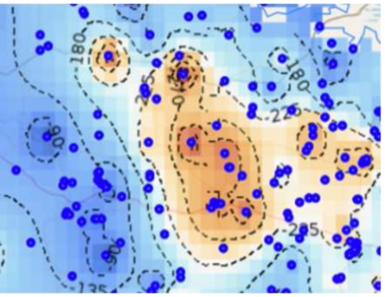
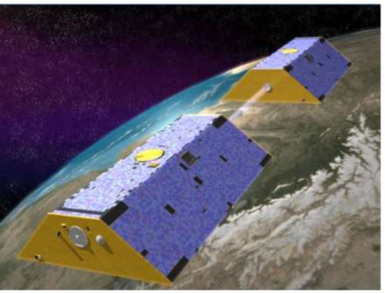
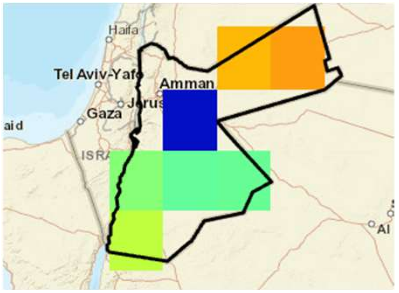
Performing a GRACE groundwater analysis in small basins

Use of the Gravity Recovery and Climate Experiment (GRACE) mission to monitor groundwater storage change: National workshop for Jordan and State of Palestine

Amman Jordan, February 25-26







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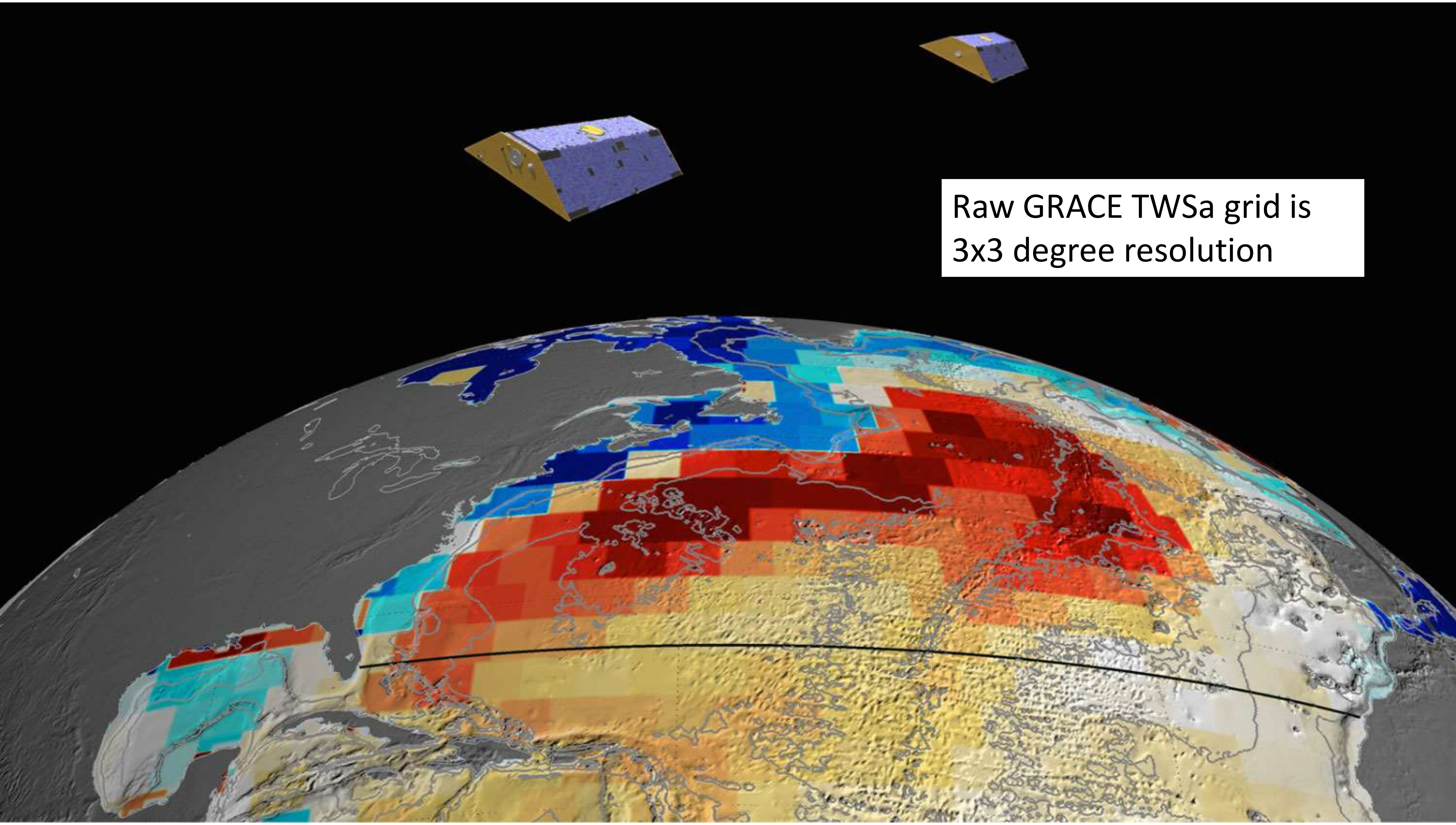
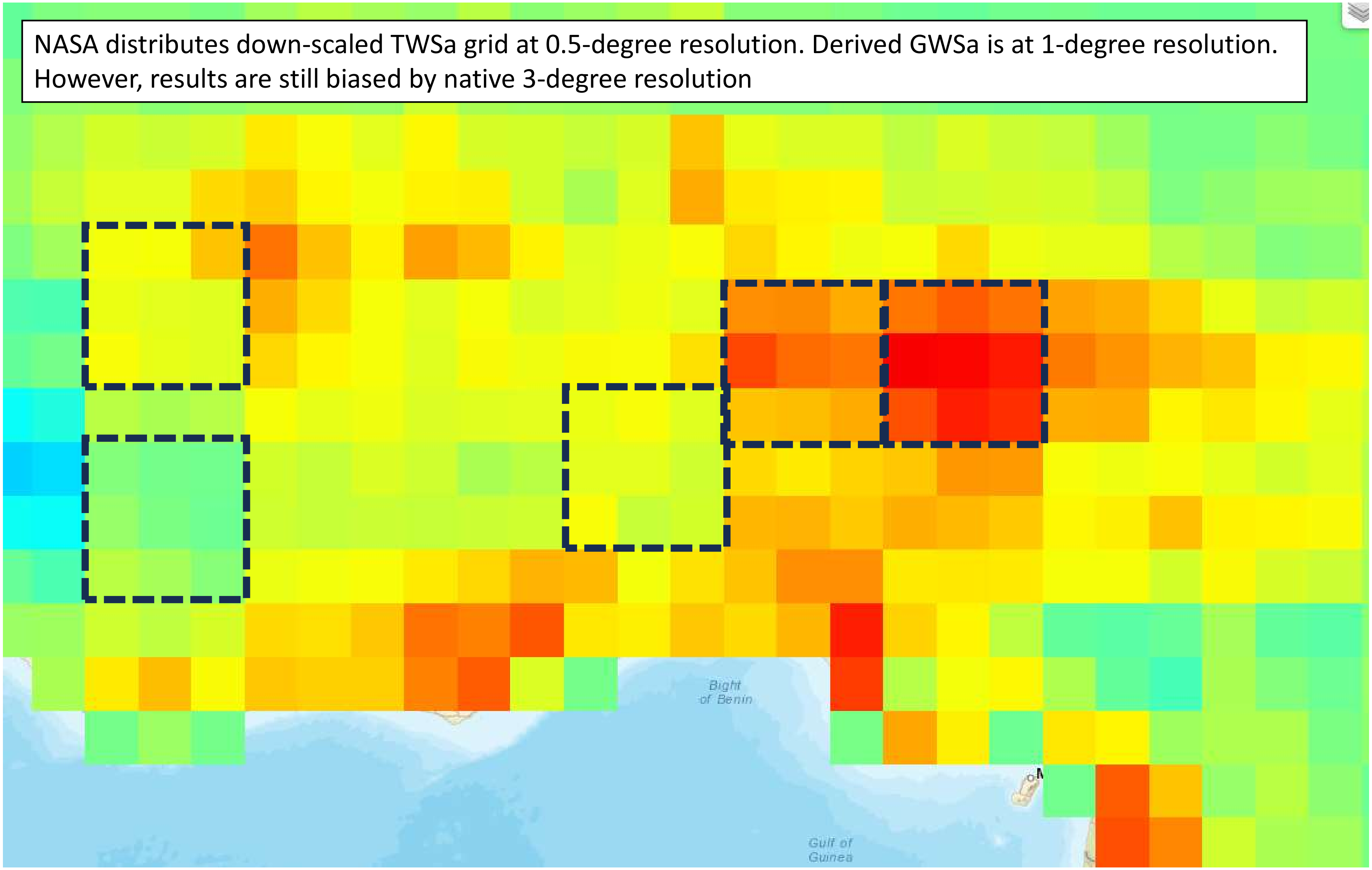
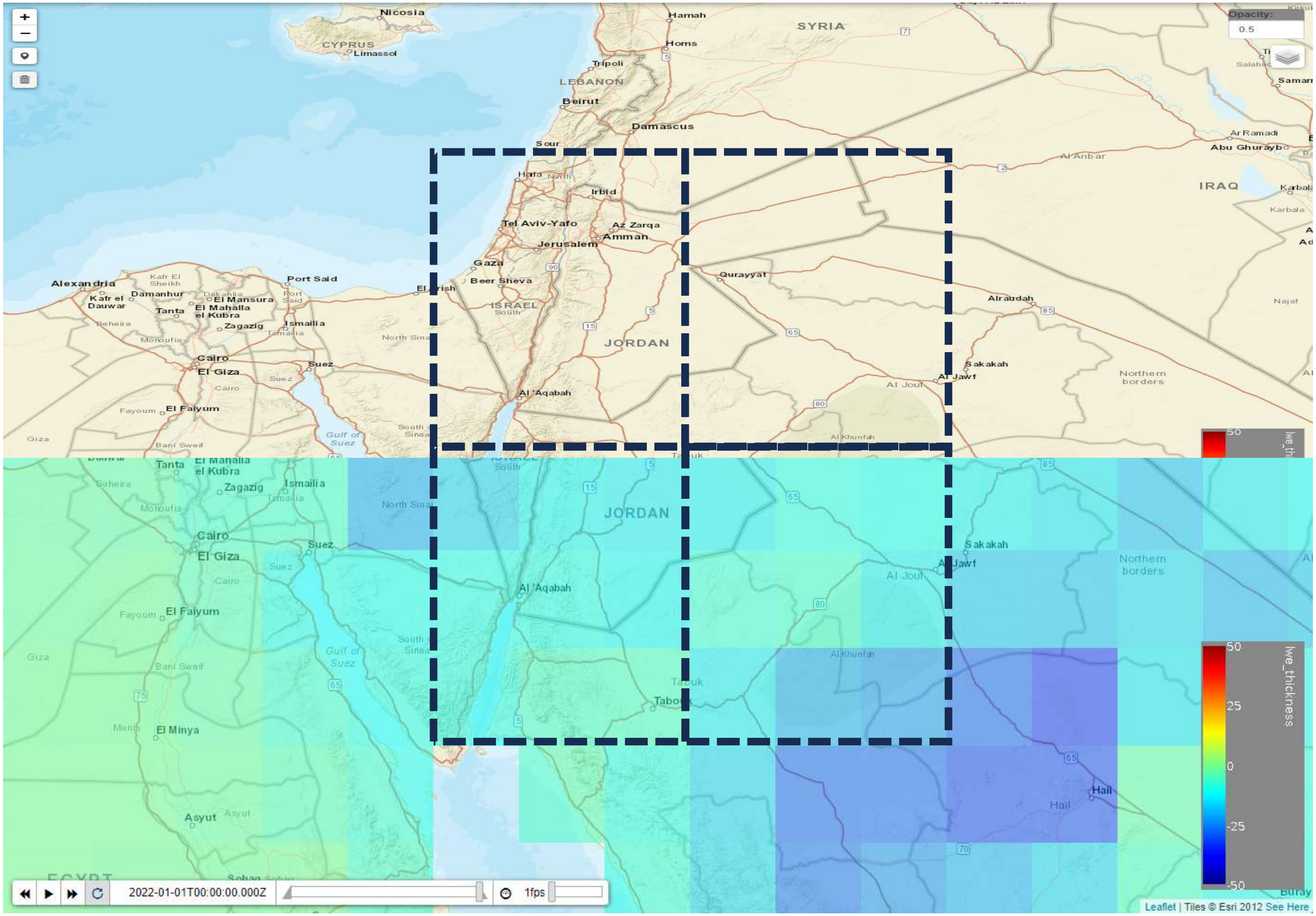
Sweden Sverige


Raw GRACE TWSa grid is
3x3 degree resolution

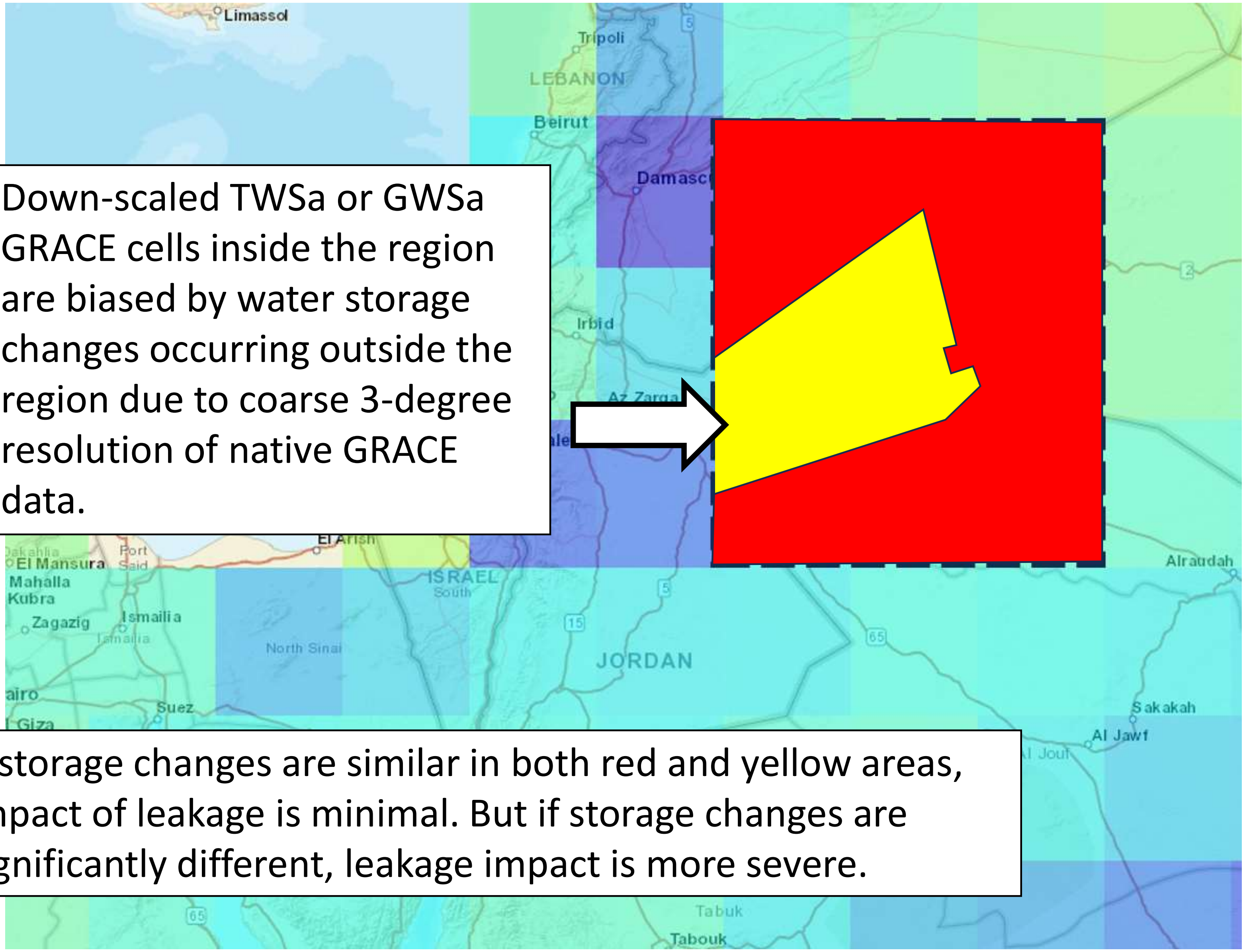
NASA distributes down-scaled TWSa grid at 0.5-degree resolution. Derived GWSa is at 1-degree resolution.
However, results are still biased by native 3-degree resolution





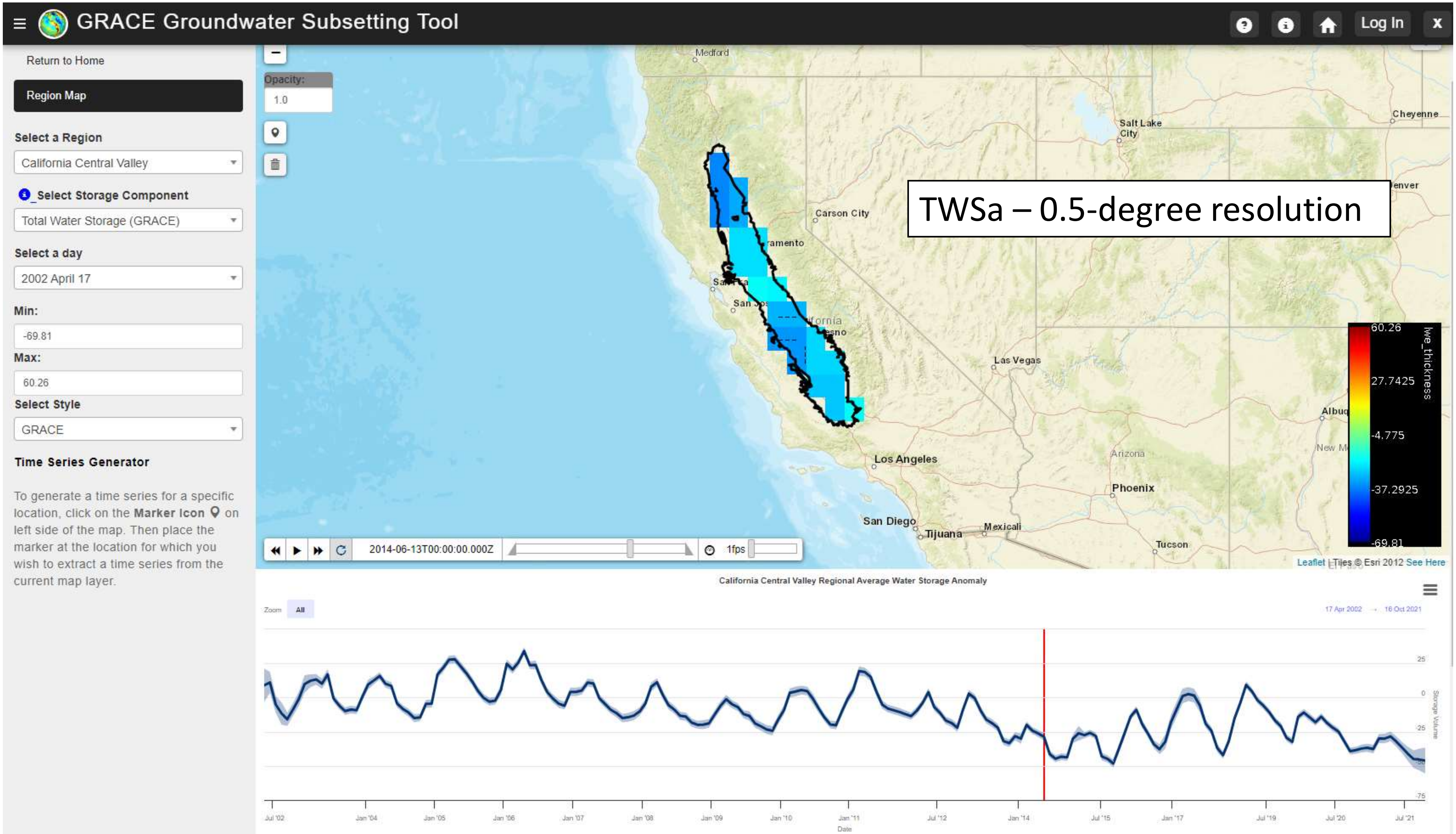
Opacity:
0.5
Nicosia
CYPRUS
Limassol
Hamah
SYRIA
Homs
Tripoli
LEBANON
Beirut
Damascus
Sour
Haifa
Irbid
Tel Aviv-Yafo
Az Zarqa
Amman
Jerusalem
Gaza
Beer Sheva
ISRAEL
Qurayyat
Alexandria
Port Said
Damanhur
El Mansura
Tanta
El Mahalla el Kubra
Zagazig
Ismailia
Cairo
El Giza
Suez
El Faiyum
Bani Sweif
El Minya
Asyut
Gulf of Suez
North Sinai
South Sinai
JORDAN
Al 'Aqabah
Tabouk
Sakakah
Al Jawf
Al Jouf
Al Khunfah
Alraudah
Northern borders
Hail
IRAQ
Ar Ramadi
Abu Ghurayb
Al Anbar
Karbala
Najaf
Samarra
lwe_thickness
50
25
0
-25
-50
2022-01-01T00:00:00.000Z
1fps
Leaflet | Tiles © Esri 2012 See Here

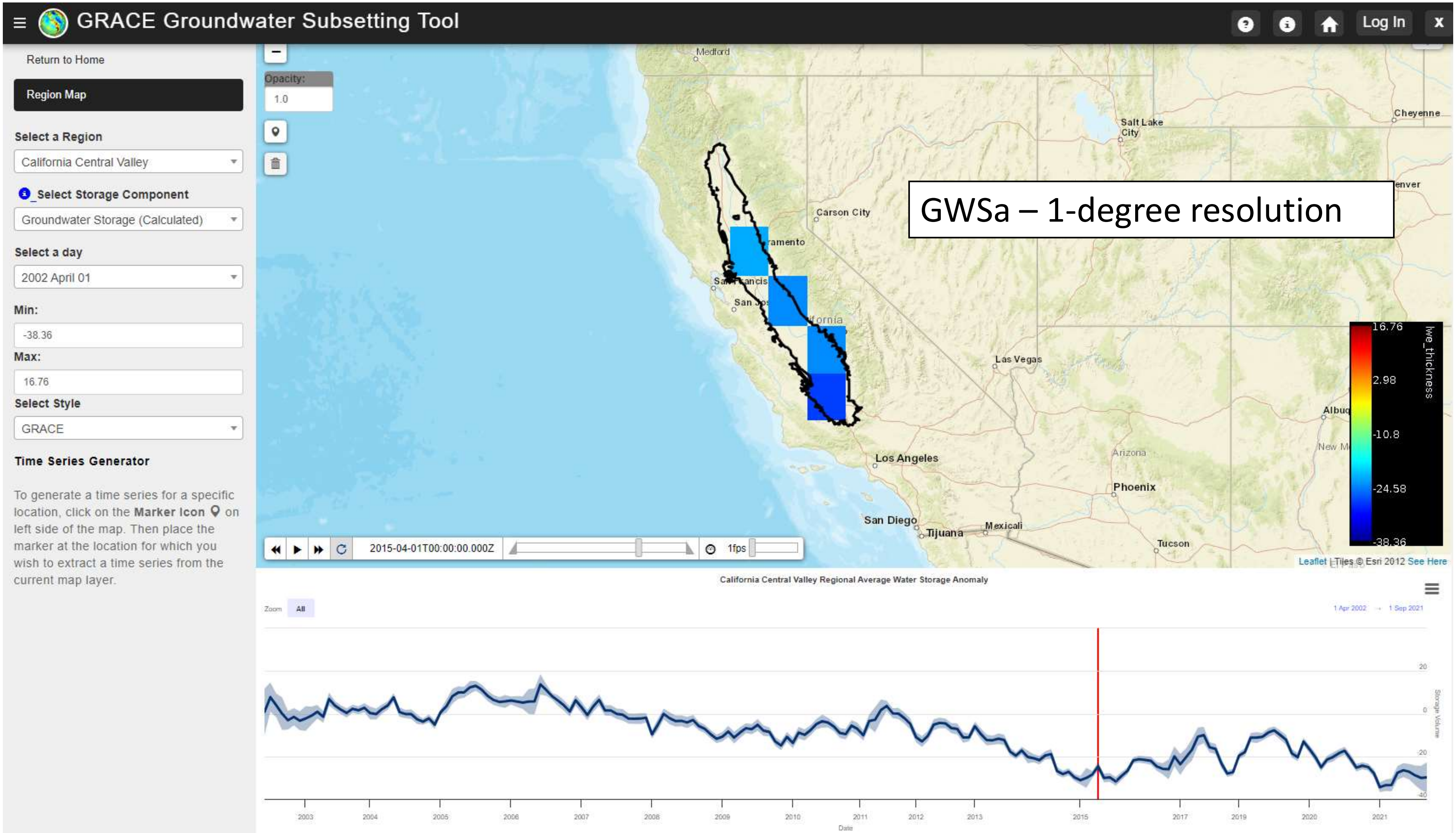
Down-scaled TWSa or GWSa GRACE cells inside the region are biased by water storage changes occurring outside the region due to coarse 3-degree resolution of native GRACE data.



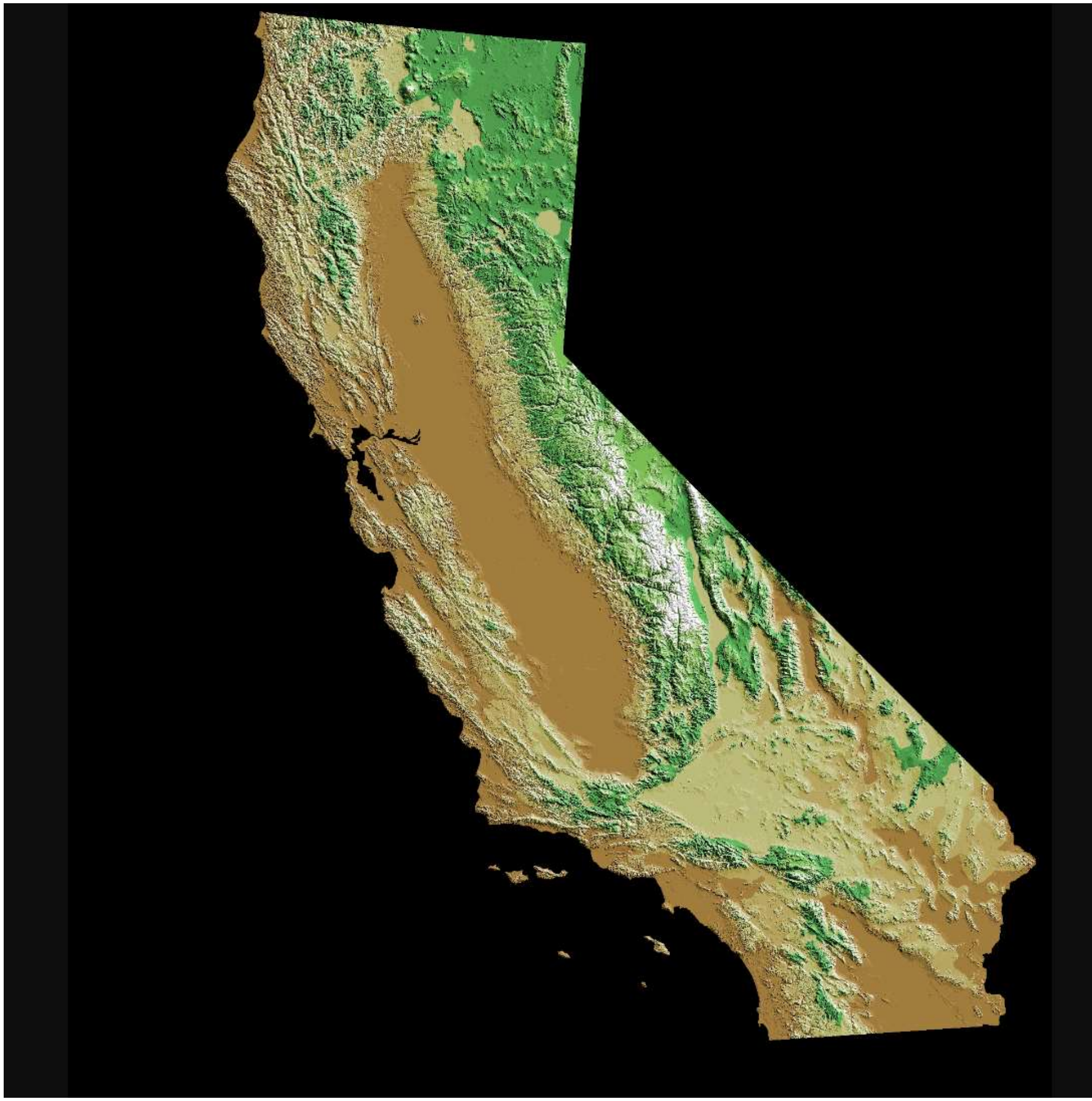
If storage changes are similar in both red and yellow areas, impact of leakage is minimal. But if storage changes are significantly different, leakage impact is more severe.

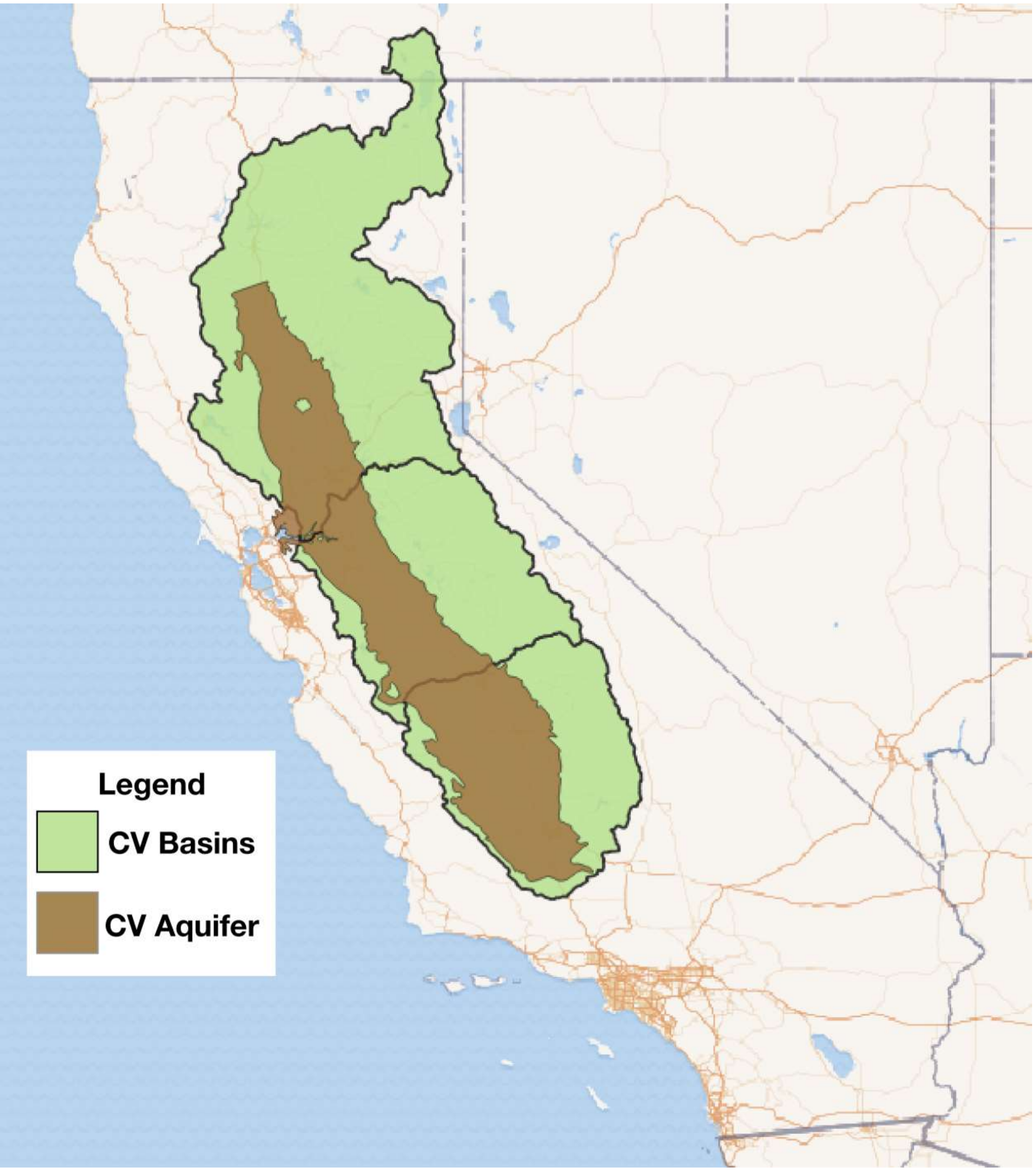
CASE STUDY - Central Valley California


GRACE Groundwater Subsetting Tool
Log In
Return to Home
Region Map
Select a Region
California Central Valley
Select Storage Component
Total Water Storage (GRACE)
Select a day
2002 April 17
Min:
-69.81
Max:
60.26
Select Style
GRACE
Time Series Generator
To generate a time series for a specific location, click on the Marker Icon on left side of the map. Then place the marker at the location for which you wish to extract a time series from the current map layer.
Opacity:
1.0
TWSa – 0.5-degree resolution
Medford
Salt Lake City
Cheyenne
Carson City
Las Vegas
Los Angeles
Arizona
Phoenix
San Diego
Tijuana
Mexicali
Tucson
60.26
27.7425
-4.775
-37.2925
-69.81
lwe_thickness
2014-06-13T00:00:00.000Z
1fps
Leaflet | Tiles © Esri 2012 See Here
California Central Valley Regional Average Water Storage Anomaly
Zoom
All
17 Apr 2002
16 Oct 2021
25
0
-25
-75
Storage Volume
Jul '02
Jan '04
Jan '05
Jan '06
Jan '07
Jan '08
Jan '09
Jan '10
Jan '11
Jul '12
Jan '14
Jul '15
Jan '17
Jul '19
Jul '20
Jul '21
Date


GRACE Groundwater Subsetting Tool
Log In
Return to Home
Region Map
Select a Region
California Central Valley
Select Storage Component
Groundwater Storage (Calculated)
Select a day
2002 April 01
Min:
-38.36
Max:
16.76
Select Style
GRACE
Time Series Generator
To generate a time series for a specific location, click on the Marker Icon on left side of the map. Then place the marker at the location for which you wish to extract a time series from the current map layer.
Opacity:
1.0
GWSa – 1-degree resolution
Medford
Salt Lake City
Cheyenne
Carson City
Las Vegas
Los Angeles
Phoenix
San Diego
Tijuana
Mexicali
Tucson
Arizona
16.76
2.98
-10.8
-24.58
-38.36
lwe_thickness
2015-04-01T00:00:00.000Z
1fps
Leaflet | Tiles © Esri 2012 See Here
California Central Valley Regional Average Water Storage Anomaly
Zoom
All
1 Apr 2002
1 Sep 2021
20
0
-20
-40
Storage Volume
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2015
2017
2019
2020
2021
Date

Groundwater pumping in the Central Valley is highly concentrated relative to surrounding areas, thus amplifying the leakage effect with GRACE data.





STRATEGY #1

Most researchers deal with the Central Valley leakage problem by performing a GRACE analysis on the larger hydrographic basin containing the central valley aquifer, and then using the GWSa from that analysis and assuming that the GW pumping is almost all confined to the aquifer.

$GW\_Vol_{aquifer} = LWE_{basin} * Area_{basin}$

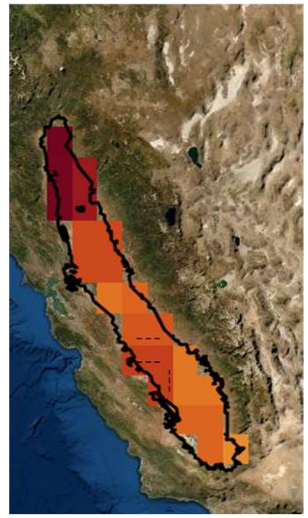
I.e., entire GWSa from basin is assumed to apply to aquifer

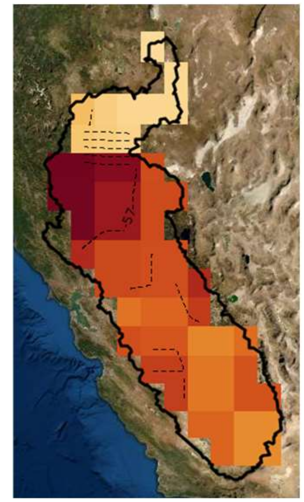
GRACE Basin Comparison

Central Valley

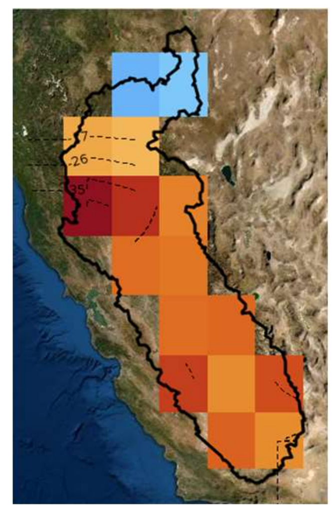
Sacramento / SJ River Basins

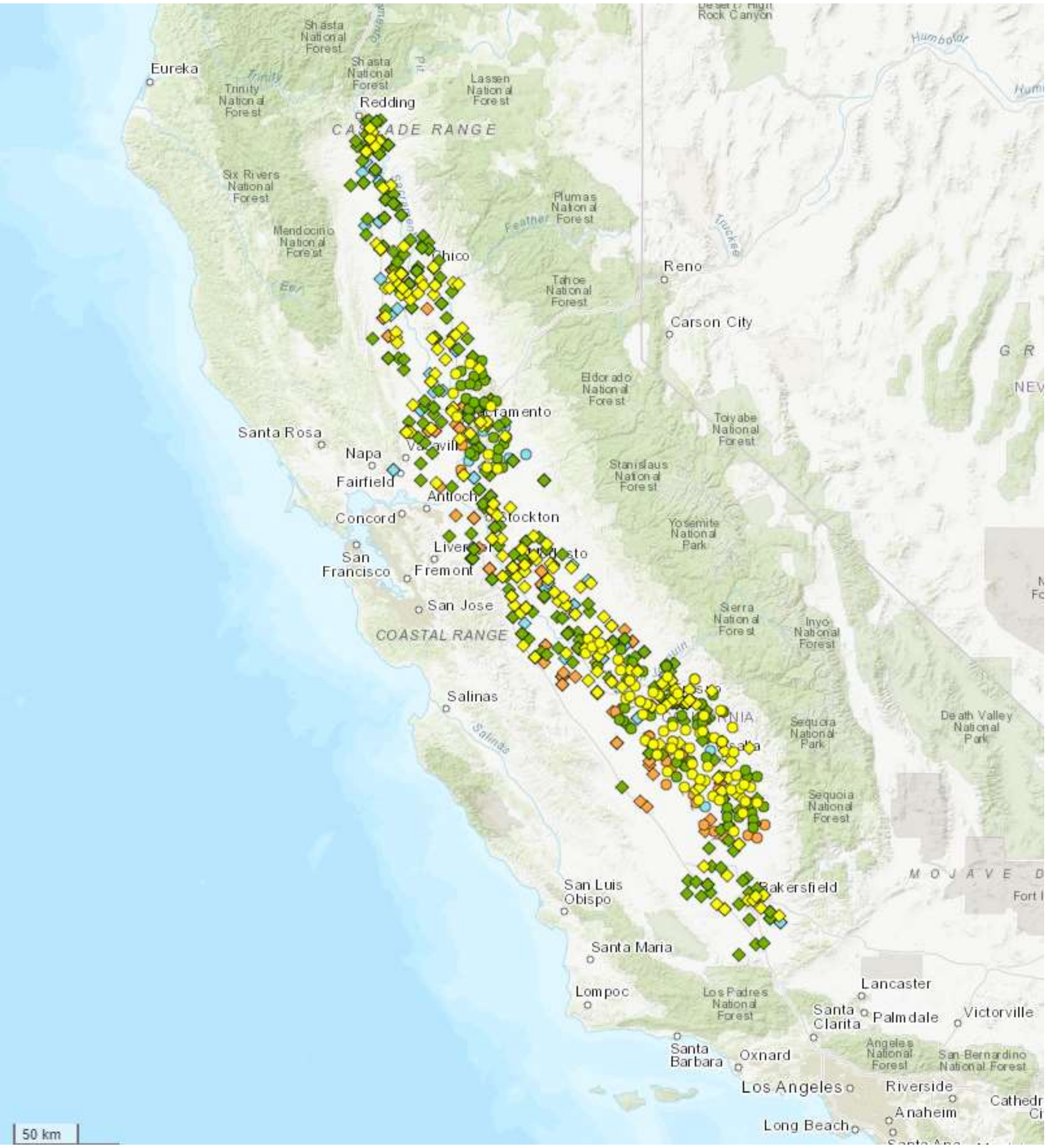
GRACE **TWSa**
0.5° Resolution





GRACE-derived **GWa**
1° Resolution



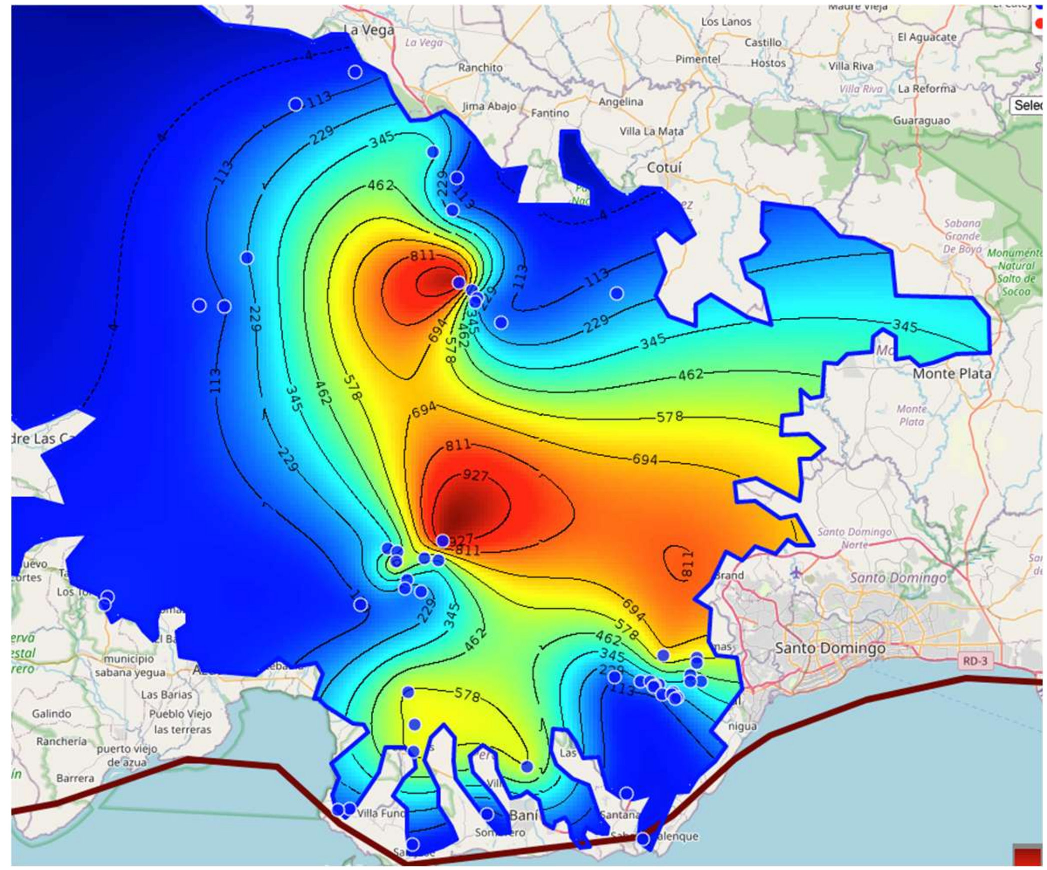


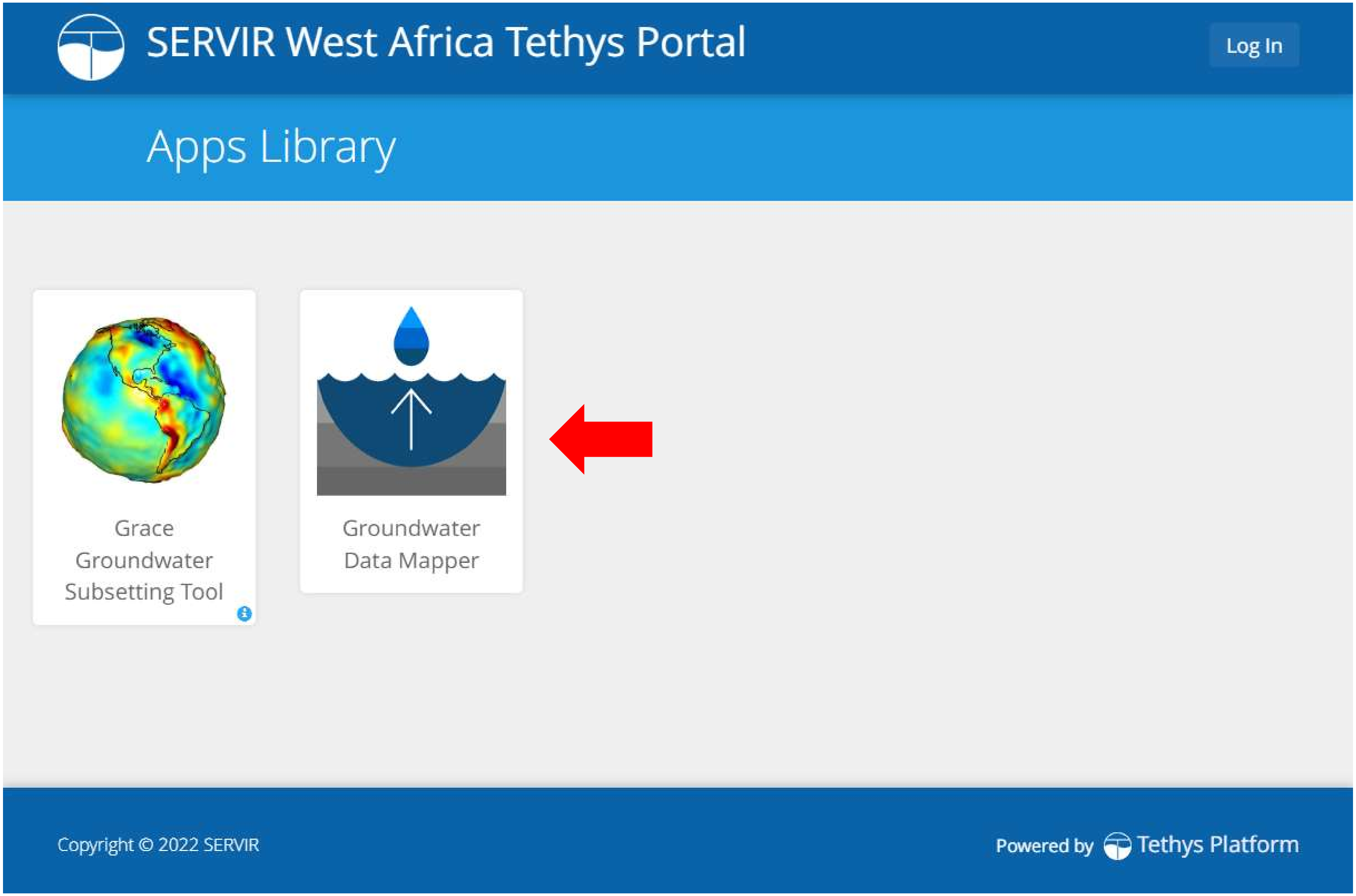
STRATEGY #2

Analyze in situ well data and look at long-term groundwater level changes to estimate groundwater storage change (GWSa) over the entire region over the same time period as GRACE data. Compare GWSa from both GRACE and in situ method and calculate a scaling ratio to apply to GRACE GWSa to account for leakage.

Our BYU research team recently completed a study to do this.

Groundwater Level Mapping and Storage Analysis

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Log In
Apps Library
Grace Groundwater Subsetting Tool
Groundwater Data Mapper
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Overview

Select Language

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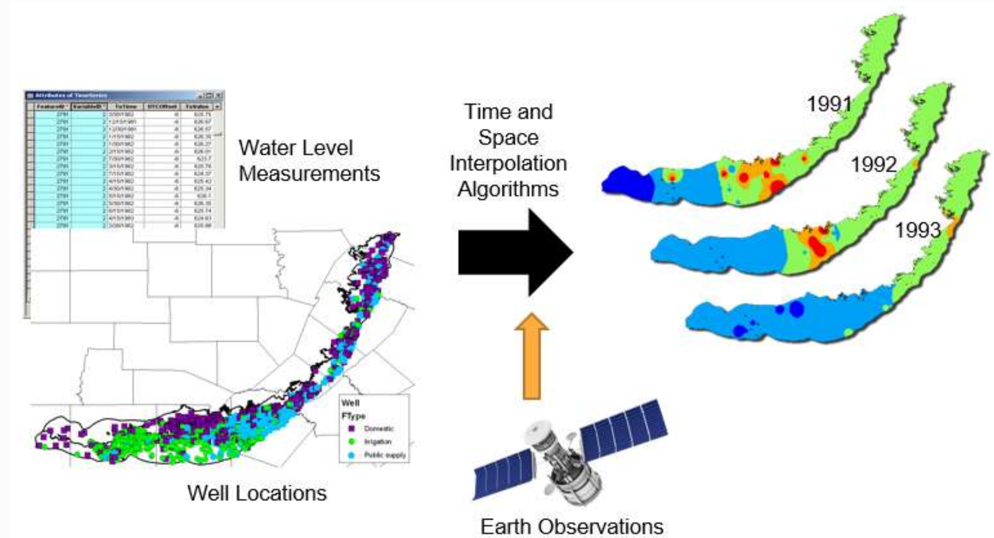
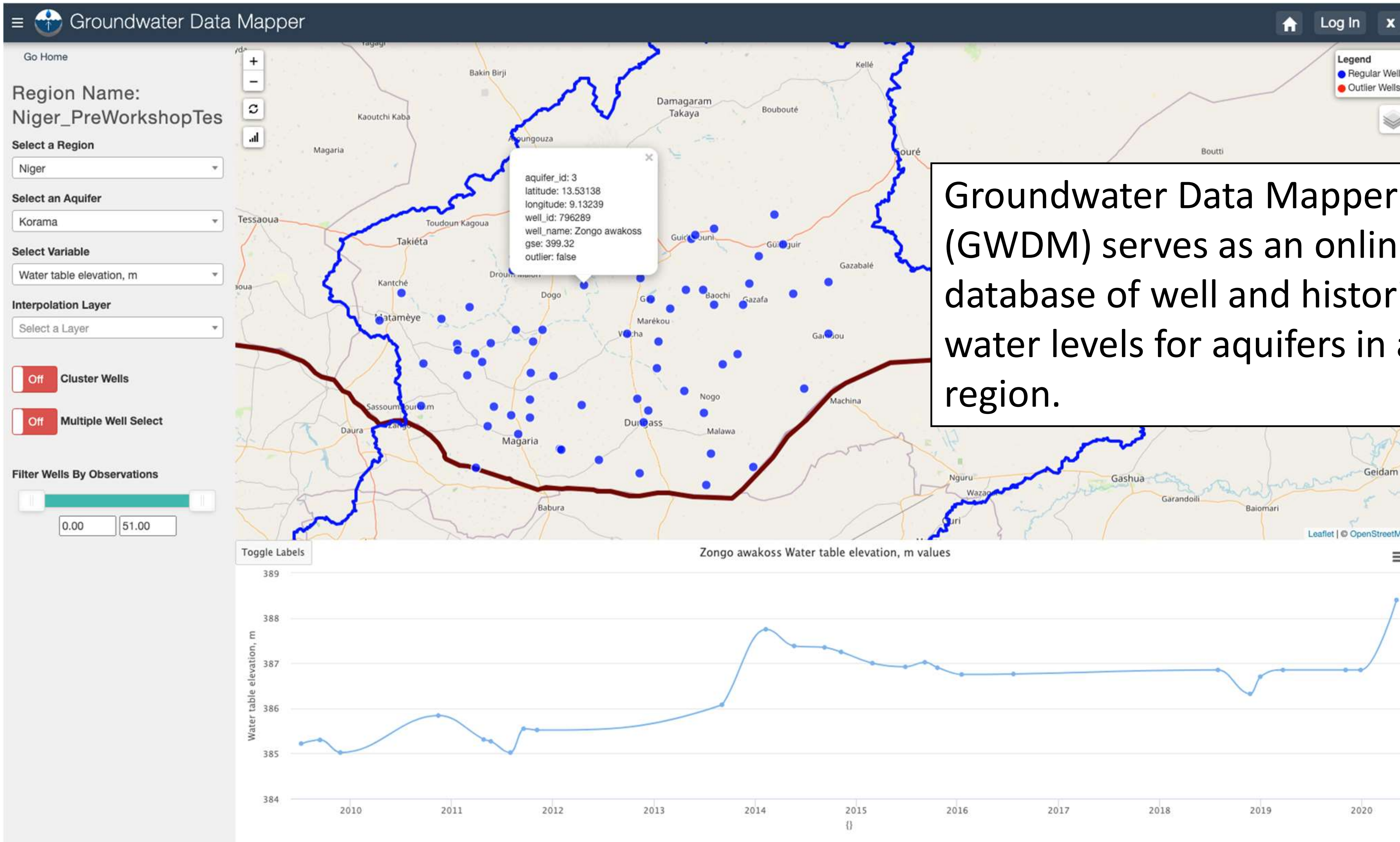
Water managers in Western Africa and around the world face the daunting task of managing freshwater resources in the face of increased demand from industry, agriculture, climate change, and population growth. As surface water resources become fully allocated, groundwater is increasingly targeted to make up surface water deficits, particularly during periods of drought. As a result, many of our aquifers are not being managed in a sustainable fashion, resulting in reduced water quality, land subsidence, increased pumping costs, and in some cases, the complete exhaustion of an aquifer and the loss of groundwater as a buffer during times of drought.

Mapping Algorithm

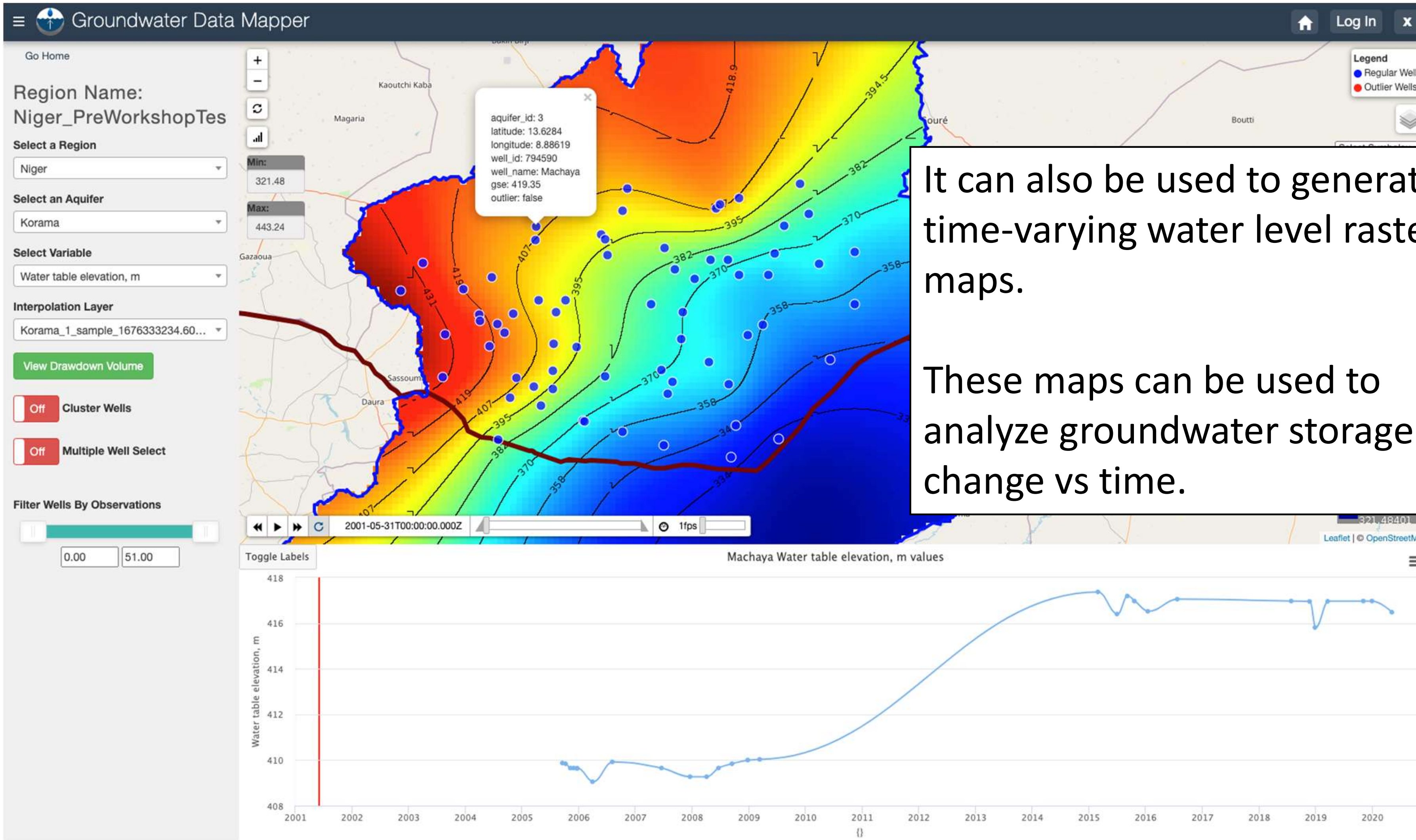


Even when water managers have access to large data sets of historical groundwater level measurements, at any individual well these measurements often exhibit significant time gaps. Aggregating and synthesizing these well measurements to provide information that supports a holistic assessment of aquifer level sustainability can be a challenging task. In partnership with NASA SERVIR, we have developed a series of algorithms that use these existing well measurements combined with Earth Observation data to analyze changes in water tables and characterize aquifer storage over time. Our approach involves collecting data describing well locations and any historical water level measurements in an aquifer. To evaluate aquifer behavior, we need to impute missing data at each well location so that we have data at each time step for analysis. To impute (or estimate) missing measurements at each well, we use a machine learning approach that trains models to use Earth observation data. Using this approach, we generate a time series for each well and use these data to spatially interpolate the water table at each time step.

These interpolated water table maps can be used to evaluate the sustainability of the aquifer by looking at the changes to aquifer storage over time. We



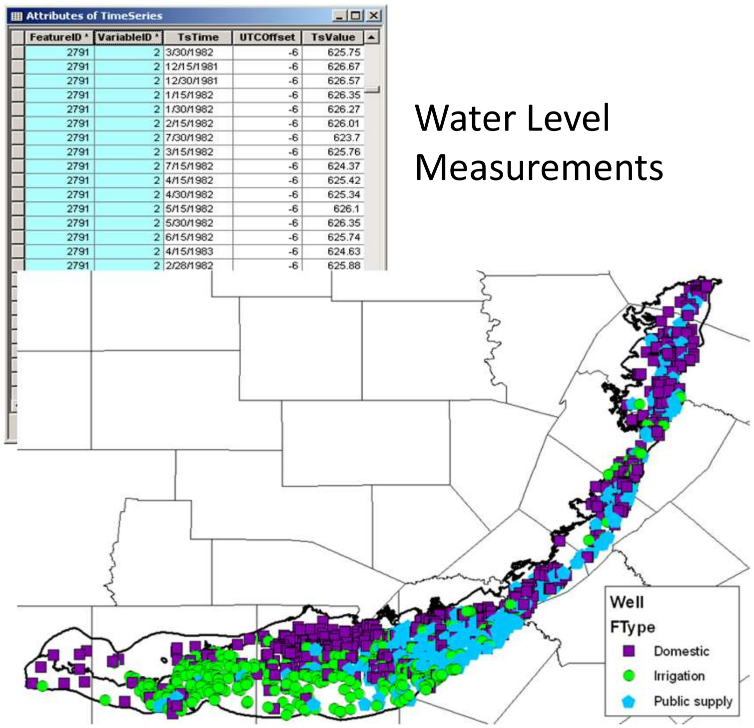
Groundwater Data Mapper (GWDM) serves as an online database of well and historical water levels for aquifers in a region.



It can also be used to generate time-varying water level raster maps.

These maps can be used to analyze groundwater storage change vs time.

Groundwater Data Mapping



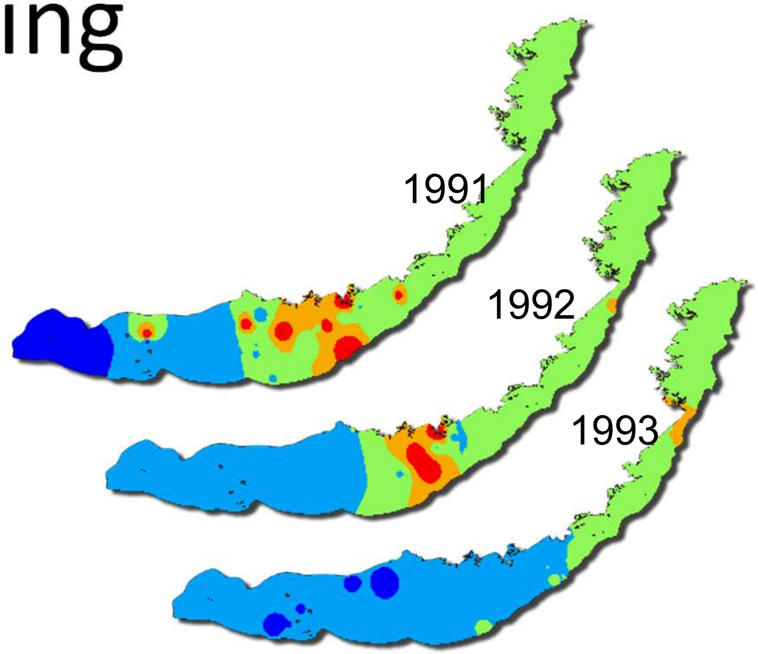
Attributes of TimeSeries

FeatureID *	VariableID *	TsTime	UTCOffset	TsValue
2791	2	3/30/1982	-6	625.75
2791	2	12/15/1981	-6	626.67
2791	2	12/30/1981	-6	626.57
2791	2	1/15/1982	-6	626.35
2791	2	1/30/1982	-6	626.27
2791	2	2/15/1982	-6	626.01
2791	2	7/30/1982	-6	623.7
2791	2	3/15/1982	-6	625.76
2791	2	7/15/1982	-6	624.37
2791	2	4/15/1982	-6	625.42
2791	2	4/30/1982	-6	625.34
2791	2	5/15/1982	-6	626.1
2791	2	5/30/1982	-6	626.35
2791	2	6/15/1982	-6	625.74
2791	2	4/15/1983	-6	624.63
2791	2	2/28/1982	-6	625.88

Water Level Measurements

Well Locations

Time and Space Interpolation Algorithms



Earth Observations

Step 1

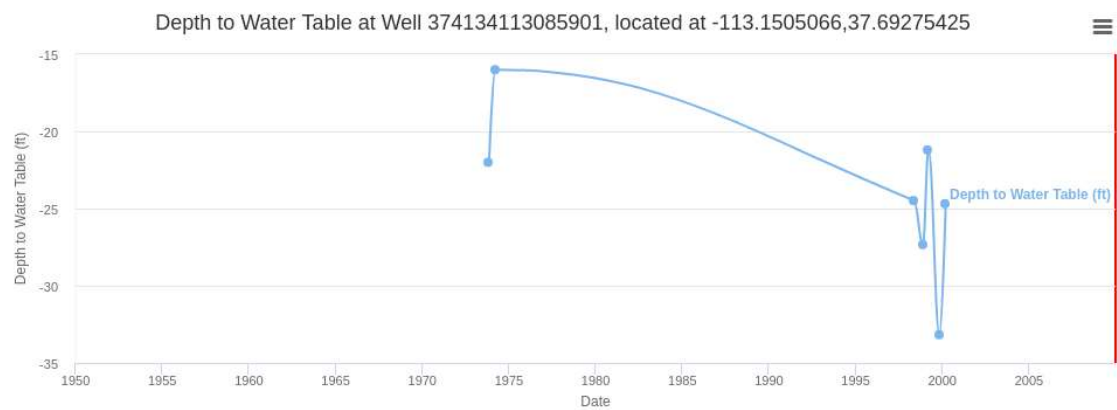
Impute gaps in water level time series using machine learning and Earth observations

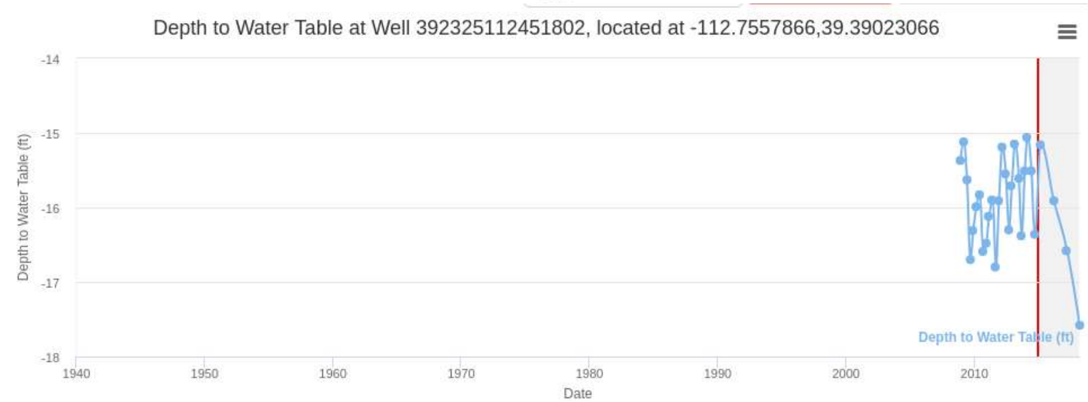
The Challenge - Temporally Sporadic Data

- Well Time series often include large gaps in collected data

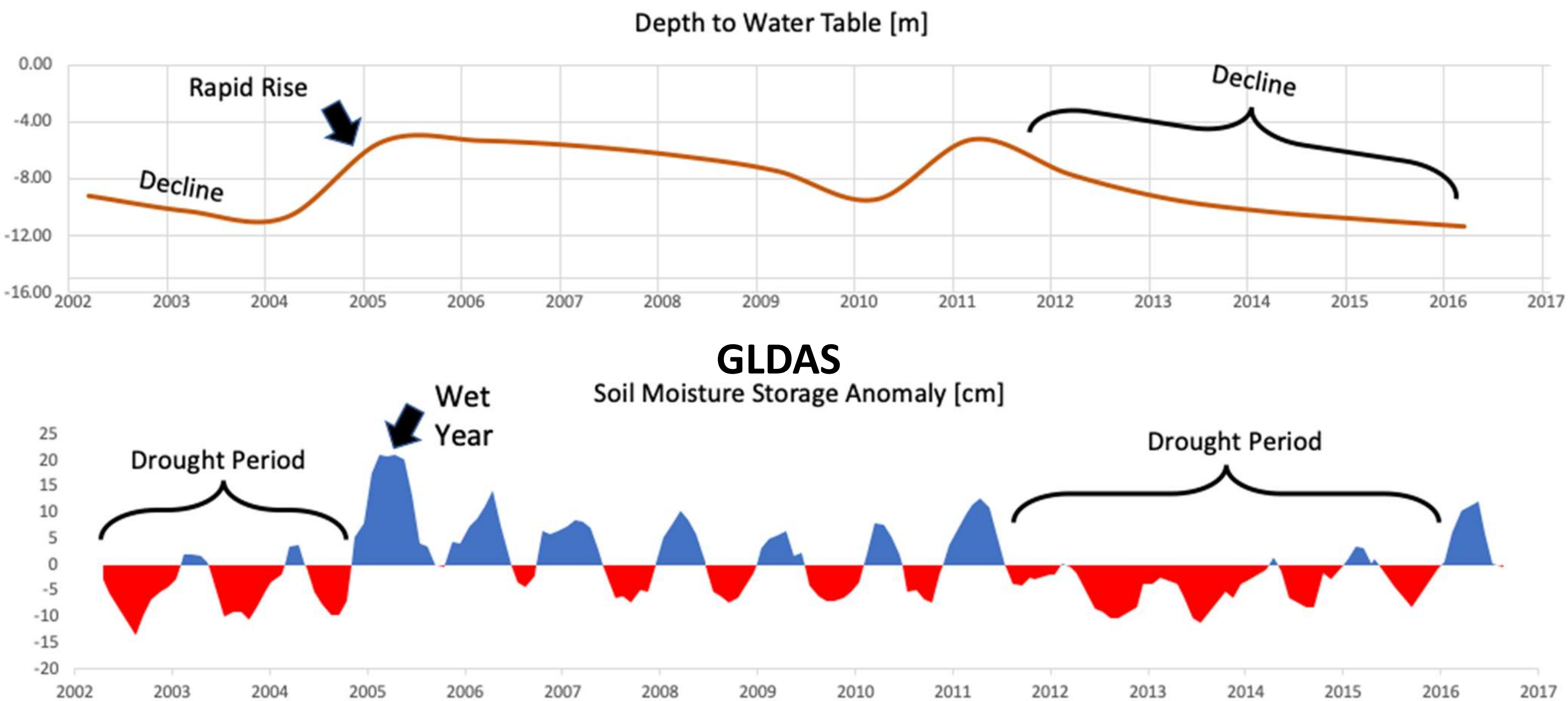
- Some wells may only have data for one or two years

We need a more complete water level time series dataset to adequately characterize groundwater storage changes

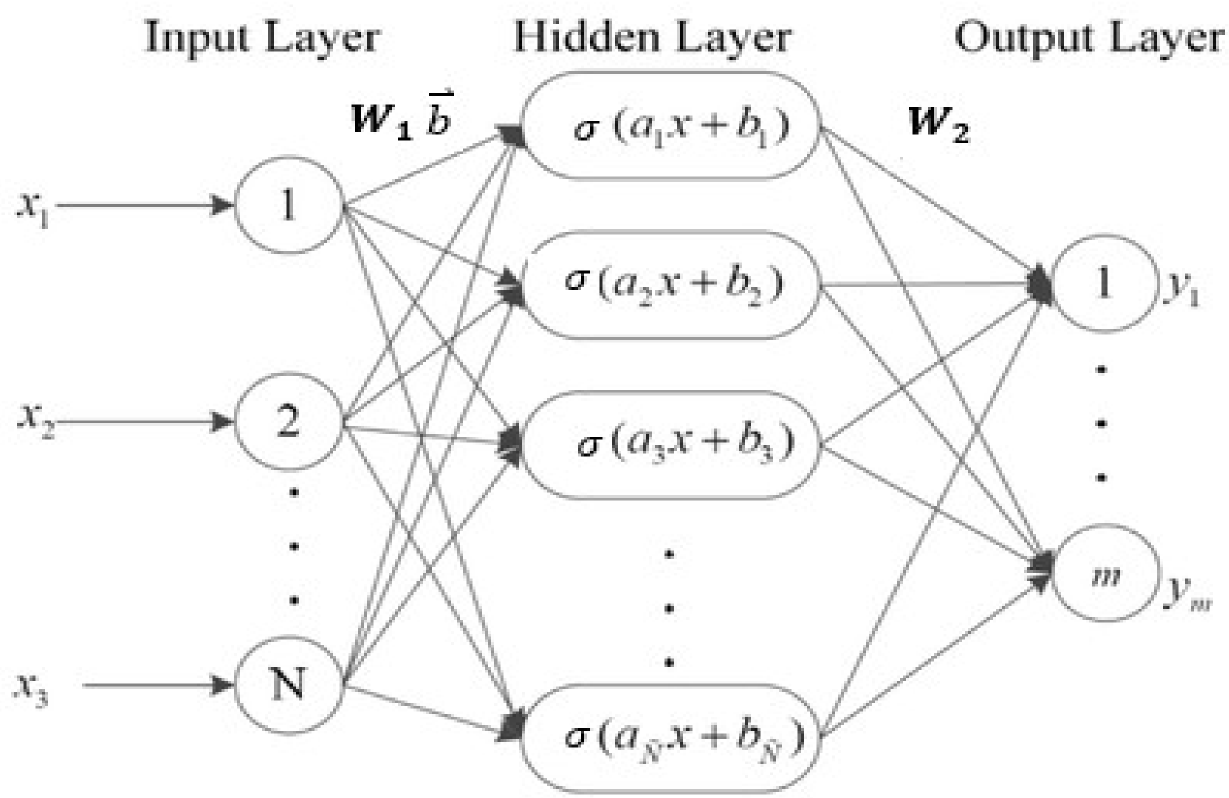




Correlation with Earth Observations



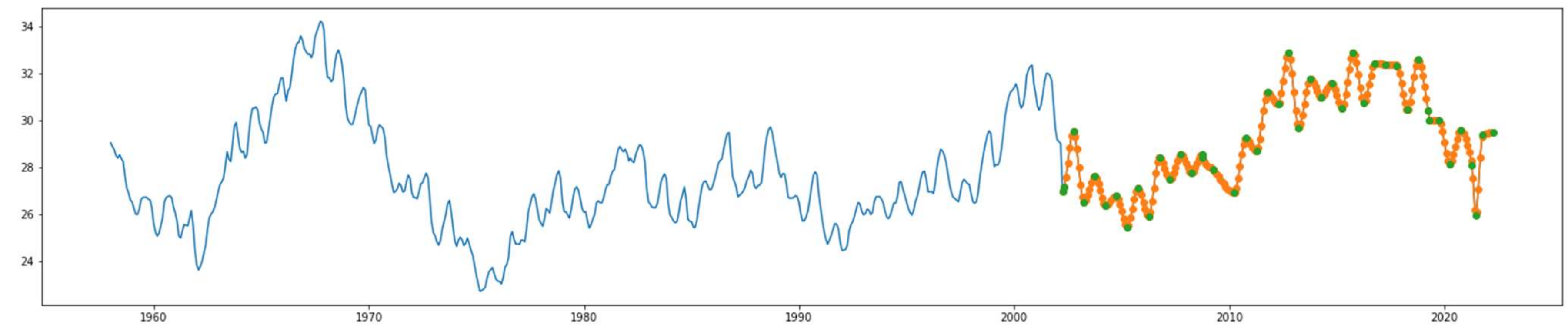
Extreme Learning Machine

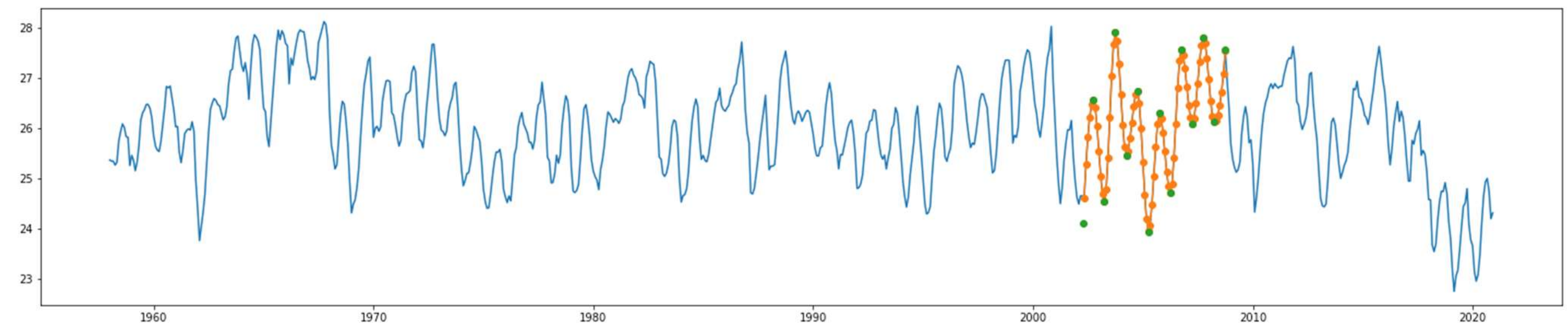


$$\vec{Y} = \boldsymbol{W}_2 * \sigma(\boldsymbol{W}_1\boldsymbol{X} + \vec{b})$$

$$\sigma(x) = \max(0, x)$$

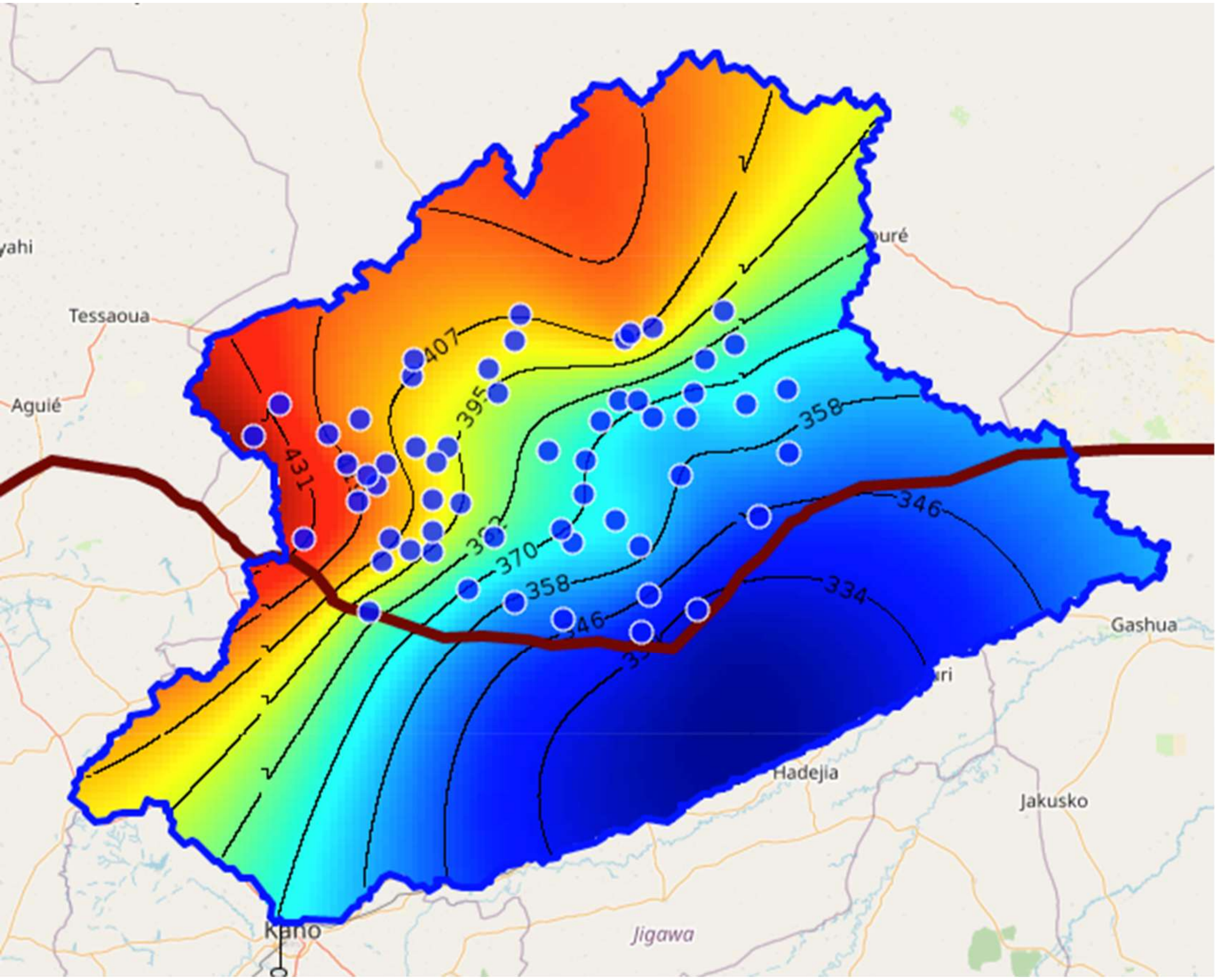
At the end of this step, we have a complete time series for each well over the mapping/interpolation range (one value per month)





Step 2

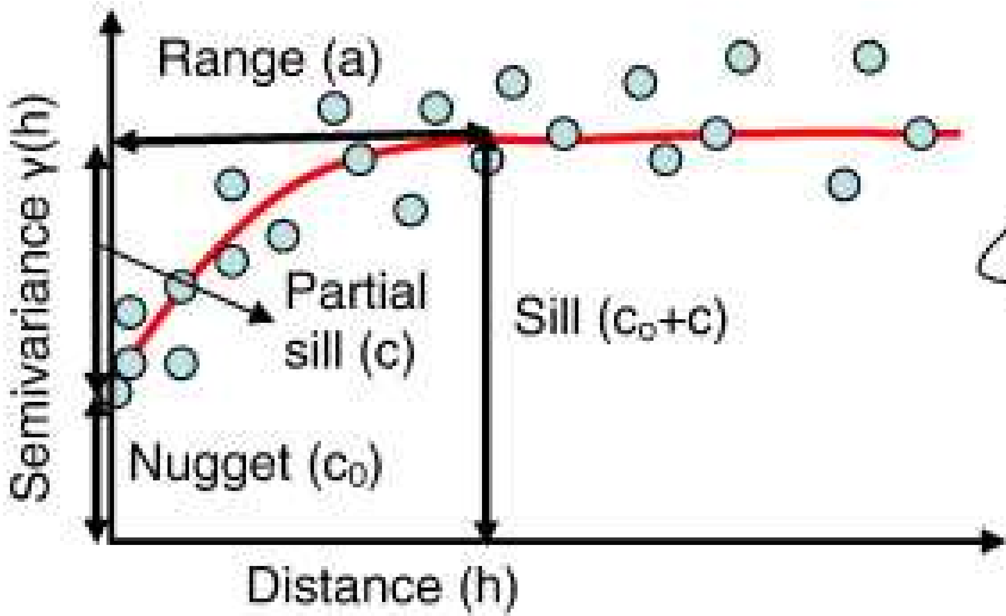
Generate rasters by spatially interpolating values from time series at selected points in time

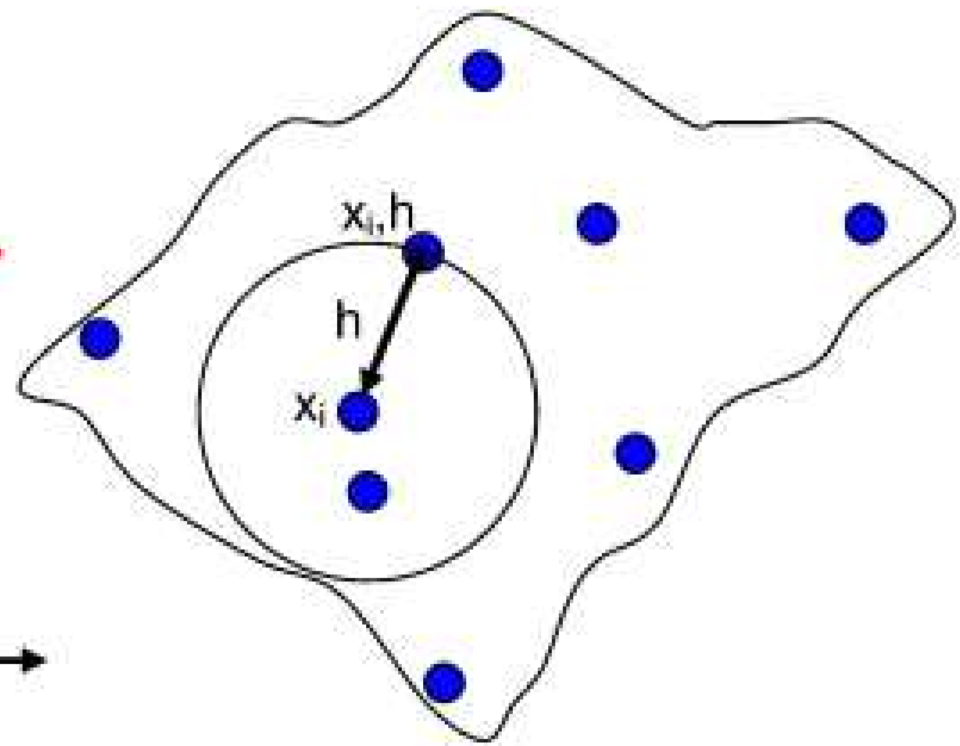


In this step we interpolate from the well locations using water levels at selected time intervals to create one raster for each time internal (2000, 2001, 2002, etc.)

The output is a time-varying array of rasters

Kriging Algorithm

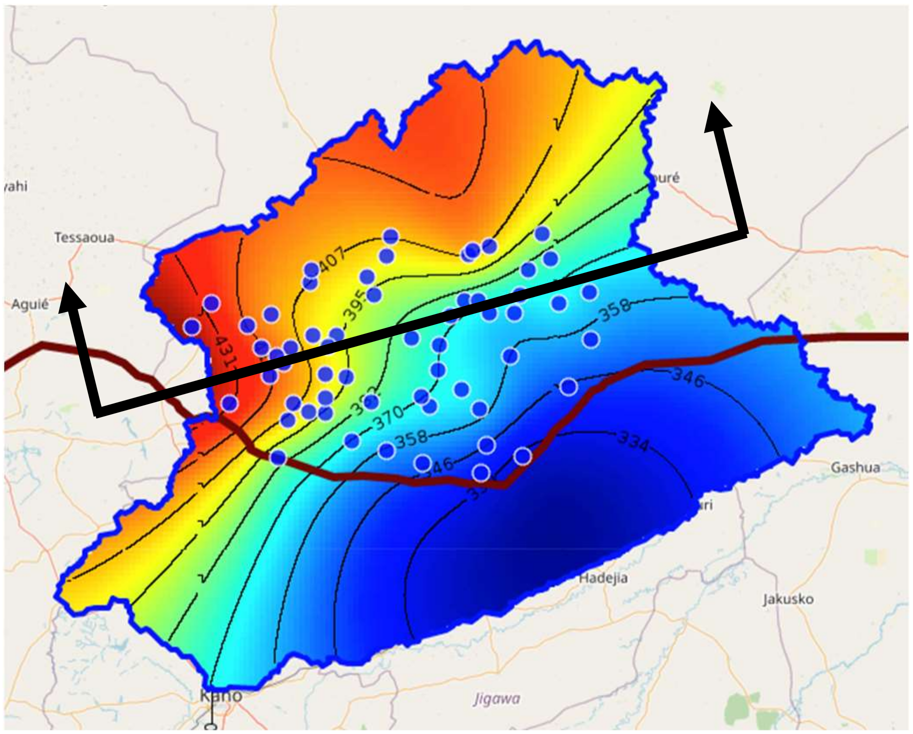


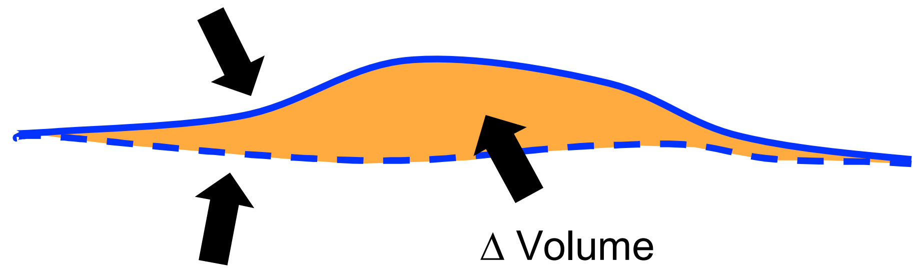


Step 3

Evaluate changes in rasters over time to calculate groundwater storage time series

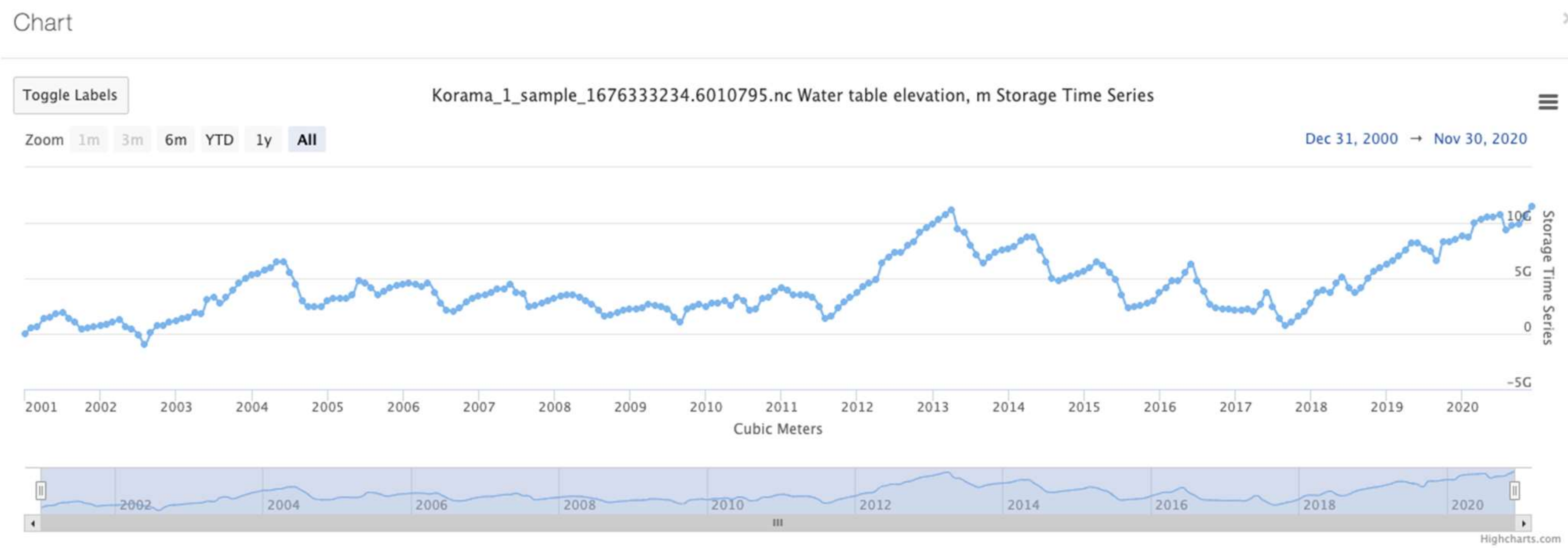
Storage Time Series Calculations





Δ GW Storage = Sy * Δ Volume

Storage Change Time Series



Mapping Algorithm Python Script – Colab Notebook

Aquifer-Interpolation-Final.ipynb

File Edit View Insert Runtime Tools Help Last saved at 8:35 AM

+ Code + Text

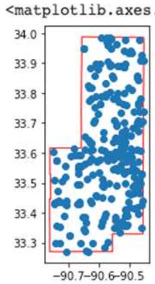
264	335860090334401	133A0089 SUNFLOWER	33.983100	-90.562128	150.53	133
265	335905090343001	133A0054 SUNFLOWER	33.984834	-90.575096	145.00	133
266	335909090353901	133A0052 SUNFLOWER	33.985945	-90.594263	145.00	133

267 rows × 6 columns

```
wells_gdf = gpd.GeoDataFrame(wells, geometry=gpd.points_from_xy(wells["long_dec"], wells["lat_dec"]))
```

```
import matplotlib.pyplot as plt
fig, ax = plt.subplots()
aquifer.plot(color="none", edgecolor="red", ax=ax)
wells_gdf.plot(ax=ax)
```

```
<matplotlib.axes._subplots.AxesSubplot at 0x7fb7f73b2be0>
```




```
upload_timeseries = files.upload()
```

Choose Files No file chosen Upload widget is only available when the cell has been executed in the current browser session. Please rerun this cell to enable.

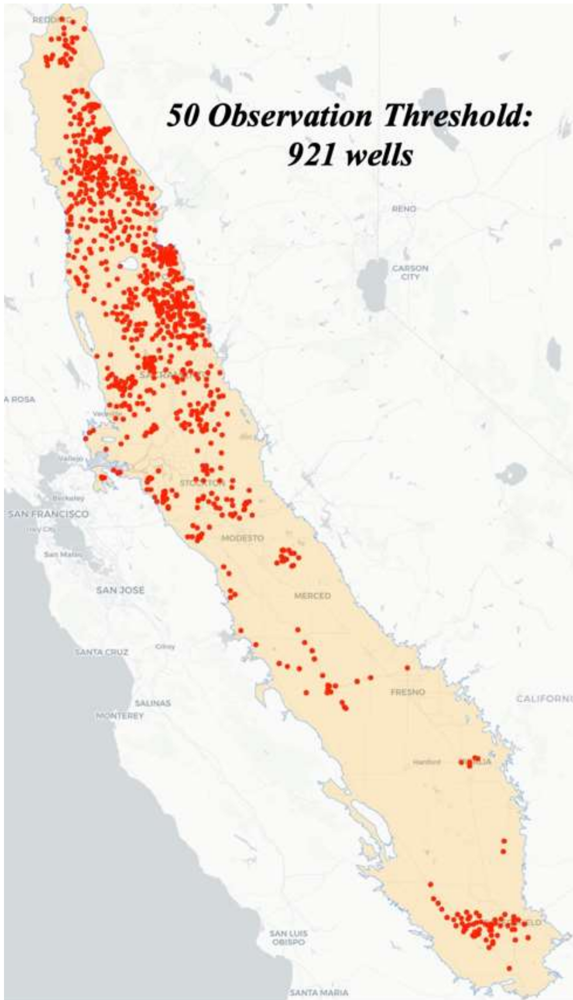
```
Saving sunflower_ts.csv to sunflower_ts.csv
```

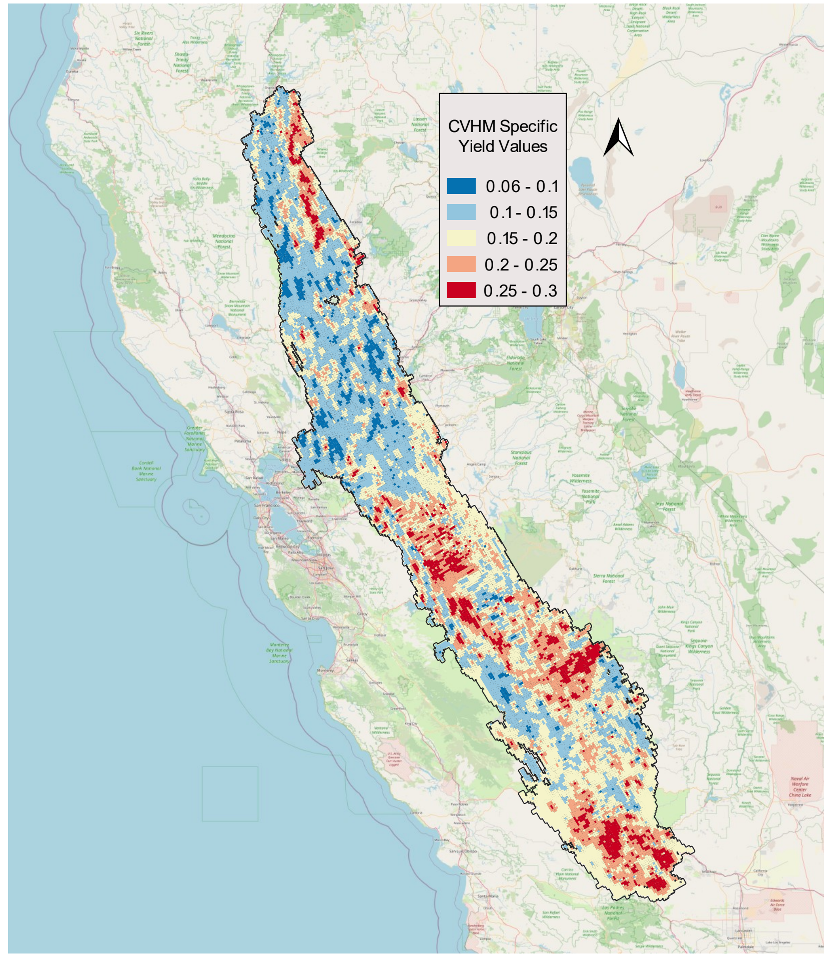
```
measurements = pd.read_csv(list(upload_timeseries.keys())[0])
measurements
```

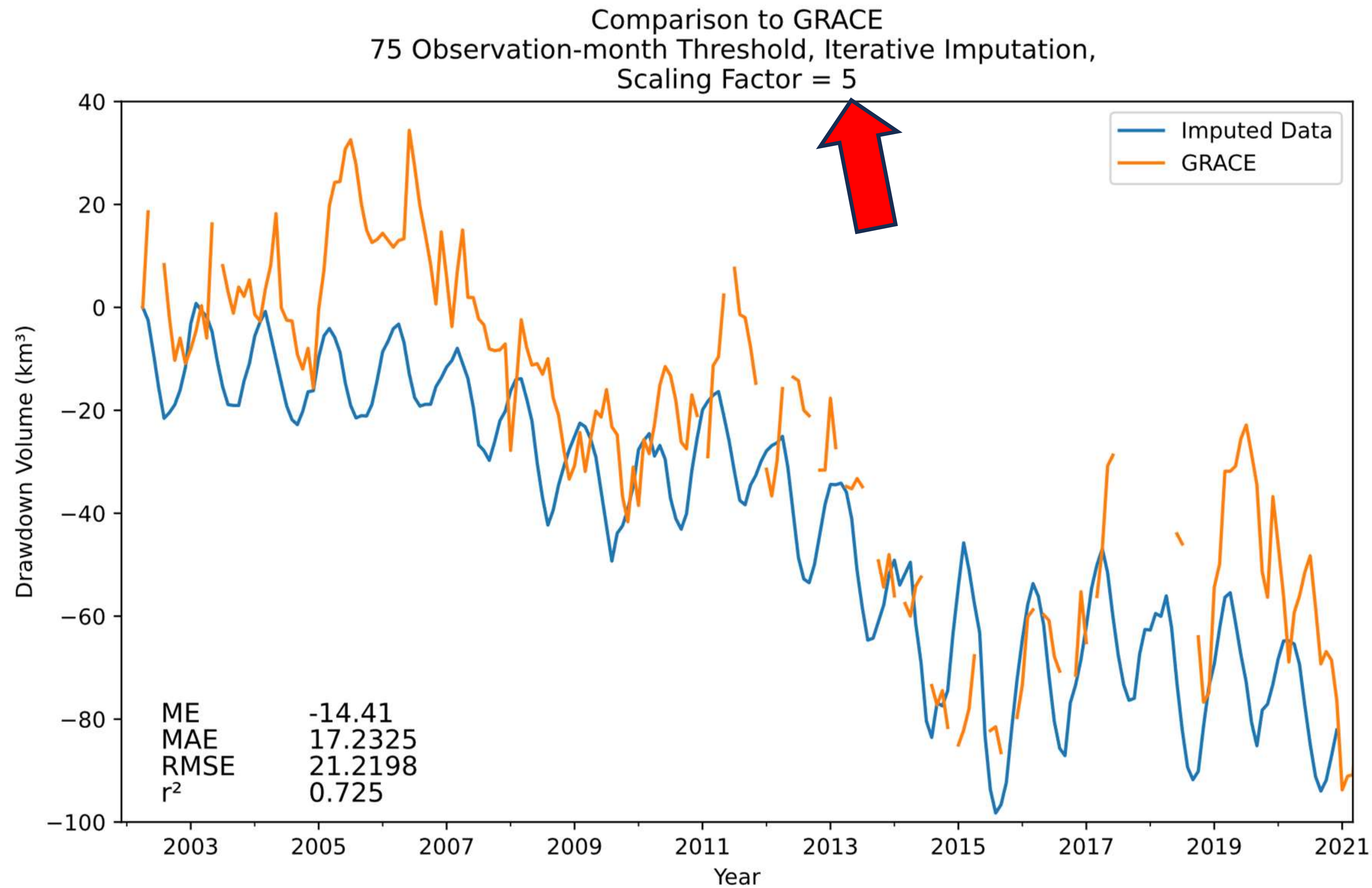
Process is executed step-by-step for better control over results

Resulting rasters can be uploaded to GWDM app via admin control panel

Application to the Central Valley






Comparison to GRACE
75 Observation-month Threshold, Iterative Imputation,
Scaling Factor = 5
Imputed Data
GRACE
Drawdown Volume (km³)
Year
40
20
0
−20
−40
−60
−80
−100
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
ME -14.41
MAE 17.2325
RMSE 21.2198
r² 0.725

Conclusion

- Good agreement between GRACE GWSa and in situ GWSa after applying scaling factor
- Going forward, GRACE GWSa can be used reliably after applying scaling factor = 5

Groundwater Storage Loss in the Central Valley Analysis Using a Novel Method based on *In Situ* Data Compared to GRACE-Derived Data

Michael D. Stevens[1], Saul G. Ramirez[1], Eva-Marie H. Martin[2], *Norman L. Jones[1], Gustavious P. Williams[1], Kyra H. Adams[3], Daniel P. Ames[1], Cedric H. David[3], J.T. Reager[3], Sarva T. Pulla[4]

[1]Brigham Young University, Department of Civil and Construction Engineering, Provo, UT, USA

[2]Eva needs to check what to put here

[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

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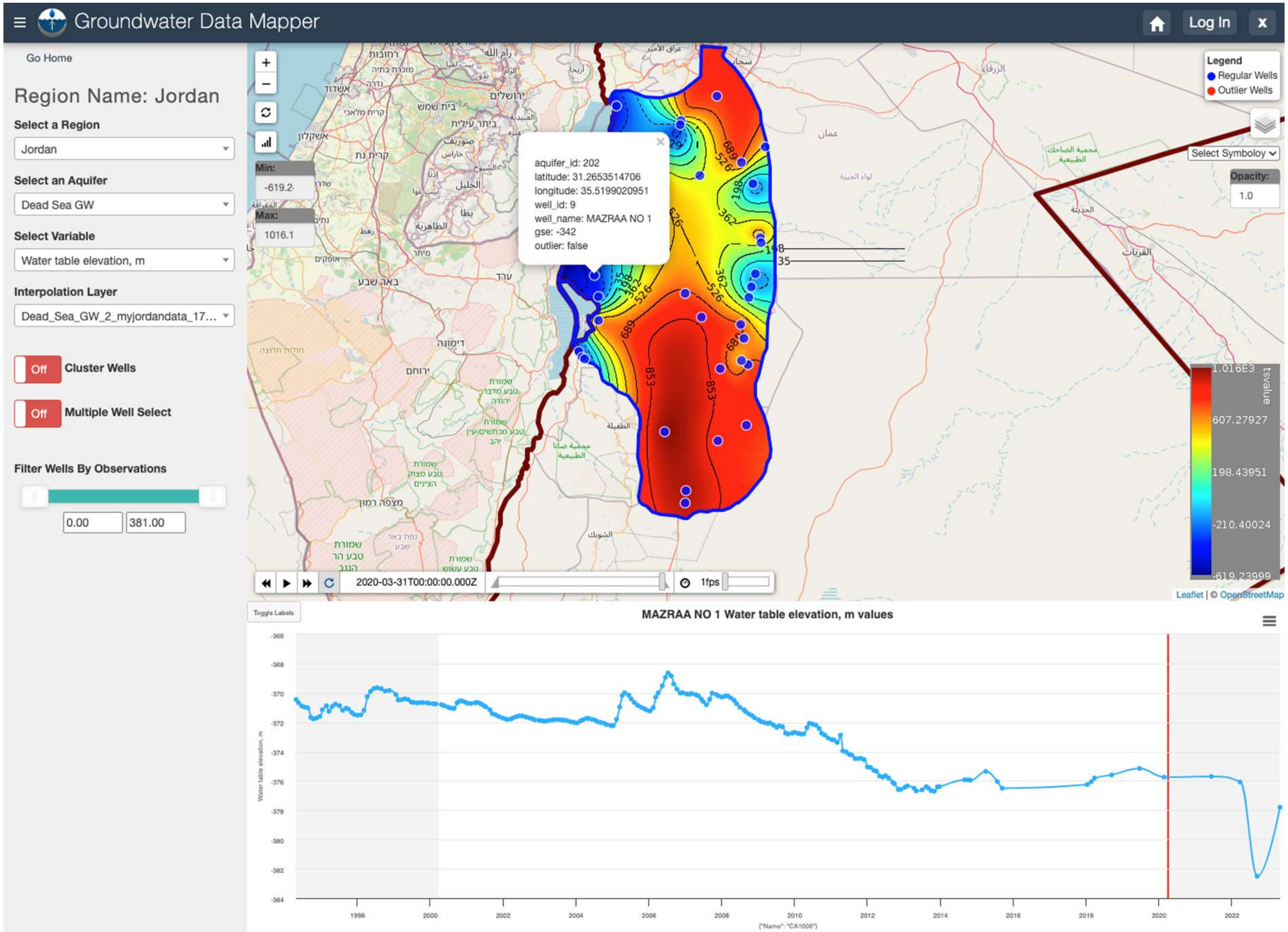
Keywords: Machine Learning, Groundwater, Central Valley, Sustainability, GRACE

Abstract

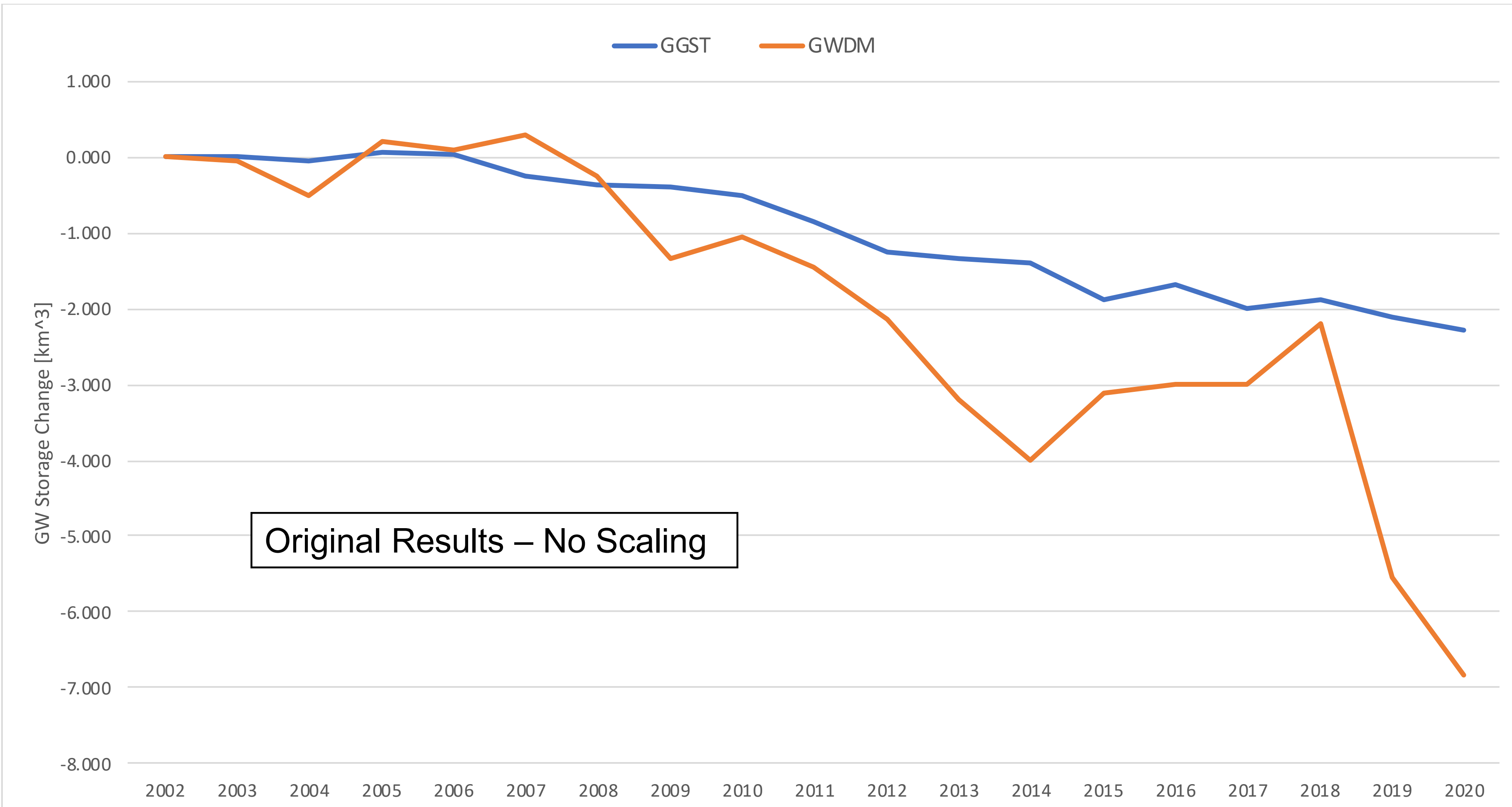
We estimate long-term groundwater storage loss in California's Central Valley (CV) with a novel data imputation method that uses *in situ* data combined with globally available Earth Observations - the Palmer Drought Severity Index (PDSI), and the Global Land Data Assimilation System (GLDAS) - to generate temporally- and spatially-interpolated groundwater elevations which we combine with storage coefficient maps to produce computed volume changes over time for the valley. We compare our results to groundwater storage changes we calculated using Gravity Recovery and Climate Experiment (GRACE) mission data and show that the two storage estimates are significantly correlated. We also compare our results with previously published groundwater storage changes using GRACE-derived data and show that the trends match well. However, while correlated, the GRACE-derived storage values are significantly lower than estimates derived from in situ data. This is because the area of the CV is small compared to GRACE pixels and therefore the GRACE data includes areas without active groundwater changes, in this case the Sierra and coastal mountain ranges, and GRACE pixels within the CV experience "leakage" where values within a pixel are influenced by surrounding areas. While other researchers have accounted for leakage by scaling the GRACE results based on the ratio of the area of the CV to the larger CV hydrographic basin.ur method demonstrates a direct method for calibrating GRACE estimated groundwater change, which can then be applied to future GRACE results with confidence. This method can be replicated globally at a variety of aquifer scales to account for both pixel size and leakage affects with minimal *in situ* data.

Journal article manuscript under development

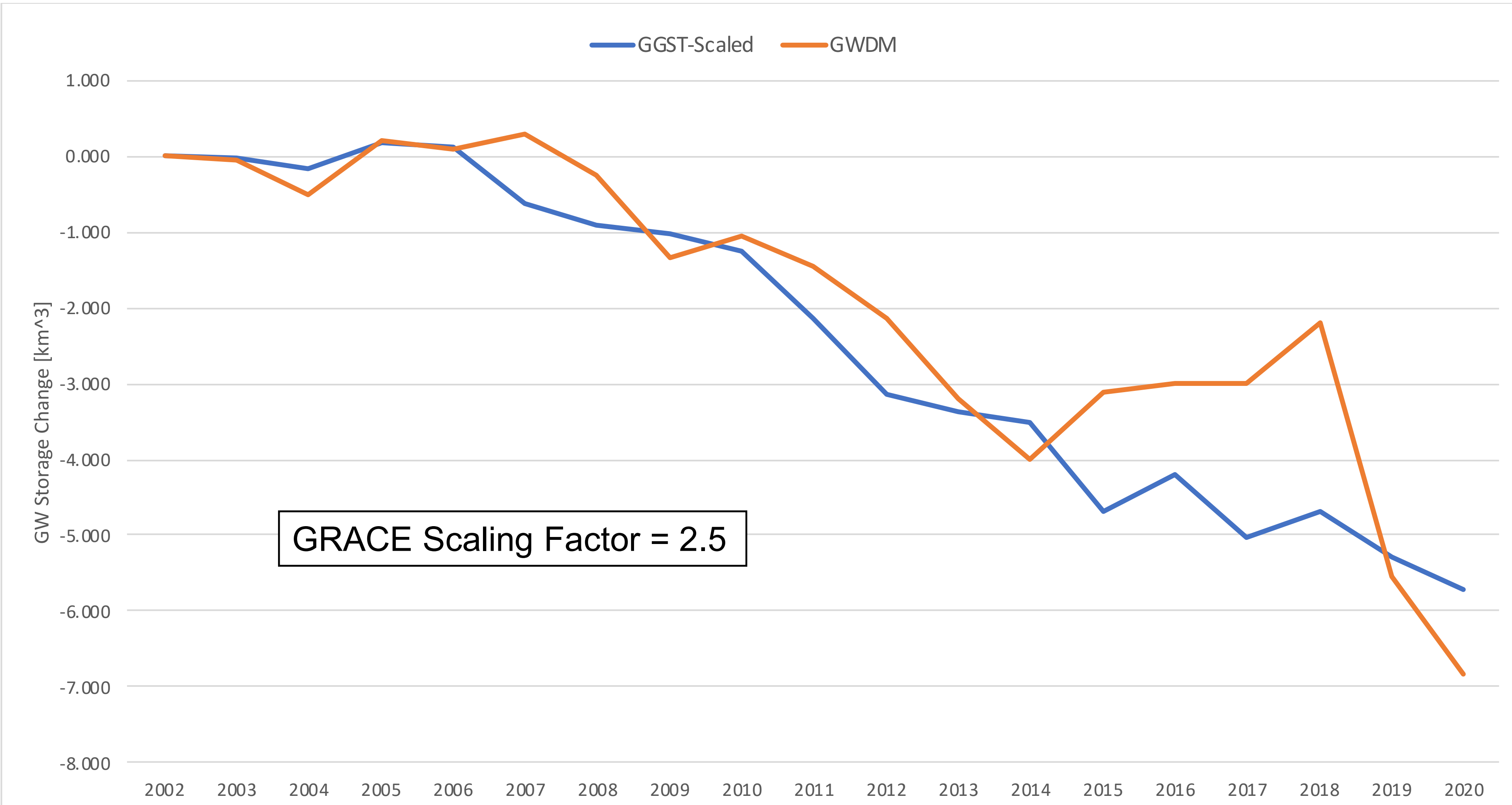


Groundwater Data Mapper
Log In
Go Home
Region Name: Jordan
Select a Region
Jordan
Select an Aquifer
Dead Sea GW
Select Variable
Water table elevation, m
Interpolation Layer
Dead_Sea_GW_2_myjordandata_17...
Off
Cluster Wells
Off
Multiple Well Select
Filter Wells By Observations
0.00
381.00
Min:
-619.2
Max:
1016.1
aquifer_id: 202
latitude: 31.2653514706
longitude: 35.5199020951
well_id: 9
well_name: MAZRAA NO 1
gse: -342
outlier: false
Legend
Regular Wells
Outlier Wells
Select Symboloy
Opacity:
1.0
1.016E3
607.27927
198.43951
-210.40024
-619.23999
tsvalue
2020-03-31T00:00:00.000Z
1fps
Leaflet | © OpenStreetMap
Toggle Labels
MAZRAA NO 1 Water table elevation, m values
Water table elevation, m
{"Name": "CA1006"}

Dead Sea Basin – Groundwater Depletion



Dead Sea Basin – Groundwater Depletion



Questions?