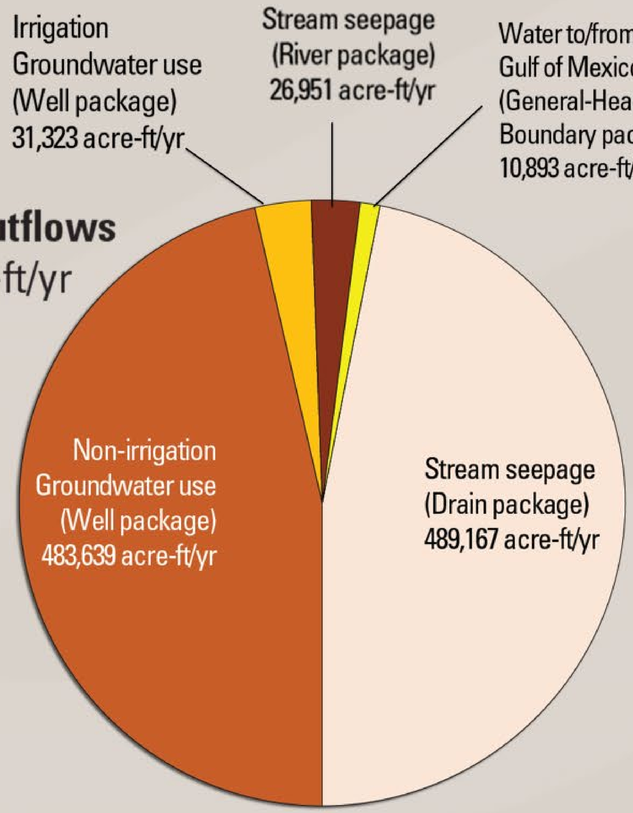
Water Budget

PRELIMINARY RESULTS

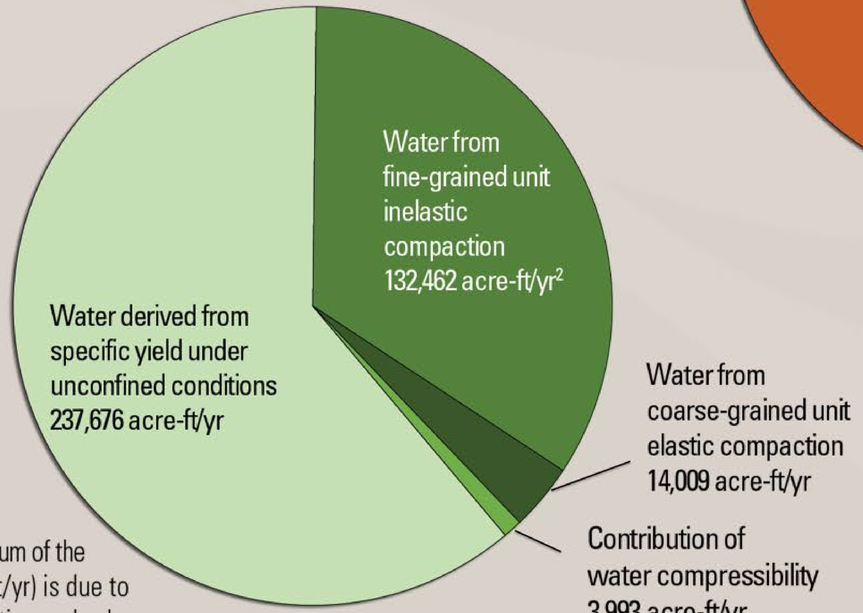
GULF model inflows
654,172 acre-ft/yr



GULF model outflows
1,041,973 acre-ft/yr



GULF model storage loss
(outflows - inflows)
388,140 acre-ft/yr



The difference between the outflows and the sum of the inflows and change in storage (-339 acre-ft/yr) is due to water from fine-grained unit elastic compaction and solver error

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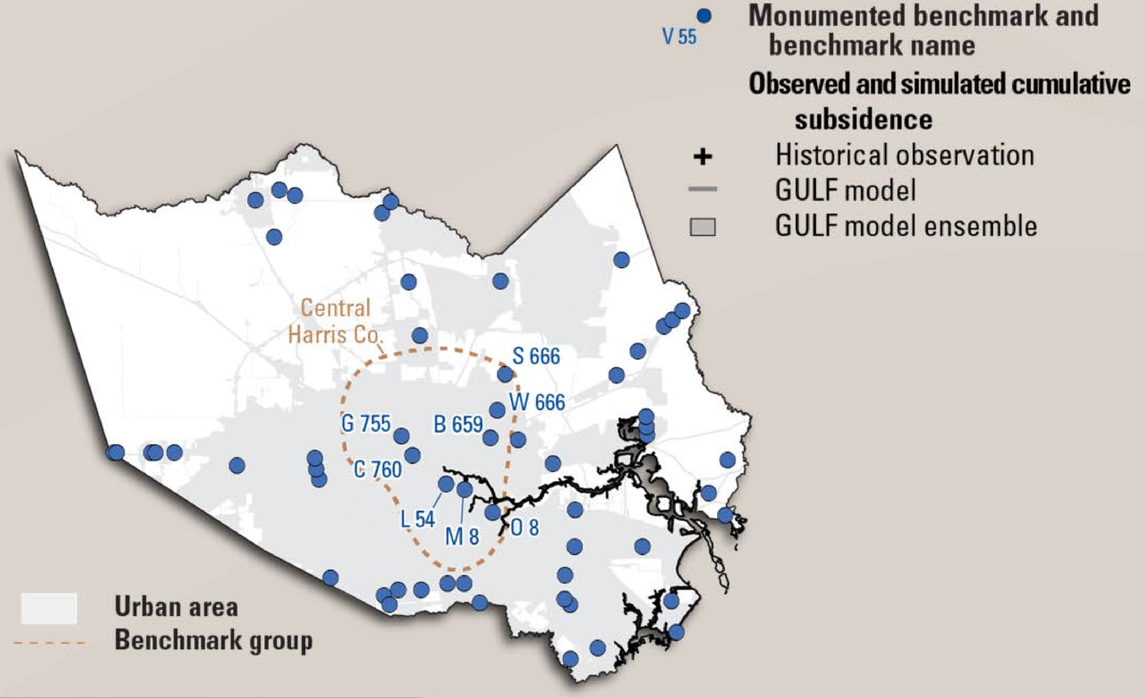
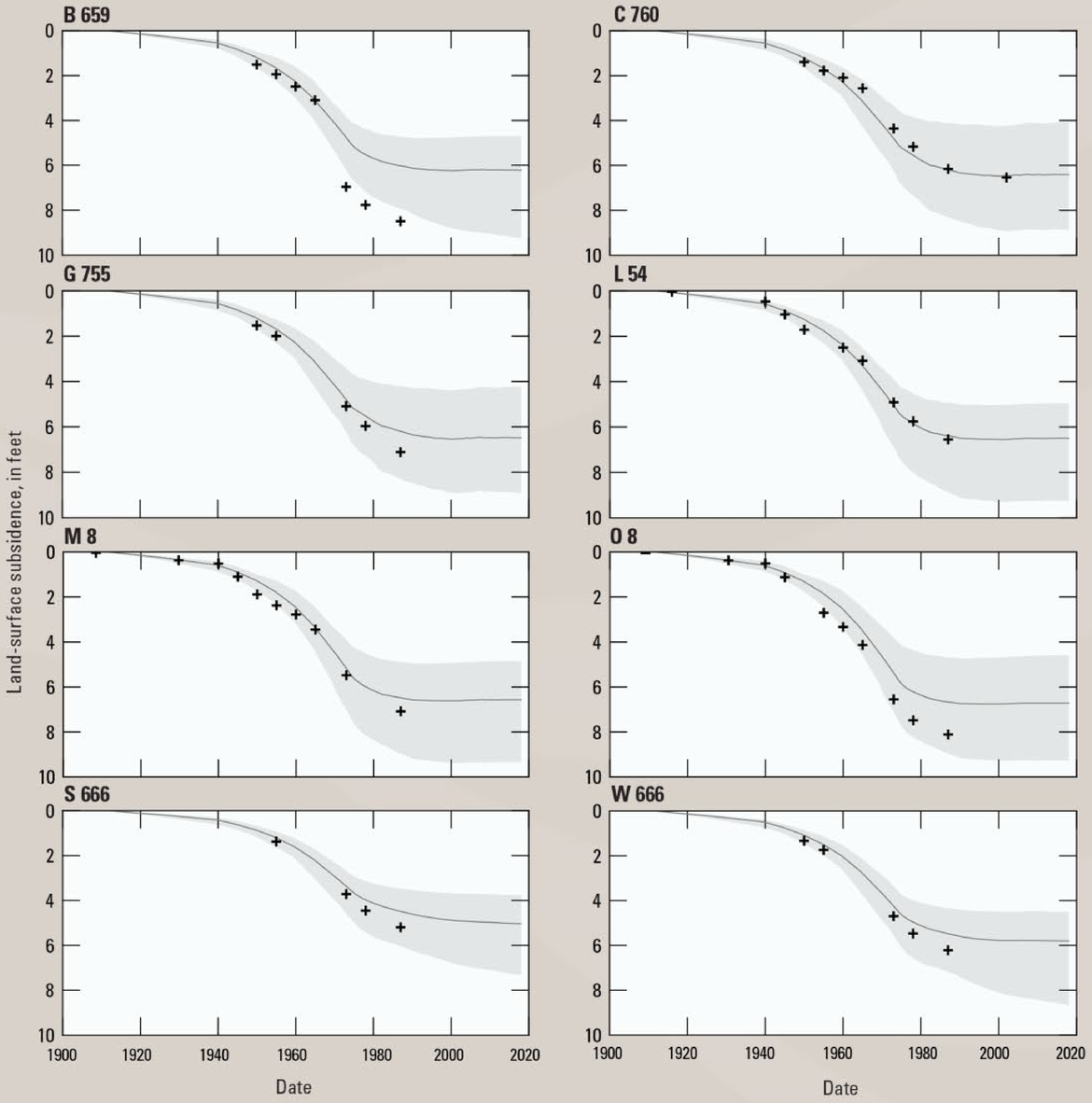
Subsidence

Observed and simulated results

- The range of simulated subsidence generally brackets the historical observations
- Subsidence slightly undersimulated in later periods in central Harris County.

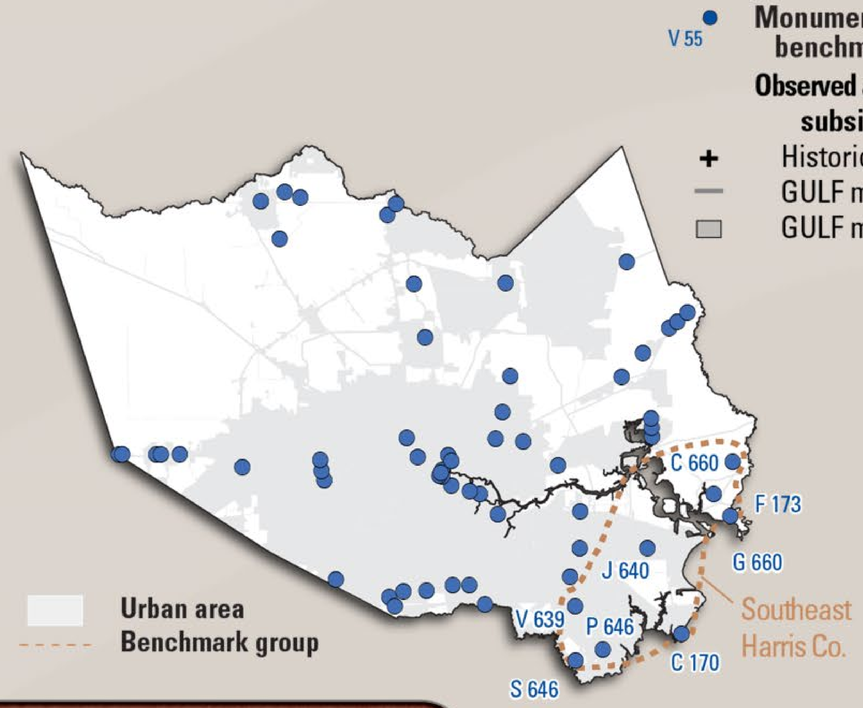


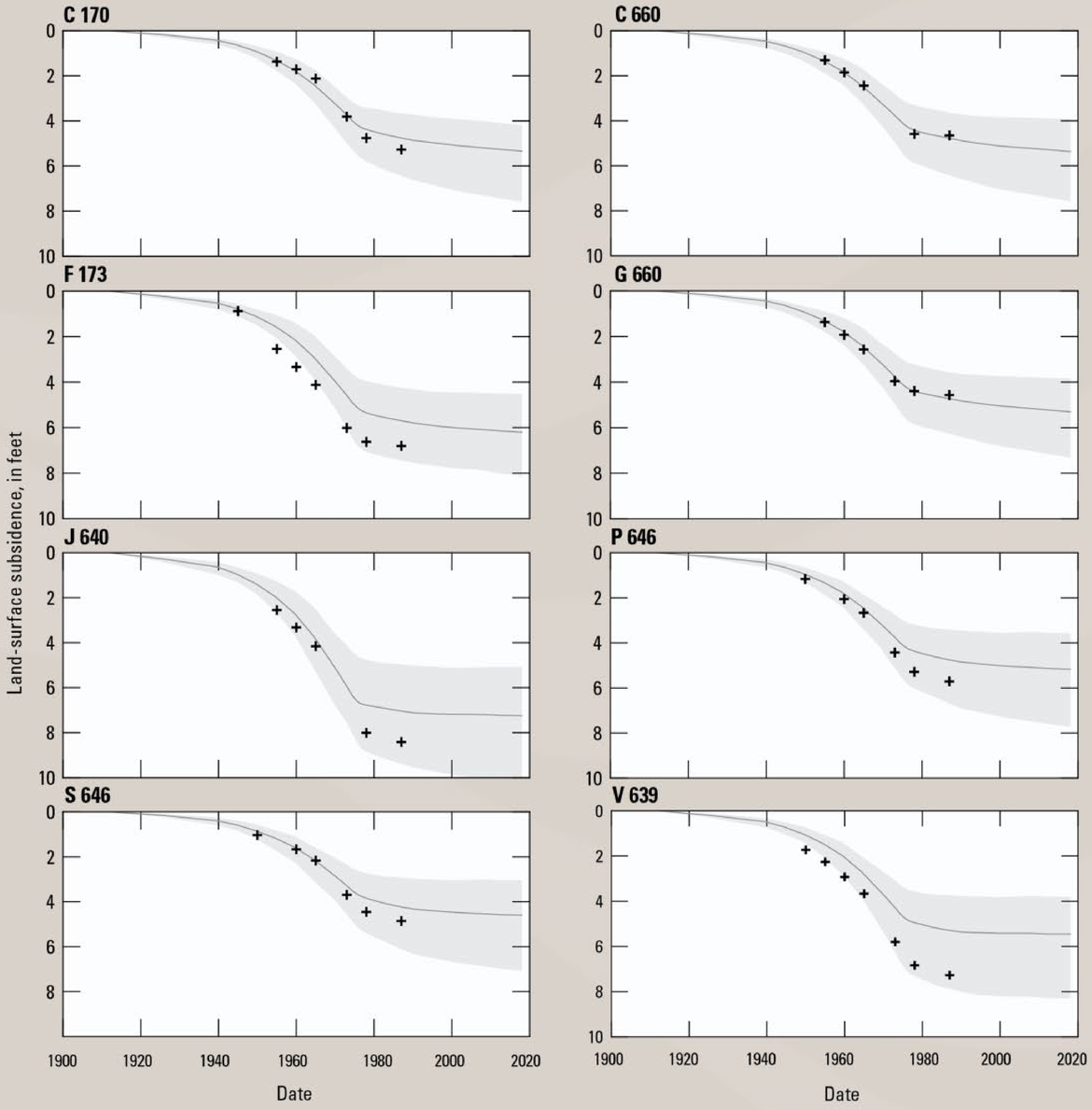


Subsidence

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

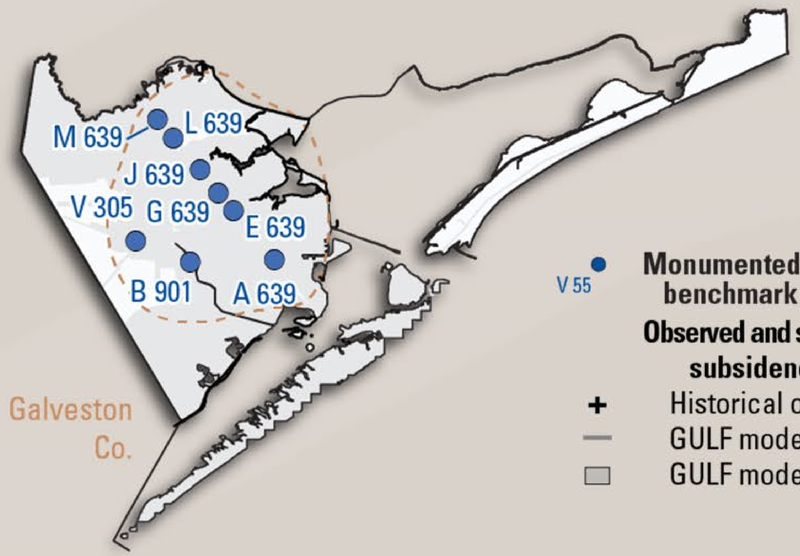


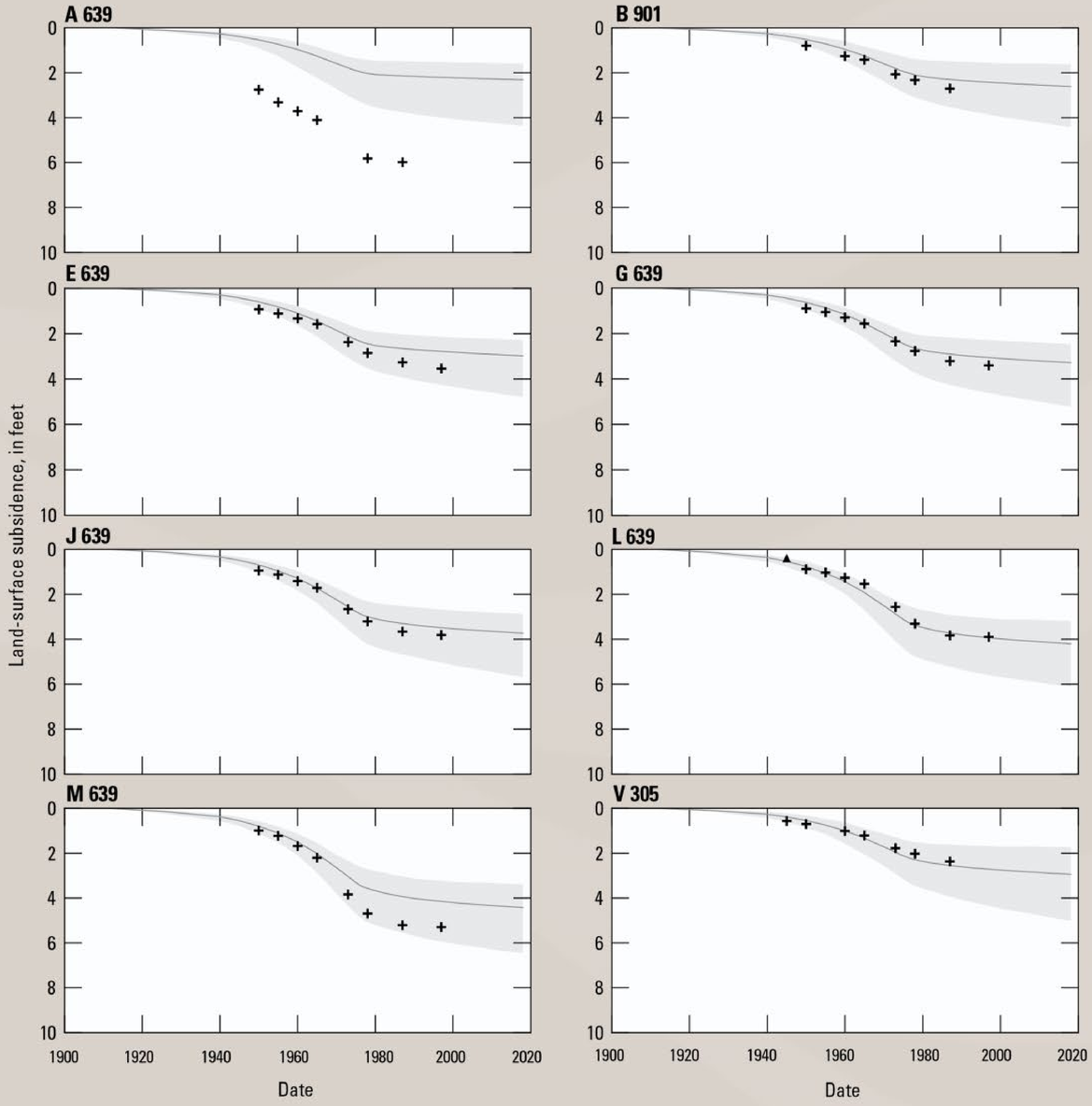


Subsidence

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

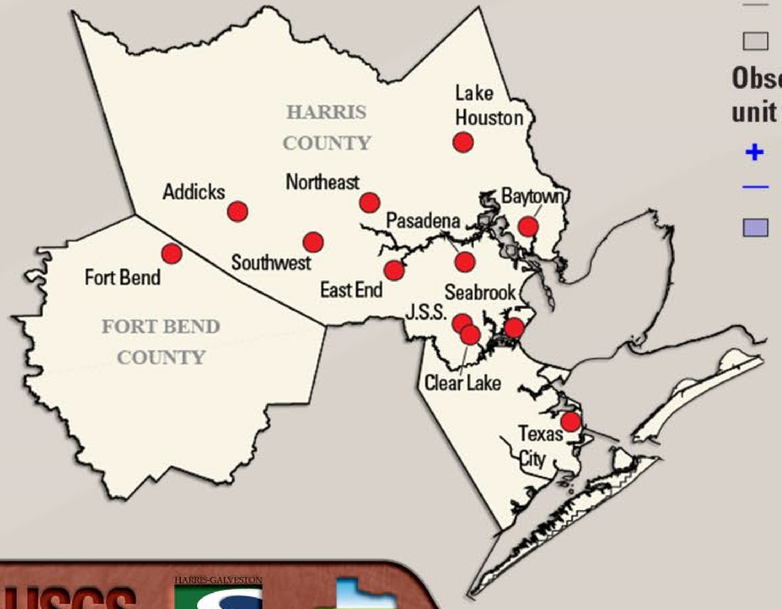




Subsidence

Observed and simulated results

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

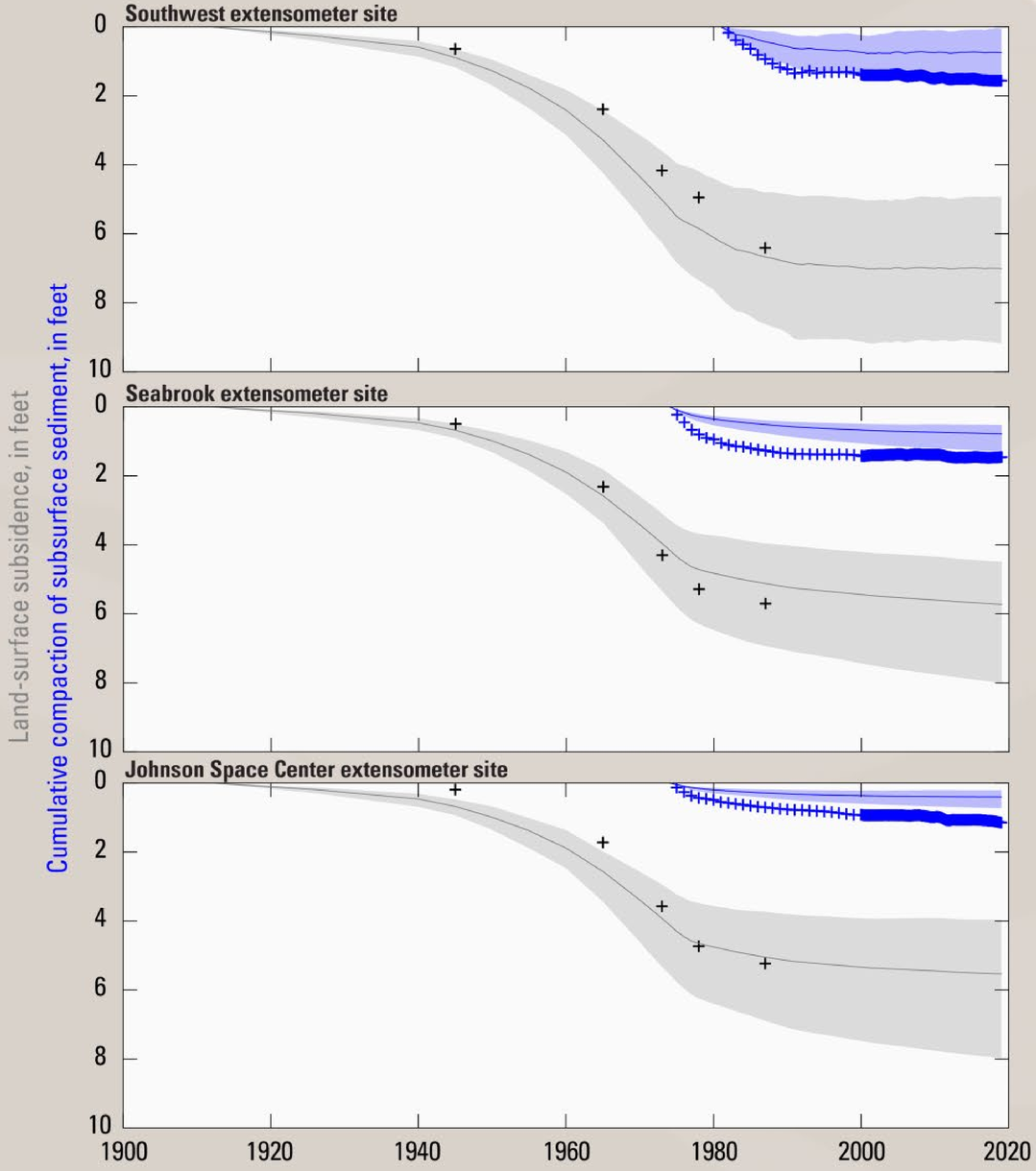


Estimated and simulated subsidence, in feet

- Estimated subsidence
- GULF model
- GULF model ensemble

Observed and simulated aquifer-unit compaction, in feet

- Historical observation
- GULF model
- GULF model ensemble



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