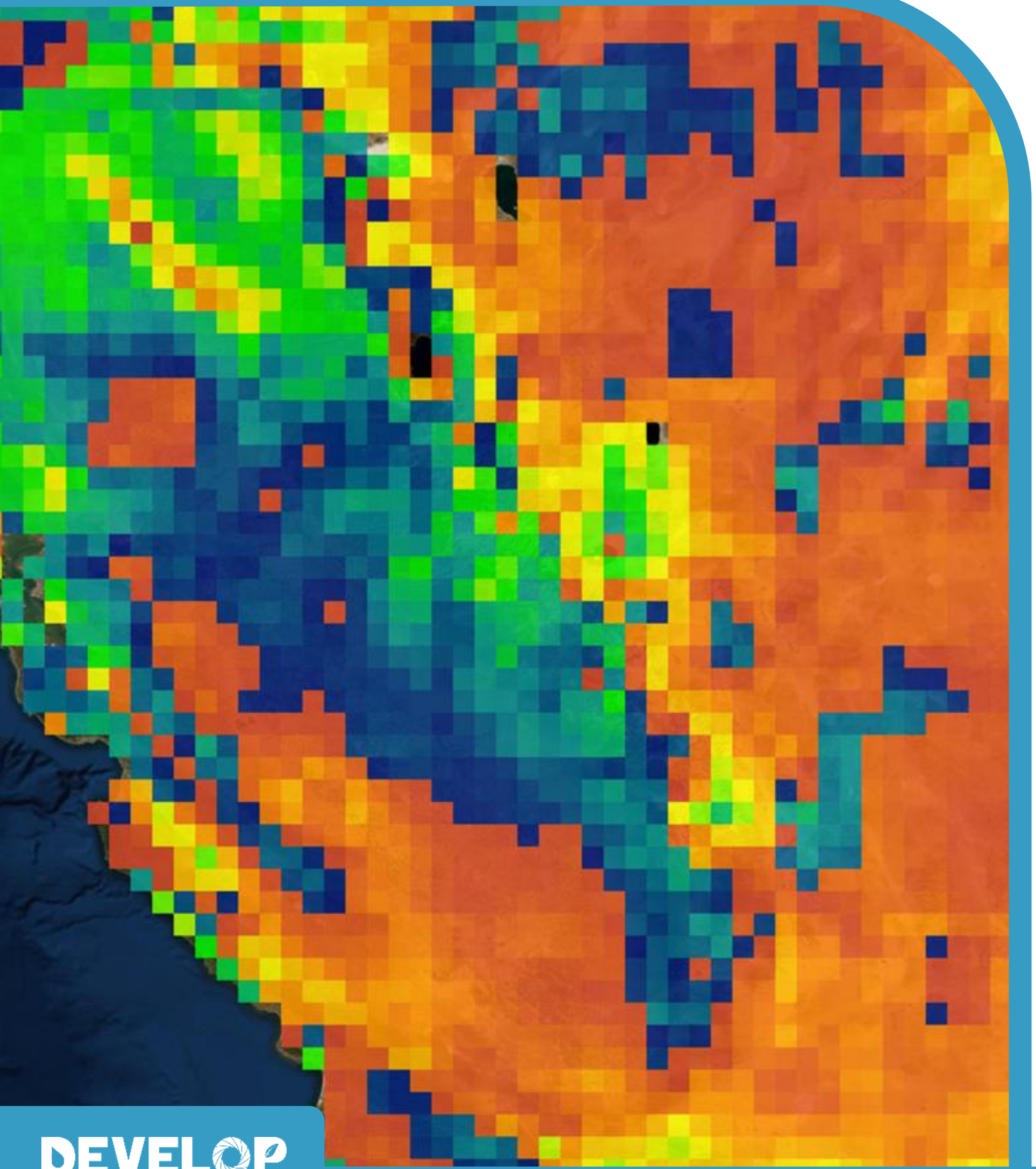


National Aeronautics and Space Administration

CENTRAL VALLEY
Water Resources

Improving California Groundwater Assessments using GRACE and InSAR Datasets for Water Resource Management

Forrest Corcoran, Marissa Dudek, James Kitchens, & Patrick Saylor

DEVELOP

California - JPL | Spring 2020

OUTLINE

- Study Area
- Community Concerns
- Partners & Collaborators
- Objectives
- Study Period
- Methodology
- Results
- Conclusions
- Future Work
- Acknowledgements

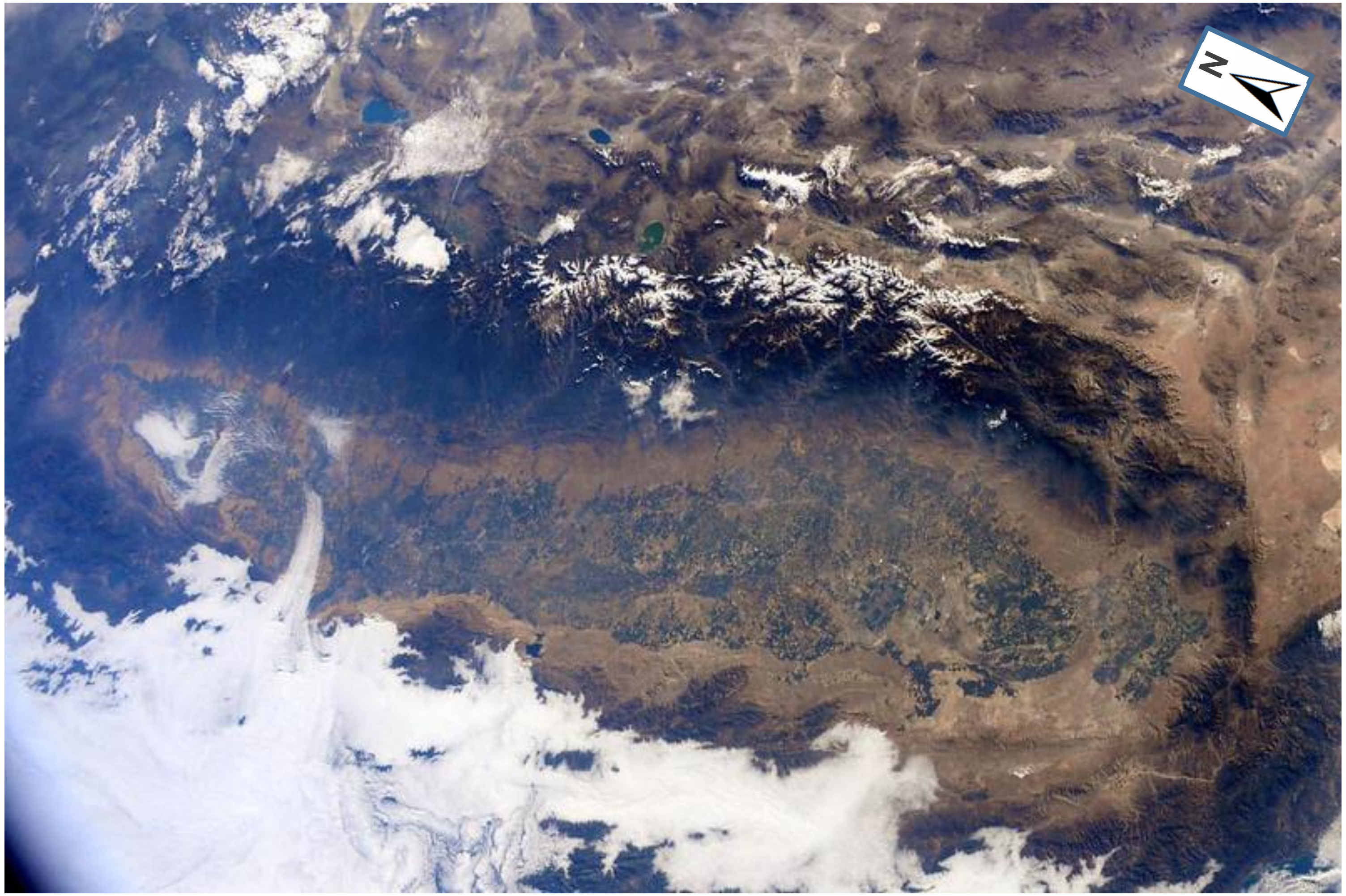


Image Credit: NASA/Terry Virts

STUDY AREA

- California's Central Valley
  - **Area:** 20,000 square miles
  - **Population:**
    - 2.0 million (1980)
    - 6.5 million (2018)
  - **California**:
    - 11% of the state's total land area
    - Supplies 60-75% of the state's water
  - **Agriculture:**
    - $20 billion in crops annually
    - 250 different crops
    - ~50% of United State's nuts, fruits, and vegetables
    - 17% of total U.S. irrigated land

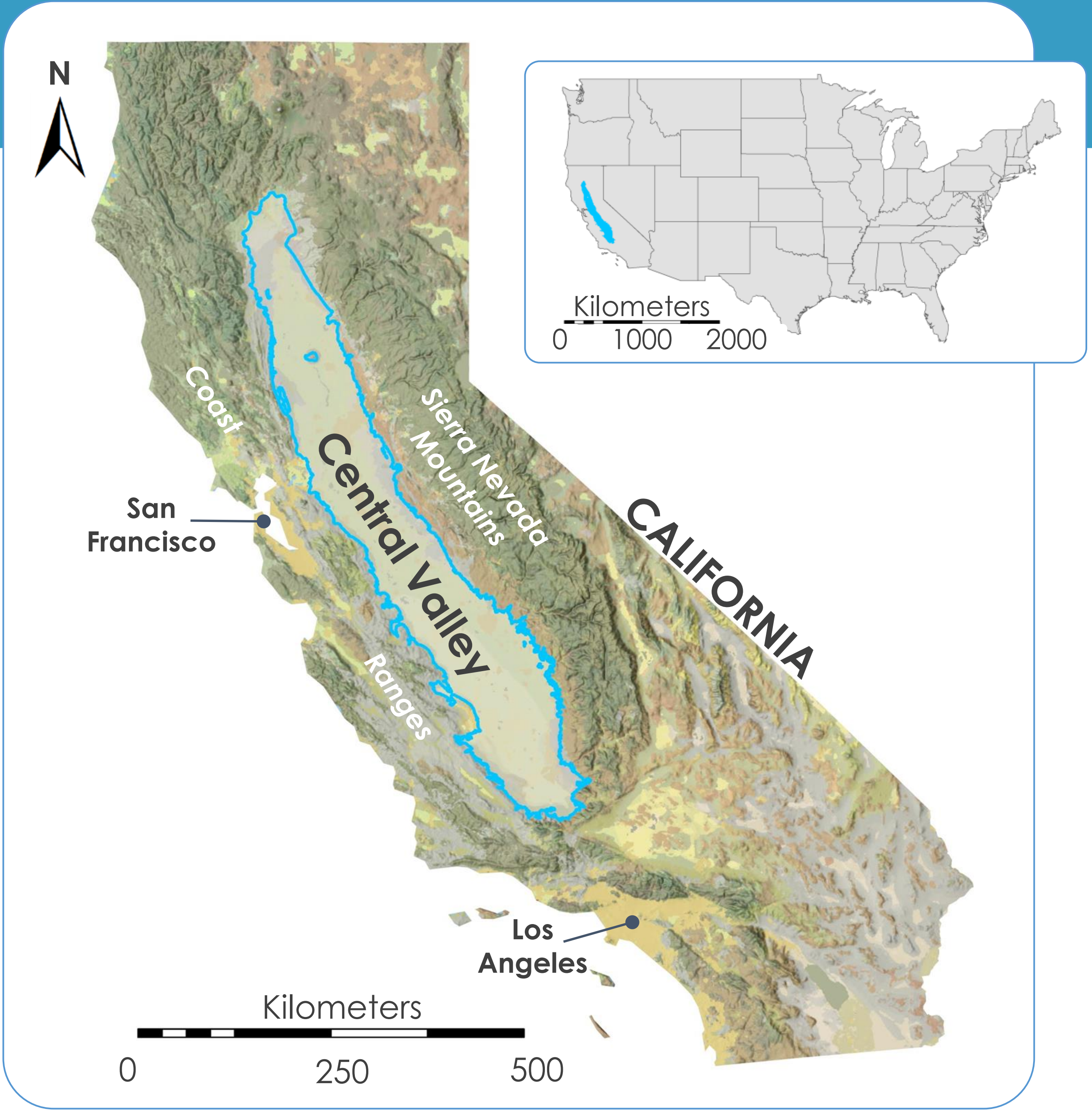


Image Credit: DEVELOP
Basemap Credit: National Geographic Style (Esri, USGS)

GEOLOGY & HYDROLOGY

- Central Valley aquifer is made up of unconfined and confined aquifer units
- Aquifers are recharged through:
  - Rainfall
  - Snowmelt
  - Stream seepage
- Corcoran Clay acts as confining layer
  - Main body of the clay
  - Shallow clay lenses
- Subsidence - decrease in surface elevation
  - Result of overdrafting from aquifer
  - Can be elastic or inelastic

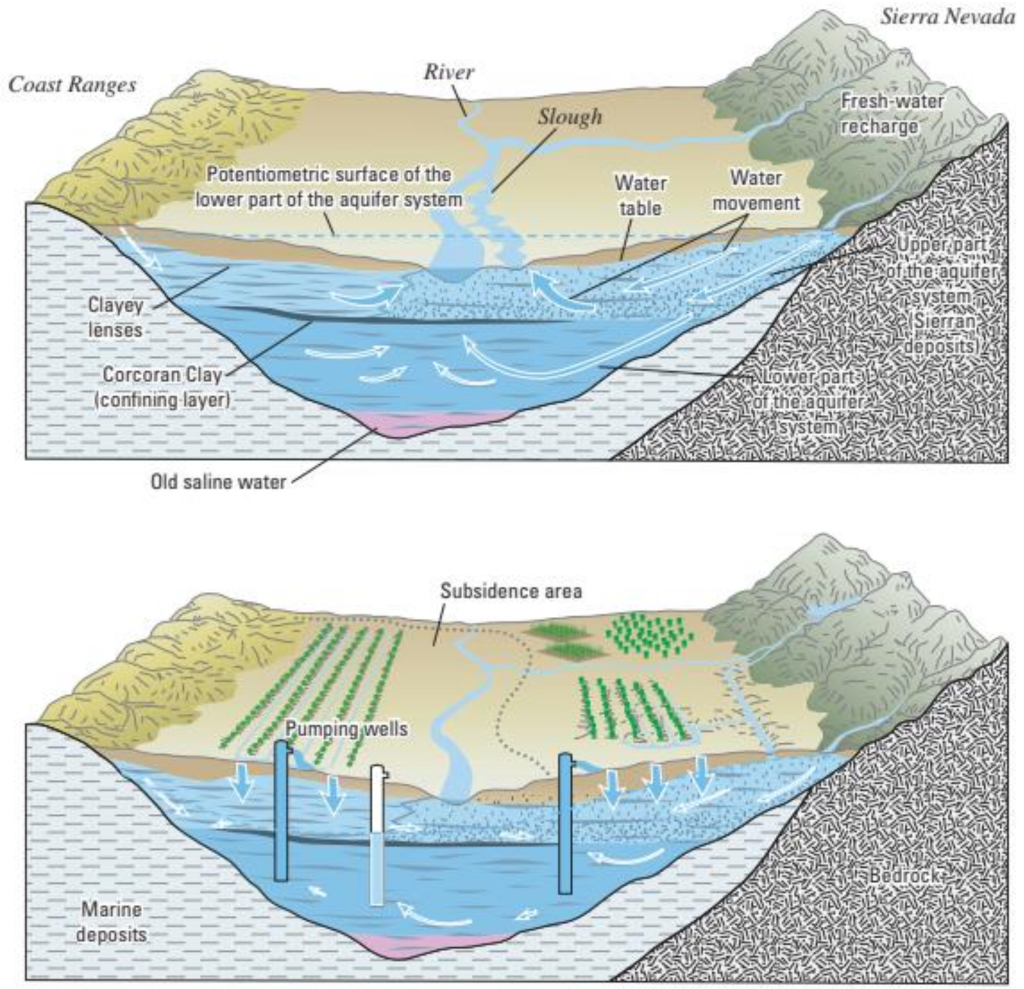


Image Credit: USGS, C.C. Faunt

COMMUNITY CONCERNS

California droughts

- 2011-2019 (376 weeks) drought was one of the most intense in CA history
- Overdrafting of Central Valley Aquifer
- Amount of groundwater pumped out of the Central Valley Aquifer is currently unknown

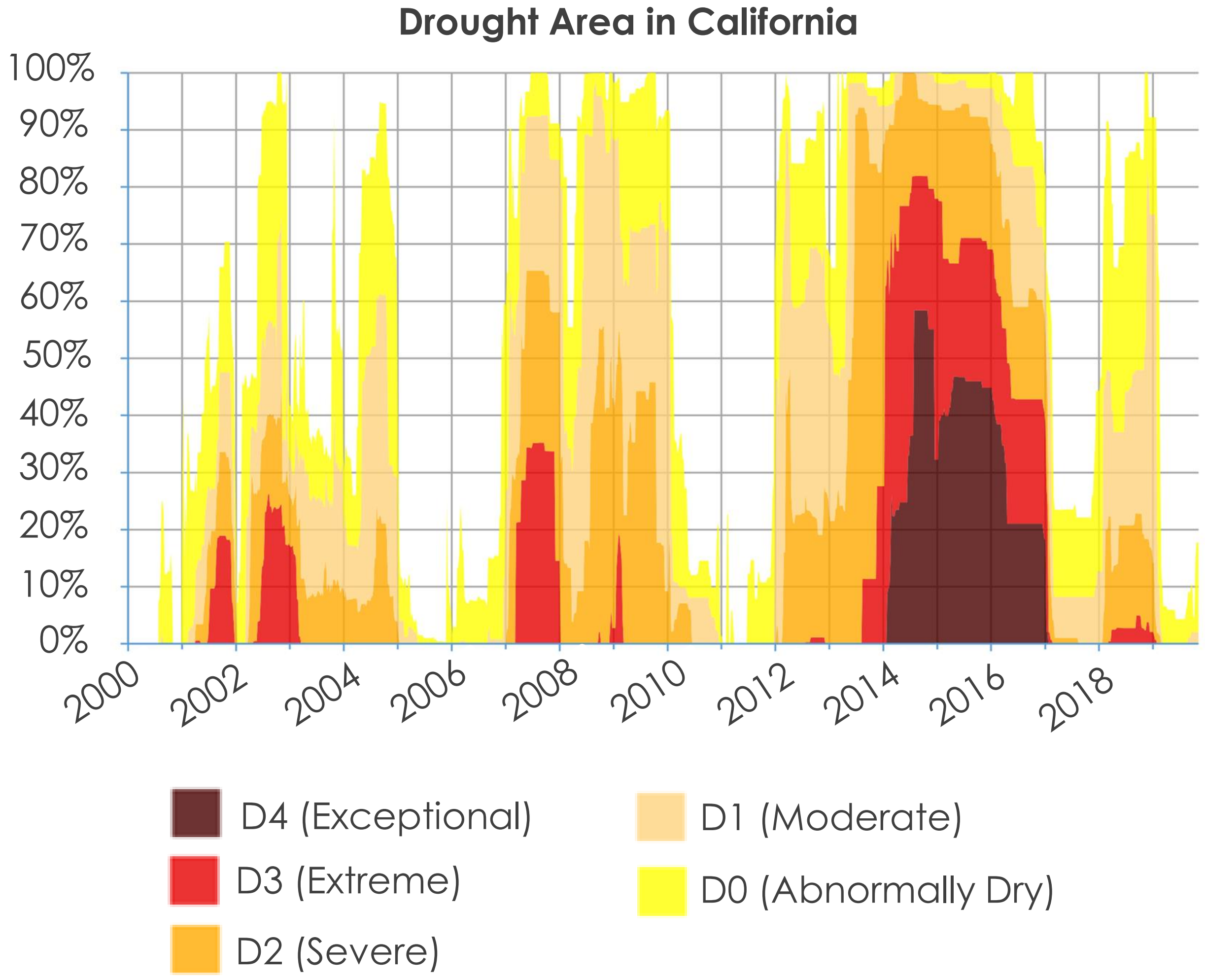


Image Credit: National Integrated Drought Information System
Image Source: National Integrated Drought Information System, National Drought Mitigation Center, USDA Federal Drought Assistance

COMMUNITY CONCERNS

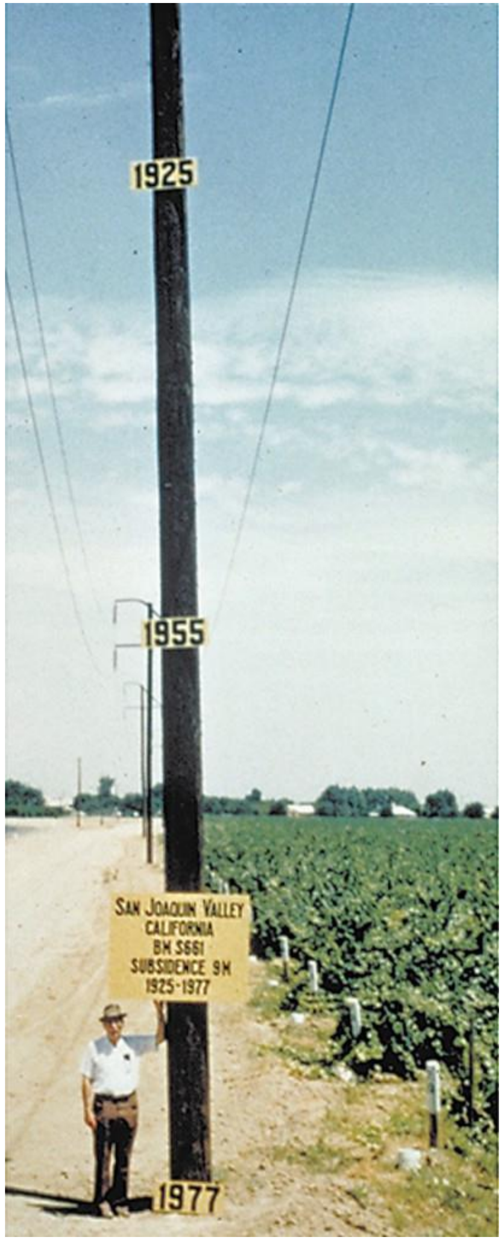
Subsidence

4 Land surface elevation dropping at record rates

4 Dropping more than 18 inches every year in some areas

4 Inelastic subsidence can cause permanent loss of the aquifer groundwater storage capabilities

Utility pole showing more than 30 feet of land surface elevation in the San Joaquin Valley from 1925 to 1977.



1925

30+ foot drop

1977

Image Credit: Richard Ireland, U.S. Geological Survey

COMMUNITY CONCERNS

- Sustainable Groundwater Management Act
  - Signed by Gov. Jerry Brown in 2014
  - Empowers local Groundwater Sustainability Agencies (GSAs), must have a plan in place by 2024
  - Goal of achieving sustainable groundwater pumping and recharge by 2042
  - Current monitoring process:
    - In-situ well data and GPS data
    - Some GSAs have no in-situ data

Image Credit: John Weiss

PARTNERS

- California Department of Water Resources End Users:
  - Bill Brewster – *Senior Engineering Geologist, NCRO*
  - Mike McKenzie – *Senior Engineering Geologist, SCRO*
  - Timothy Ross, PhD – *Senior Engineering Geologist, SRO*
  - Jack Tung – *Engineering Geologist, SRO*
- California State University, Los Angeles Collaborators:
  - Charles Hays, PhD – *Lecturer*
  - Jingjing Li, PhD – *Assistant Professor*

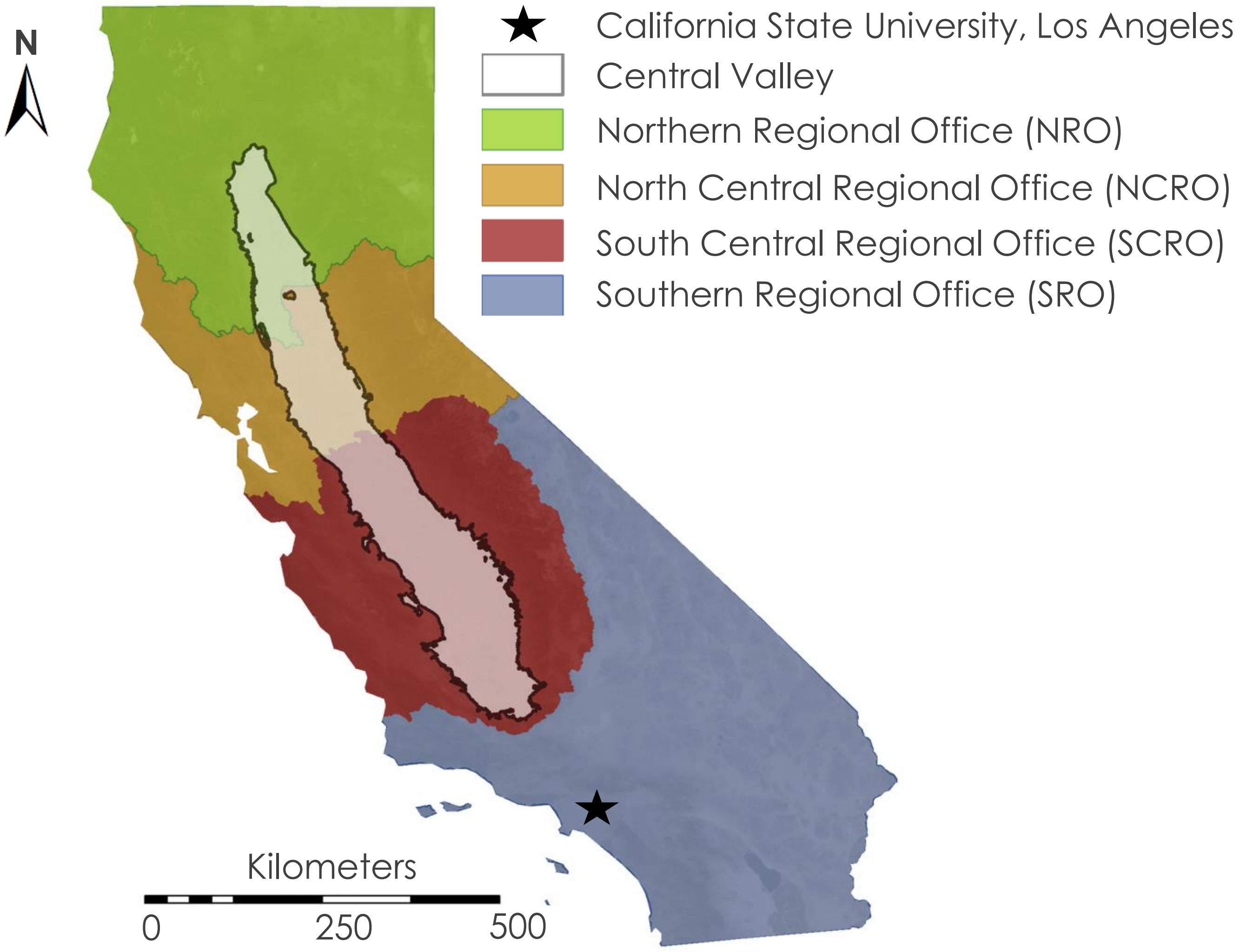


Image Credit: DEVELOP
DWR Regional Offices Shapefile Source: Department of Water Resources
Basemap Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

OBJECTIVES

1. Evaluate groundwater storage

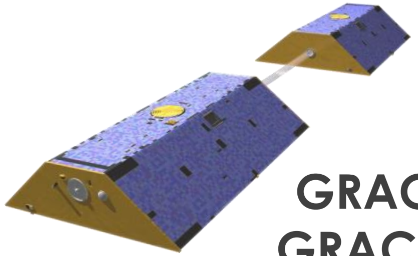
2. Evaluate surface elevation subsidence

3. Characterize the temporal relationship between groundwater storage and subsidence

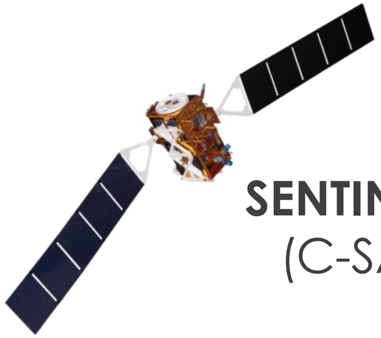
4. Characterize the spatial relationship between groundwater storage and subsidence

5. Assess change within each subbasin

EARTH OBSERVATIONS



GRACE & GRACE-FO

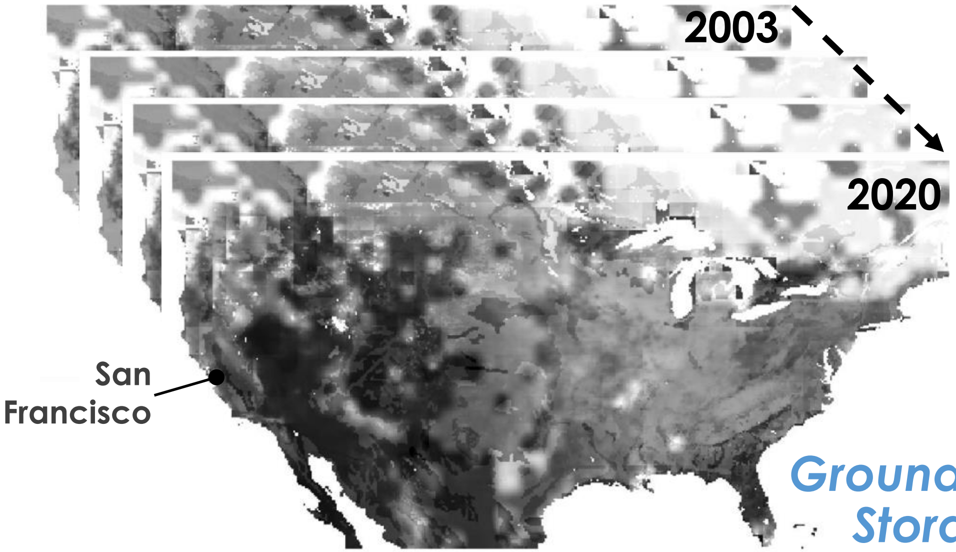


SENTINEL-1
(C-SAR)

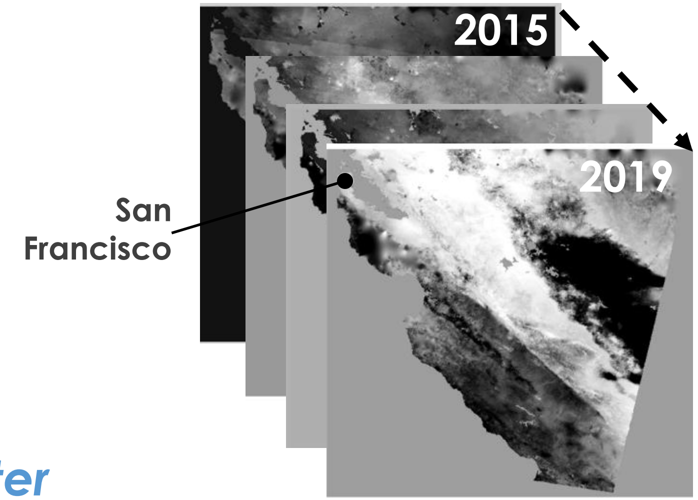
ALOS-2
(PALSAR-2)

<u>GRACE</u>: **G**ravity **R**ecovery **A**nd **C**limate **E**xperiment

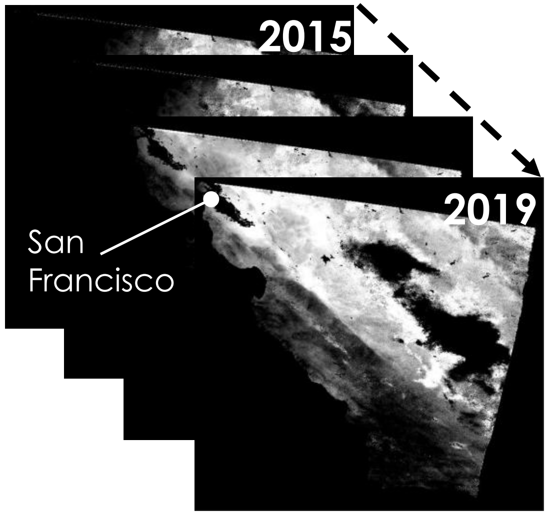
<u>InSAR</u>: **In**terferometric **S**ynthetic **A**perture **R**adar



Groundwater Storage



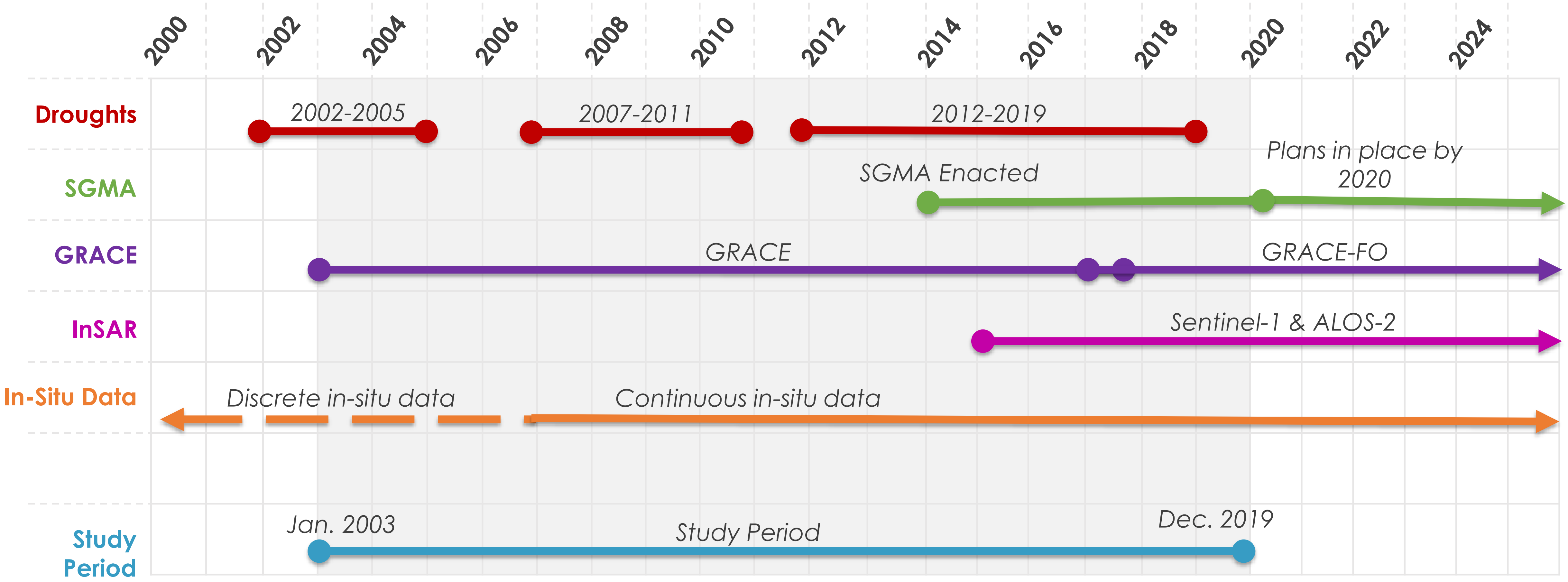
Subsidence



Subsidence

Image Credit: DEVELOP
EOS Image Credit: (1) GRACE/GRACE-FO satellite, NASA; (2) Sentinel-1 satellite, ESA; (3) ALOS-2 satellite, JAXA/EORC.

STUDY PERIOD



Timeline of the study period. **Red**: Timespans of major droughts in California. **Green**: The Sustainable Groundwater Management Act (SGMA) enacted in 2014, all Groundwater Sustainability Agencies (GSAs) must have a plan in place by 2024. **Purple**: Timespans of GRACE and GRACE Follow On (GRACE-FO) data. **Pink**: Timespans of Sentinel 1 & ALSO-2 InSAR data. **Orange**: Timespans of in-situ well water surface elevation and GPS station data. **Blue**: Study period for this project, chosen to account for as much remote sensing (GRACE/InSAR) and in-situ data as possible. **Grey**: All data included within the study period.

California Hydrologic Basins

- CENTRAL VALLEY
- CENTRAL COAST
- COLORADO RIVER
- NORTH COAST
- NORTH LAHONTAN
- SACRAMENTO RIVER
- SAN FRANCISCO BAY
- SAN JOAQUIN RIVER
- SOUTH COAST
- SOUTH LAHONTAN
- TULARE LAKE

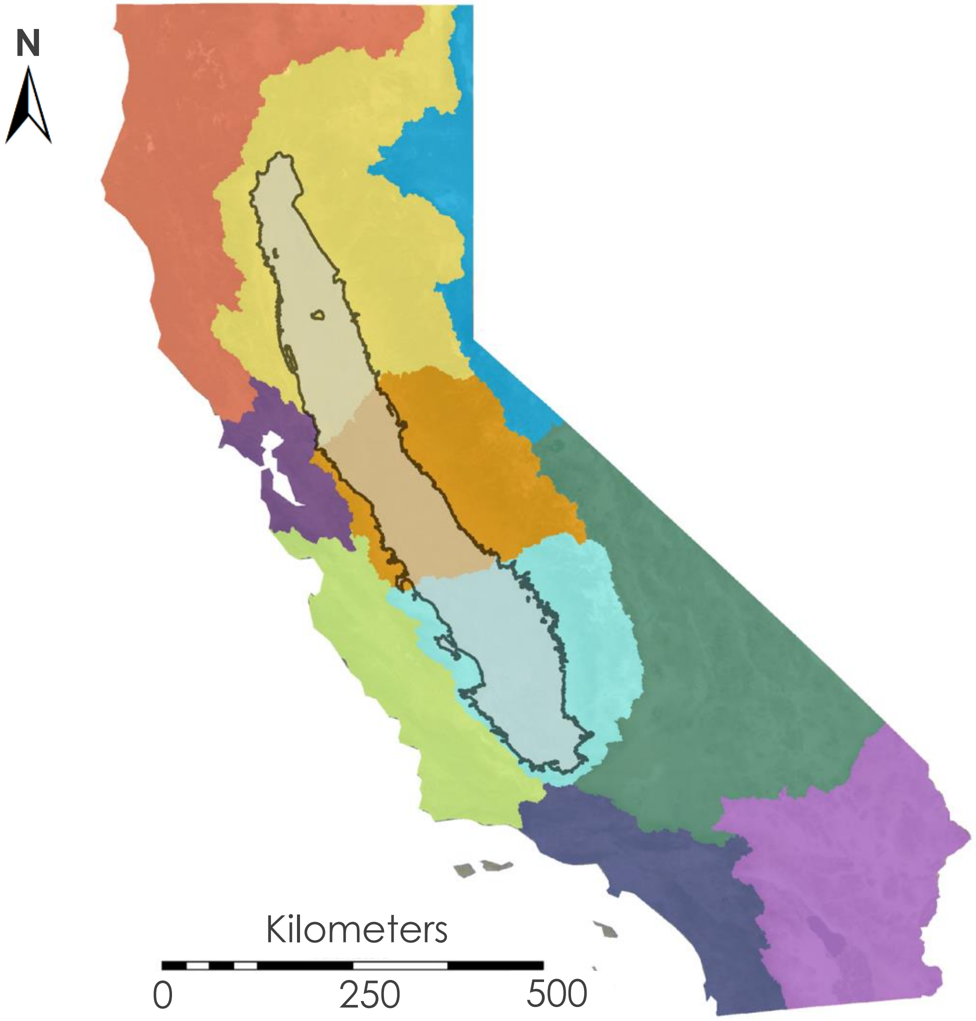


Image Credit: DEVELOP
CA Hydrologic Basins Shapefile Source: Department of Water Resources
Basemap Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Central Valley Hydrologic Basins

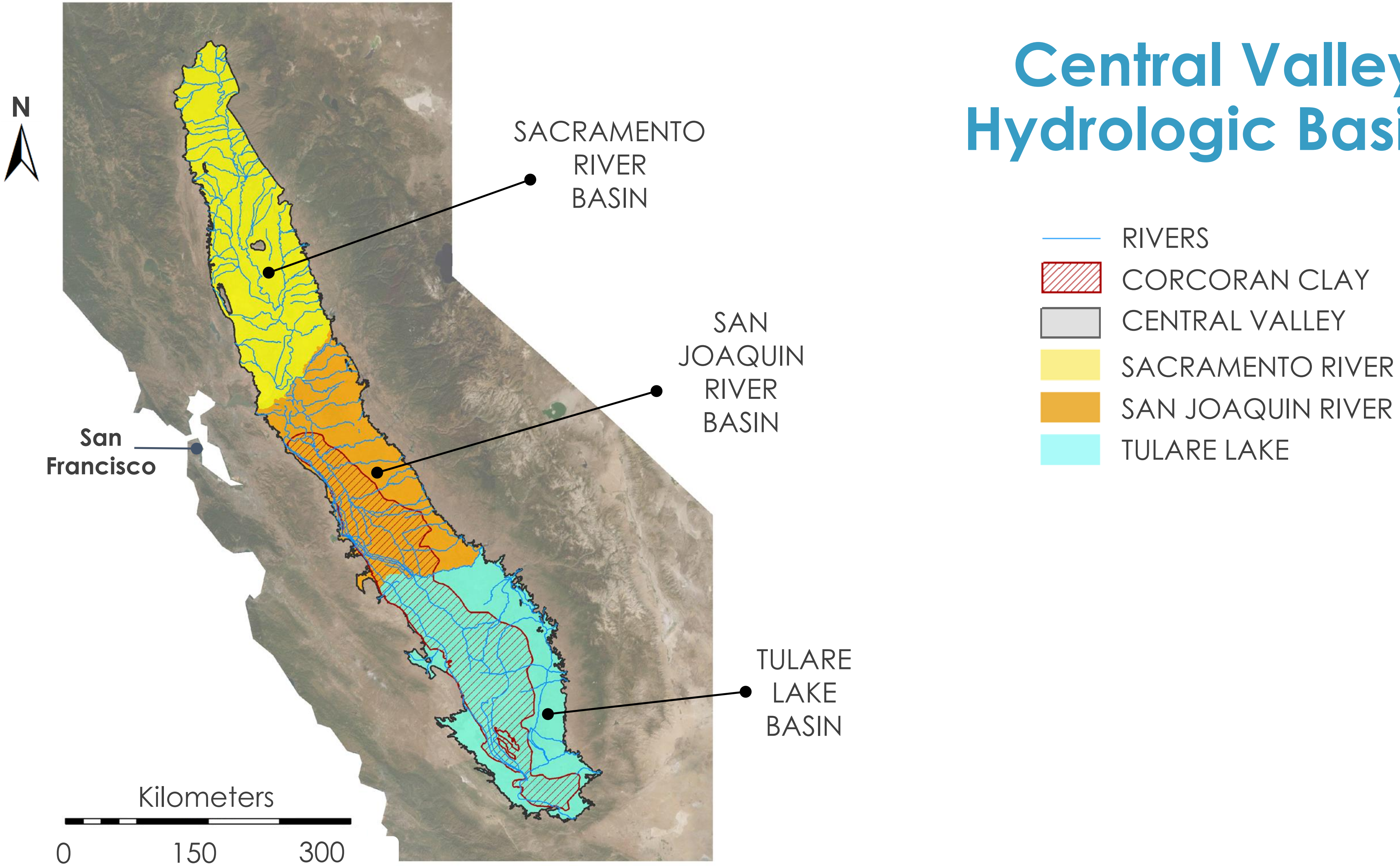
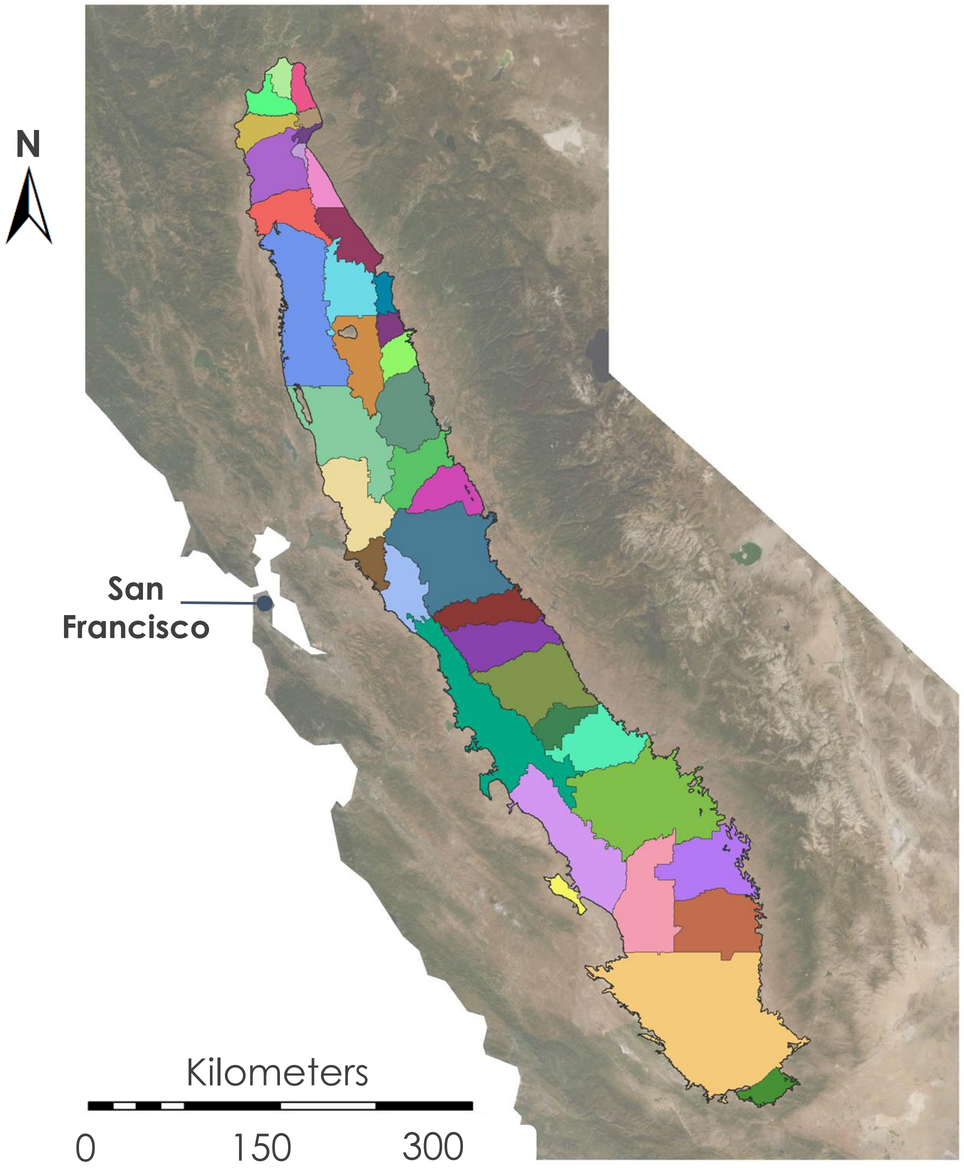


Image Credit: DEVELOP
CA Hydrologic Basins Shapefile Source: DWR; Corcoran Clay Source: California, SWRCB; Rivers Shapefile Source: U.S. Census Bureau
Basemap Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

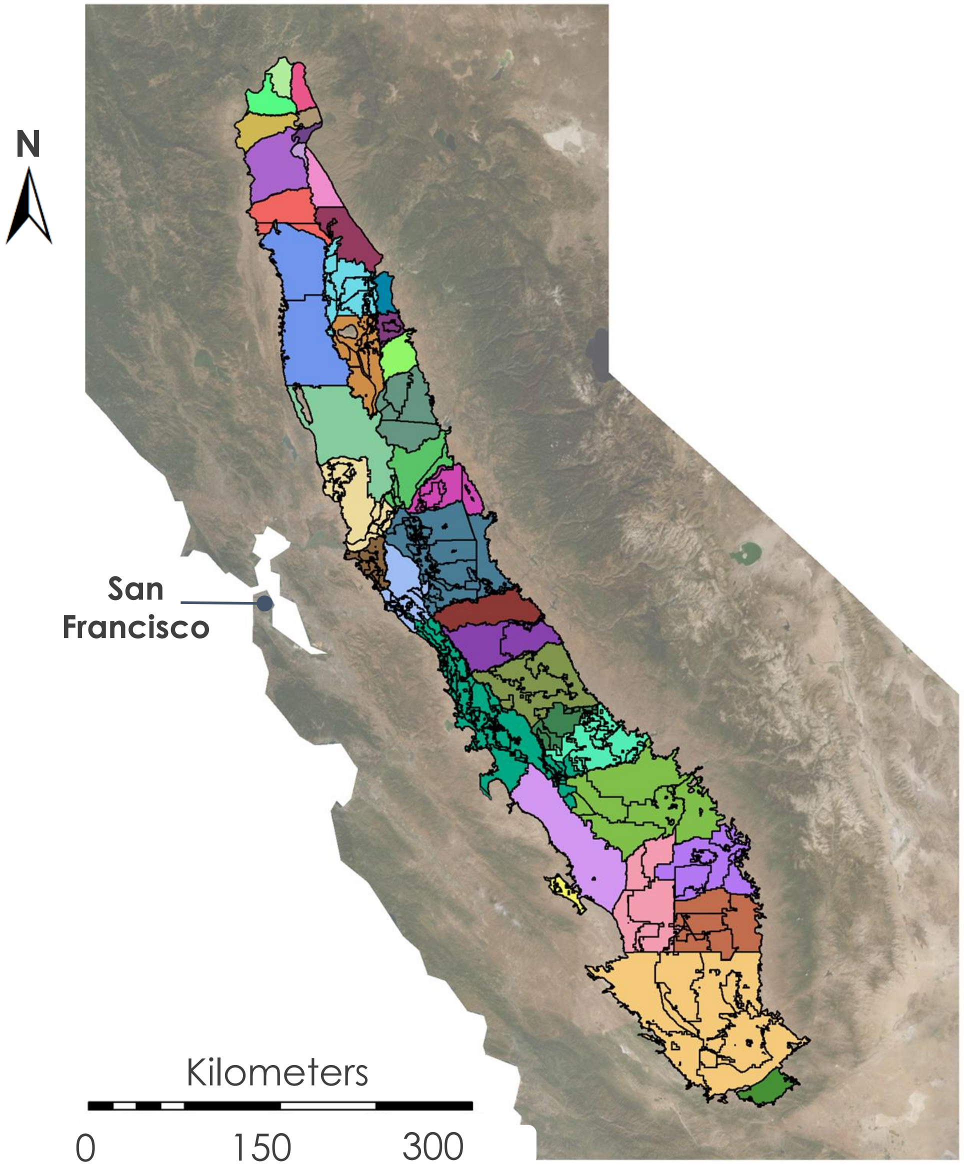
Central Valley Subbasins



ANDERSON	MODESTO
ANTELOPE	NORTH AMERICAN
BEND	NORTH YUBA
BOWMAN	PLEASANT VALLEY
BUTTE	RED BLUFF
CHOWCHILLA	SOLANO
COLUSA	SOUTH AMERICAN
CORNING	SOUTH BATTLE CREEK
COSUMNES	SOUTH YUBA
DELTA-MENDOTA	SUTTER
EAST CONTRA COSTA	TRACY
EASTERN SAN JOAQUIN	TULARE LAKE
ENTERPRISE	TULE
KAWEAH	TURLOCK
KERN COUNTY	VINA
KINGS	WESTSIDE
LOS MOLINOS	WHITE WOLF
MADERA	WYANDOTTE CREEK
MERCED	YOLO
MILLVILLE	

Image Credit: DEVELOP
DWR Subbasins Shapefile Source: Department of Water Resources
Basemap Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Central Valley Subbasins



ANDERSON
ANTELOPE
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DELTA-MENDOTA
EAST CONTRA COSTA
EASTERN SAN JOAQUIN
ENTERPRISE
KAWEAH
KERN COUNTY
KINGS
LOS MOLINOS
MADERA
MERCED
MILLVILLE
MODESTO
NORTH AMERICAN
NORTH YUBA
PLEASANT VALLEY
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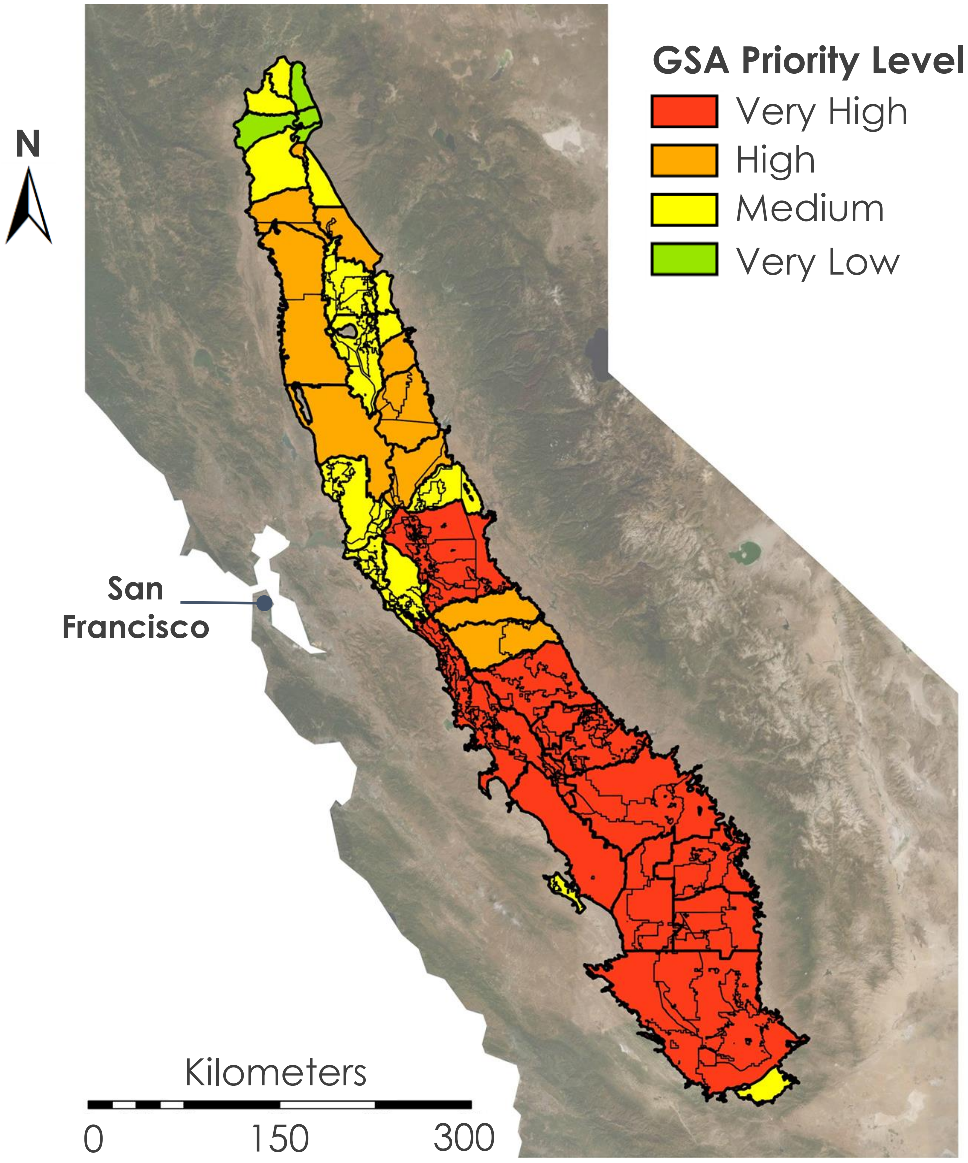
SOLANO
SOUTH AMERICAN
SOUTH BATTLE CREEK
SOUTH YUBA
SUTTER
TRACY
TULARE LAKE
TULE
TURLOCK
VINA
WESTSIDE
WHITE WOLF
WYANDOTTE CREEK
YOLO

* GSAs Outlined

Image Credit: DEVELOP
DWR Subbasins Shapefile Source: Department of Water Resources
Basemap Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



SGMA GSA Prioritization

Prioritization based 7 factors:

- Population density
- Projected population growth
- Number of public service wells
- Density of total wells per square mile
- Irrigated acreage per square mile
- Amount of groundwater used per acre
- Amount of total water provided by groundwater

Image Credit: DEVELOP
DWR Regional Offices Shapefile Source: Department of Water Resources
Basemap Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

METHODOLOGY

Step 1:
Acquire study area in-situ & remotely sensed data

- *In-Situ: Well & GPS*
- *EOS: GRACE/InSAR*

Step 2:
Process raw data

- *Quality Control*
- *Normalize data*

Step 3:
Aggregate in-situ and remote sensing datasets

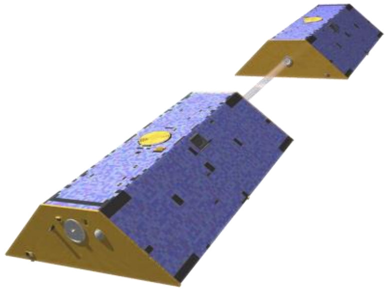
- *Spatial*
- *Temporal*

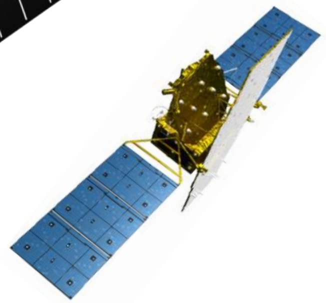
Step 4:
Evaluate surface subsidence and groundwater storage change temporally and spatially

Maps, time-series, rate of change charts

Image Credit: DEVELOP

DATA ACQUISITION

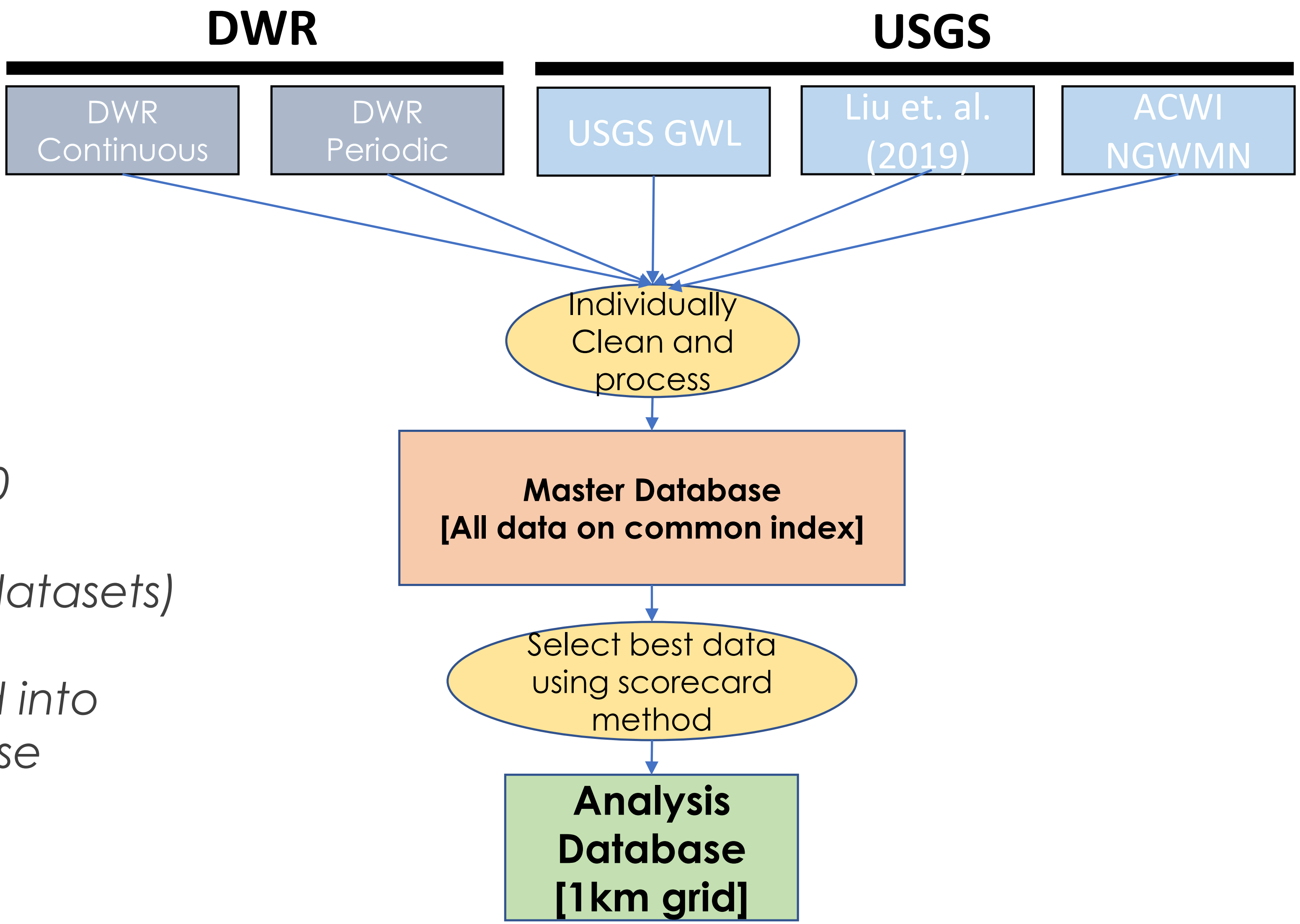




Data Type:	GRACE & GRACE-FO	SENTINEL-1 & ALOS-2 (InSAR)	Well Data	GPS Data
Source:	NASA JPL/Goddard	Processed: NASA JPL Data: ESA	DWR USGS	Nevada Geodetic Laboratory

Image Credit: (1) GRACE/GRACE-FO satellite, NASA; (2) Sentinel-1 satellite, ESA; (3) ALOS-2 satellite, JAXA/EORC.

In-Situ: Well Station Processing



Time Period: January 2003-2020

USGS and DWR databases (5 datasets)

Merged datasets incorporated into ~1km gridded analysis database

Image Credit: DEVELOP

In-Situ: Well Station Processing

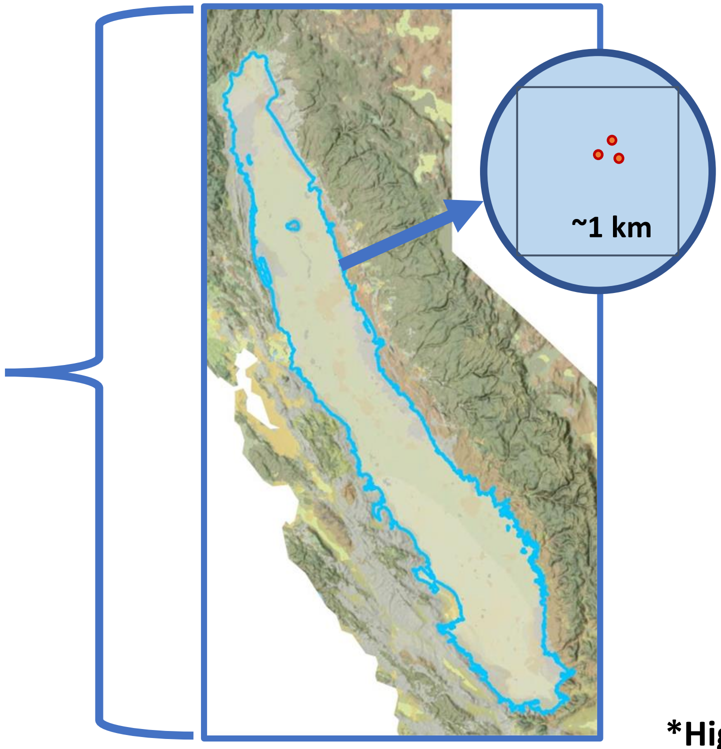
- "Scorecard" method selects highest quality data and grids to ~1km.
- Wells selected based on:
  - # observations
  - # months in observation
  - # observations per month
- Select for highest quality well data (quality and quantity)

Select best data using scorecard method

Analysis Database [1km grid]

Scorecard Method

Grid: ~1km (1/100 Decimal Degree)



Observations (normalized)

+

Months with Obs. (normalized)

+

Obs / Month (normalized)

SCORE

Highest scoring well selected at each gridpoint

Image Credit: DEVELOP

In-Situ: Wells

<u>Total Well Stations</u>
7,706

<u>Total Observations</u>
642,736

Number of <u>Observations/Station:</u>
Mean: 83.4
St. Dev: 501.06
Maximum: 13,949
Median: 11
Minimum: 1.00

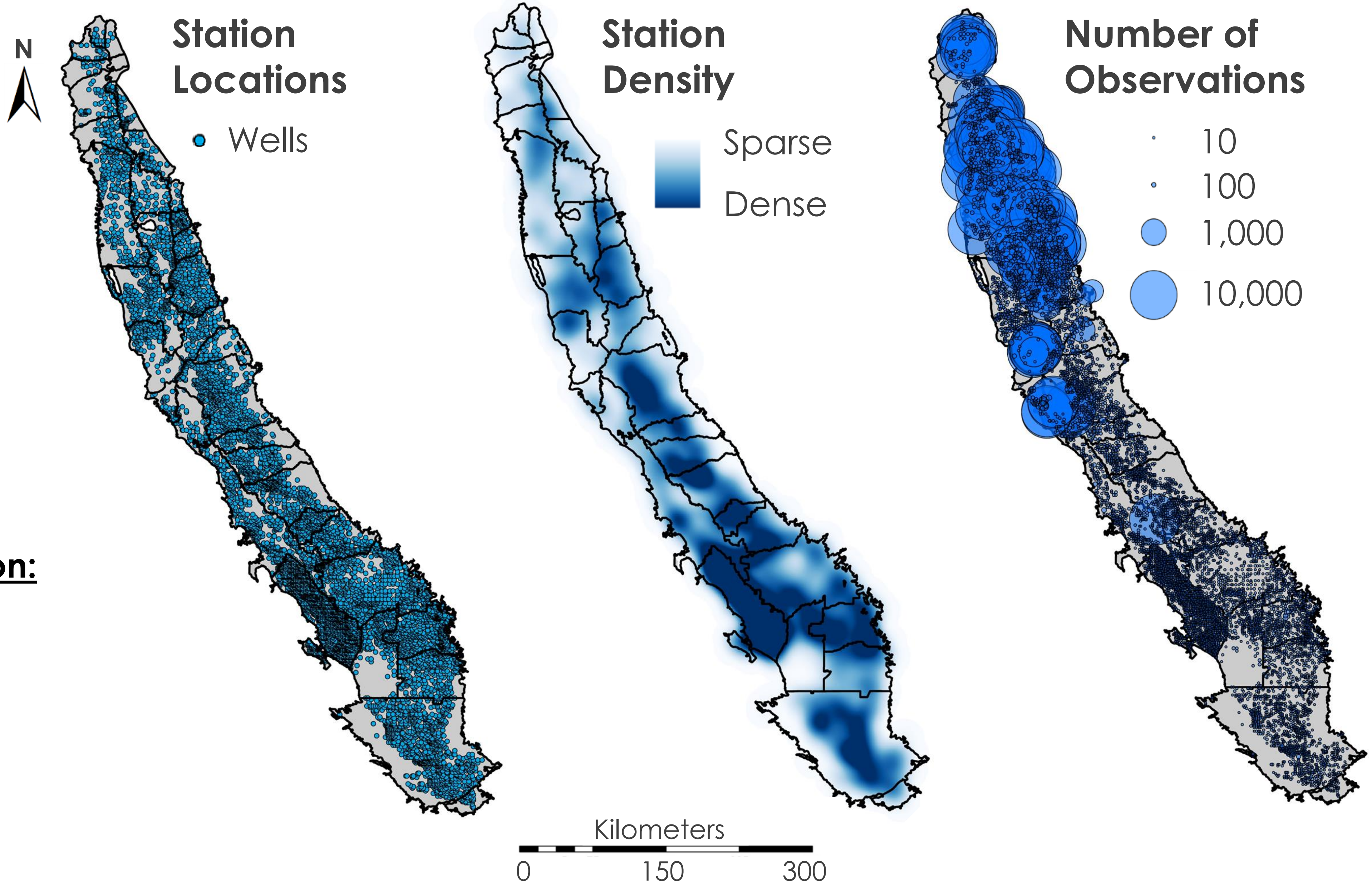


Image Credit: DEVELOP
DWR Subbasins Shapefile Source: Department of Water Resources

In-Situ: GPS Station Processing

- UNR - - University of Nevada Reno Geodetic Library
- Systematically downloaded GPS stations within Central Valley boundary
- Corrected Z (elevation) to Sentinel/ALOS Line of Sight (LOS)
- LOS = Z/cos(θLOS)

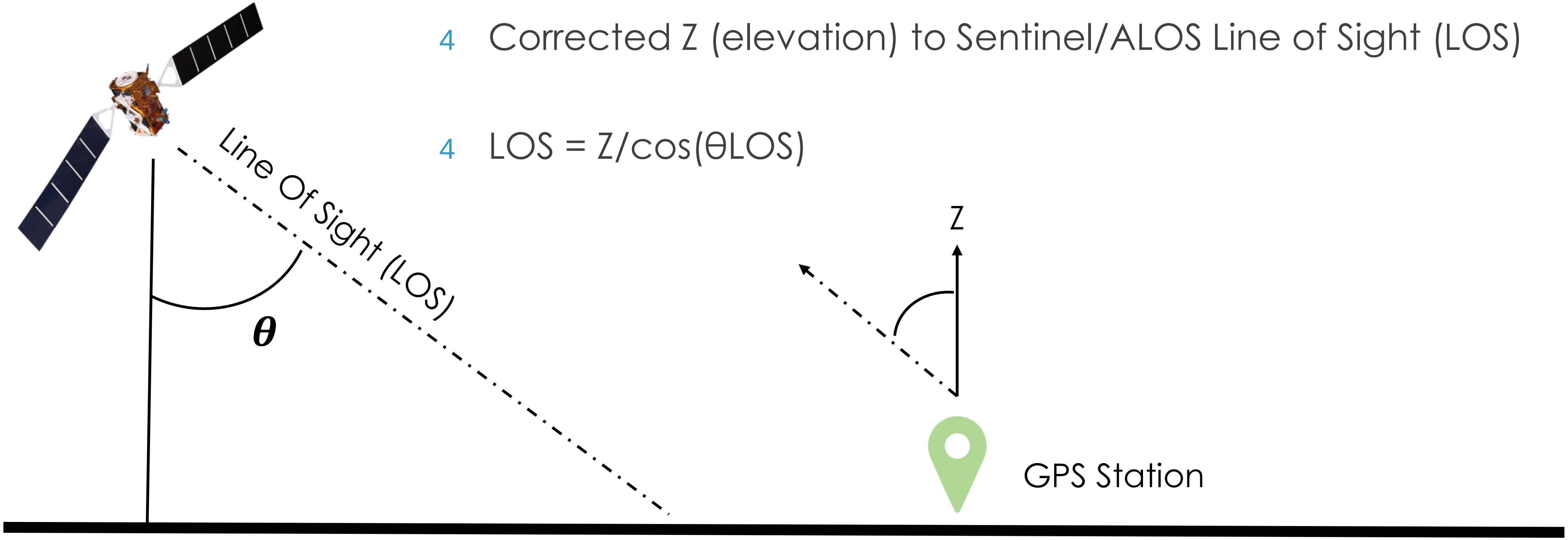


Image Credit: DEVELOP

In-Situ: GPS

Total GPS Stations
125

Total Observations
359,800

Number of Observations/Station:
Mean: 2,878.4
St. Dev: 2,126.51
Maximum: 7,619
Median: 2,784
Minimum: 1.00

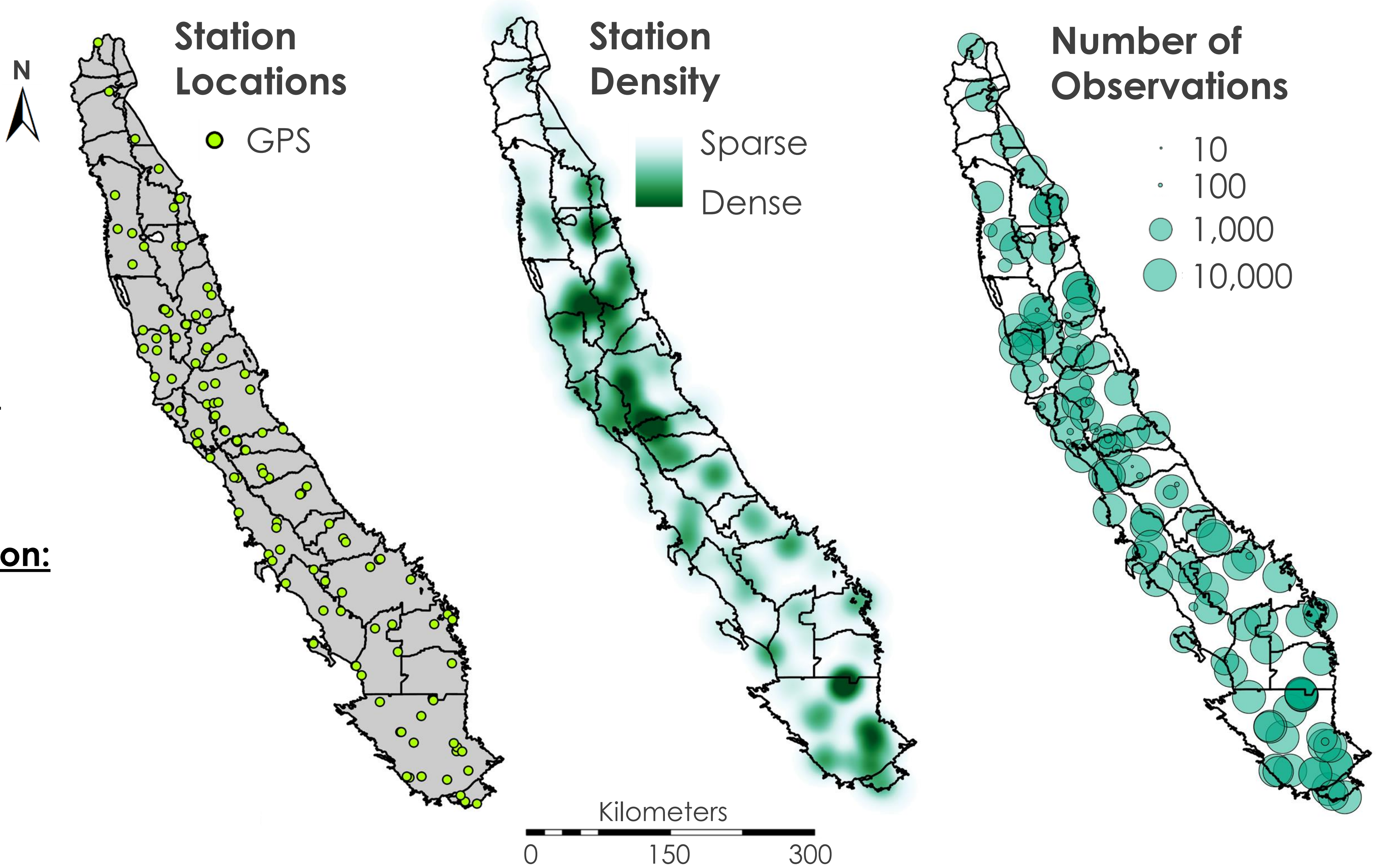
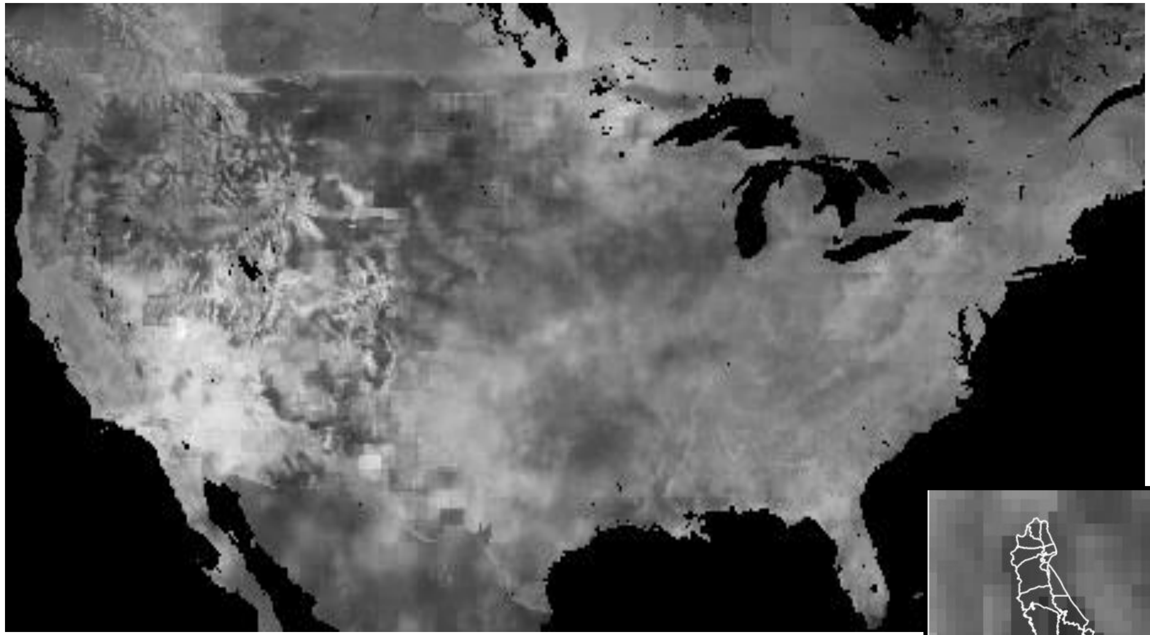


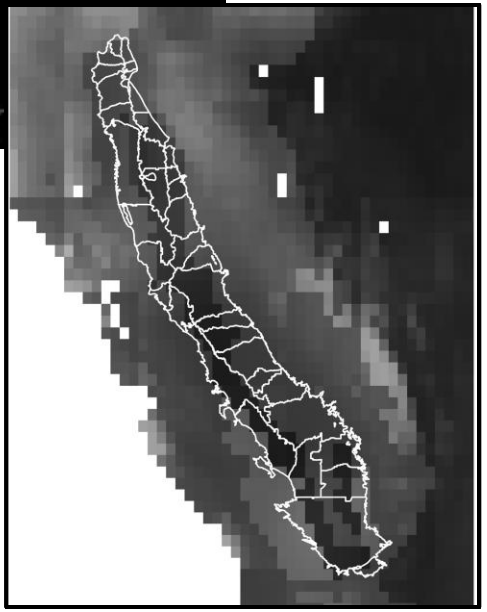
Image Credit: DEVELOP
DWR Subbasins Shapefile Source: Department of Water Resources

Remote Sensing: GRACE & GRACE-FO

- *GRACE:* 2003 – 2017
- *GRACE-FO:* 2017 – Present
- *Temporal Frequency:* Monthly
- *Processed by:* NASA Goddard Space Flight Center using North American Land Data Assimilation System (NLDAS)



North America GRACE coverage

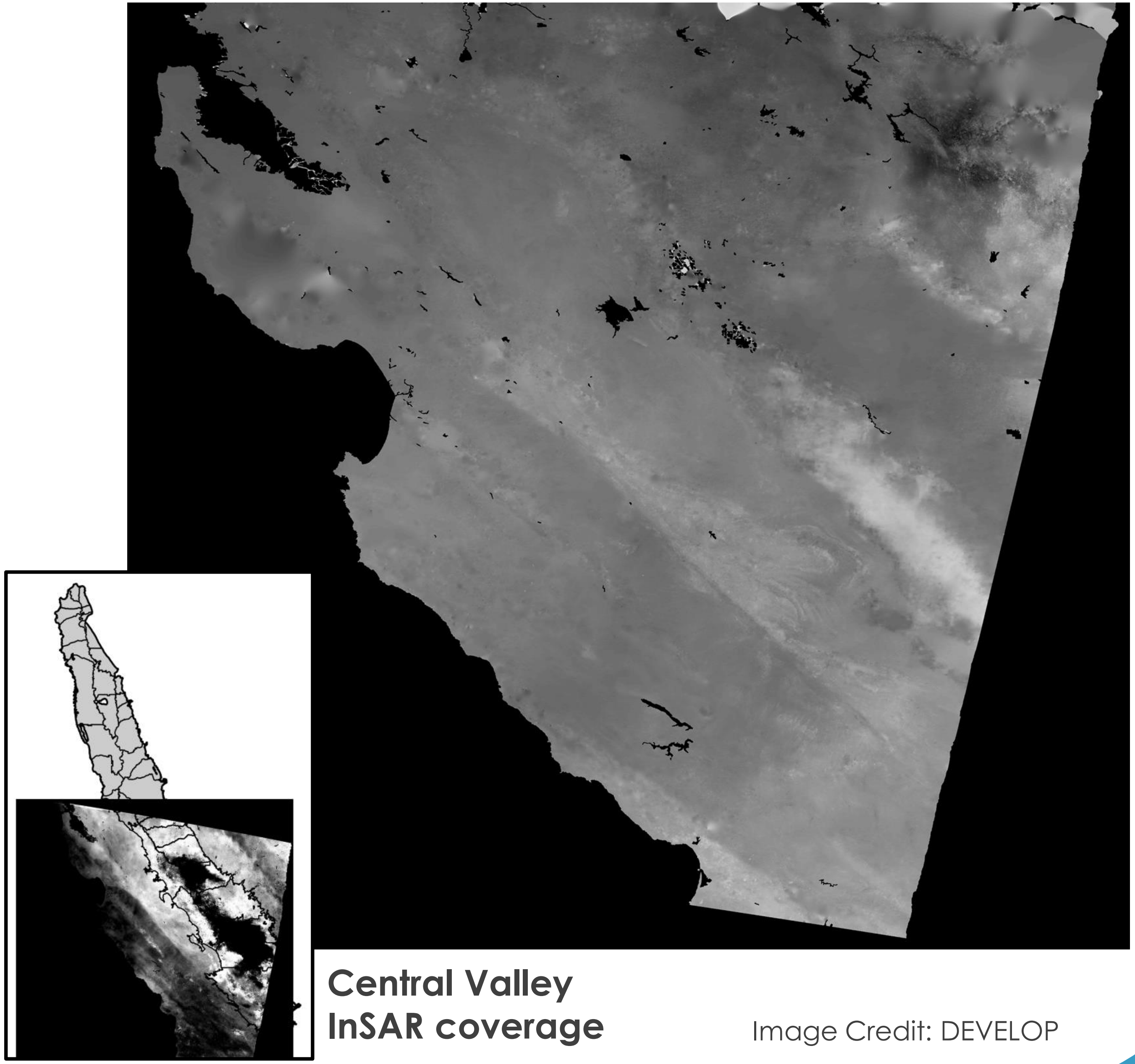


Central Valley GRACE coverage

Image Credit: DEVELOP

Remote Sensing:
InSAR

- *Time Period:* 2015 – Present
- *Temporal Frequency:* ~24 days
- *Processed by:* NASA's Jet Propulsion Laboratory (Zhen Liu, Ph.D.)



Central Valley InSAR coverage

Image Credit: DEVELOP

ZONAL ANALYSIS - PROCESS

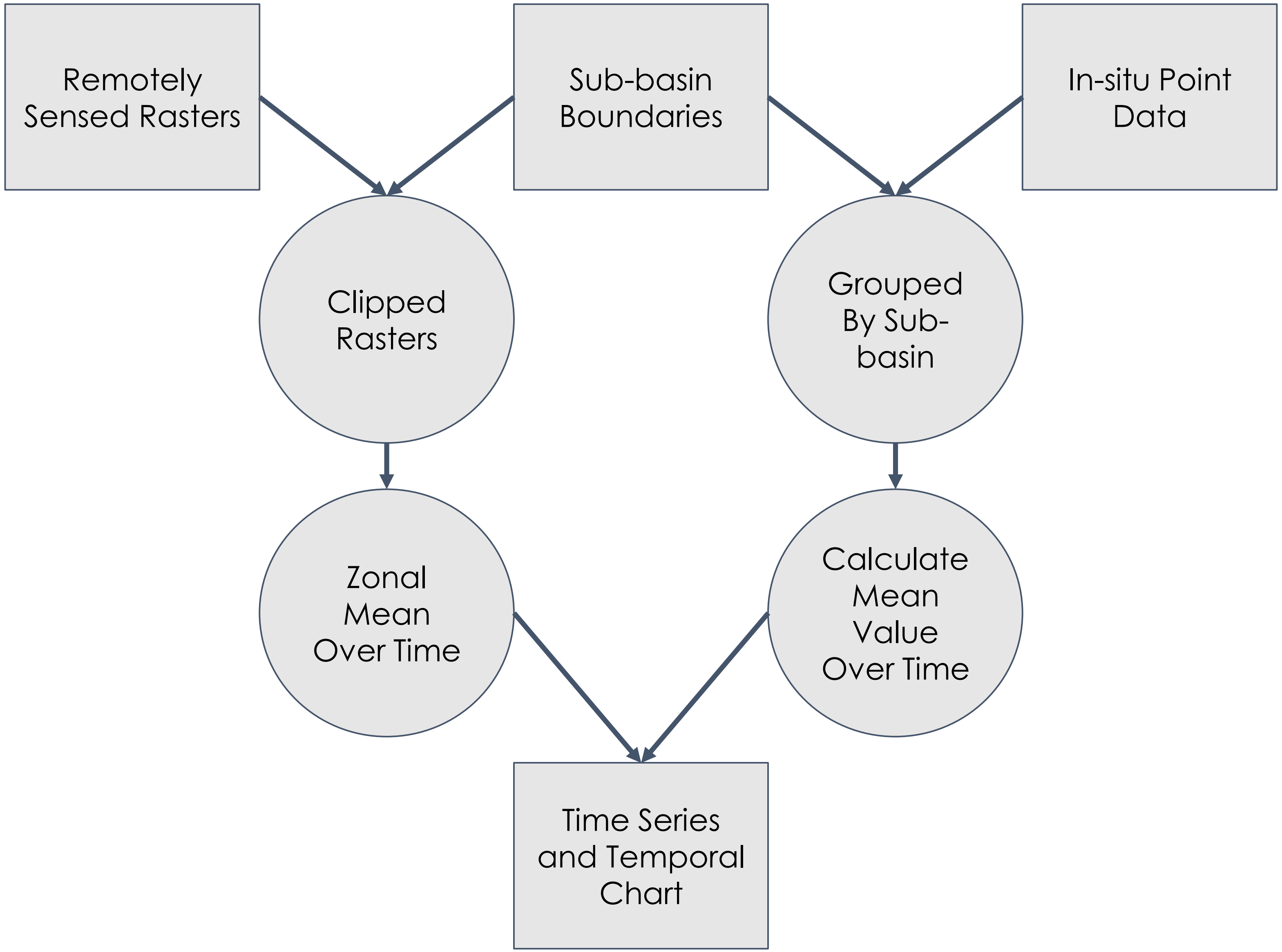
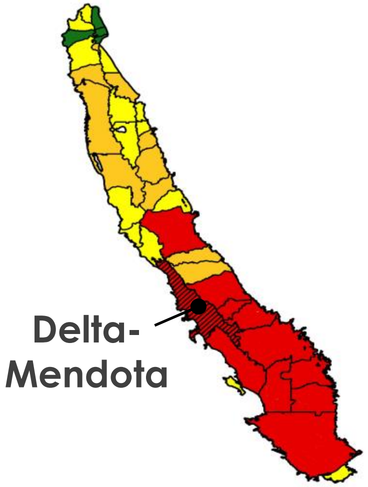


Image Credit: DEVELOP

ZONAL ANALYSIS - RESULTS



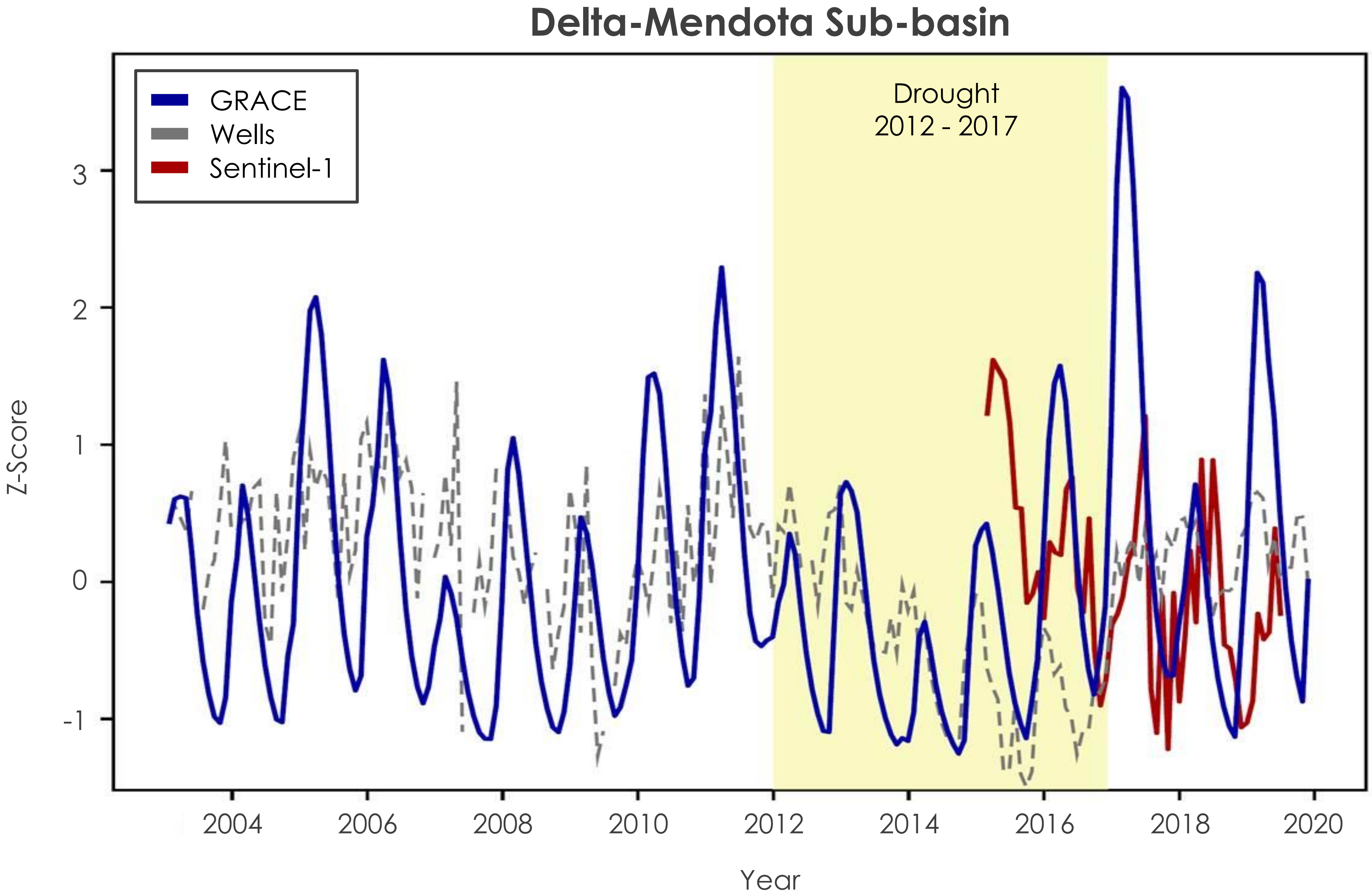
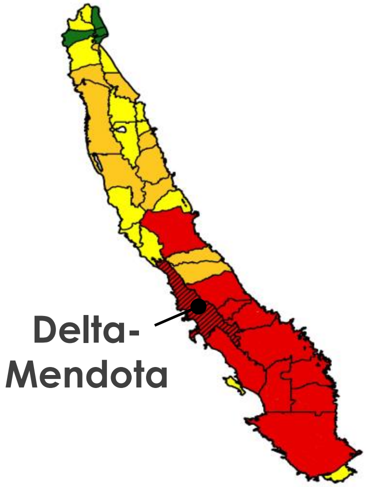


Image Credit: DEVELOP

ZONAL ANALYSIS - RESULTS



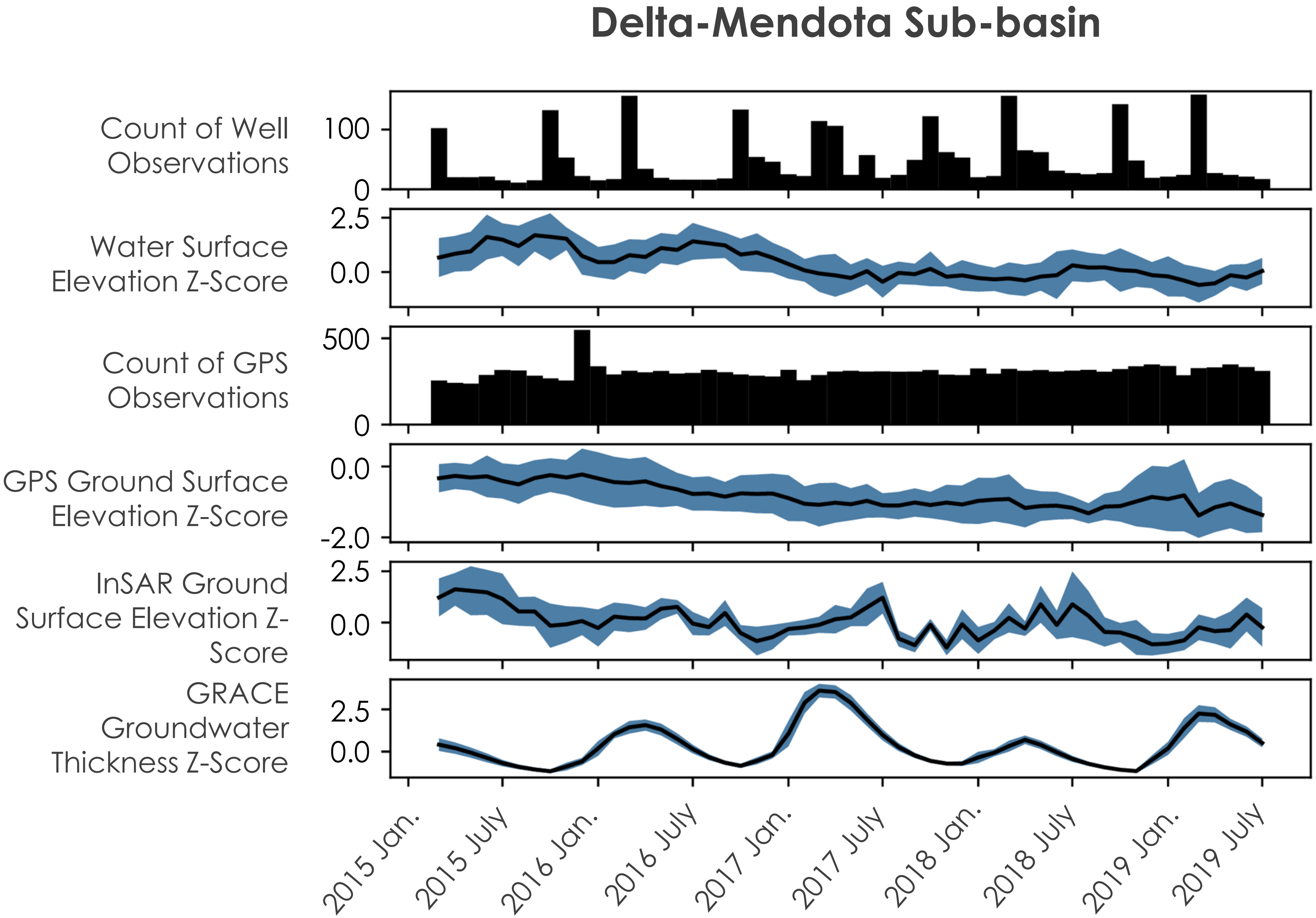


Image Credit: DEVELOP

CONCLUSIONS

- GRACE and InSAR data **can be relied on** to provide groundwater storage and subsidence data in regions with sparse in-situ well and GPS data.

- GRACE time series show **strong similarities** to the well data time series.

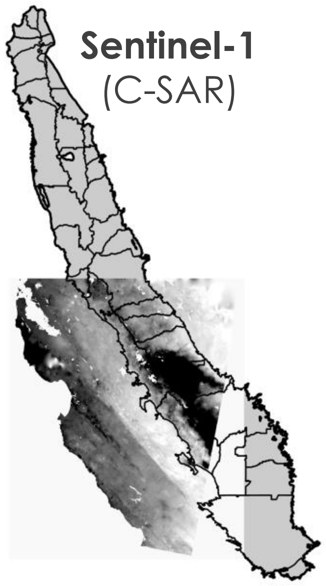
- Short-term subsidence within Delta-Mendota sub-basin, measured by InSAR, **did not rebound** after end of drought in 2017.

- Seasonal minima and maxima, in addition to periods of **drought can be detected** and readily correlated across in-situ (well and GPS) and remotely sensed (InSAR and GRACE) analysis methods.

- Sub-basin scale snapshots provide **locally-relevant information** as a basis for land manager decision-making.

FUTURE WORK

- Point analysis - comparing trends at specific locations across the Central Valley
- Combining InSAR sources (Sentinel-1 & ALOS-2)
- Expand InSAR coverage to entire Central Valley
- Visualization of In-situ and Remotely sensed Observations (VIRGO)
    - Software tool for re-creating project workflow as more data become available
    - Tool to be used by GSA managers including generating actionable data for GSA annual reports



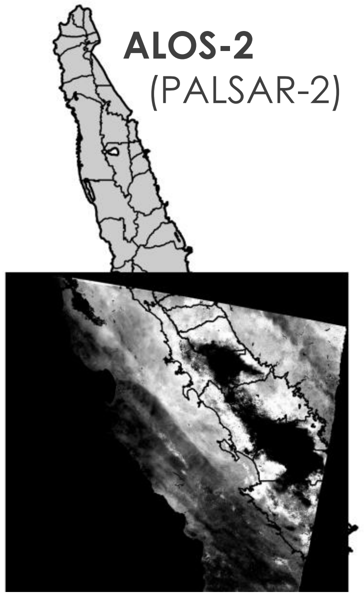


Image Credit: DEVELOP

ACKNOWLEDGEMENTS

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  - Zhen Liu, PhD - Earth Surface And Interior Scientist
  - John T. Reager, PhD - Terrestrial Hydrology Scientist
  - Kyra Kim, PhD - Terrestrial Hydrology Postdoctoral Fellow
- **California DWR Partners:**
  - Bill Brewster - Senior Engineering Geologist, NCRO
  - Mike McKenzie - Senior Engineering Geologist, SCRO
  - Timothy Ross, PhD - Senior Engineering Geologist, SRO
  - Jack Tung - Engineering Geologist, SRO
- **Collaborators:**
  - Charles Hays, PhD - Lecturer, California State University, Los Angeles
  - Jingjing Li, PhD - Assistant Professor, California State University, Los Angeles
  - Benjamin Holt - NASA Jet Propulsion Laboratory
- **With Support From:**
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  - Benjamin Holt - NASA Jet Propulsion Laboratory

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