# GPS Subsidence Update

*2019 Glenn Groundwater Authority Meeting*

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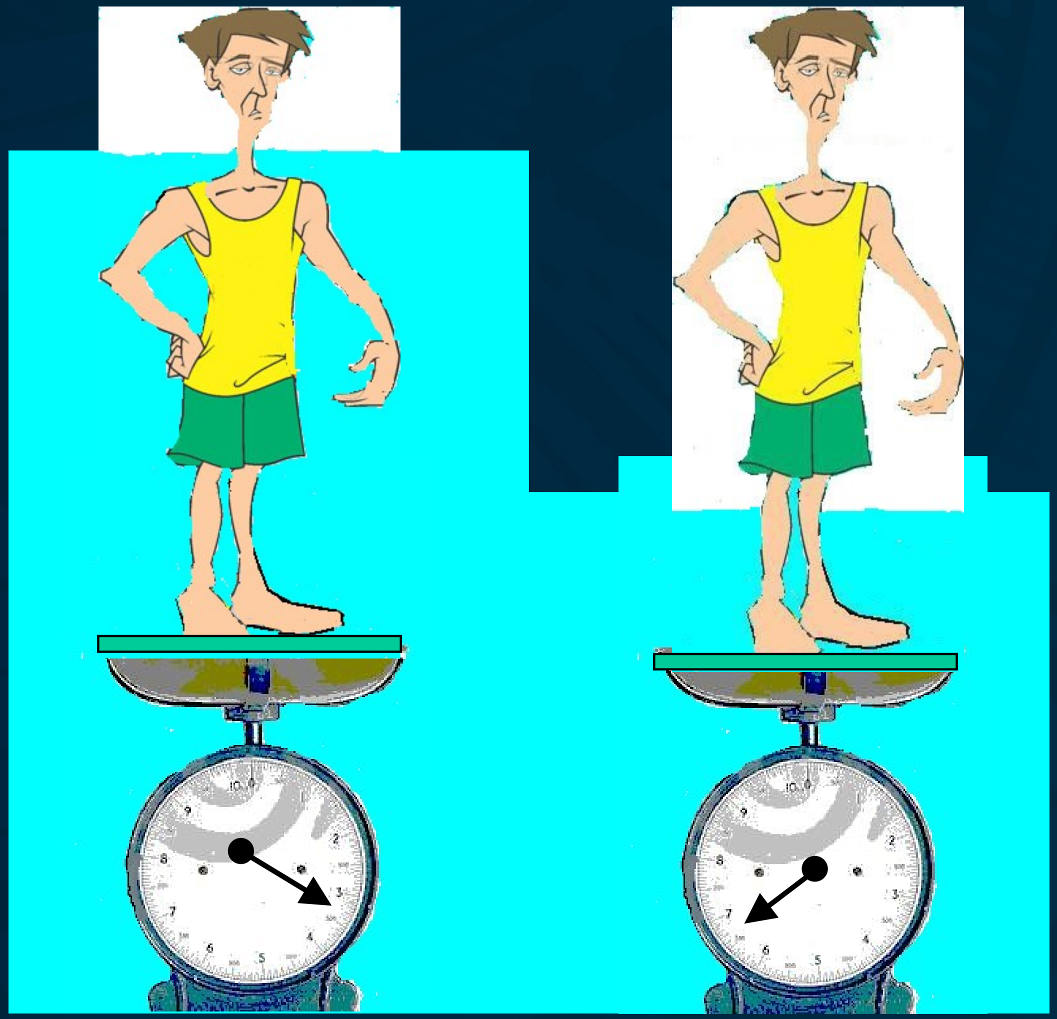
Northern Region Office
California Department of Water Resources

# Outline

1. Elastic and Inelastic Land Subsidence
2. GPS Survey Background
3. GPS Survey Results
4. Extensometers
5. Groundwater Conditions

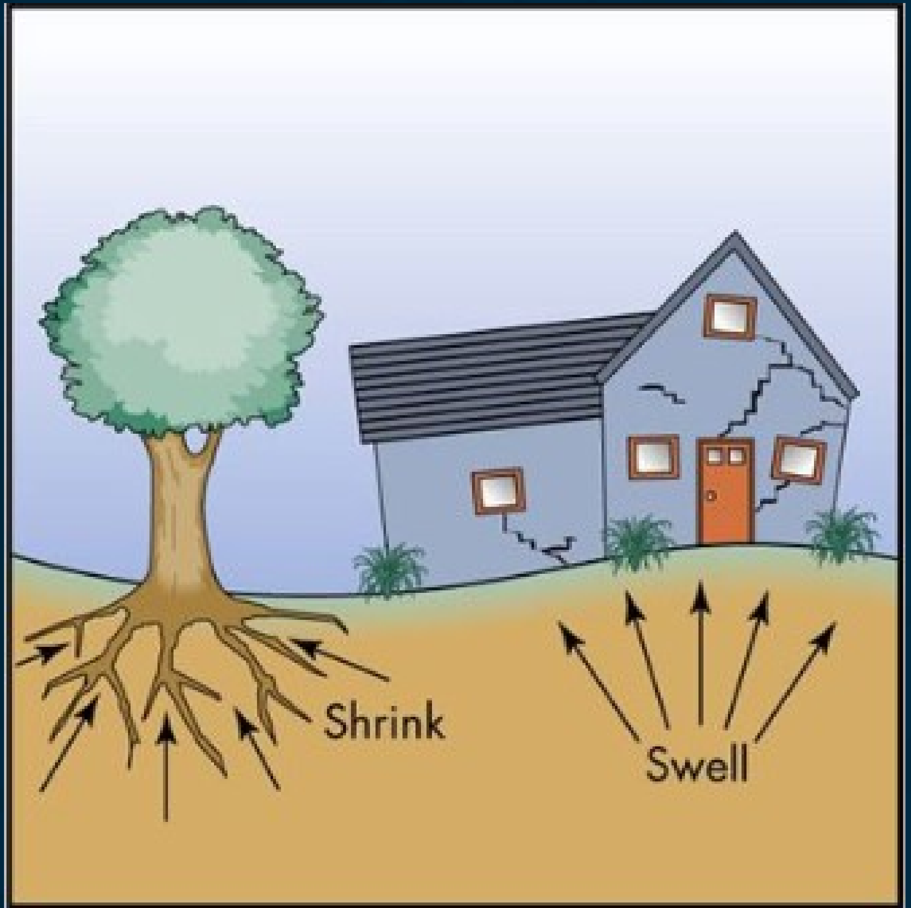
# Elastic versus Inelastic Subsidence

- Groundwater withdrawal results in fluid pressure change within the lithologic layers causing the gravels and sands to become less buoyant and exert a downward force.



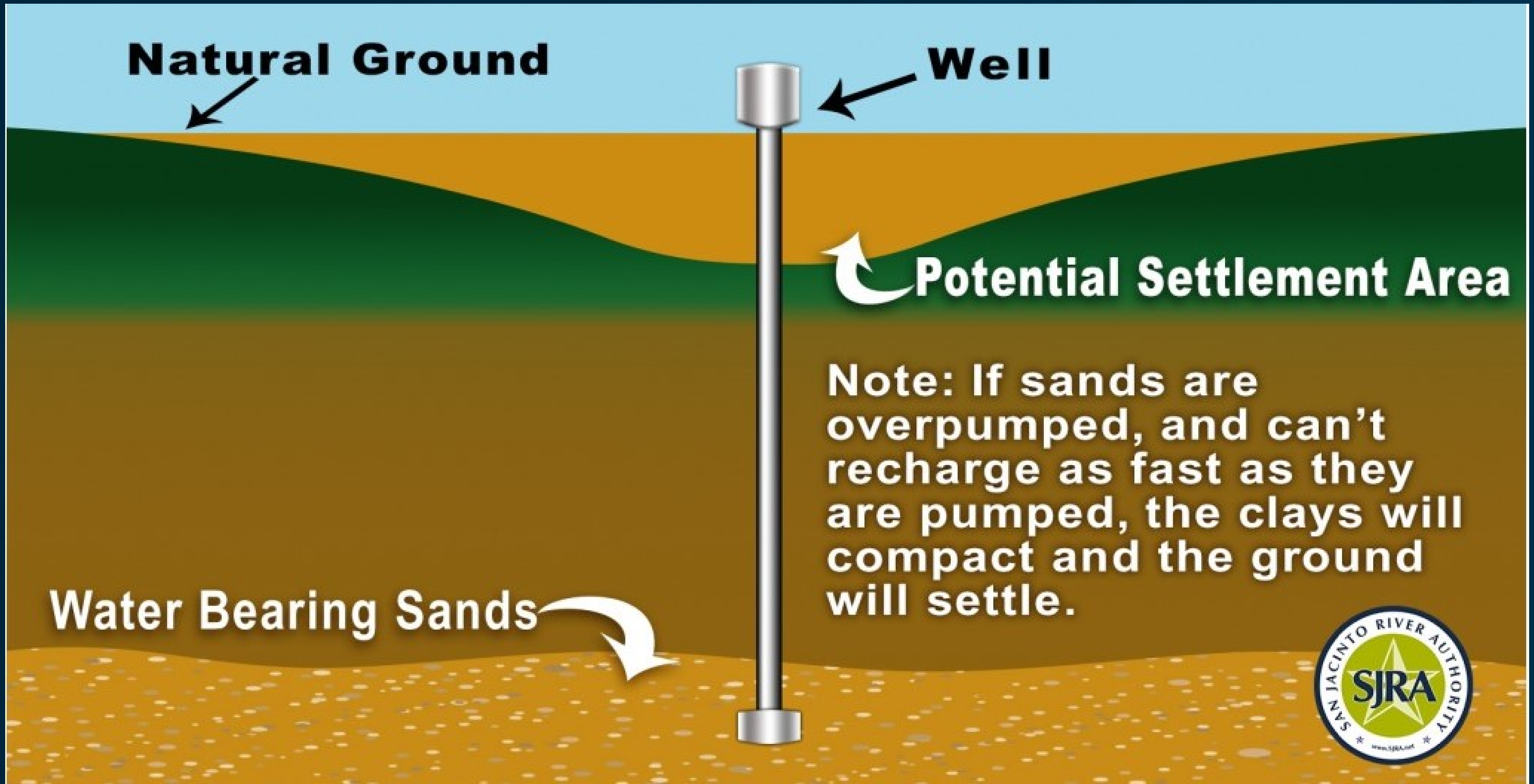
# Elastic versus Inelastic Subsidence

- If the groundwater levels are restored, the sands, gravels, and fine grains are re-wetted, the buoyancy of the grains are renewed and the land surface rebounds resulting in *elastic* land subsidence.
- In the Northern Sacramento Valley, elastic subsidence we've observed are changes in the land surface of up to +/– 0.1-0.2 ft.

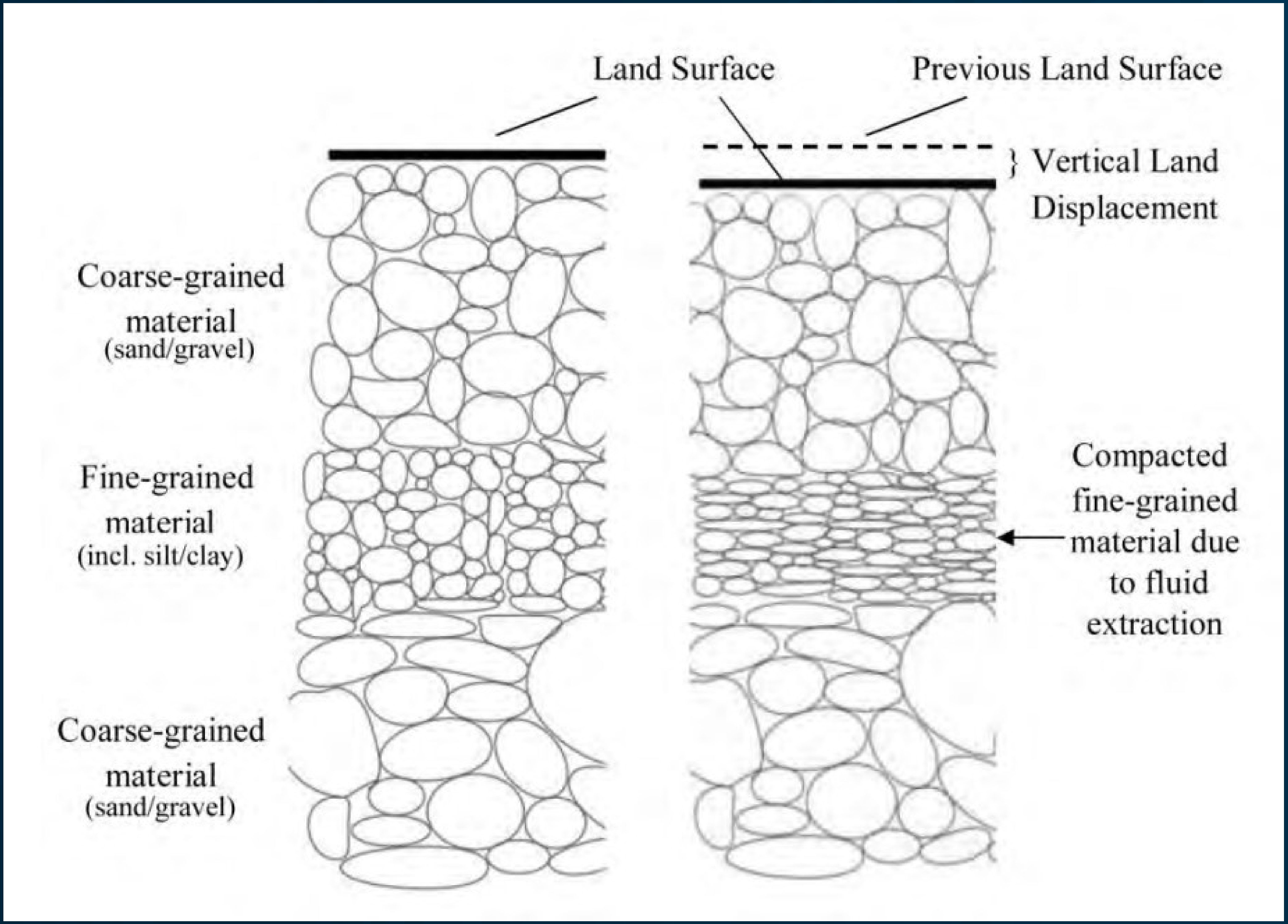


# Elastic versus Inelastic Subsidence

- However, if groundwater levels decline to a certain critical level, the water held within the clays can no longer withstand the increase in downward pressure, the clays are compressed, and the water is squeezed out of them.
- When this happens, the clays will never reabsorb the water, and permanent, or *inelastic* subsidence occurs.



# Inelastic Subsidence

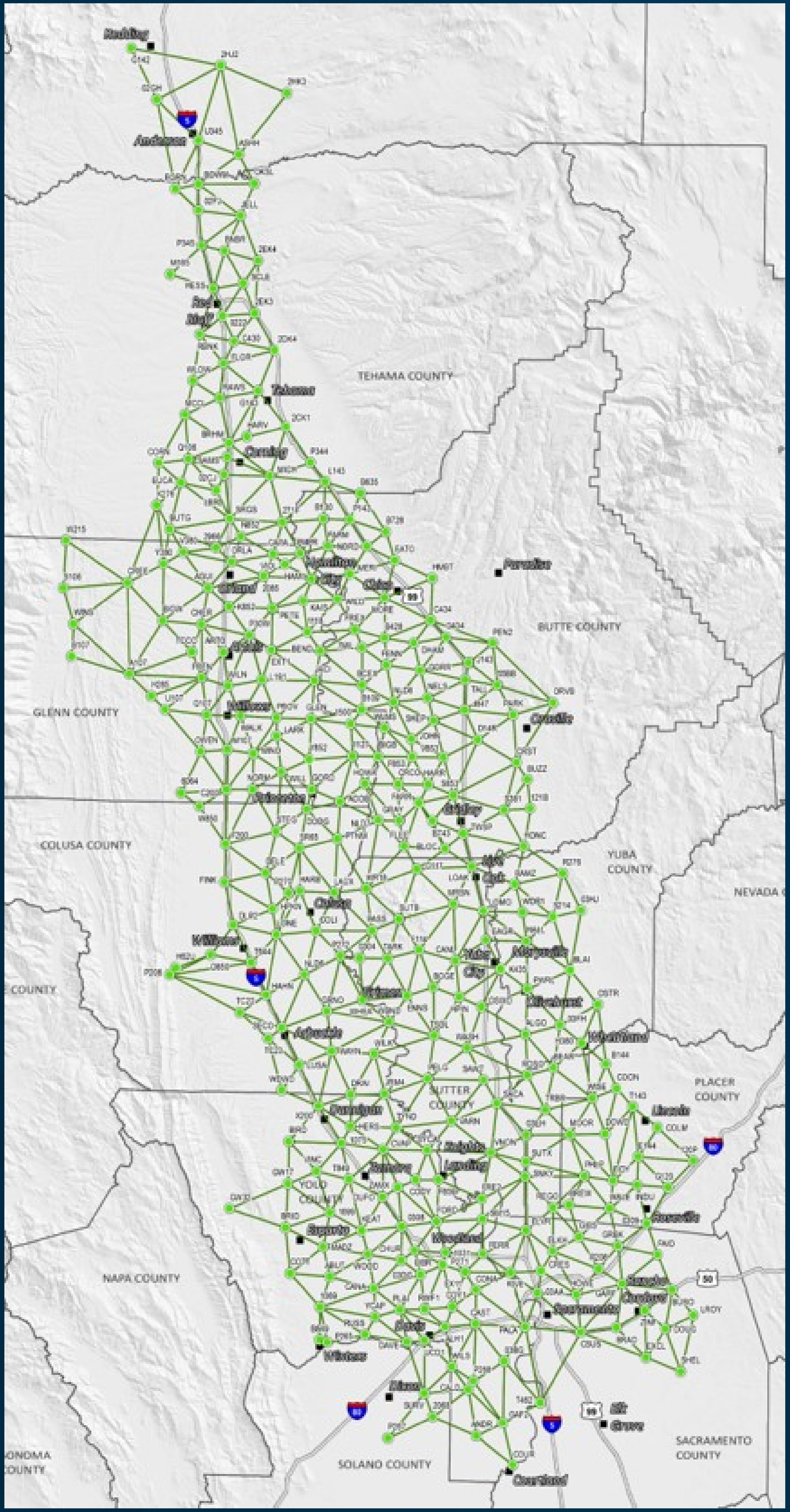


# Inelastic Land Subsidence

- Results in damage to infrastructure
- Results in loss of aquifer storage (minor)

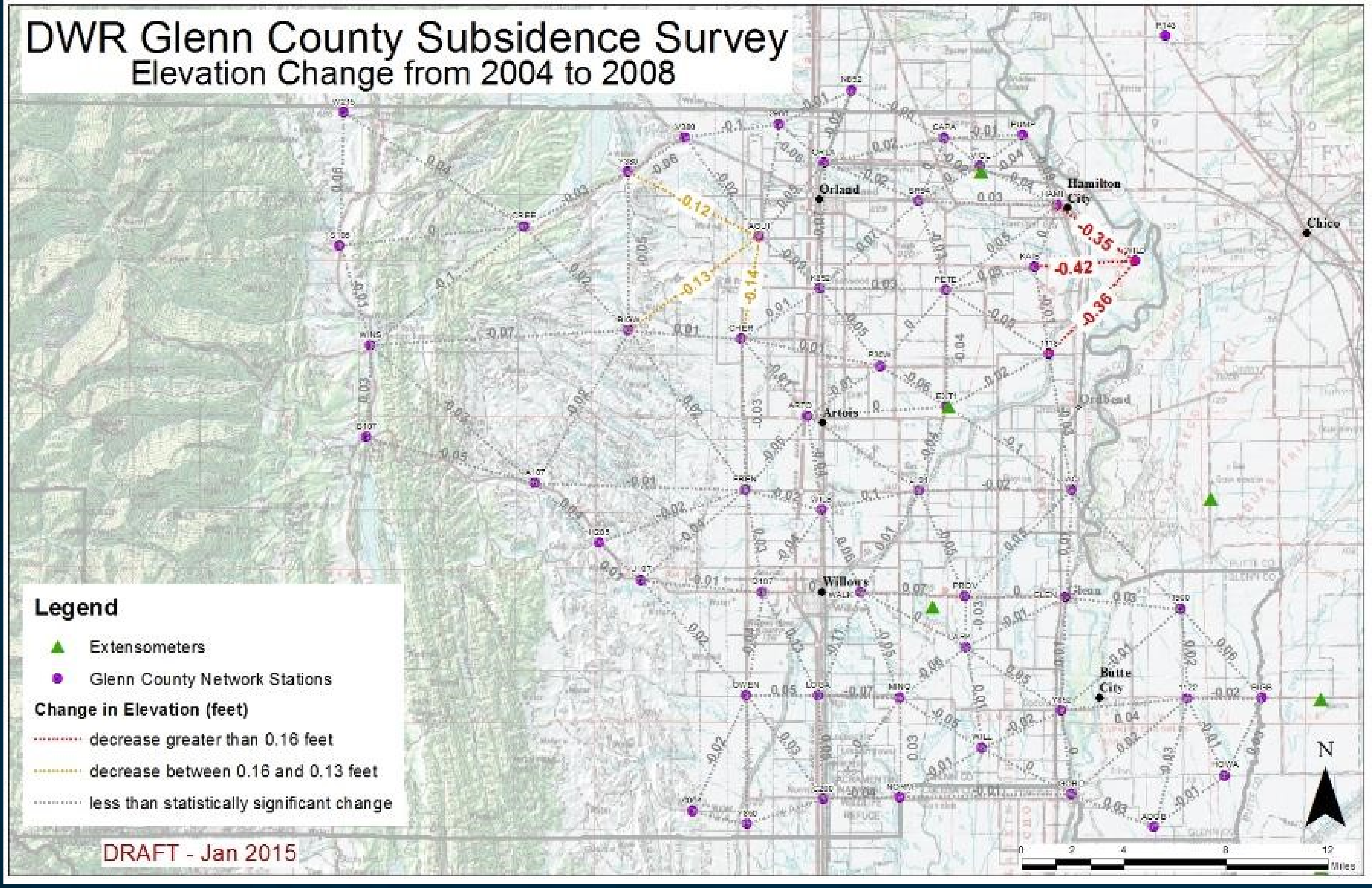
# GPS Survey Background

- 2004 Glenn County Survey
- 2008 Sacramento Valley Survey
- 2017 Sacramento Valley Re-survey



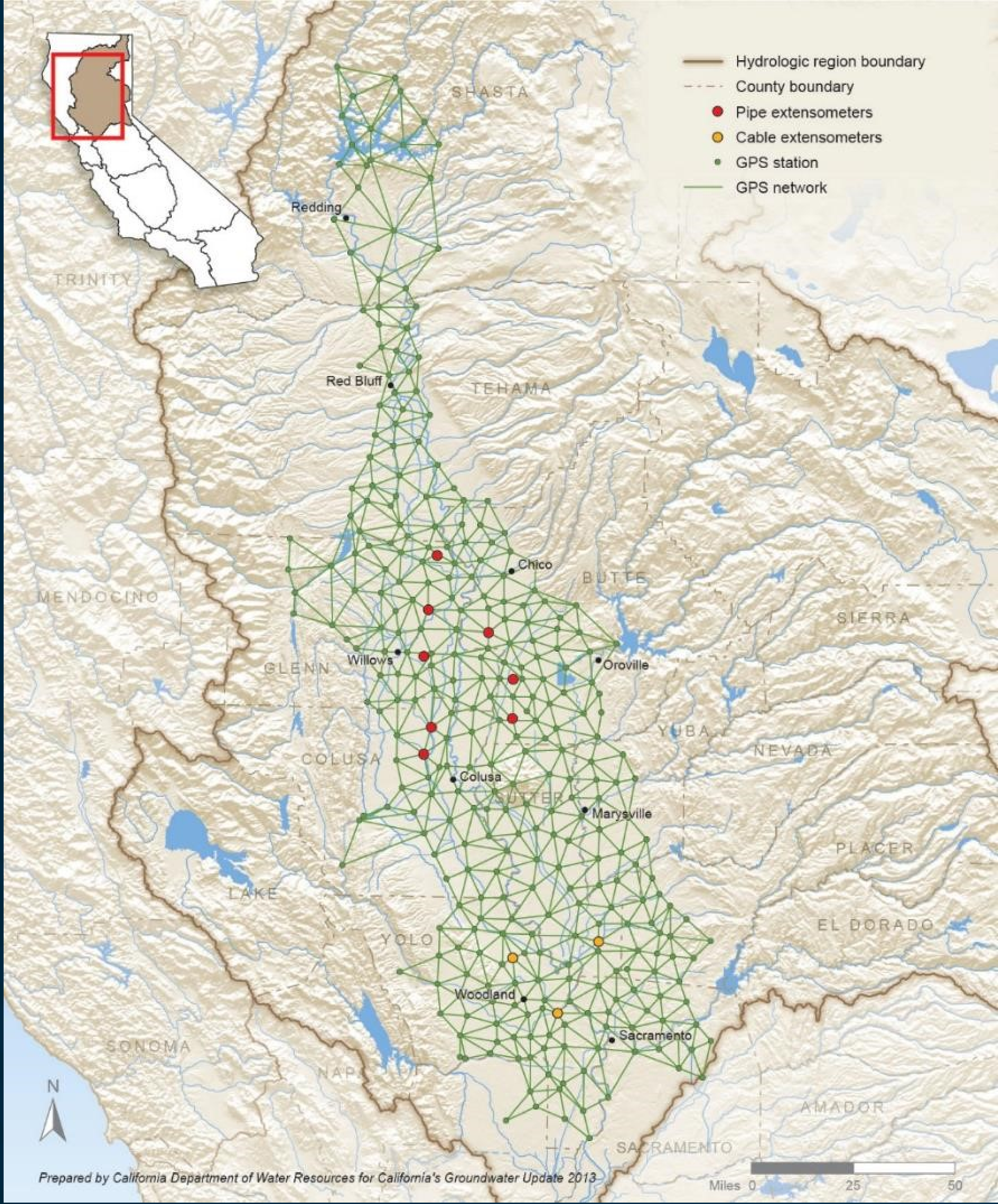
# Background

- In 2004 the subsidence network consisted of 58 stations, half were existing and the other half were installed as part of the project.



# Background

- In 2008, DWR contracted with a private consultant to establish over 300 survey monuments that span 11 counties.



# Background

- 25 local, state, and federal agencies assisted with the GPS survey at each location.

# Background

- Due to inconsistent methods in the two surveys, direct comparison with 2004 was not possible at some locations and would require a substantial amount of data analysis and the results were not produced.

| r | Elevation | RefName | Style | Text |
|---|---|---|---|---|
| 1 | 0 | 83.3 | HZ | 83.3 |
| 1 | 0 | 82.9 | HZ | 82.9 |
| 1 | 0 | 82.8 | HZ | 82.8 |
| 1 | 0 | 77.9 | HZ | 77.9 |
| 1 | 0 | 84.4 | HZ | 84.4 |
| 1 | 0 | 77.4 | HZ | 77.4 |
| 1 | 0 | 78.1 | HZ | 78.1 |
| 1 | 0 | 82.6 | HZ | 82.6 |
| 1 | 0 | 79.4 | HZ | 79.4 |
| 1 | 0 | 74.3 | HZ | 74.3 |
| 1 | 0 | 78.8 | HZ | 78.8 |
| 1 | 0 | 84.7 | HZ | 84.7 |
| 1 | 0 | 83.6 | HZ | 83.6 |
| 1 | 0 | 78.7 | HZ | 78.7 |
| 1 | 0 | 80.2 | HZ | 80.2 |
| 1 | 0 | 80.8 | HZ | 80.8 |
| 1 | 30.24 | 30 | HZ | 30 |
| 1 | 30.24 | 2 | HZ | 2 |
| 1 | 30.69 | 30 | HZ | 30 |
| 1 | 30.69 | 7 | HZ | 7 |
| 1 | 30.69 | 30 | HZ | 30 |
| 1 | 30.69 | 7 | HZ | 7 |
| 1 | 30.86 | 30 | HZ | 30 |
| 1 | 30.86 | 9 | HZ | 9 |
| 1 | 30.86 | 30 | HZ | 30 |
| 1 | 30.86 | 9 | HZ | 9 |
| 1 | 31.15 | 31 | HZ | 31 |
| 1 | 31.15 | 2 | HZ | 2 |

Satellite (SV) coordinates in ECEF XYZ from Ephemeris Parameters and SV Time

$SVx_0 := 15524471.175$ $SVy_0 := -16649826.222$ $SVz_0 := 13512272.387$ SV 15

$SVx_1 := -2304058.534$ $SVy_1 := -23287906.465$ $SVz_1 := 11917038.105$ SV 27

$SVx_2 := 16680243.357$ $SVy_2 := -3069625.561$ $SVz_2 := 20378551.047$ SV 31

$SVx_3 := -14799931.395$ $SVy_3 := -21425358.24$ $SVz_3 := 6069947.224$ SV 7

Satellite Pseudoranges in meters (from C/A code epochs in milliseconds)

$P_0 := 89491.971$ $P_1 := 133930.500$ $P_2 := 283098.754$ $P_3 := 205961.742$ Range + Receiver Clock Bias

Receiver Position Estimate in ECEF XYZ

$Rx := -730000$ $Ry := -5440000$ $Rz := 3230000$

For Each of 4 SVs $i := 0..3$

Ranges from Receiver Position Estimate to SVs (R) and Array of Observed - Predicted Ranges

$$R_i := \sqrt{(SVx_i - Rx)^2 + (SVy_i - Ry)^2 + (SVz_i - Rz)^2} \qquad L_i := \mathrm{mod}\left[(R_i), 299792.458\right] - P_i$$

Compute Directional Derivatives for XYZ and Time

$$Dx_i := \frac{SVx_i - Rx}{R_i} \qquad Dy_i := \frac{SVy_i - Ry}{R_i} \qquad Dz_i := \frac{SVz_i - Rz}{R_i} \qquad Dt_i := -1$$

Solve for Correction to Receiver Position Estimate

$$A := \begin{bmatrix} Dx_0 & Dy_0 & Dz_0 & Dt_0 \\ Dx_1 & Dy_1 & Dz_1 & Dt_1 \\ Dx_2 & Dy_2 & Dz_2 & Dt_2 \\ Dx_3 & Dy_3 & Dz_3 & Dt_3 \end{bmatrix} \qquad dR := (A^T \cdot A)^{-1} \cdot A^T \cdot L \qquad dR = \begin{bmatrix} -3186.496 \\ -3791.932 \\ 1193.286 \\ 12345.997 \end{bmatrix}$$

Apply Corrections to Receiver XYZ and Compute Receiver Clock Bias Estimate

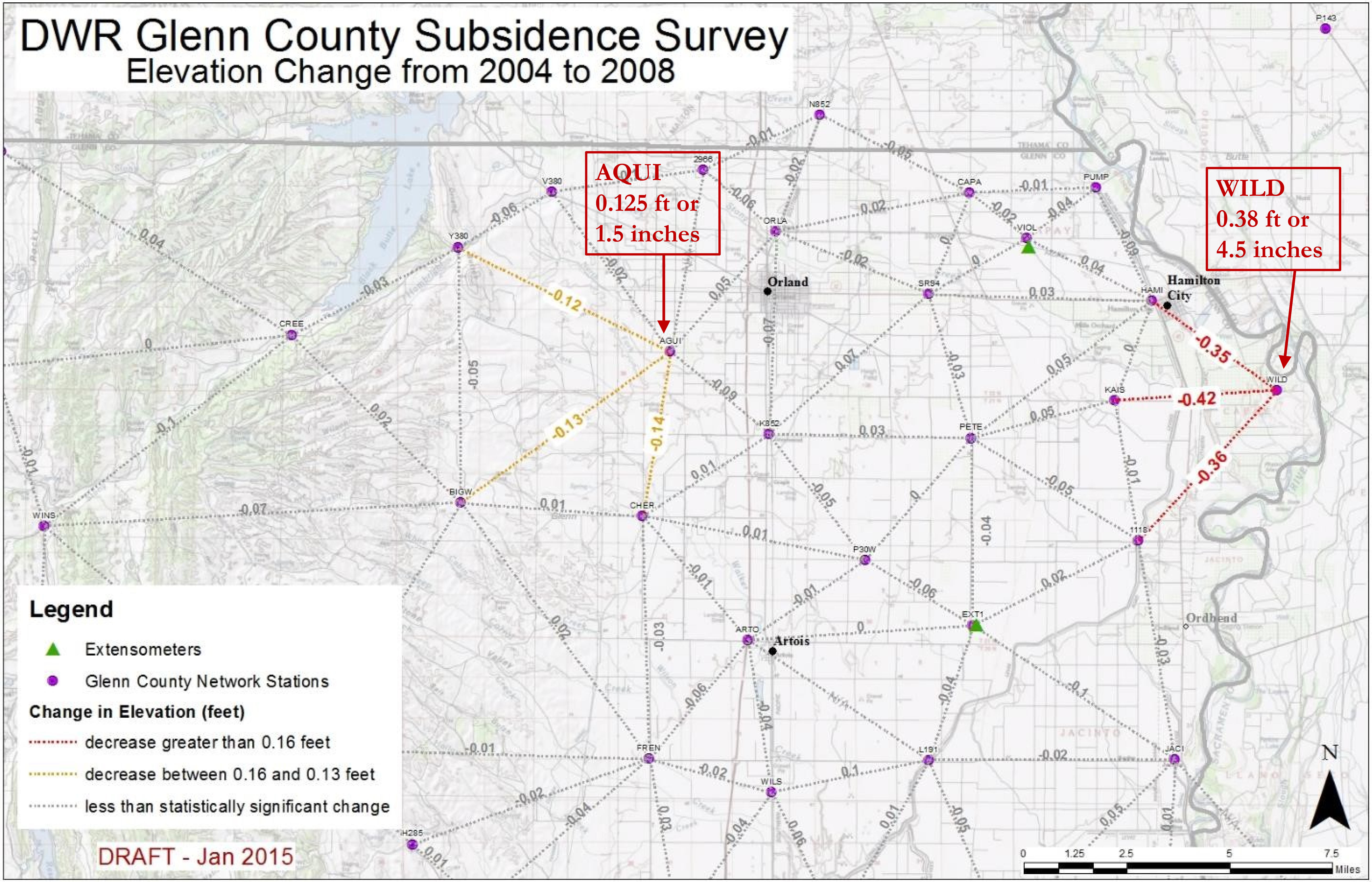
$Rx := Rx + dR_0$ $Ry := Ry + dR_1$ $Rz := Rz + dR_2$ $Time := dR_3$

$Rx = -733186.496$ $Ry = -5443791.932$ $Rz = 3231193.286$ $Time = 12345.997$

# Background

- During the drought of 2014 and 2015, the need to compare the 2008 survey with the 2004 was evident and some funding was redirected and DWR's NRO performed the analysis.

# Background

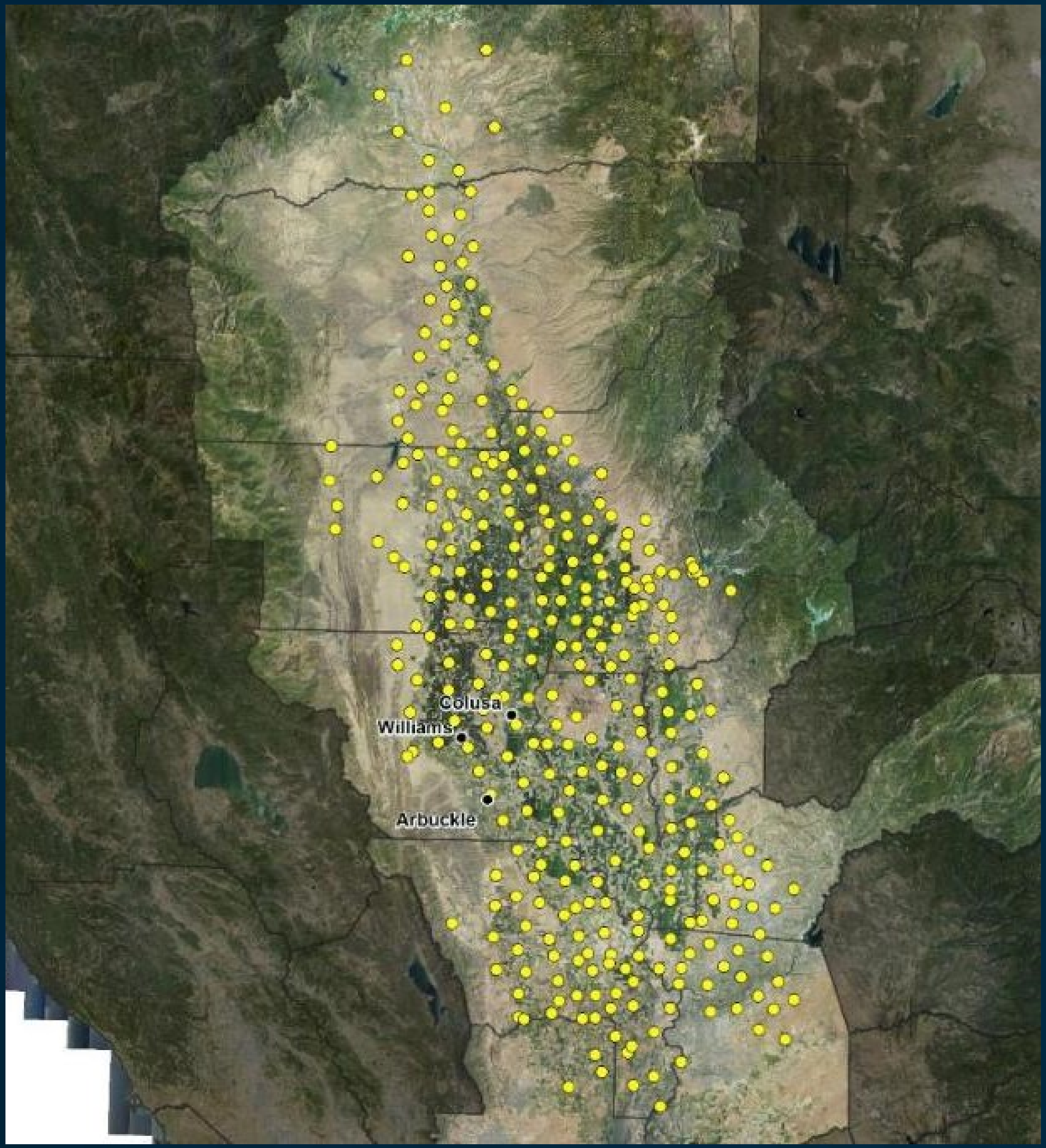


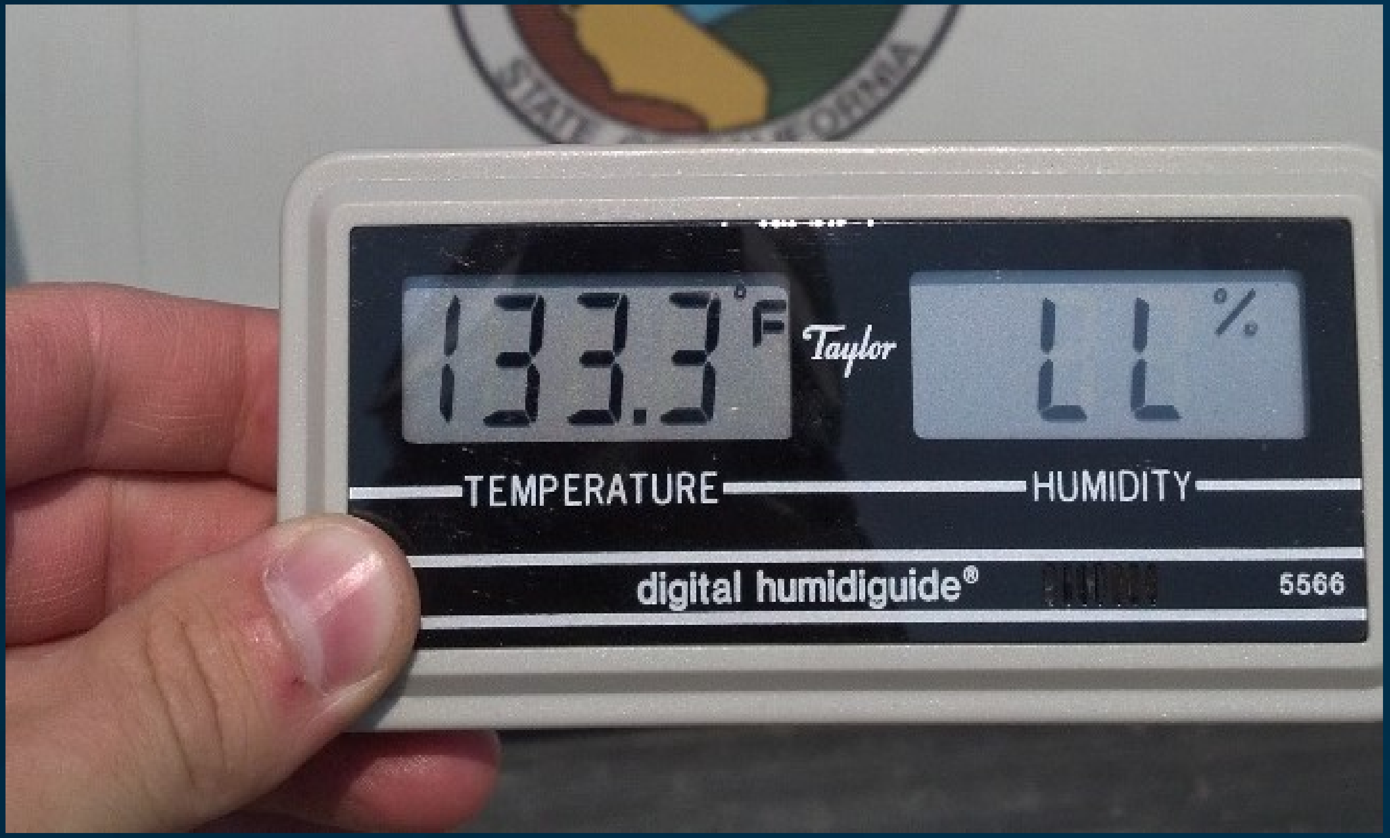
DWR Glenn County Subsidence Survey
Elevation Change from 2004 to 2008
AQUI
0.125 ft or
1.5 inches
WILD
0.38 ft or
4.5 inches
Orland
Hamilton City
Artois
Ordbend
-0.12
-0.13
-0.14
-0.35
-0.42
-0.36
Legend
Extensometers
Glenn County Network Stations
Change in Elevation (feet)
decrease greater than 0.16 feet
decrease between 0.16 and 0.13 feet
less than statistically significant change
DRAFT - Jan 2015
N
0
1.25
2.5
5
7.5
Miles

# Background

- In 2017, DWR with the help of 18 local, state, and federal agencies, resurveyed the GPS monument grid in order to determine any change in land surface elevation

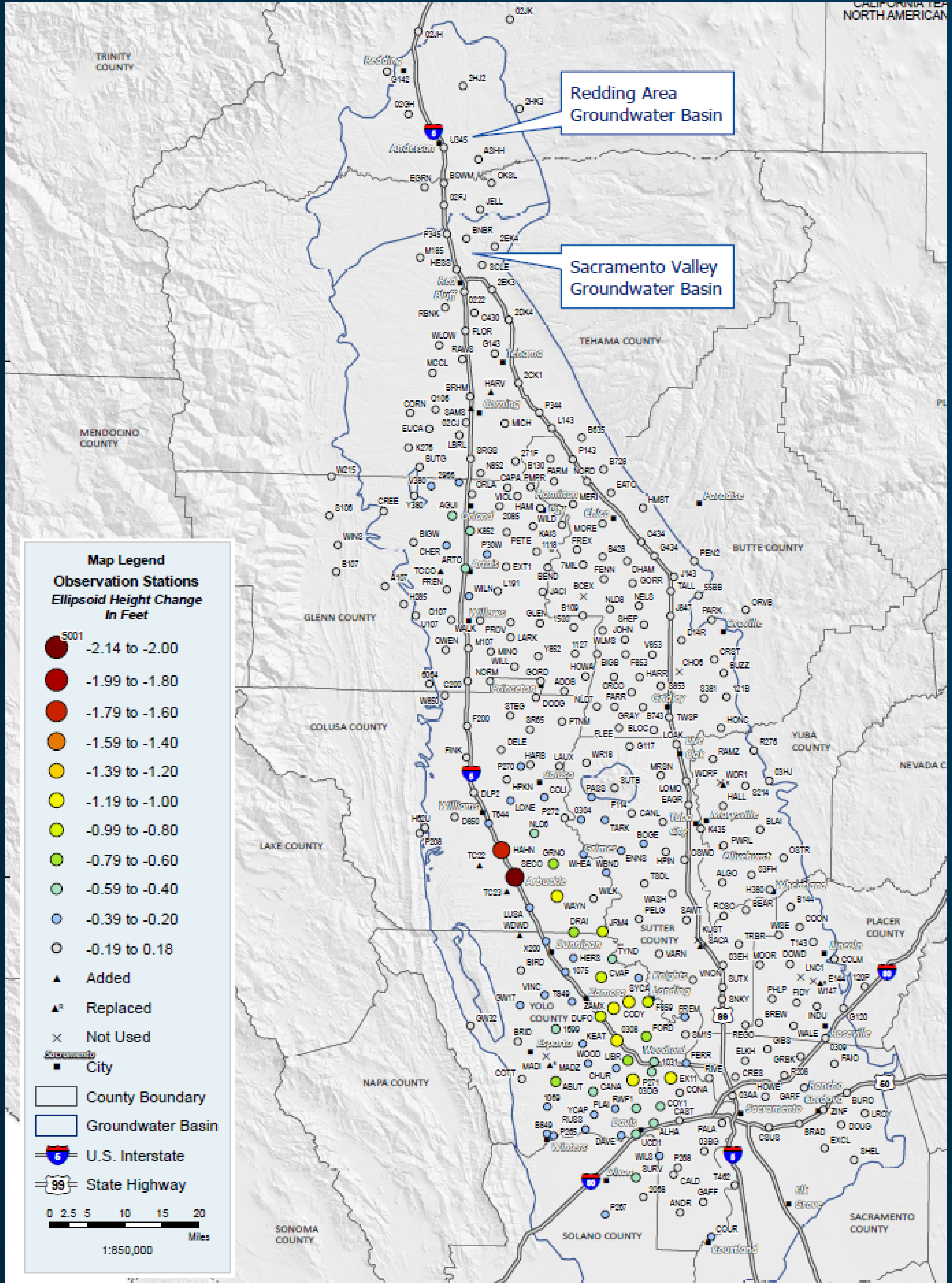
# Key Findings



# Key Findings

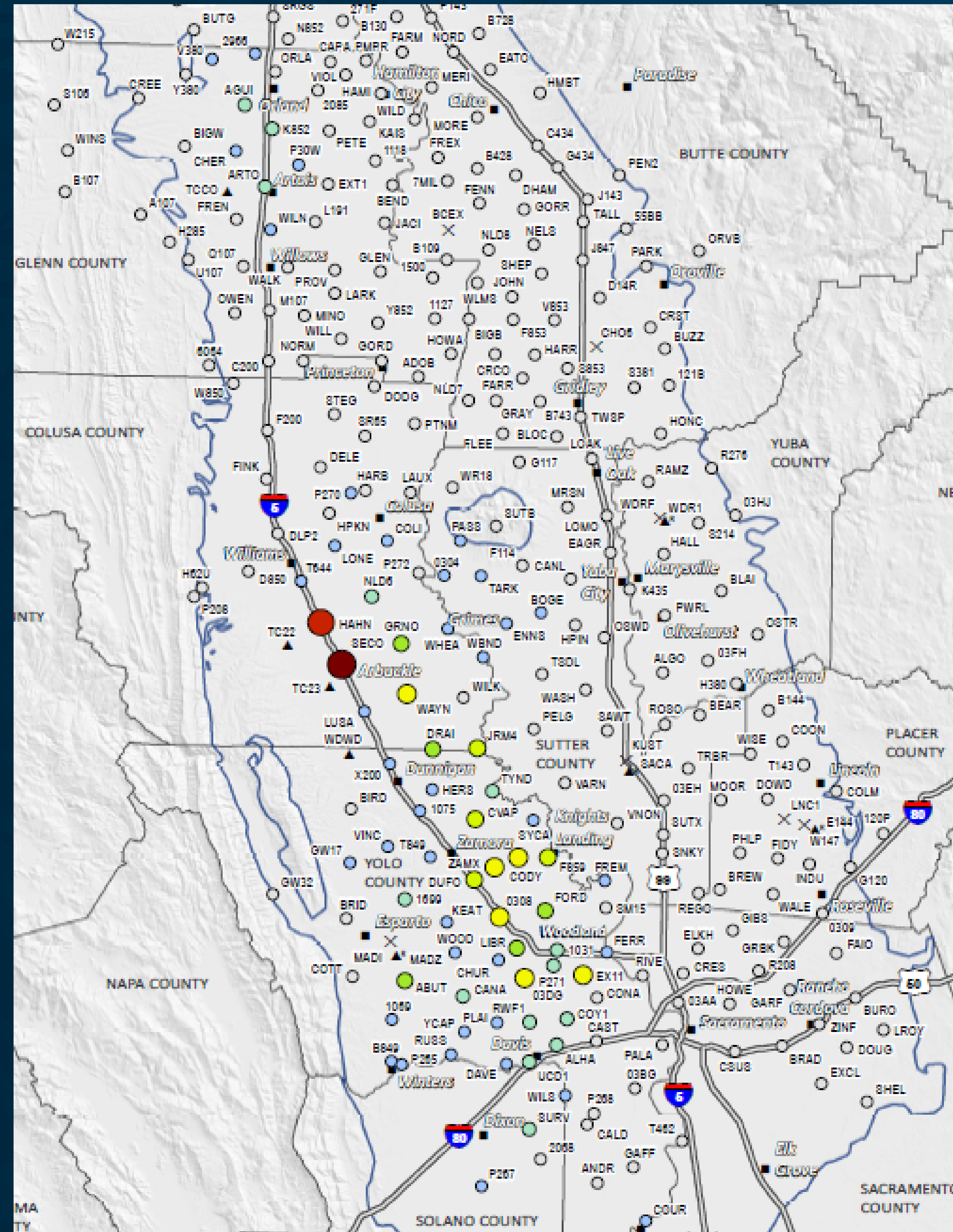
- Error in the method
- Changes in elevation of less than 0.17 feet (~2”) are not considered statistically significant



# Key Findings

Colusa County

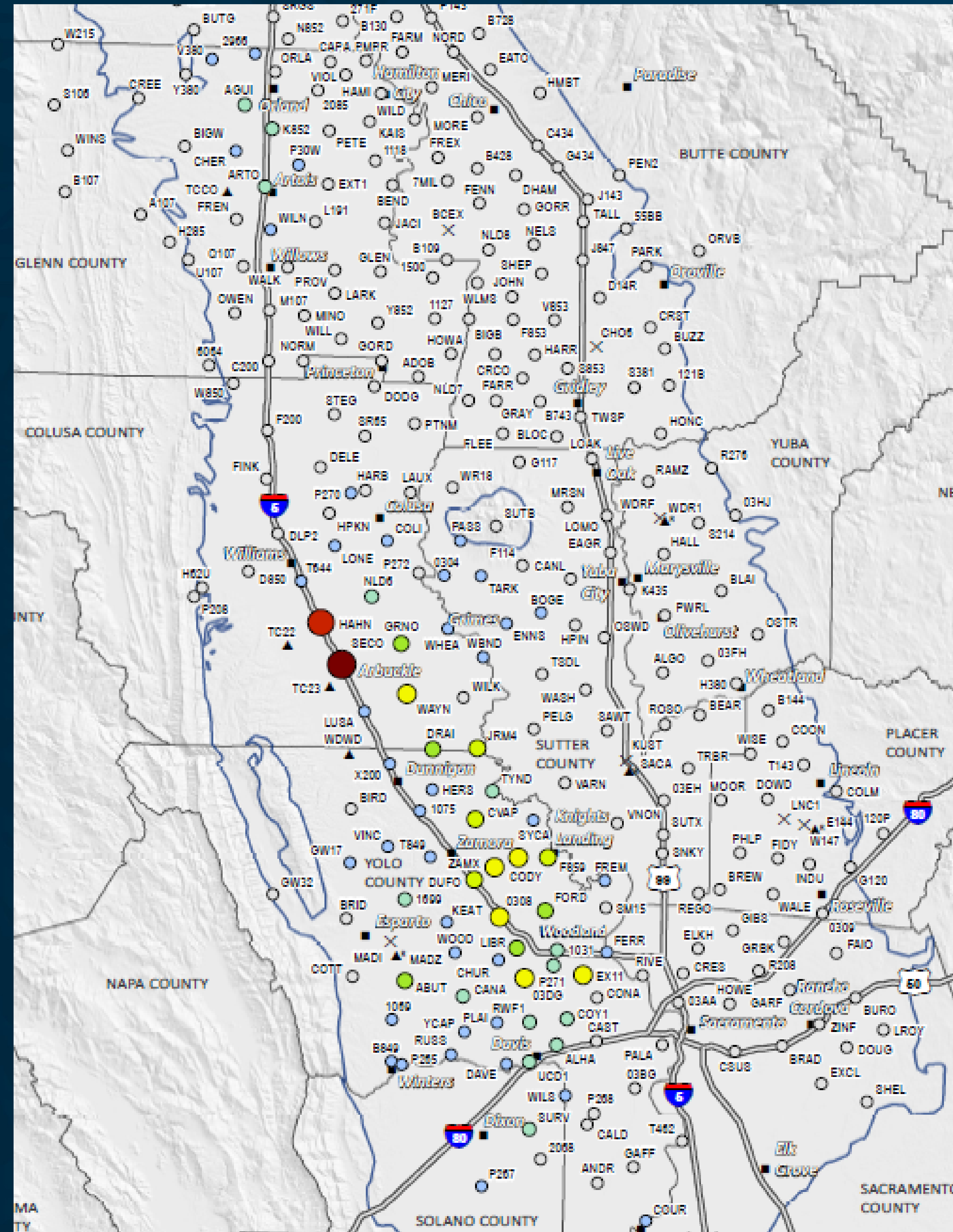
- The Arbuckle area experienced the most subsidence with a maximum change of -2.14 feet.



# Key Findings

## Yolo County

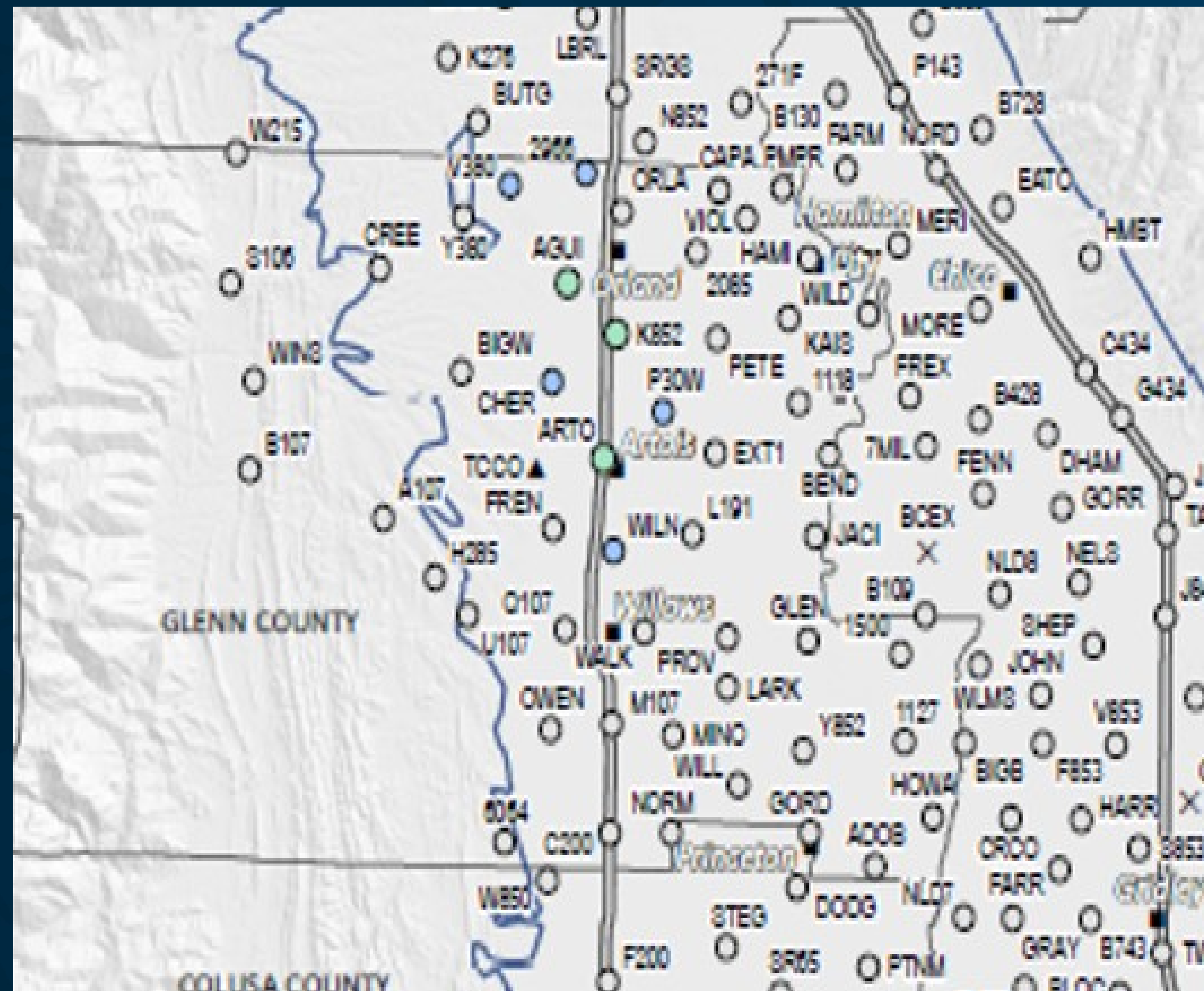
- Exhibits the largest spatial extent of subsidence that range from -0.3 to -1.1 feet at 31 monuments.



# Key Findings

Glenn County

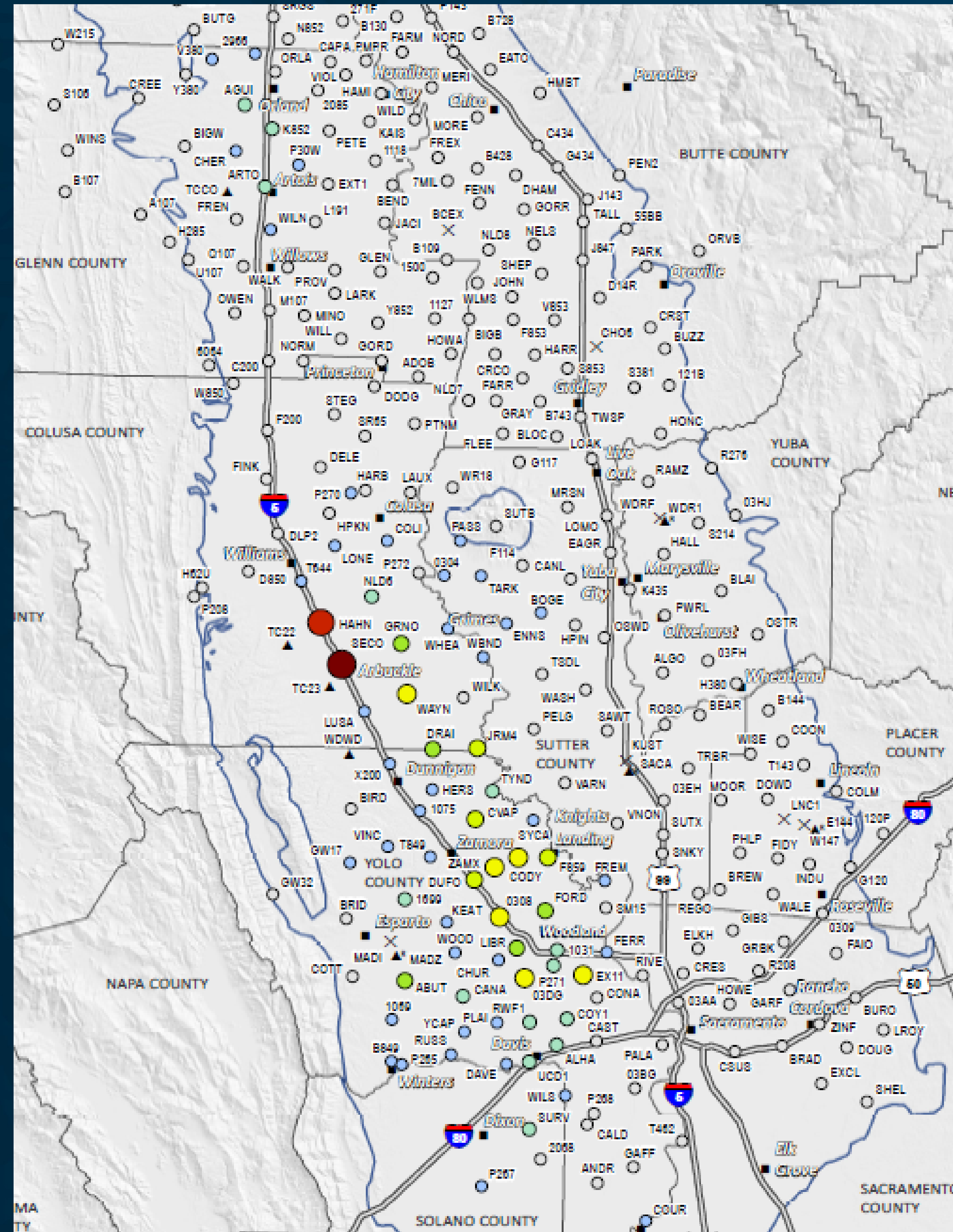
- Three monuments showed subsidence ranging from -0.44 to -0.59 feet.



# Key Findings

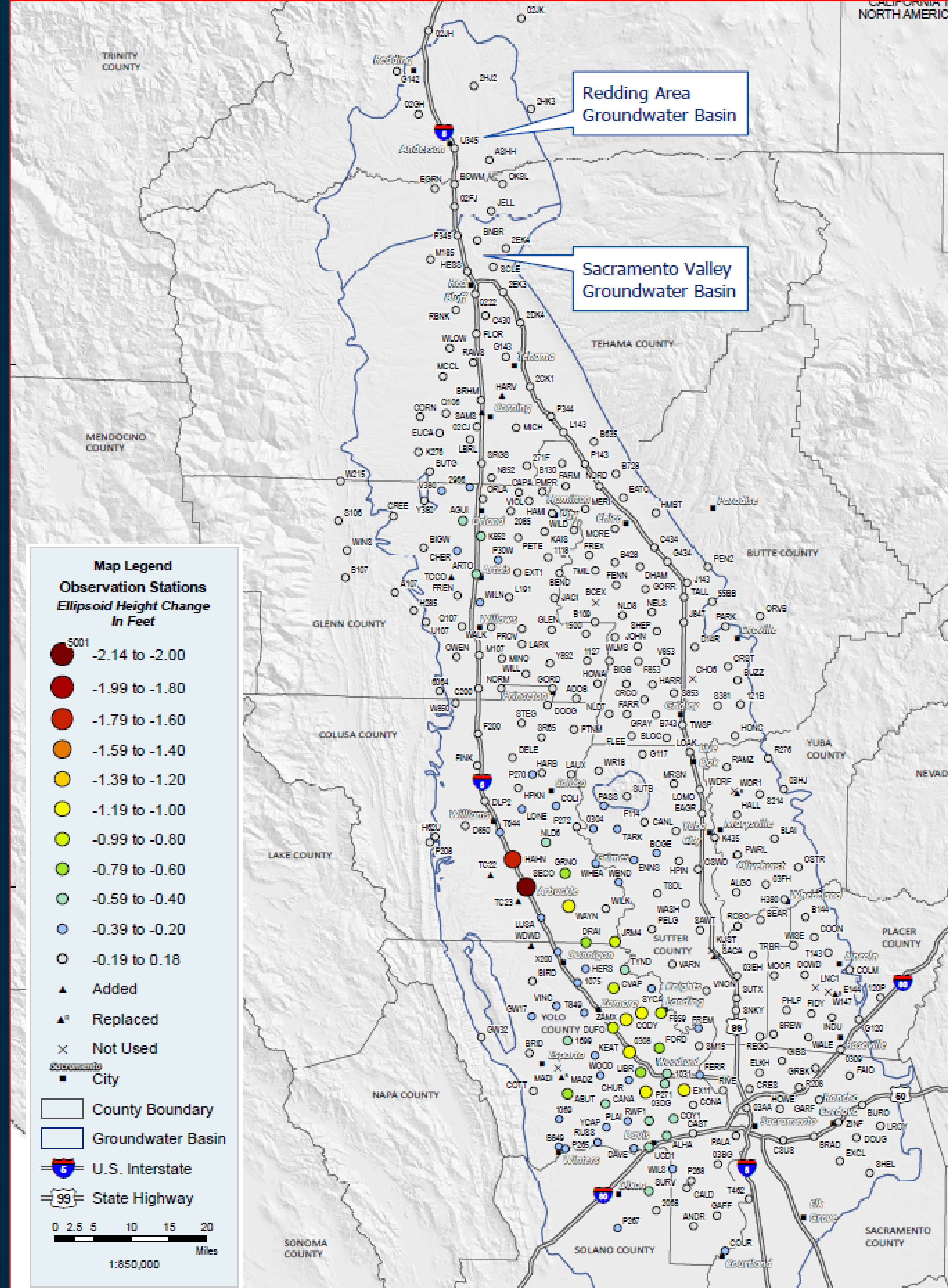
## Sutter County

- Five monuments showed -0.20 to -0.36 feet of subsidence.



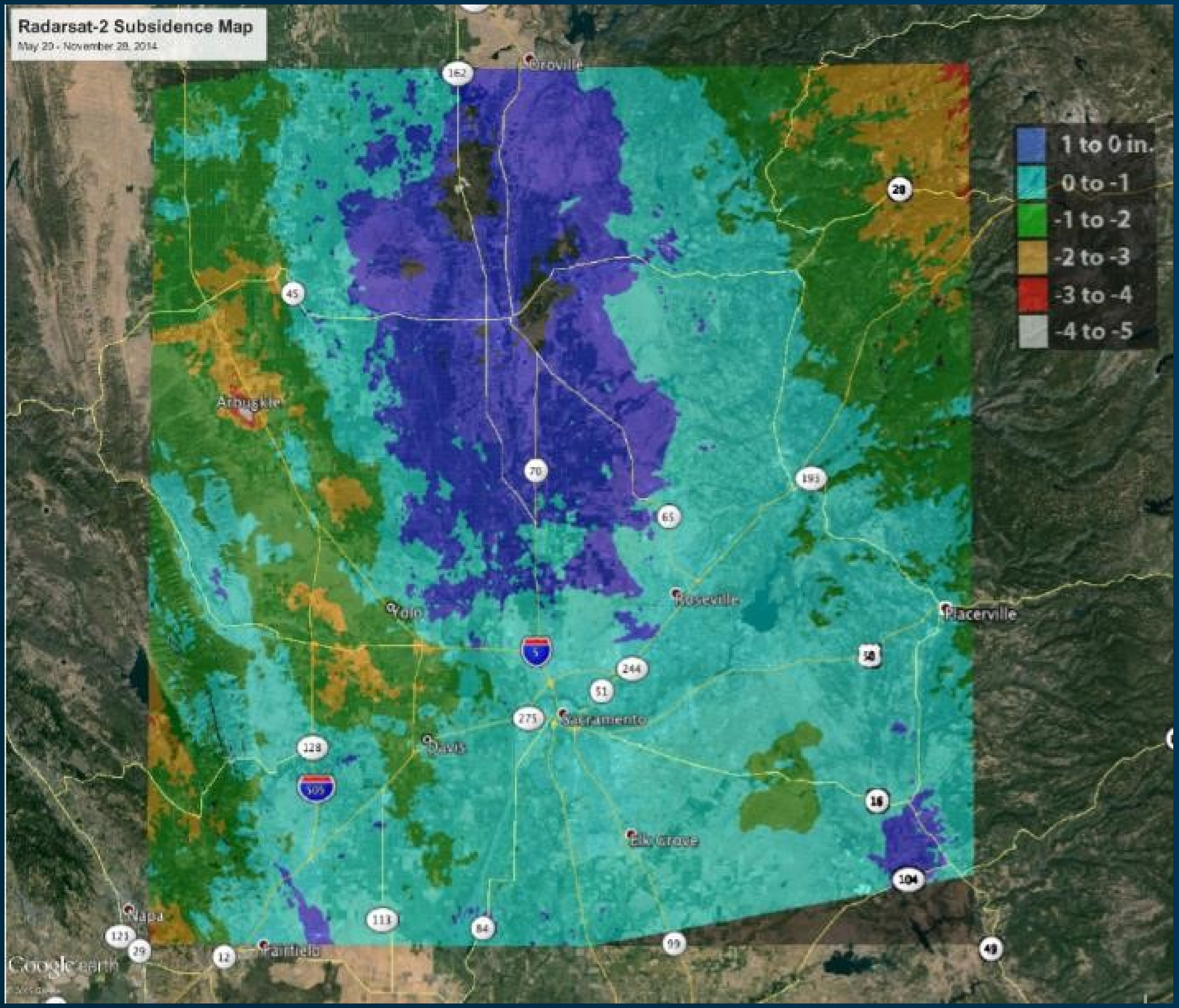
# Key Findings

- The remainder of the Sacramento Valley showed little to no statistically significant land subsidence.



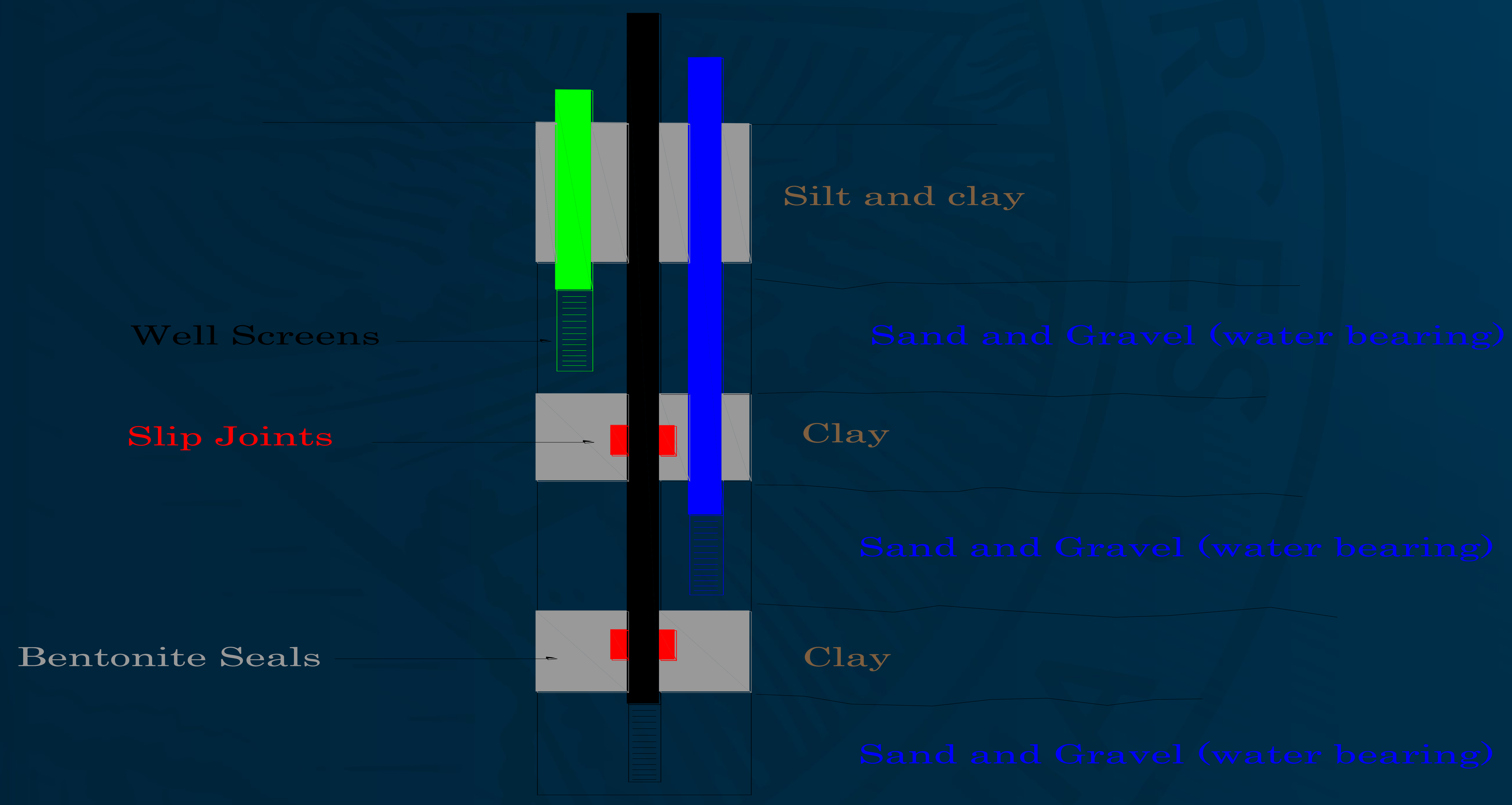
# Key Findings

- The GPS survey results are consistent with the limited InSAR data.
- However, further investigation and comparison are needed.



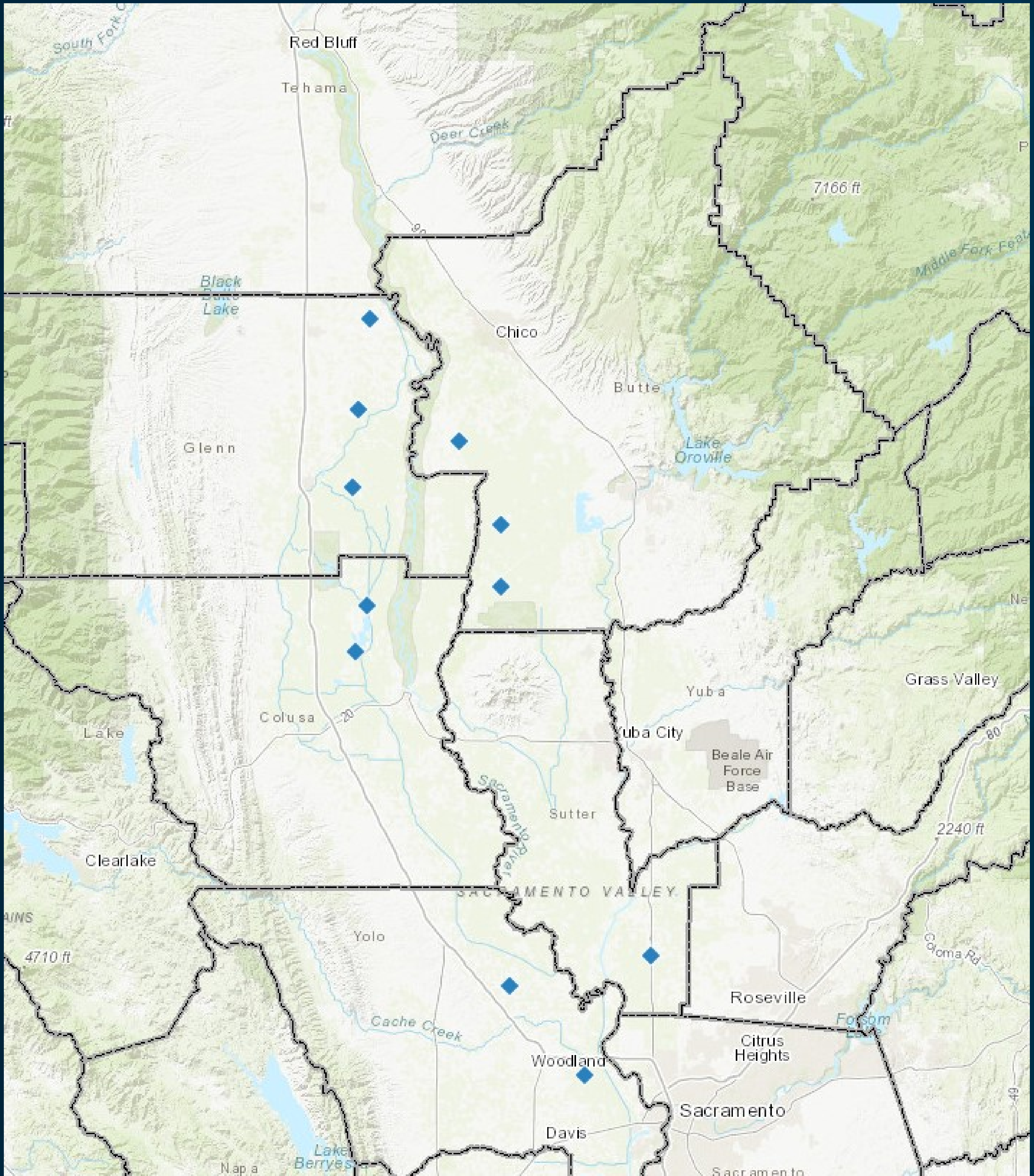
# Extensometer

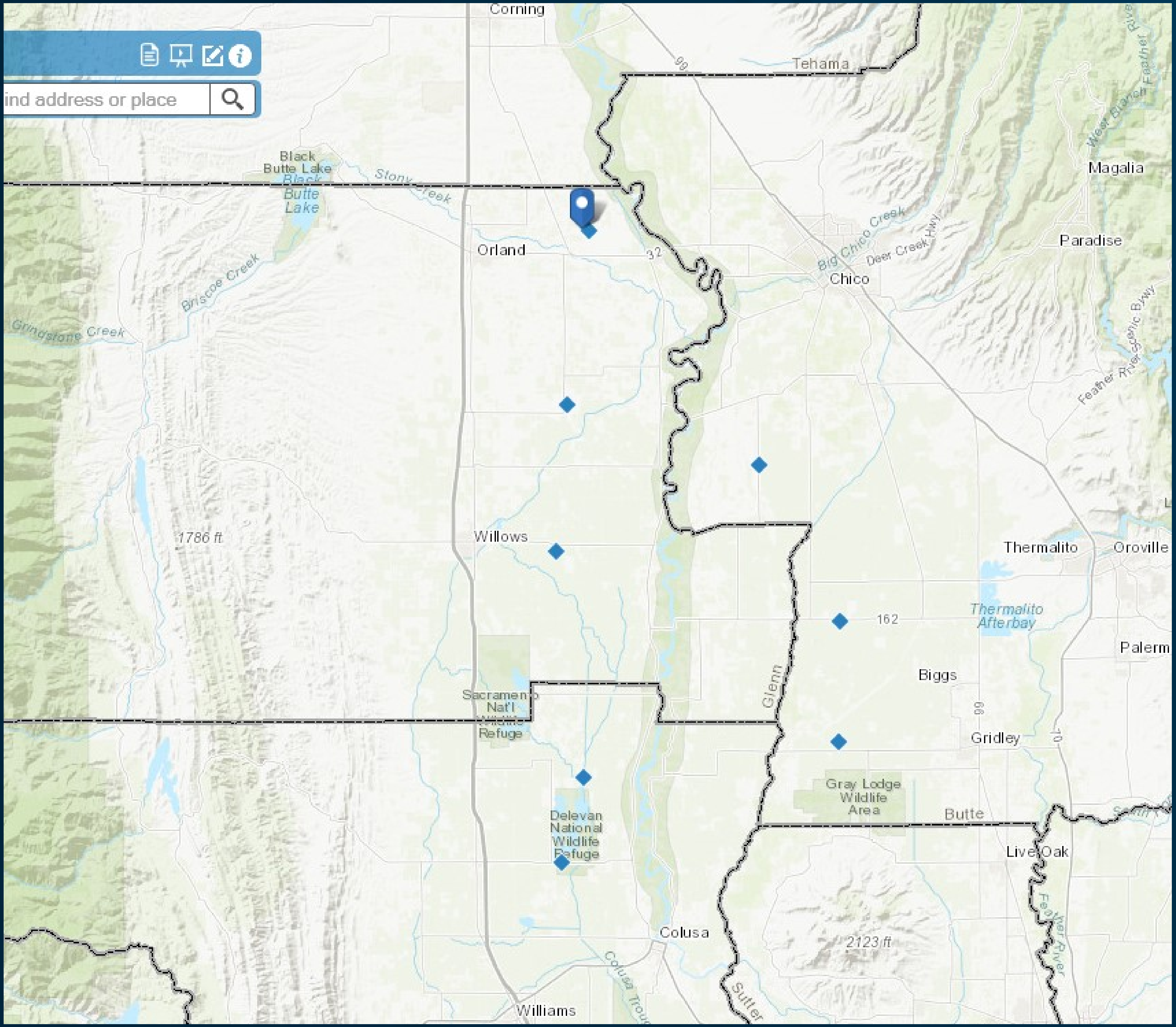
# Extensometer



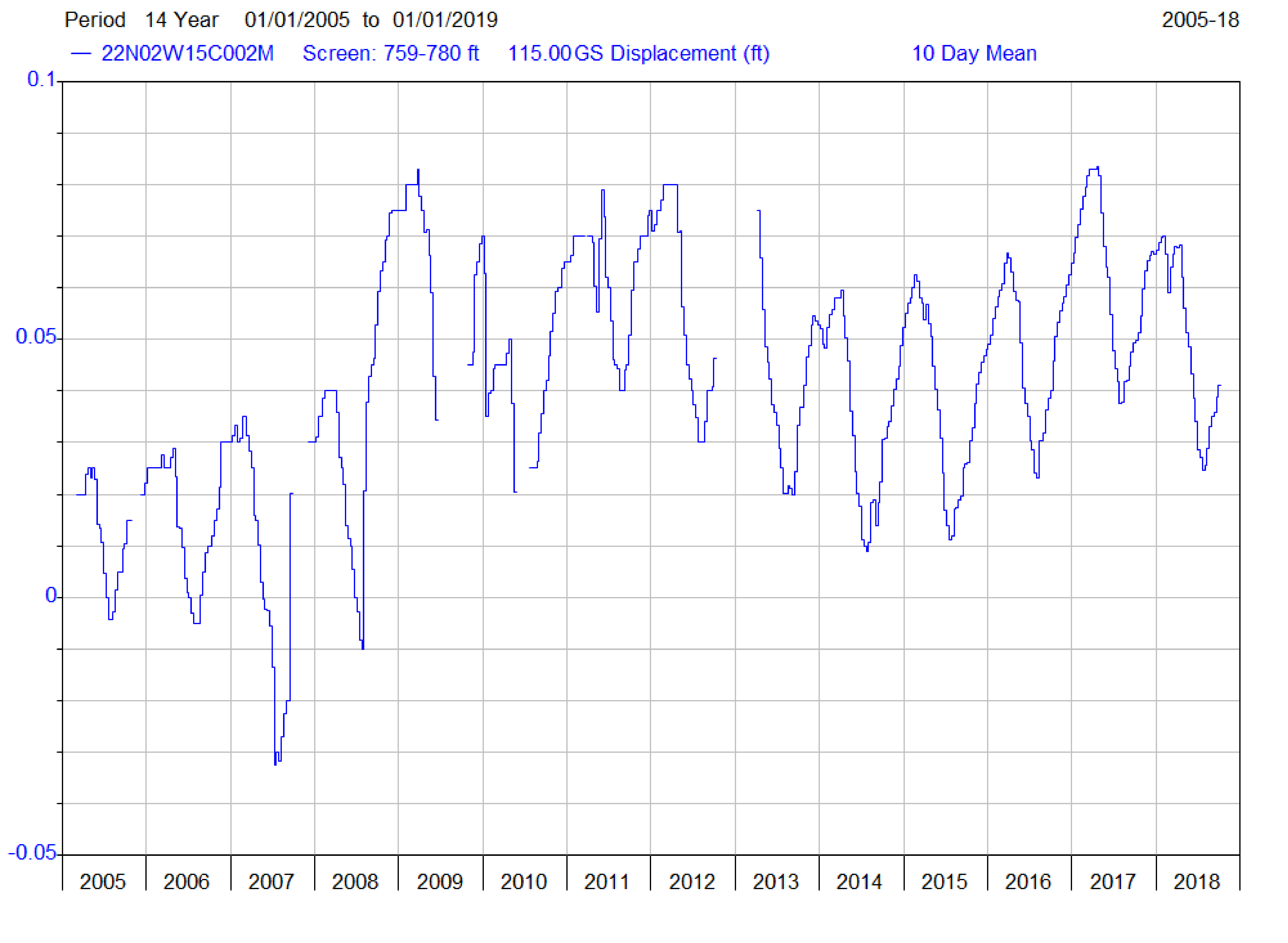
# Extensometer

# Extensometer Locations

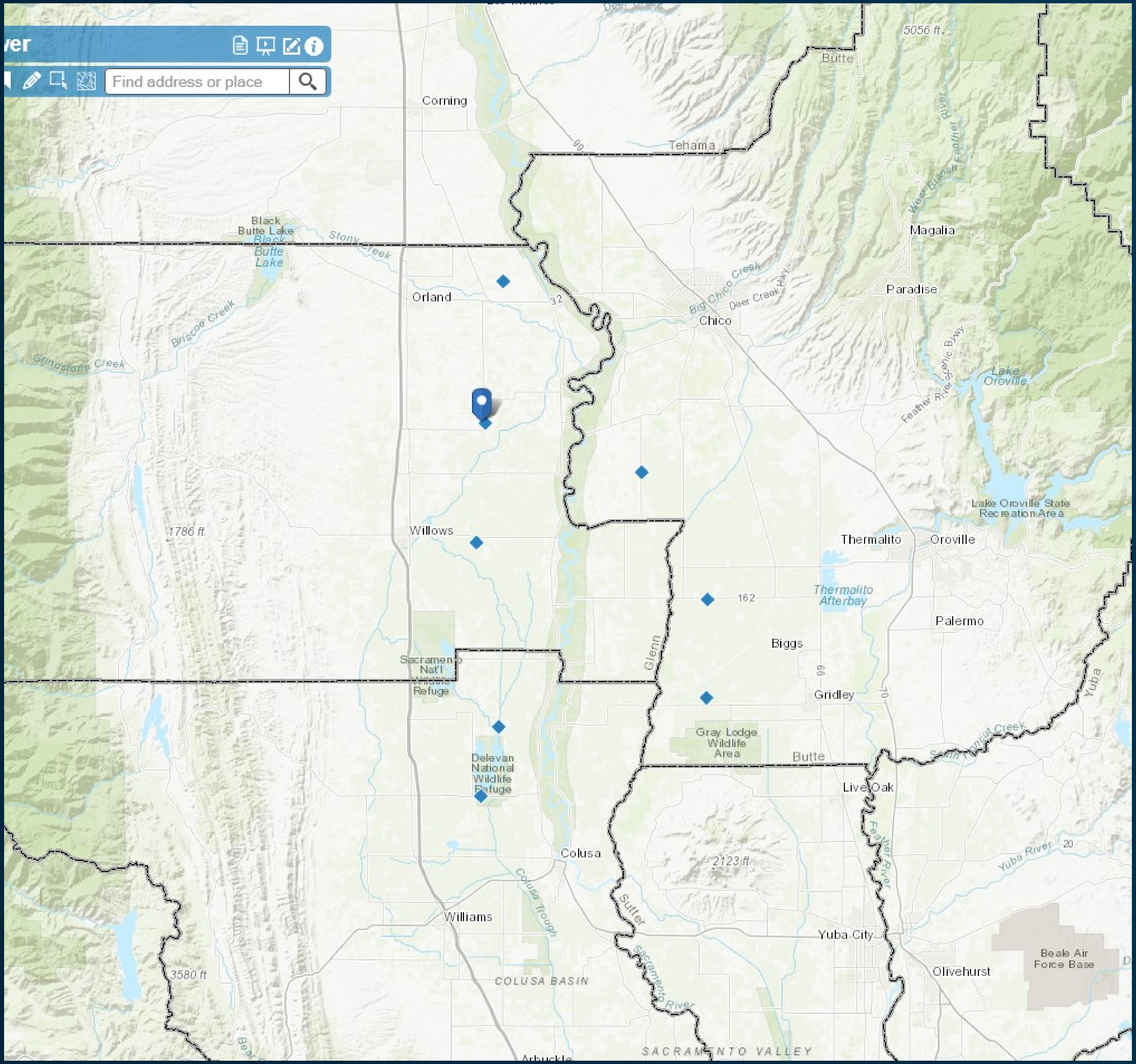




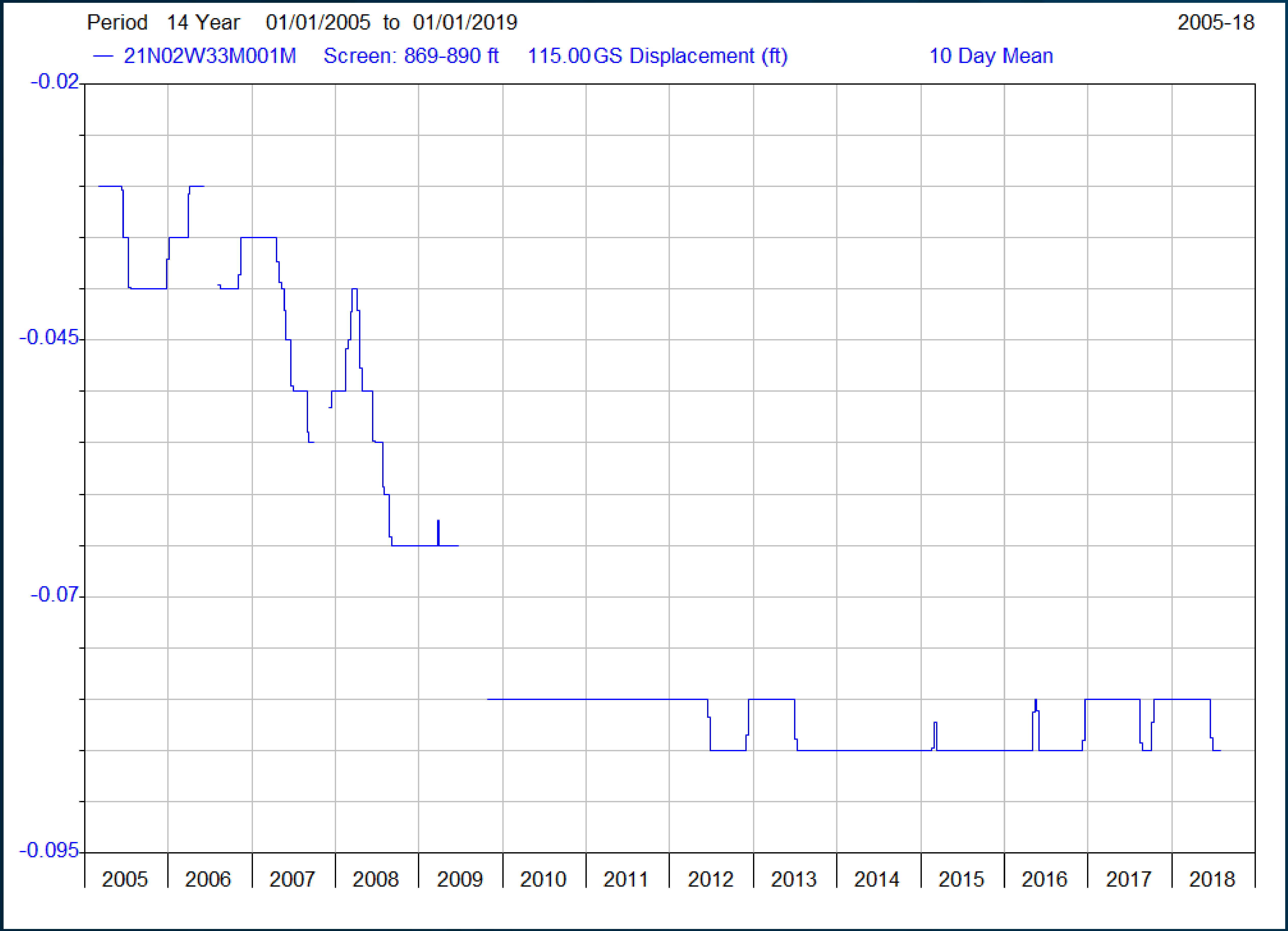
ind address or place
Corning
Tehama
99
Black Butte Lake
Black Butte Lake
Stony Creek
Orland
32
Chico
Big Chico Creek
Deer Creek Hwy
Magalia
Paradise
West Branch Feather River
Briscoe Creek
Grindstone Creek
Feather River Scenic Byway
1786 ft
Willows
Thermalito
Oroville
162
Thermalito Afterbay
Palerm
Biggs
Glenn
Sacramento Nat'l Wildlife Refuge
99
Gridley
70
Gray Lodge Wildlife Area
Butte
Delevan National Wildlife Refuge
Live Oak
Feather River
Colusa
2123 ft
Colusa Trough
Sutter
Williams



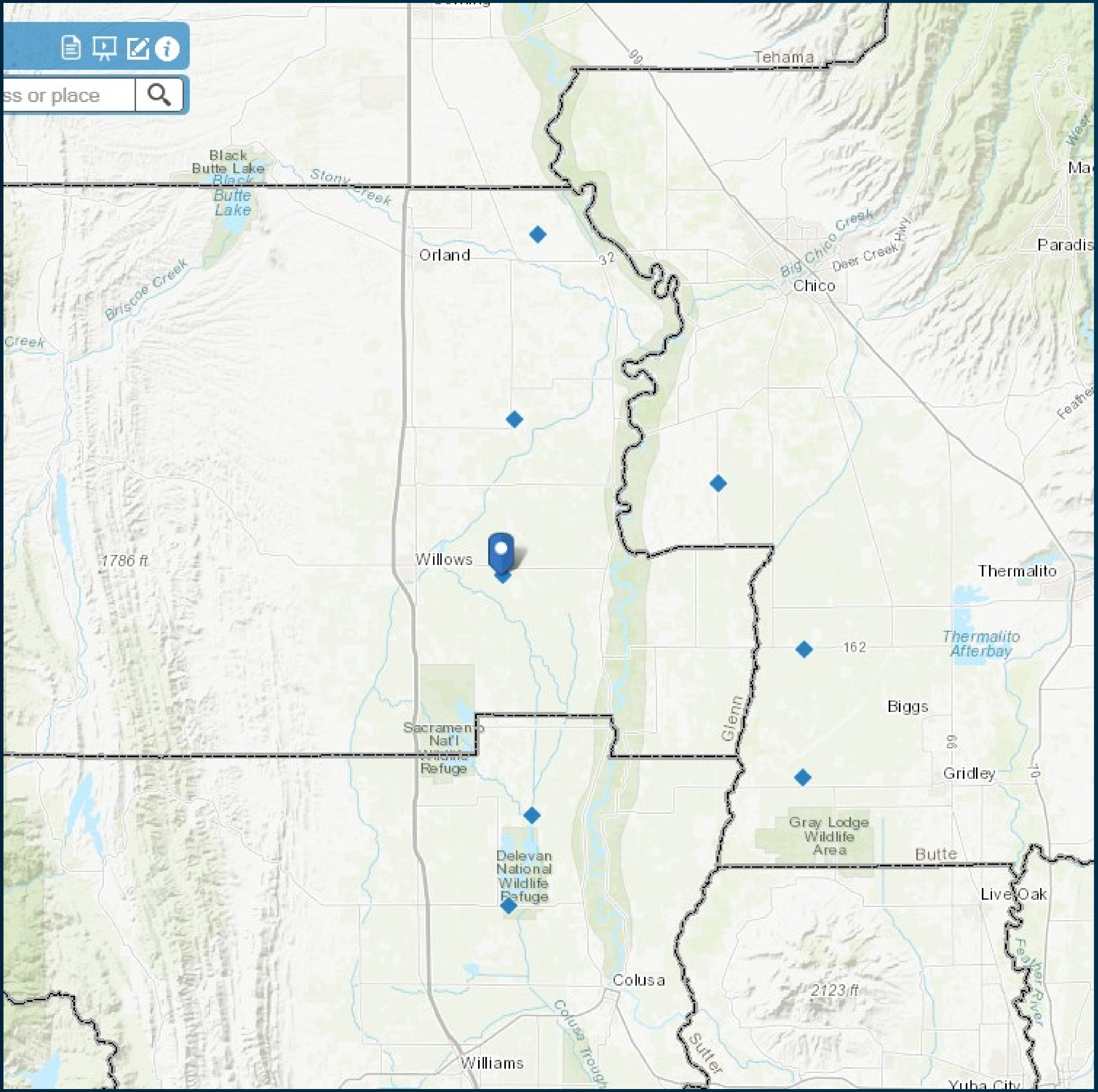
Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 22N02W15C002M Screen: 759-780 ft 115.00GS Displacement (ft) 10 Day Mean
0.1
0.05
0
-0.05
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

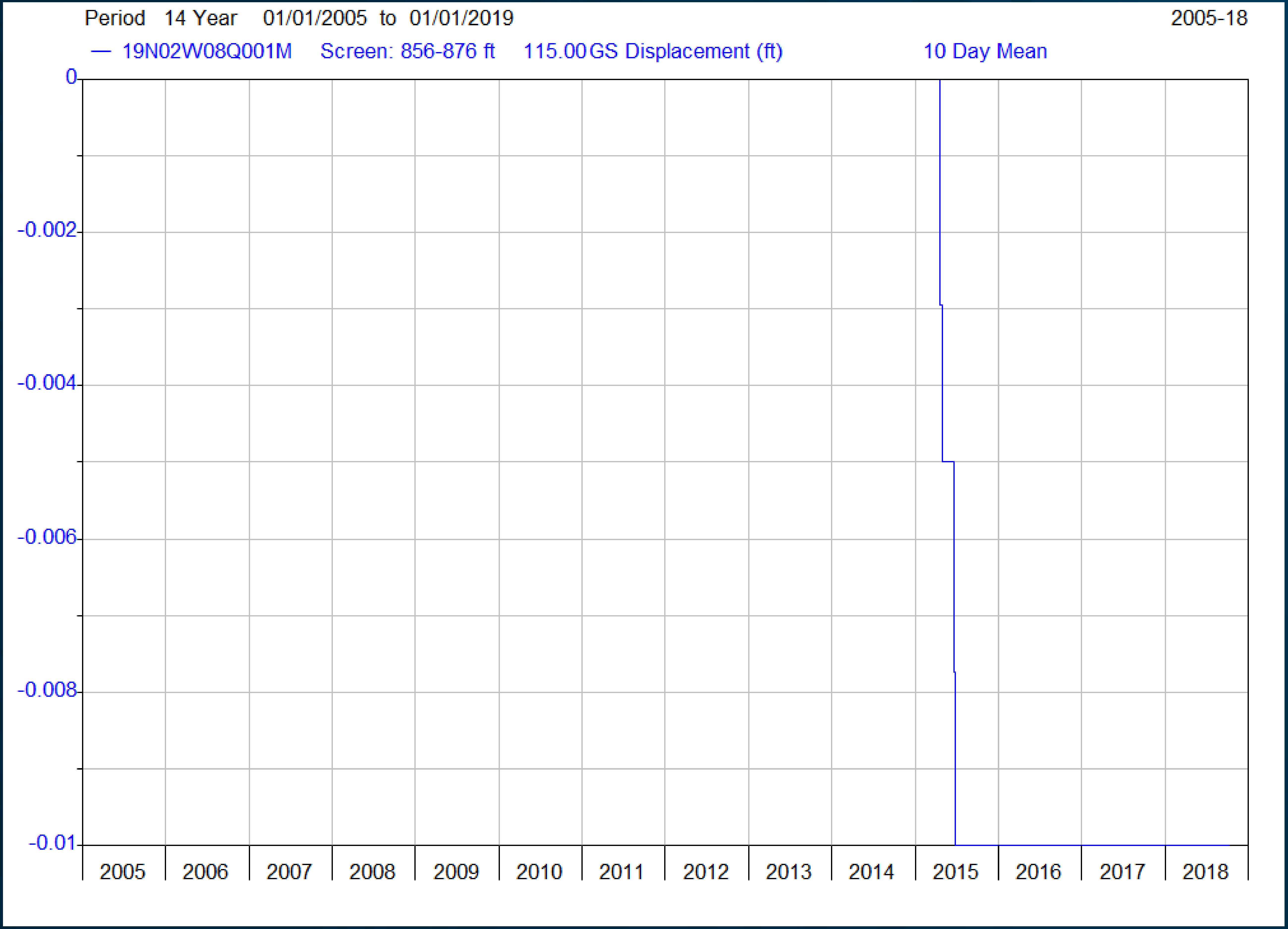


Find address or place
Corning
Tehama
Butte
5056 ft.
Black Butte Lake
Stony Creek
Orland
Chico
Magalia
Paradise
Big Chico Creek
Briscoe Creek
Grindstone Creek
Lake Oroville
Lake Oroville State Recreation Area
Willows
1786 ft
Thermalito
Oroville
Thermalito Afterbay
Palermo
Biggs
Glenn
Sacramento Nat'l Wildlife Refuge
Gridley
Gray Lodge Wildlife Area
Butte
Delevan National Wildlife Refuge
Live Oak
Colusa
2123 ft
Yuba River
Williams
Yuba City
Sutter
Colusa Trough
Beale Air Force Base
Olivehurst
3580 ft
COLUSA BASIN
SACRAMENTO VALLEY
Sacramento River
Feather River
Arbuckle

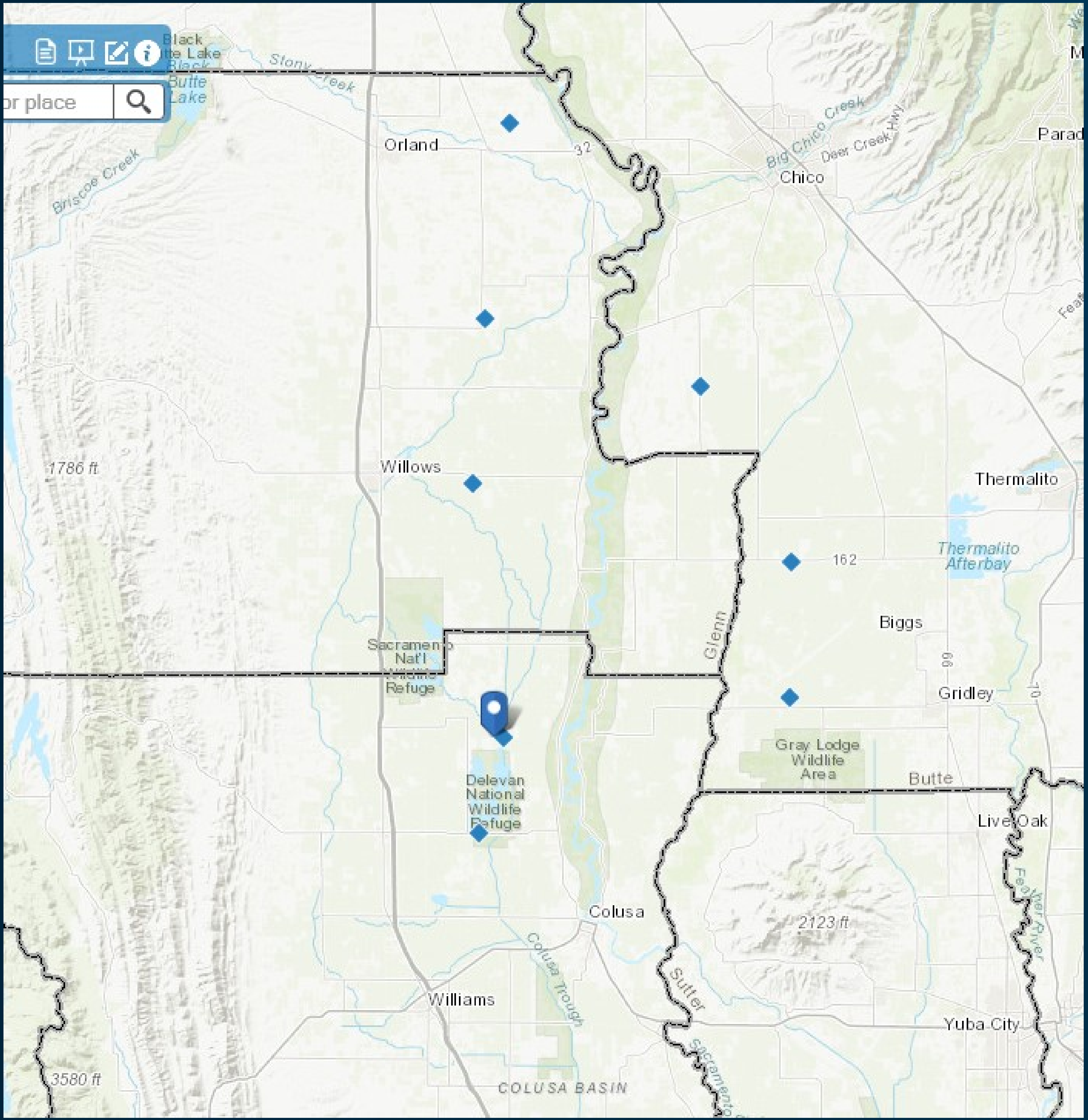


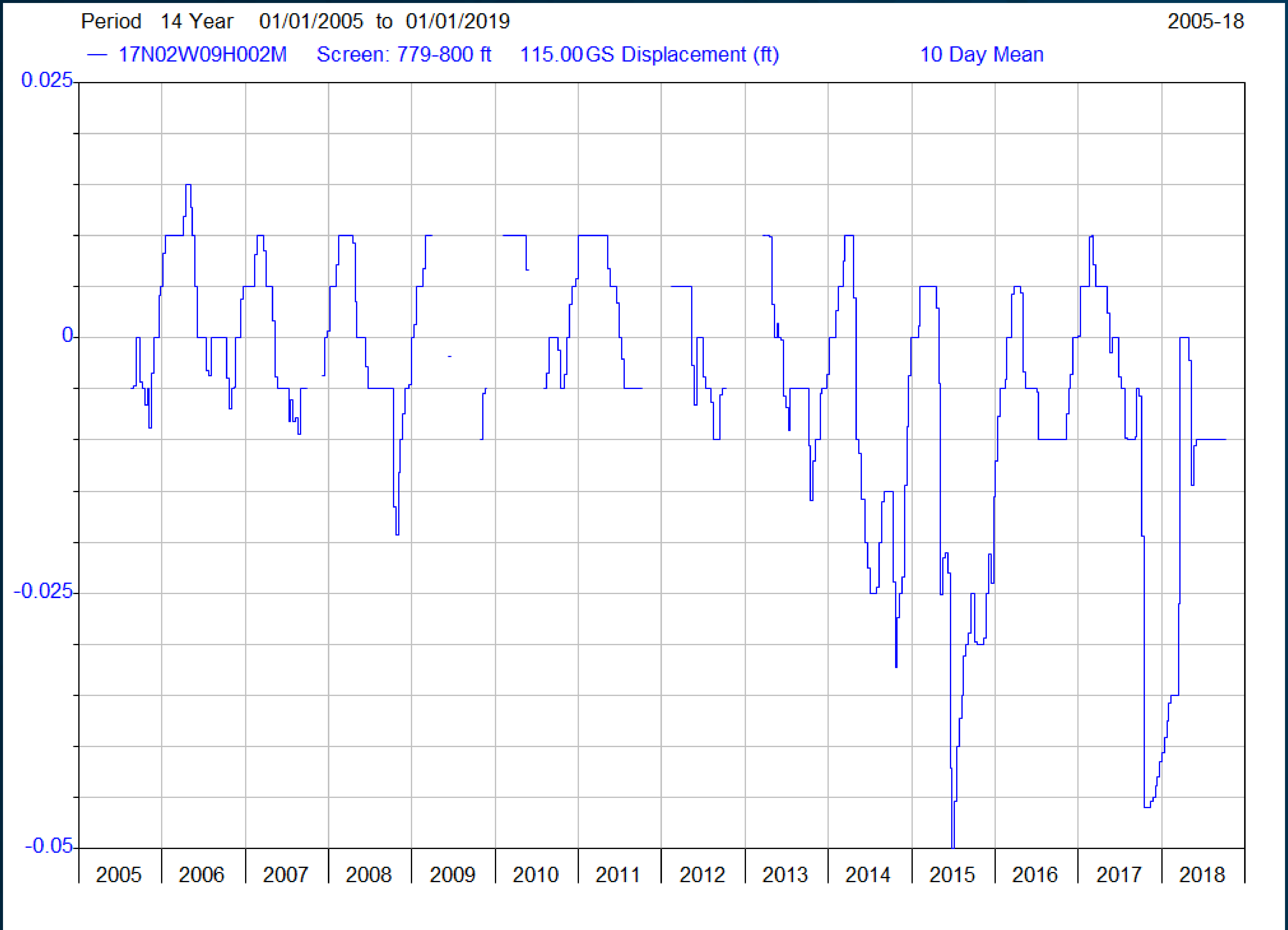
Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 21N02W33M001M Screen: 869-890 ft 115.00 GS Displacement (ft) 10 Day Mean
-0.02
-0.045
-0.07
-0.095
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018


ss or place
Tehama
Black Butte Lake
Black Butte Lake
Stony Creek
Orland
Briscoe Creek
Creek
Big Chico Creek
Deer Creek Hwy
Chico
Paradis
Ma
Willows
1786 ft
Thermalito
Thermalito Afterbay
162
Biggs
Glenn
Sacramento Nat'l Wildlife Refuge
Gridley
Gray Lodge Wildlife Area
Butte
Live Oak
Delevan National Wildlife Refuge
Colusa
2123 ft
Colusa Trough
Sutter
Williams
Yuba City
99
32
70

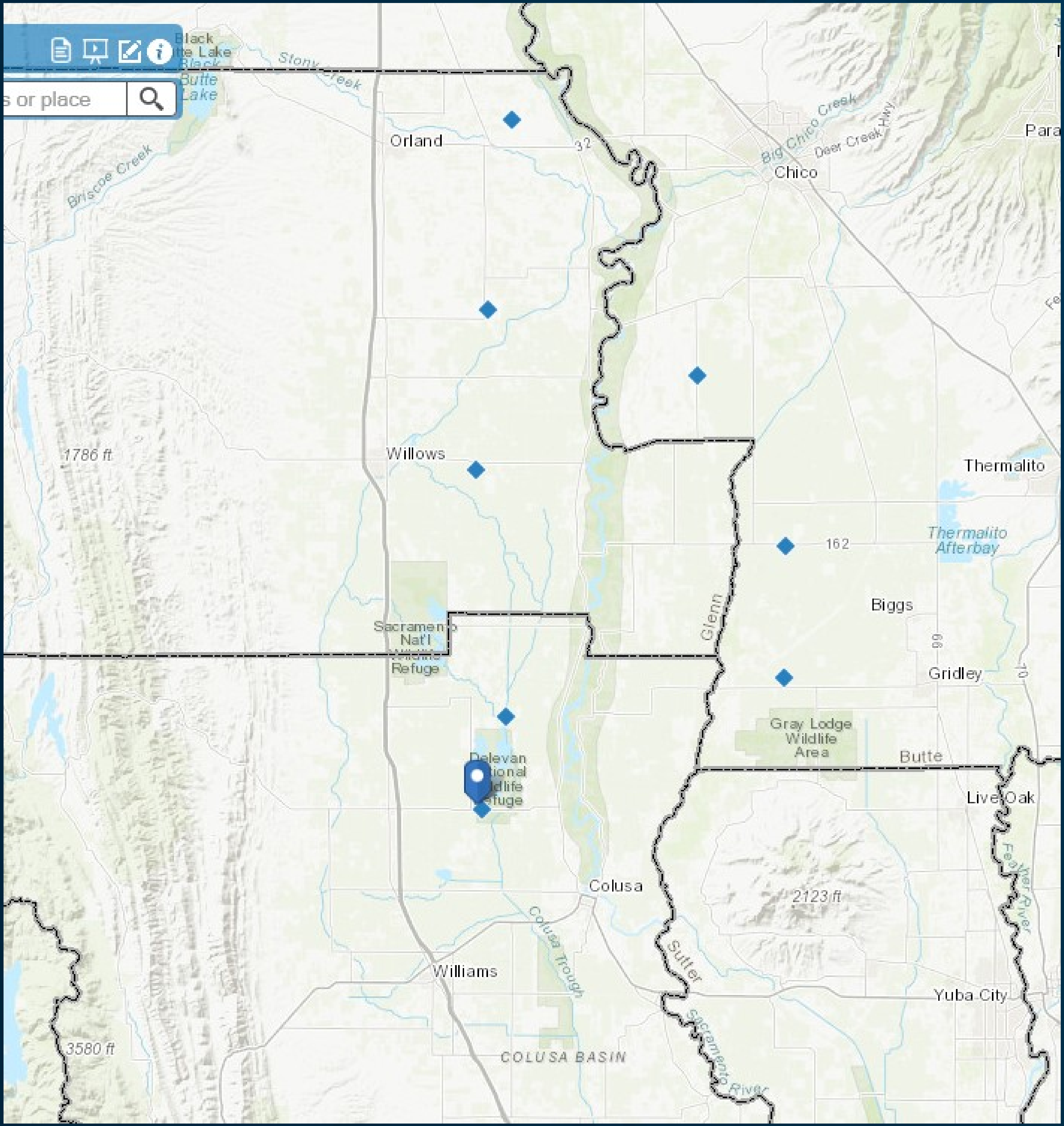


Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 19N02W08Q001M Screen: 856-876 ft 115.00 GS Displacement (ft) 10 Day Mean
0
-0.002
-0.004
-0.006
-0.008
-0.01
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

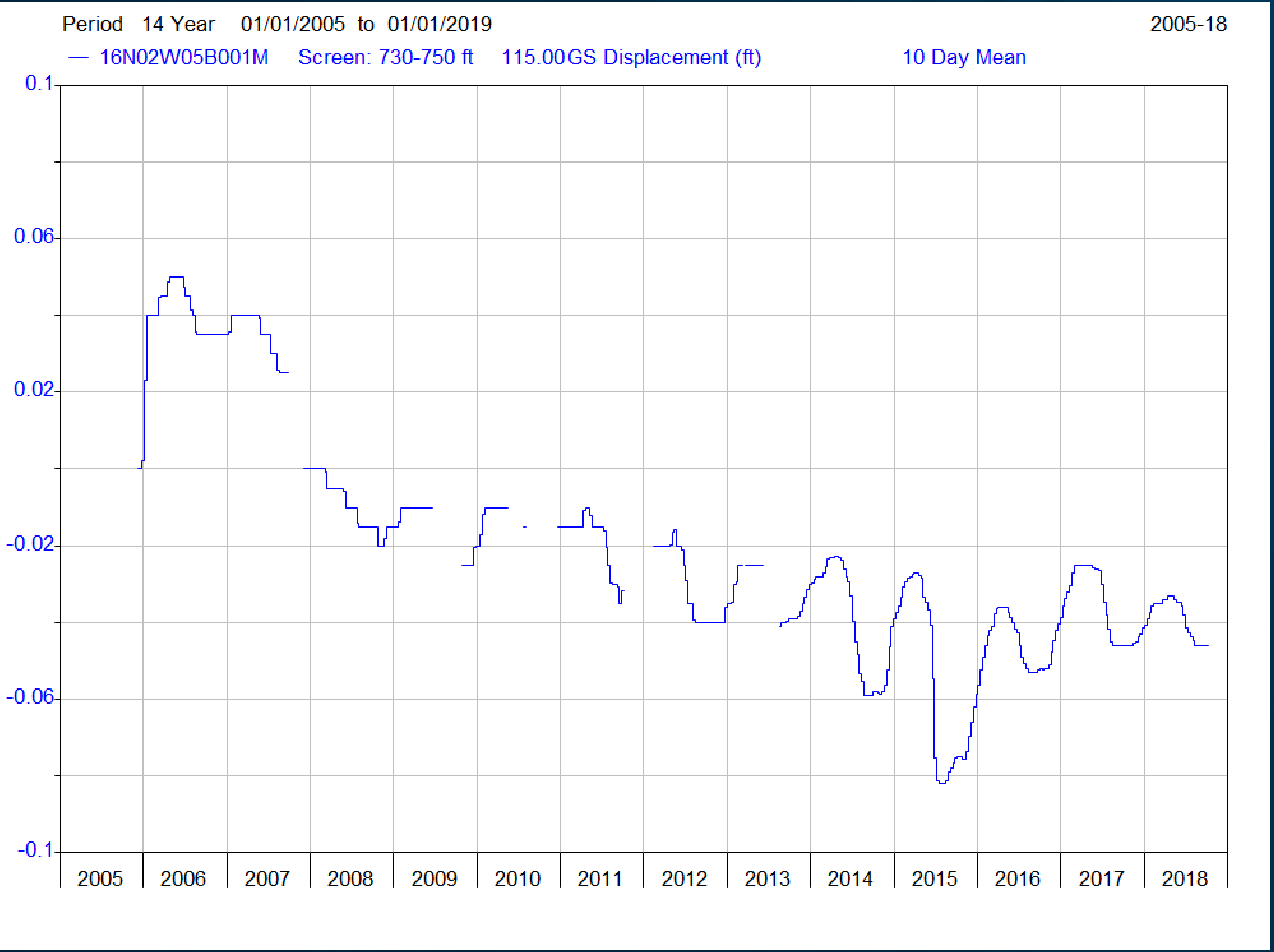

or place
Black
tte Lake
Black
Butte
Lake
Stony Creek
Briscoe Creek
Orland
32
Big Chico Creek
Deer Creek Hwy
Chico
Parad
1786 ft
Willows
Thermalito
Thermalito
Afterbay
162
Biggs
Glenn
Sacramento
Nat'l
Wildlife
Refuge
Gridley
99
70
Gray Lodge
Wildlife
Area
Butte
Delevan
National
Wildlife
Refuge
Live Oak
Feather River
2123 ft
Colusa
Colusa Trough
Sutter
Williams
Yuba City
3580 ft
COLUSA BASIN
Sacramento



Period 14 Year 01/01/2005 to 01/01/2019
2005-18
17N02W09H002M Screen: 779-800 ft 115.00GS Displacement (ft) 10 Day Mean
0.025
0
-0.025
-0.05
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018



s or place
Black Butte Lake
Stony Creek
Briscoe Creek
Orland
32
Chico
Big Chico Creek
Deer Creek Hwy
1786 ft
Willows
Thermalito
162
Thermalito Afterbay
Biggs
Glenn
Sacramento Nat'l Wildlife Refuge
Gridley
99
70
Gray Lodge Wildlife Area
Butte
Delevan National Wildlife Refuge
Live Oak
Colusa
2123 ft
Feather River
Colusa Trough
Sutter
Williams
Yuba City
Sacramento River
3580 ft
COLUSA BASIN



Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 16N02W05B001M Screen: 730-750 ft 115.00GS Displacement (ft) 10 Day Mean
0.1
0.06
0.02
-0.02
-0.06
-0.1
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 21N02W33M001M Screen: 869-890 ft 115.00GS Displacement (ft)
10 Day Mean
-0.02
-0.045
-0.07
-0.095
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 22N02W15C002M Screen: 759-780 ft 115.00GS Displacement (ft)
10 Day Mean
0.1
0.05
0
-0.05
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 19N02W08Q001M Screen: 856-876 ft 115.00GS Displacement (ft)
10 Day Mean
0
-0.002
-0.004
-0.006
-0.008
-0.01
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 17N02W09H002M Screen: 779-800 ft 115.00GS Displacement (ft)
10 Day Mean
0.025
0
-0.025
-0.05
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Period 14 Year 01/01/2005 to 01/01/2019
2005-18
— 16N02W05B001M Screen: 730-750 ft 115.00GS Displacement (ft)
10 Day Mean
0.1
0.06
0.02
-0.02
-0.06
-0.1
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Corning
Orland
Willows
Colusa
Williams
Magalia
Stony Creek
Briscoe Creek
Grindstone Creek
Sacramento Nat'l Wildlife Refuge
Delevan National Wildlife Refuge
Thermalito Afterbay
Glenn
Colusa Trough
Sutter
99
32
162

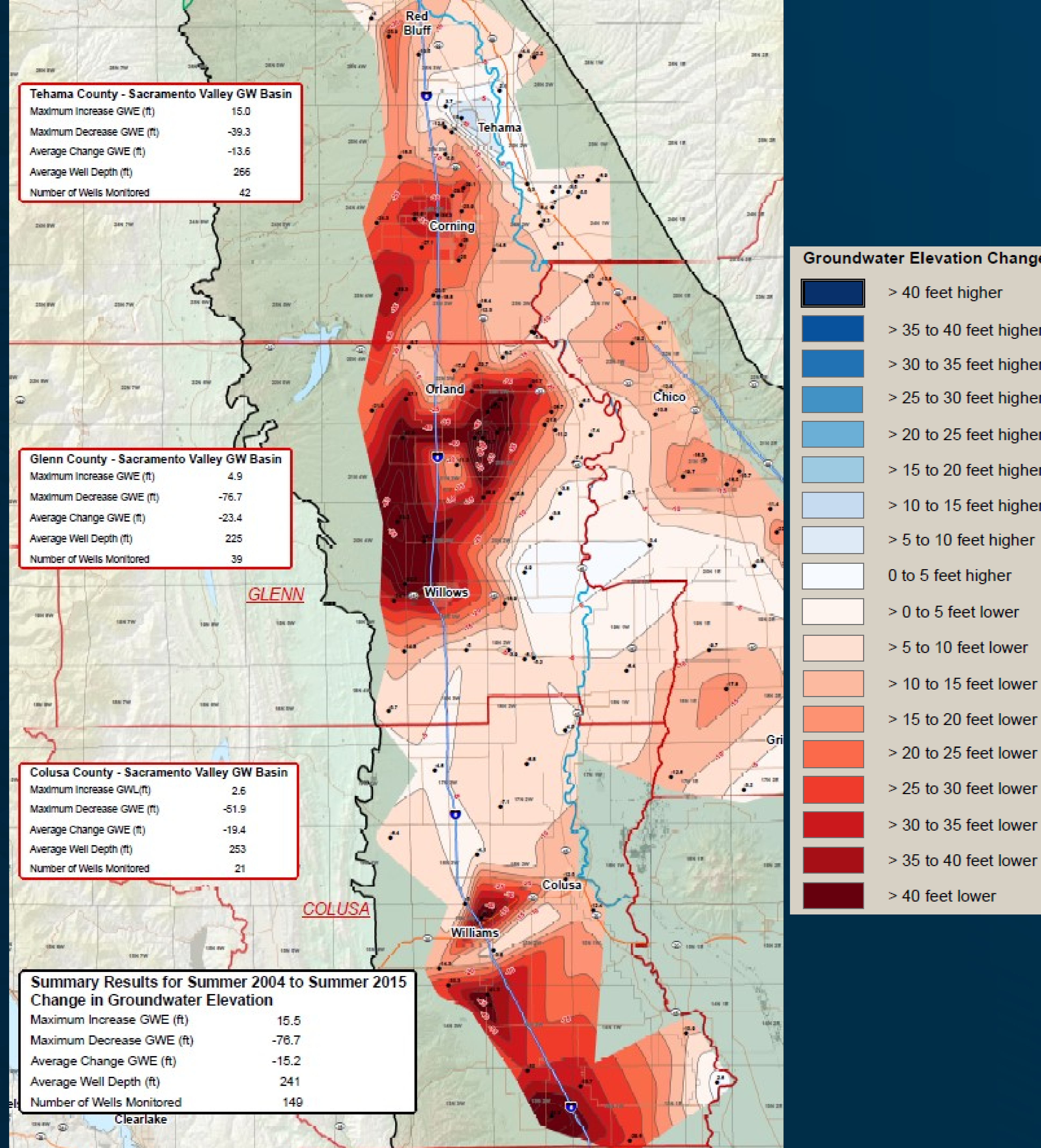
# Groundwater Conditions Related to Subsidence

- Severe drought in 2012-2016 caused historic lows in many wells in the Sacramento Valley.
- Maximum decreases were in Glenn and Colusa counties showing declines of 58 and 43 feet, respectively.
- The subsidence observed is likely caused by these groundwater level declines.

# Groundwater Conditions Related to Subsidence

- 2004-2015: Groundwater Elevation Change Map

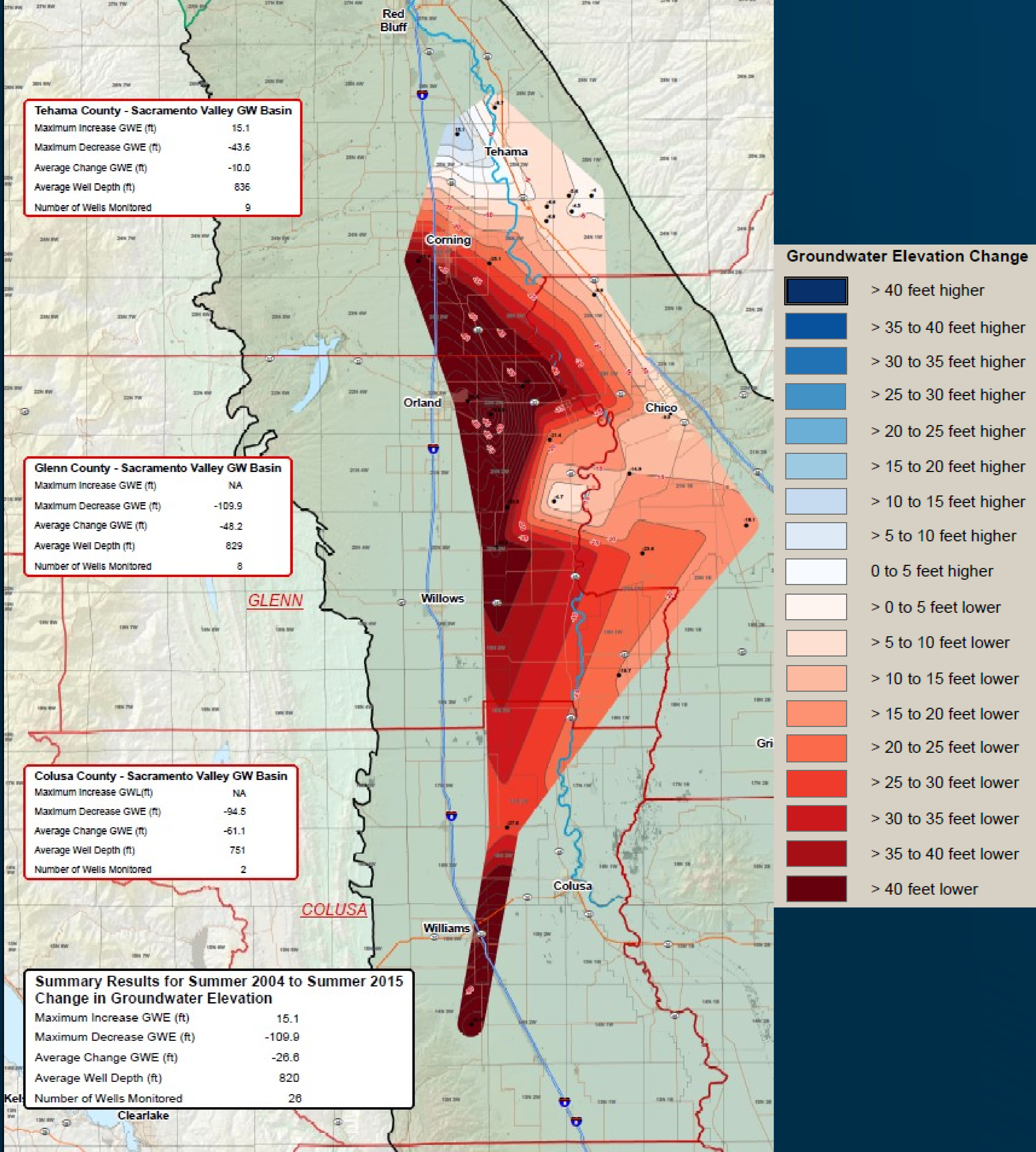
  Summer
  150-400 ft deep wells



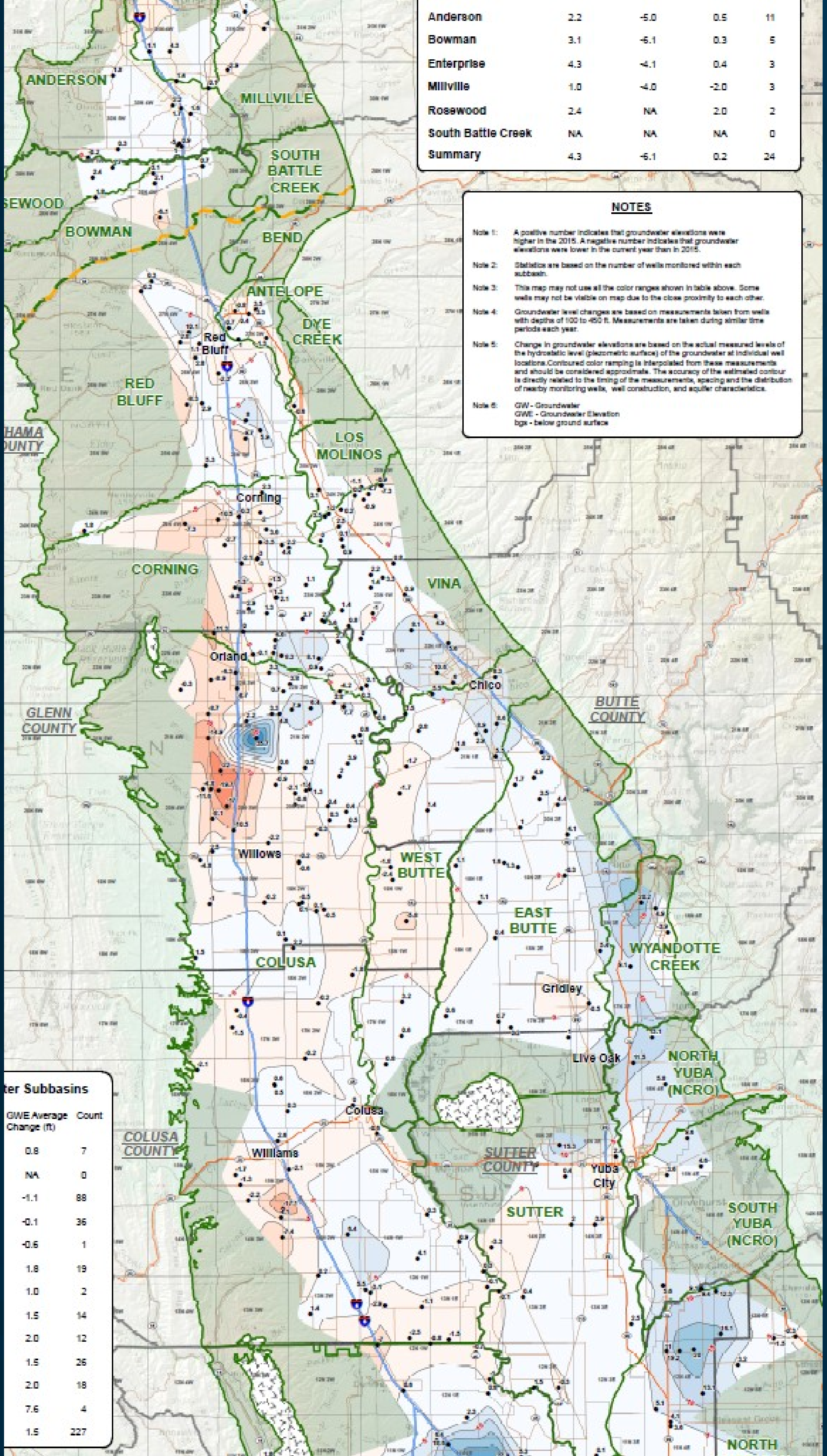
# Groundwater Conditions Related to Subsidence

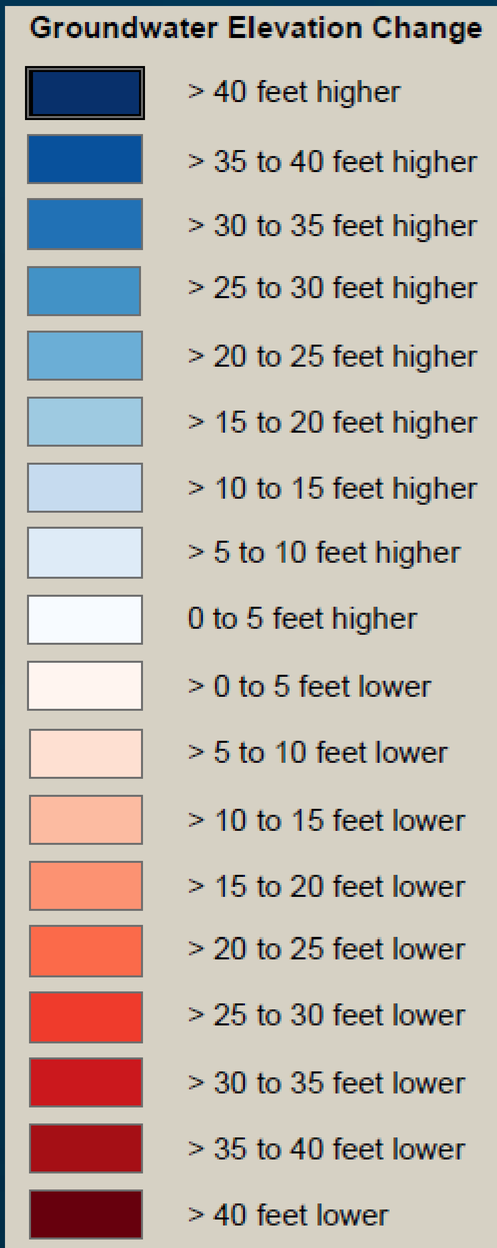
- 2004-2015: Groundwater Elevation Change Map

  Summer
  deep wells > 600 ft.



# Groundwater Conditions Since 2015



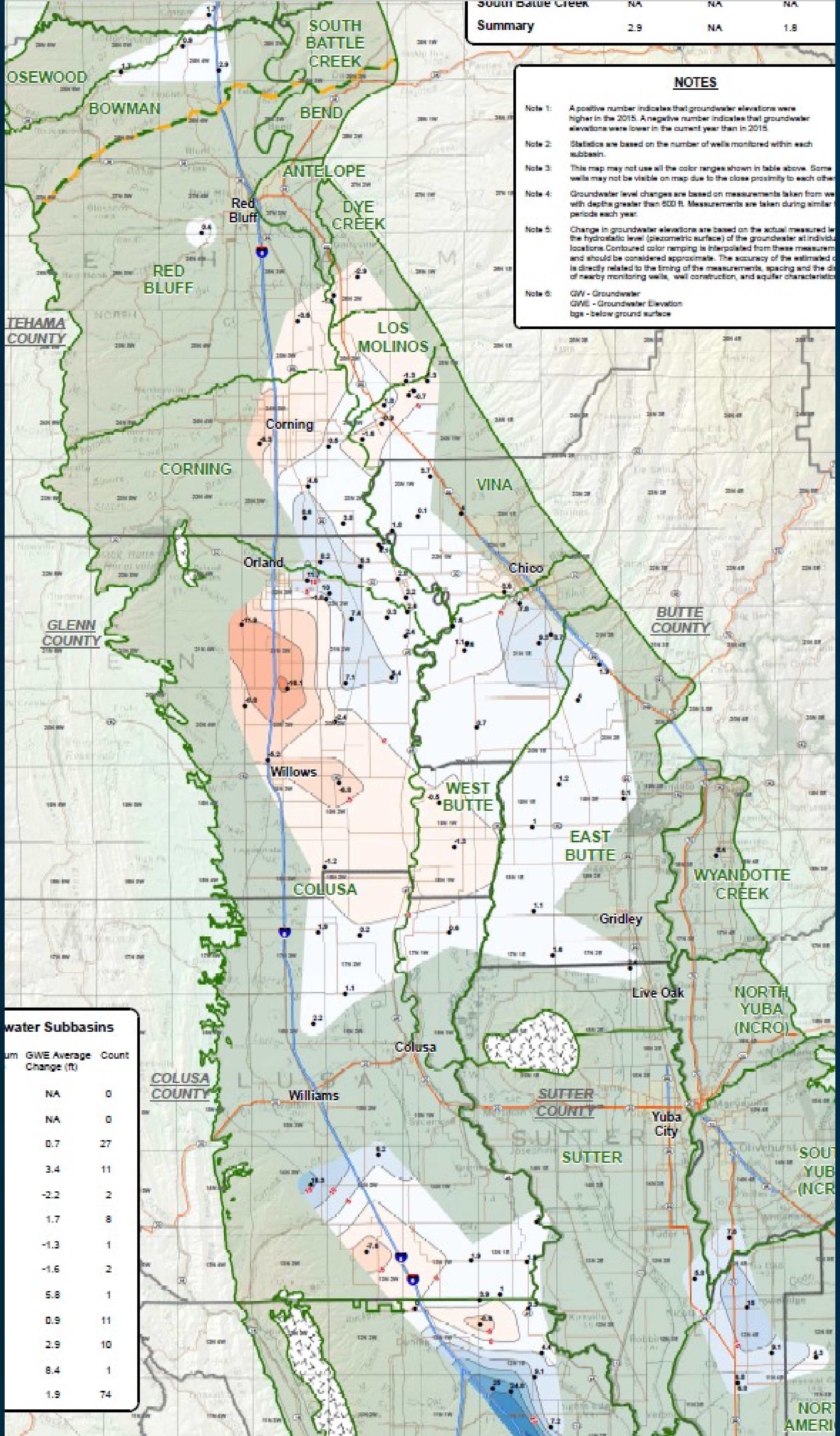

- 2015-2018: Groundwater Elevation Change Map

  Spring
  150-400 ft deep wells

# Groundwater Conditions Since 2015

- 2015-2018: Groundwater Elevation Change Map

Spring
deep wells > 600 ft.




**Groundwater Elevation Change**

- > 40 feet higher
- > 35 to 40 feet higher
- > 30 to 35 feet higher
- > 25 to 30 feet higher
- > 20 to 25 feet higher
- > 15 to 20 feet higher
- > 10 to 15 feet higher
- > 5 to 10 feet higher
- 0 to 5 feet higher
- > 0 to 5 feet lower
- > 5 to 10 feet lower
- > 10 to 15 feet lower
- > 15 to 20 feet lower
- > 20 to 25 feet lower
- > 25 to 30 feet lower
- > 30 to 35 feet lower
- > 35 to 40 feet lower
- > 40 feet lower

# Thank You


# Questions? Comments?