Sustained water loss in California's mountain ranges during harsh drought from 2012 through 2015 inferred from GPS

Donald Argus
Felix Landerer
David Wiese
Hilary Martens
Yuning Fu
Jay Famiglietti
Tom Farr
Brian Thomas
Angelyn Moore
Mike Watkins

Jet Propulsion Labotratory
NASA Earth Surface Interior

Manuscript revised for JGR Solid Earth
October 2017

Donald.F.Argus@jpl.nasa.gov

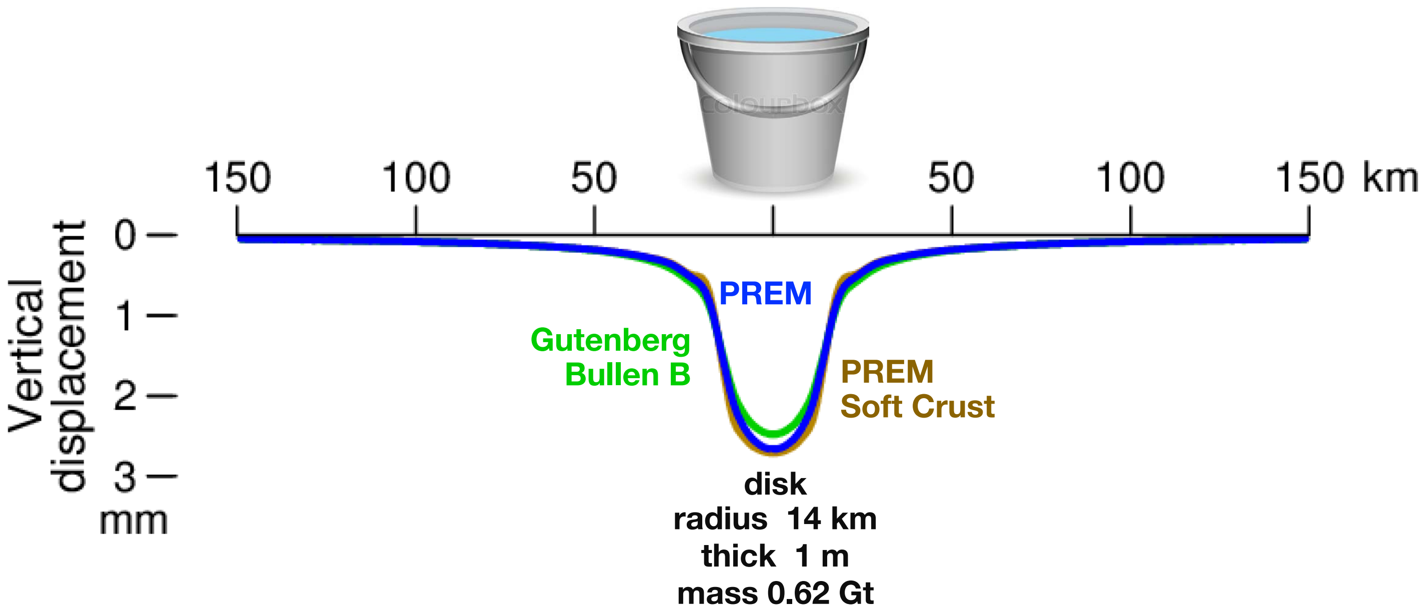
Product

Changes in total water storage
as a function of location across the western U.S.
each month from January 2006 to the Present
inferred from GPS vertical displacements

Part 1

Inversion of
GPS vertical displacements
for water change

Solid Earth's elastic response to a mass load is known



- Solid Earth's elastic response is tight in space.

- Elastic deformation is not sensitive to Earth's rheology.

not for a non-gravitating half space

- The elastic response is calculated for a gravitating, spherical, stratified Earth.

Loading Vs. Aquifer

Elastic response to a Water load

Mountains subside in elastic response to a snow or water load
85% of GPS sites

Porous response to Groundwater change

Aquifers expand as groundwater fills the pores between the silts, sands, and gravels comprising the aquifer
15% of GPS sites

Distinguish porous response on the basis of:

1. Time of maximum height around April
2. Subsiding faster than 2.5 mm/yr
3. Within 10 km of a groundwater well
4. Episodic transients

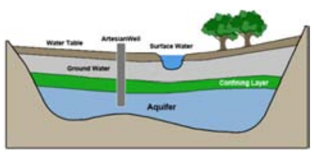
Inversion of GPS vertical displacements for water change

GPS

vertical displacement
each month
relative to Jan 2011.
Uninterrupted by offset
due to
antenna substitution
or earthquake.
JPL, NGL

Omit

GPS sites
affected by
149 Aquifers
and
53 Volcanoes.



Keep
1320 Water elastic

Remove atmosphere

Remove

elastic deformation
produced by
Artificial reservoir
surface water change

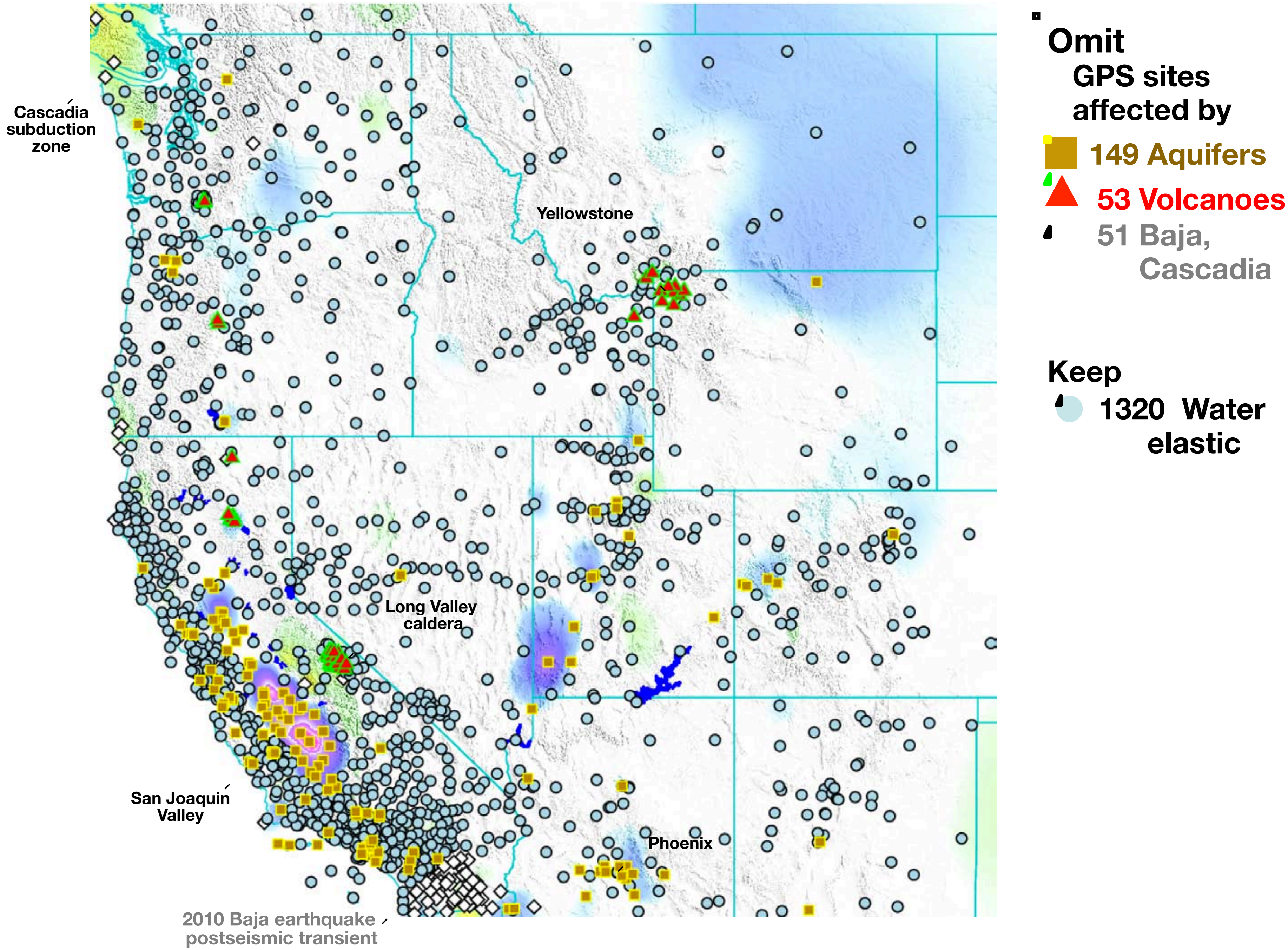
Constrain
Central Valley
groundwater change
CVHM Faunt et al. 2015

Remove postglacial rebound

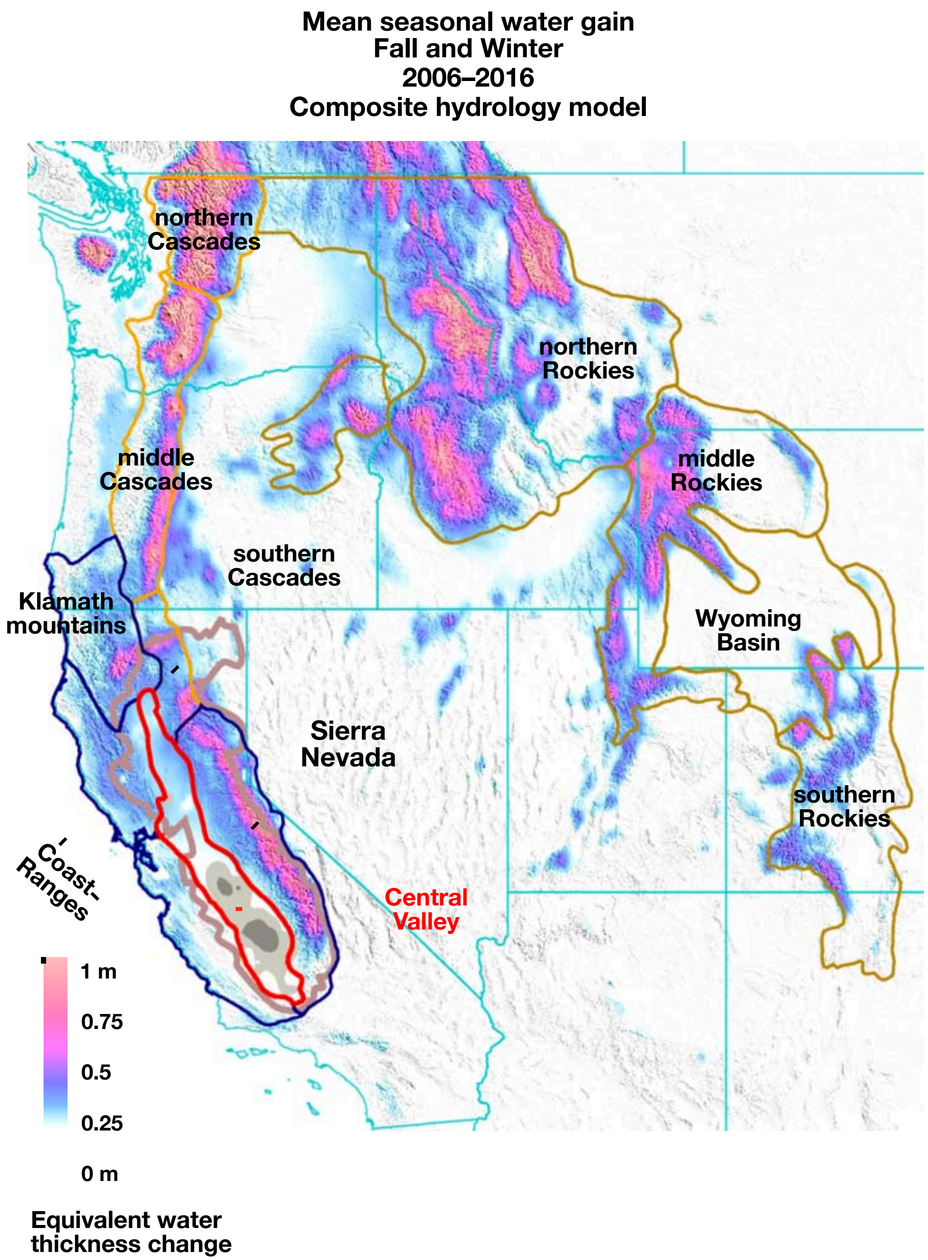
Invert for

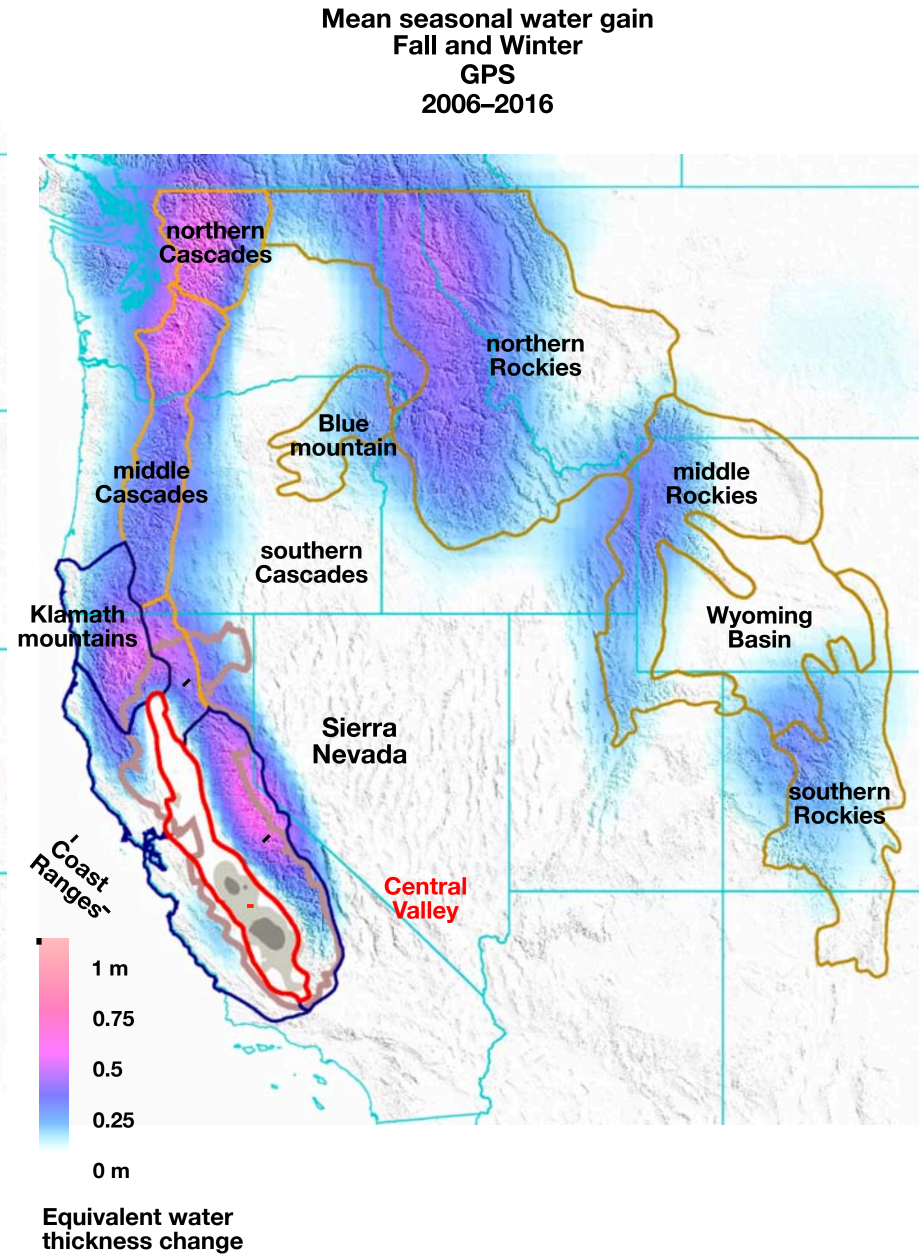
changes in total water
each month Jan 2006 – Aug 2017
in 1/4 deg. lat, lon pixels.
Apply a Laplacian constraint
to limit water changes
between adjacent pixels.
Estimate uncertainty
using linear propagation of errors
and goodness of fit of the model.

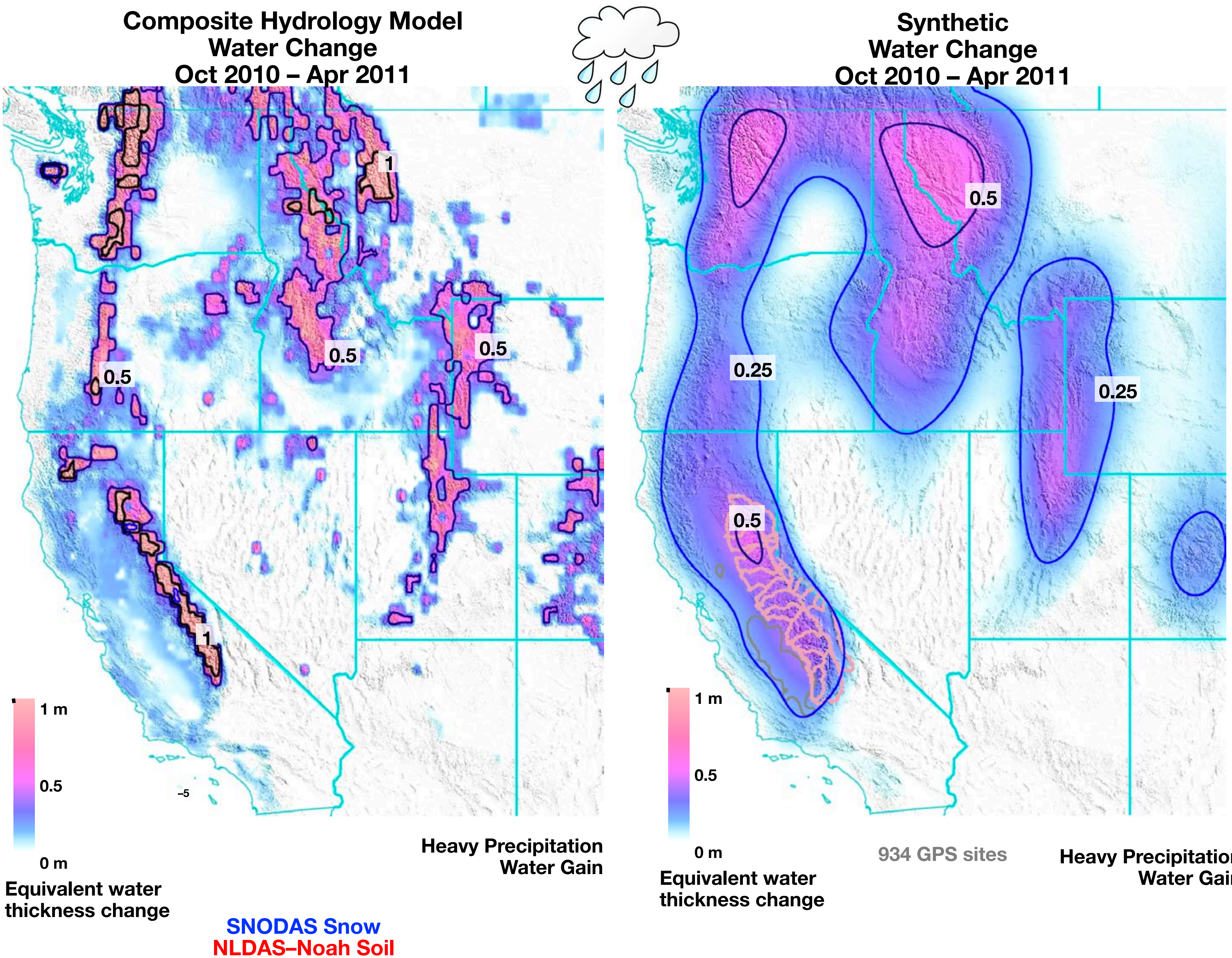
GPS Sites



Cascadia subduction zone
Yellowstone
Long Valley caldera
San Joaquin Valley
Phoenix
2010 Baja earthquake postseismic transient
Omit
GPS sites affected by
149 Aquifers
53 Volcanoes
51 Baja, Cascadia
Keep
1320 Water elastic

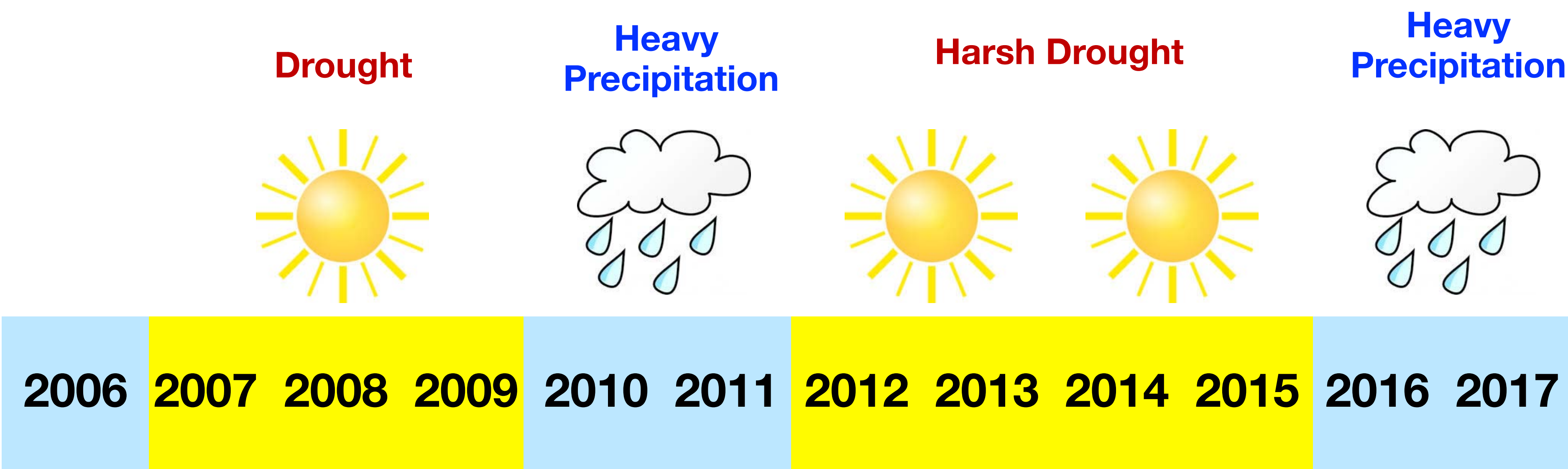

Mean seasonal water gain
Fall and Winter
2006–2016
Composite hydrology model
northern Cascades
northern Rockies
middle Cascades
middle Rockies
southern Cascades
Klamath mountains
Wyoming Basin
Sierra Nevada
southern Rockies
Coast-Ranges
Central Valley
1 m
0.75
0.5
0.25
0 m
Equivalent water thickness change


Mean seasonal water gain
Fall and Winter
GPS
2006–2016
northern Cascades
northern Rockies
Blue mountain
middle Cascades
middle Rockies
southern Cascades
Klamath mountains
Wyoming Basin
Sierra Nevada
southern Rockies
Coast Ranges
Central Valley
1 m
0.75
0.5
0.25
0 m
Equivalent water thickness change


Composite Hydrology Model
Water Change
Oct 2010 – Apr 2011
1
0.5
0.5
0.5
1
1 m
0.5
0 m
Equivalent water thickness change
Heavy Precipitation Water Gain
SNODAS Snow
NLDAS–Noah Soil
Synthetic
Water Change
Oct 2010 – Apr 2011
0.5
0.25
0.25
0.5
1 m
0.5
0 m
Equivalent water thickness change
934 GPS sites
Heavy Precipitation Water Gain

Part 2

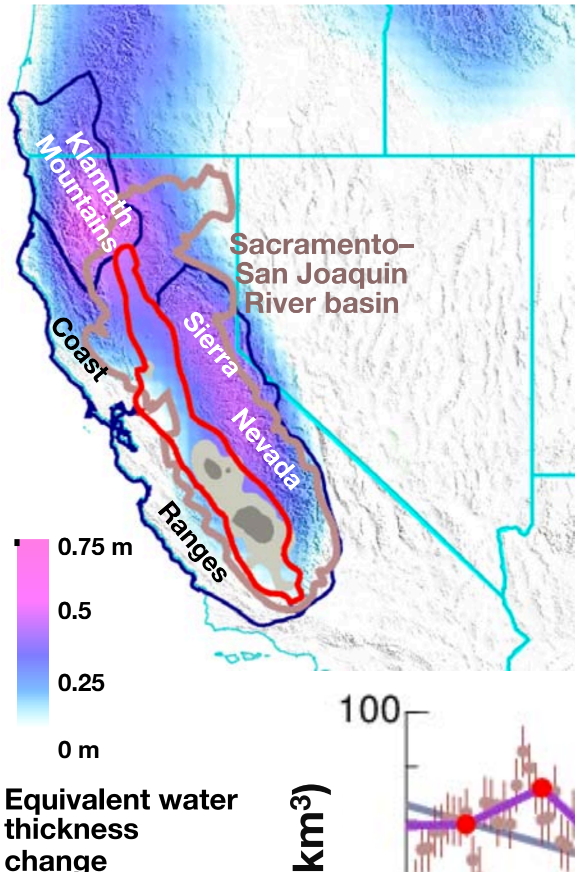
Water changes sustained over periods of drought or heavy precipitation

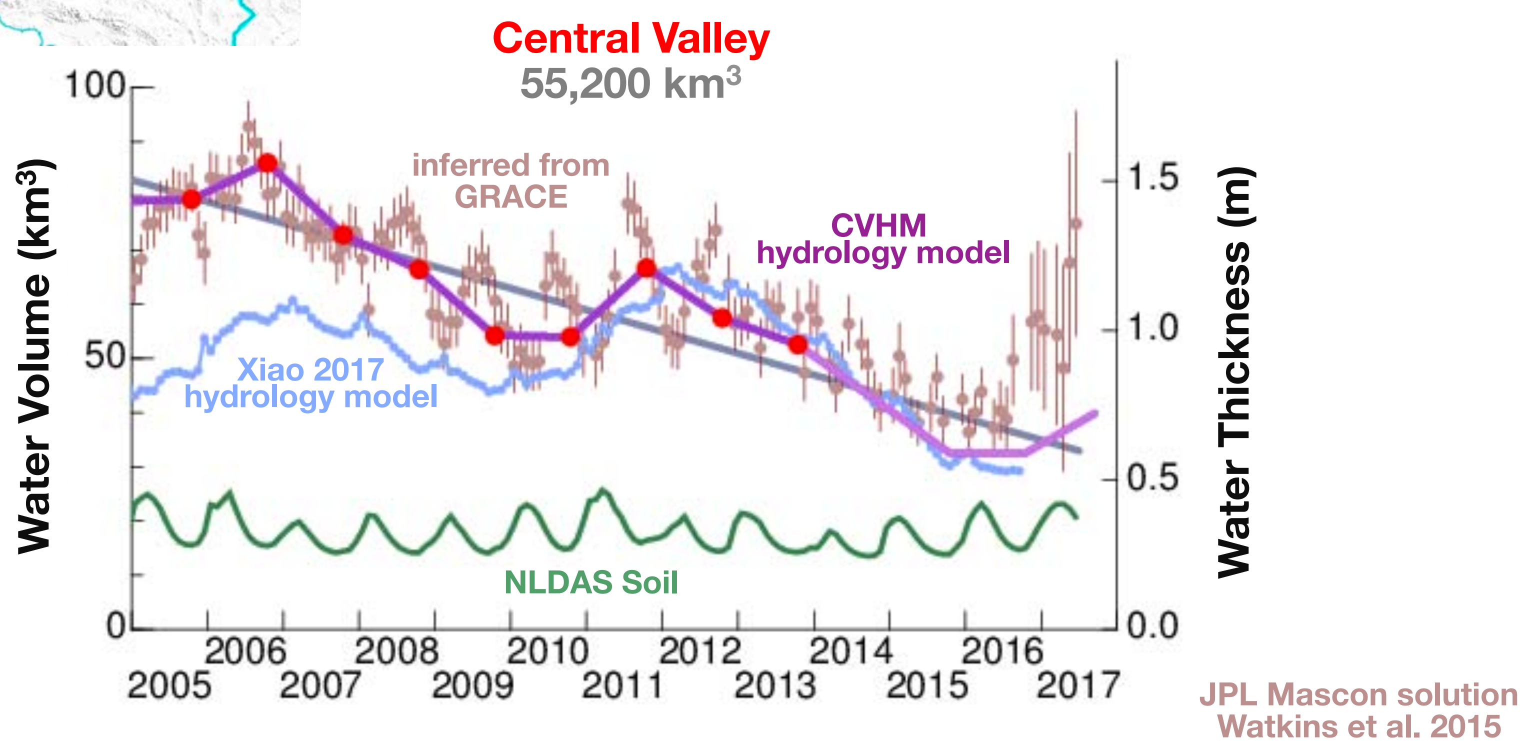


Model of groundwater change in Central Valley

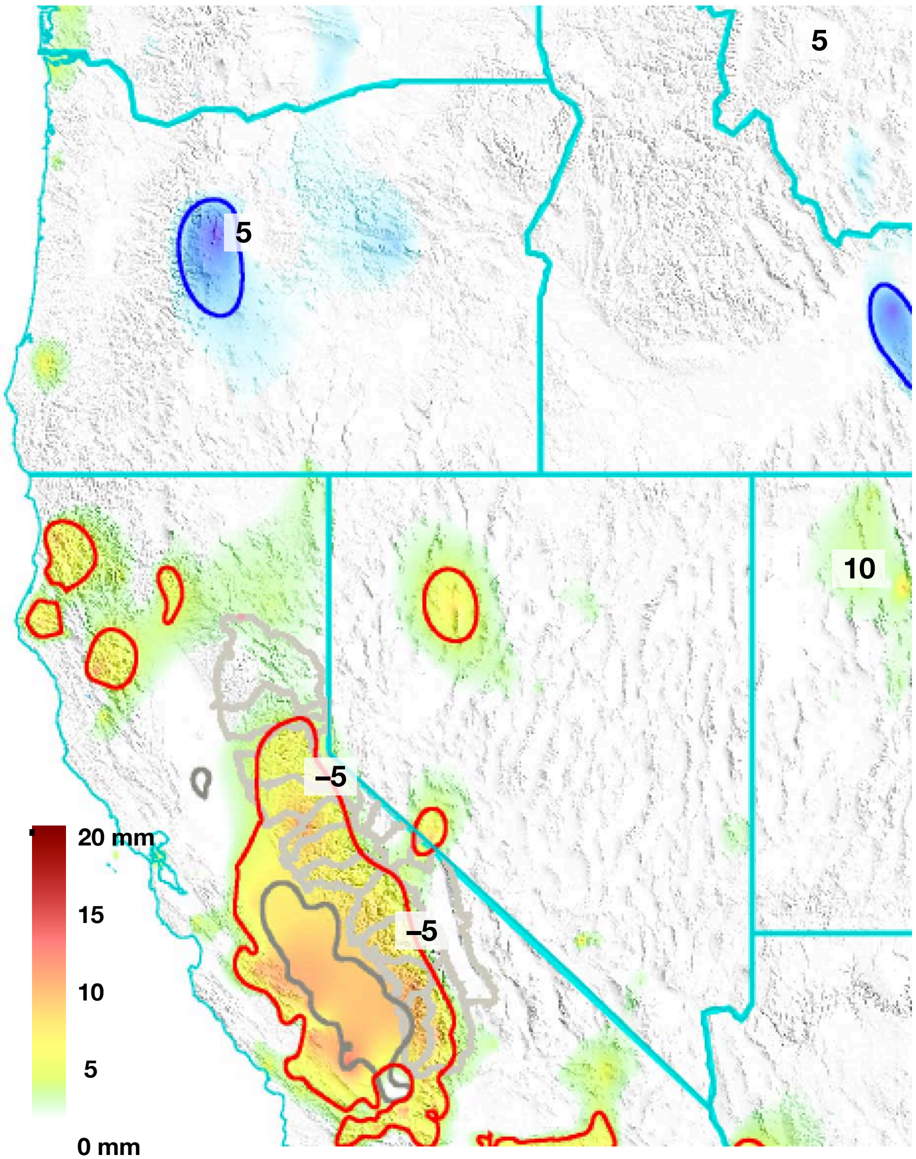
Set total groundwater change equal to CVHM [Faunt et al. 2015].

Distribute groundwater loss across Great Valley using subsidence observed with GPS and InSAR.



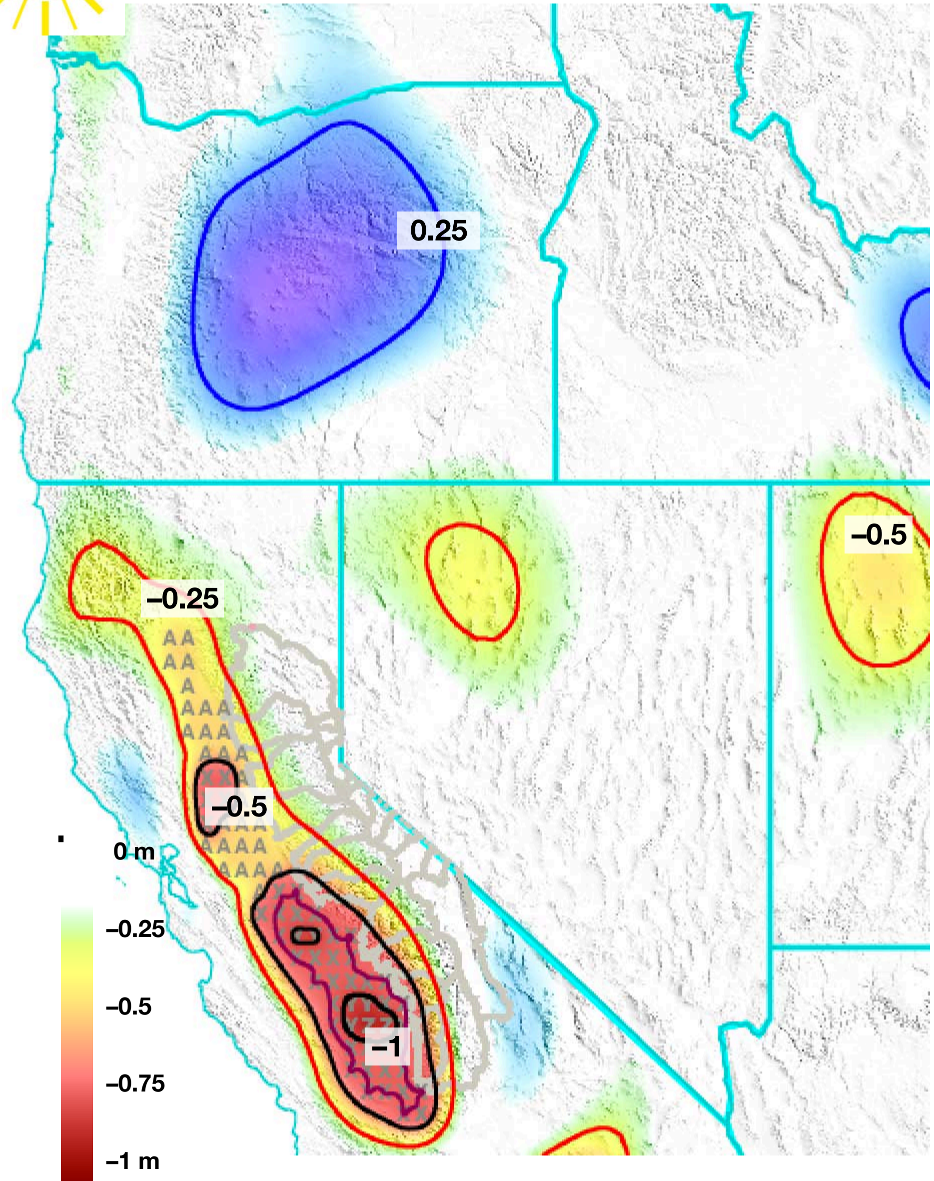


Uplift GPS
Drought
Oct 2011 – Oct 2015



Water Loss GPS
Drought
Oct 2006 – Oct 2009

–29 ±28 km3



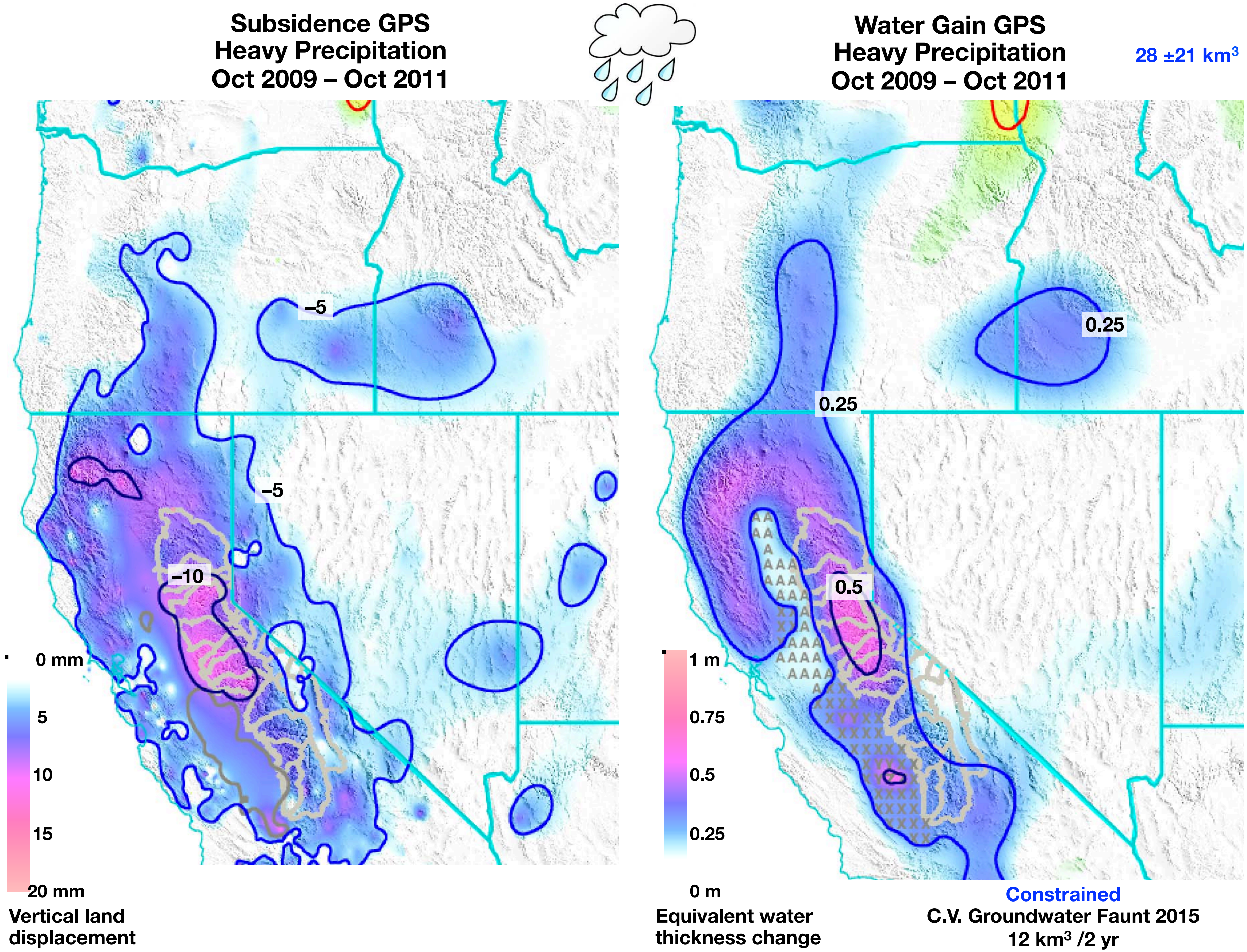
Vertical land displacement

Removed
Artificial reservoir surface water

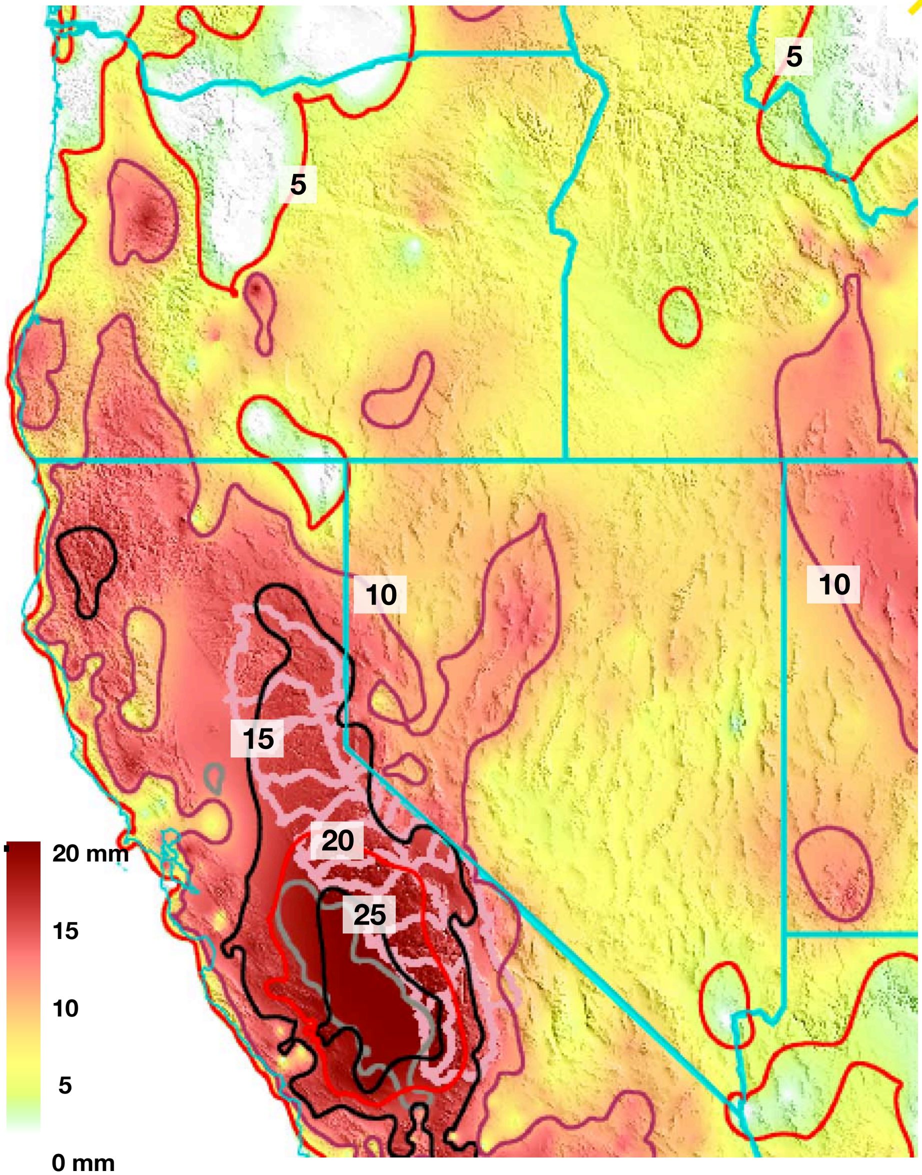
Equivalent water thickness change

Constrained
C.V. Groundwater Faunt 2015
–32 km3 /4 yr

13 Sep 2017


Subsidence GPS
Heavy Precipitation
Oct 2009 – Oct 2011
Water Gain GPS
Heavy Precipitation
Oct 2009 – Oct 2011
28 ±21 km³
–5
–5
–10
0.25
0.25
0.5
0 mm
5
10
15
20 mm
Vertical land displacement
1 m
0.75
0.5
0.25
0 m
Equivalent water thickness change
Constrained
C.V. Groundwater Faunt 2015
12 km³ /2 yr

Uplift GPS
Harsh Drought
Oct 2011 – Oct 2015

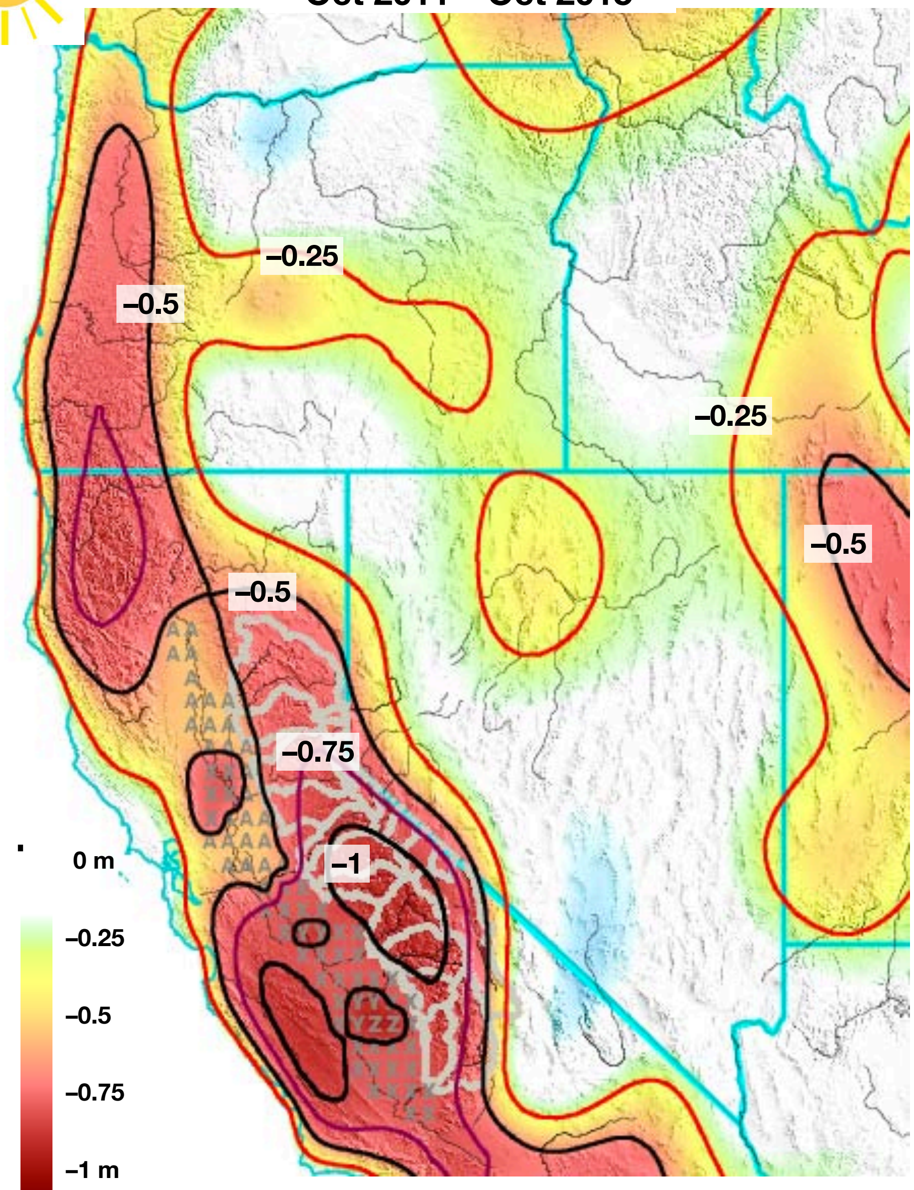


Vertical land displacement

Removed
Artificial reservoir surface water

Water Loss GPS
Harsh Drought
Oct 2011 – Oct 2015

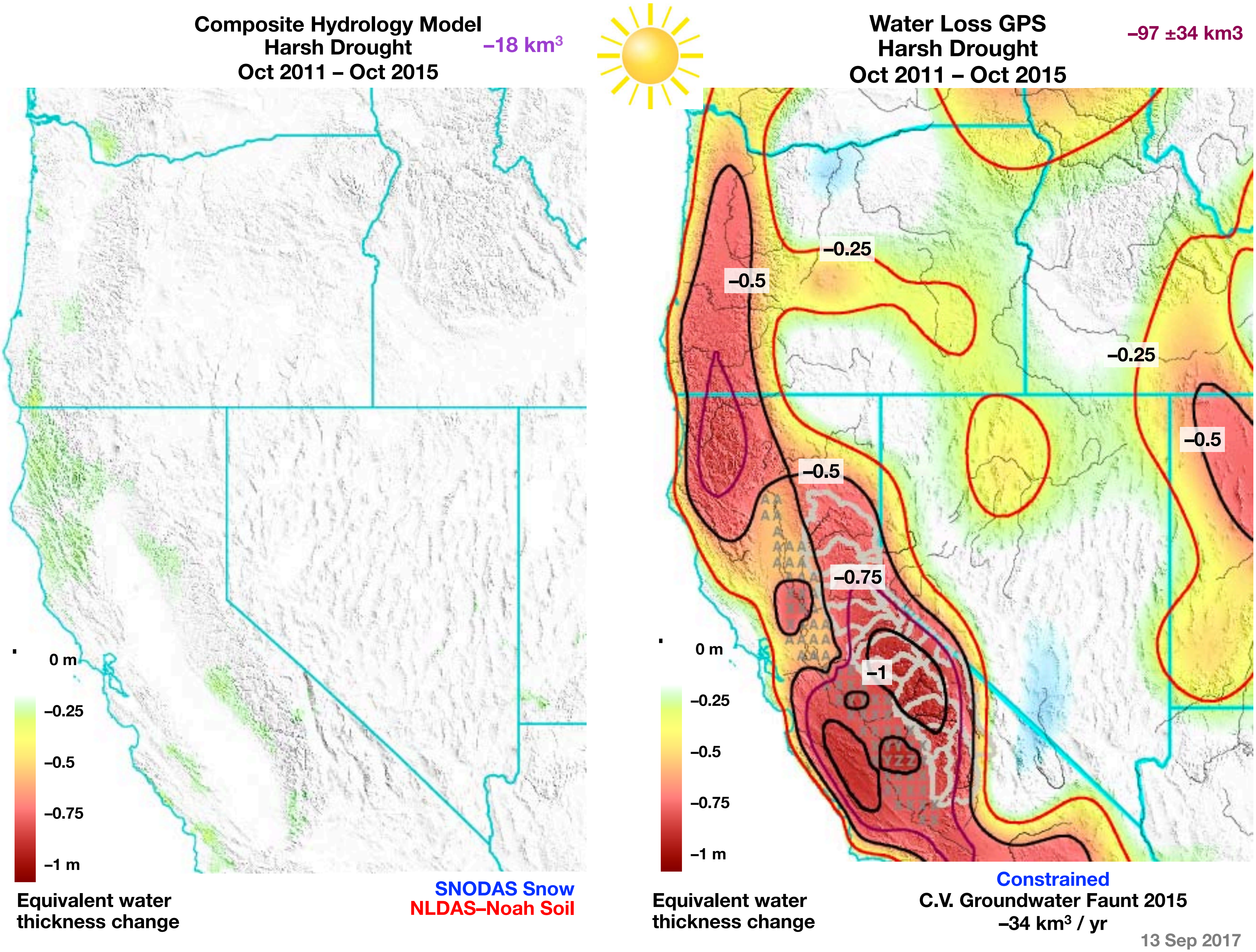
–97 ±34 km3

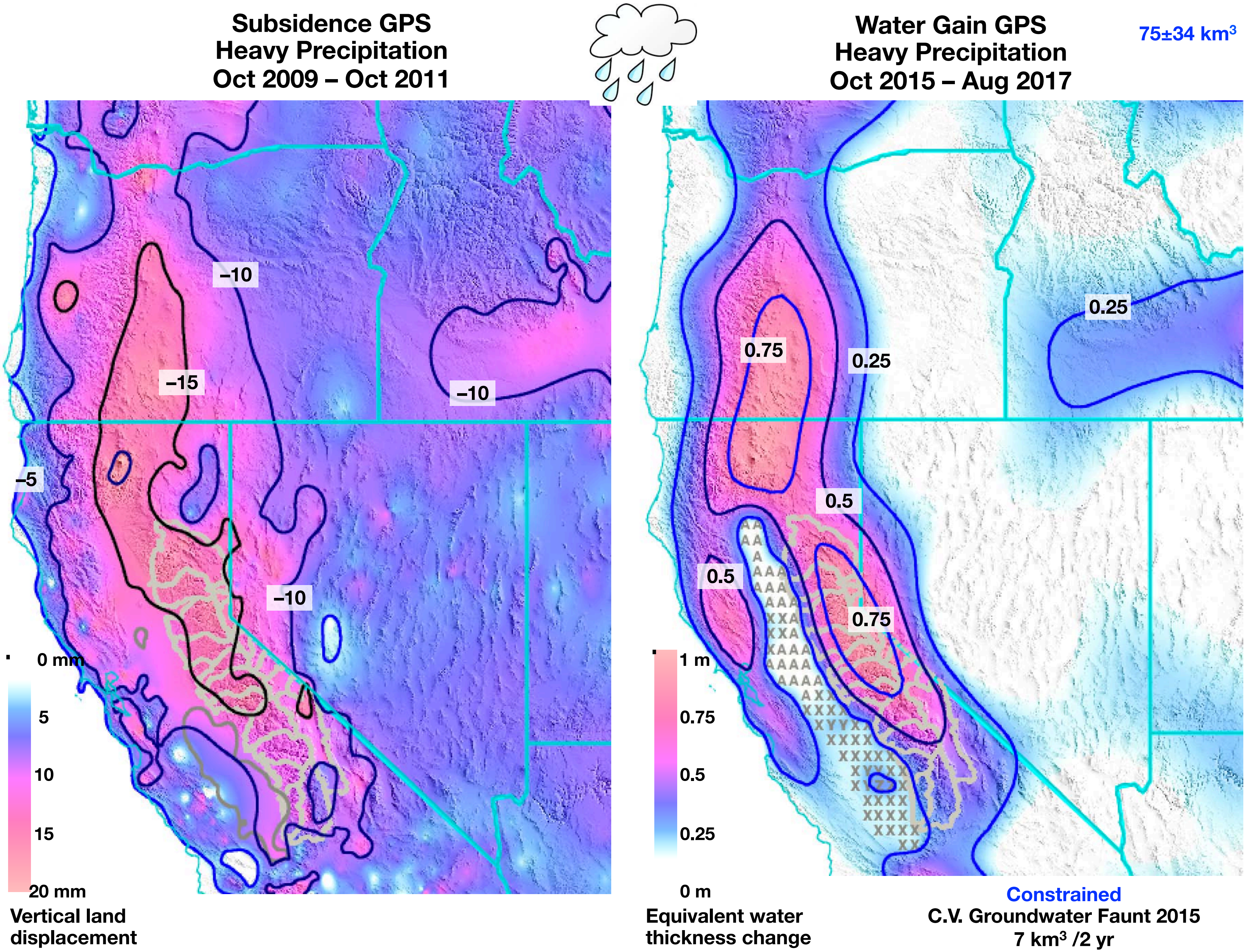


Equivalent water thickness change

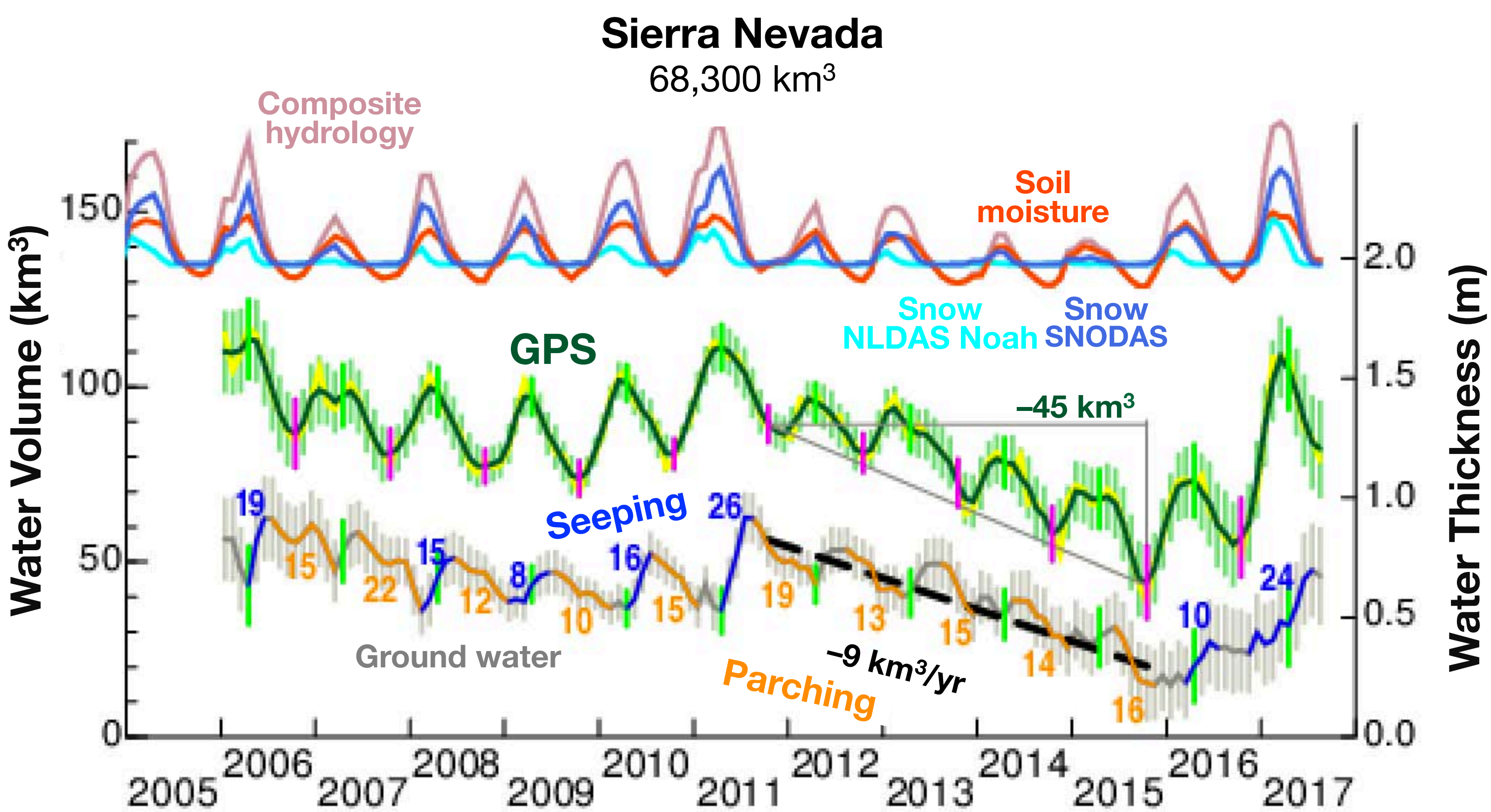
Constrained
C.V. Groundwater Faunt 2015
–34 km3 /4 yr

13 Sep 2017

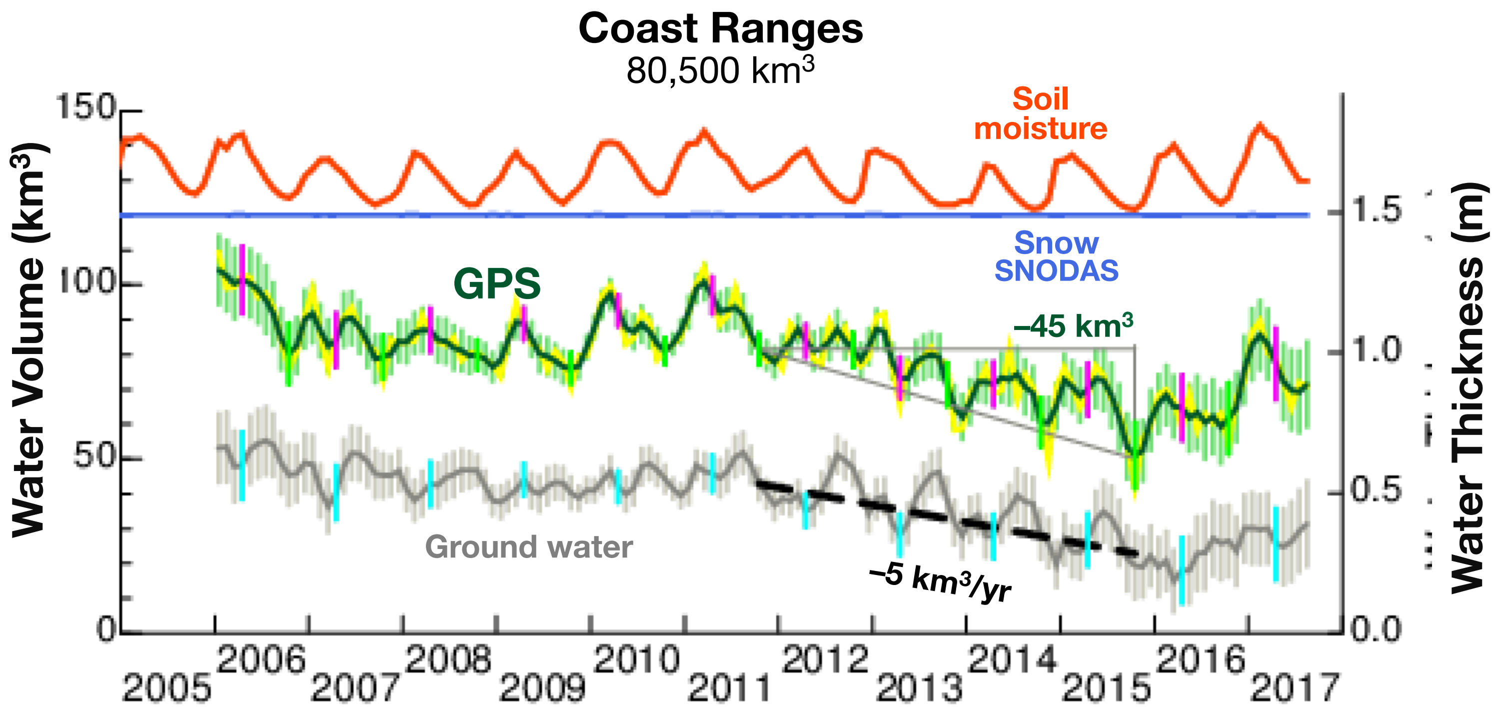

Composite Hydrology Model
Harsh Drought
Oct 2011 – Oct 2015
–18 km³
0 m
–0.25
–0.5
–0.75
–1 m
Equivalent water thickness change
SNODAS Snow
NLDAS–Noah Soil
Water Loss GPS
Harsh Drought
Oct 2011 – Oct 2015
–97 ±34 km3
–0.25
–0.5
–0.25
–0.5
–0.5
–0.75
–1
0 m
–0.25
–0.5
–0.75
–1 m
Equivalent water thickness change
Constrained
C.V. Groundwater Faunt 2015
–34 km³ / yr
13 Sep 2017



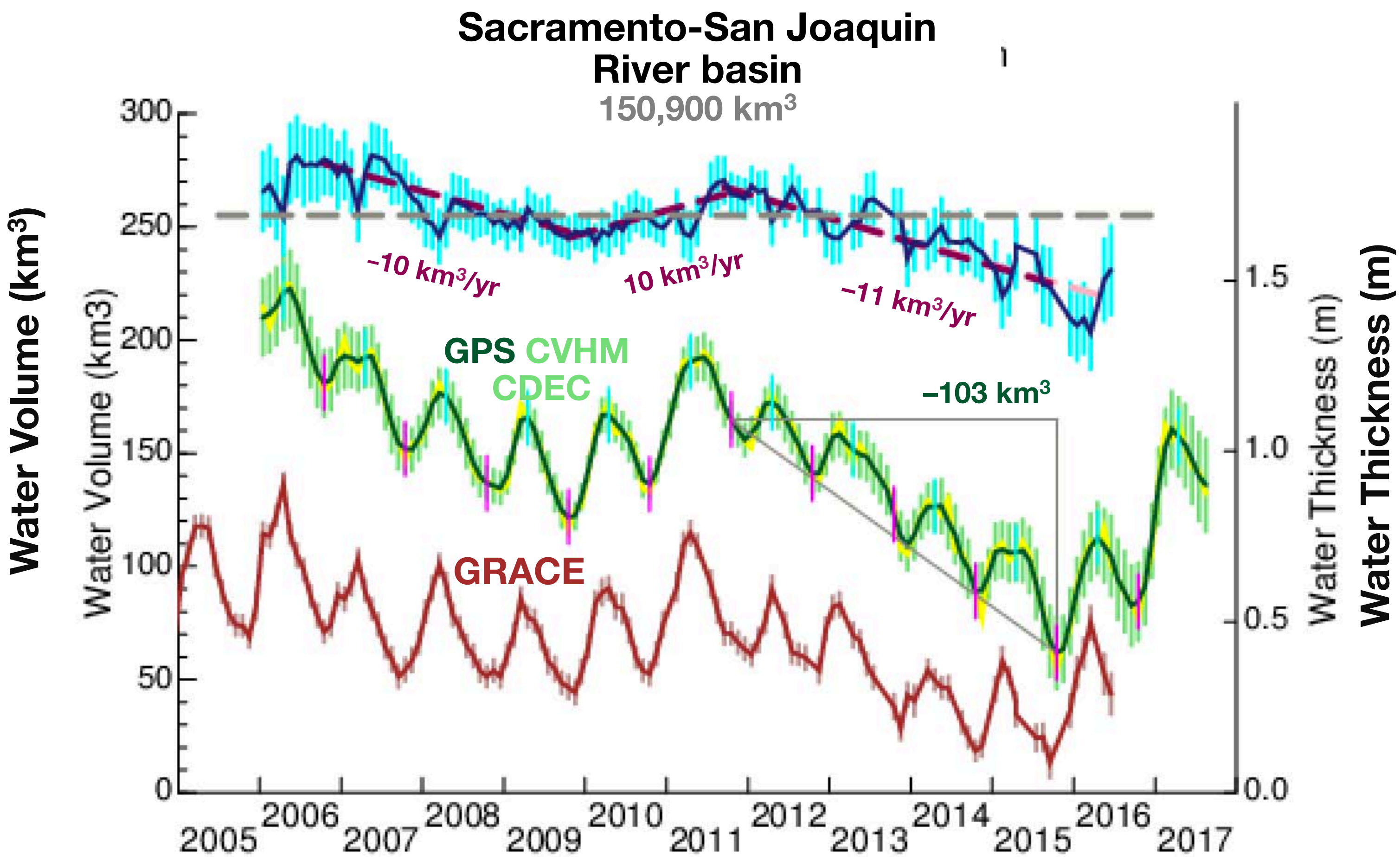
Subsidence GPS
Heavy Precipitation
Oct 2009 – Oct 2011
–10
–15
–10
–5
–10
0 mm
5
10
15
20 mm
Vertical land
displacement
Water Gain GPS
Heavy Precipitation
Oct 2015 – Aug 2017
75±34 km³
0.25
0.75
0.25
0.5
0.5
0.75
1 m
0.75
0.5
0.25
0 m
Equivalent water
thickness change
Constrained
C.V. Groundwater Faunt 2015
7 km³ /2 yr



- The Sierra Nevada lost 45 ± 21 km^3 of water in the ground during drought from October 2011 to October 2015, exceeding the 6 km^3 of soil moisture lost in the hydrology model.



- The Sierra Nevada lost 31 ± 20 km^3 of water in the ground during drought from October 2011 to October 2015, exceeding the 7 km^3 of soil moisture lost in the hydrology model.



- Water loss inferred from GPS during drought exceeds that from GRACE. Water gain inferred from GPS during heavy precipiaton also exceeds that from GRACE

Part 3

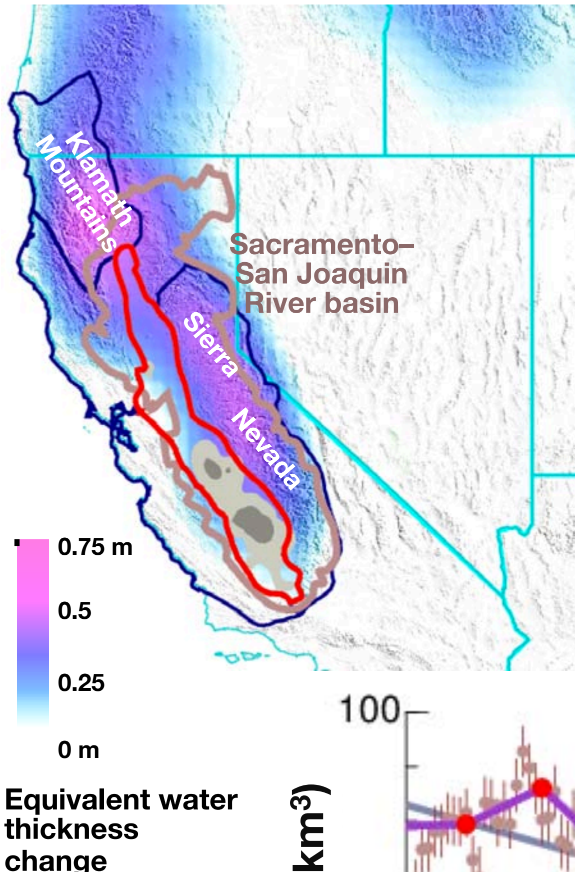
Elastic model of
Central Valley groundwater loss

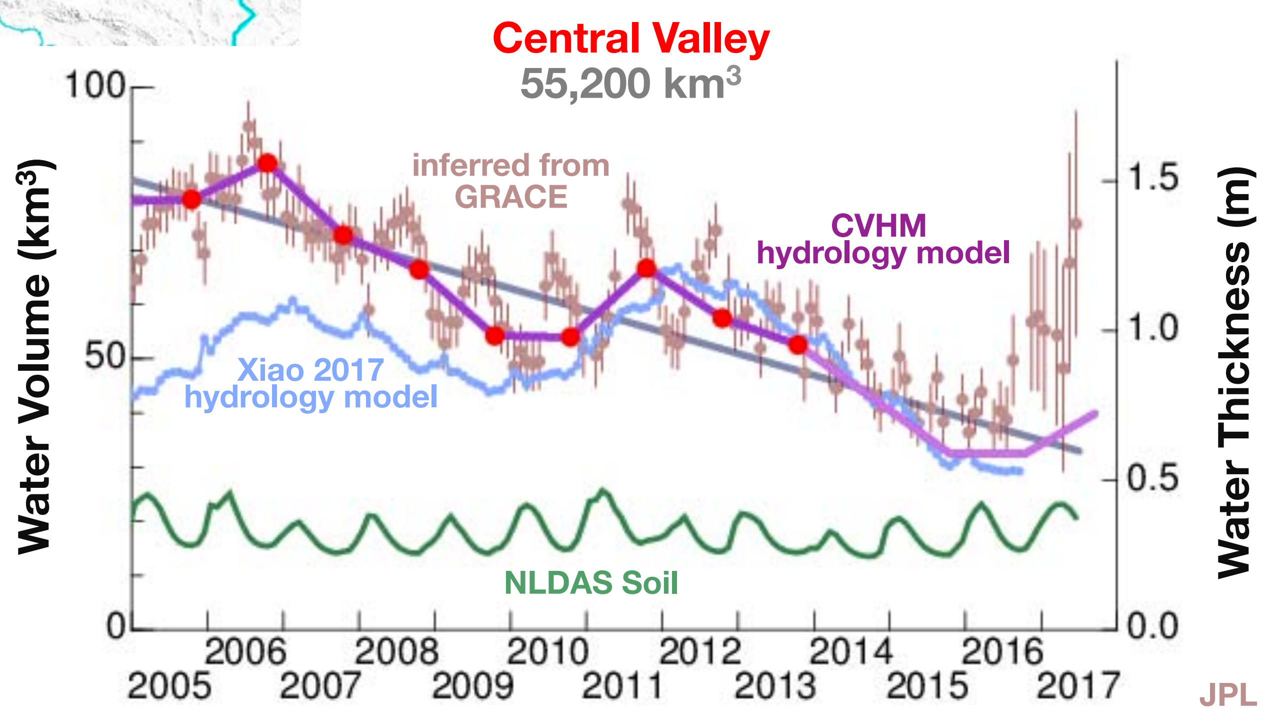
Uplift of the Sierra Nevada

Model of groundwater change in Central Valley

Set total groundwater change equal to CVHM [Faunt et al. 2015].

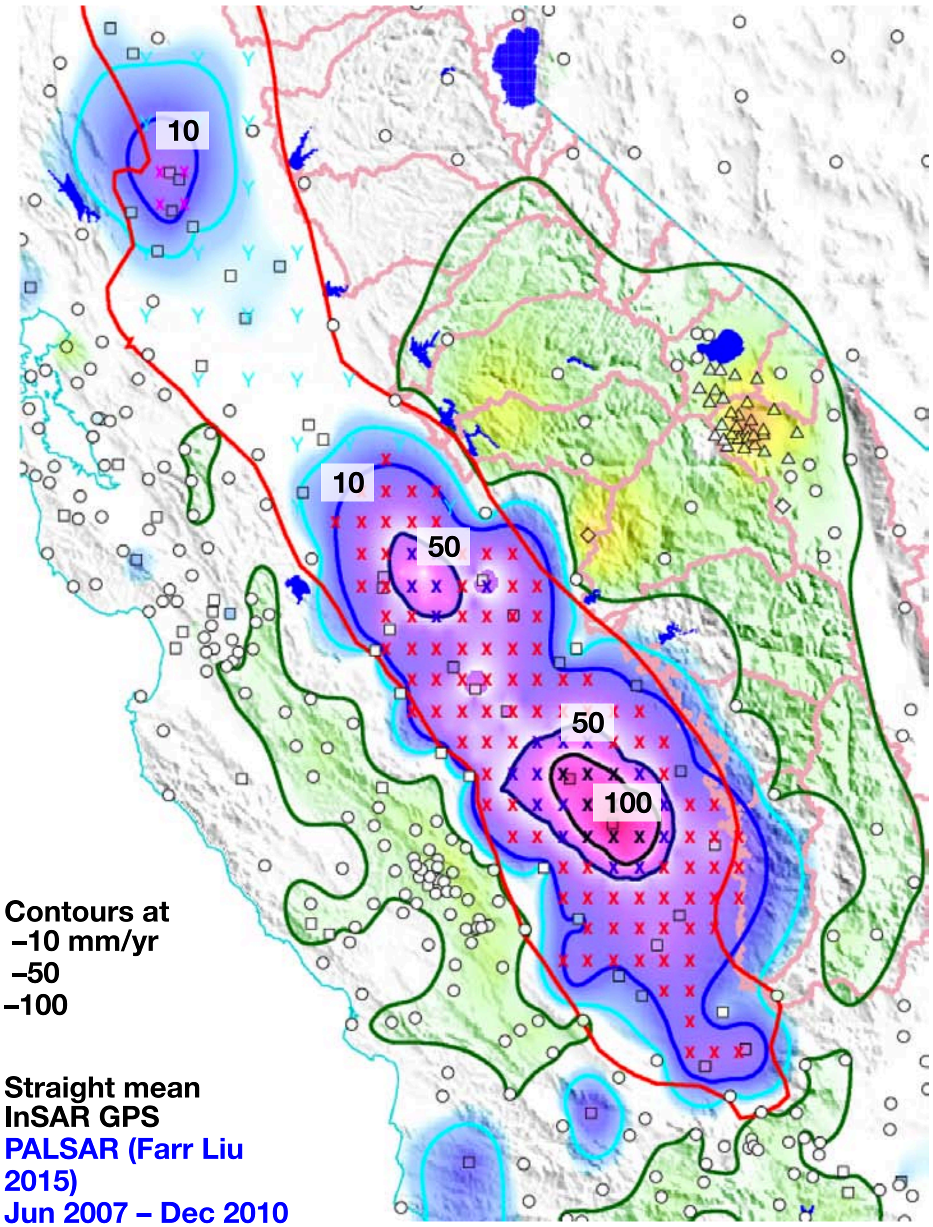
Distribute groundwater loss across Great Valley using subsidence observed with GPS and InSAR.

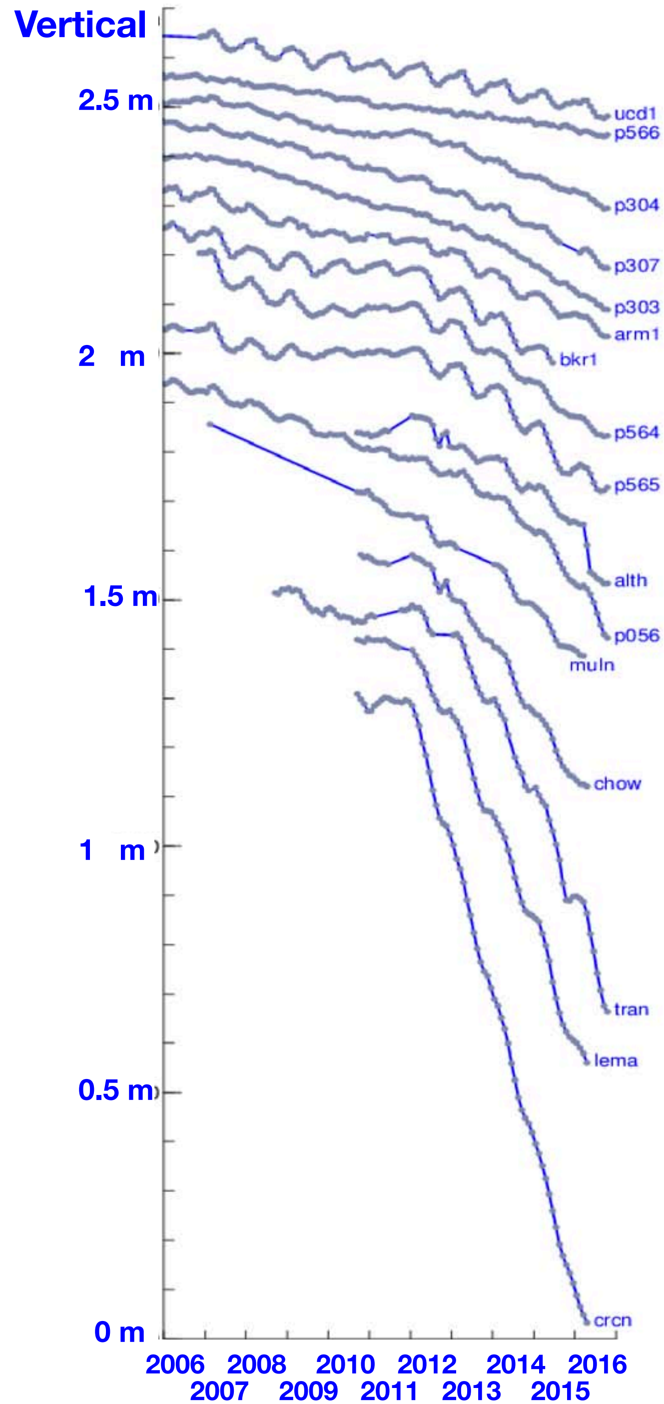




JPL Mascon solution Watkins et al. 2015

Subsidence GPS
Central Valley
2006 – 2016

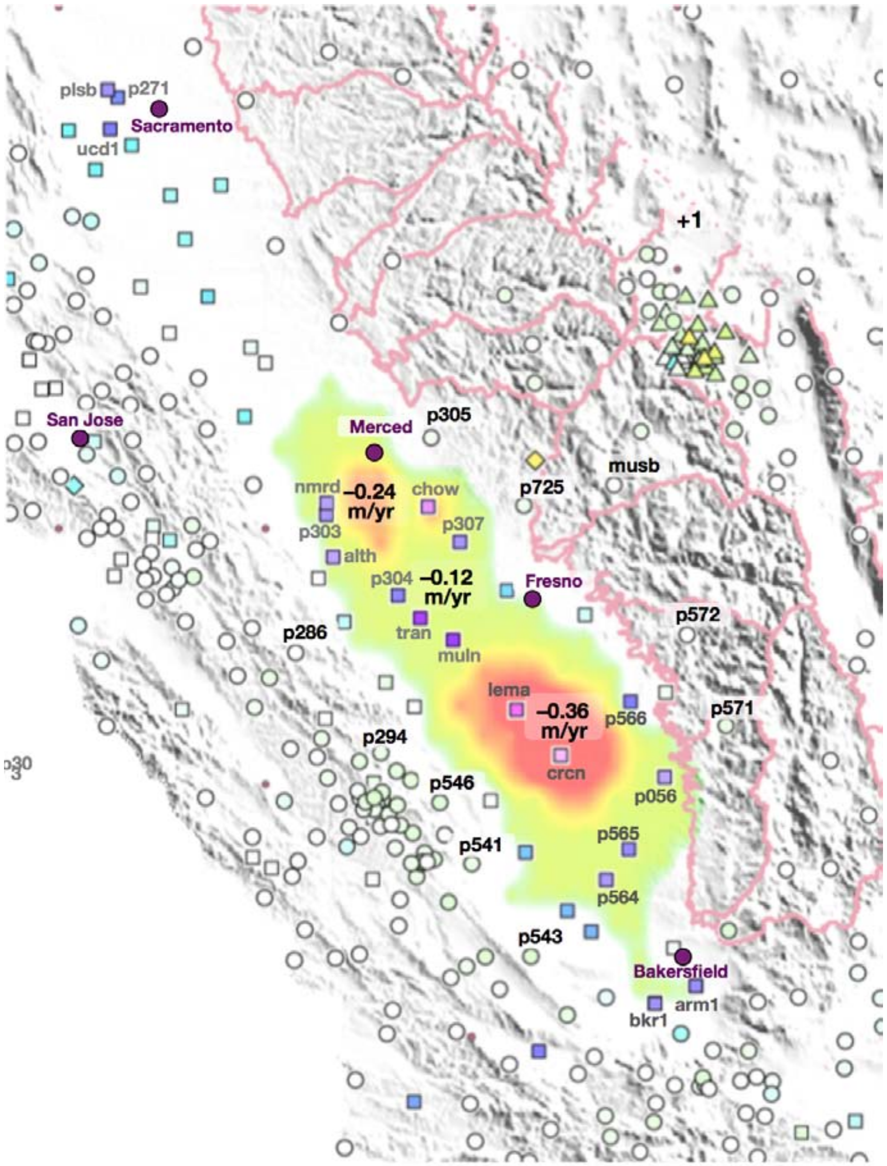




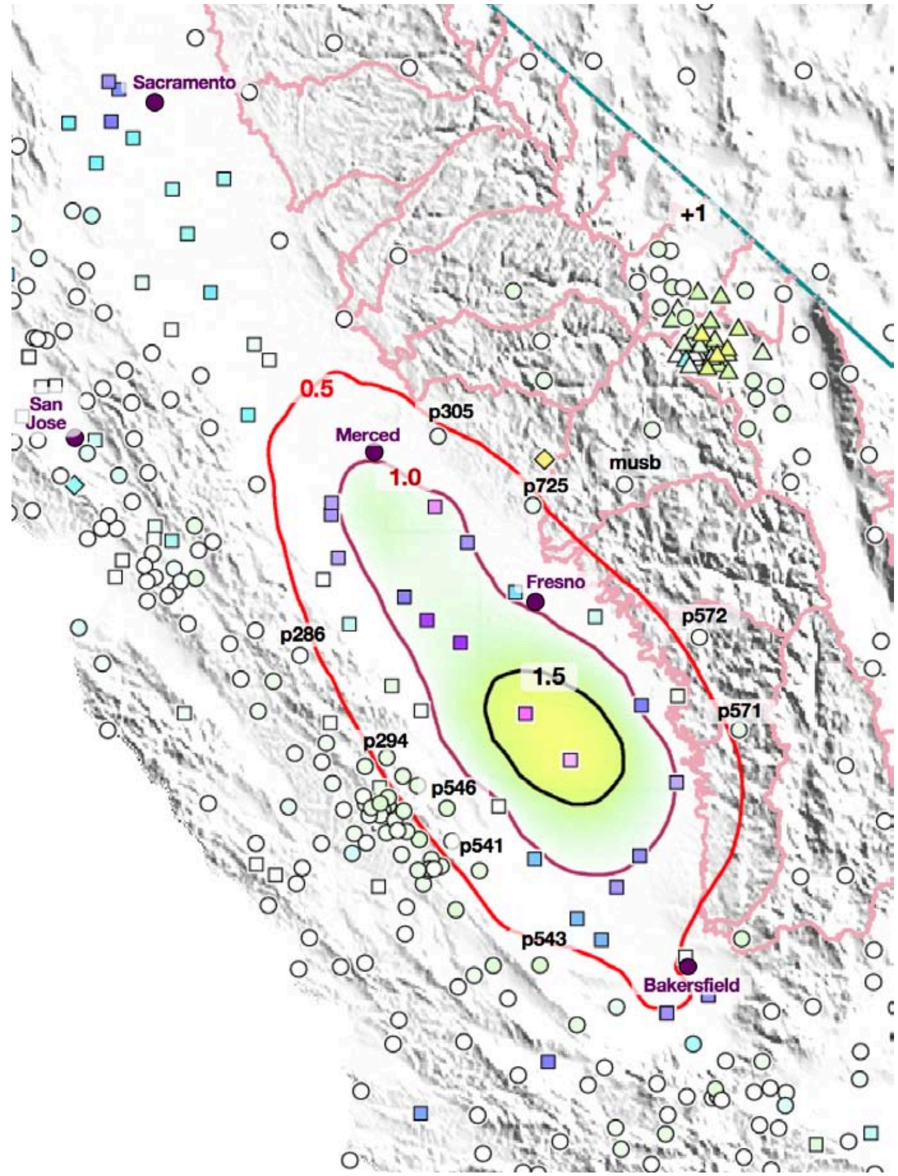
- Contours at
  –10 mm/yr
  –50
  –100

- Straight mean
  InSAR GPS
  PALSAR (Farr Liu 2015)
  Jun 2007 – Dec 2010

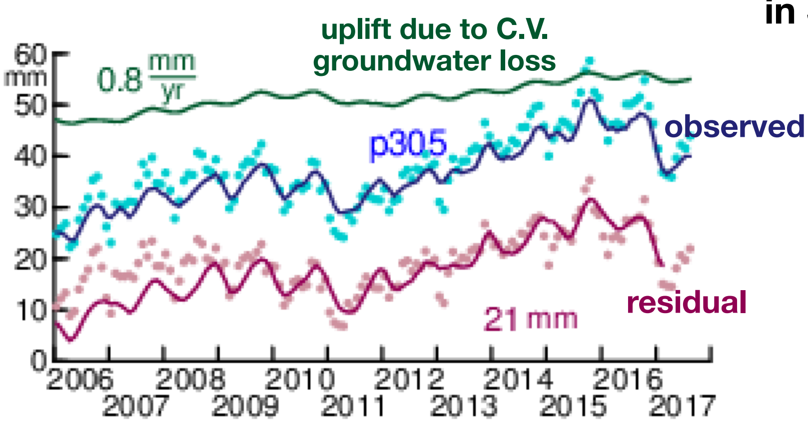
Mean rate of Central Valley groundwater loss 2006 – 2015

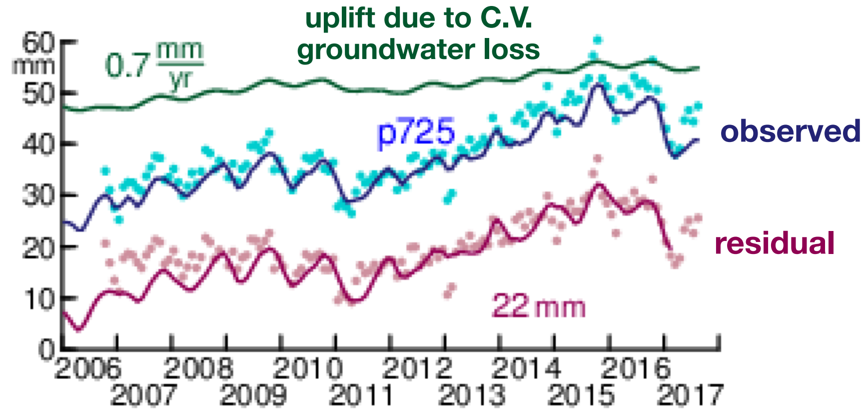


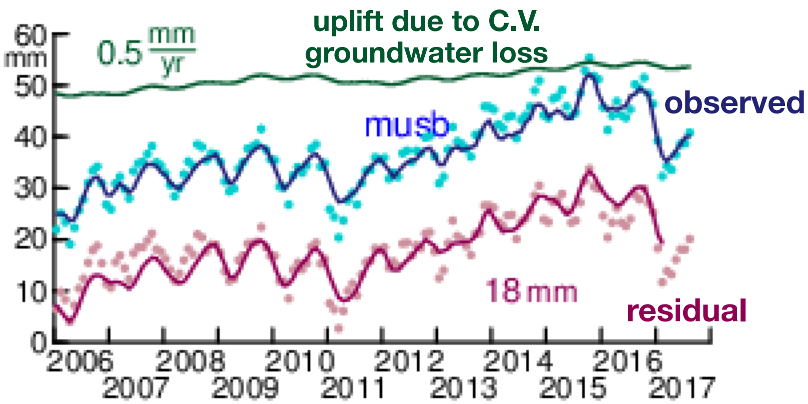
Central Valley Model Uplift Rate

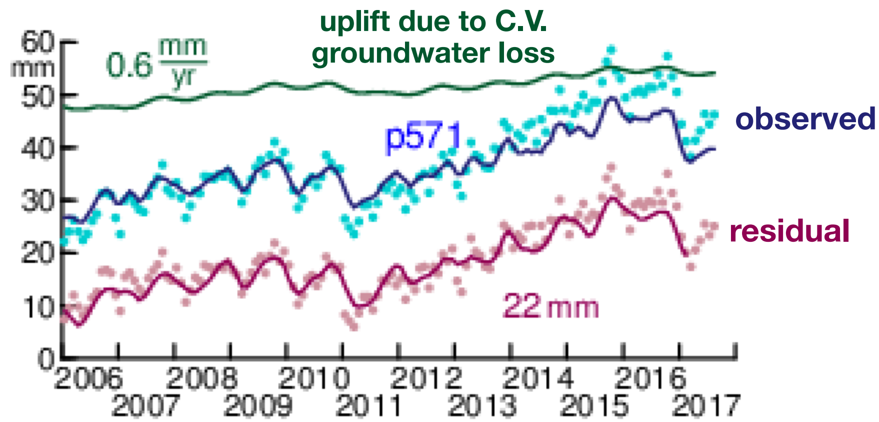


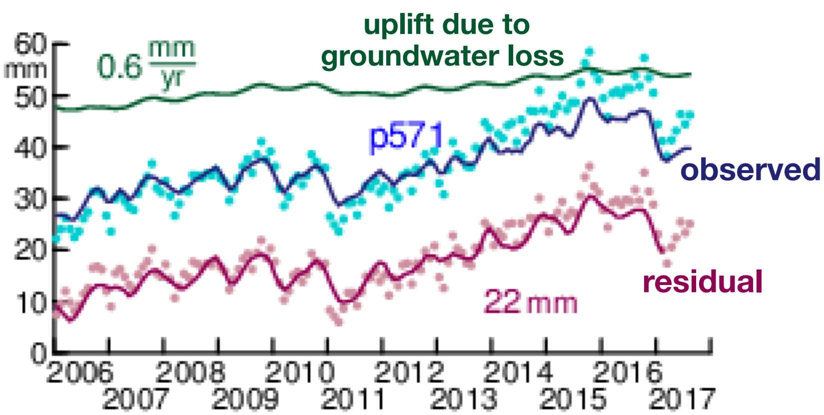
GPS Vertical displacement in Sierra Nevada











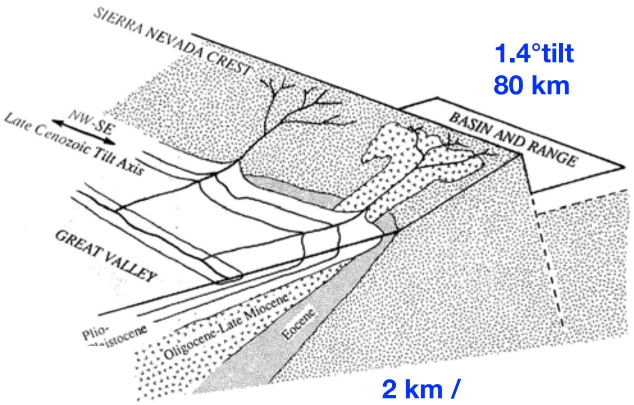
RESULT 3

Of the 24 mm of uplift of the Sierra Nevada during from October 2011 to October 2015, just 5 mm is produced by Central Valley groundwater loss, less than 2 mm is tectonic uplift, and 17 mm is solid Earth's elastic response to water loss in the Sierra Nevada.

Late Cenozoic tilting of strata in eastern Great Valley

0.4 mm/yr

Unruh 1991



1.4°tilt
80 km

2 km /
5 Ma

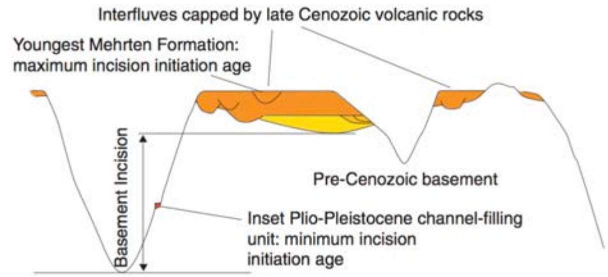
Sierra Nevada rose before 30 Ma

0.2 mm/yr

Cassel et al. 2009

River incision rates 0.2 – 0.4 mm/yr

Wakaybashi 2013
Wakayabashi Sawyer 2011



Geomorphic interpretations are unfounded

0.1 mm/yr

Gabet 2014

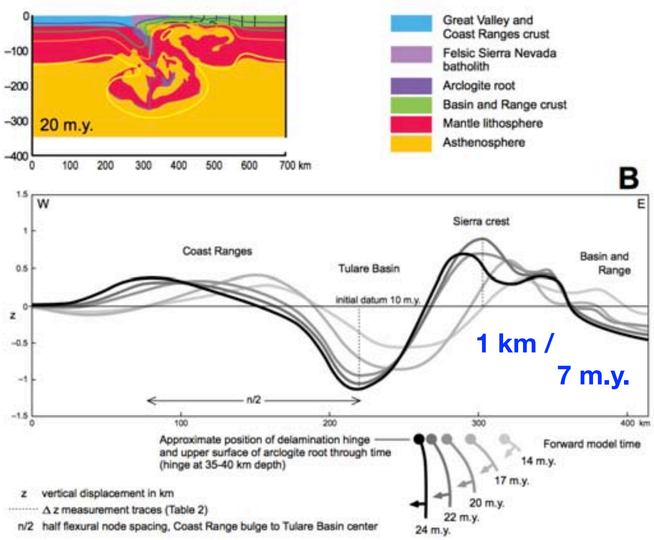
Cave river incision at 0.2 mm/yr from 2.7 to 1.5 Ma, 0.03 mm/yr since 1.5 Ma

Stock et al. 2004

Epeirogenic uplift 0.15 mm/yr

Thermodynamic models of delamination of the mantle root of the Sierra Nevada

Saleeby et al. 2012, 2013



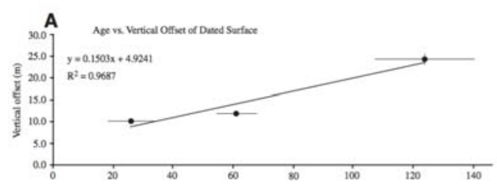
1 km /
7 m.y.

Sierra Nevada frontal fault

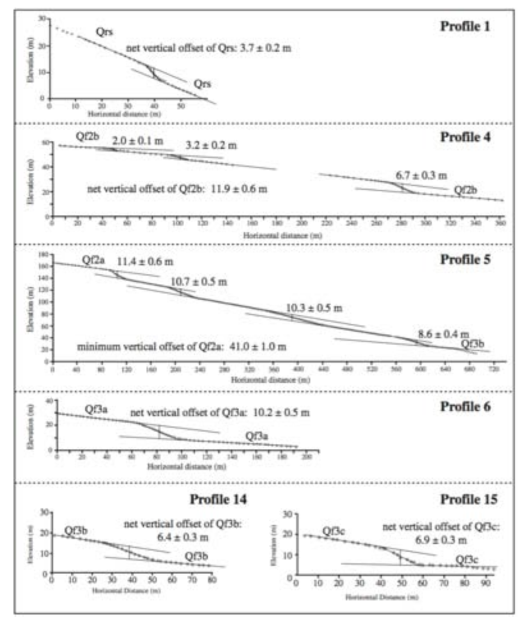
0.2 mm/yr

Normal slip from paleoseismology

Lee et al. 2007



24 m /
124 ka



1872 Owens Valley M 7.6 earthquake

6 m right lateral slip

Beanland Clark 1972

Conclusion

- **Product**
  Changes in water storage
  across the western U.S.
  each month
  from Jan 2006 to Aug 2017.

- **Result 2**
  Water changes are sustained
  over periods of drought or
  heavy precipitation.
  Such sustained changes are
  not in hydrology models.

- **Result 1**
  The Sierra Nevada rose
  24 mm from 2011 to 2015
  mainly in elastic
  response to
  water loss of 0.75 m
  in the Sierra Nevada,
  Not because of
  groundwater loss in the
  Central Valley,
  Not because of
  normal slip along
  the Sierra Nevada
  frontal fault.

- **Result 3**
  The Sierra Nevada, Coast Ranges,
  and Klamath Mountains
  lost 94 ±50 km^3 of water
  during harsh drought
  from 2011 to 2015.
  Mountain groundwater
  in river alluvium and
  in crystalline basement fractures
  are playing an important role
  in California's water resources.