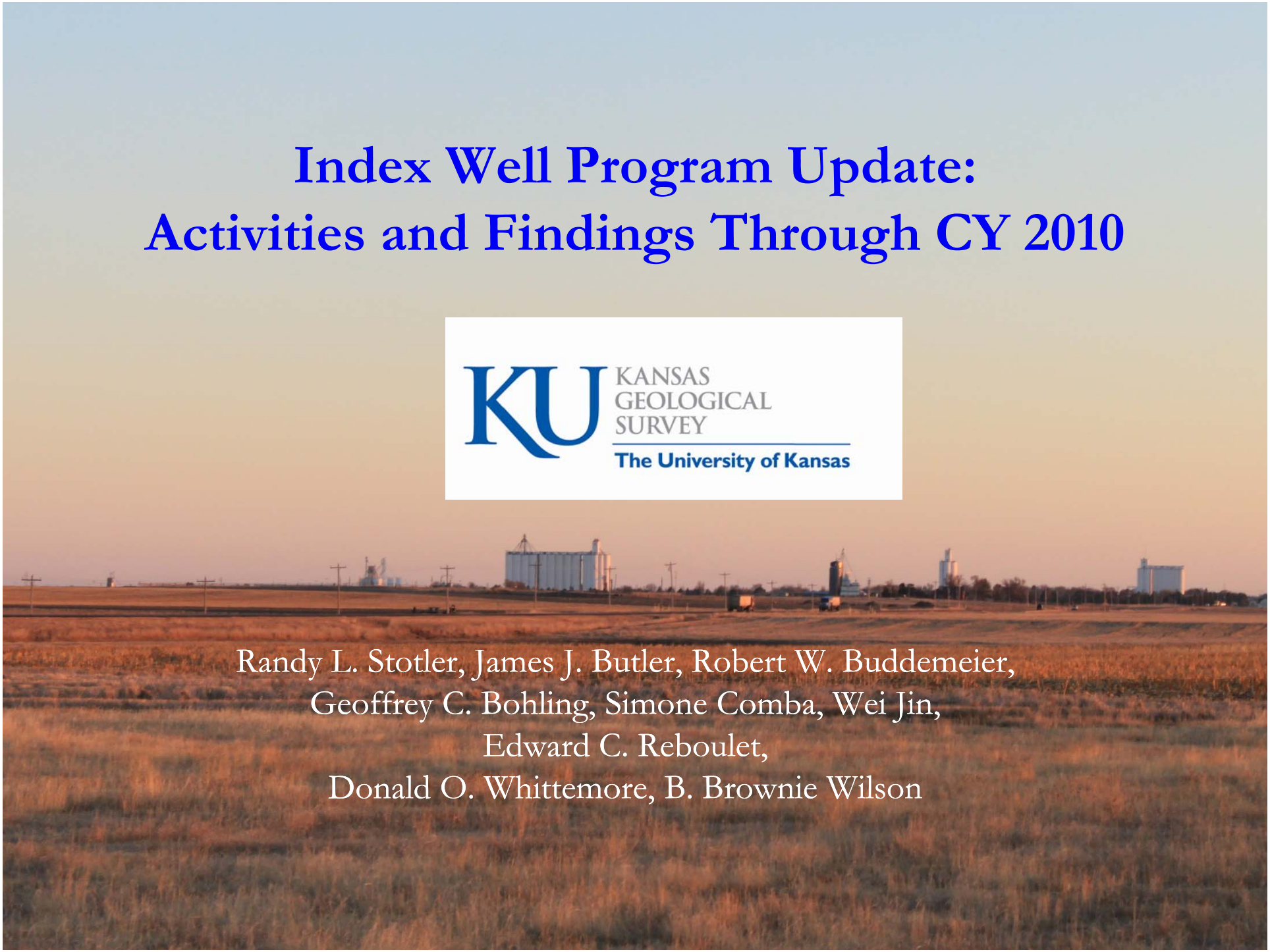
Index Well Program Update: Activities and Findings Through CY 2010

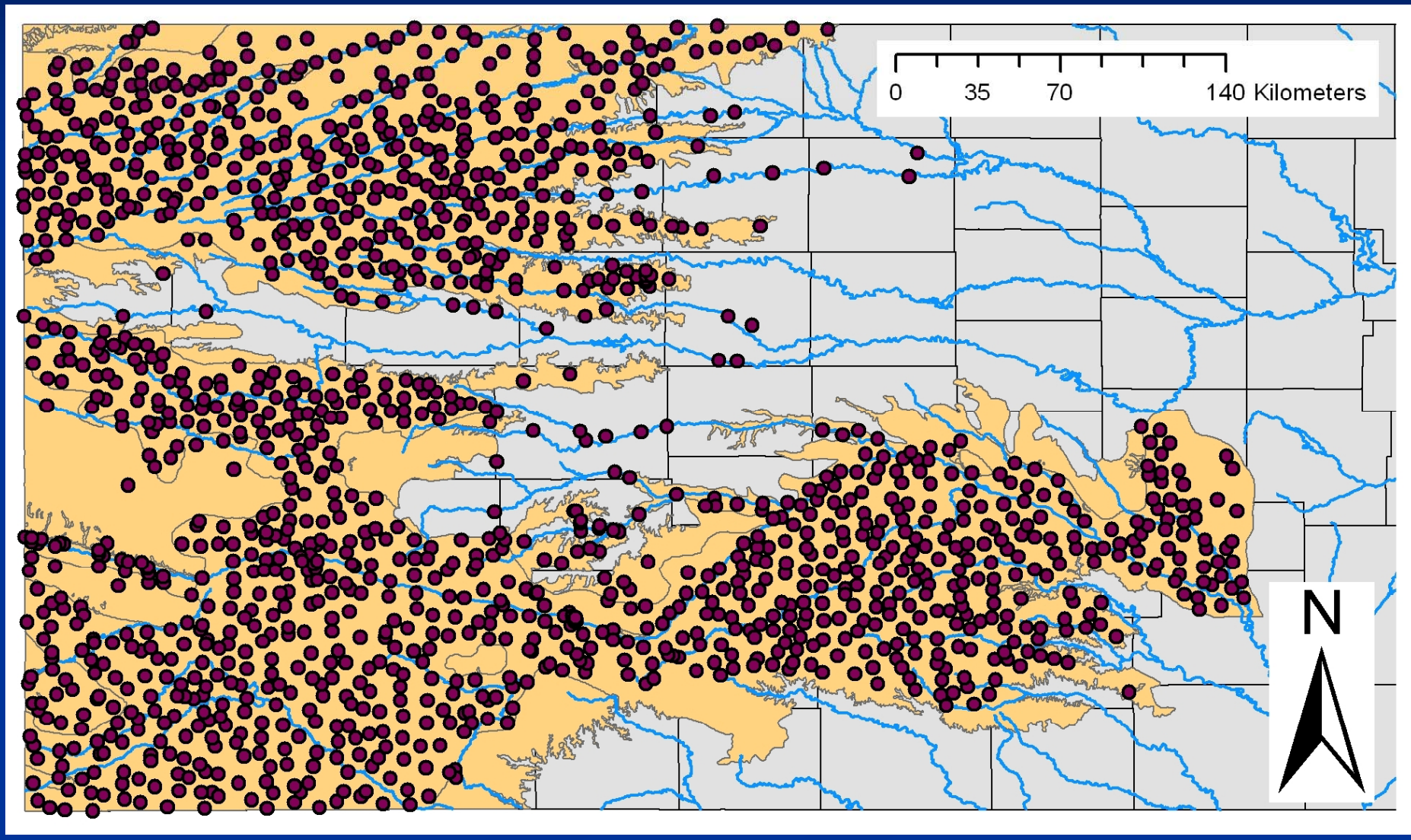


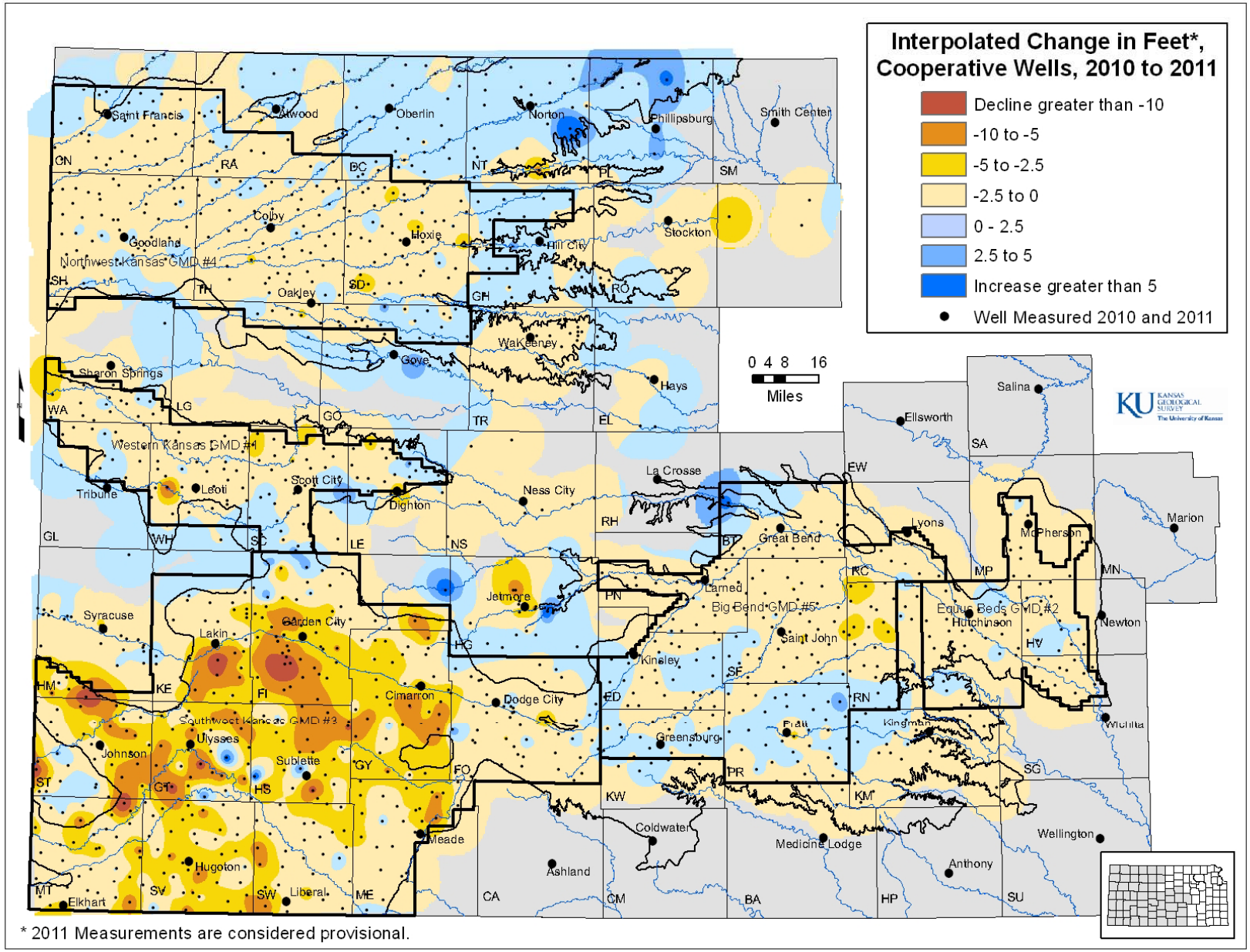
Randy L. Stotler, James J. Butler, Robert W. Buddemeier,
Geoffrey C. Bohling, Simone Comba, Wei Jin,
Edward C. Reboulet,
Donald O. Whittemore, B. Brownie Wilson

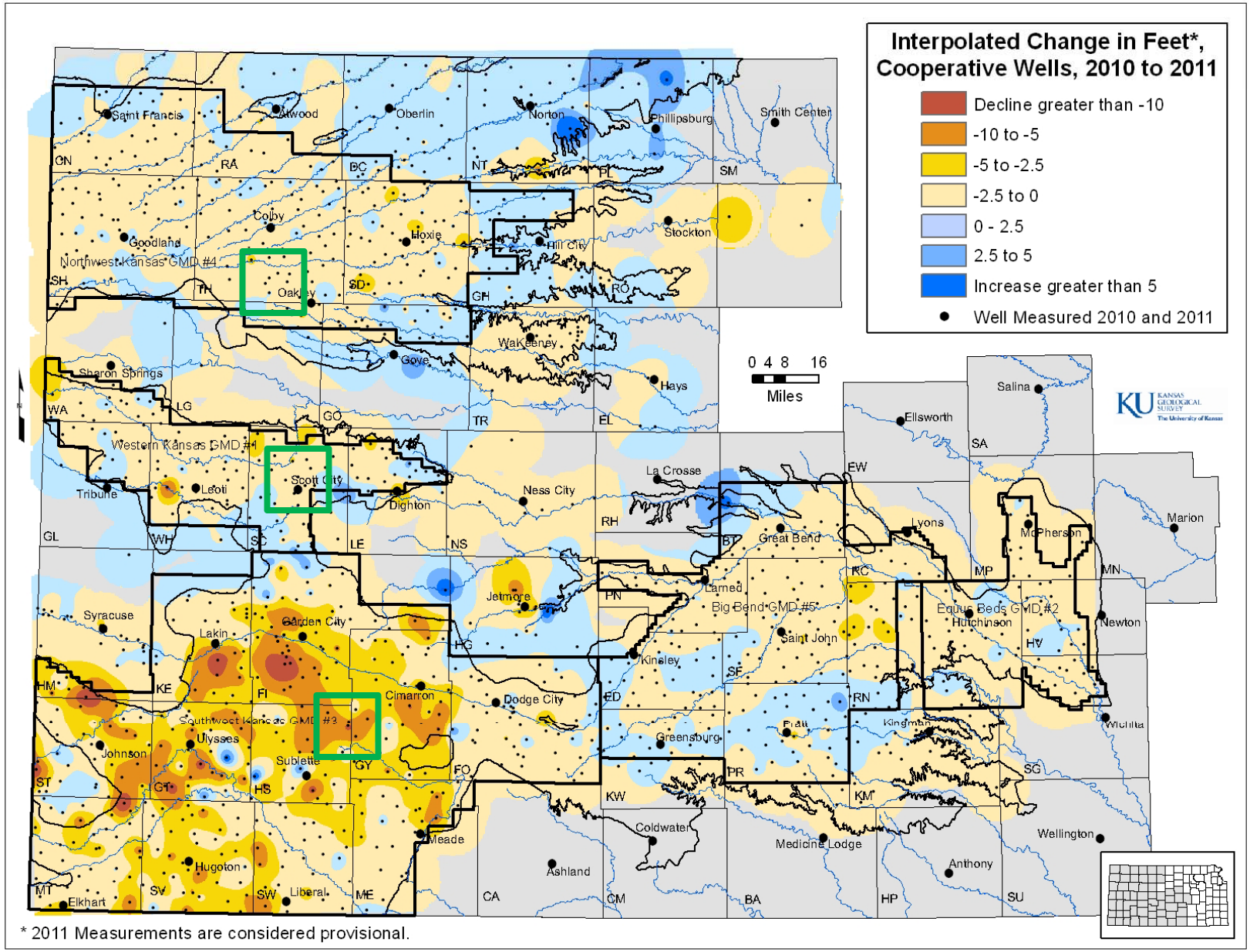
Outline

- Introduction to water-level determination in Kansas
  - Annual Well Program
  - Factors affecting water levels
- The index (or calibration) well concept
  - Pressure transducer measurements
  - Index Well dataset
- Applications in 2010
  - Determination of equilibrium water levels
  - Thomas County expansion project update
- Summary
- Related research efforts by KGS

Annual Water Level Monitoring

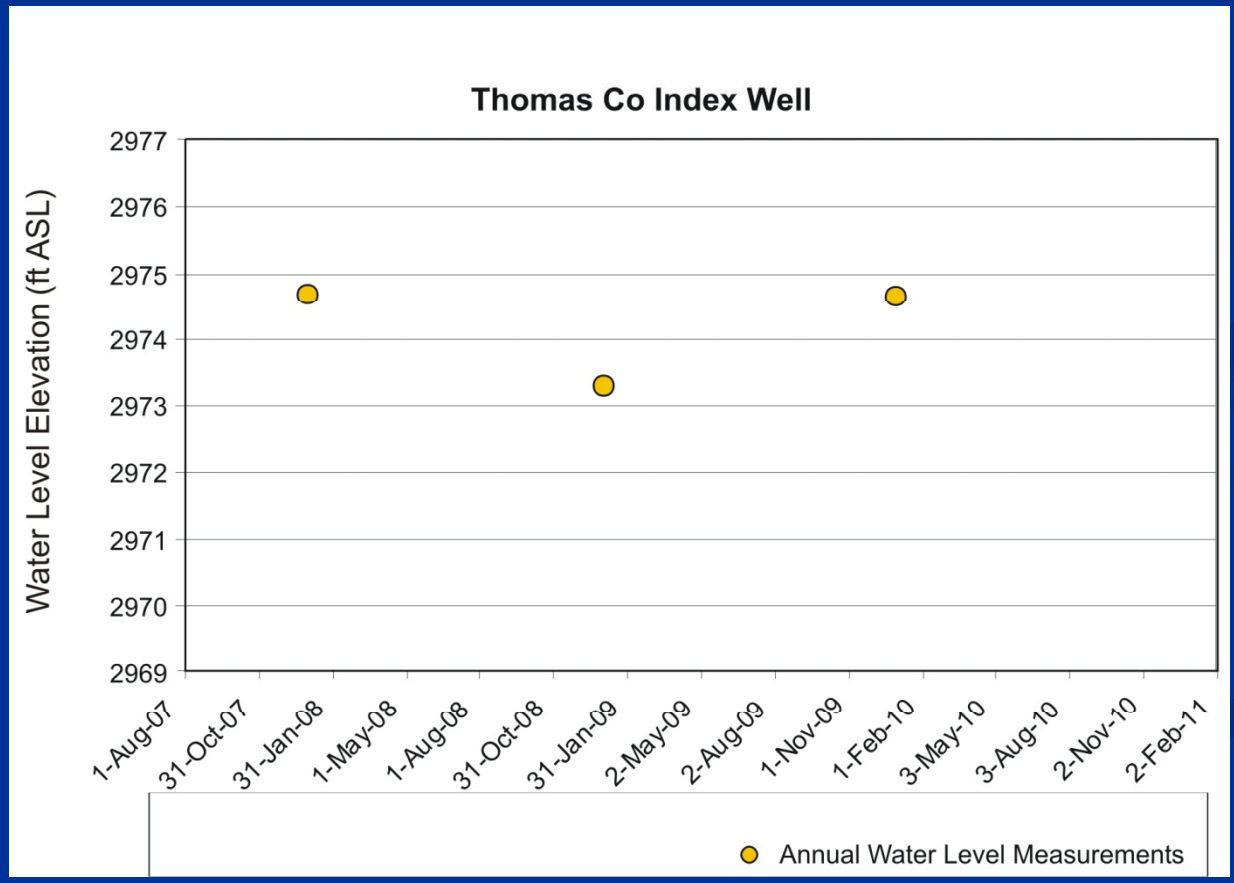



Interpolated Change in Feet*, Cooperative Wells, 2010 to 2011
Decline greater than -10
-10 to -5
-5 to -2.5
-2.5 to 0
0 - 2.5
2.5 to 5
Increase greater than 5
Well Measured 2010 and 2011
0 4 8 16
Miles
Northwest Kansas GMD #4
Western Kansas GMD #4
Southwest Kansas GMD #3
Big Bend GMD #5
Equus Beds GMD #2
Saint Francis
Atwood
Oberlin
Norton
Phillipsburg
Smith Center
Colby
Goodland
Hoxie
Hill City
Stockton
Oakley
WaKeeney
Gove
Hays
Sharon Springs
Tribune
Leoti
Scott City
Dighton
Ness City
La Crosse
Salina
Ellsworth
Lyons
McPherson
Marion
Great Bend
Larned
Jetmore
Syracuse
Lakin
Garden City
Kinsley
Saint John
Hutchinson
Newton
Cimarron
Dodge City
Ulysses
Johnson
Sublette
Greensburg
Pratt
Kingman
Wichita
Meade
Coldwater
Medicine Lodge
Wellington
Anthony
Hugoton
Ashland
Elkhart
Liberal
* 2011 Measurements are considered provisional.

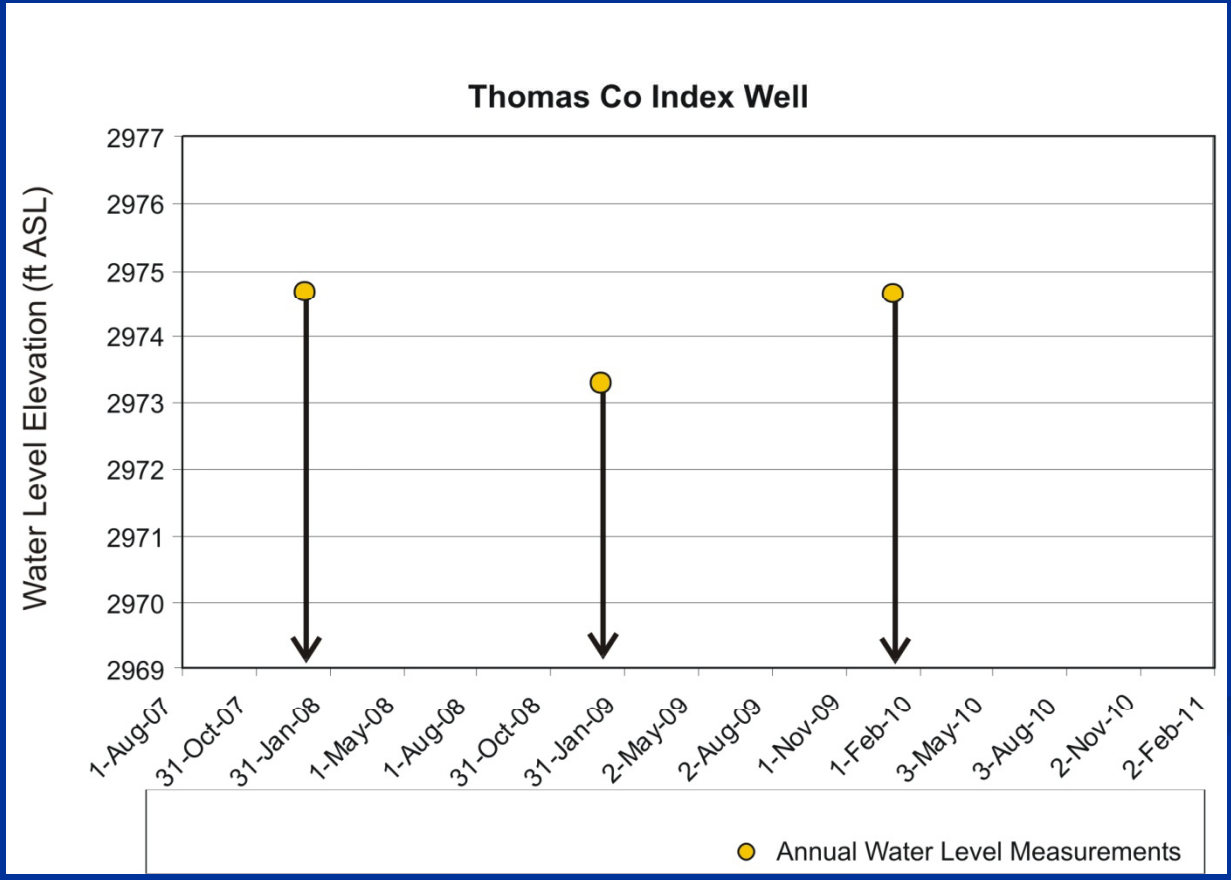


* 2011 Measurements are considered provisional.

How Often?


Thomas Co Index Well
Water Level Elevation (ft ASL)
2977
2976
2975
2974
2973
2972
2971
2970
2969
1-Aug-07
31-Oct-07
31-Jan-08
1-May-08
1-Aug-08
31-Oct-08
31-Jan-09
2-May-09
2-Aug-09
1-Nov-09
1-Feb-10
3-May-10
3-Aug-10
2-Nov-10
2-Feb-11
Annual Water Level Measurements

How Often?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Water Level Elevation (ft ASL)
2977
2976
2975
2974
2973
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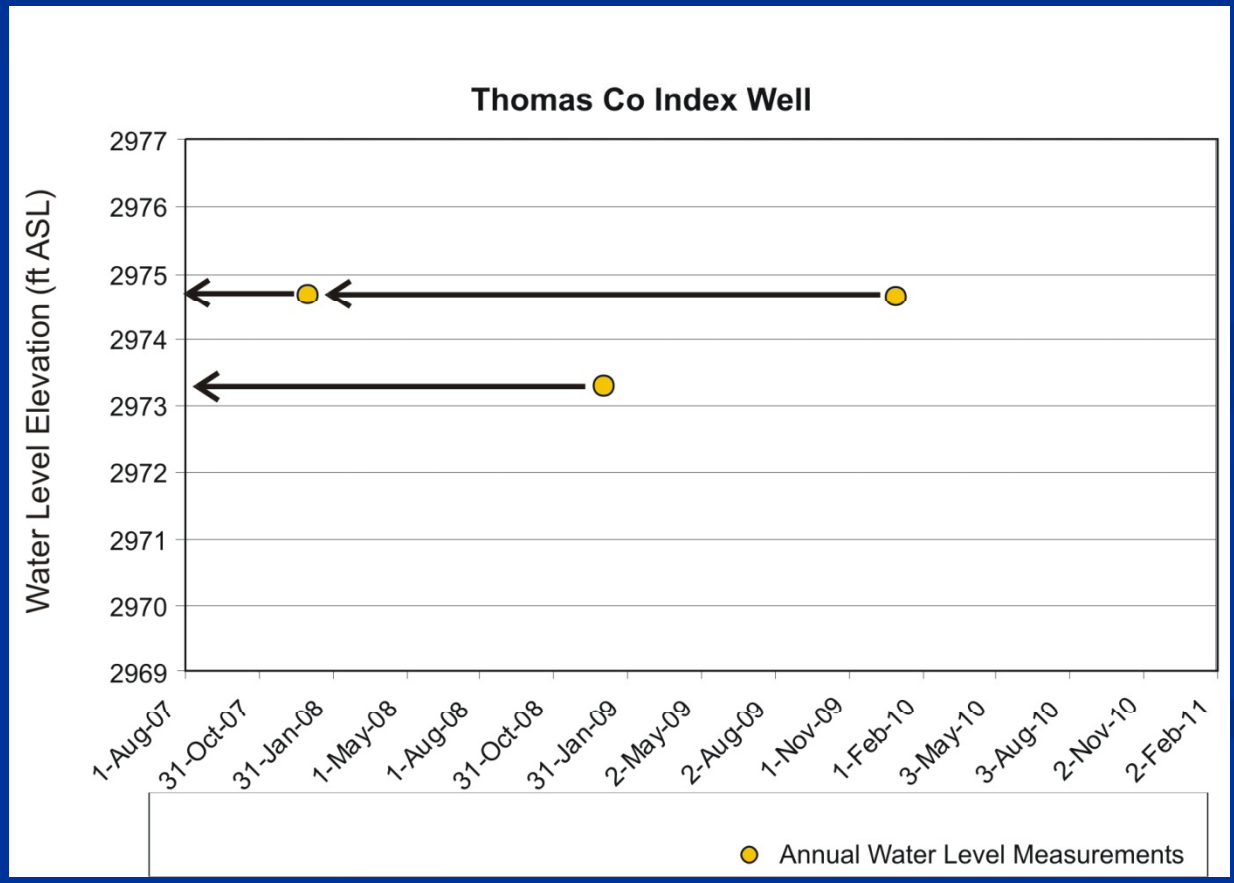
2969
1-Aug-07
31-Oct-07
31-Jan-08
1-May-08
1-Aug-08
31-Oct-08
31-Jan-09
2-May-09
2-Aug-09
1-Nov-09
1-Feb-10
3-May-10
3-Aug-10
2-Nov-10
2-Feb-11
Annual Water Level Measurements

How Often?


Thomas Co Index Well
Water Level Elevation (ft ASL)
2977
2976
2975
2974
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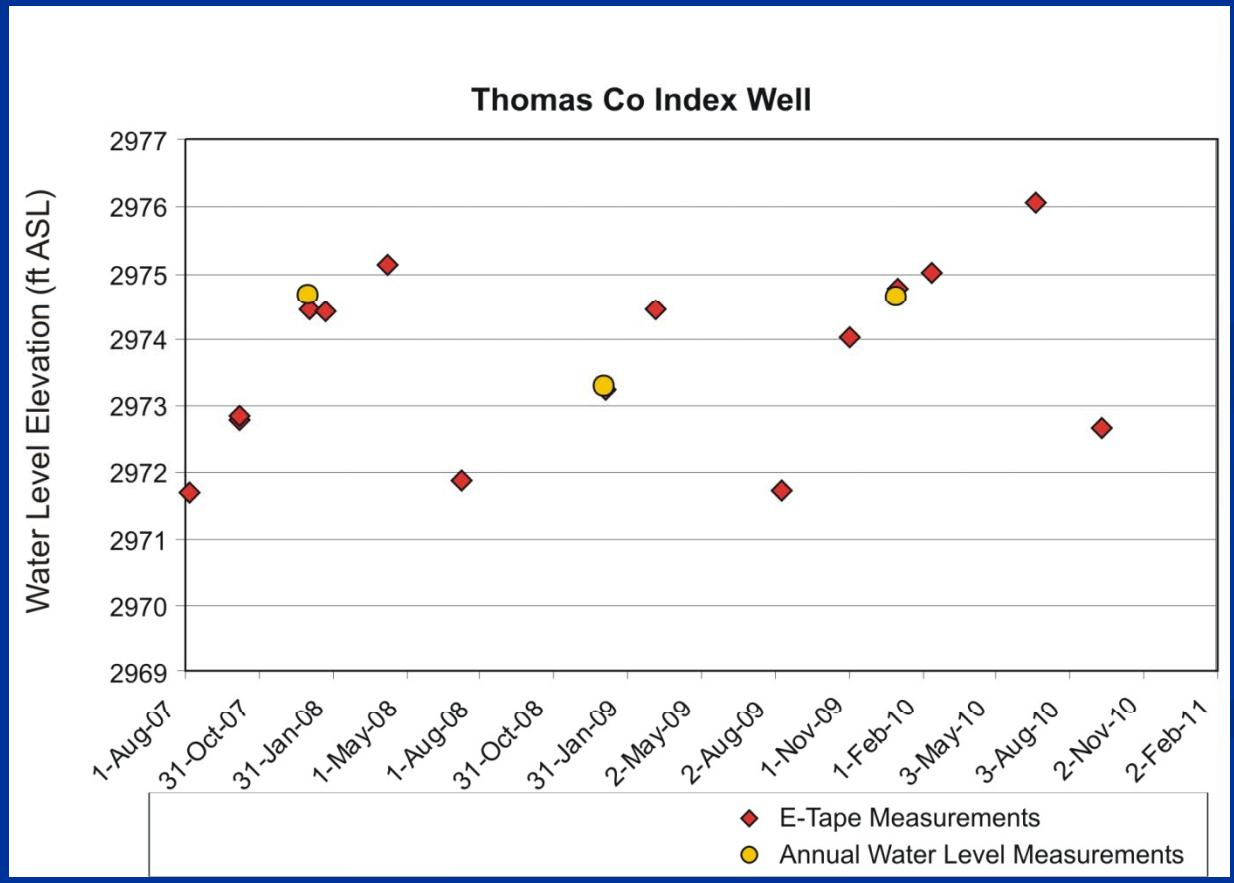
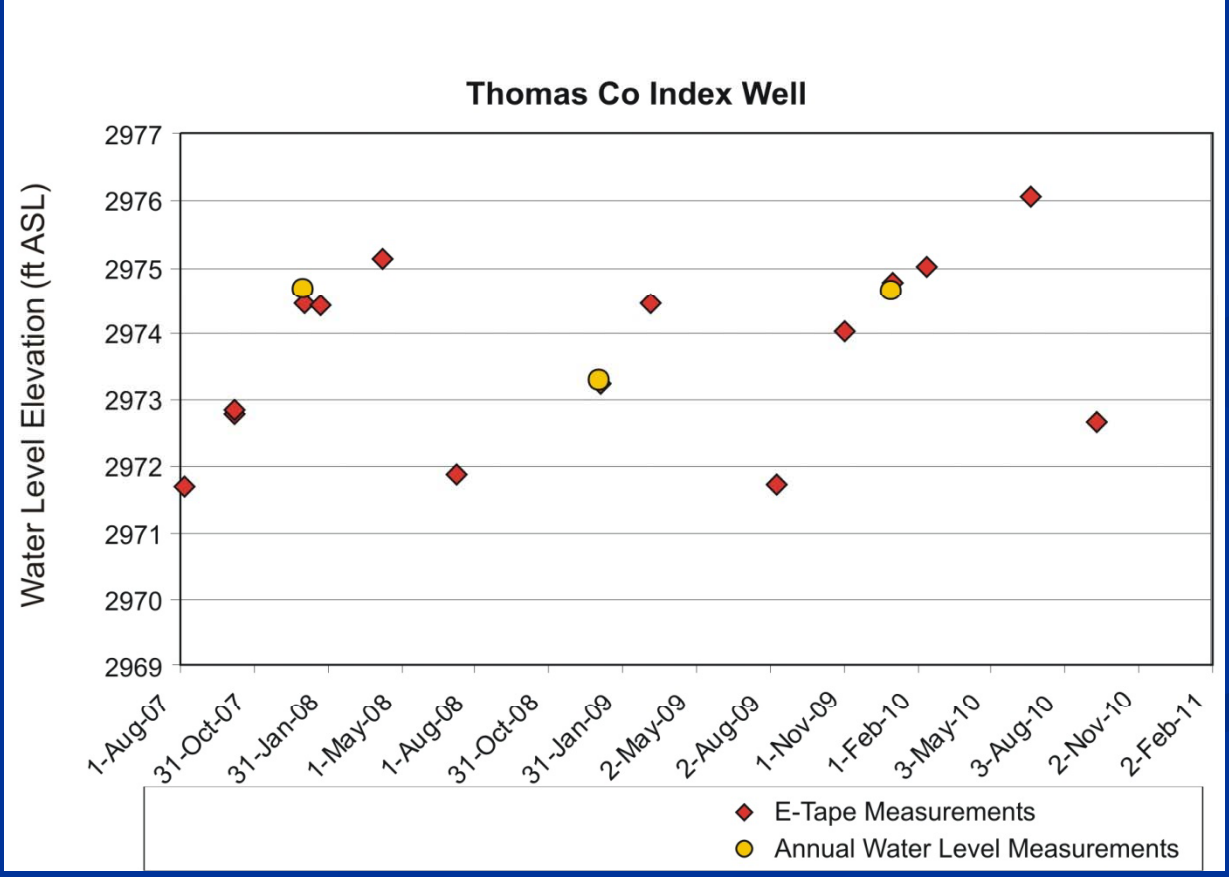
2972
2971
2970
2969
1-Aug-07
31-Oct-07
31-Jan-08
1-May-08
1-Aug-08
31-Oct-08
31-Jan-09
2-May-09
2-Aug-09
1-Nov-09
1-Feb-10
3-May-10
3-Aug-10
2-Nov-10
2-Feb-11
Annual Water Level Measurements

How Often?


Thomas Co Index Well
Water Level Elevation (ft ASL)
2977
2976
2975
2974
2973
2972
2971
2970
2969
1-Aug-07
31-Oct-07
31-Jan-08
1-May-08
1-Aug-08
31-Oct-08
31-Jan-09
2-May-09
2-Aug-09
1-Nov-09
1-Feb-10
3-May-10
3-Aug-10
2-Nov-10
2-Feb-11
E-Tape Measurements
Annual Water Level Measurements

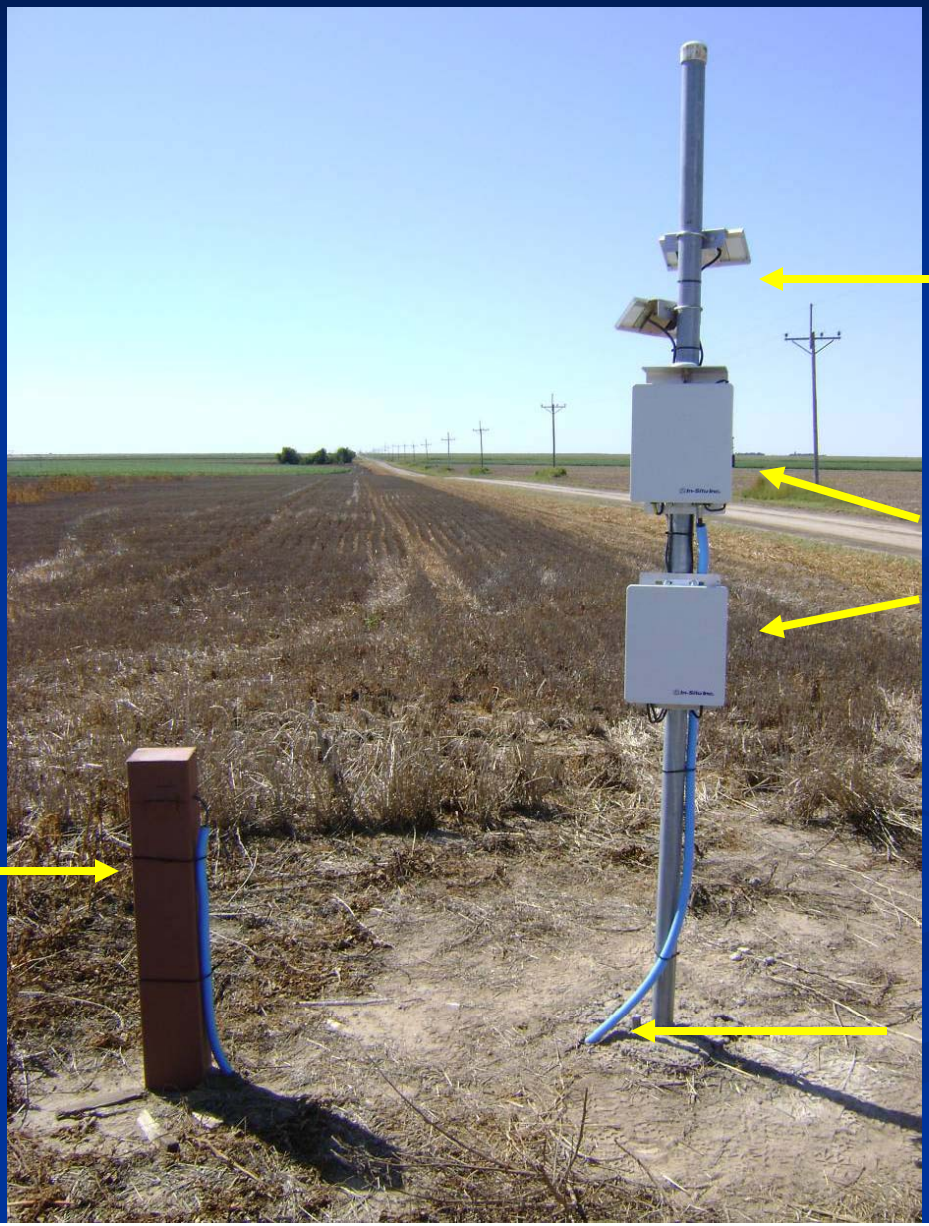
How Often?

- Relation to "equilibrium" water surface (recovery)
  - **Frequency of observations**
  - **Timing of observations**



"Index Well"

Typical Installation
(Thomas County Site)



Solar panels

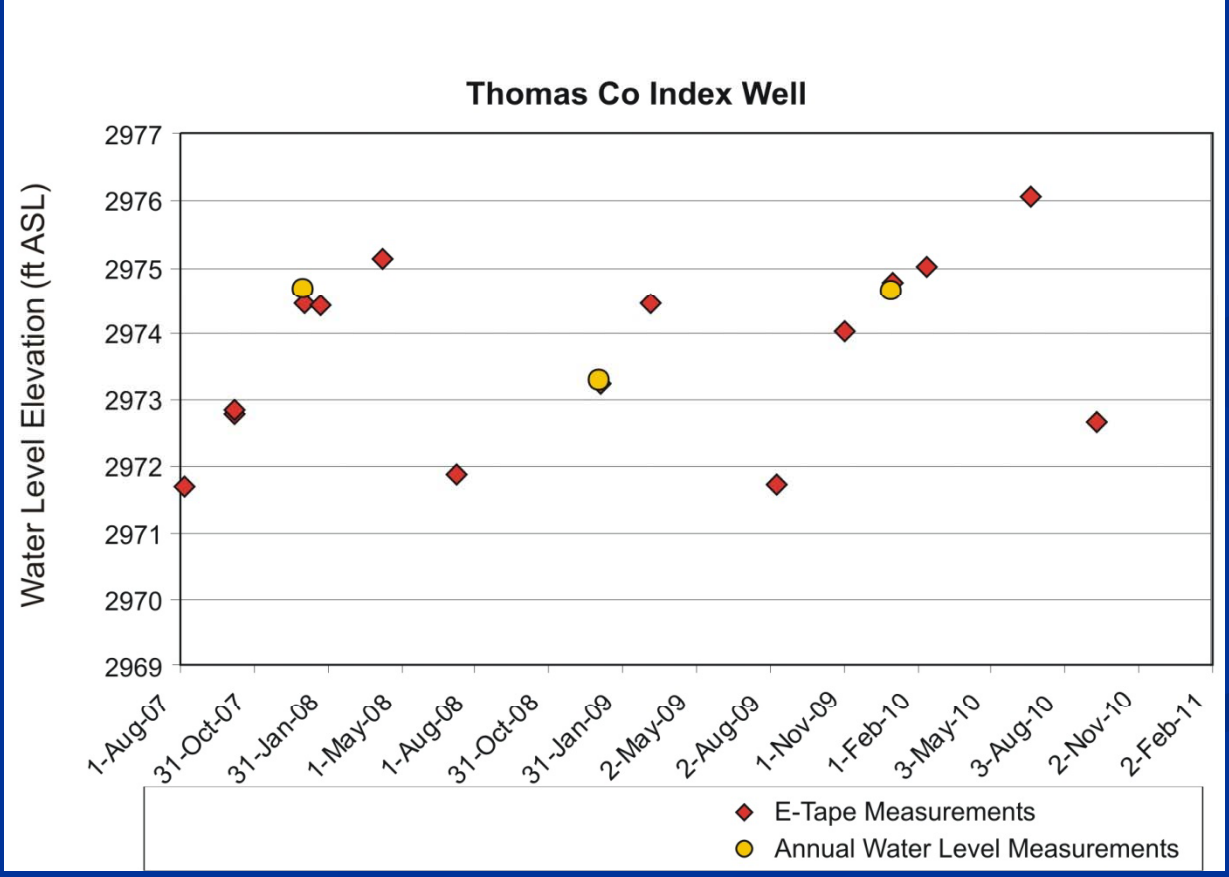
Telemetry system and batteries
Data available online for users and managers

2.5" PVC well with steel wellhead protector

Cable from pressure transducer in well to telemetry system

How Often?

- Relation to "equilibrium" water surface (recovery)
  - **Frequency of observations**
  - **Timing of observations**



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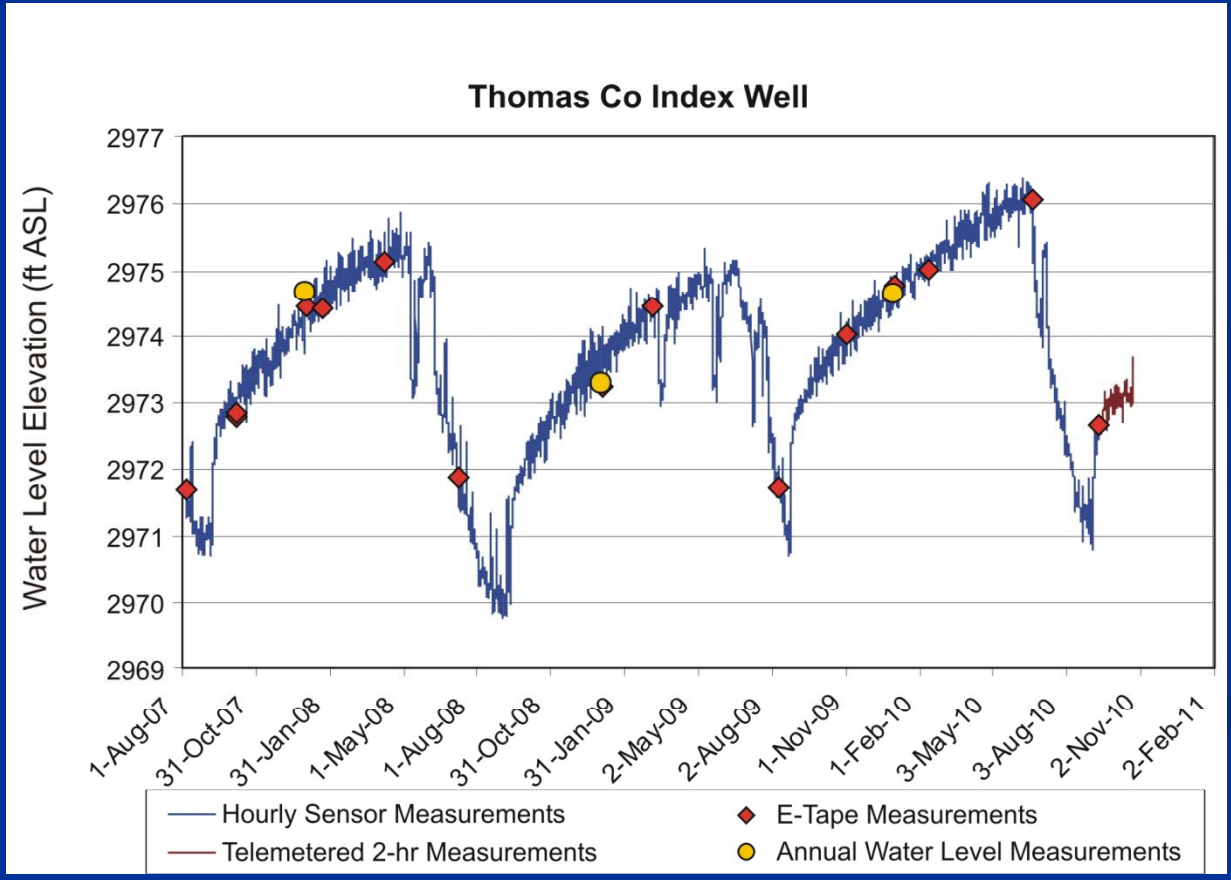

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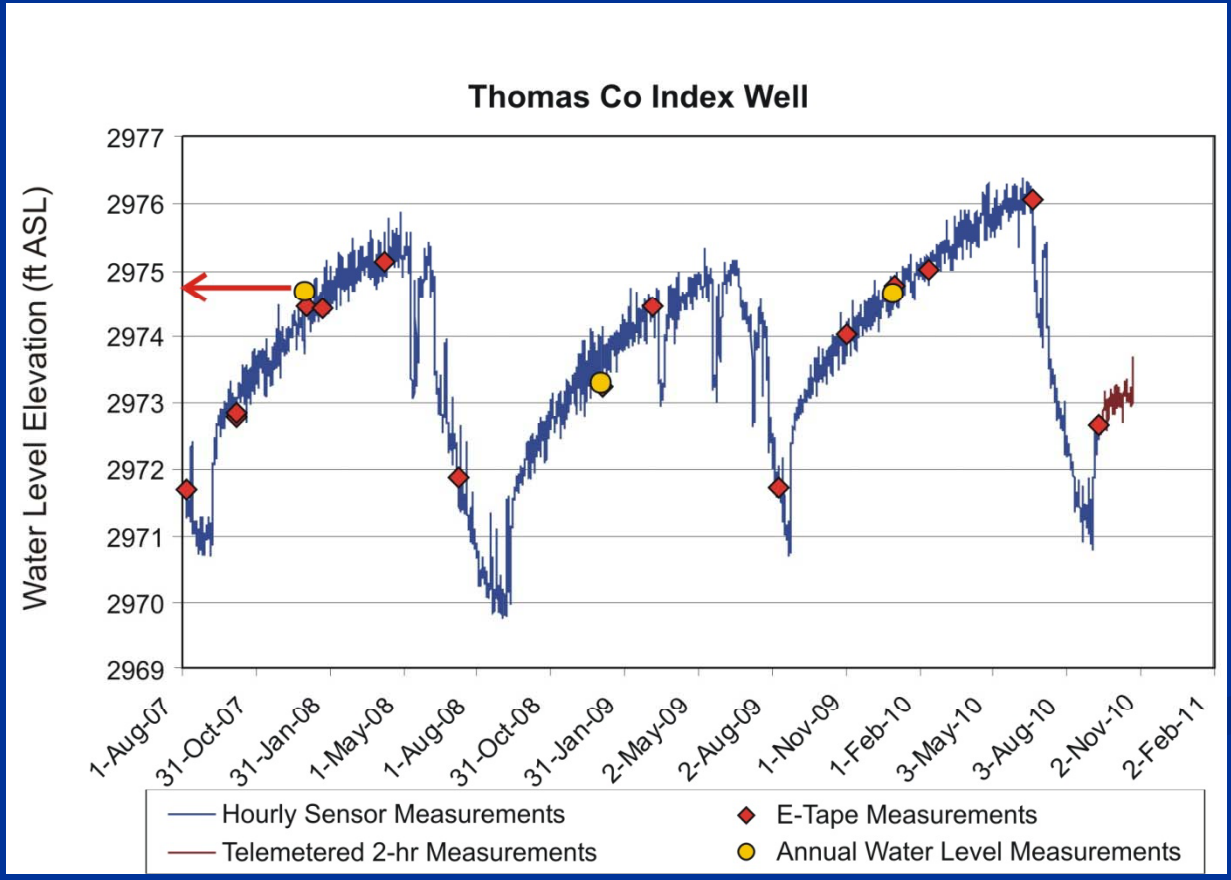

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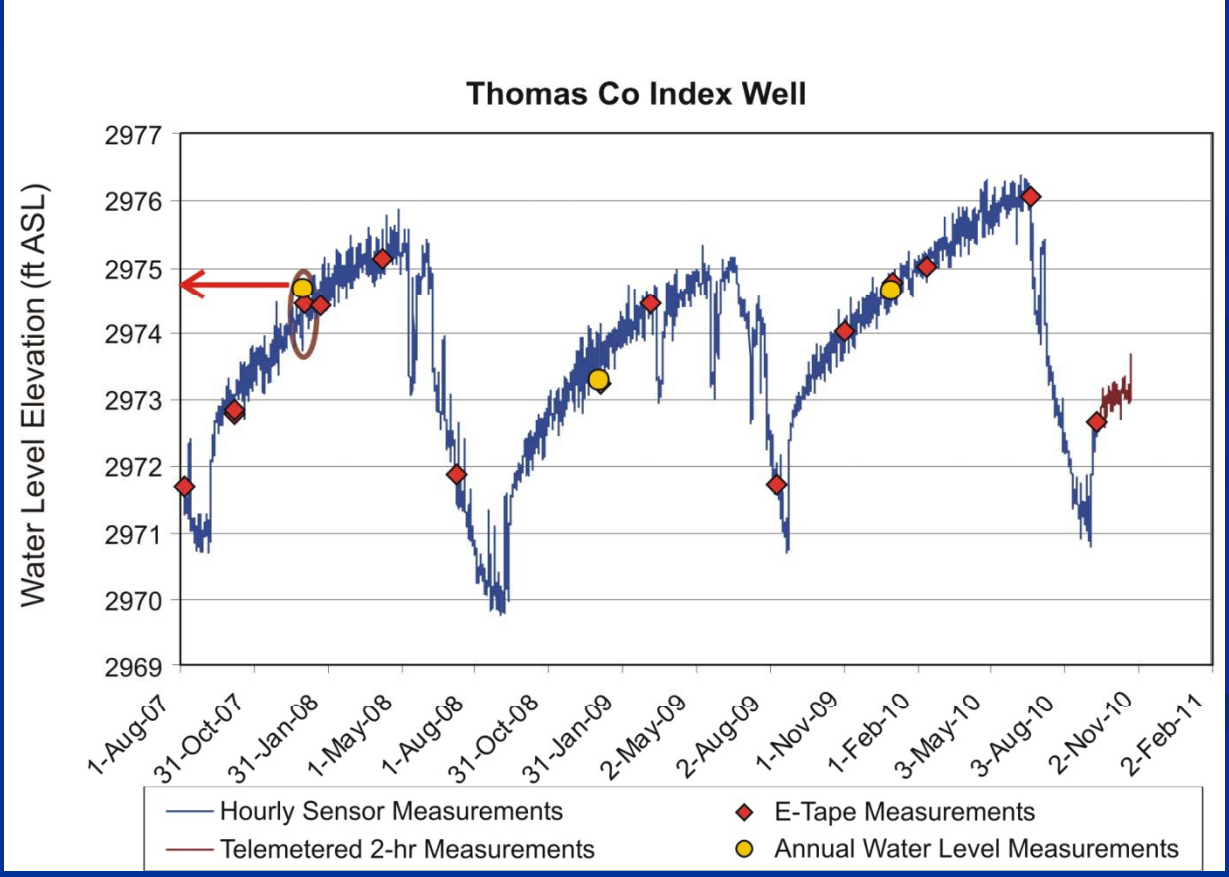

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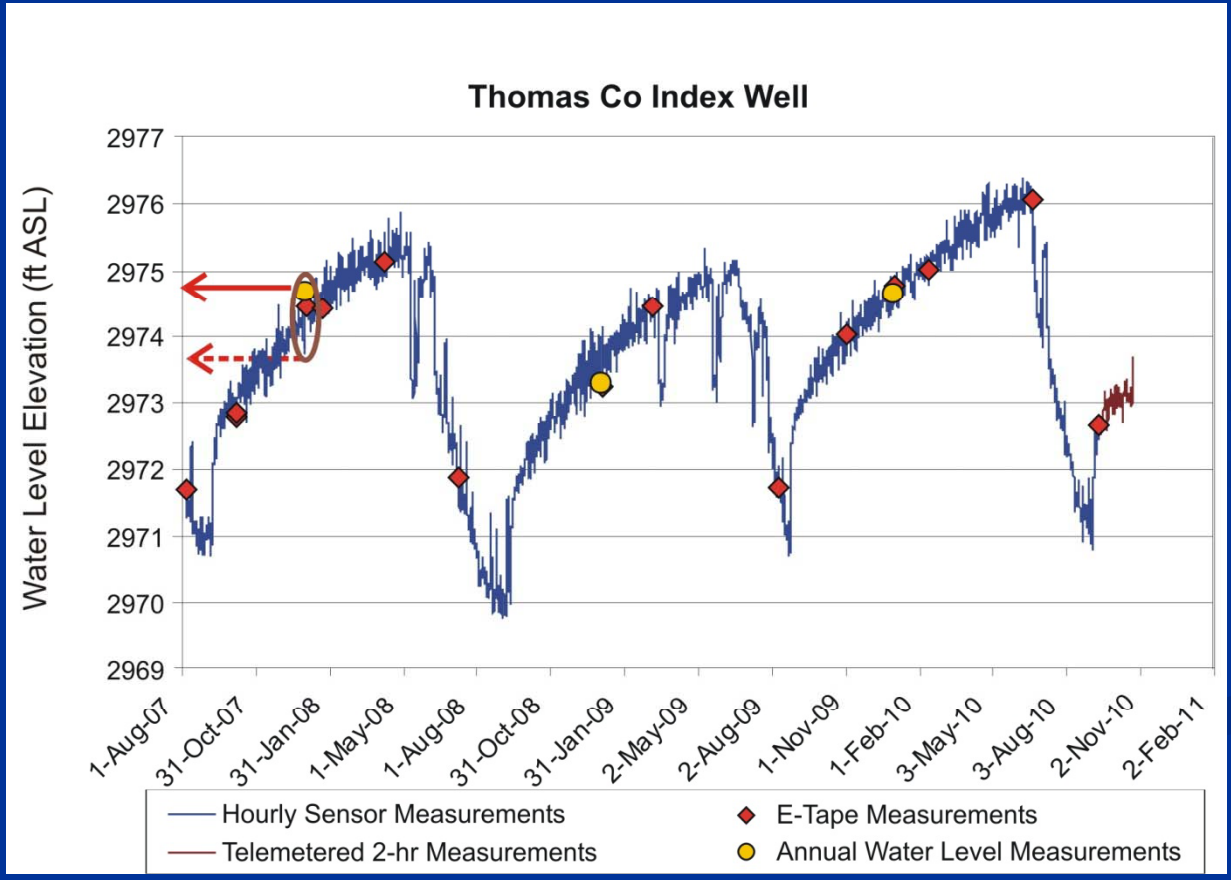
  - **Timing of observations**



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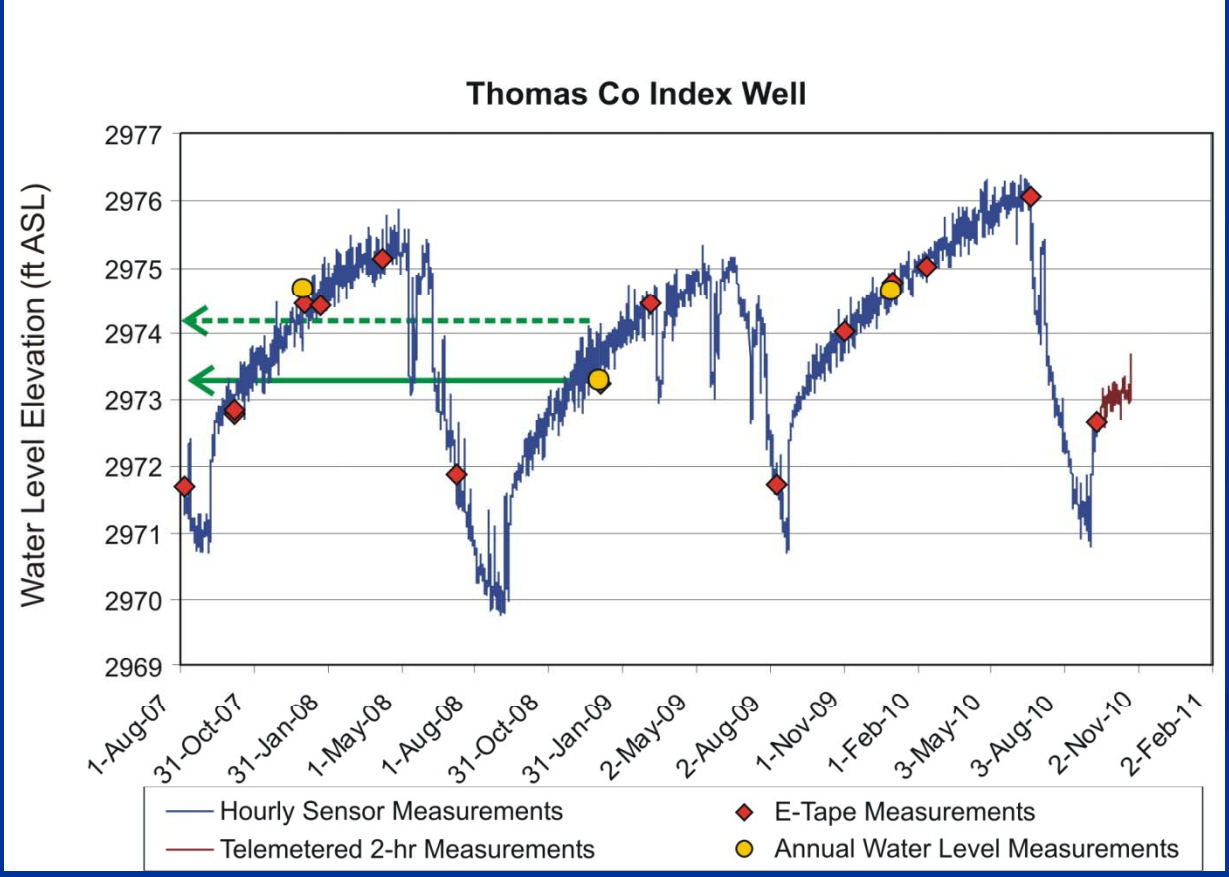
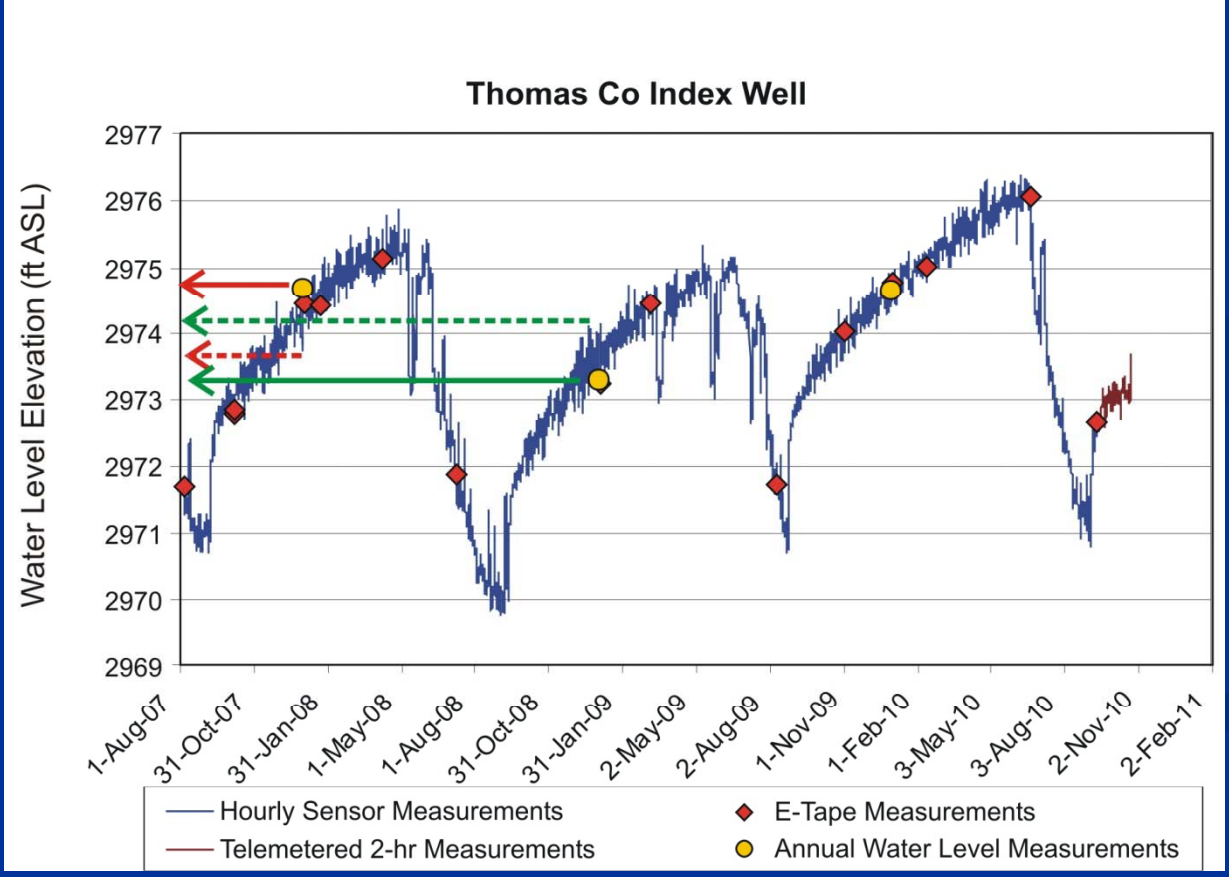
  - **Frequency of observations**
  - **Timing of observations**



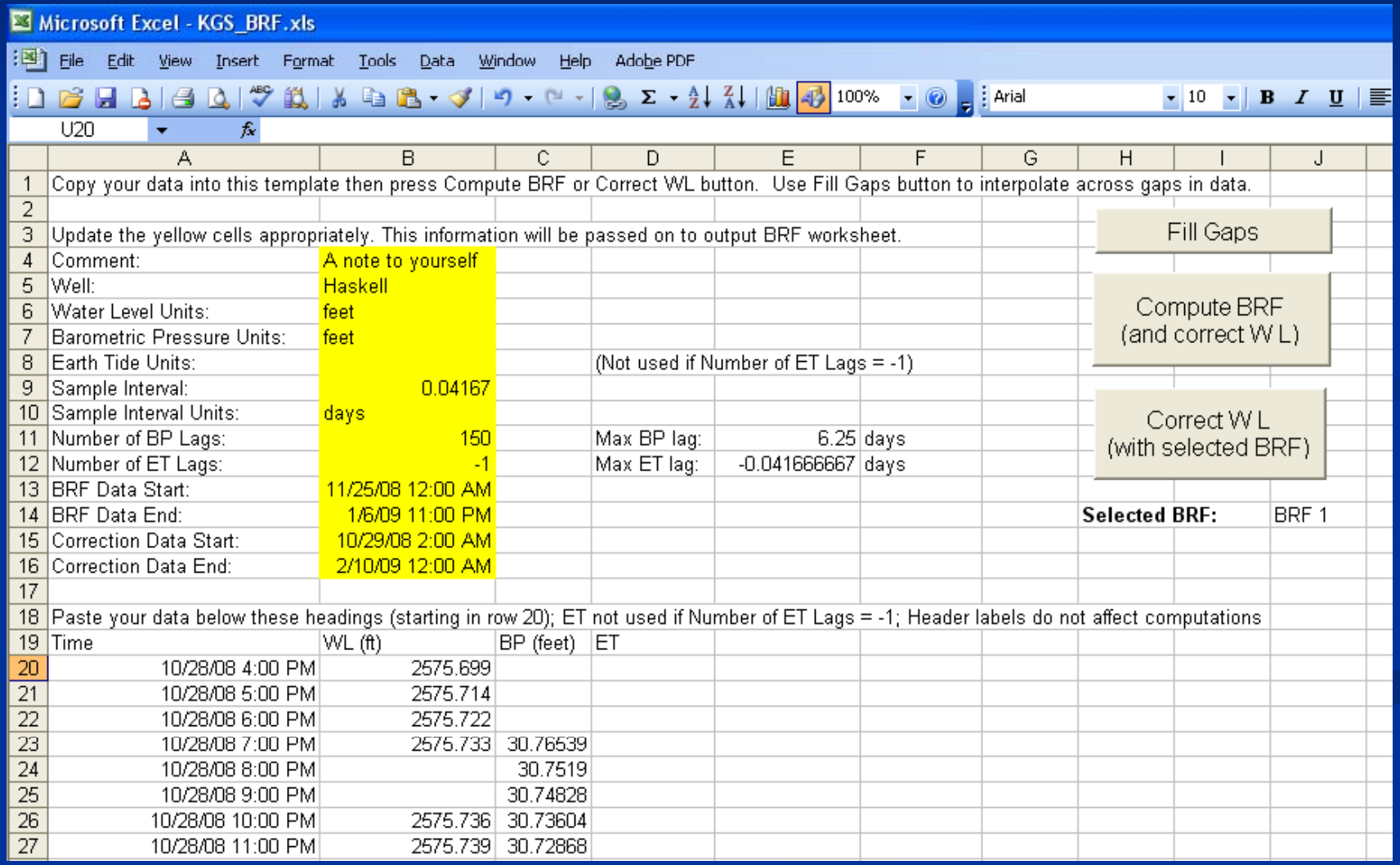
How Often?

- Relation to "equilibrium" water surface (recovery)
  - **Frequency of observations**
  - **Timing of observations**

With ~5ft of annual water-level variation, ignoring barometric effect in annual measurements = error equivalent to ~20% of annual drawdown



KGS_BRF Excel Spreadsheet



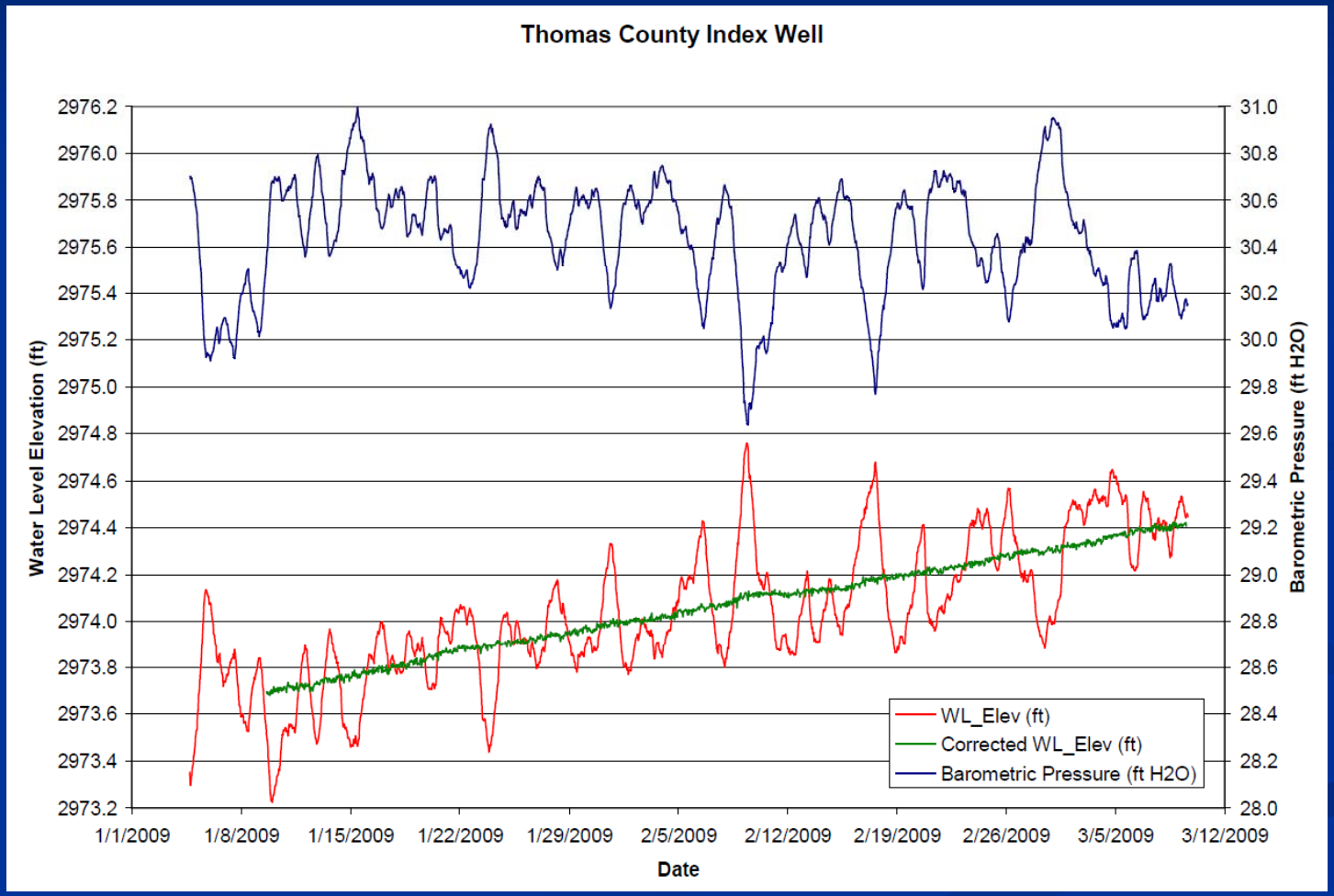
Microsoft Excel - KGS_BRF.xls

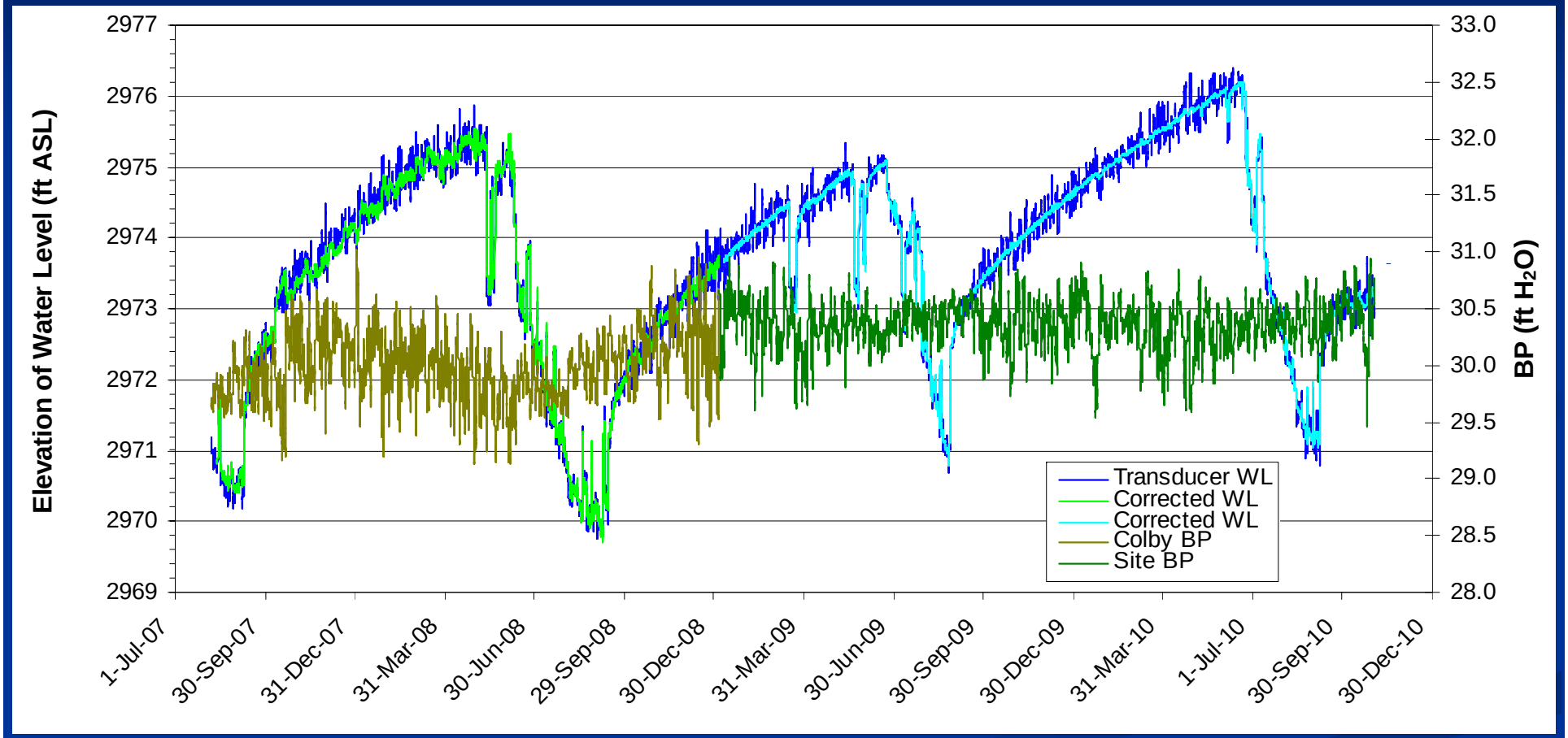
File Edit View Insert Format Tools Data Window Help Adobe PDF

U20

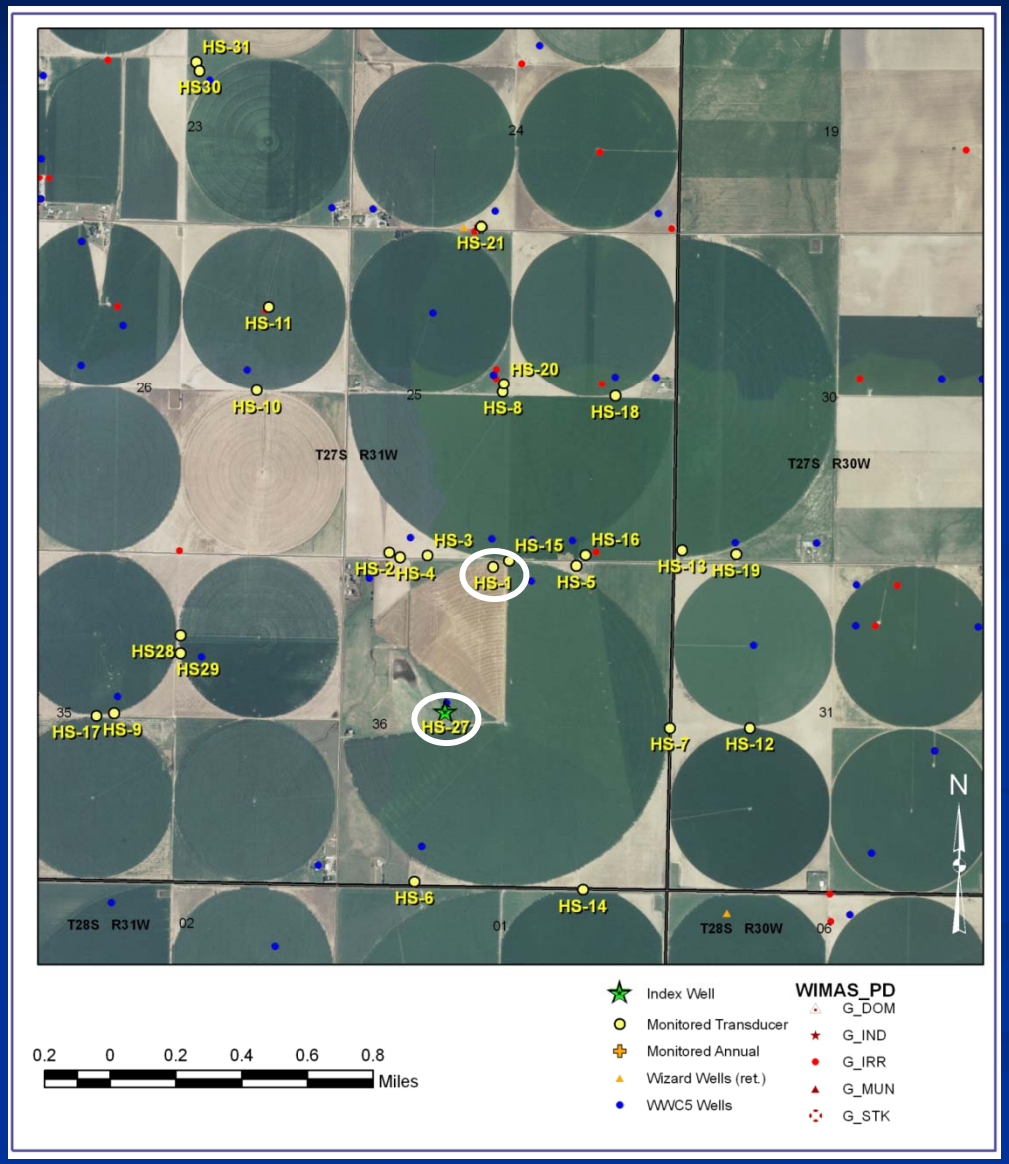
	A	B	C	D	E	F	G	H	I	J
1	Copy your data into this template then press Compute BRF or Correct WL button. Use Fill Gaps button to interpolate across gaps in data.									
2										
3	Update the yellow cells appropriately. This information will be passed on to output BRF worksheet.							Fill Gaps		
4	Comment:	A note to yourself								
5	Well:	Haskell						Compute BRF (and correct WL)		
6	Water Level Units:	feet								
7	Barometric Pressure Units:	feet								
8	Earth Tide Units:			(Not used if Number of ET Lags = -1)						
9	Sample Interval:	0.04167								
10	Sample Interval Units:	days						Correct WL (with selected BRF)		
11	Number of BP Lags:	150		Max BP lag:	6.25	days				
12	Number of ET Lags:	-1		Max ET lag:	-0.041666667	days				
13	BRF Data Start:	11/25/08 12:00 AM								
14	BRF Data End:	1/6/09 11:00 PM						**Selected BRF:**		BRF 1
15	Correction Data Start:	10/29/08 2:00 AM								
16	Correction Data End:	2/10/09 12:00 AM								
17										
18	Paste your data below these headings (starting in row 20); ET not used if Number of ET Lags = -1; Header labels do not affect computations									
19	Time	WL (ft)	BP (feet)	ET						
20	10/28/08 4:00 PM	2575.699								
21	10/28/08 5:00 PM	2575.714								
22	10/28/08 6:00 PM	2575.722								
23	10/28/08 7:00 PM	2575.733	30.76539							
24	10/28/08 8:00 PM		30.7519							
25	10/28/08 9:00 PM		30.74828							
26	10/28/08 10:00 PM	2575.736	30.73604							
27	10/28/08 11:00 PM	2575.739	30.72868							

Barometric Pressure Correction



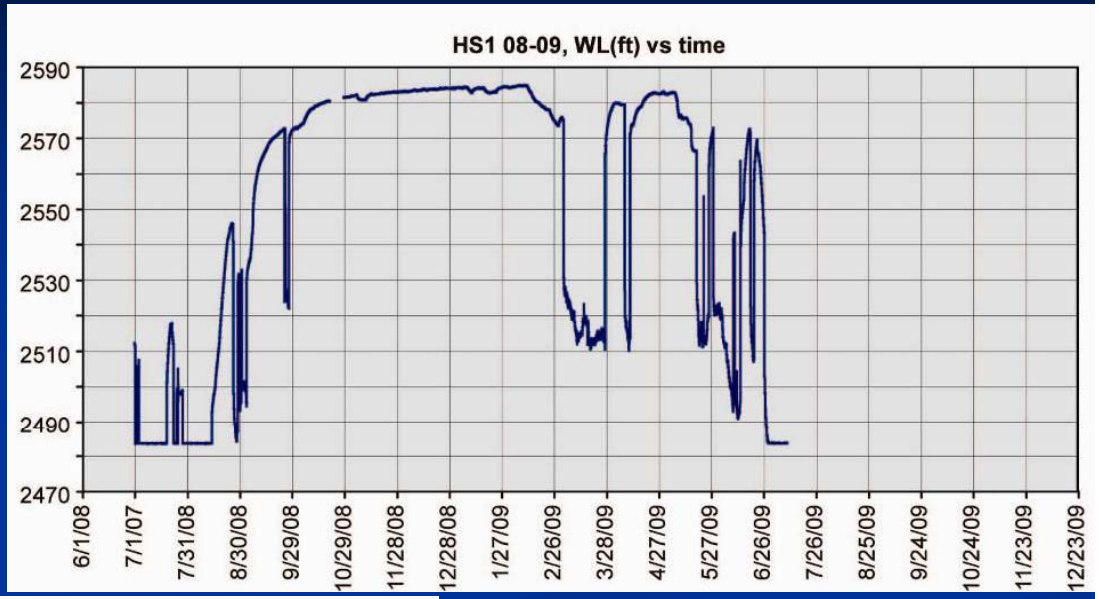

Elevation of Water Level (ft ASL)
BP (ft H2O)
2977
2976
2975
2974
2973
2972
2971
2970
2969
33.0
32.5
32.0
31.5
31.0
30.5
30.0
29.5
29.0
28.5
28.0
1-Jul-07
30-Sep-07
31-Dec-07
31-Mar-08
30-Jun-08
29-Sep-08
30-Dec-08
31-Mar-09
30-Jun-09
30-Sep-09
30-Dec-09
31-Mar-10
1-Jul-10
30-Sep-10
30-Dec-10
Transducer WL
Corrected WL
Corrected WL
Colby BP
Site BP

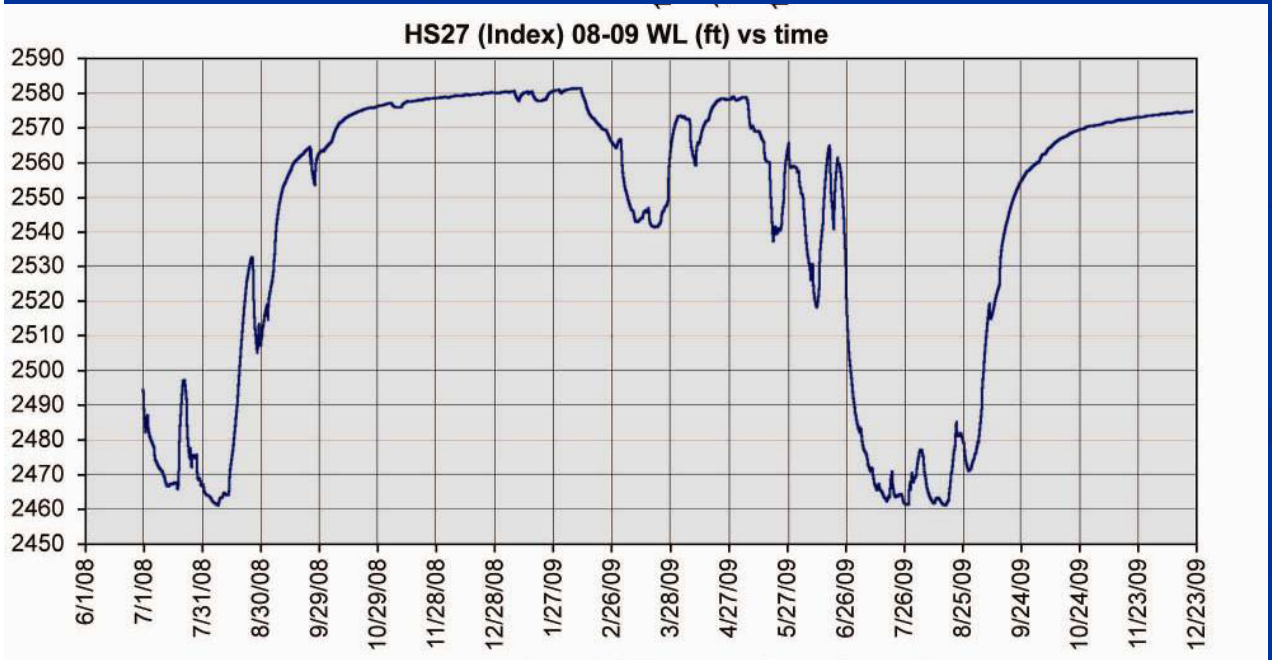
Complex Geology – Haskell County



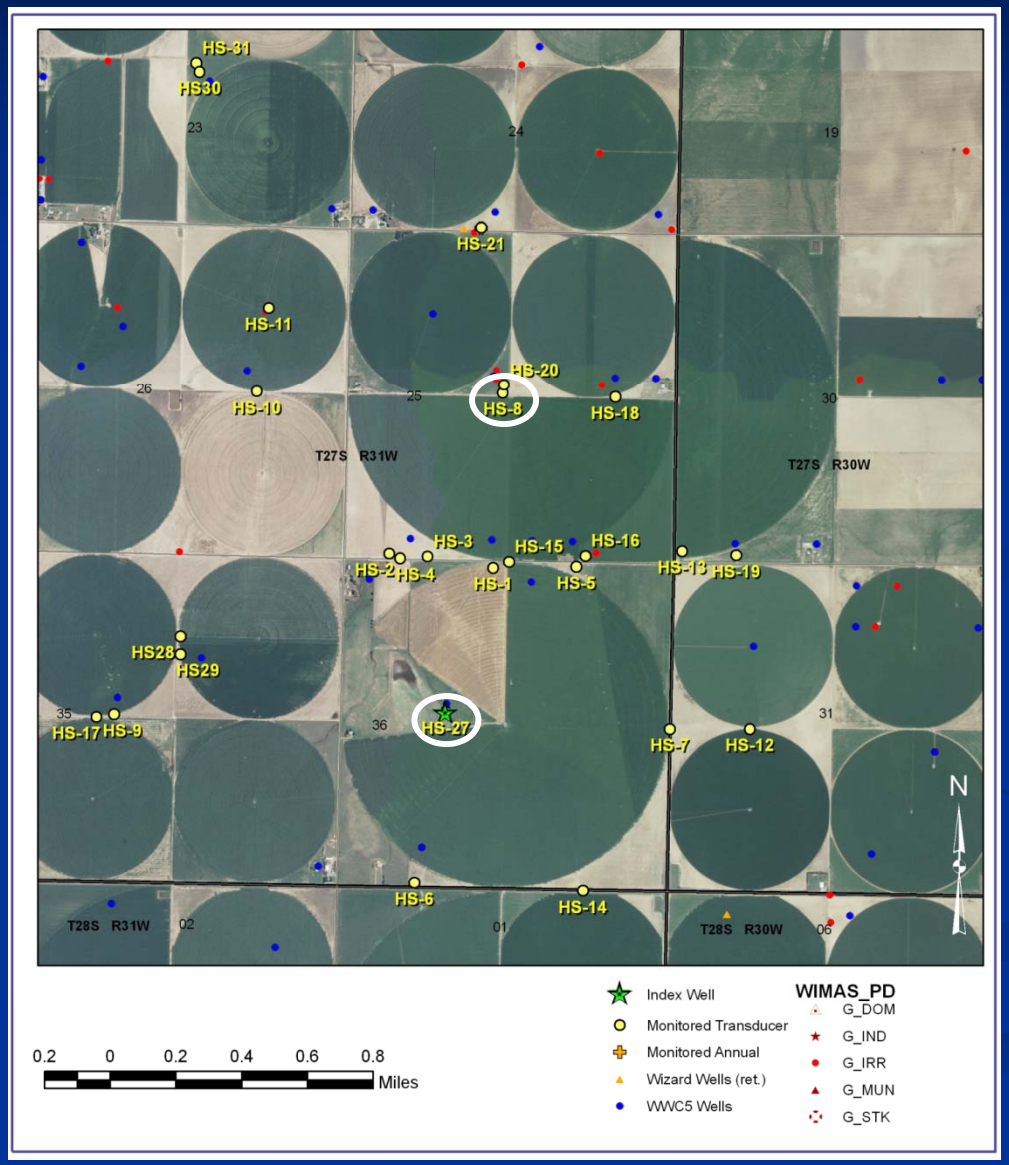
Similar Magnitude Responses

- Wells screened in same aquifer unit (confined)

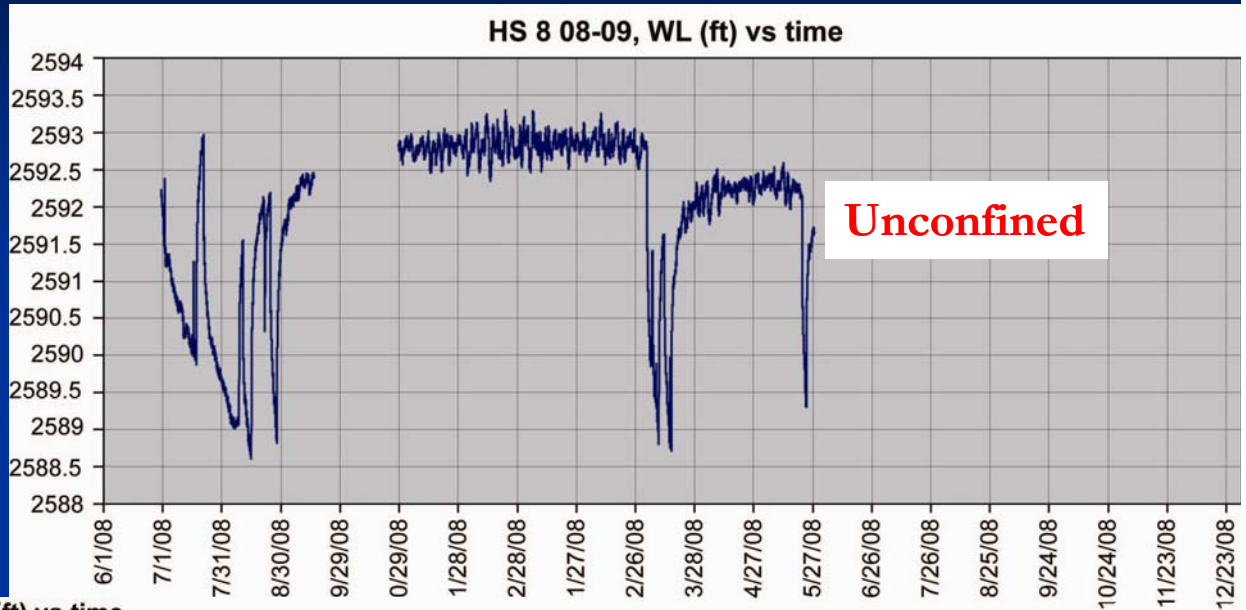


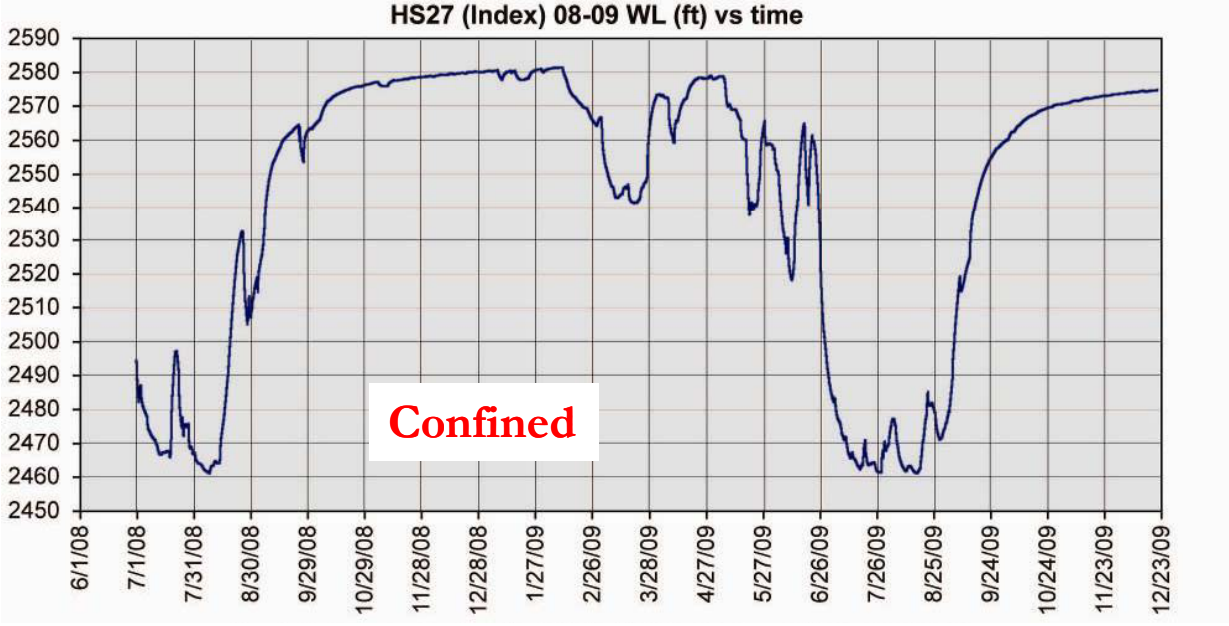


Complex Geology

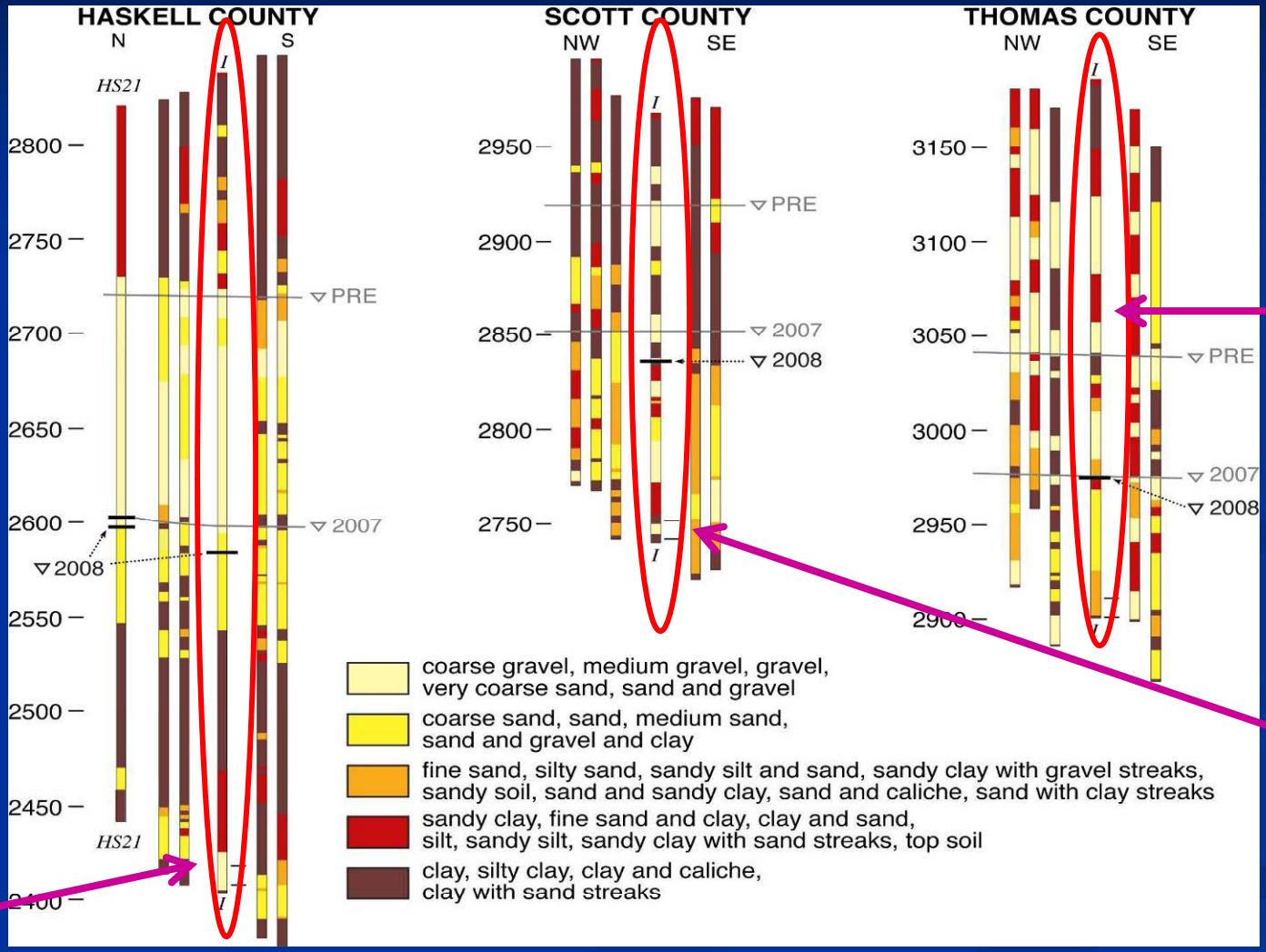


- Complex geology requires more control on well selection/construction





Geological Complexity and Water Availability



Index Well:
Unconfined
ST: 70.2'
PST: 49.9'
(2009 data)

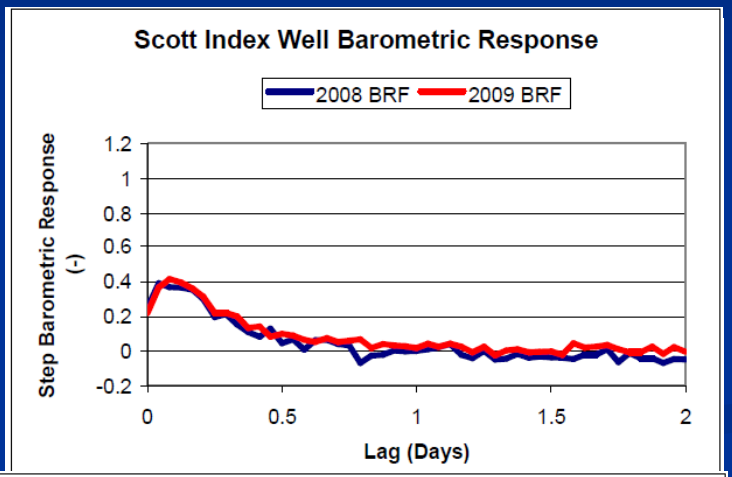
Index Well:
Unconfined
ST: 90.2'
PST: 54.8'
(2009 data)

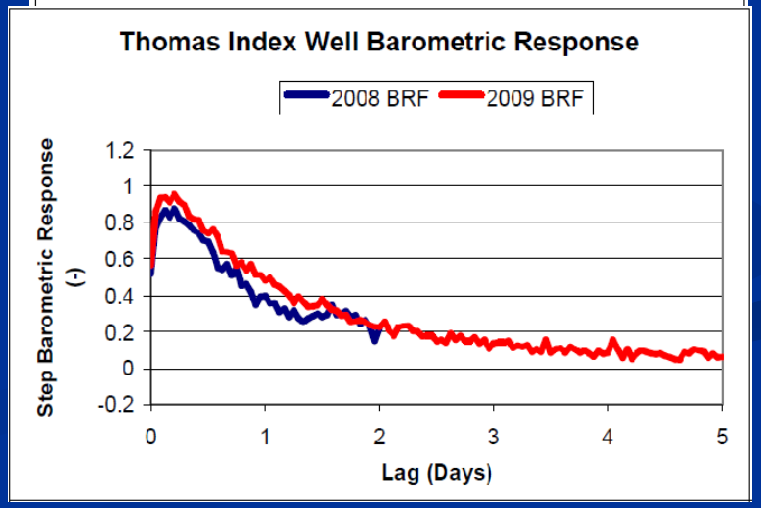
Index Well:
Confined
ST: 175.4'
PST: 63'
(2009 data)

Permeable (light) and impermeable (dark) zones

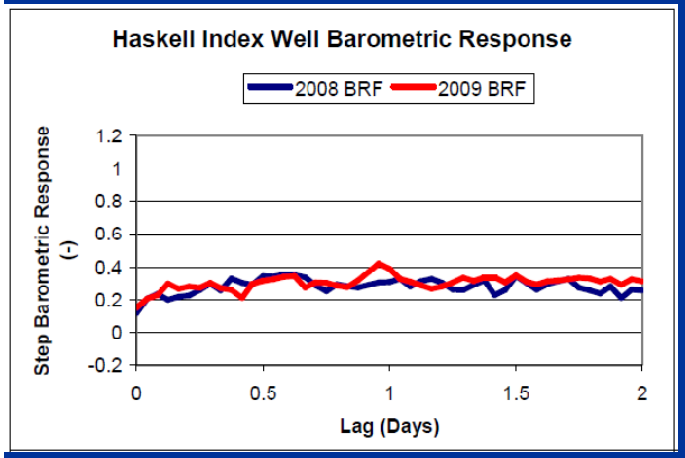
Geology and Barometric Pressure Response

Unconfined:





Confined:



Water Levels

- Measurements affected on different spatial and temporal scales by:
  - Timing, rate of, and distance to:
    - recharge/discharge
    - pumping
  - Hydrostratigraphy

Water Levels

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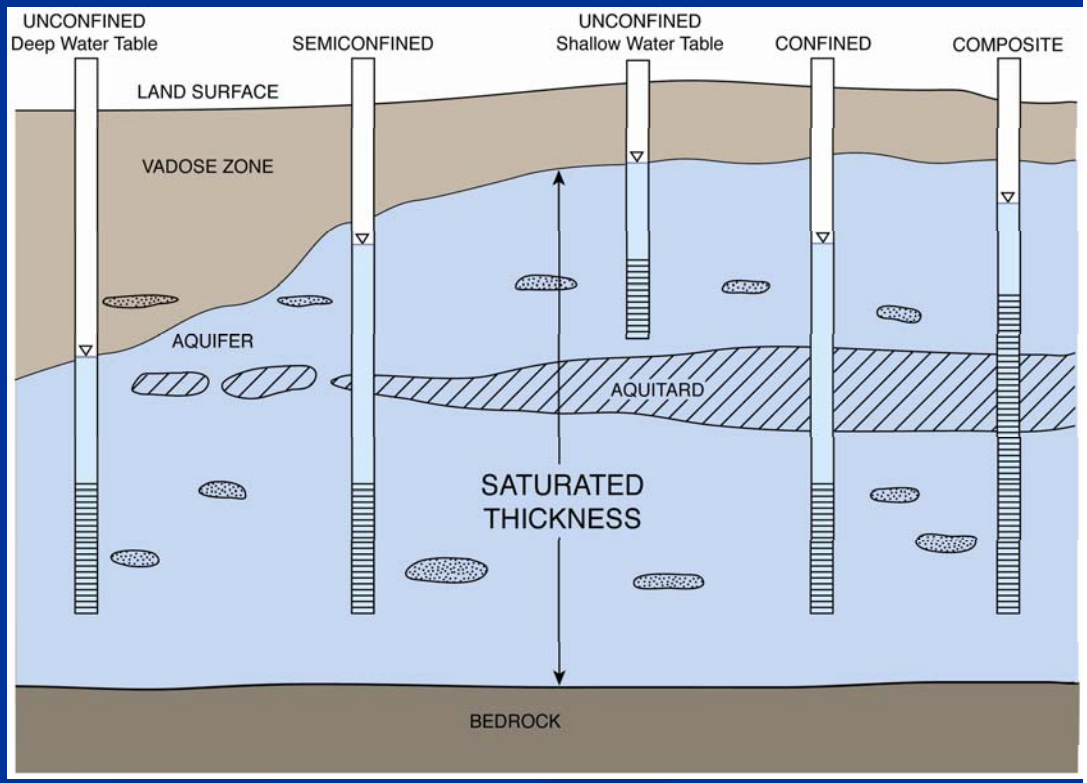
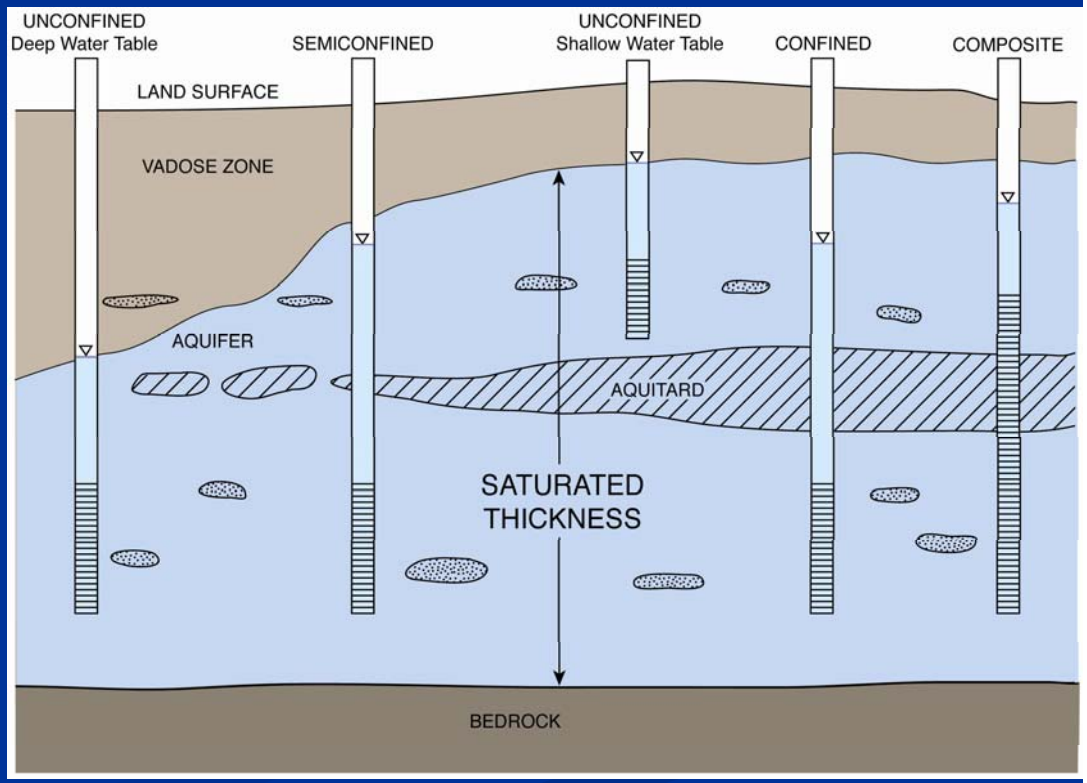


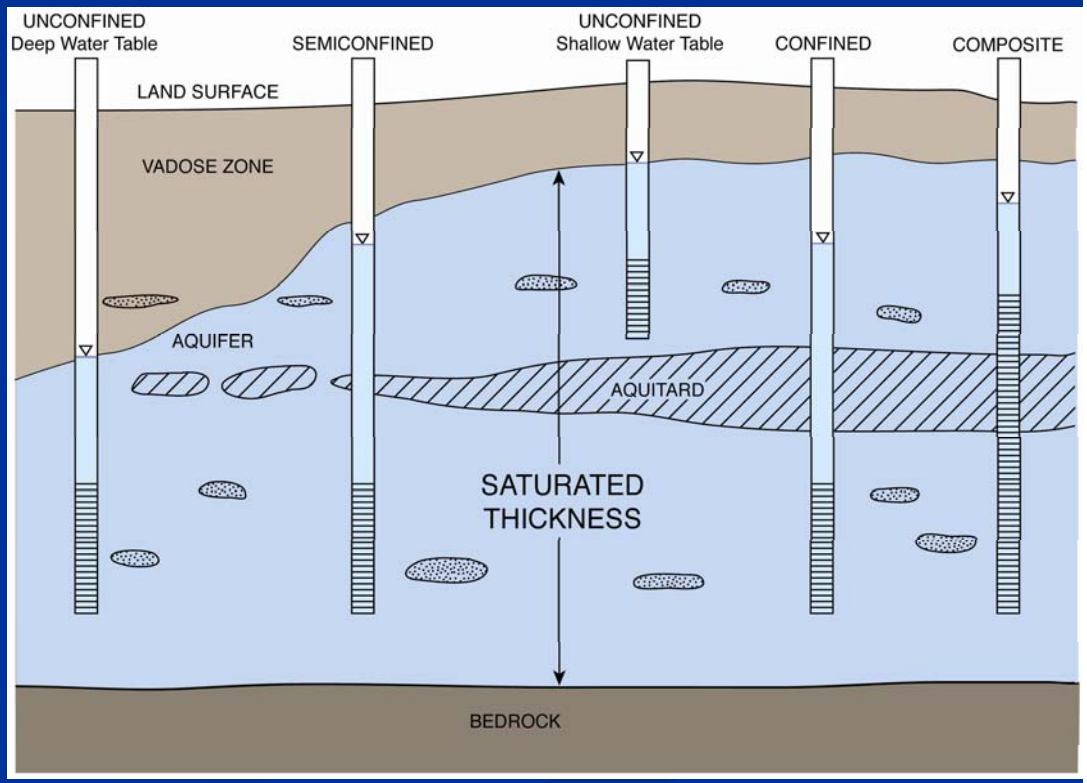
Water Levels

- Measurements affected on different spatial and temporal scales by:
  - Timing, rate of, and distance to:
    - recharge/discharge
    - pumping
  - Hydrostratigraphy
  - Well construction

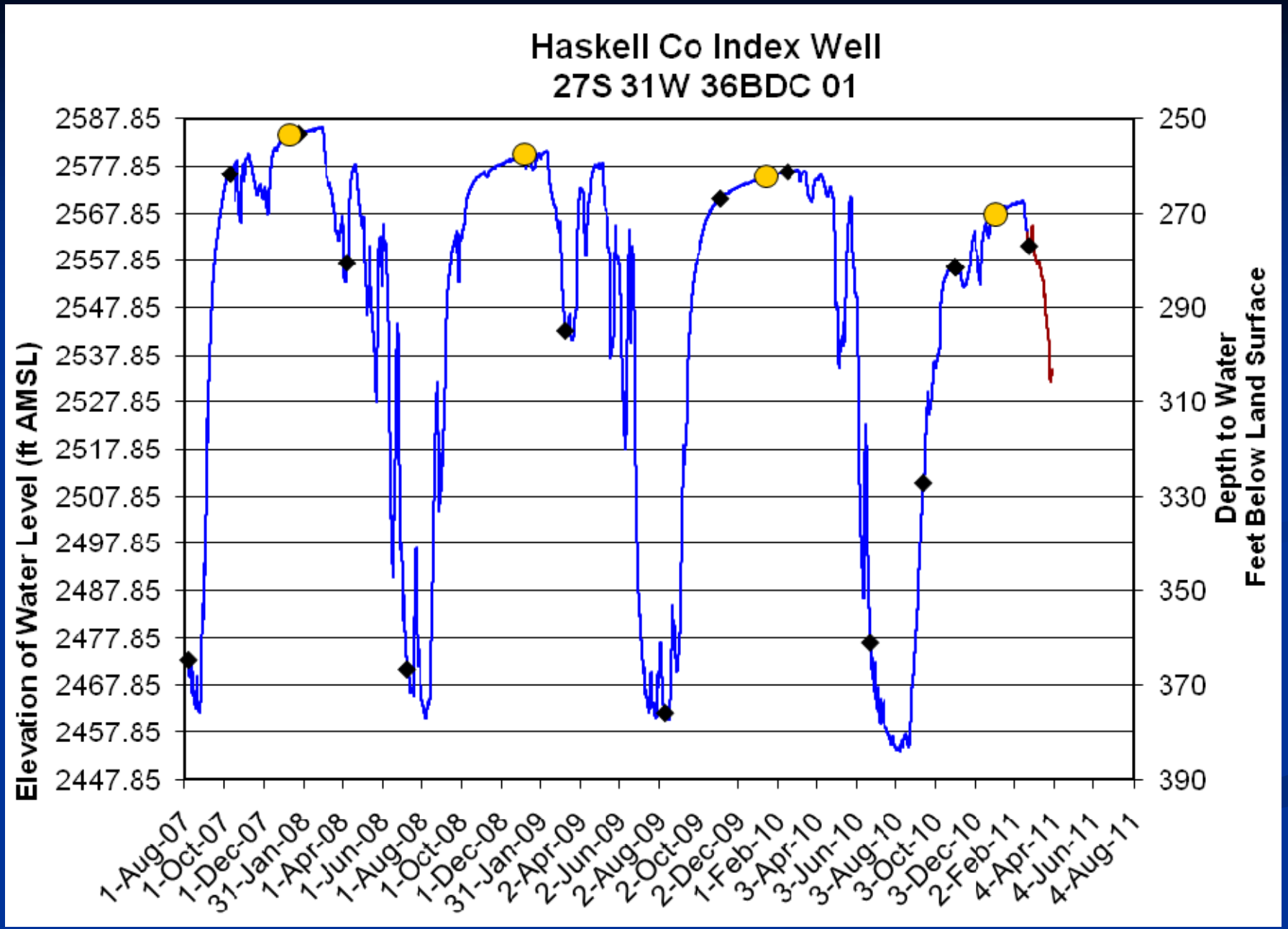


Water Levels

- Measurements affected on different spatial and temporal scales by:
  - Timing, rate of, and distance to:
    - recharge/discharge
    - pumping
  - Hydrostratigraphy
  - Well construction
  - Atmospheric pressure variation
  - Earth tides
  - Transient surface pressure loads (e.g. trains)



Index Well Hydrograph Updates


Haskell Co Index Well
27S 31W 36BDC 01
Elevation of Water Level (ft AMSL)
Depth to Water
Feet Below Land Surface
2587.85
2577.85
2567.85
2557.85
2547.85
2537.85
2527.85
2517.85
2507.85
2497.85
2487.85
2477.85
2467.85
2457.85
2447.85
250
270
290
310
330
350
370
390
1-Aug-07
1-Oct-07
1-Dec-07
31-Jan-08
1-Apr-08
1-Jun-08
1-Aug-08
1-Oct-08
1-Dec-08
31-Jan-09
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2-Jun-09
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2-Oct-09
2-Dec-09
1-Feb-10
3-Apr-10
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3-Aug-10
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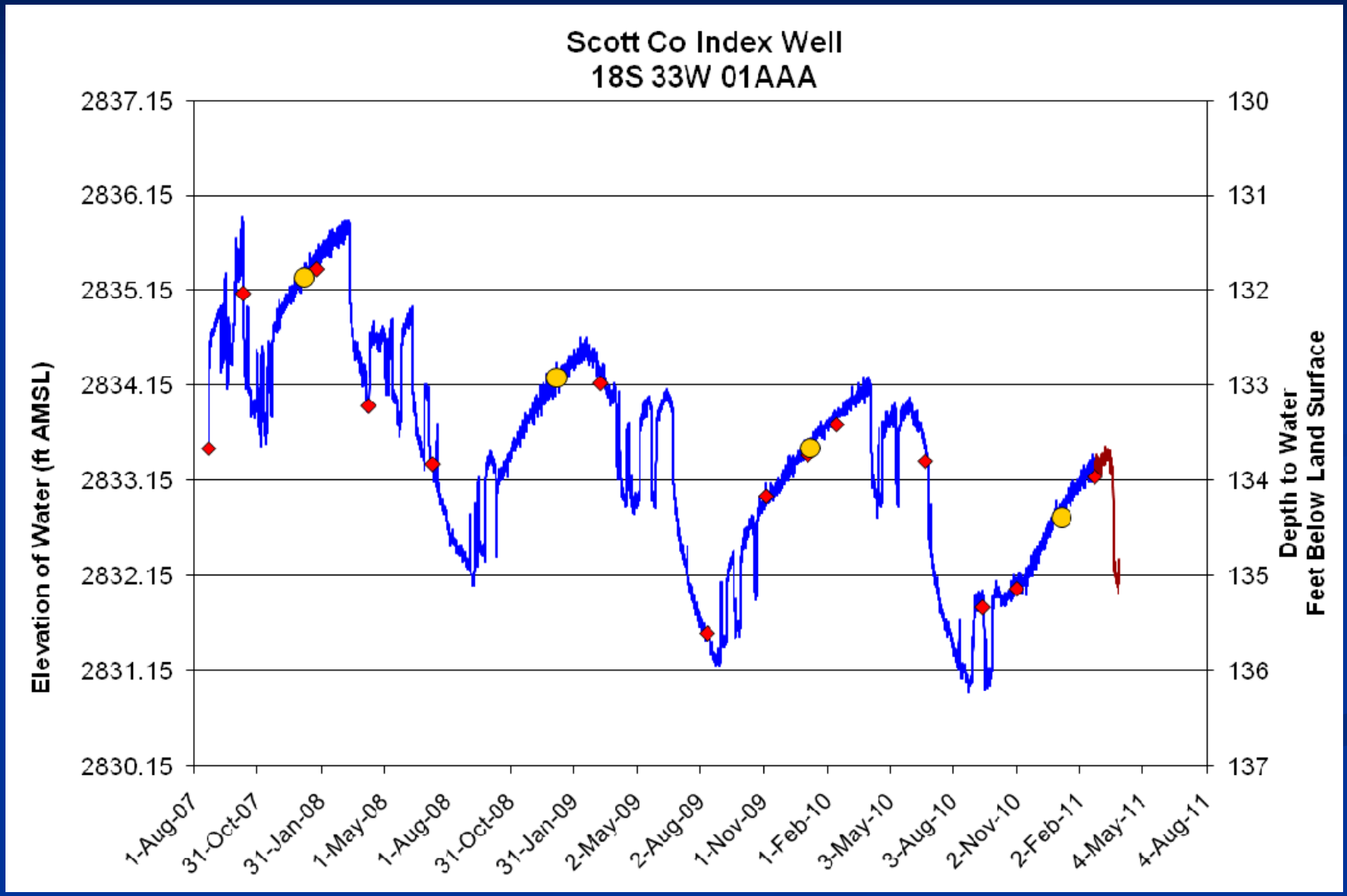
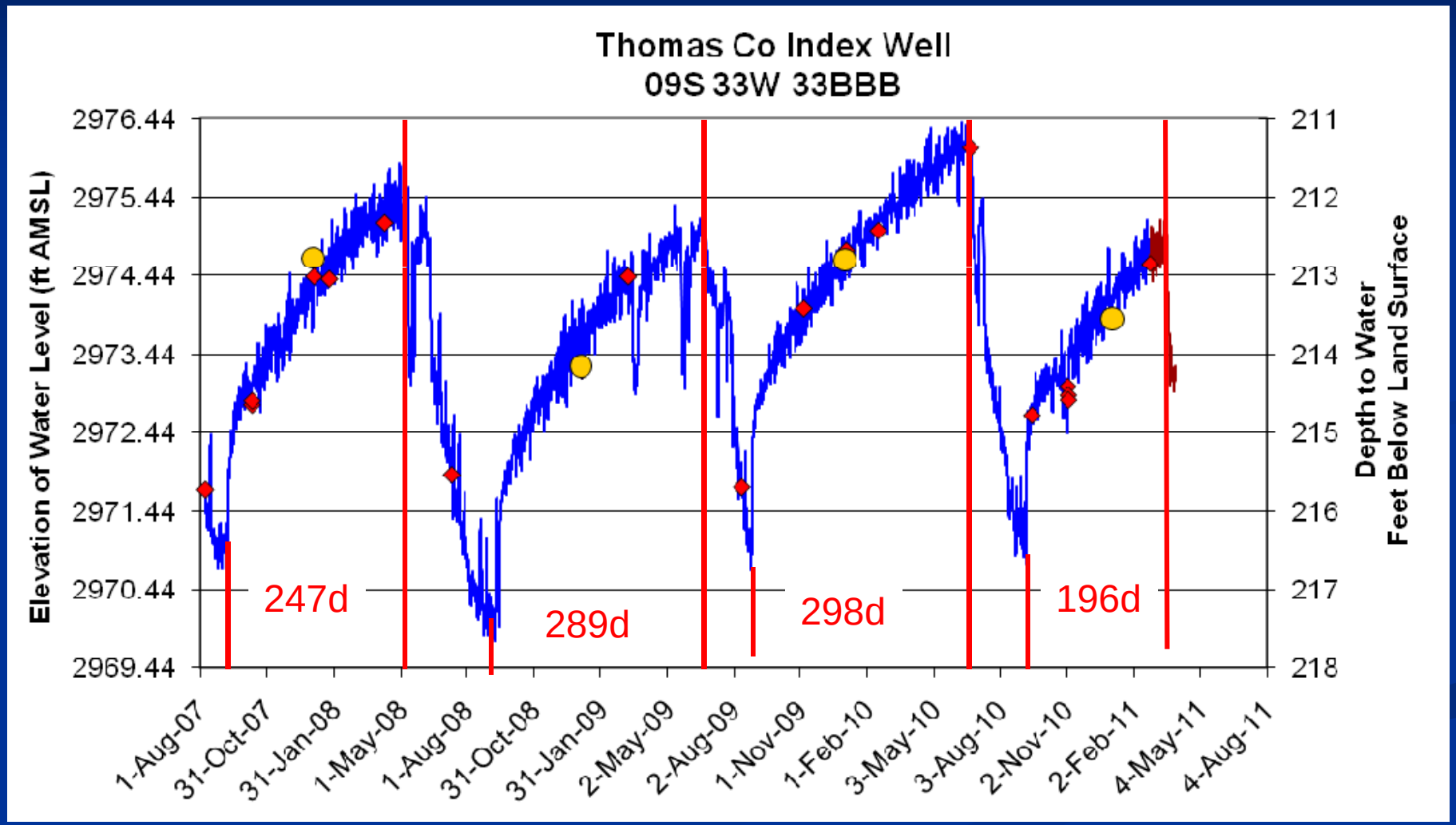
2-Feb-11
4-Apr-11
4-Jun-11
4-Aug-11

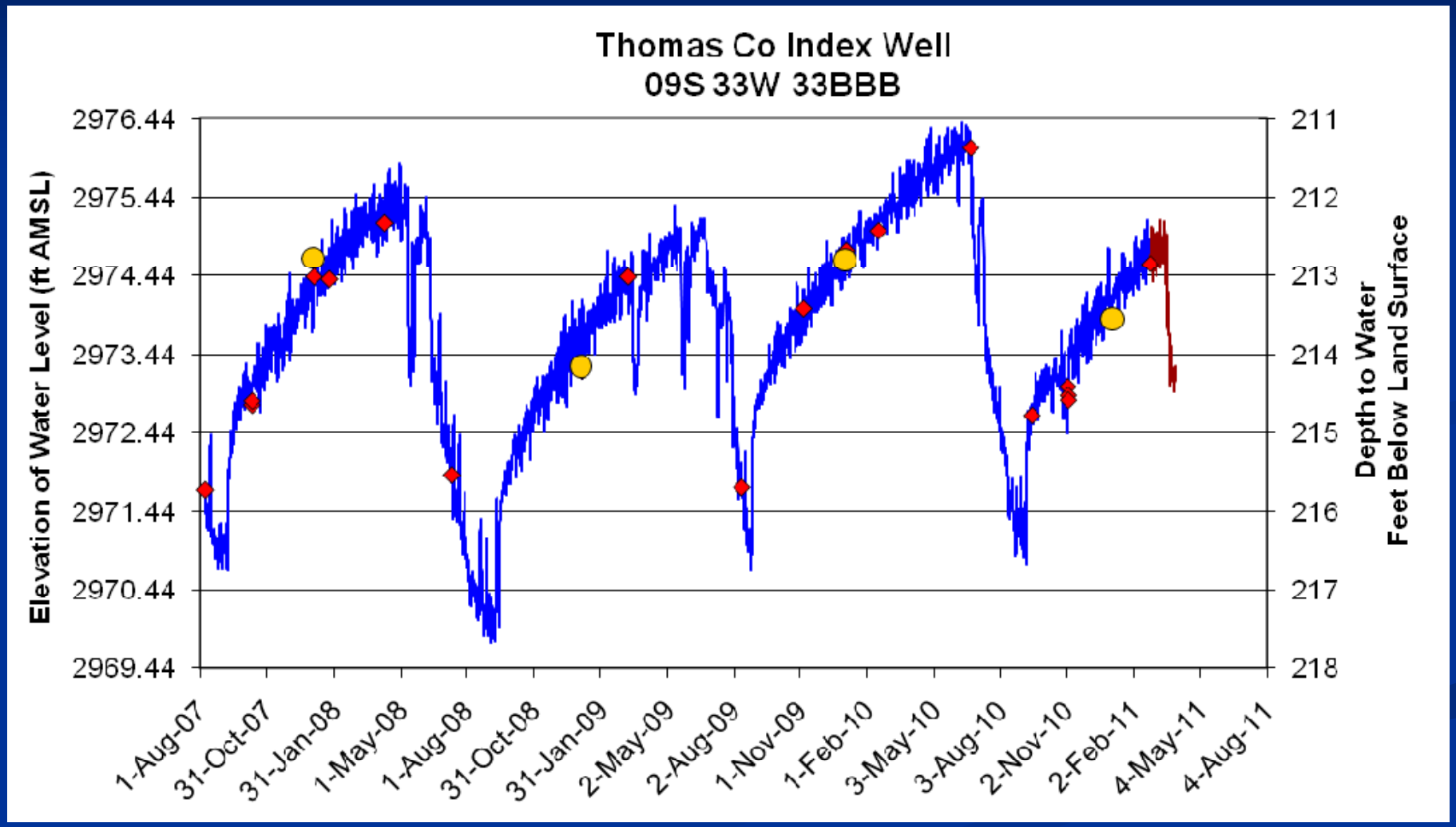

Scott Co Index Well
18S 33W 01AAA
Elevation of Water (ft AMSL)
Depth to Water
Feet Below Land Surface
2837.15
2836.15
2835.15
2834.15
2833.15
2832.15
2831.15
2830.15
130
131
132
133
134
135
136
137
1-Aug-07
31-Oct-07
31-Jan-08
1-May-08
1-Aug-08
31-Oct-08
31-Jan-09
2-May-09
2-Aug-09
1-Nov-09
1-Feb-10
3-May-10
3-Aug-10
2-Nov-10
2-Feb-11
4-May-11
4-Aug-11


Thomas Co Index Well
09S 33W 33BBB
Elevation of Water Level (ft AMSL)
Depth to Water
Feet Below Land Surface
2976.44
2975.44
2974.44
2973.44
2972.44
2971.44
2970.44
2969.44
211
212
213
214
215
216
217
218
247d
289d
298d
196d
1-Aug-07
31-Oct-07
31-Jan-08
1-May-08
1-Aug-08
31-Oct-08
31-Jan-09
2-May-09
2-Aug-09
1-Nov-09
1-Feb-10
3-May-10
3-Aug-10
2-Nov-10
2-Feb-11
4-May-11
4-Aug-11

Hydrograph Update

- During observed recovery:
  - Haskell County – continued declines of 4-6' /yr
  - Scott County – continued declines of 0.5-1' /yr
  - Thomas County –
    - increased water level 09-10 (highest yet observed);
    - 10-11 same as 08-09
- Full recovery still not observed at any site, in any year, prior to resumption of pumping activities

What is Full Recovery?



Horner Recovery Method

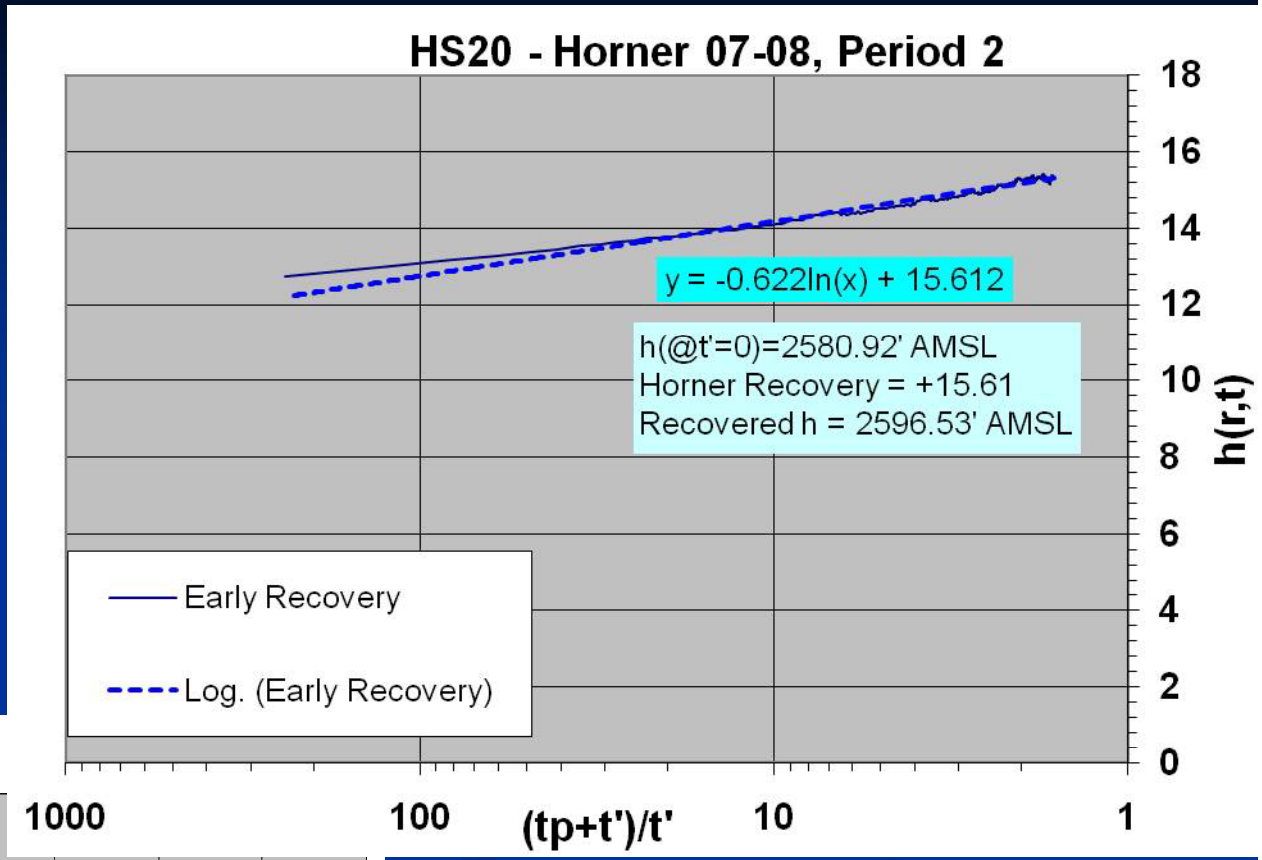
- Developed by petroleum industry
- Based on Theis recovery method (similar assumptions)
  - Utilizes same truncation used in Theis and Cooper-Jacob
- Solve following equation for h_o when the log ratio = 0

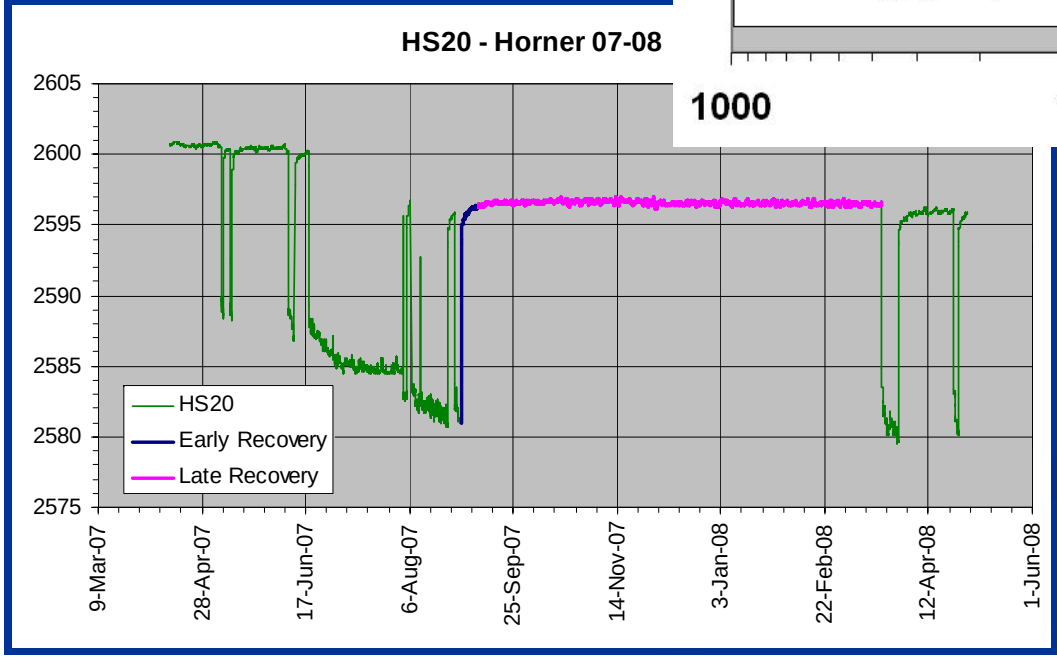
$$h(r,t) \approx h_o - A\log\left(\frac{t_p + t'}{t'}\right)$$

- Where:
  - [h(r,t)] = water level
  - t' = time since end of pumping period
  - t_p = total time of pumping period
  - A = constant coefficient
  - h_o = recovered water level

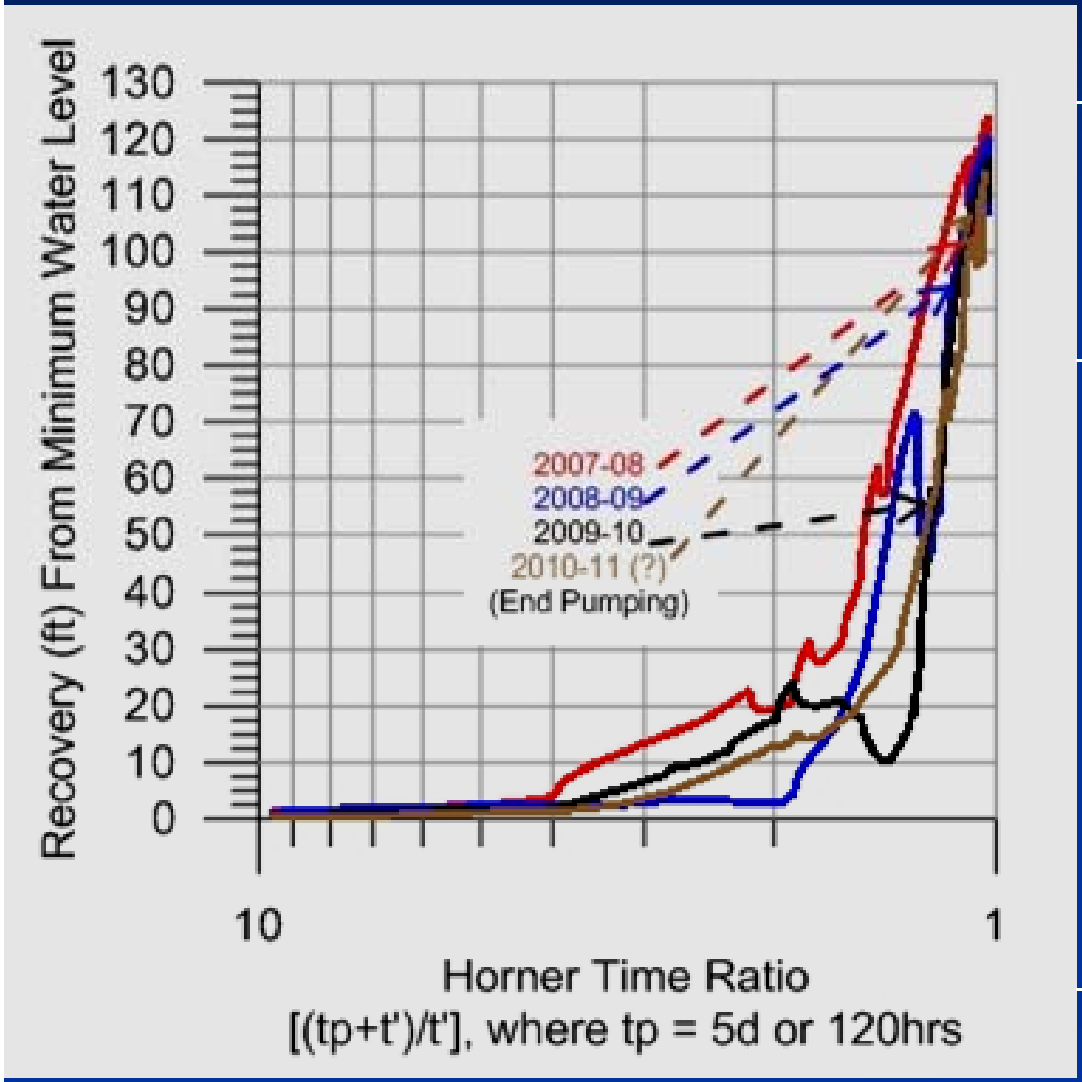
Example:

Six month ave: **2596.54'**
Estimates:
Early time: **2596.53'**

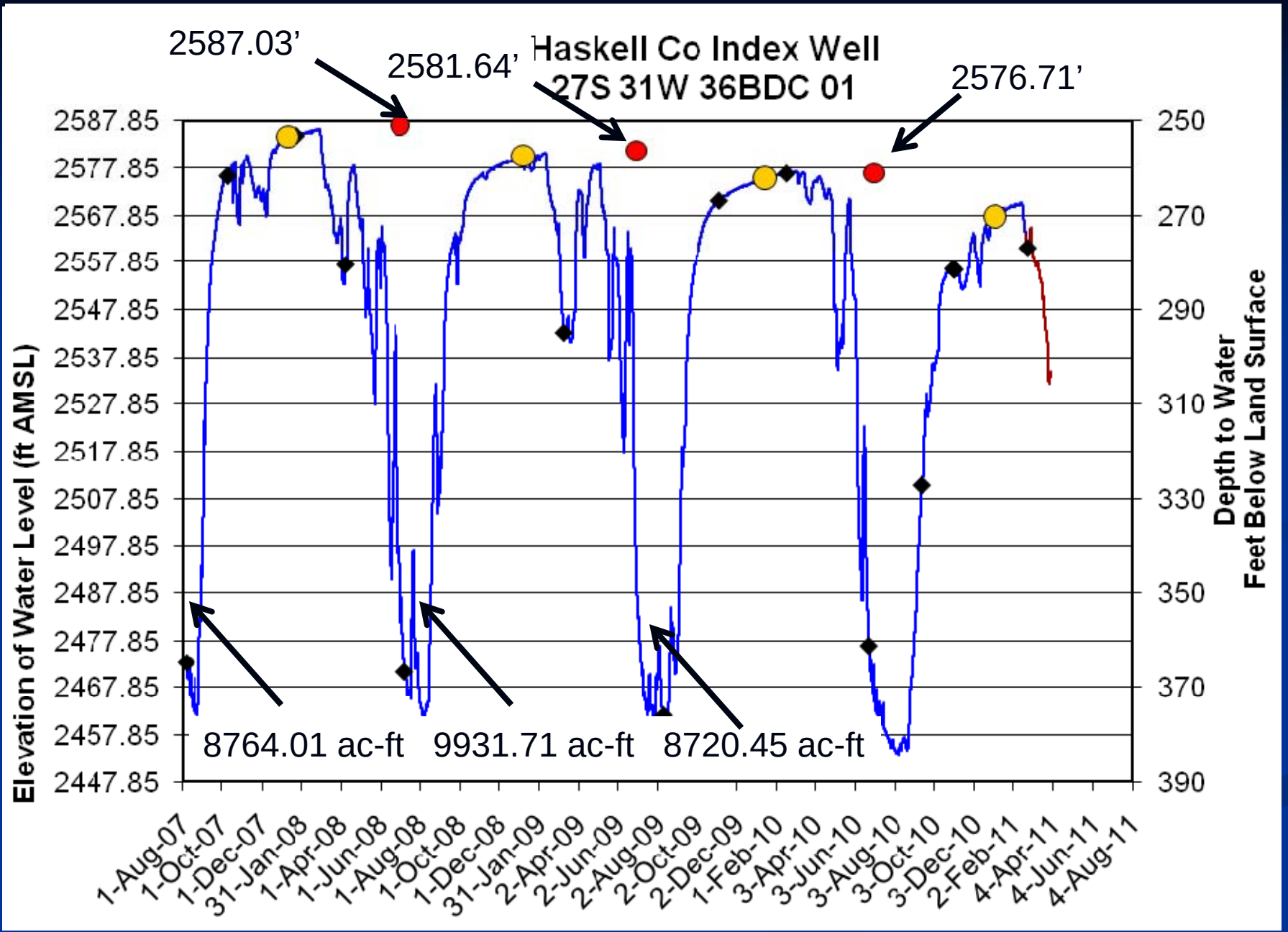




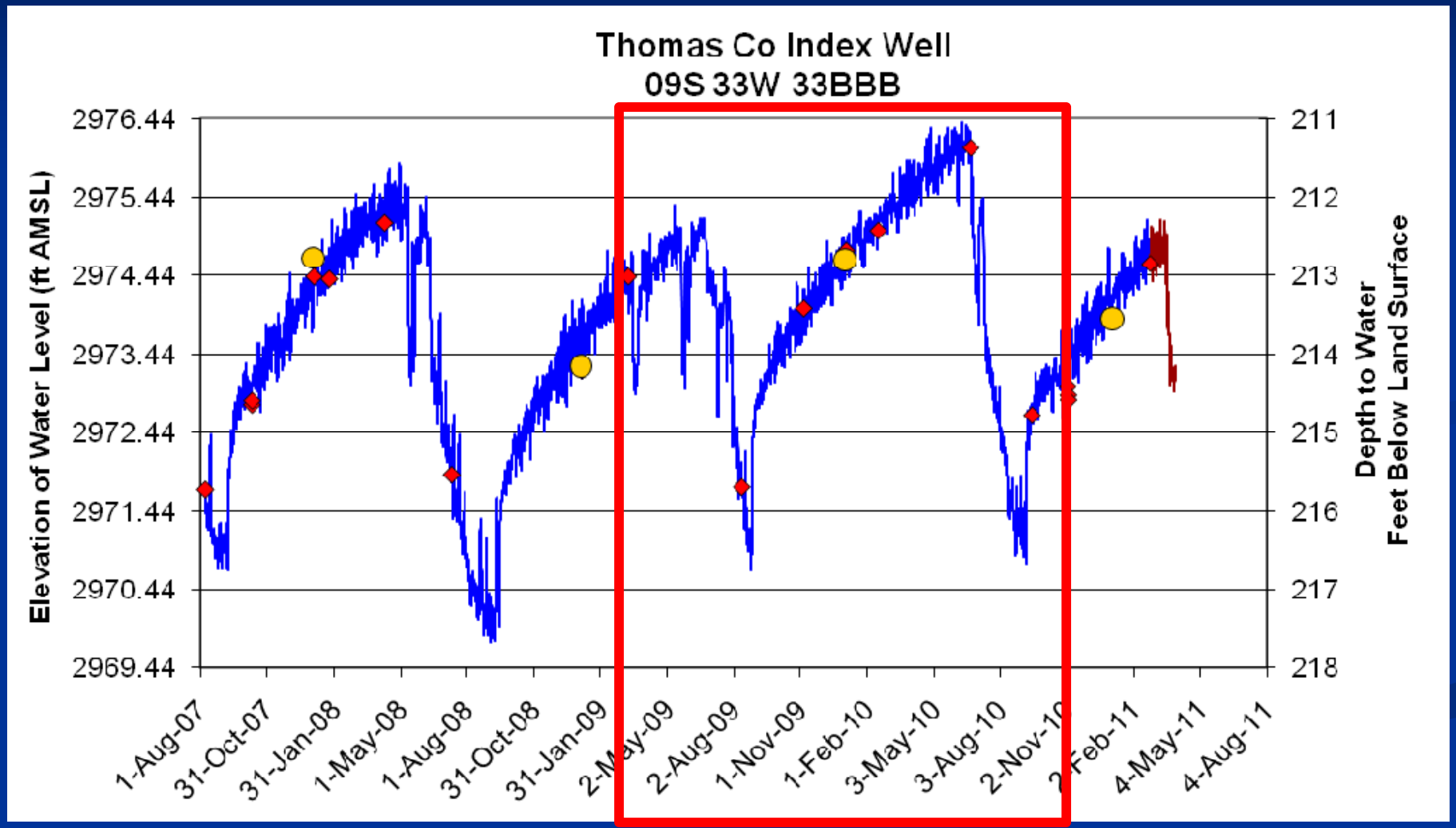
Haskell Index Well Recovery



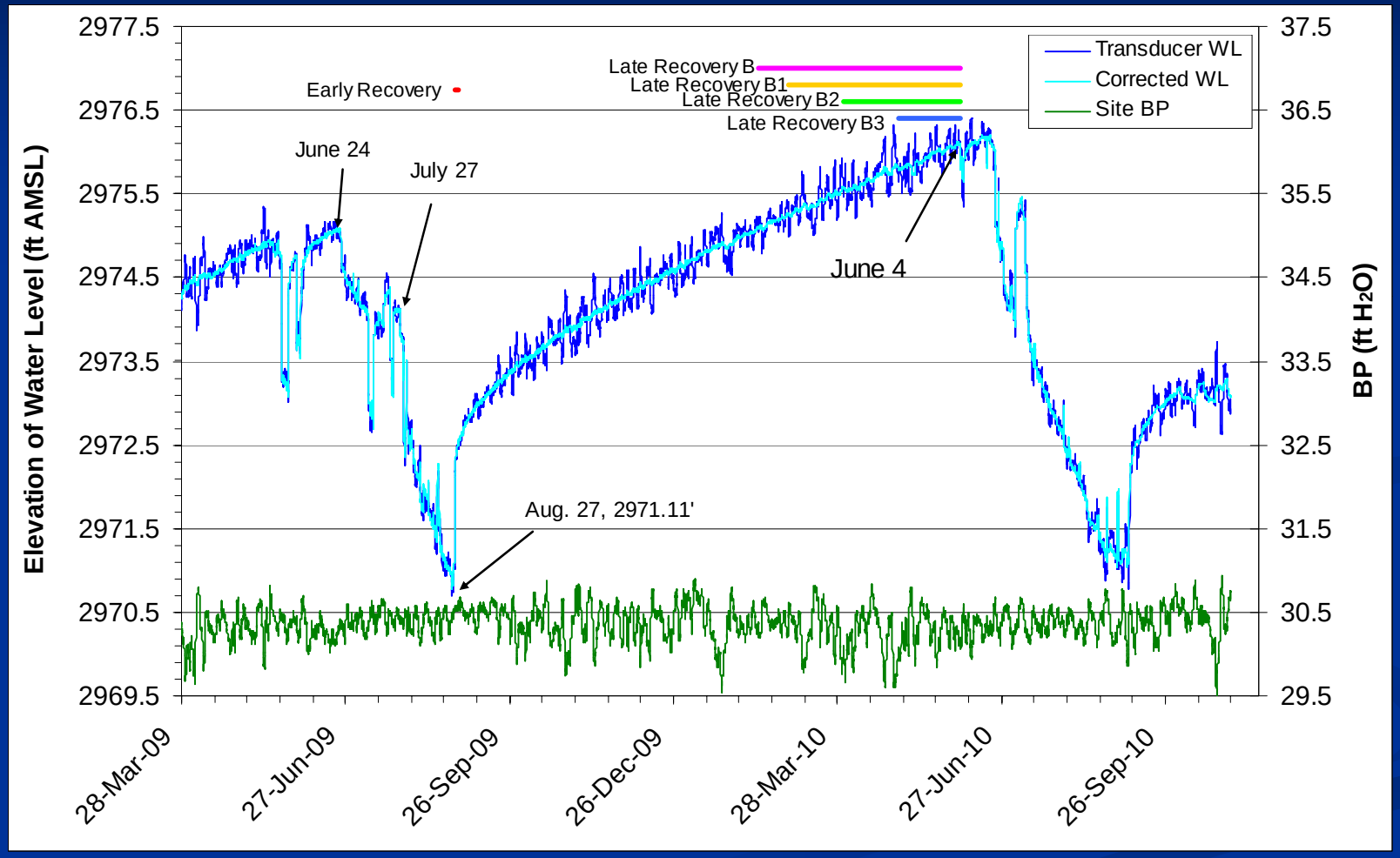
	H_{max} **predicted** ft AMSL
2008 (07-08 Recovery)	2587.03
2009 (08-09 Recovery)	2581.64
2010 (09-10 Recovery)	2576.71


2587.03’
2581.64’
Haskell Co Index Well
27S 31W 36BDC 01
2576.71’
Elevation of Water Level (ft AMSL)
Depth to Water
Feet Below Land Surface
2587.85
2577.85
2567.85
2557.85
2547.85
2537.85
2527.85
2517.85
2507.85
2497.85
2487.85
2477.85
2467.85
2457.85
2447.85
250
270
290
310
330
350
370
390
8764.01 ac-ft
9931.71 ac-ft
8720.45 ac-ft
1-Aug-07
1-Oct-07
1-Dec-07
31-Jan-08
1-Apr-08
1-Jun-08
1-Aug-08
1-Oct-08
1-Dec-08
31-Jan-09
2-Apr-09
2-Jun-09
2-Aug-09
2-Oct-09
2-Dec-09
1-Feb-10
3-Apr-10
3-Jun-10
3-Aug-10
3-Oct-10
3-Dec-10
2-Feb-11
4-Apr-11
4-Jun-11
4-Aug-11

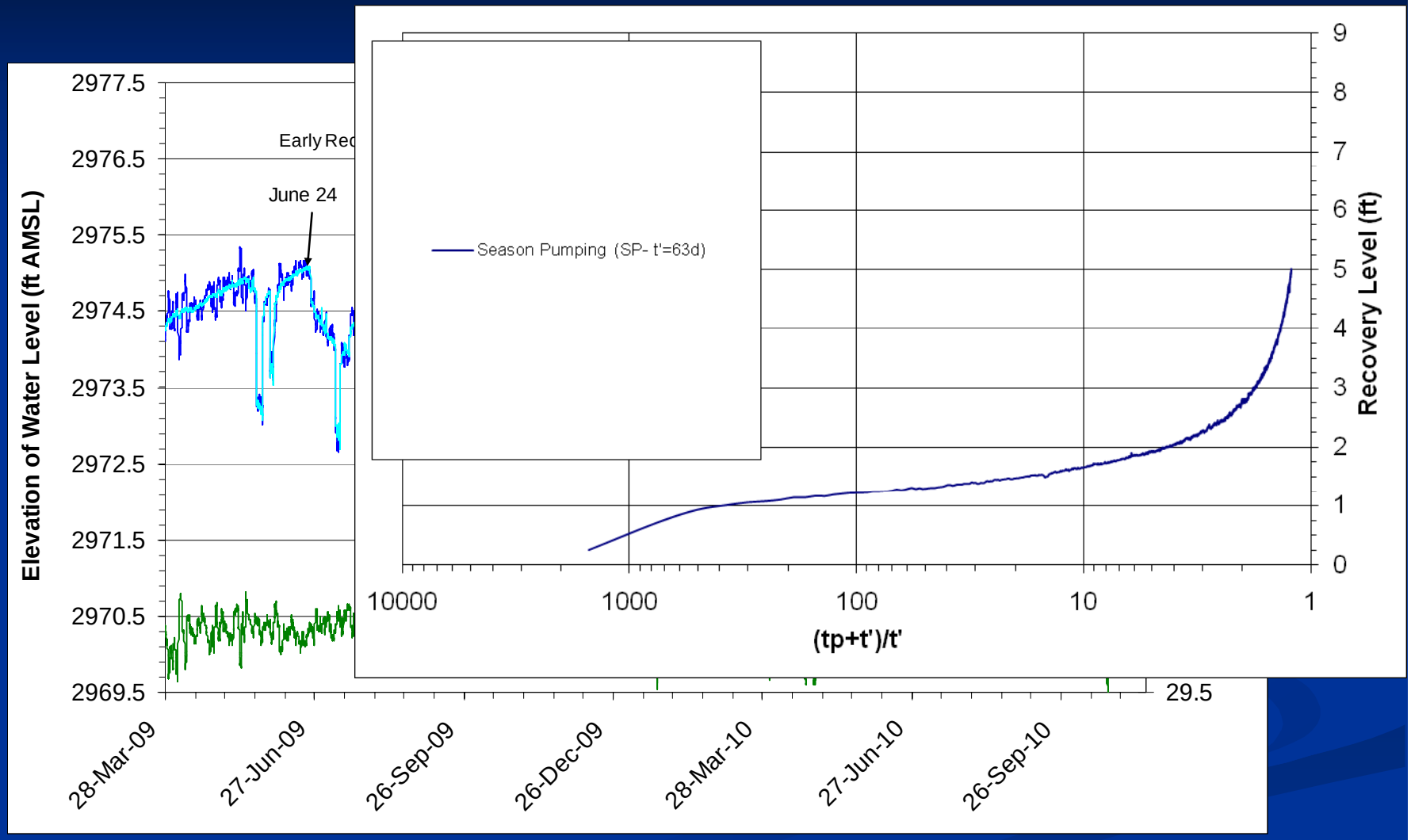
Thomas Co. Index Well



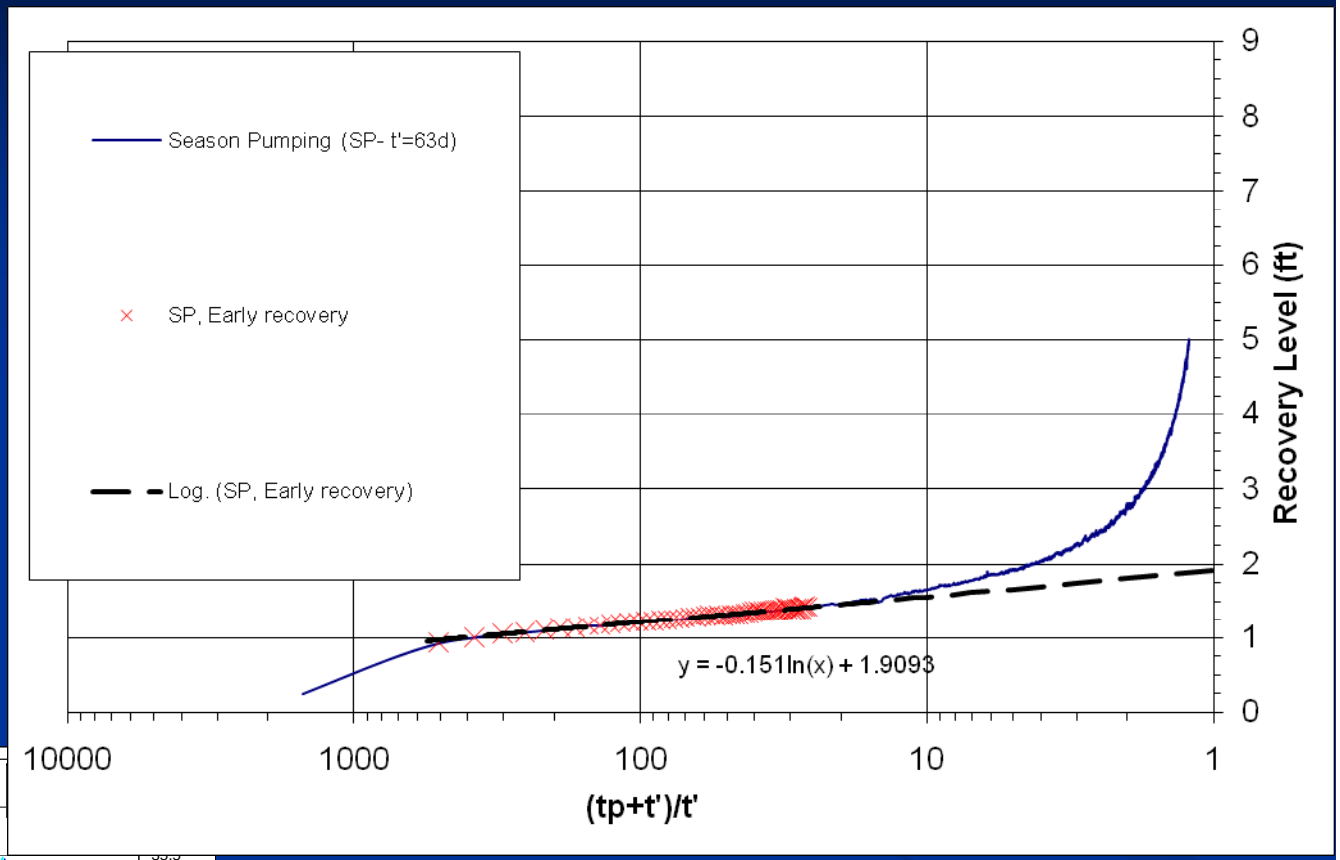
Thomas Co. Index Well

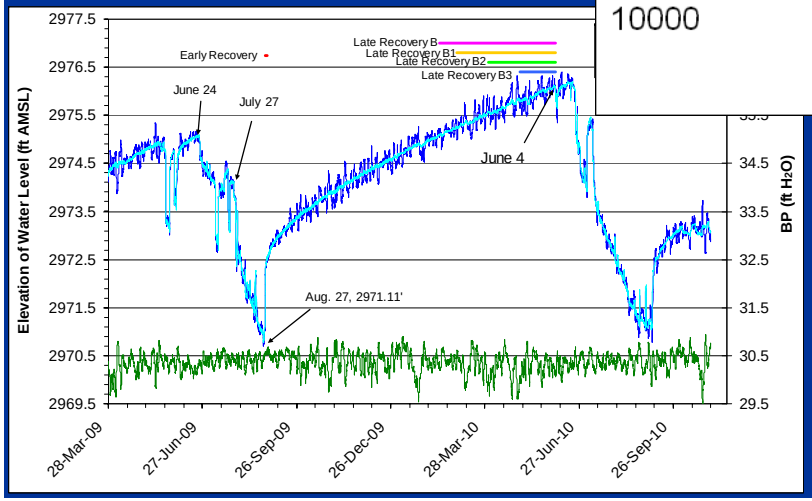


Thomas Co. Index Well

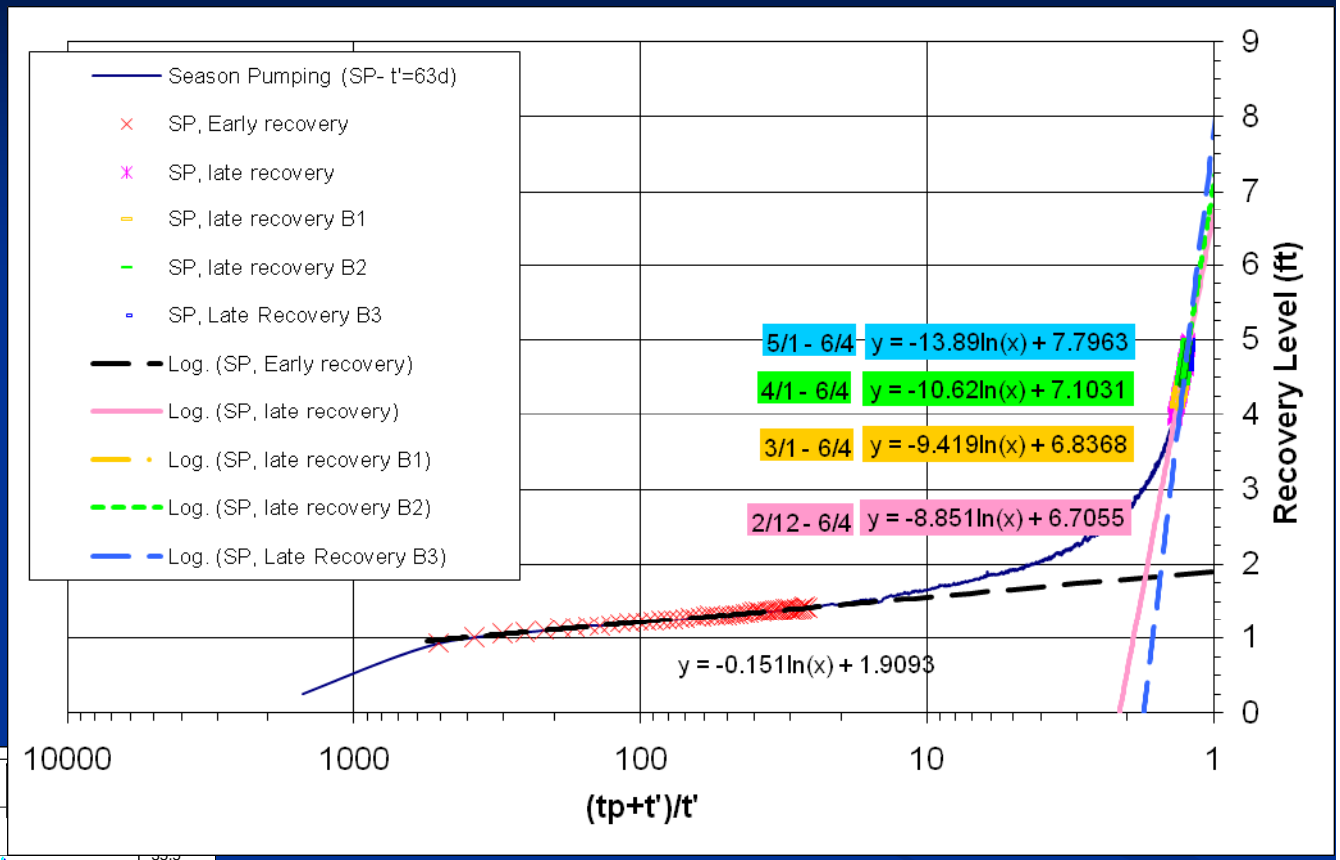


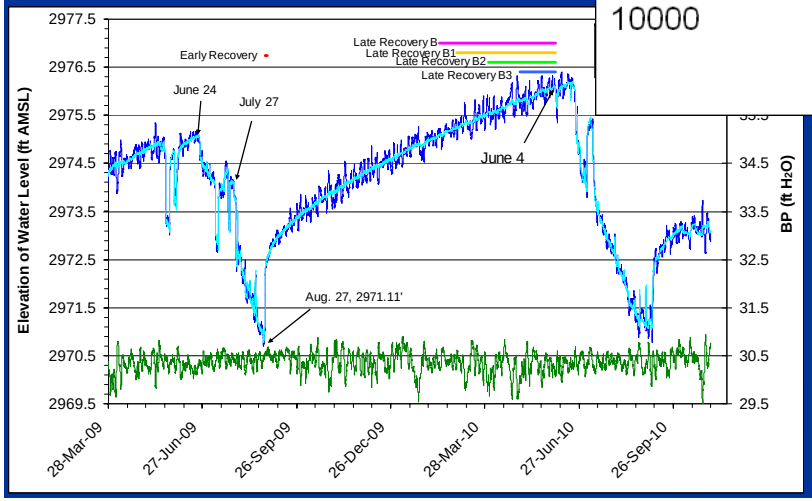
Thomas Co. Index Well



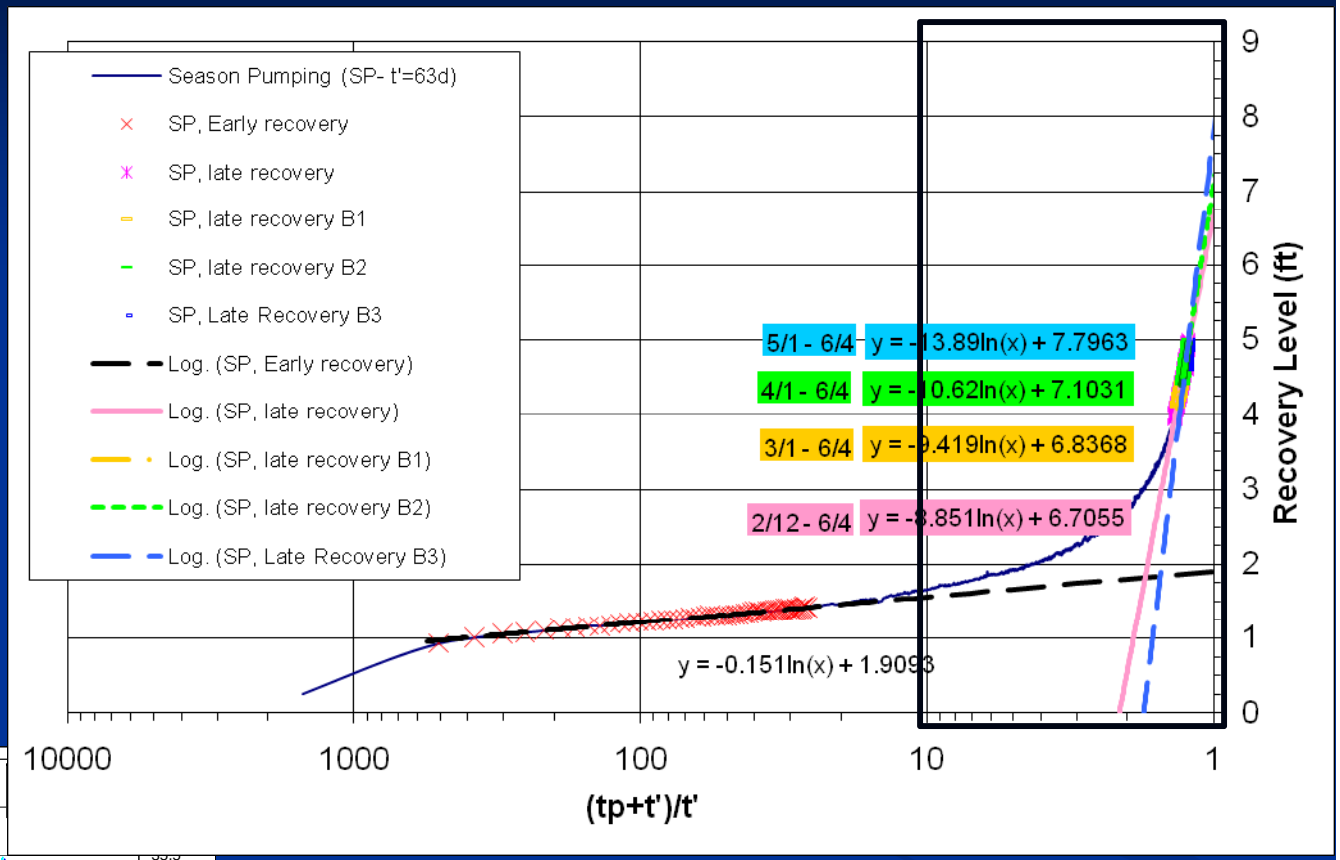


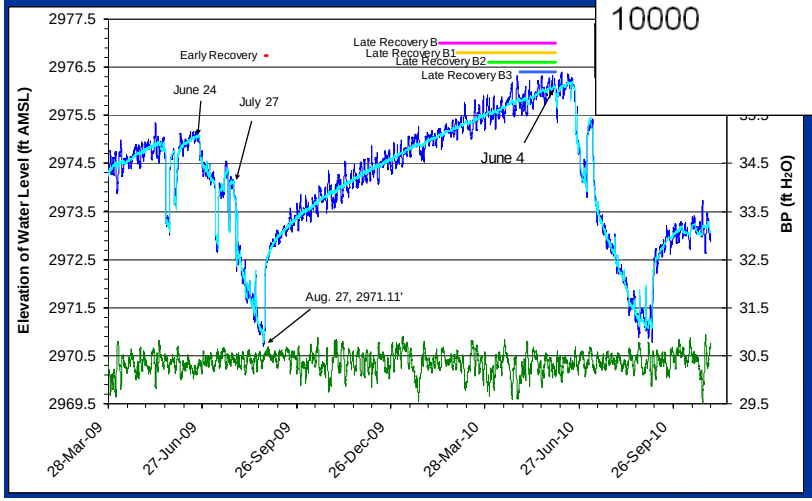
Thomas Co. Index Well



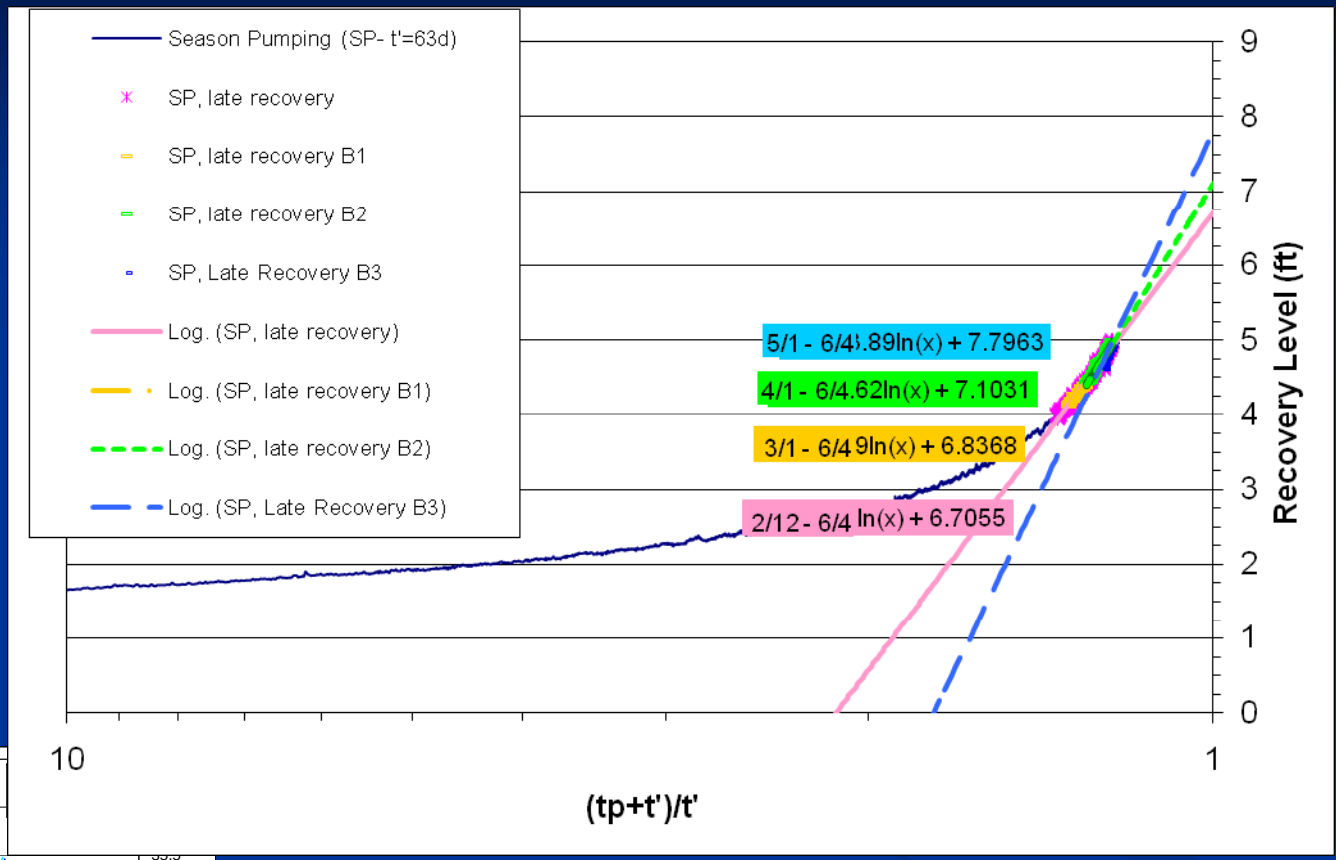


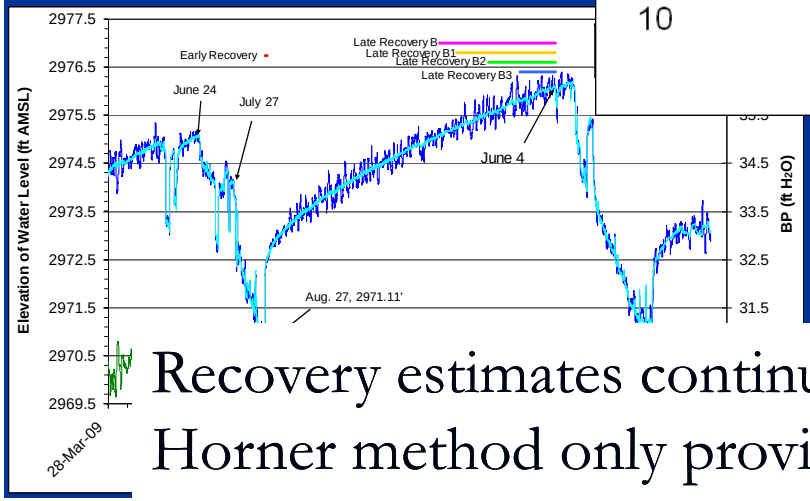
Thomas Co. Index Well





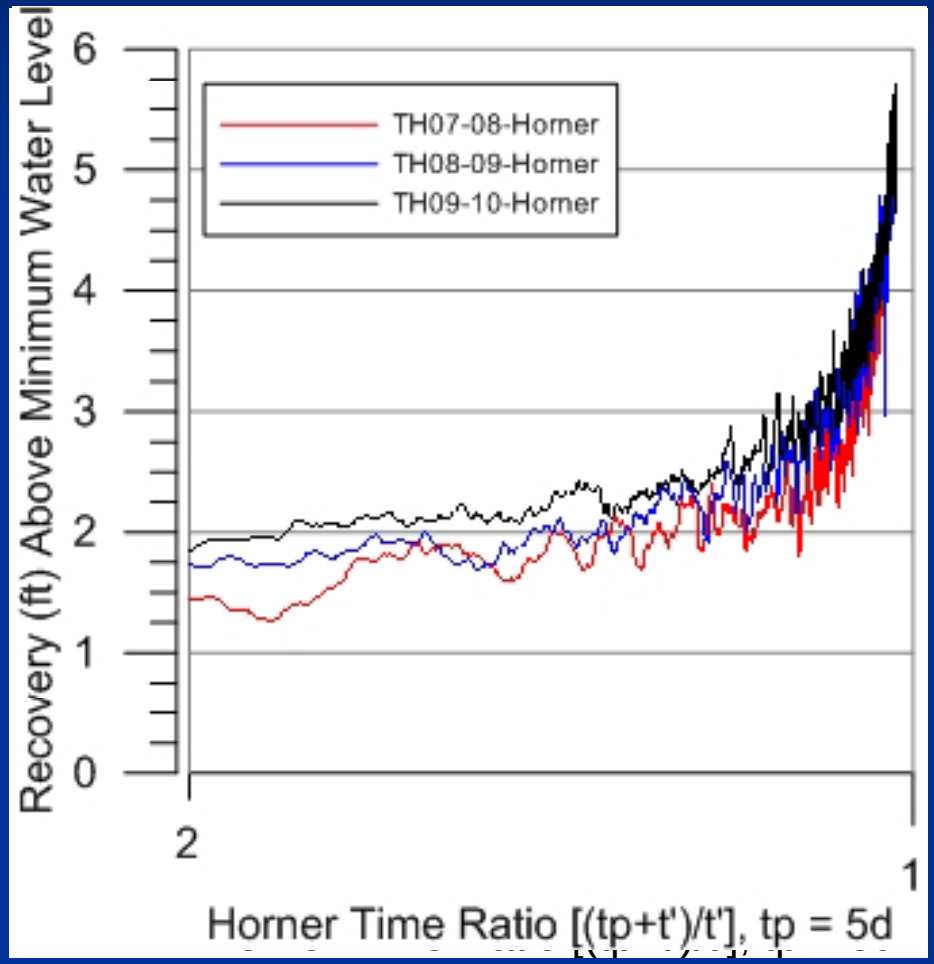
Thomas Co. Index Well





Recovery estimates continually increase – in this situation, Horner method only provides a minimum recovery estimate.

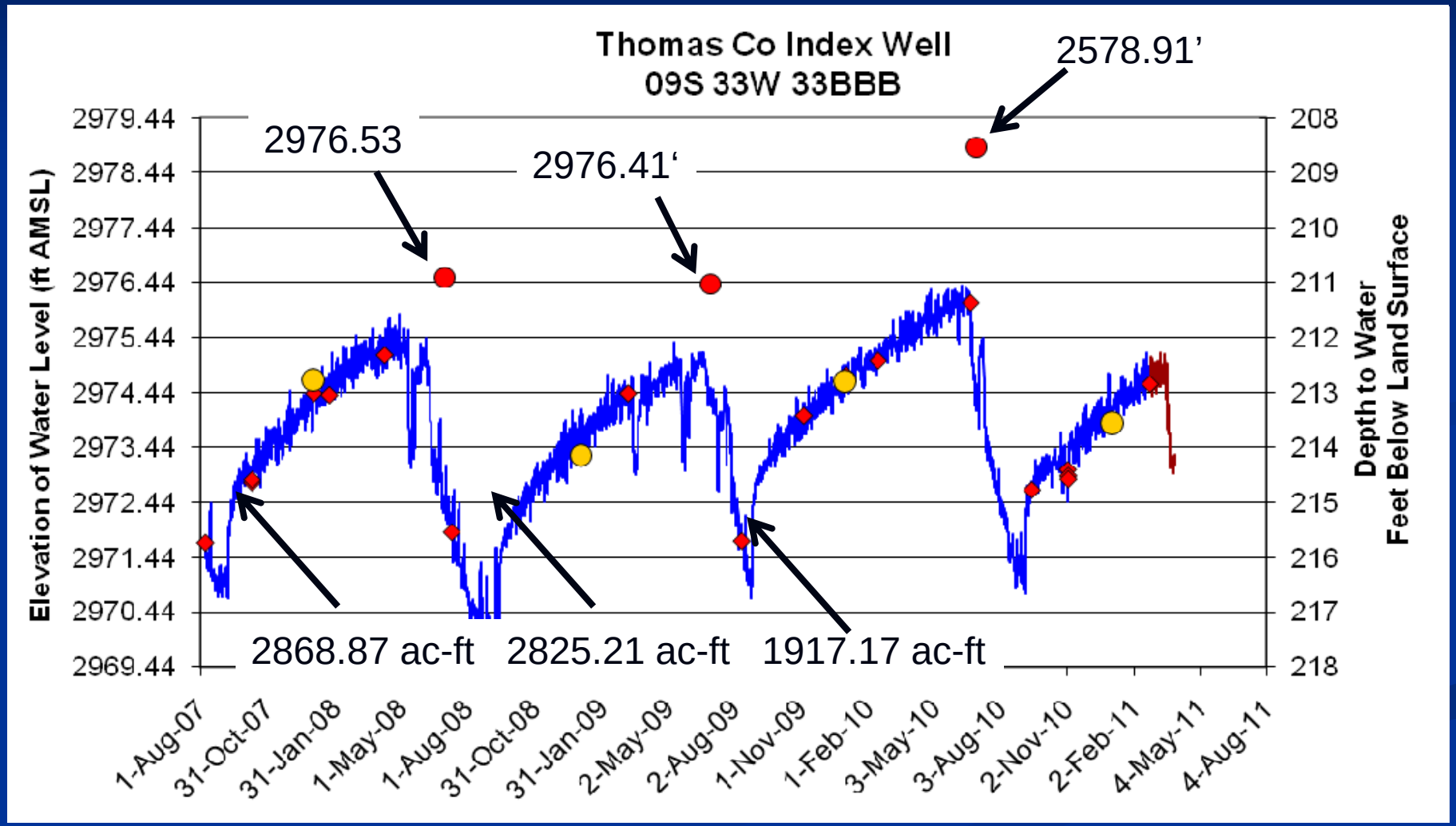
Comparing Annual Recoveries



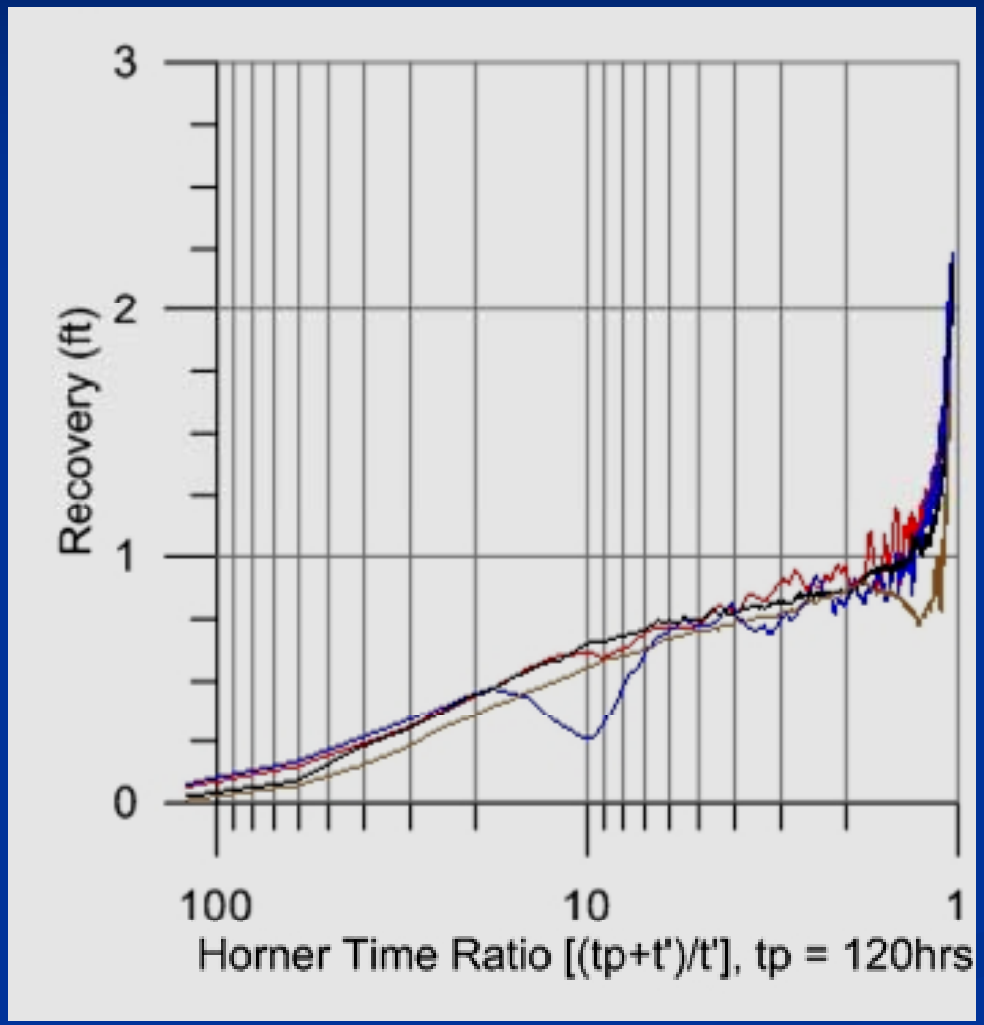
- Similar every year
  - Unconfined storage?
  - Recharge boundary / regional flow?

	H_{max} predicted ft AMSL
2008 (07-08 Recovery)	2976.53
2009 (08-09 Recovery)	2976.41
2010 (09-10 Recovery)	2978.91

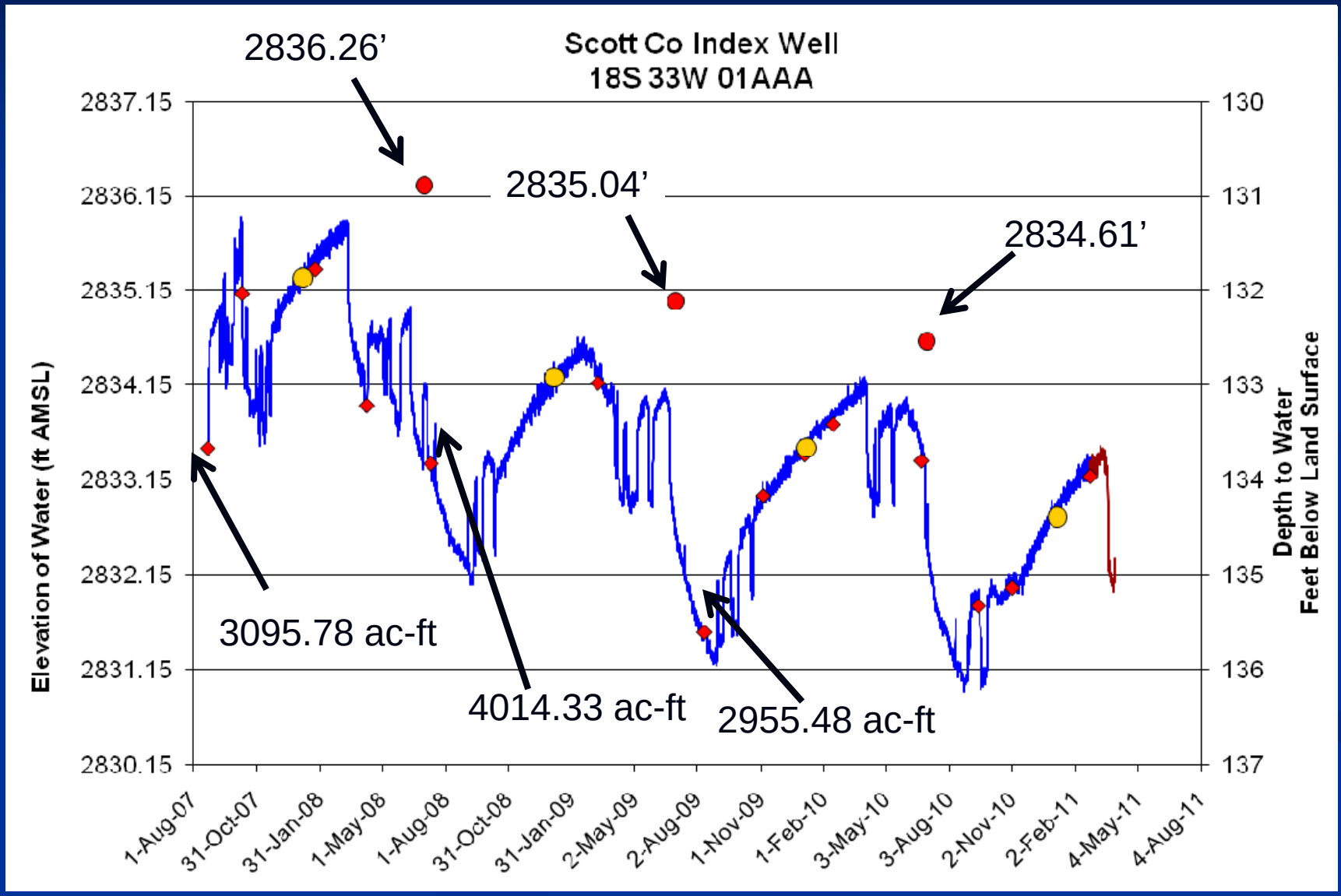
Thomas Co. Index Well



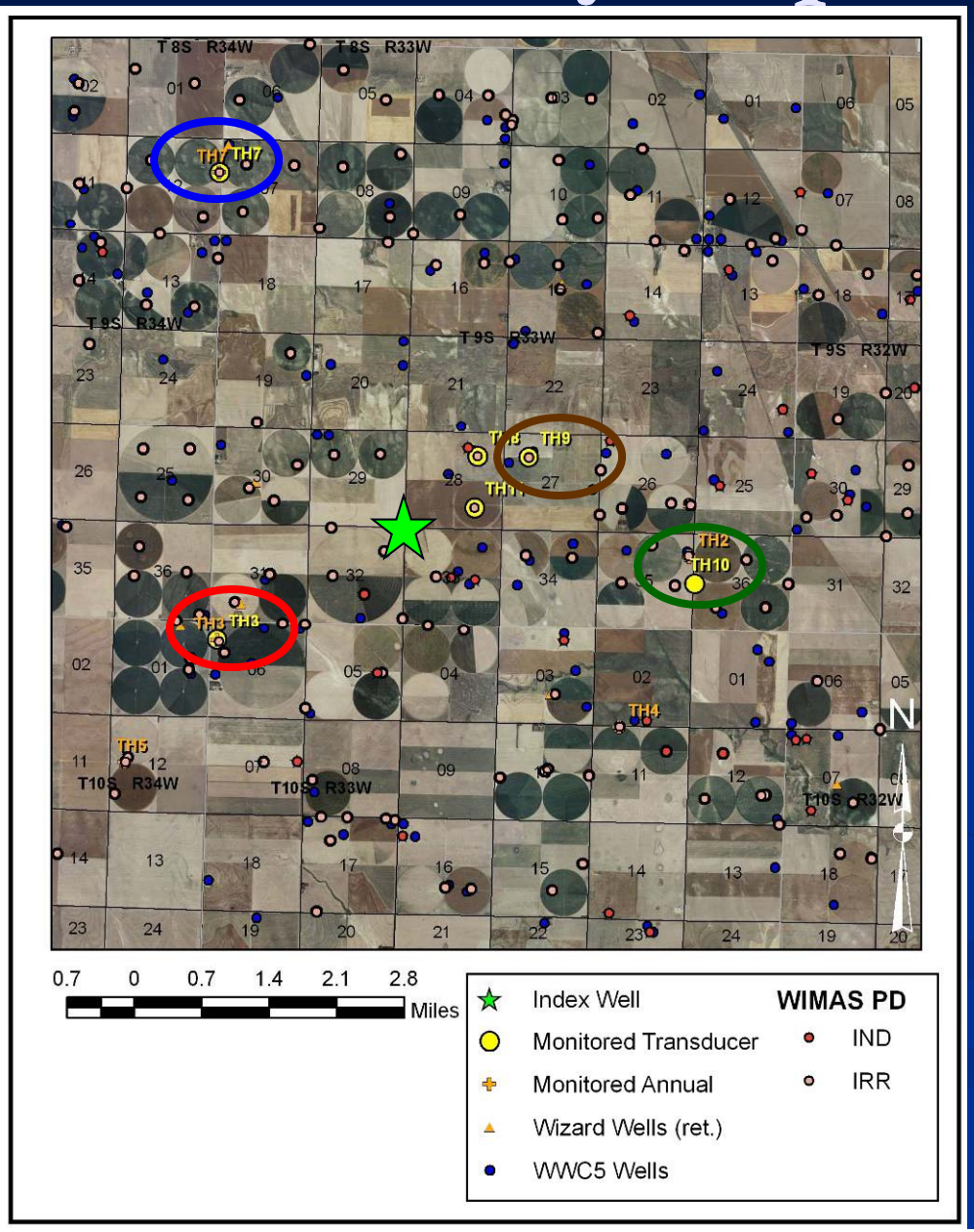
Scott County Index Well



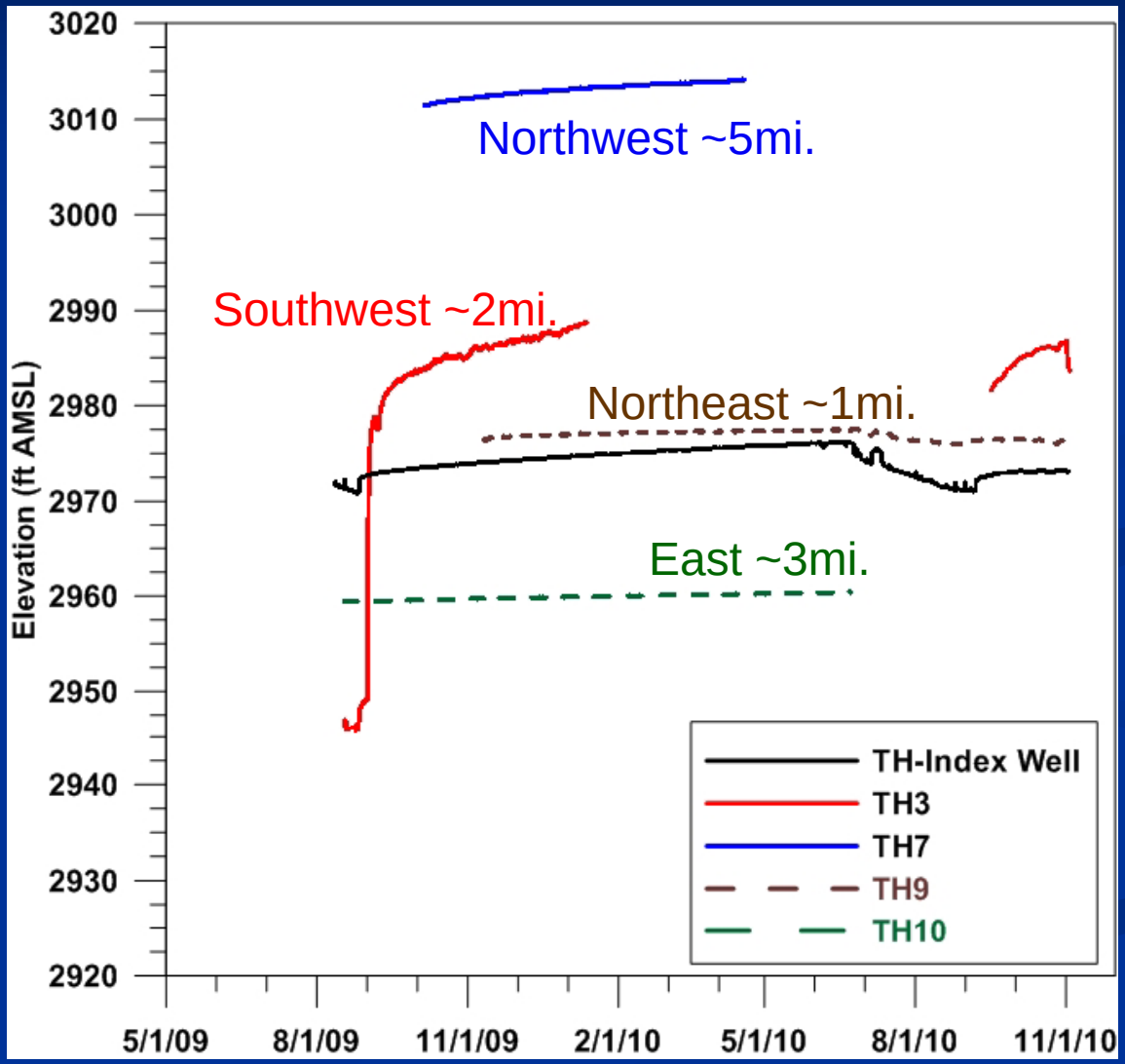
	H_{max} **predicted** ft AMSL
2008 (07-08 Recovery)	2836.26
2009 (08-09 Recovery)	2835.04
2010 (09-10 Recovery)	2834.61

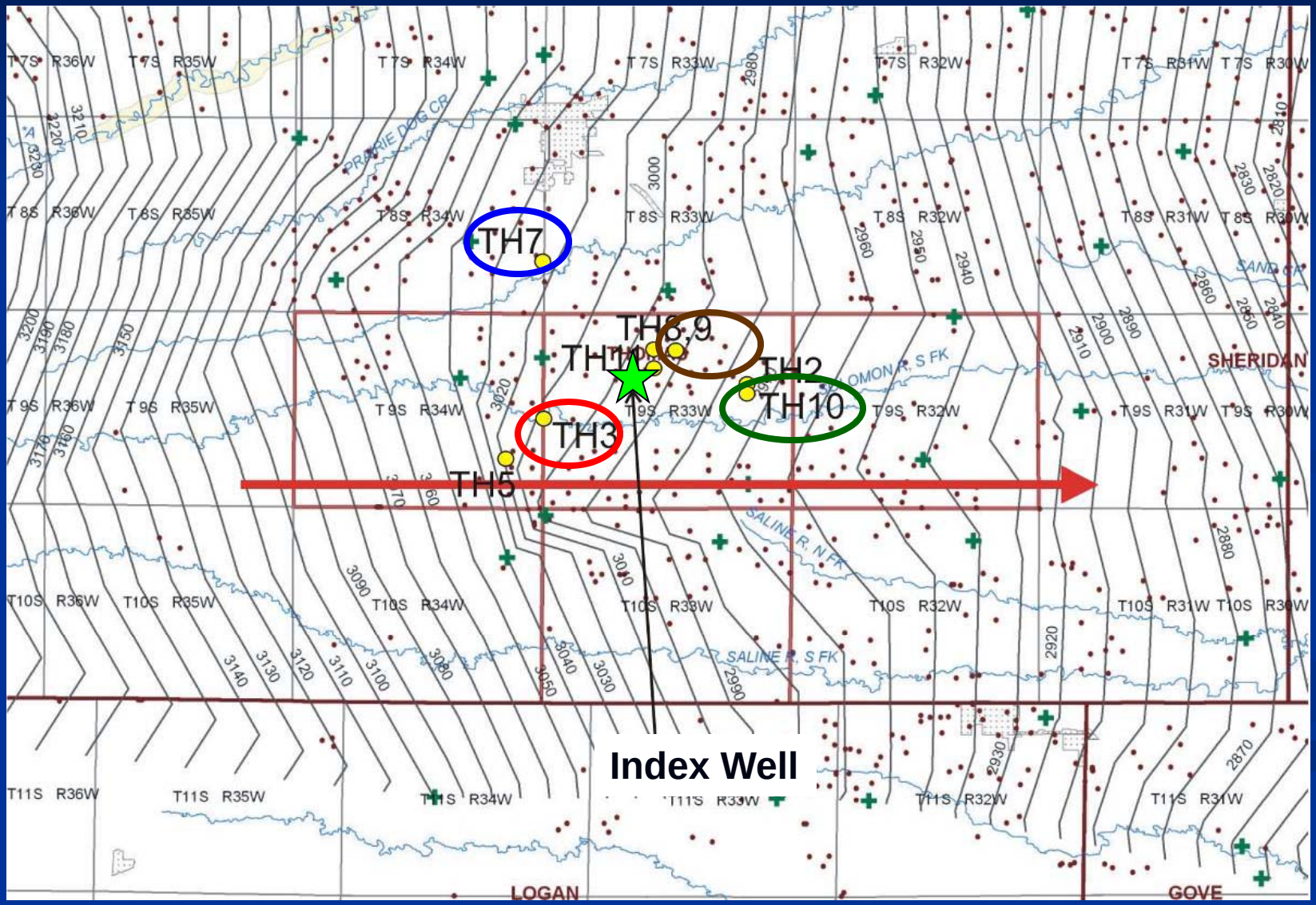

Scott Co Index Well
18S 33W 01AAA
2836.26'
2835.04'
2834.61'
3095.78 ac-ft
4014.33 ac-ft
2955.48 ac-ft
Elevation of Water (ft AMSL)
Depth to Water
Feet Below Land Surface
2837.15
2836.15
2835.15
2834.15
2833.15
2832.15
2831.15
2830.15
130
131
132
133
134
135
136
137
1-Aug-07
31-Oct-07
31-Jan-08
1-May-08
1-Aug-08
31-Oct-08
31-Jan-09
2-May-09
2-Aug-09
1-Nov-09
1-Feb-10
3-May-10
3-Aug-10
2-Nov-10
2-Feb-11
4-May-11
4-Aug-11

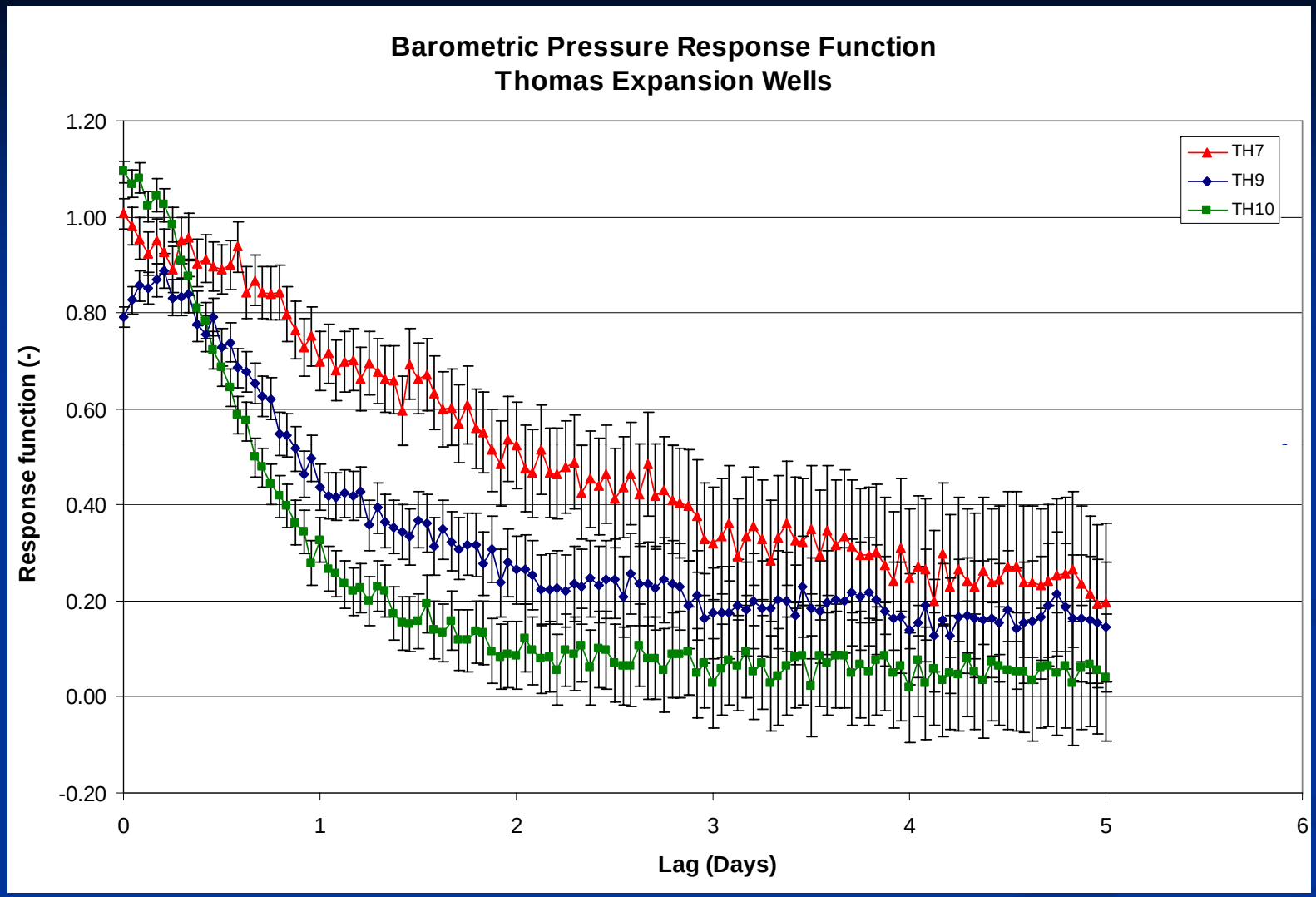
Thomas County Expansion



Thomas County Expansion




TH7
TH8,9
TH11
TH2
TH10
TH3
TH5
Index Well
T7S R36W
T7S R35W
T7S R34W
T7S R33W
T7S R32W
T7S R31W
T8S R36W
T8S R35W
T8S R34W
T8S R33W
T8S R32W
T8S R31W
T9S R36W
T9S R35W
T9S R34W
T9S R33W
T9S R32W
T9S R31W
T10S R36W
T10S R35W
T10S R34W
T10S R33W
T10S R32W
T10S R31W
T11S R36W
T11S R35W
T11S R34W
T11S R32W
T11S R31W
PRAIRIE DOG CR
SALINE R, N FK
SALINE R, S FK
SHERIDAN
LOGAN
GOVE

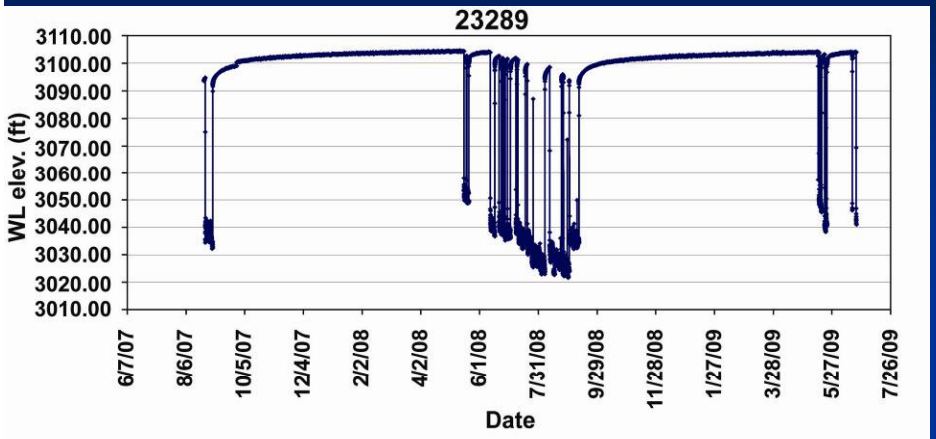


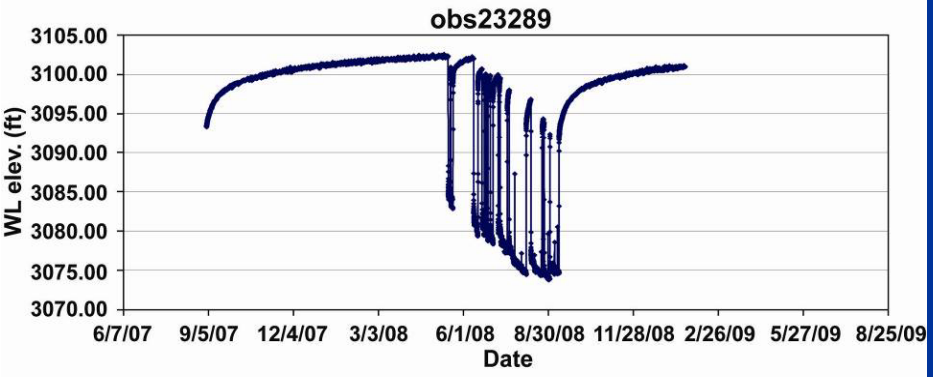
- Expansion wells: similar BRF to index well

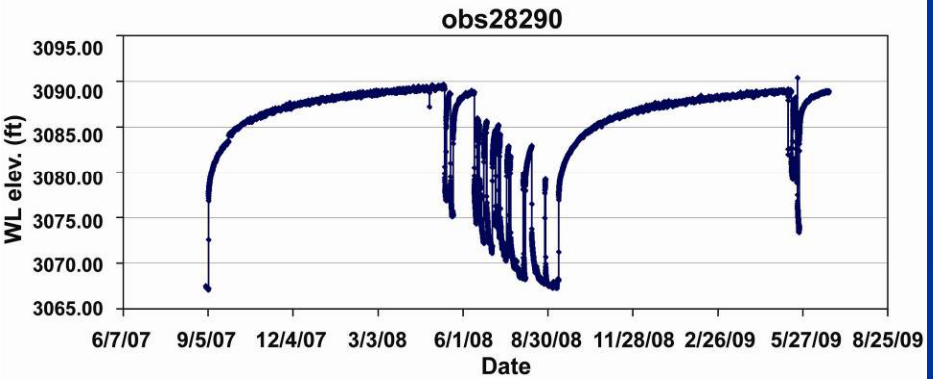
Index Well Summary

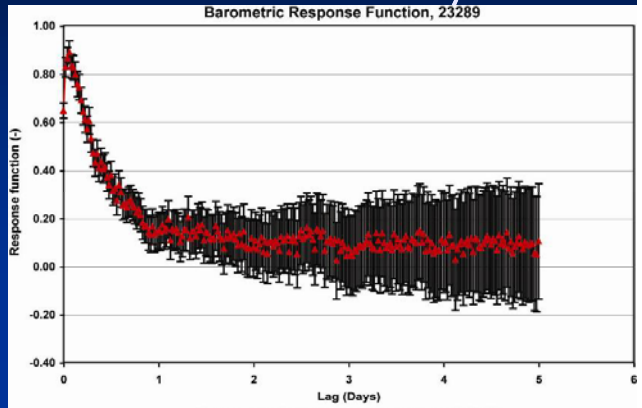
- In areas of high use, annual/semi-annual measurement not accurate at either township- or short- time scales
  - Local influences on water-levels
- Full recovery estimation
  - Possible in confined settings
  - Refinement needed for unconfined
  - Decline in ST less important than PST
- Relationship between water use and water-level decline?
- Thomas Expansion Well project:
  - Early results broadly confirm flow path set out in KGS Water Budget study
  - Similar BRF to index well
  - Need more consistent water level data

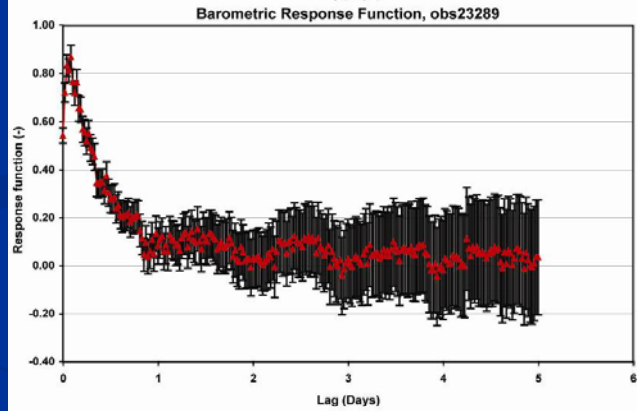
Related Research – Rawlins County

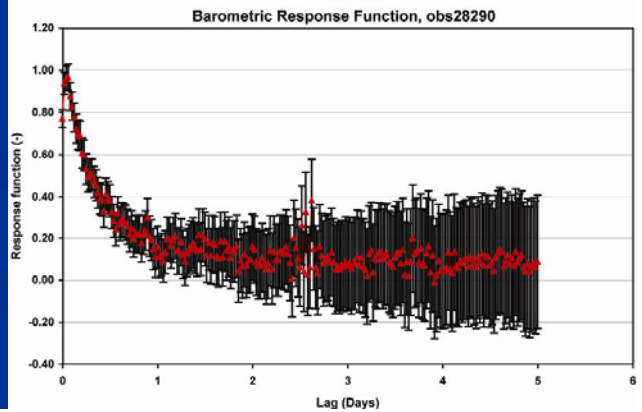




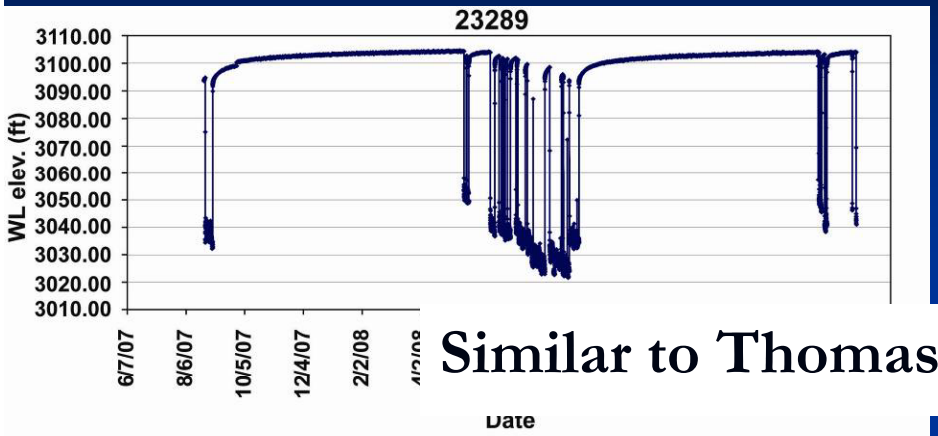


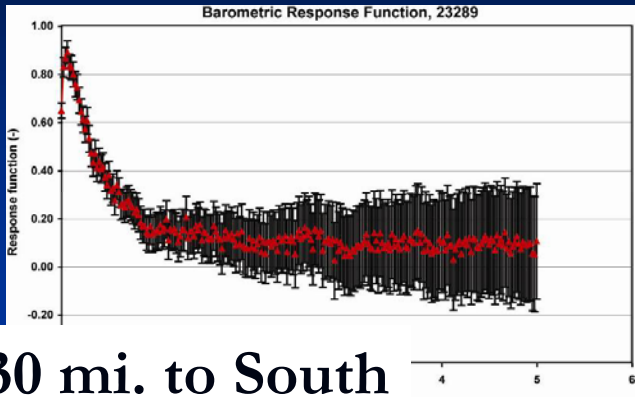




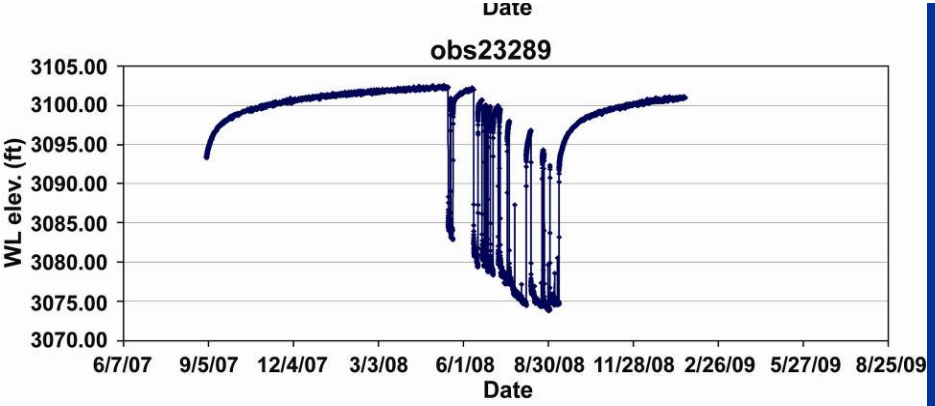


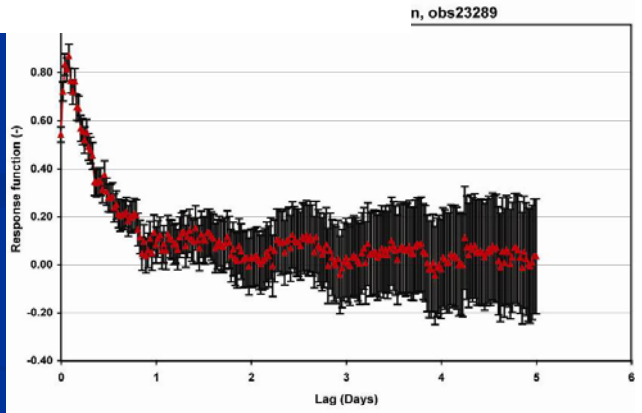
Related Research – Rawlins County

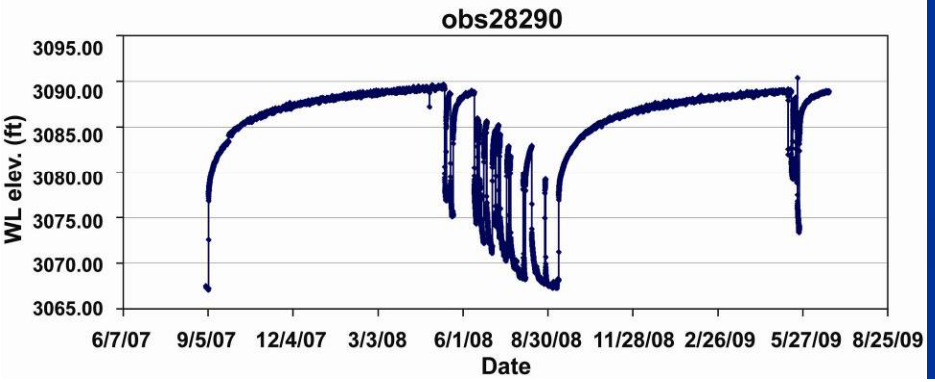


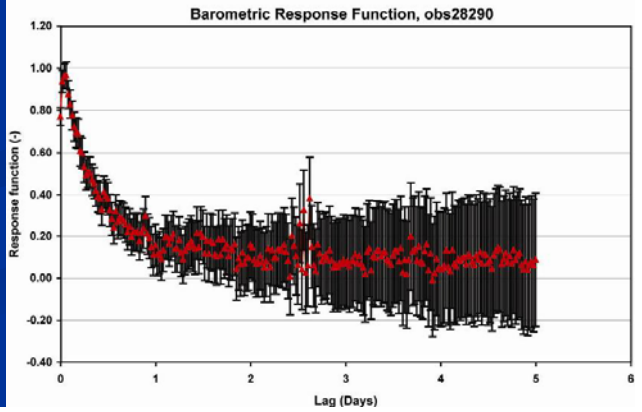


Similar to Thomas Index well, 30 mi. to South

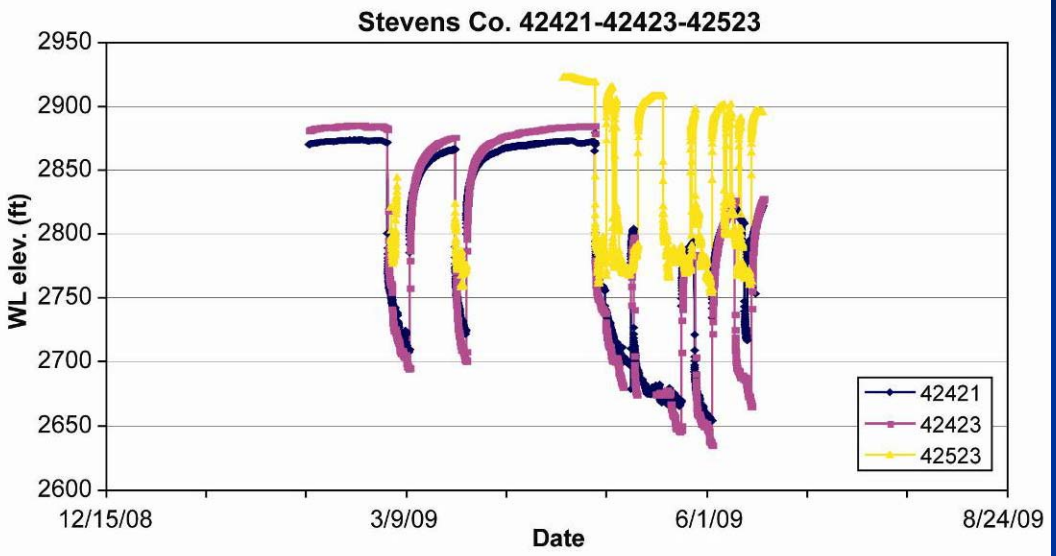


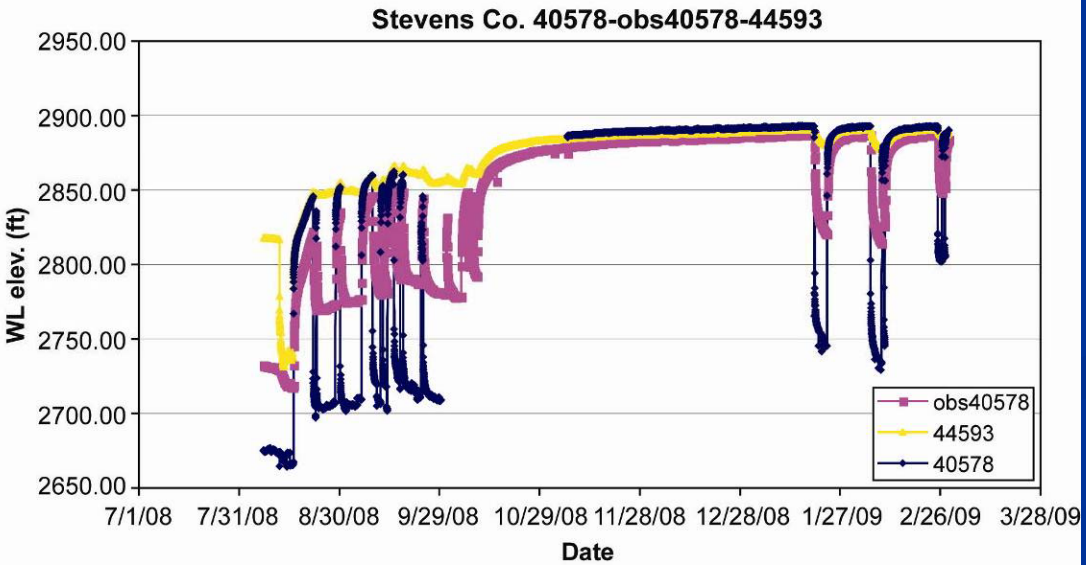




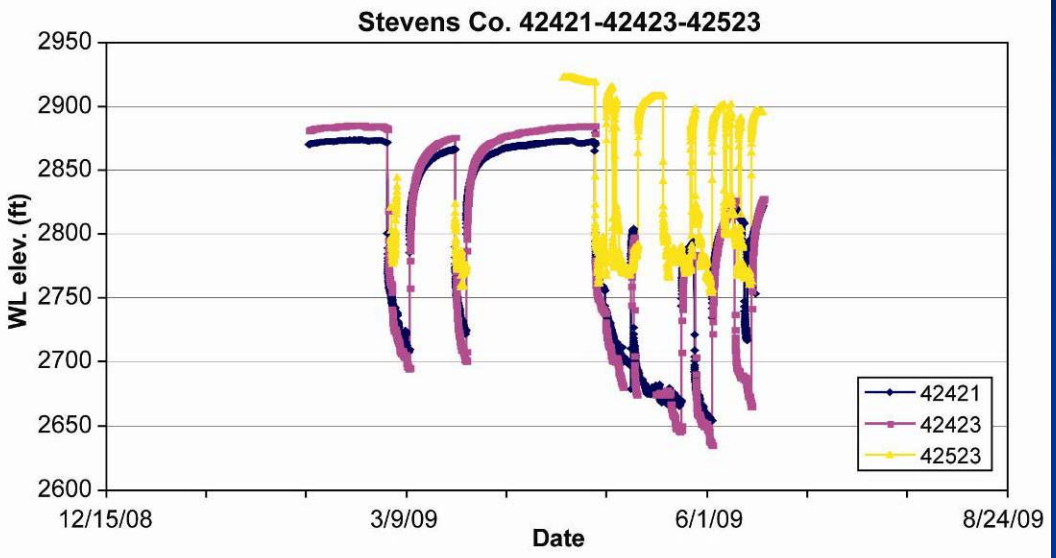


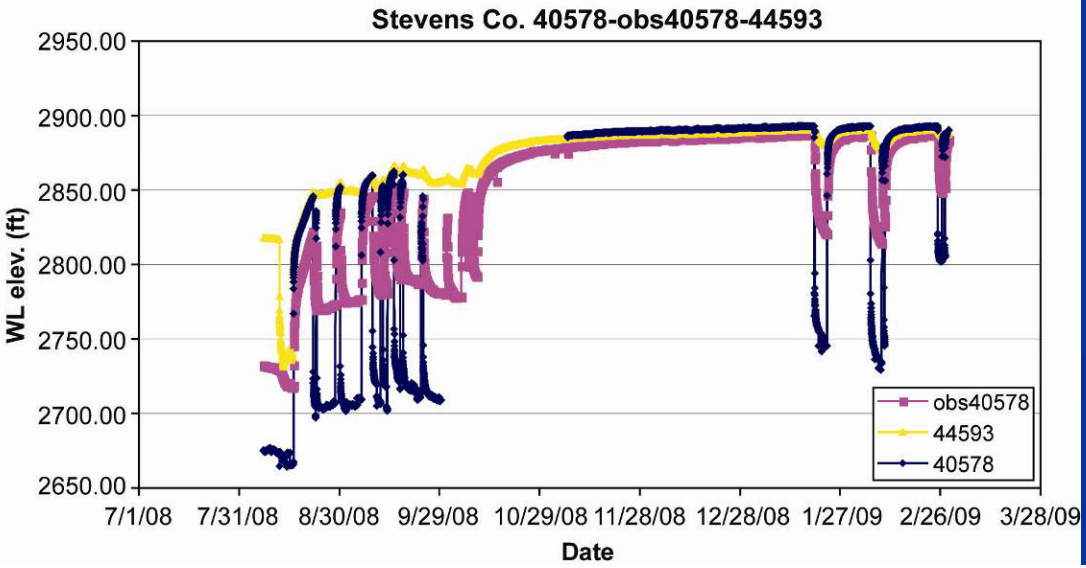
Related Research – Stevens County





Related Research – Stevens County





- Similar to Haskell County index well to the northeast
- ~200’ annual drawdown

Other Related Research by the KGS

- Stratigraphic correlation, hydrostratigraphic characterization of fluid chemistry and age, Haskell and Stevens counties
  - NSF award to KGS
  - STATEMAP project
  - KWO-BOR support
- NMR testing, Haskell and Thomas Index Wells
  - Department of Energy


QUESTIONS?