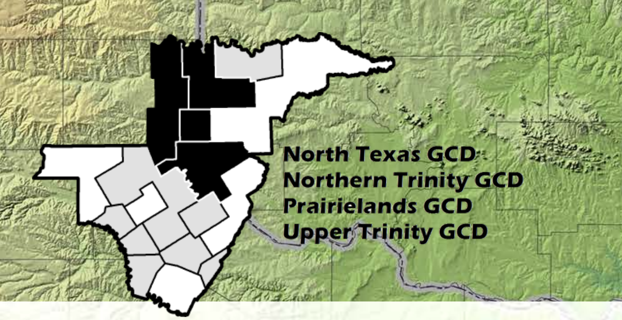
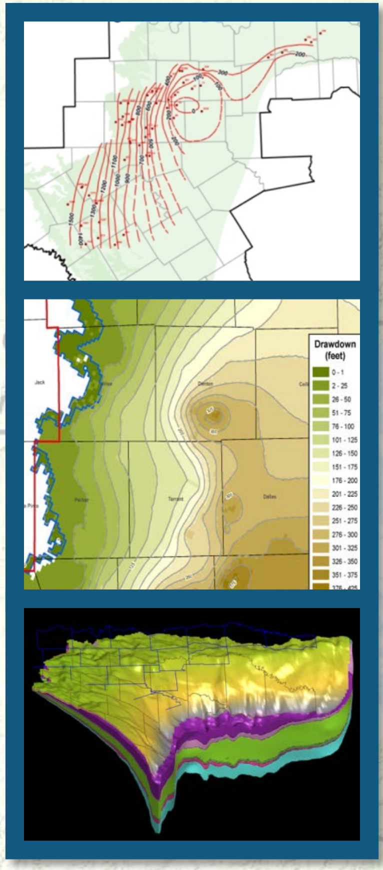


Final Report on the Update of the Trinity/Woodbine Groundwater Availability Model



Presented To:

Groundwater Management Area 8

Presented By:

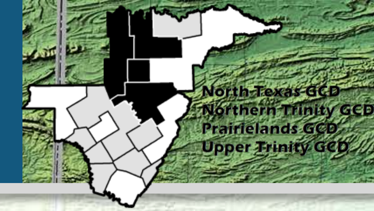
INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

In Association With:

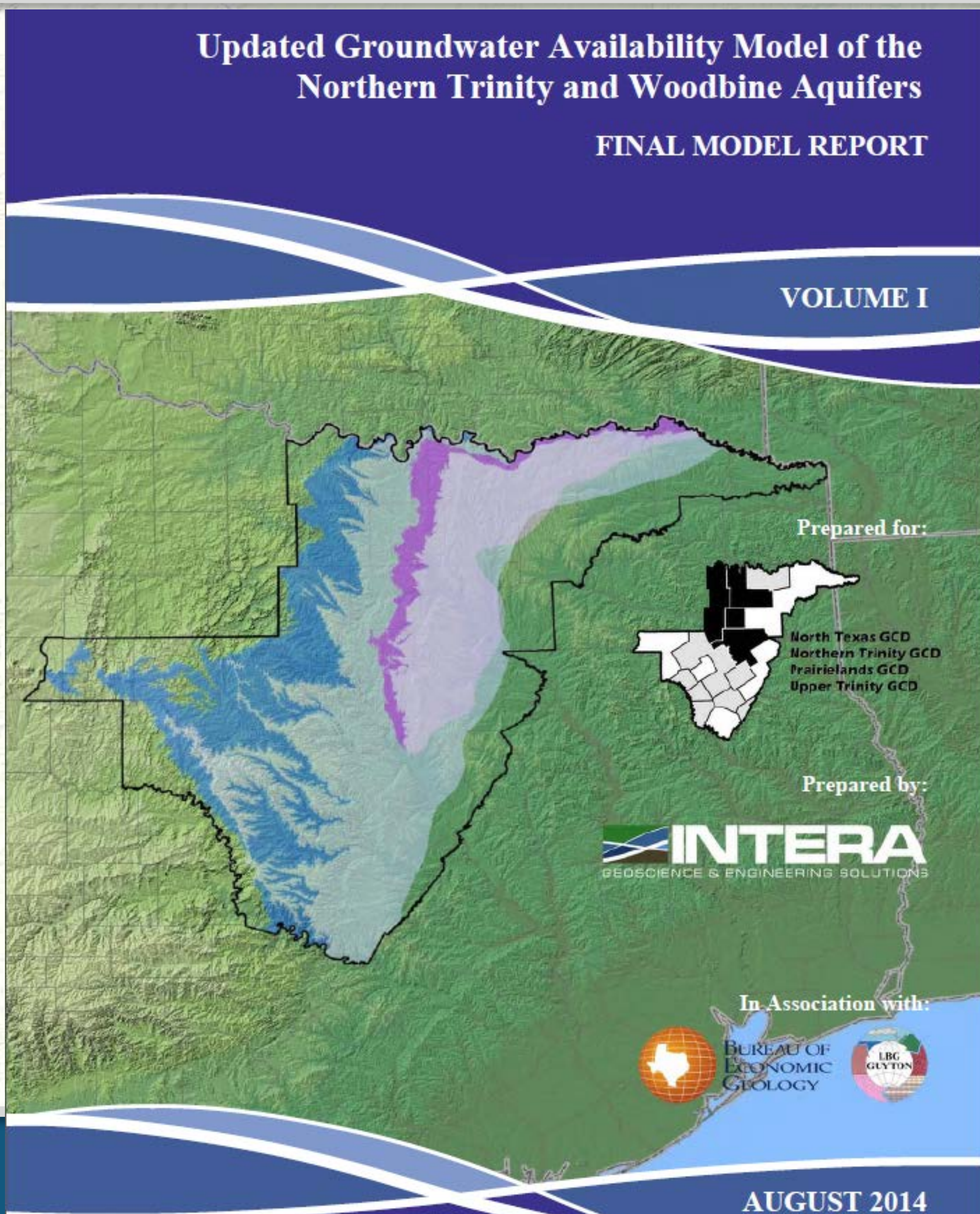
Bureau of Economic Geology

LBG Guyton

November 3, 2014



Model Report



- Developed over a 2 year period with oversight of the Technical Advisory Committee
- Draft Model June 2014
- Final Model August 2014

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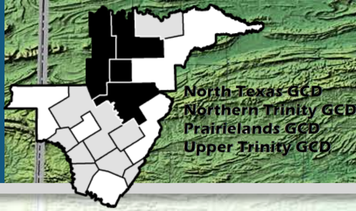
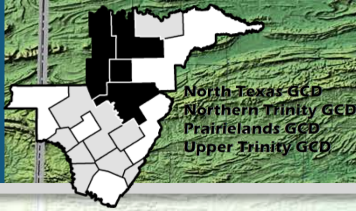
Model Review

- Central Texas GCD
- Southern Trinity GCD
- Dr. Hughbert Collier, P.G. and Mr. Lou Fleischhauer, P.G. of Collier Consulting, Inc;
- Mr. Dennis Erinakes, P.G. of the Prairielands GCD;
- Mr. Mike Massey of the Upper Trinity GCD;
- Mr. Bill Mullican, P.G. of Mullican and Associates;
- Dr. Robert Mace, P.G., Mr. Larry French, P.G., Ms. Cindy Ridgeway, P.G. and Dr. Jerry Shi, P.G. of the TWDB;
- Mr. Mark Kasmarek, P.G., Robert Joseph, P.G. and Mike Turco, P.G., of the United States Geological Survey;
- Mr. Charles Williams, P.G. of WBar-W Groundwater Exploration
- Texas Oil and Gas Association



Hydrologic Conditions

Aquifer Dynamics



Pre-development

recharge → aquifer → discharge

Dynamic equilibrium:
Aquifer recharge is balanced by aquifer discharge

Post-development

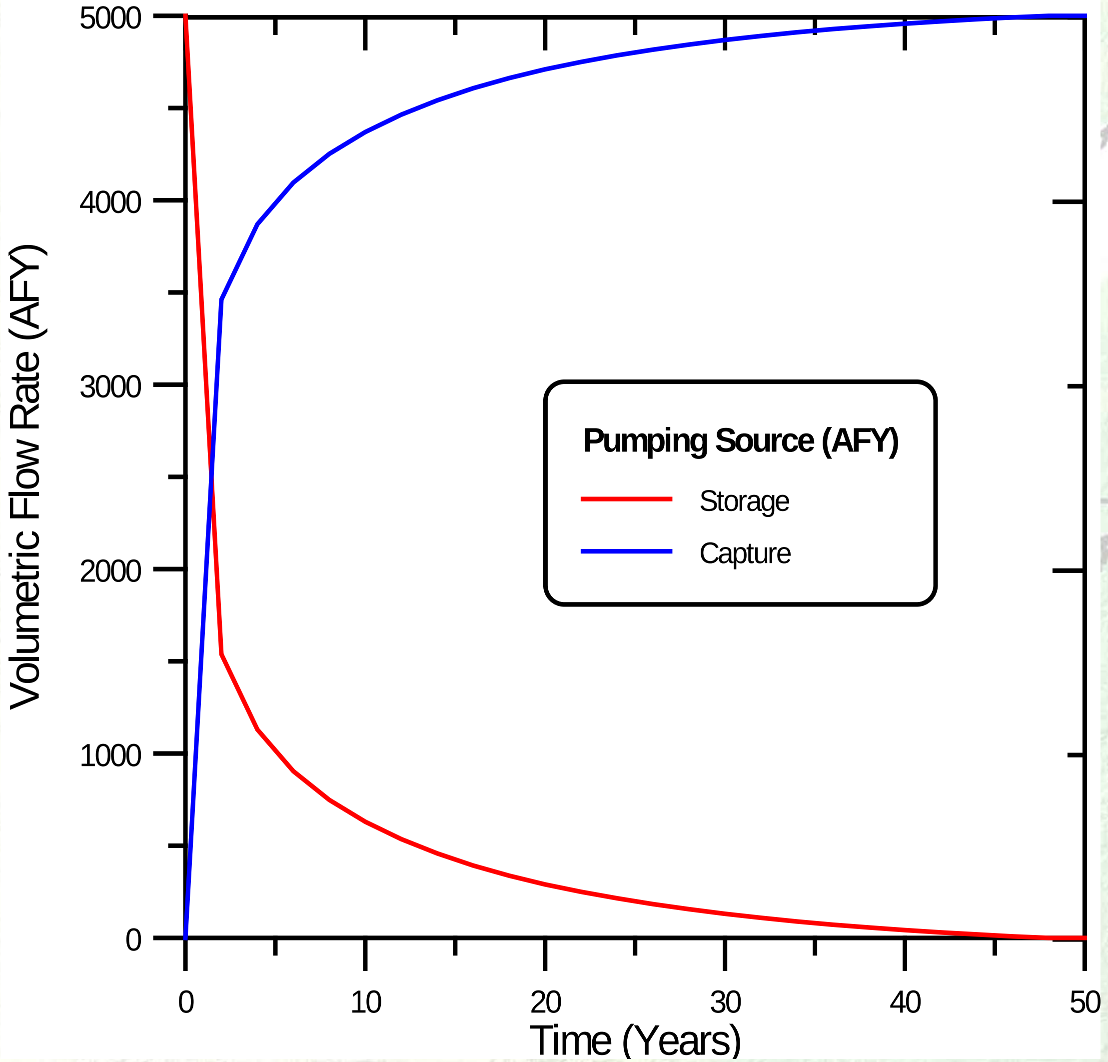
pumping

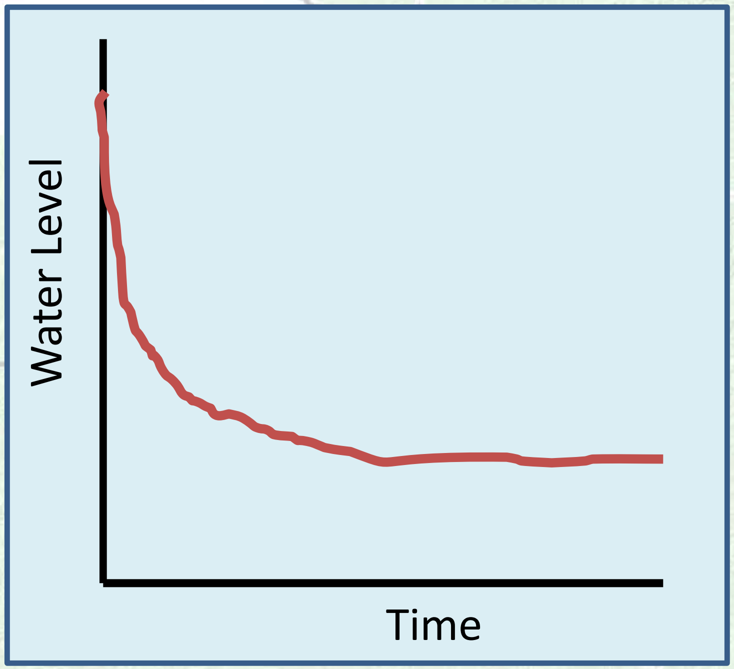
recharge → aquifer → discharge

Dynamic equilibrium:
Pumping is balanced by a reduction in discharge and in some cases an increase in recharge – sometimes termed "capture"

After Alley et al, (1999) and Bredehoeft (2002)

Aquifer Response to Pumping

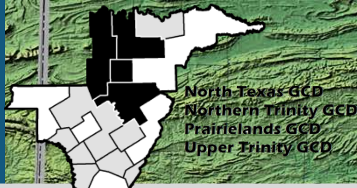


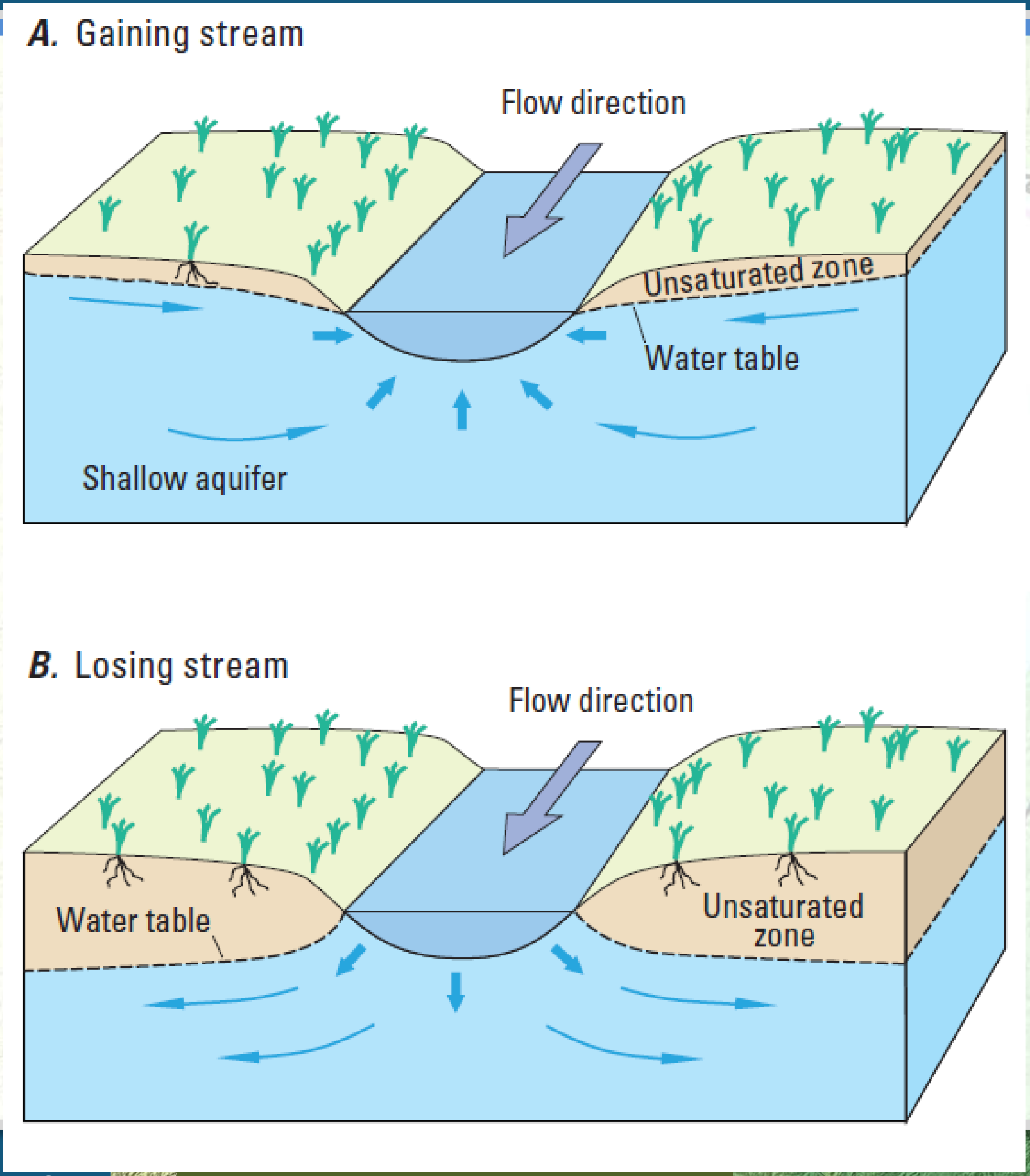


Sources of Capture

- Capture is a decrease in discharge from:
  - Streams
  - Groundwater ET
  - Cross-formational flow to younger formations
  - Springs
- Also can be increased recharge in certain circumstances once streams become dominantly losing

Stream-Aquifer Terminology

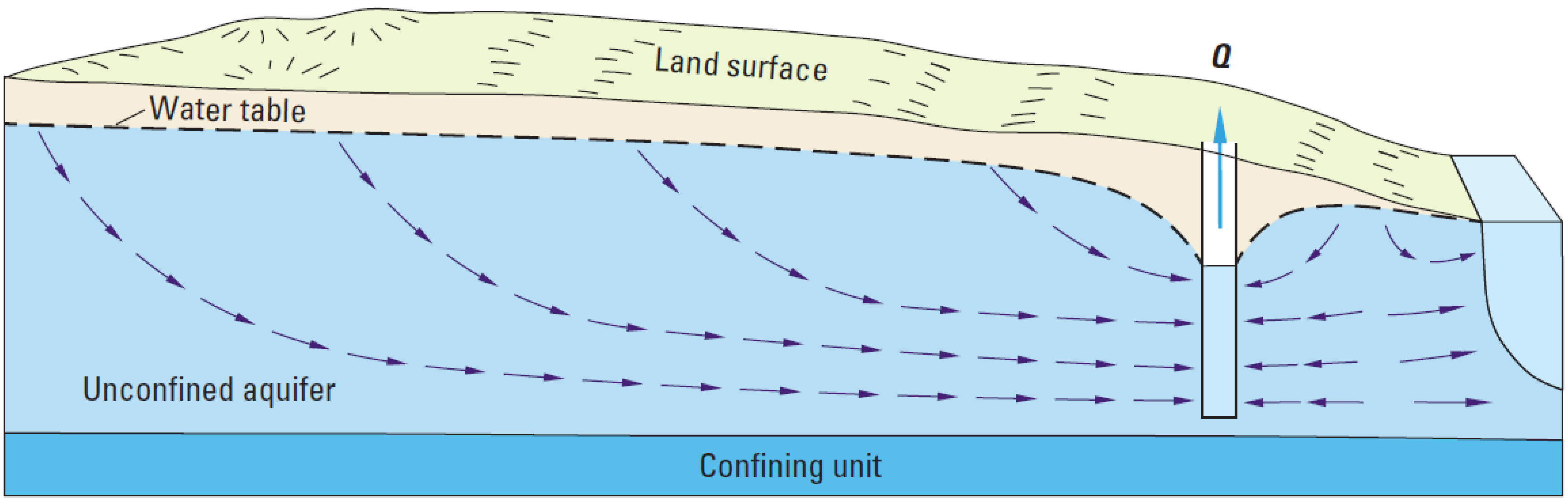


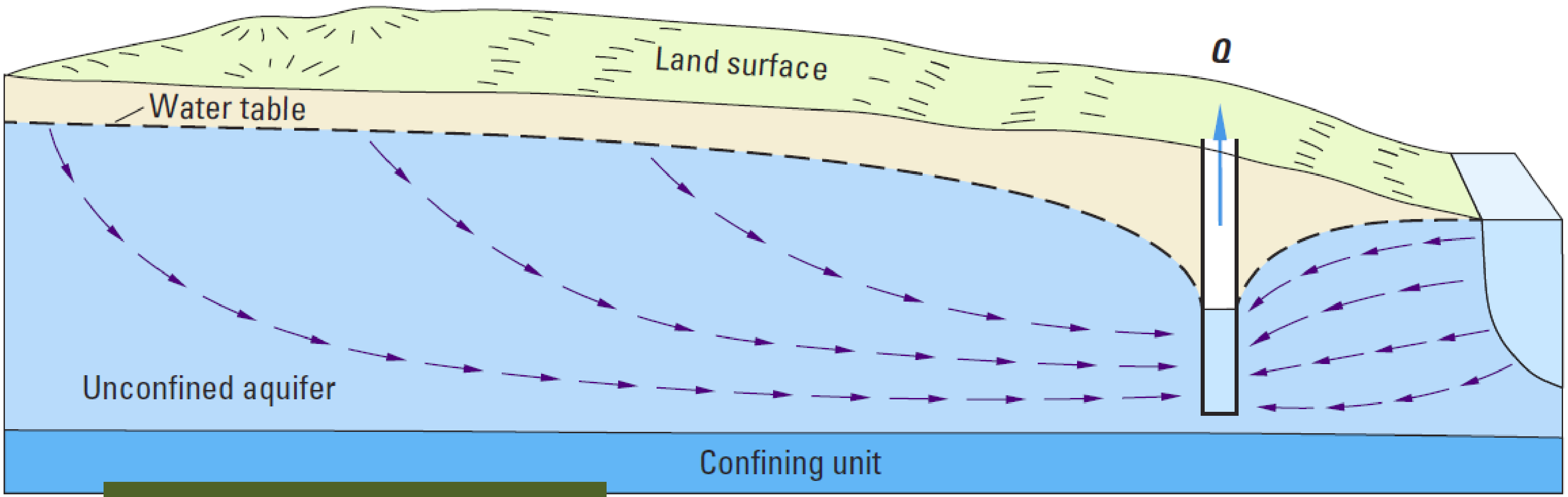


USGS Circular 1376, 2012

- Gaining
  - Net discharge of groundwater to surface water “ base flow”
- Losing:
  - Net discharge of surface water to groundwater “recharge”

Shallow Pumping Near a Stream

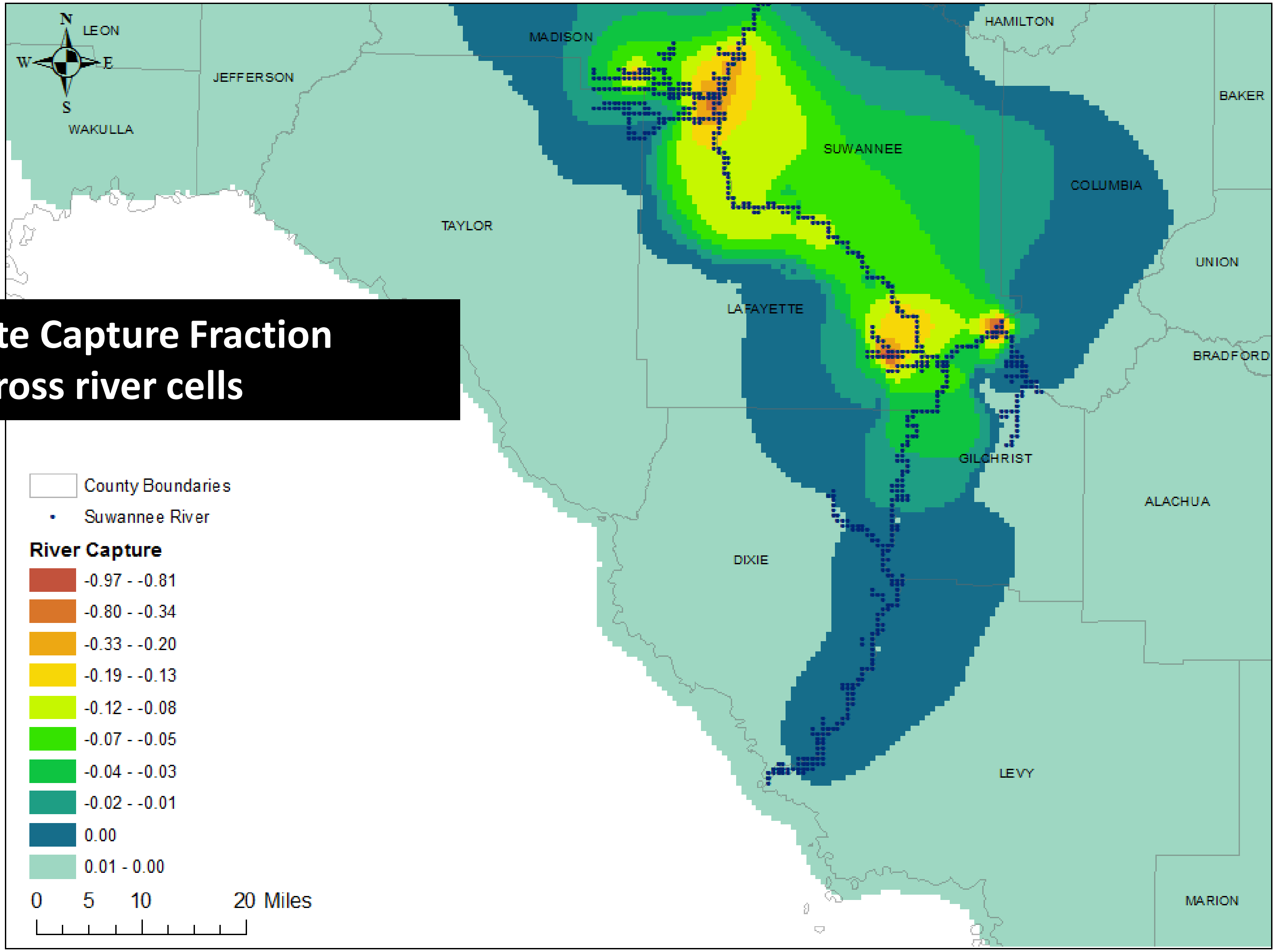




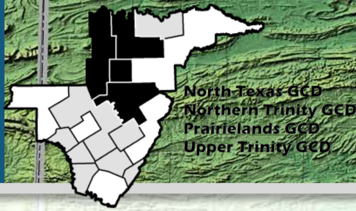
USGS Circular 1376, 2012

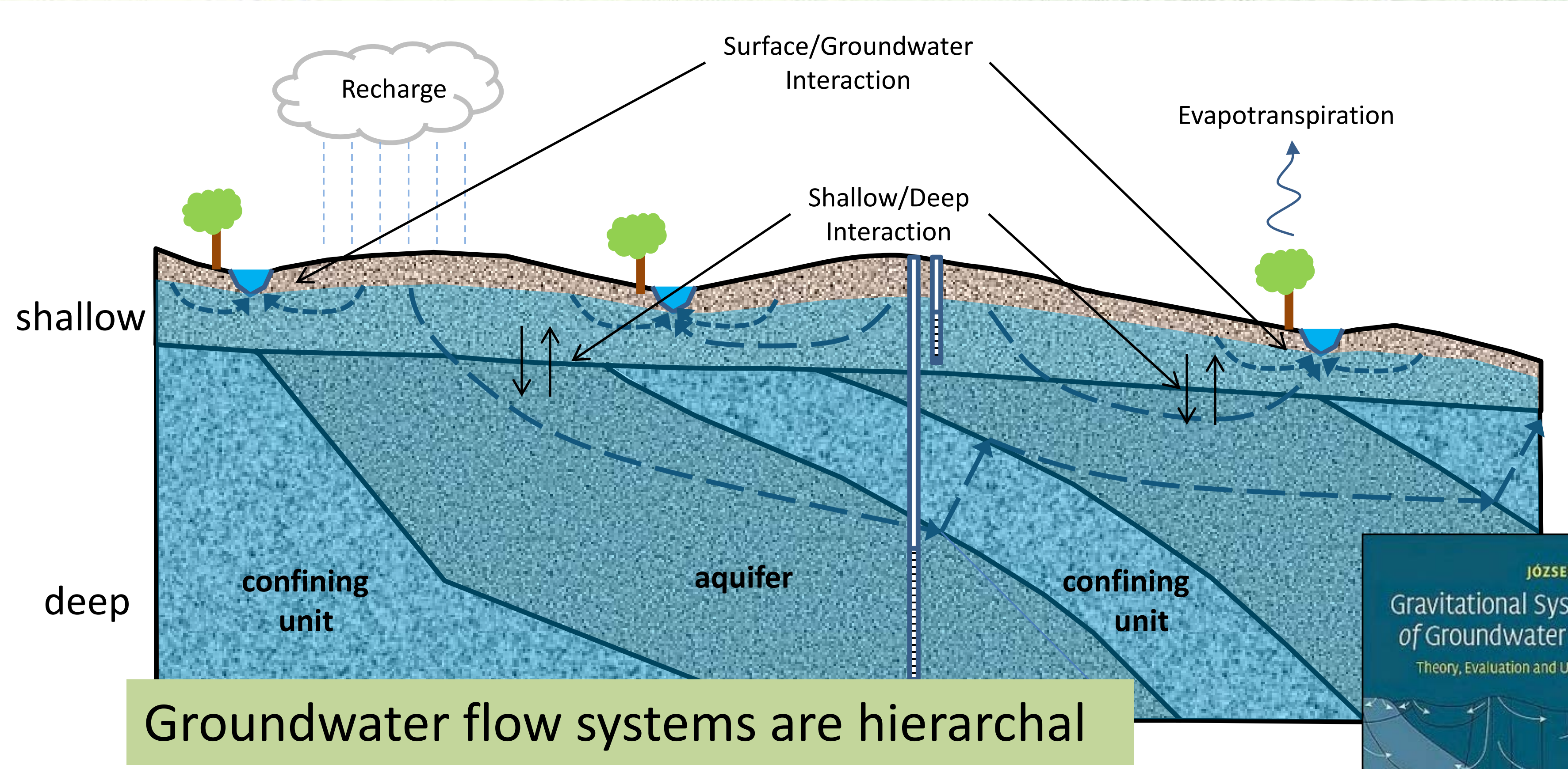
Regional Depiction of Base Flow Capture

Steady-State Capture Fraction for flow across river cells



Groundwater Systems are Hierarchal

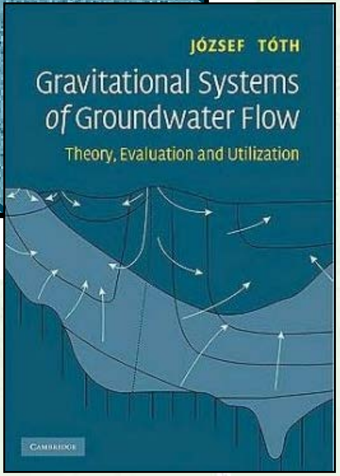




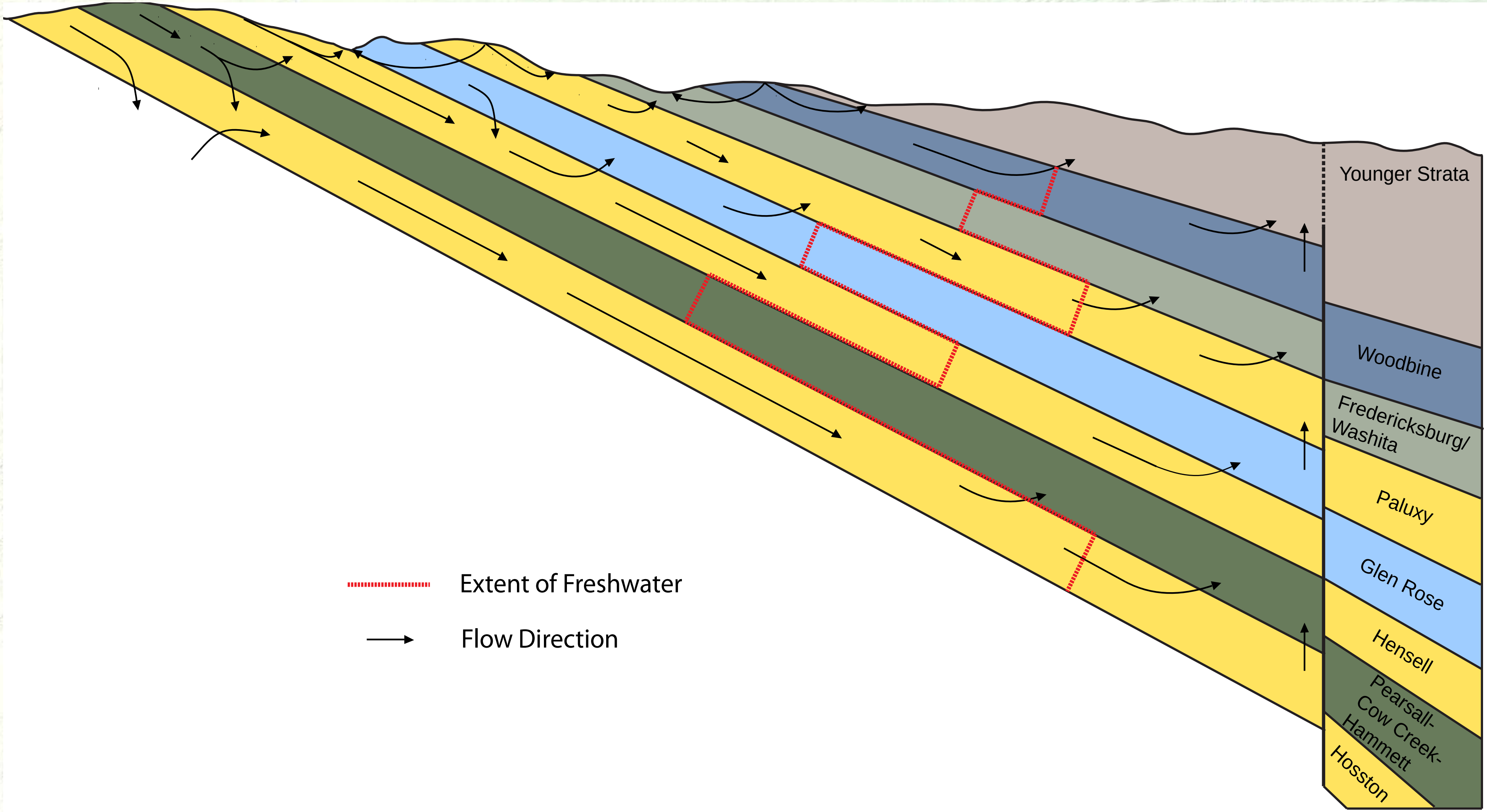
Groundwater flow systems are hierarchal

Local Flow System: < 1-mile Model Grid Scale

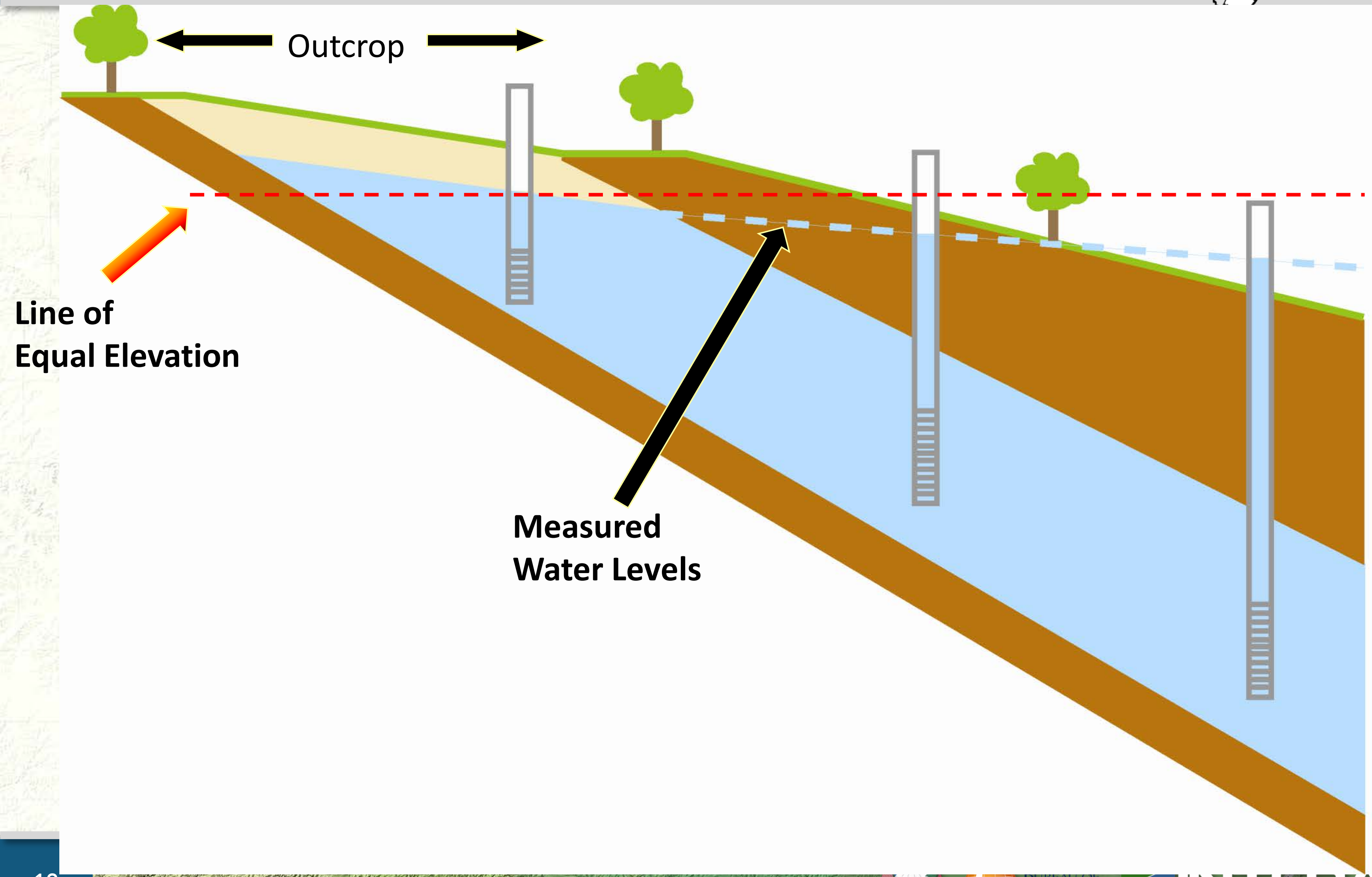
Regional Flow System: > 1-mile Model Grid Scale



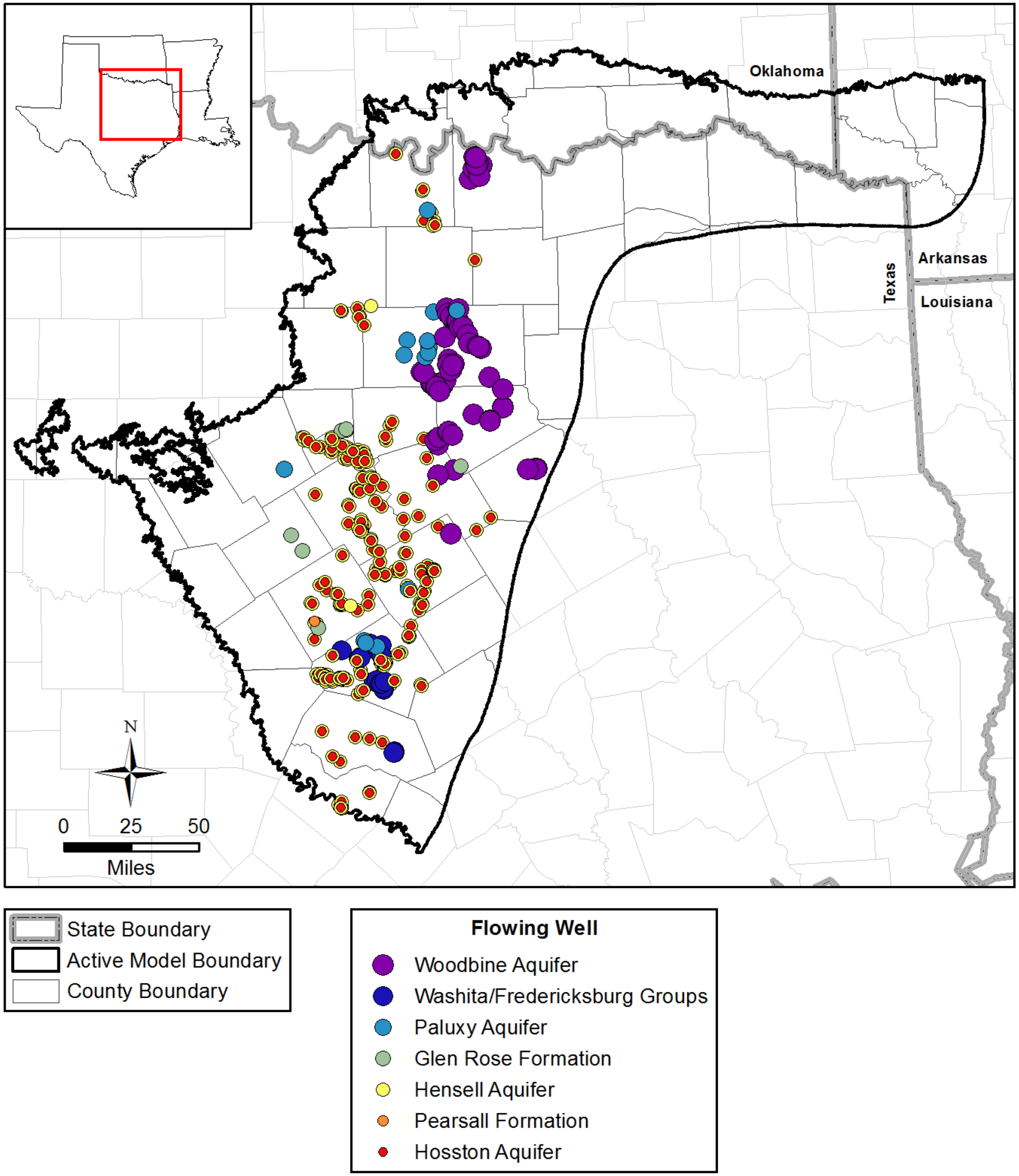
Predevelopment Schematic of Flow

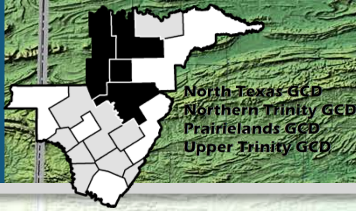


Predevelopment

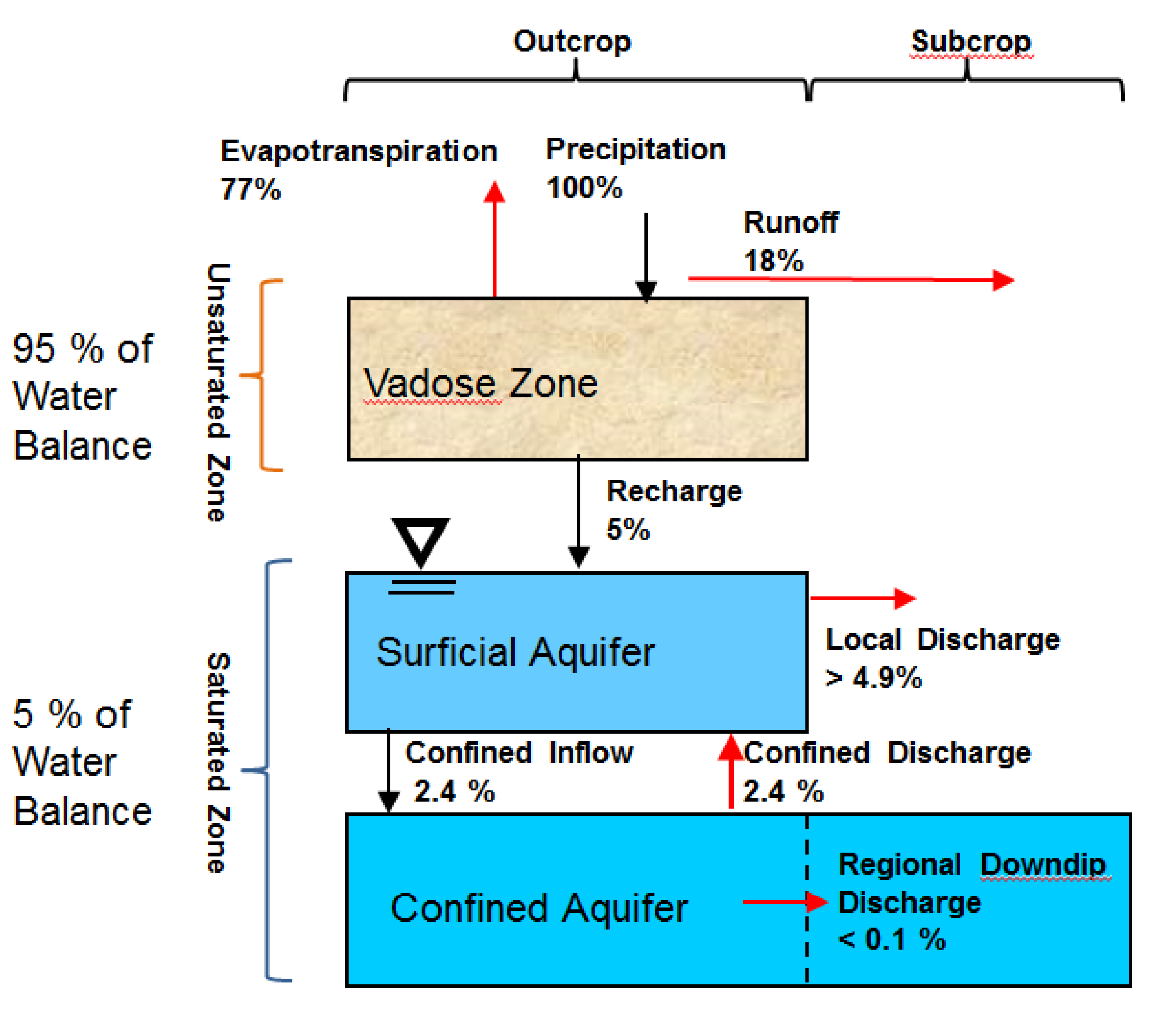


Flowing Wells

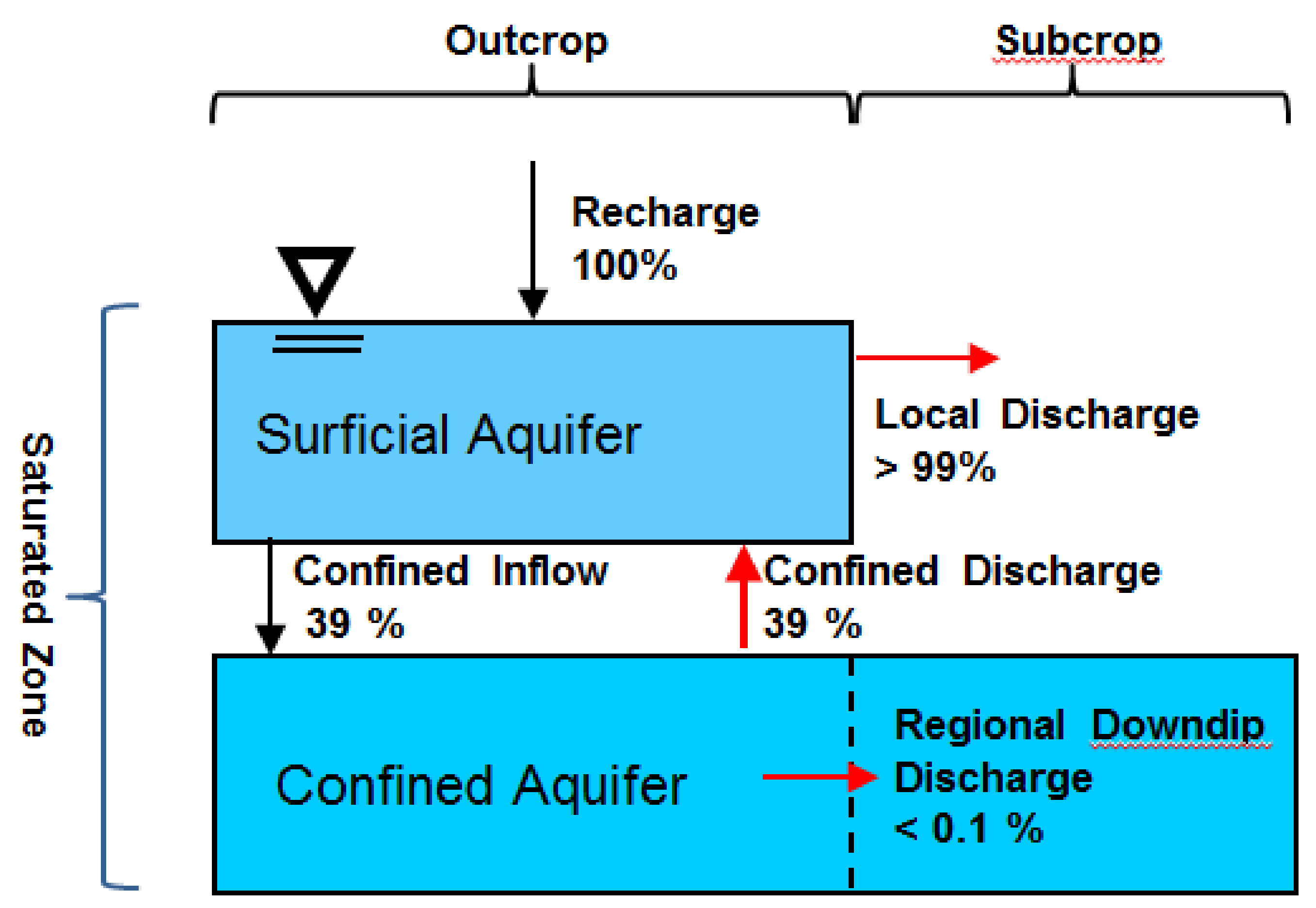




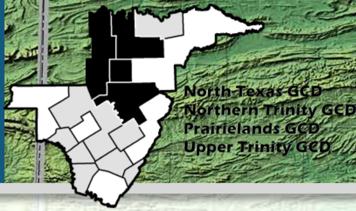
Conceptual Total Water Balance



Conceptual Groundwater Balance

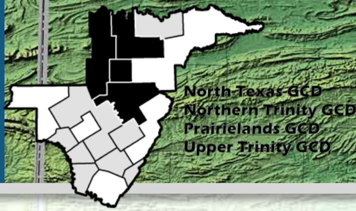


Hydrostratigraphic Framework



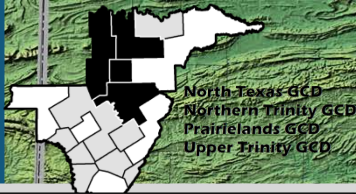
- First comprehensive hydrostratigraphic framework developed for the northern Trinity and Woodbine aquifers from the Colorado River through Oklahoma Antlers
- Correlation using modern methods and tools
- Assembled 1498 geophysical logs
  - 1302 used for Aquifer/Formation boundaries
  - 988 used for lithology interpretation at the few foot level
- Developed
  - Structure, Cross-Sections, Net Sand & Depositional Environments

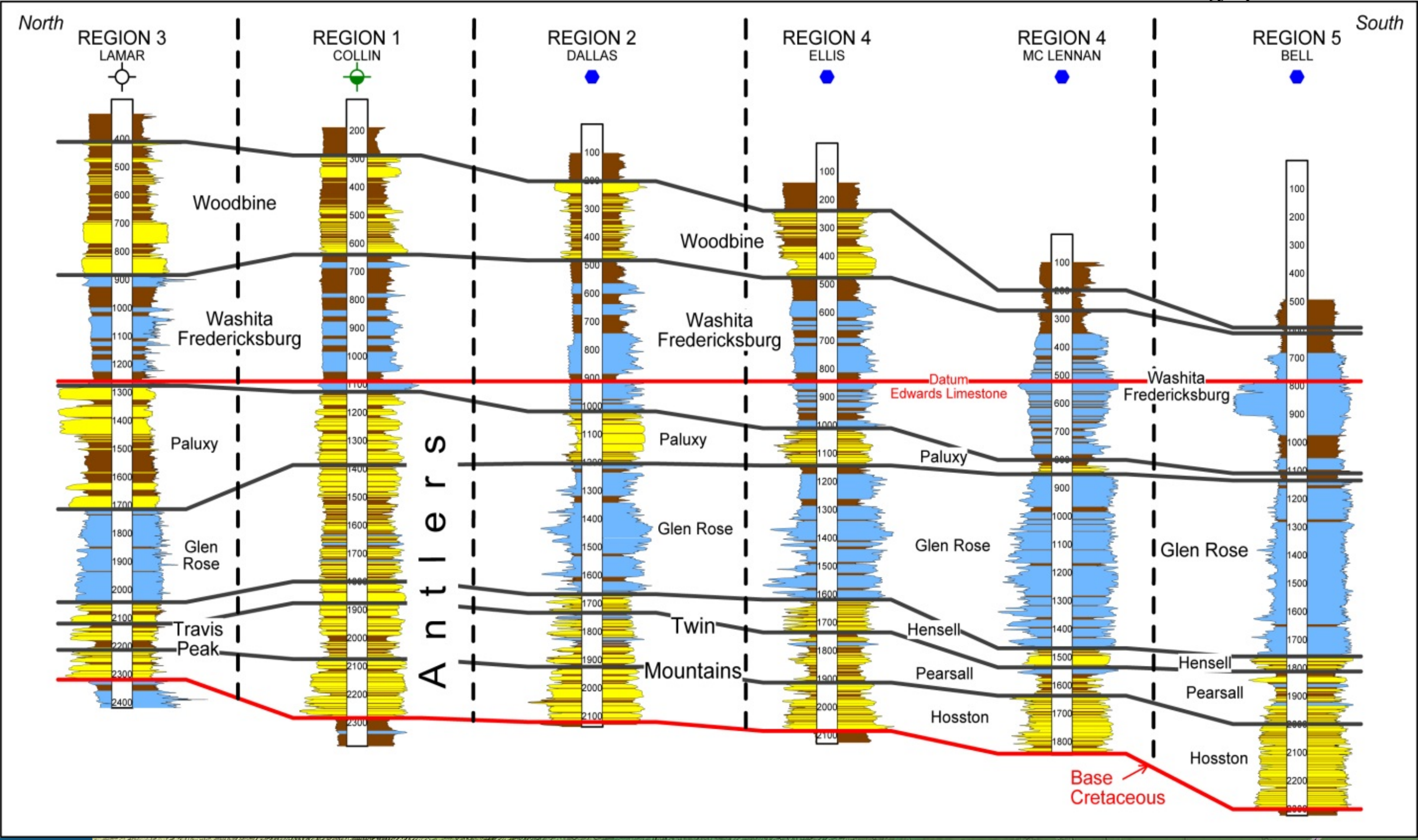
Hydrostratigraphic Framework



Regions defined by stratigraphic and lithologic similarity

Hydrostratigraphic Framework





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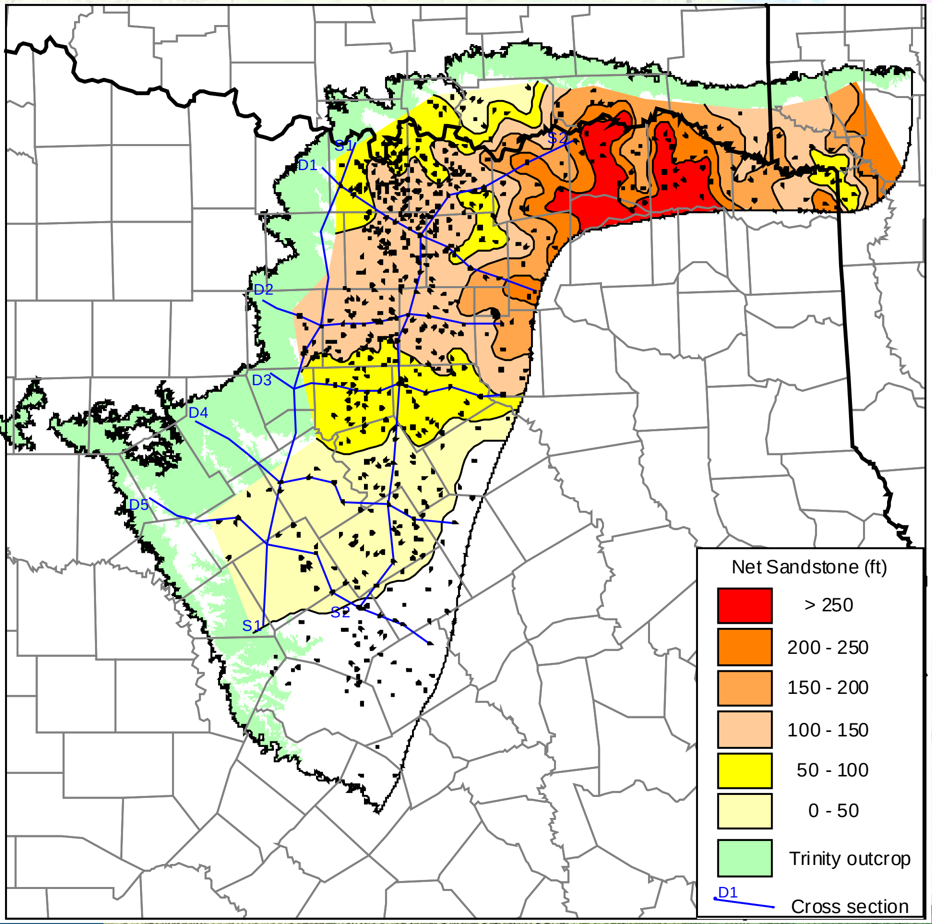
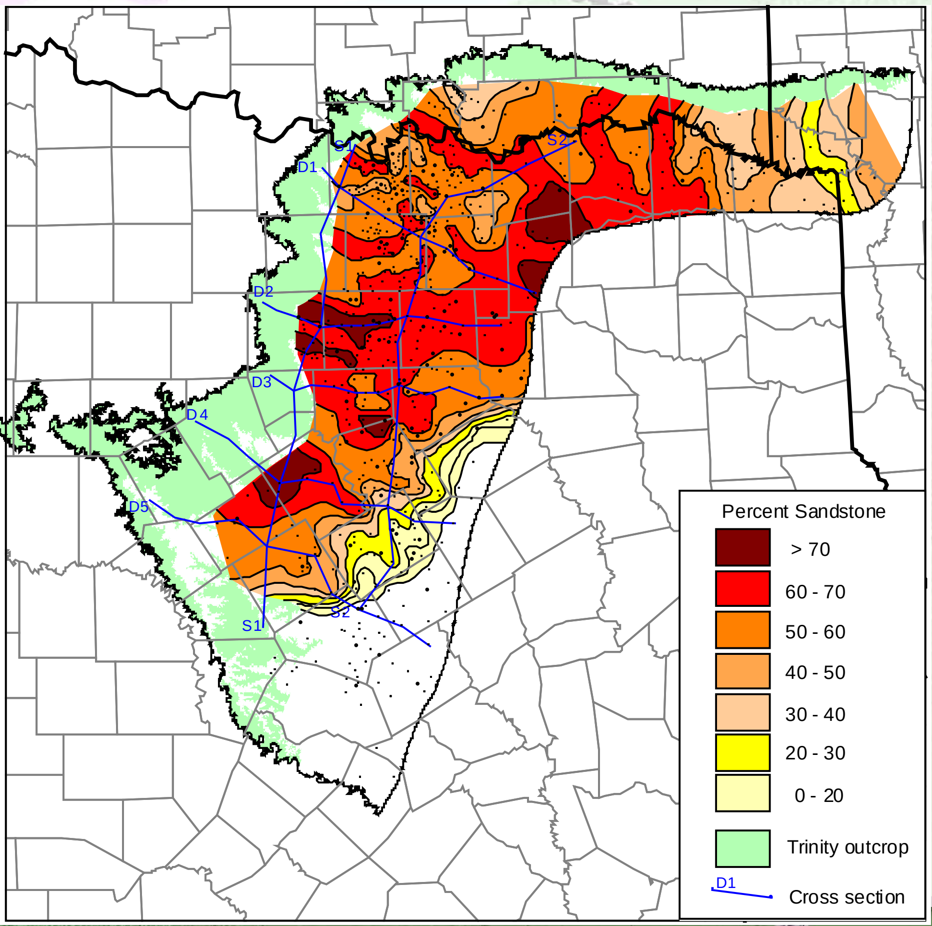
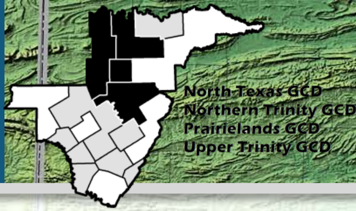
Hydrostratigraphic Framework

- Developed Structure, Cross-Sections, Net Sand & Depositional Environments



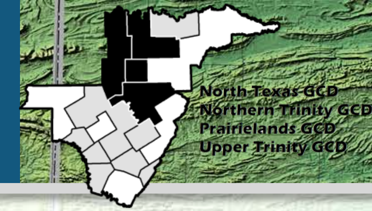


Hydraulic Properties

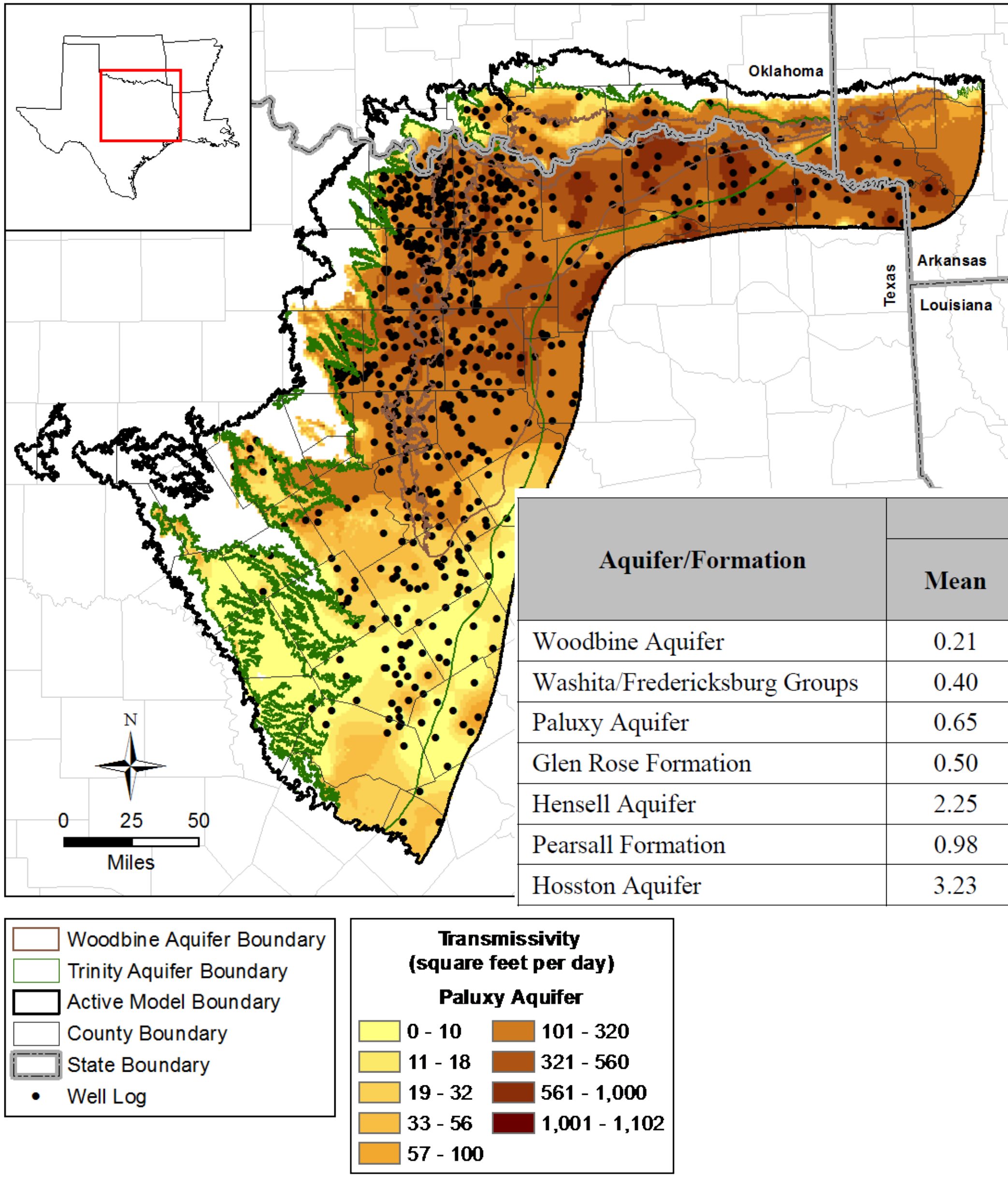


- Assemble Aquifer Pump & Specific Capacity Test Data and Calculate Transmissivities
  - 500 pump tests – 12,364 SC tests
- Develop Lithologic-Unit Profiles from Geophysical logs for all HSU represented in model
- Calculate “Average” K’s of Lithologic Units from Aquifer Tests
- Estimate a “Average Transmissivity” for HSUs at each geophysical log location
- Calibrate model to water levels as well be constrained to Measured and Estimated Aquifer Parameters

Hydraulic Properties

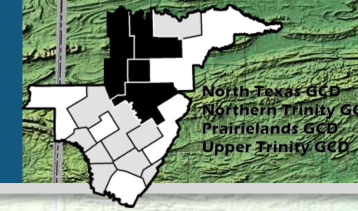


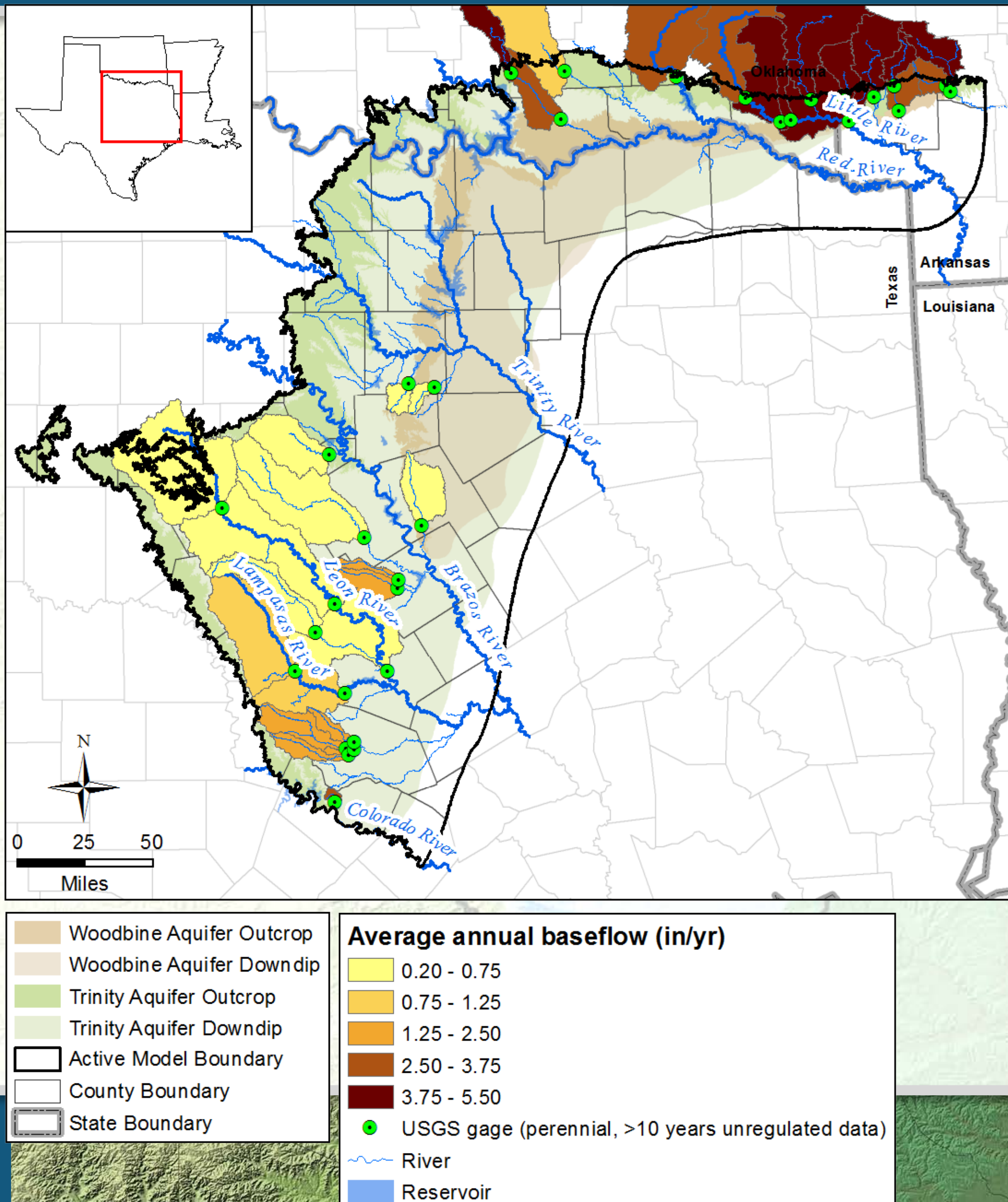
Initial Transmissivity for the Paluxy (ft2/day)

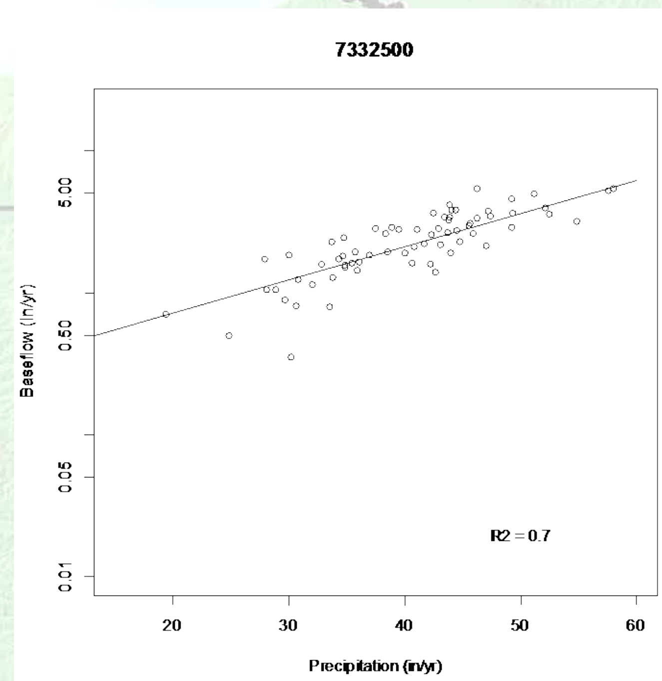


Aquifer/Formation	Horizontal Hydraulic Conductivity (feet per day)							
	Mean	Standard Deviation	Median	Percentiles				
				5	25	50	75	95
Woodbine Aquifer	0.21	0.23	0.15	0.002	0.01	0.15	0.32	0.73
Washita/Fredericksburg Groups	0.40	0.24	0.32	0.13	0.18	0.32	0.61	0.81
Paluxy Aquifer	0.65	0.52	0.47	0.01	0.26	0.47	1.06	1.61
Glen Rose Formation	0.50	0.32	0.37	0.18	0.21	0.37	0.77	1.04
Hensell Aquifer	2.25	1.88	1.67	0.09	0.70	1.67	3.66	5.79
Pearsall Formation	0.98	0.86	0.84	0.03	0.29	0.84	1.27	2.81
Hosston Aquifer	3.23	2.07	2.27	1.17	1.46	2.27	5.13	7.02

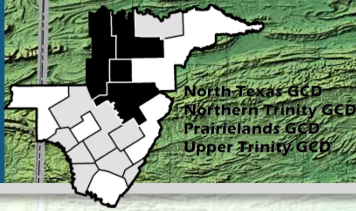
Stream – Aquifer Interaction

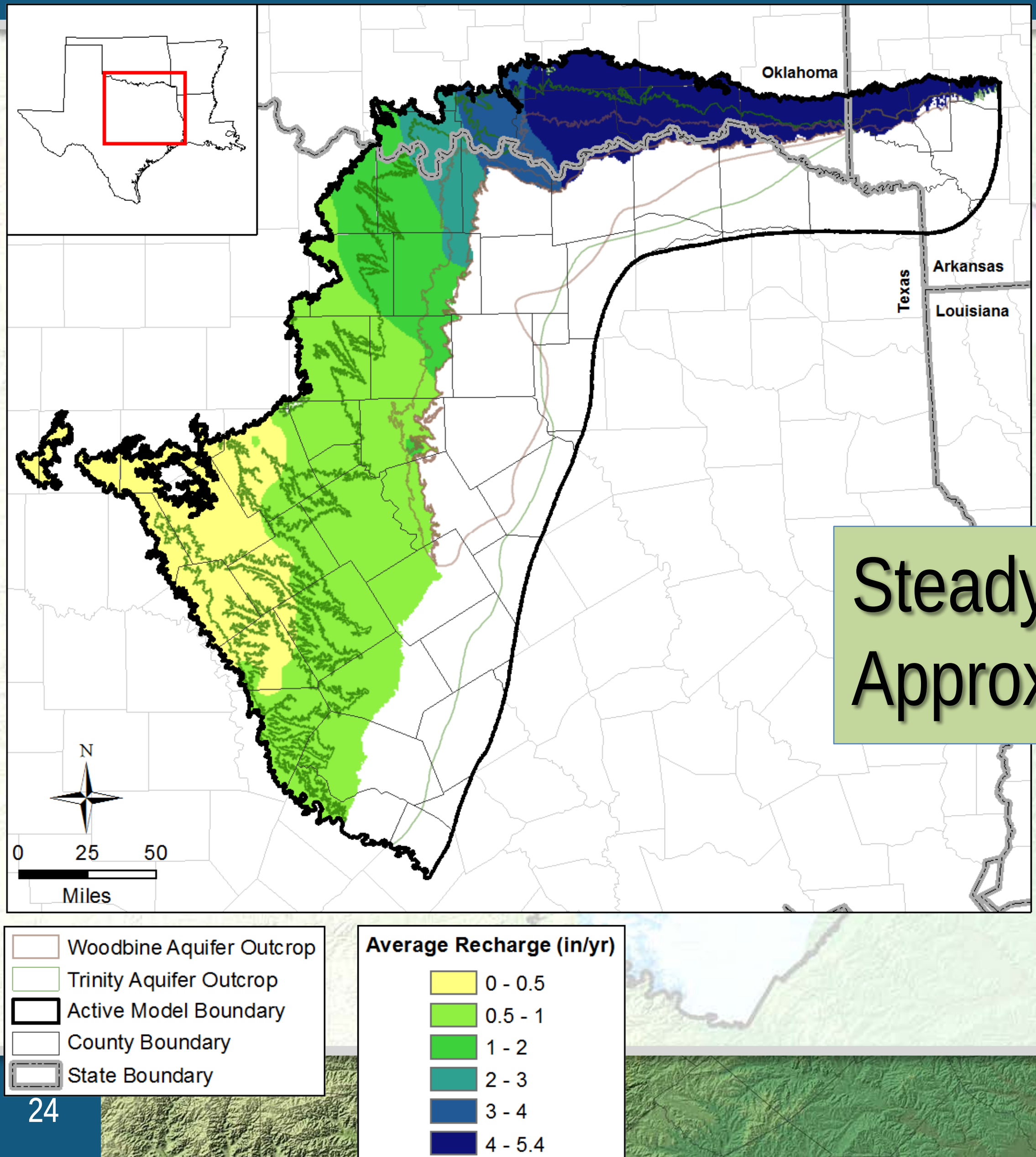






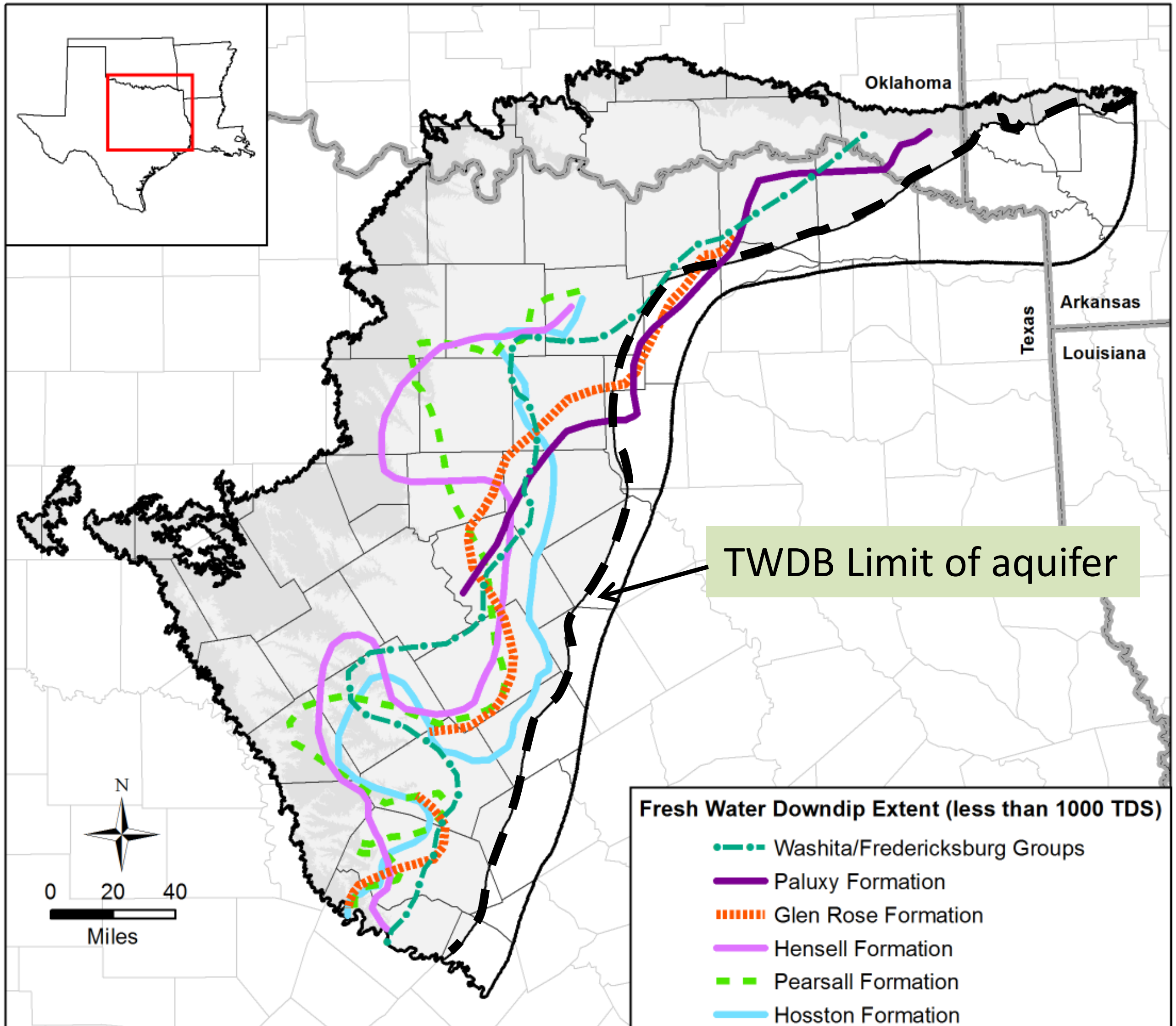
Recharge



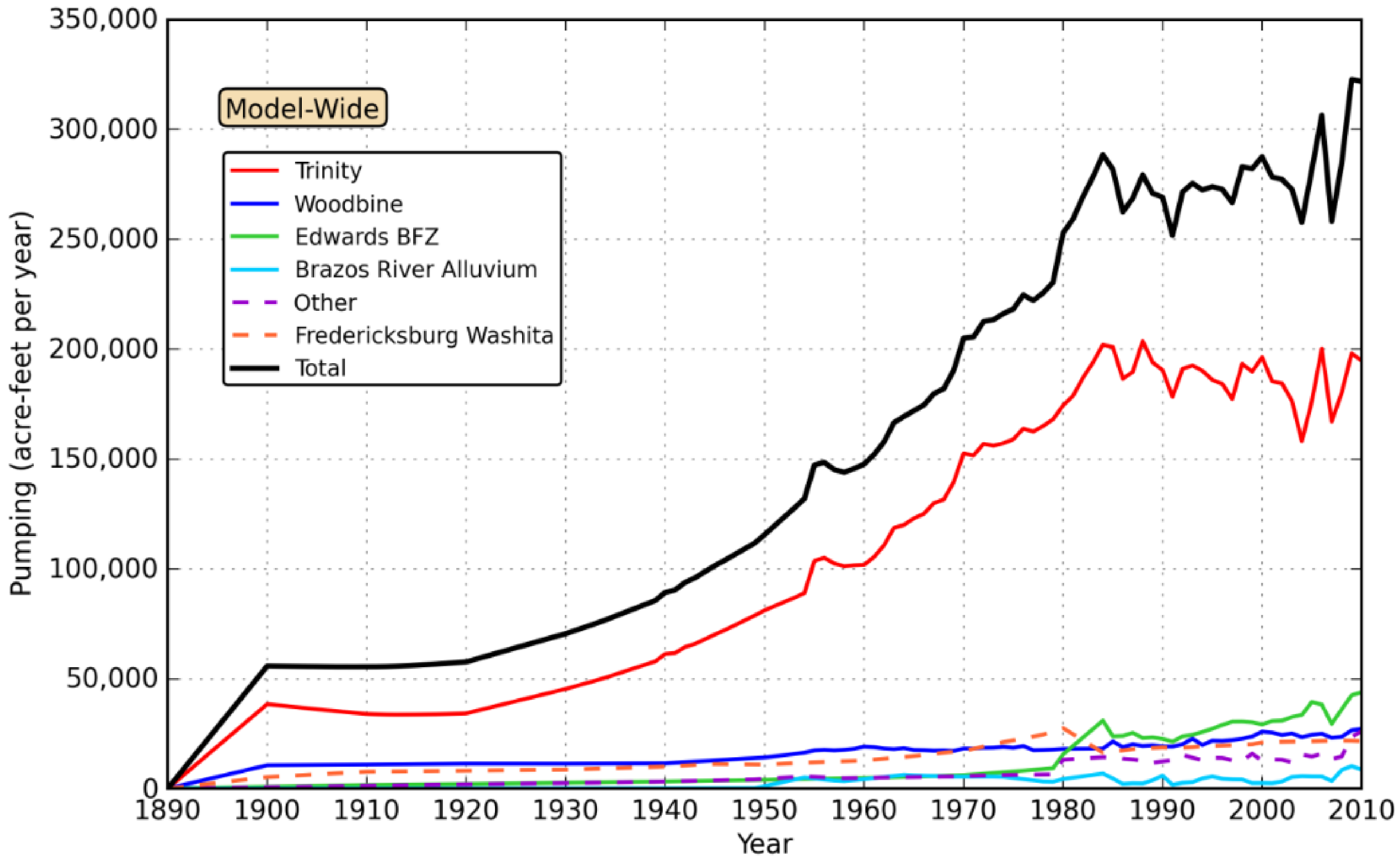


Steady State Recharge Approximately 1.6 in/yr

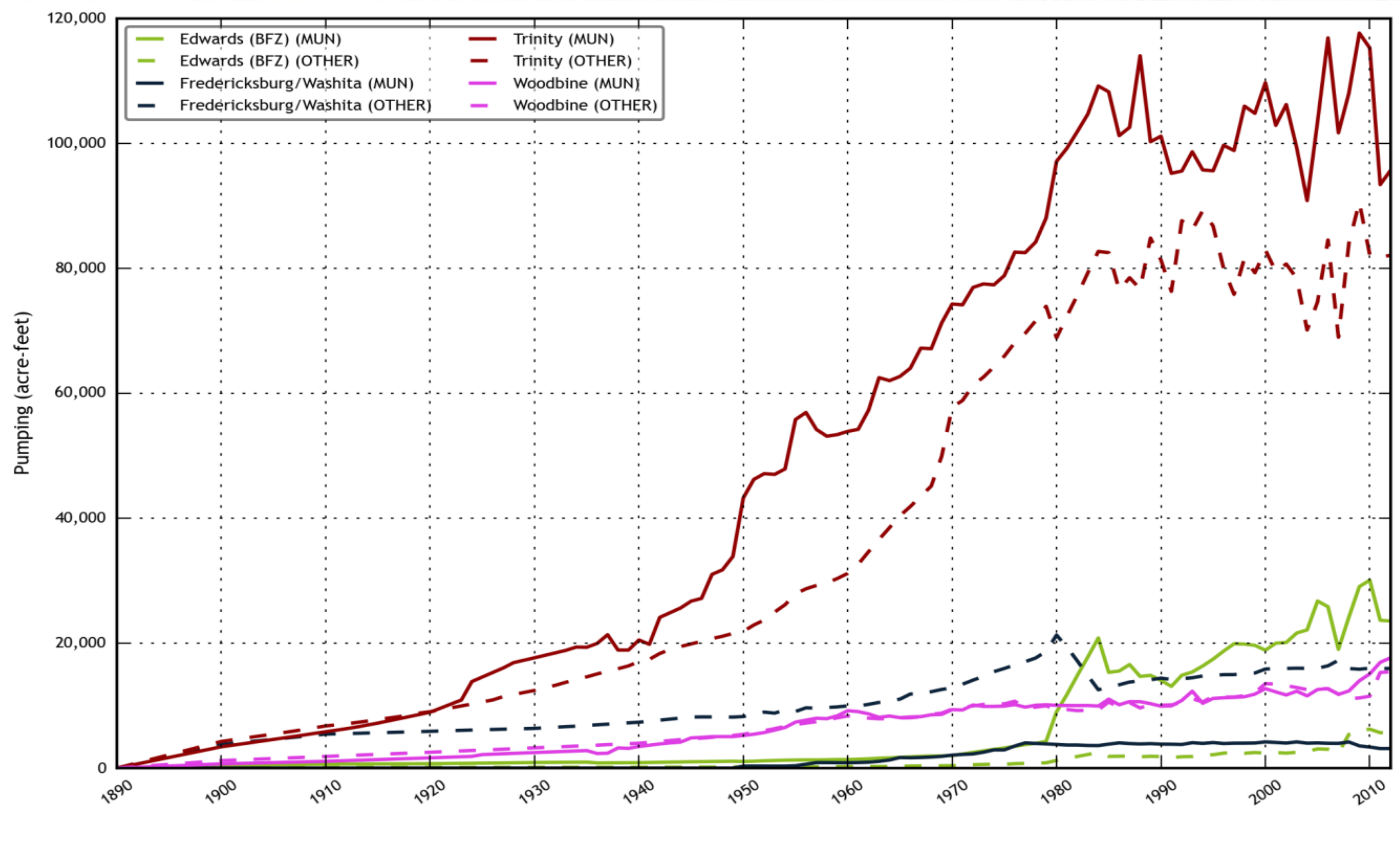
Water Quality – 1,000 ppm TDS Limit



Pumping by Aquifer – 1890-2012



Pumping by Aquifer – 1890 to 2012



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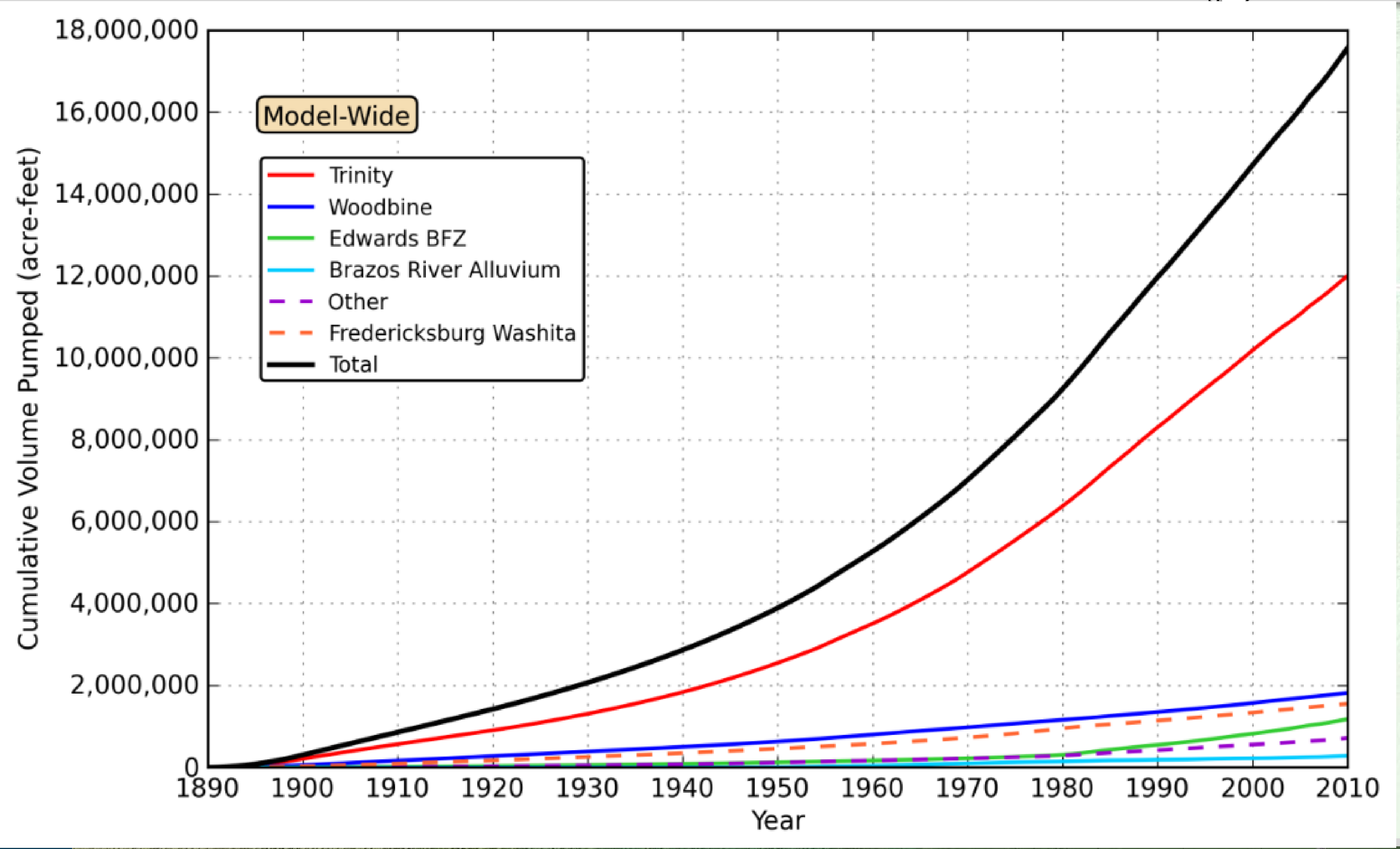
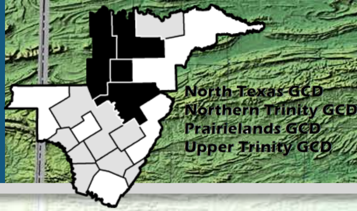
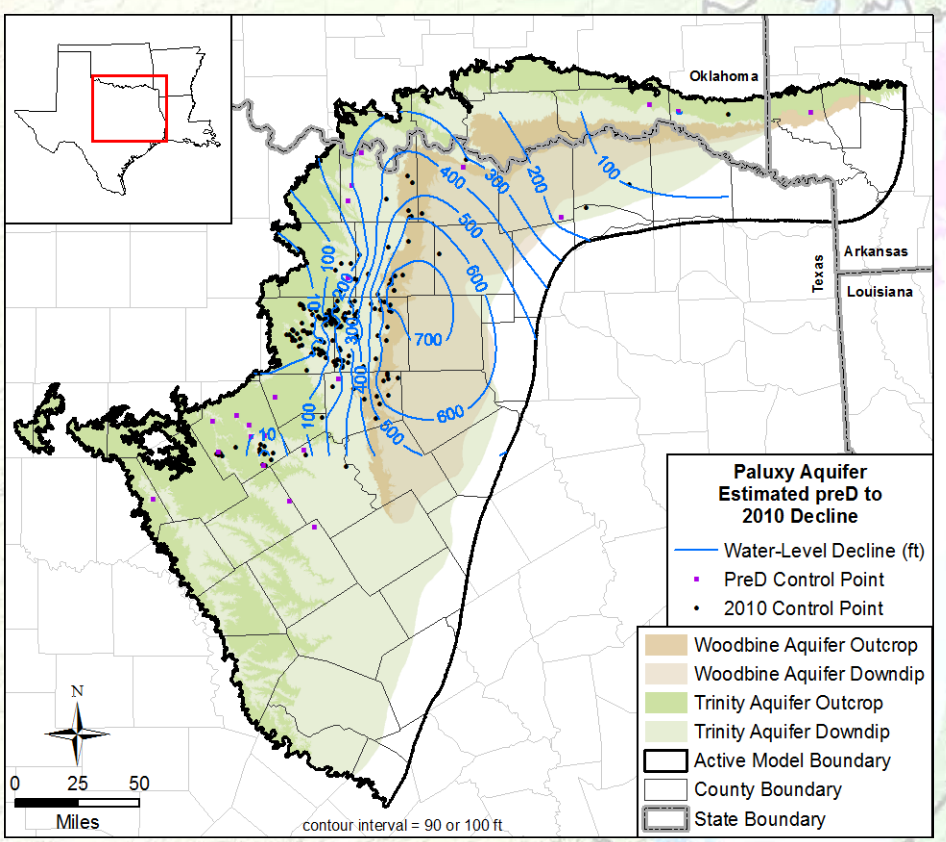
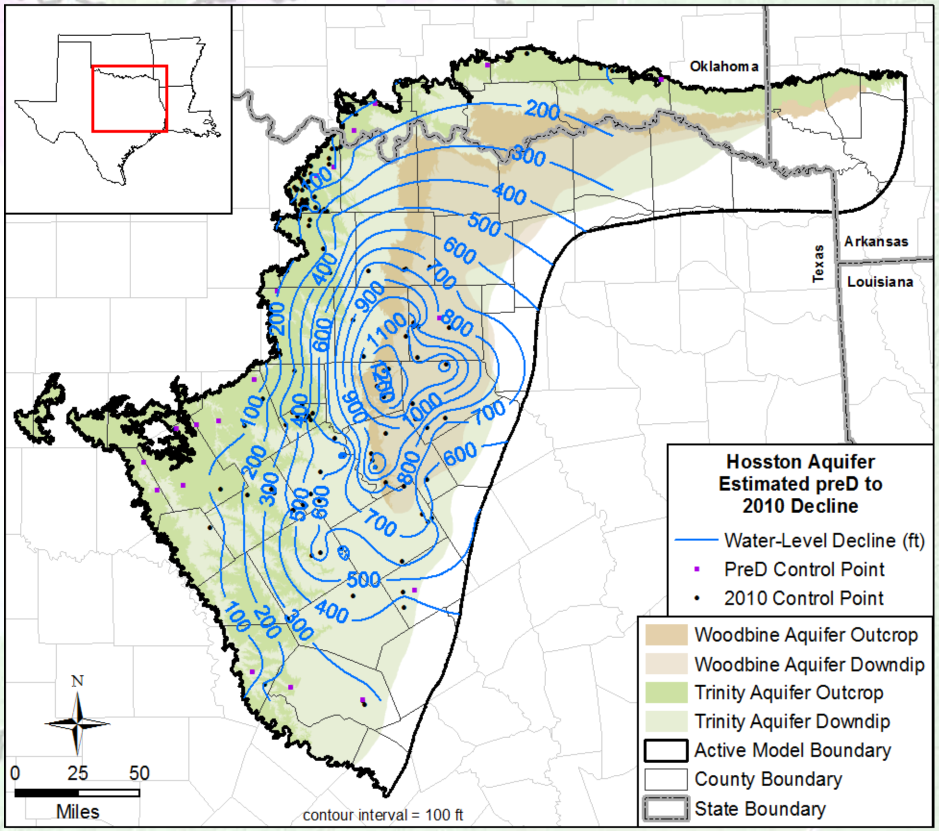
Cumulative Pumping by Aquifer



Estimated Observed Drawdown (ft)







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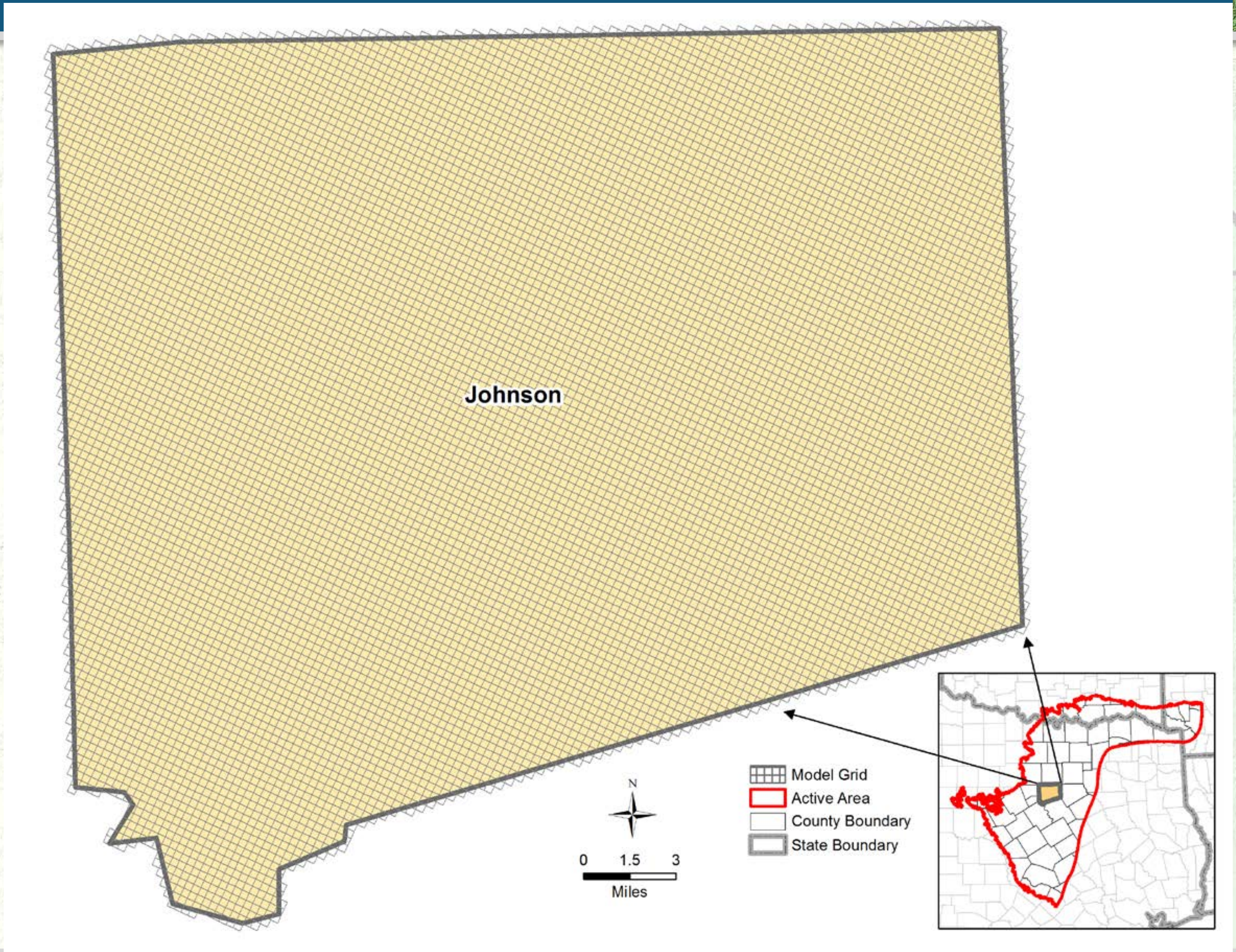
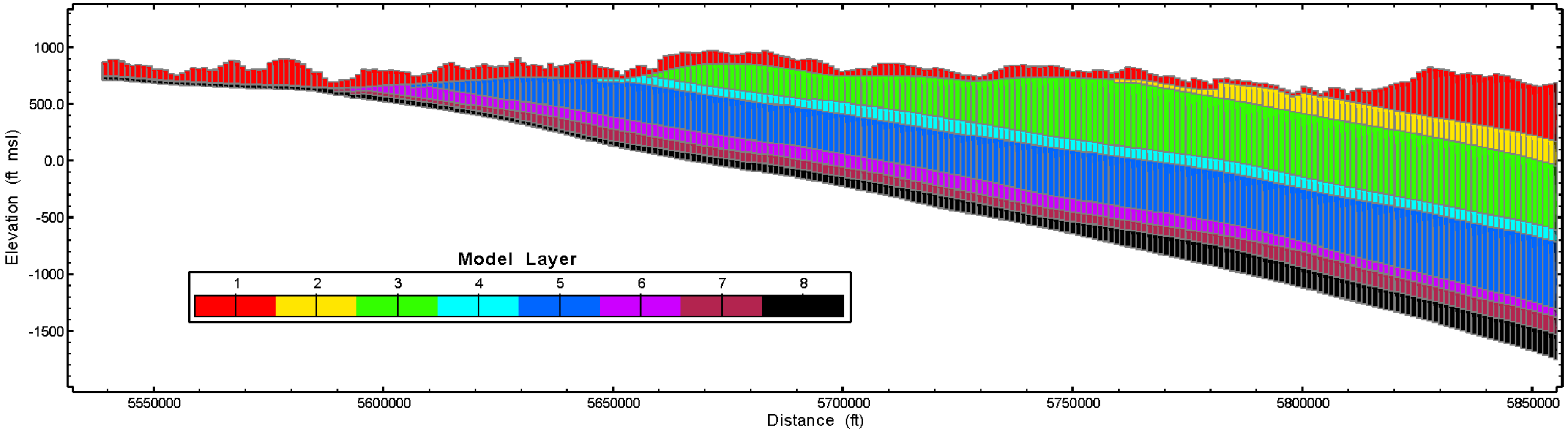
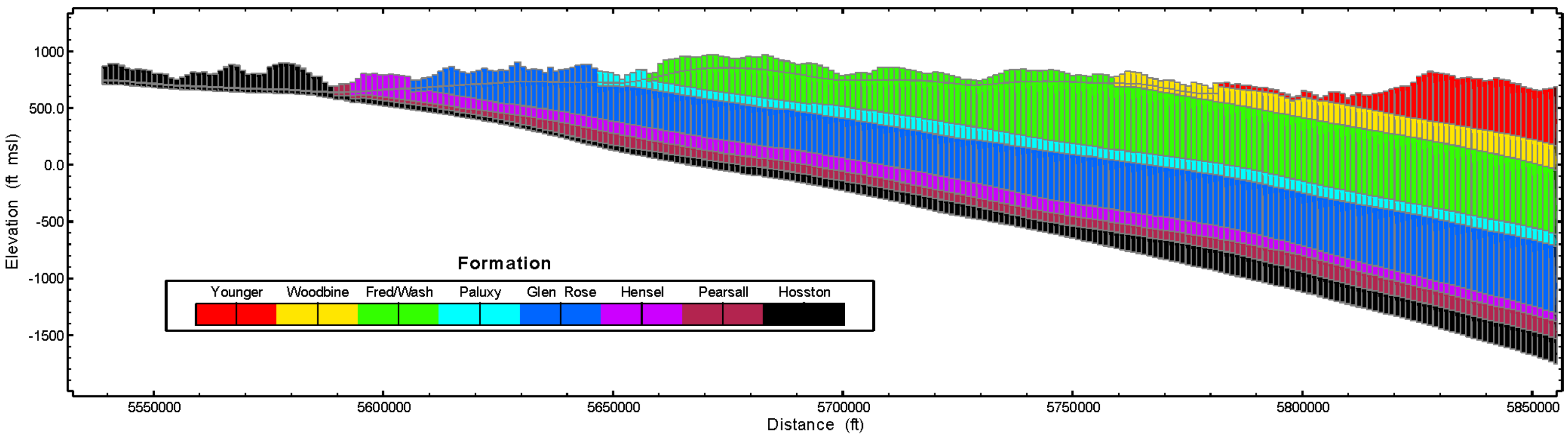
Horizontal Discretization

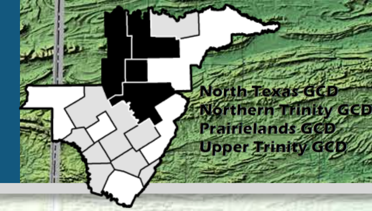


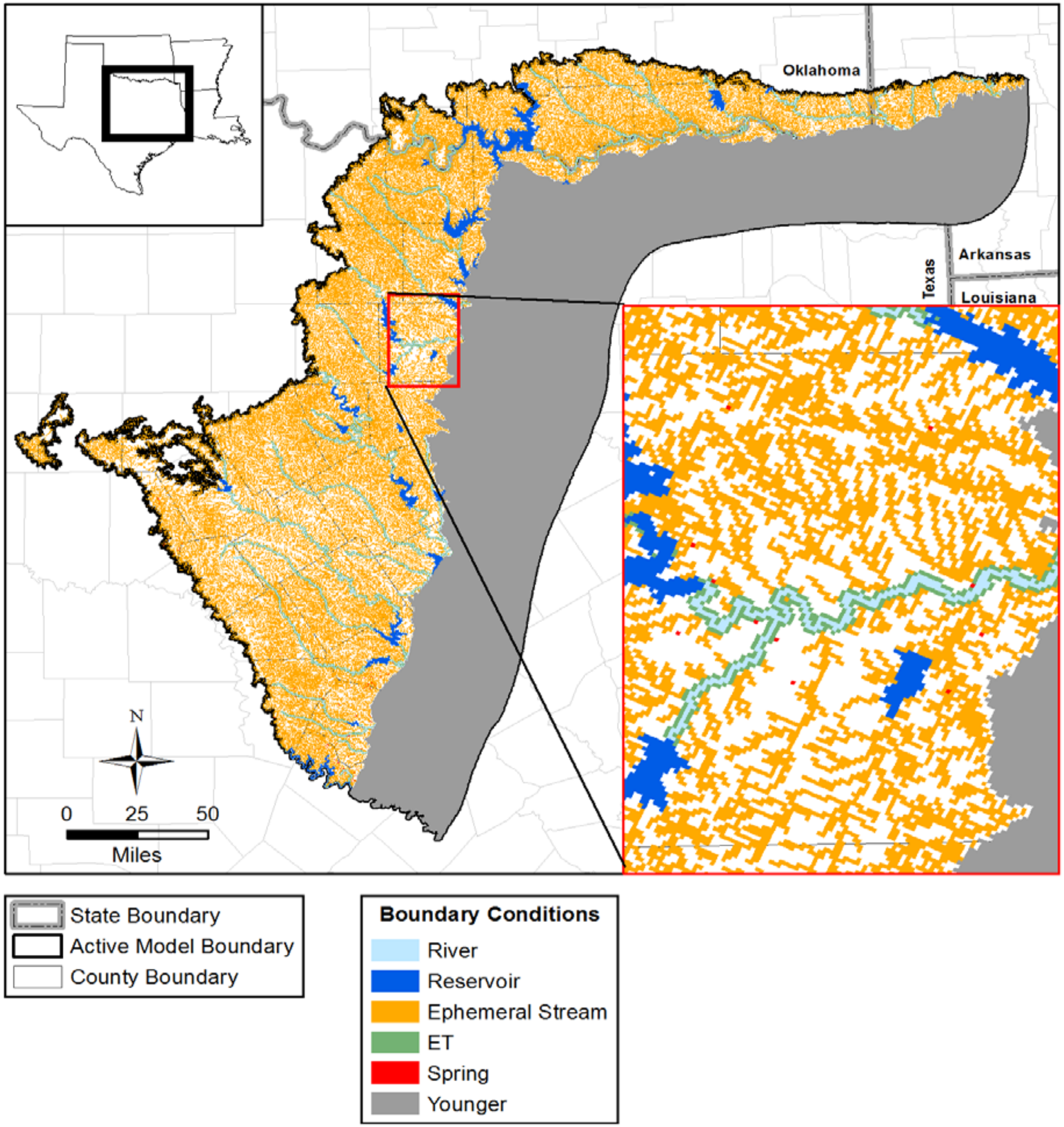
Vertical Discretization



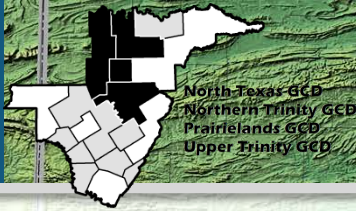


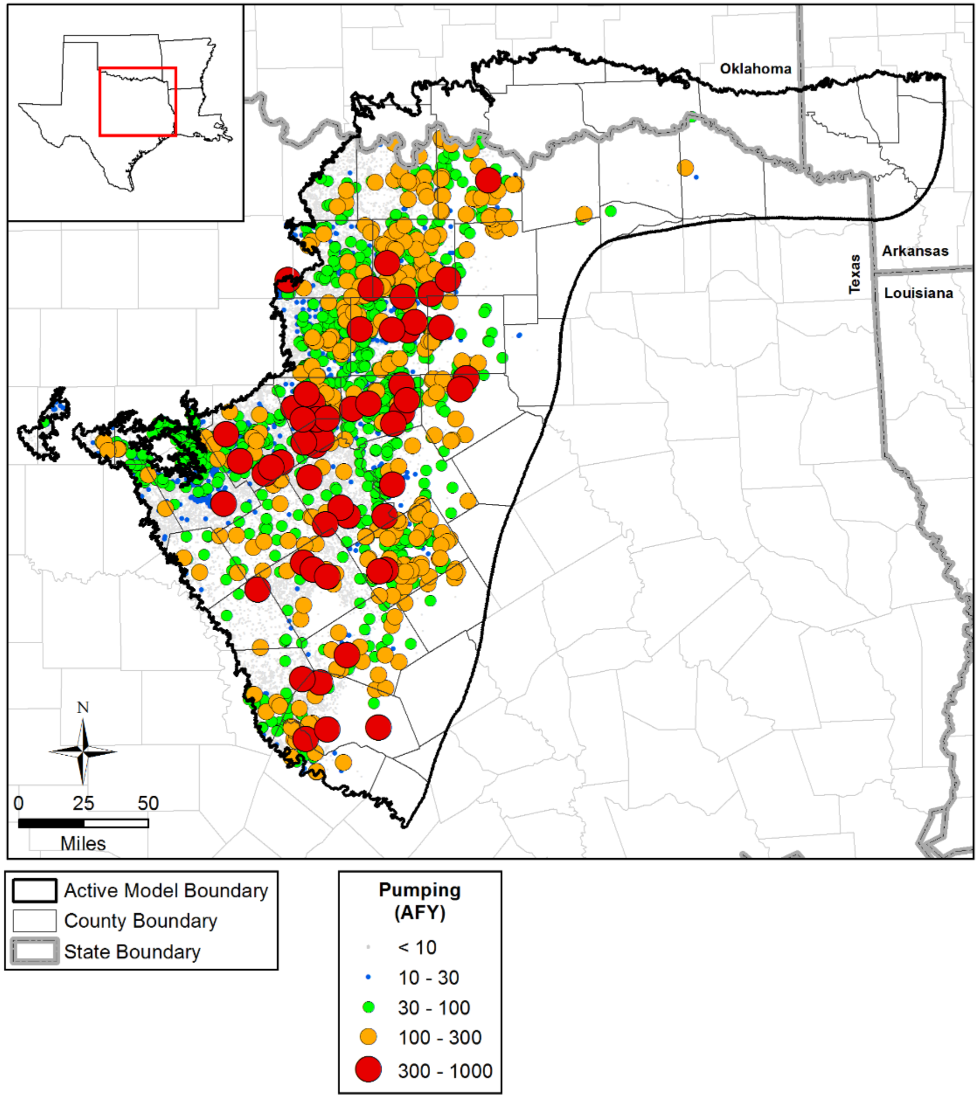
Surficial Boundary Conditions





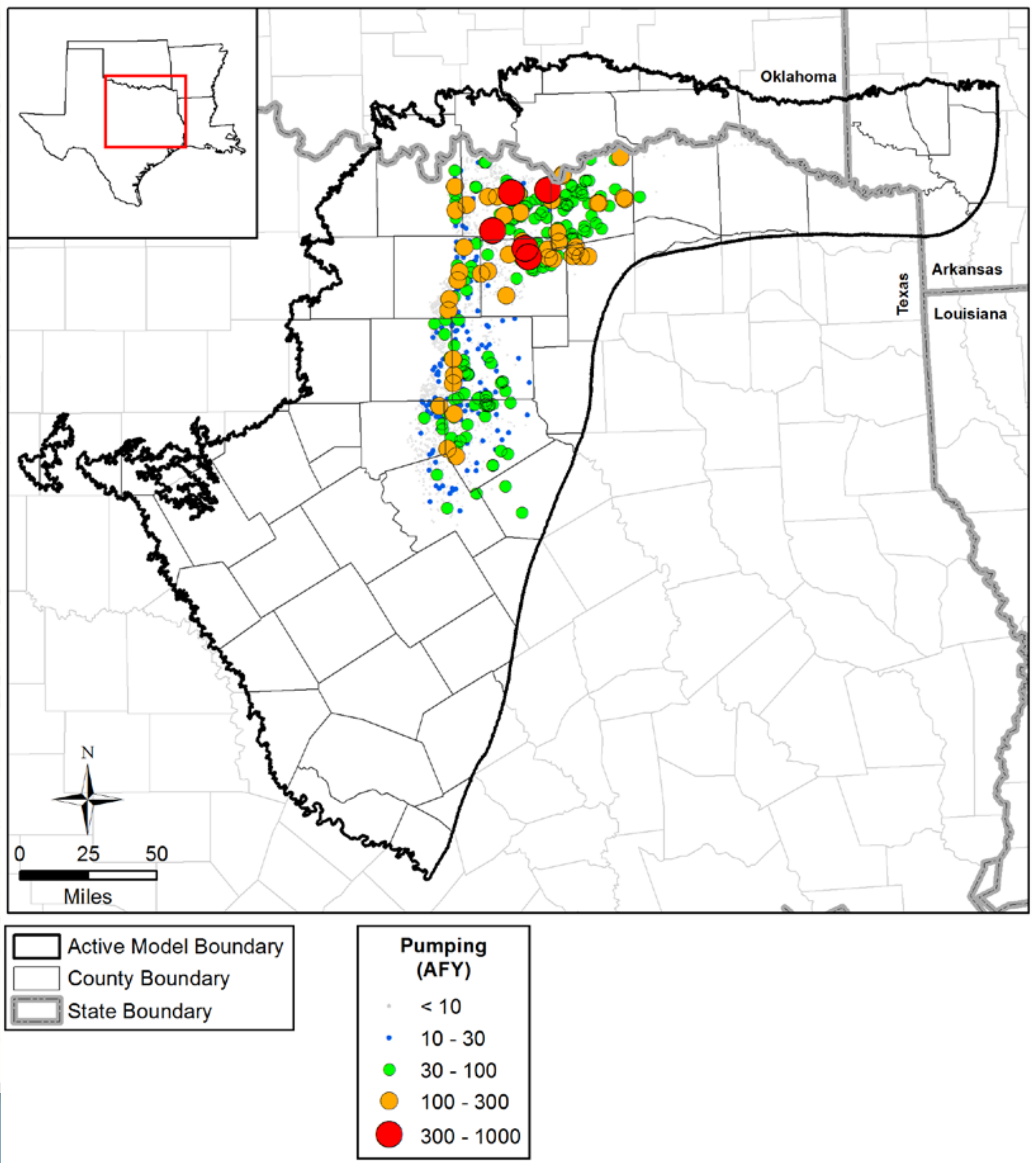
Pumping in Trinity Aquifer: 2012





- Metered data is used as provided
- Pumping assigned by county, aquifer and water use group
- Pumping distributed to wells by use type and drill date
- Pumping rates weighted by drawdown and transmissivity
- Pumping is conserved by county, aquifer and water use group

Pumping in Woodbine Aquifer: 2012



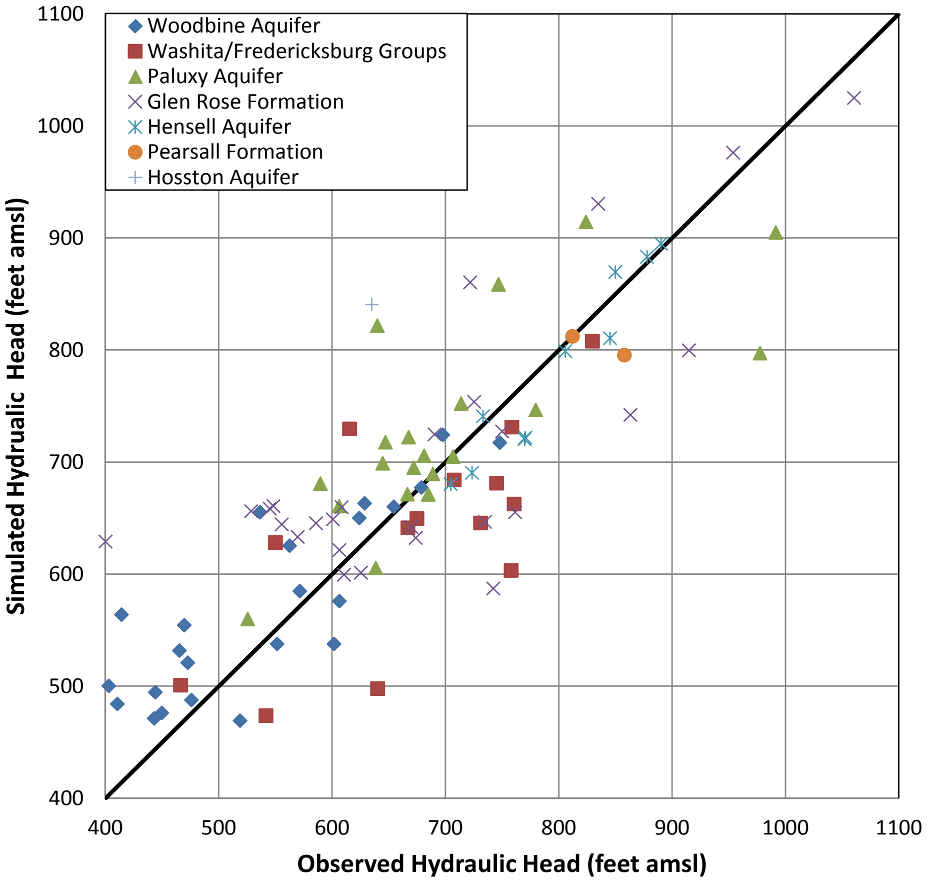
Calibration Approach

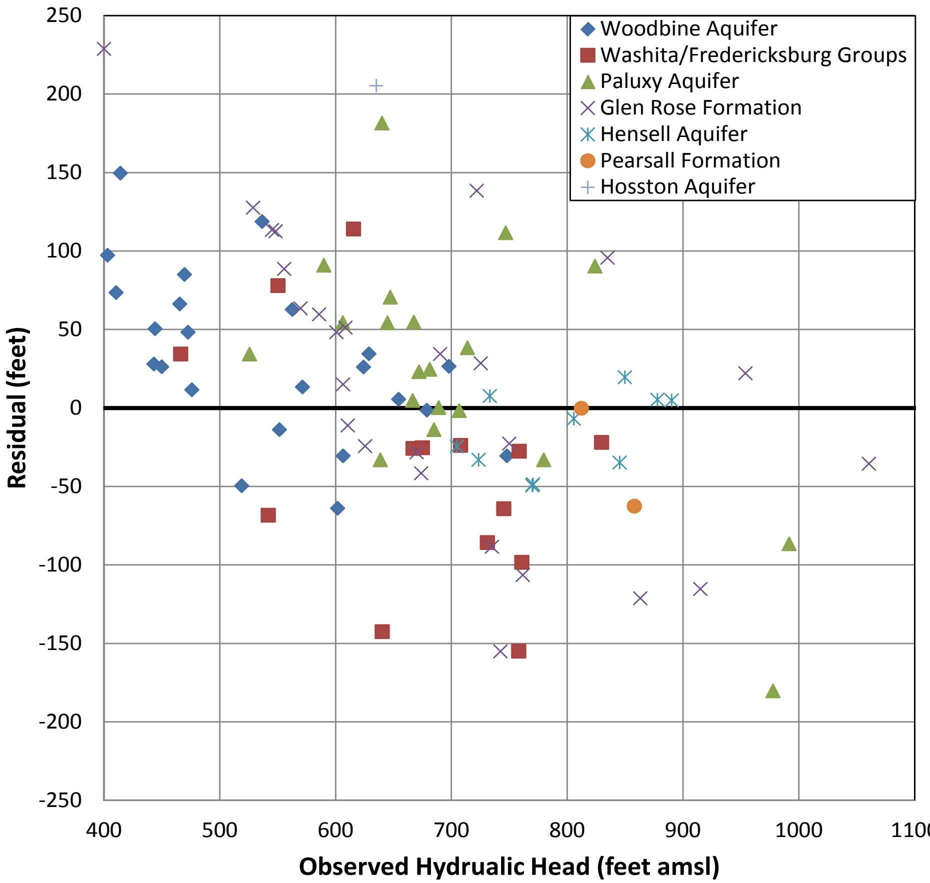
- Steady-State Calibration
  - 96 water level measurements prior to 1900
  - Artesian conditions during predevelopment
  - Fresh water at depth in the aquifers
- Transient Calibration
  - 27,490 water level measurements between 1890 and 2012
  - 706 hydrographs with more than 5 measurements
  - 33 stream base flow analyses

Steady-State Calibration

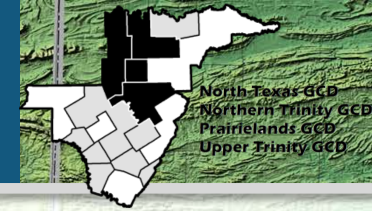
Count	Mean Error (feet)	MAE (feet)	Range (feet)	Adjusted MAE
96	12.0	59.8	660	0.091

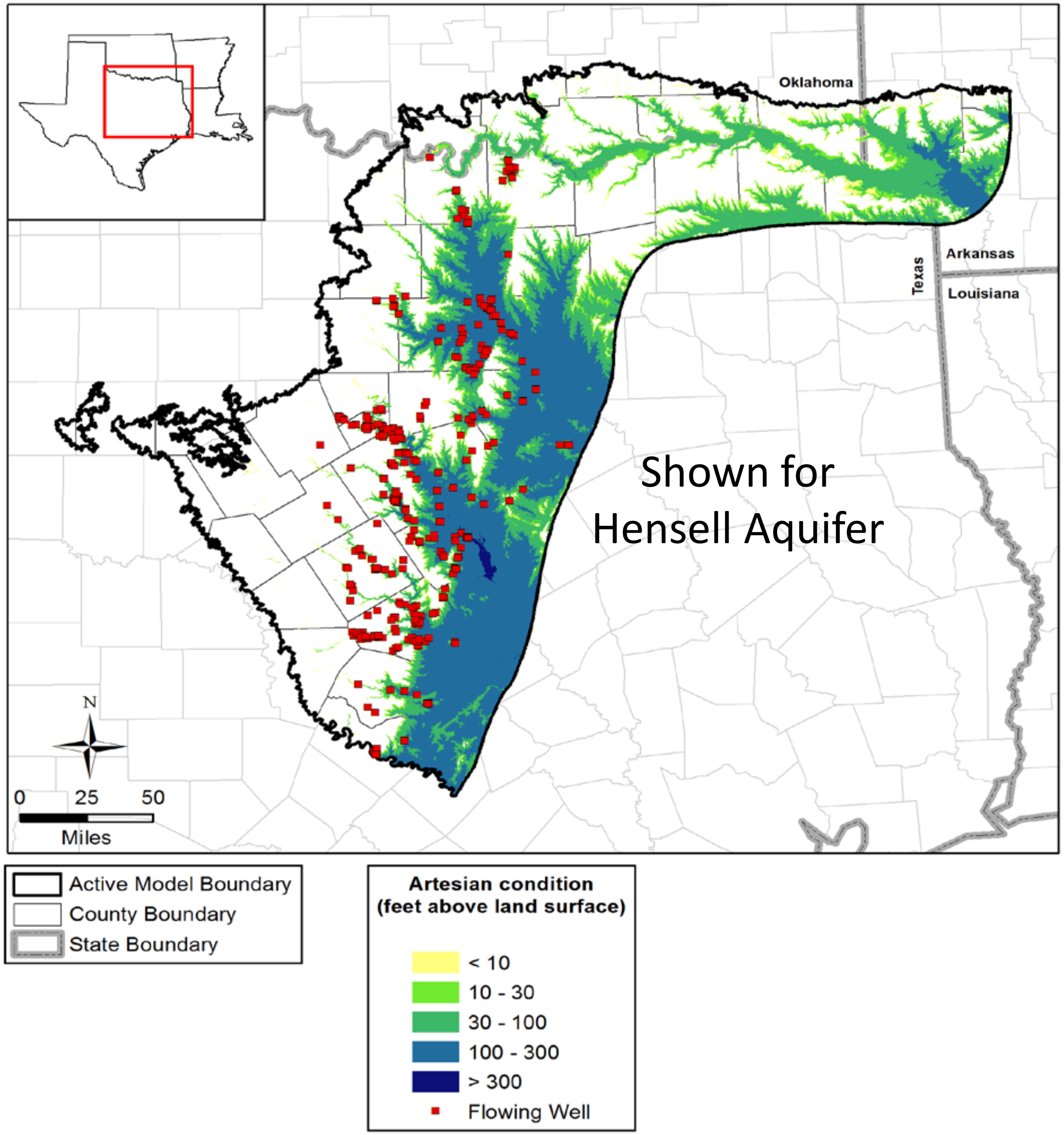
MAE = mean absolute error





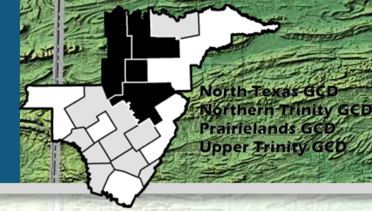
Simulated Steady-State Artesian Heads





- Out of 420 documented flowing wells, 304 exhibit artesian conditions in the Hensell Aquifer
- An additional 47 flowing wells exhibit artesian conditions in the Hosston
- 84% of documented flowing wells are simulated as artesian

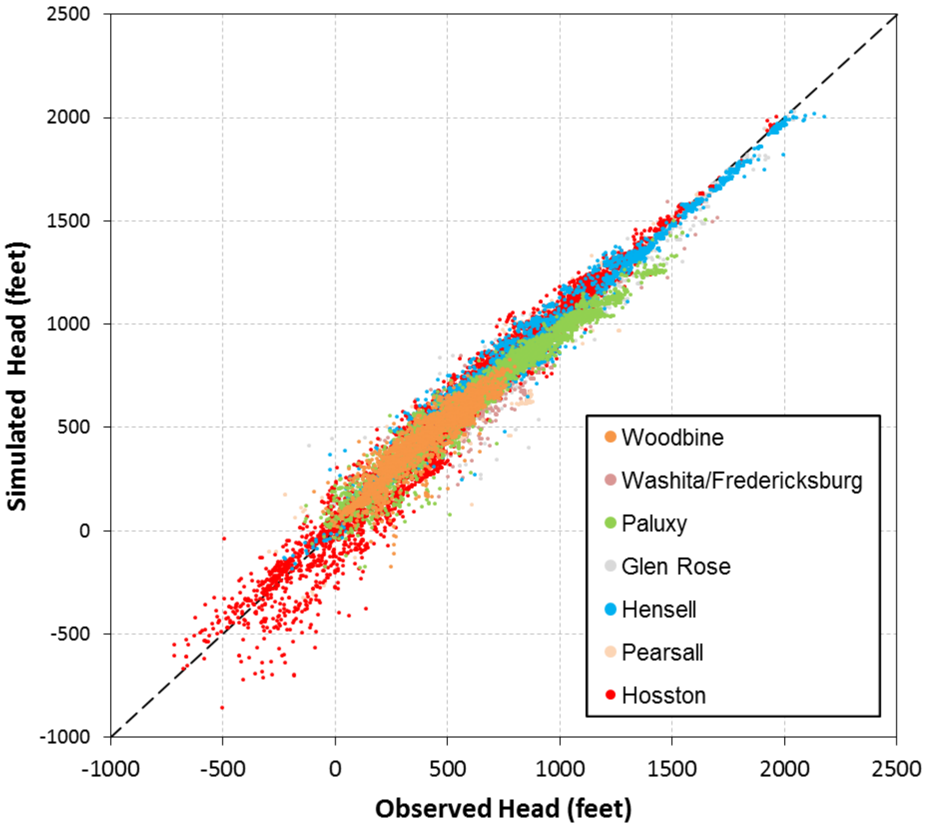
Simulated Steady-State Water Balance (AFY)

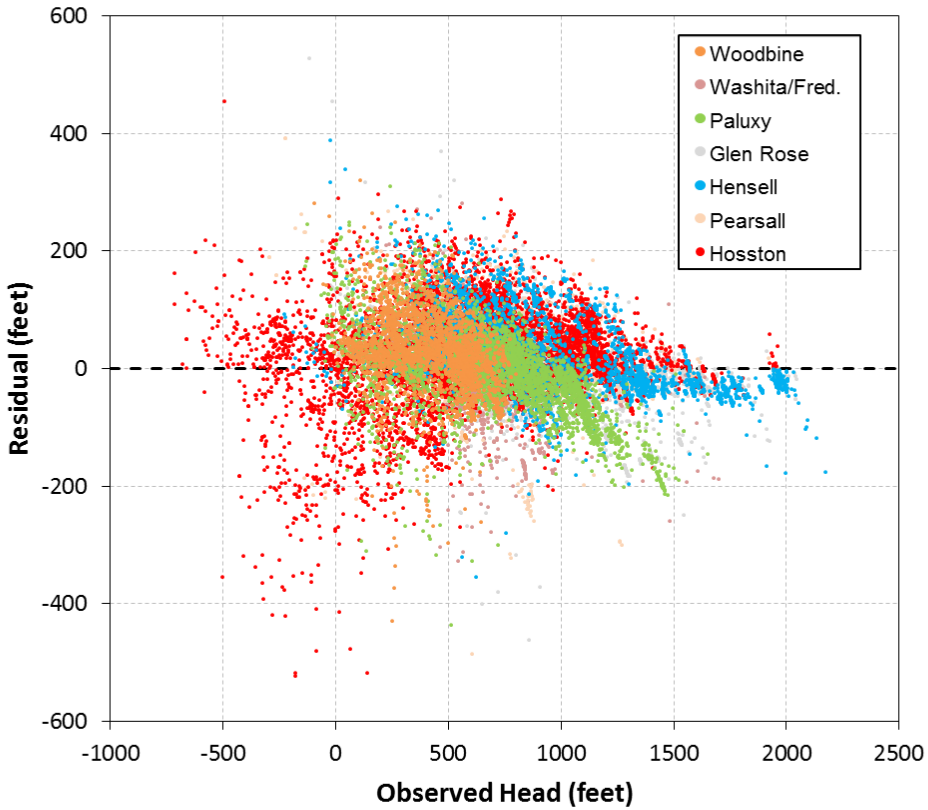


Pre-development	Cross-formational Flow			Recharge	ET	Ephemeral Streams	Perennial Streams	Spring	Younger
	Surficial	Top	Bottom						
Younger Formations	0	0	8,354	0	0	0	0	0	-13,711
Woodbine Aquifer	2,561	-8,354	5,901	326,201	-13,334	-197,776	-97,917	-61	0
Wash/Fred groups	5,886	-5,901	275	532,484	-6,633	-270,802	-236,638	-286	0
Paluxy Aquifer	1,859	-275	-1,565	245,673	-6,771	-113,235	-120,812	-126	0
Glen Rose Formation	16,844	1,565	-18,638	230,422	-6,503	-83,409	-131,395	-86	0
Hensell Aquifer	-11,214	18,638	-6,579	208,440	-11,756	-130,060	-67,678	-188	0
Pearsall Formation	3,374	6,579	-9,899	45,455	-3,697	-38,571	-24,689	0	0
Hosston Aquifer	-7,050	9,899	0	177,891	-4,352	-122,037	-58,080	-343	0
Total	12,259	22,151	-22,151	1,766,567	-53,046	-955,888	-737,209	-1,090	-13,711

Water balance information per county can be found at: http://ntwgam.intera.com/reports.html

Transient Calibration: 1890 to 2012

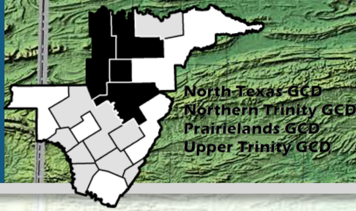




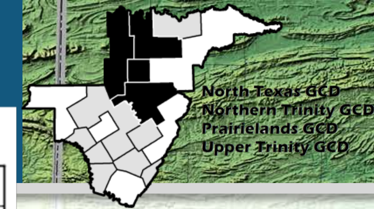
Transient Calibration: 1980 to 2012

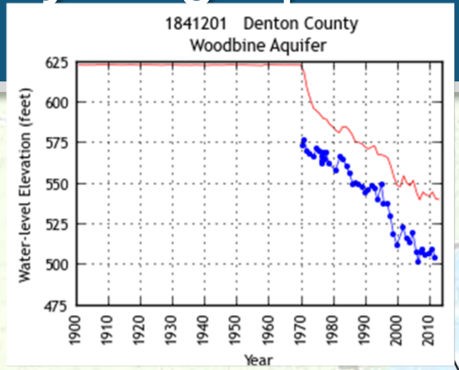
Unit	Count	Mean Error (feet)	Mean Absolute Error (feet)	Range (feet)	MAE/Range
All	21234	9.1	48.7	2891	0.017
Woodbine Aquifer	2093	19.0	50.8	975.5	0.052
Wash/Fred Groups	2044	-11.8	42.4	1658	0.026
Paluxy Aquifer	3655	-11.0	46.9	1778	0.026
Glen Rose Formation	3735	-11.1	38.3	2166	0.018
Hensell Aquifer	2410	17.0	54.9	2369	0.023
Pearsall Formation	1962	27.6	48.8	2262	0.022
Hosston Aquifer	5335	30.8	56.2	2690	0.021

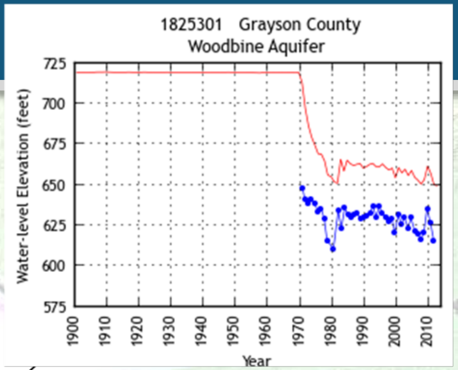
MAE = mean absolute error Wash/Fred = Washita/Fredericksburg

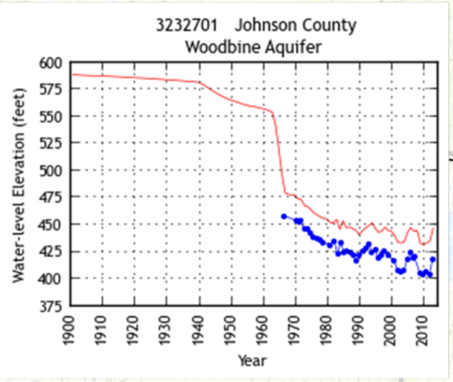


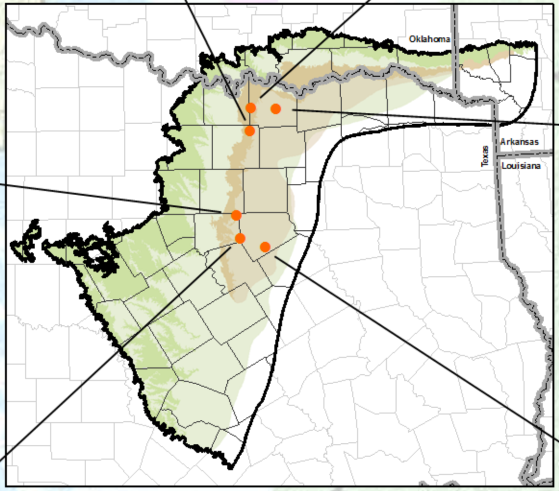
Transient Hydrographs: Woodbine

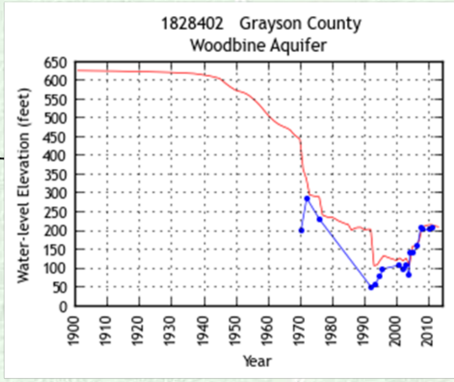


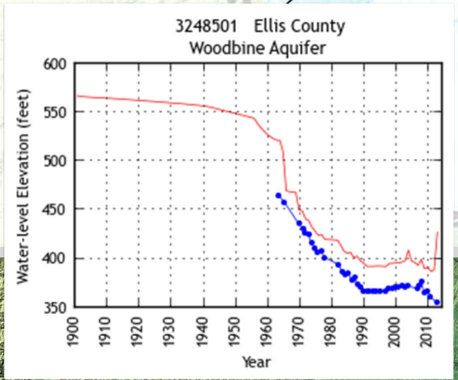


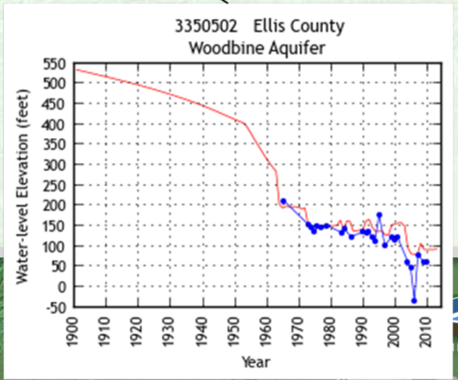












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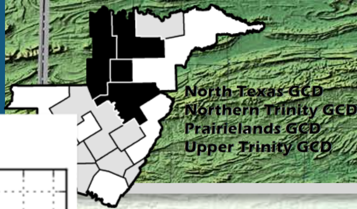
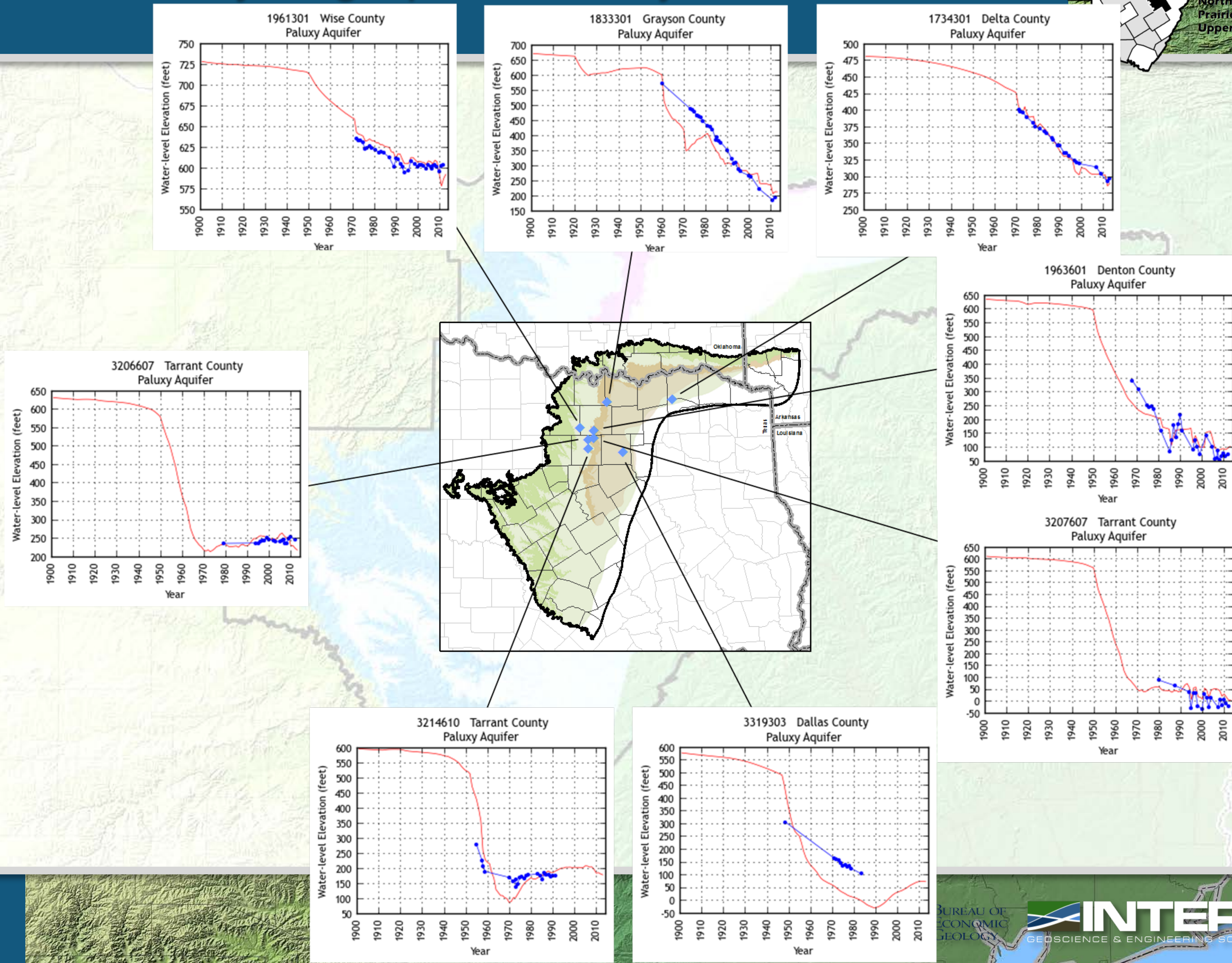
Transient Hydrographs: Paluxy





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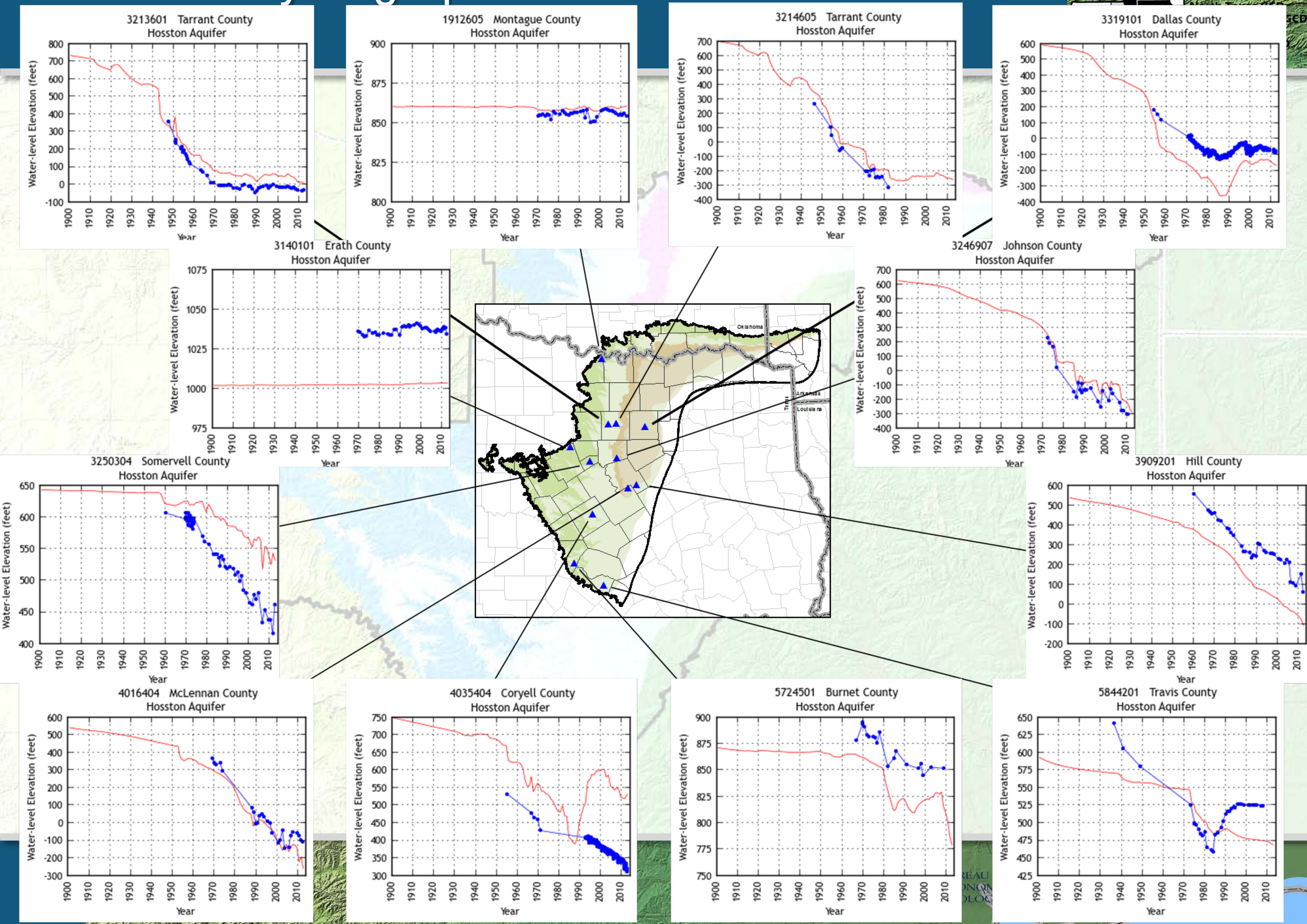
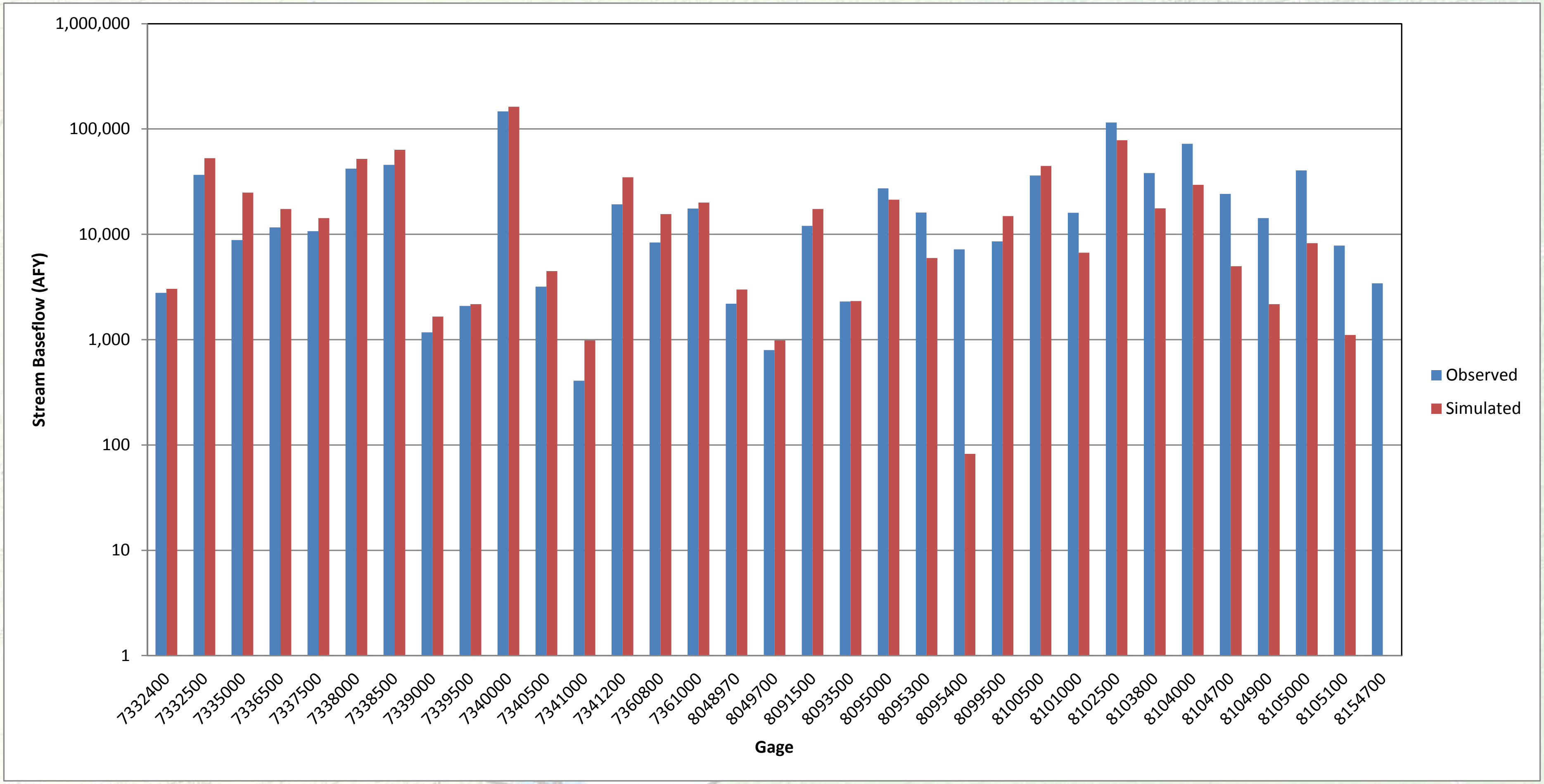
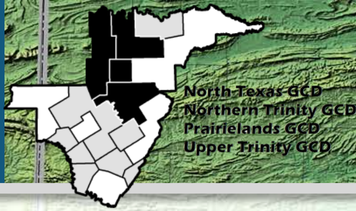
Transient Hydrographs: Hosston



Simulated Stream Gains



Simulated Transient Water Balance: 1980



1980	Cross-formational Flow			Recharge	ET	Ephemeral	Perennial	Reservoir	Spring	Younger	Well	Flowing	Storage
Unit	Surficial	Top	Bottom										
Younger Formations	0	0	-2,313	0	0	0	0	0	0	-9,756	0	0	5,647
Woodbine Aquifer	17,993	2,313	-2,870	348,250	-13,255	-189,629	-93,459	-2,547	-56	0	-19,424	-900	-13,119
Wash/Fred Groups	49,915	2,870	-20,875	639,582	-7,998	-267,058	-186,977	-13,072	-234	0	-35,241	-18	-98,129
Paluxy Aquifer	19,540	20,875	-17,916	286,293	-6,997	-112,334	-100,153	404	-118	0	-25,252	-35	-39,594
Glen Rose Formation	56,934	17,916	-65,791	289,389	-6,470	-81,345	-120,107	14	-81	0	-13,283	-57	-30,544
Hensell Aquifer	10,481	65,791	-46,725	232,918	-11,746	-127,525	-55,024	110	-179	0	-30,690	-823	-12,780
Pearsall Formation	17,439	46,725	-62,858	48,412	-3,616	-36,388	-22,087	-295	0	0	-7,764	-12	8,776
Hosston Aquifer	15,986	62,858	0	188,659	-4,191	-118,217	-51,244	-445	-338	0	-96,295	-502	23,019
Total	188,288	219,348	-219,348	2,033,503	-54,272	-932,495	-629,052	-15,832	-1,006	-9,756	-227,948	-2,346	-156,723

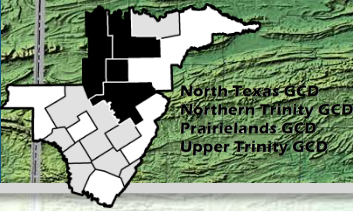
Water balance information per county can be found at:
http://ntwgam.intera.com/reports.html

Simulated Transient Water Balance: 2000

2000	Cross-formational Flow			Recharge	ET	Ephemeral	Perennial	Reservoir	Spring	Younger	Well	Flowing	Storage
Unit	Surficial	Top	Bottom										
Younger	0	0	-5,407	0	0	0	0	0	0	-7,940	0	0	9,365
Woodbine Aquifer	24,864	5,407	-5,976	231,840	-13,556	-208,440	-96,990	-4,596	-64	0	-26,241	-904	136,163
Wash/Fred Groups	58,069	5,976	-25,510	345,628	-8,652	-298,137	-181,195	-11,257	-227	0	-41,062	0	226,979
Paluxy Aquifer	23,325	25,510	-21,510	173,587	-7,235	-124,408	-99,809	-459	-118	0	-31,035	-56	91,566
Glen Rose Formation	64,531	21,510	-73,590	142,829	-6,716	-88,150	-114,108	-540	-85	0	-16,179	-6	125,376
Hensell Aquifer	17,688	73,590	-56,062	151,900	-12,074	-137,903	-56,508	-821	-198	0	-37,487	-520	89,177
Pearsall Formation	21,485	56,062	-72,303	32,744	-3,702	-38,336	-22,424	-384	0	0	-8,821	-15	25,638
Hosston Aquifer	22,725	72,303	0	127,805	-4,270	-126,396	-50,753	-991	-318	0	-105,581	-226	91,890
Total	232,686	260,358	-260,358	1,206,333	-56,205	-1,021,770	-621,787	-19,048	-1,010	-7,940	-266,407	-1,727	796,154

Water balance information per county can be found at:
http://ntwgam.intera.com/reports.html

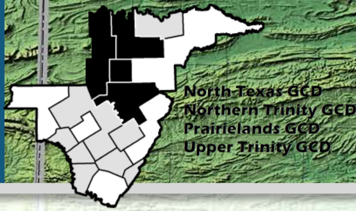
Conclusions



- A unique collaboration of the GCDs within GMA-8 have worked together to develop a new Draft northern Trinity and Woodbine aquifers GAM

- The model has been successfully calibrated to both steady-state and transient conditions (1890-2012) consistent with GAM standards from predevelopment to 2012
  - 706 transient hydrographs and >27,000 individual water level measurements used for transient calibration targets

Conclusions



- The model is a significant step forward in our understanding and modeling of the northern Trinity and Woodbine aquifers
- The model successfully reproduces the important aquifer dynamics that govern sustainability and a policy definition of availability
- It serves as a good foundation for planning and future improvements
- The model has been developed in a public process

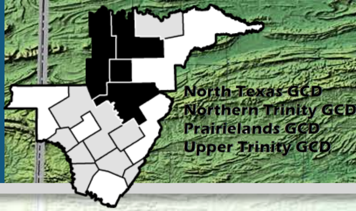
Conclusions

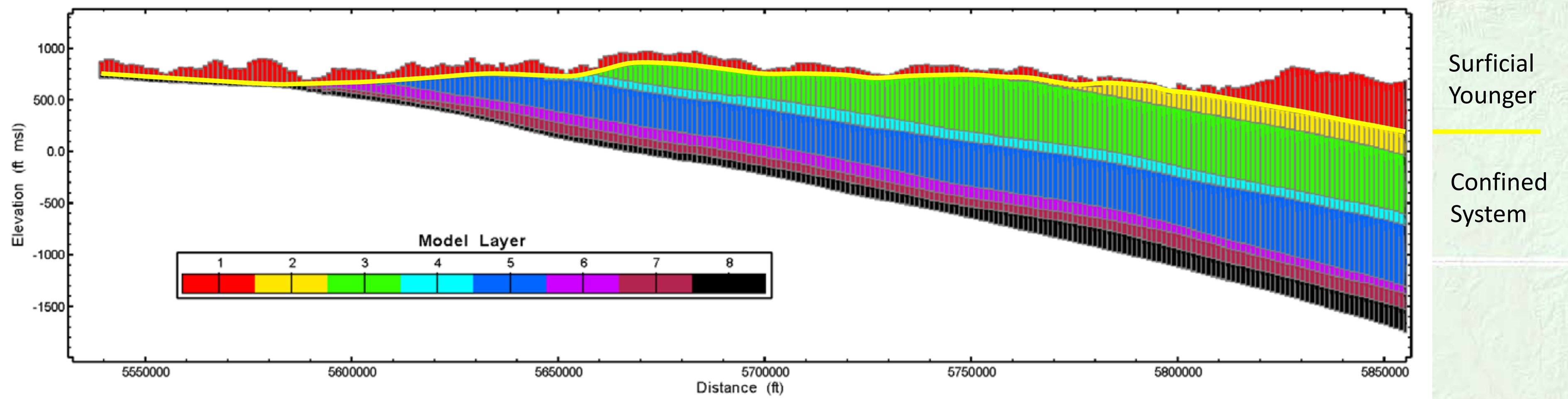
- This model offers advantages that include:
  - Refined model grid provides better placement of wells, rivers and other hydraulic boundaries
  - Calibration period extends through the major water level decline period which helps constrain storativity
  - The calibration period has been extended 12 years which improves our planning starting point
  - The draft model calibration is improved
  - The draft model incorporated GCD pumping data including metered data and wells
  - The draft model and data are publically available

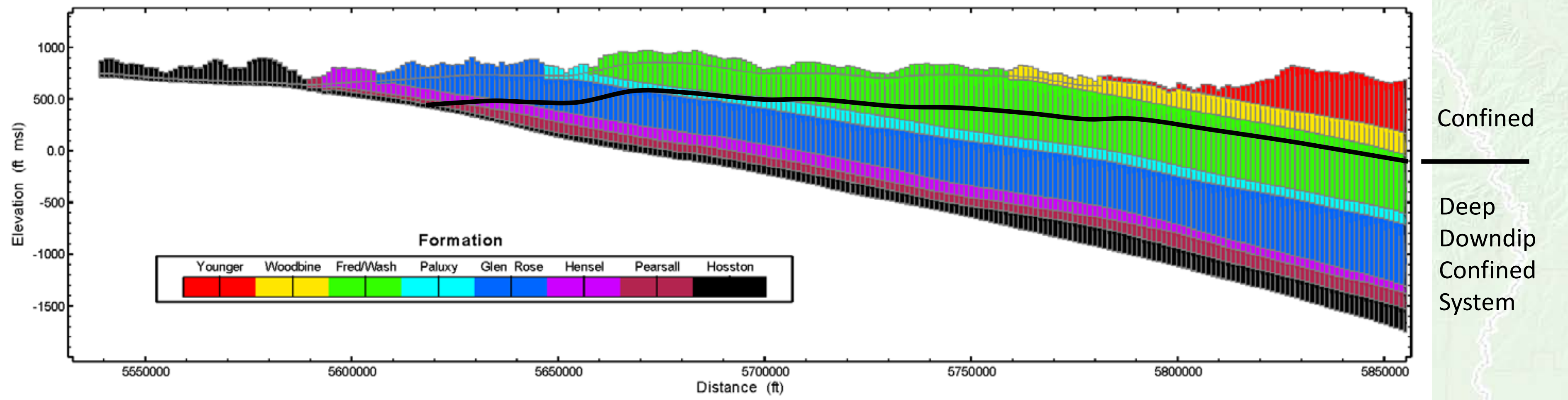
Conclusions

- The northern Trinity and Woodbine aquifers are a very complex aquifer system in Texas which is a challenge to model with one model
- Even the sand-rich aquifers are very stratified in their nature which results in low vertical hydraulic conductivities
- In steady-state model
  - Approximately 40% of the recharge moves into the confined portions of the aquifers and flows back to surface for discharge
  - The predevelopment system was defined by rejected recharge

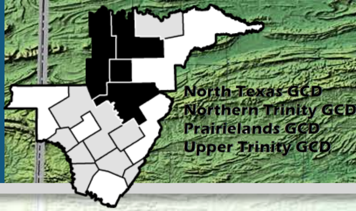
Water Balance Zones







Water Balance (AFY)



Year	Recharge (AFY)	Total Pumping (AFY)	Net Confined Flow[a] (AFY)	Deep Pumping[b] (AFY)	Net Downdip Confined Flow[c] (AFY)	Deep Storage[d] (AFY)
1889	1,766,549	0	503	0	2	0
1940	1,266,049	-58327.1	53,298	-31,749	23,446	8,304
1950	2,181,606	-91299.1	72,248	-48,113	30,401	17,713
1960	1,972,149	-121543	95,138	-61,981	42,364	19,617
1980	2,033,527	-227956	185,324	-104,552	75,799	28,755
1990	2,193,932	-241691	212,141	-107,284	92,347	14,937
2000	1,206,348	-266419	232,231	-117,533	100,167	17,363
2010	2,888,125	-285357	248,096	-127,078	112,140	14,937

[a] net model flow in AFY from the surficial outcrop area of Layer 1 to underlying layers
[b] model pumping that occurs approximately below a depth of 300 feet below the base of the surficial outcrop area of Layer 1
[c] net model flow in AFY that occurs to aquifers at a depth of 300 feet below the base of the surficial outcrop area of Layer 1
[d] model outflow from storage in AFY occurring within aquifers at a depth of 300 feet below the base of the surficial outcrop area of Layer 1

Conclusions

- After development
  - The volume of groundwater that enters the confined portion of the aquifers increases
  - After development there is a net loss from the surficial aquifers to the confined outcrop aquifers that reaches approximately 262,000 AF in 2010
  - The groundwater that reaches that down dip deeper confined portions of the aquifer reaches 15% of recharge in 2010 as a result of pumping
- The deep portions of the aquifers do not have adequate confined storage or available cross-flow to meet pumping volumes, therefore downdip flow increases