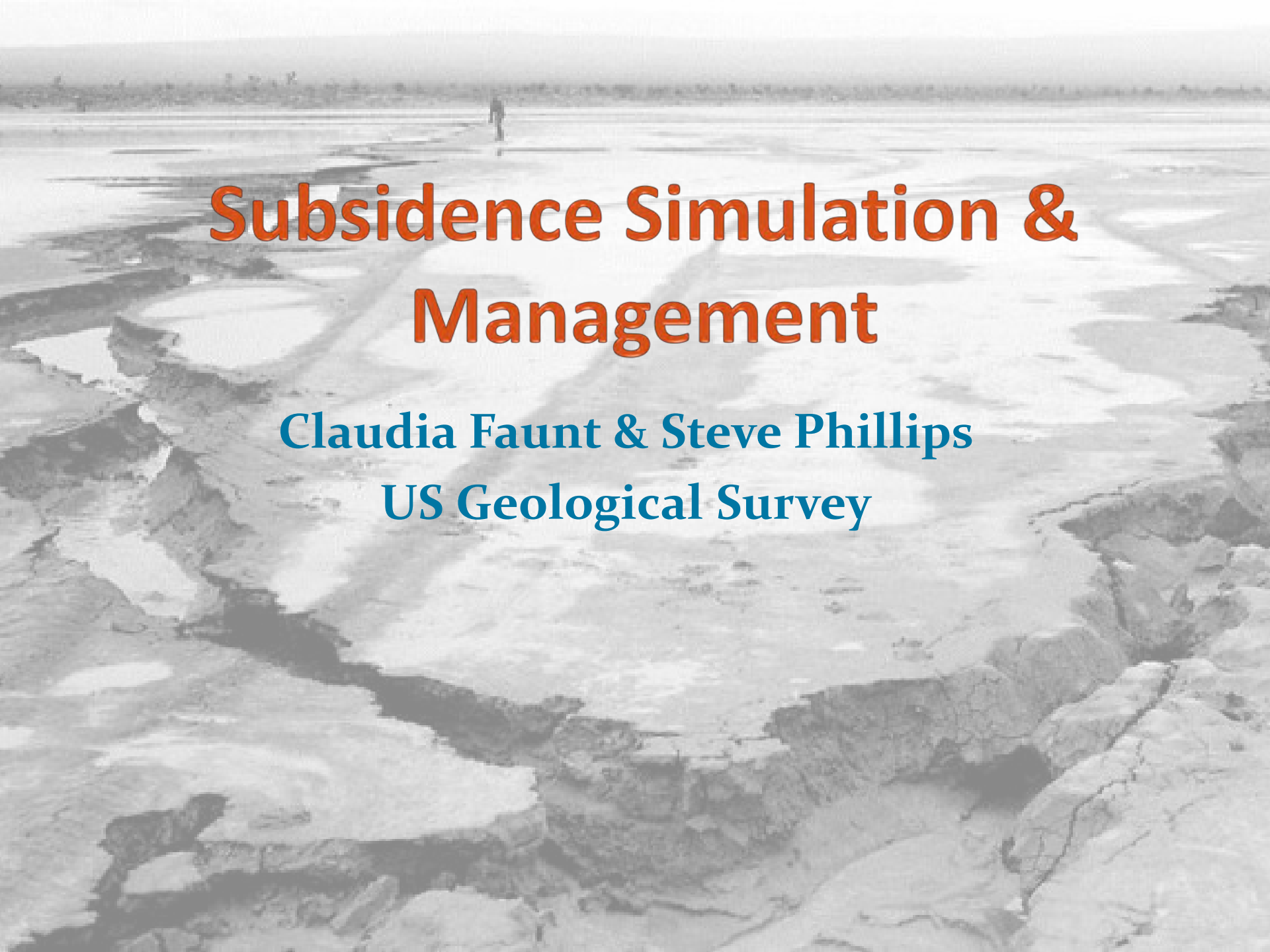


The background image is a grayscale photograph of a coastal or wetland area that has experienced significant subsidence. The foreground and middle ground are dominated by large, irregular, and deeply cracked mudflats or salt flats. These areas are separated by narrow, winding channels of water. In the far distance, a small, dark silhouette of a person stands on a slightly elevated path, providing a sense of scale to the vast, desolate landscape. The horizon is flat, with a faint line of trees or vegetation visible under a pale sky.

Subsidence Simulation & Management

Claudia Faunt & Steve Phillips
US Geological Survey

An aerial photograph of a severely subsided and cracked landscape, likely a dry lake bed or agricultural field. The ground is broken into large, irregular blocks by deep, dark fissures. Patches of water are trapped in the depressions. In the far distance, a small figure of a person stands on a relatively flat area, providing a sense of scale to the vast, damaged terrain.

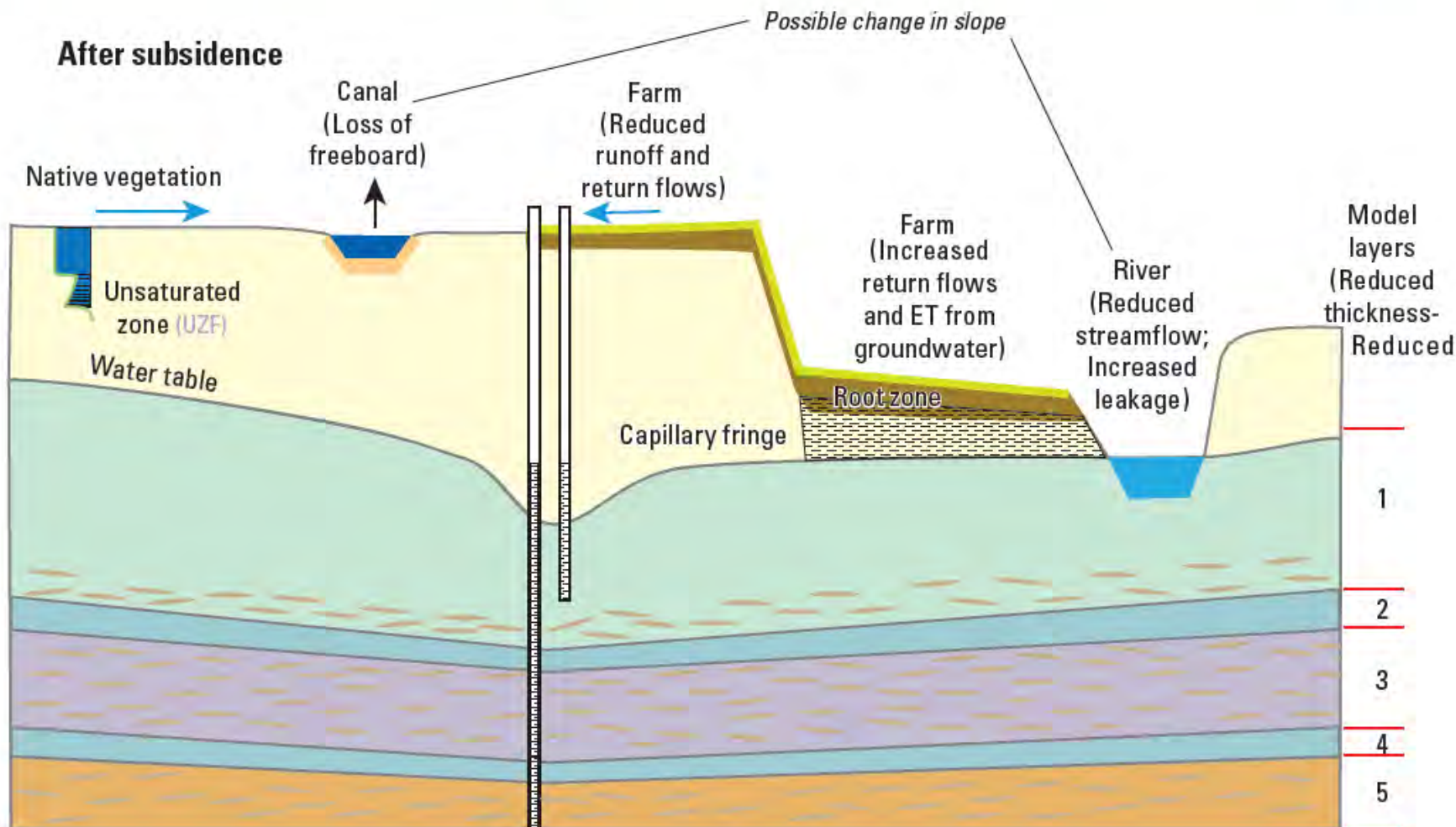
Topics

- Subsidence simulation tools
- Case studies, San Joaquin Valley
- Subsidence management, Antelope Valley

Overview of USGS Subsidence Simulation Tools

Simulation Feature	SUB	SUB-WT	SUB-OWHM
3D regional flow and subsidence	☺	☺	same
Variable geostatic loads		☺	same
Hydrodynamic lag	☺		same
Stress-dependent storage properties		☺	same
Deformable mesh			☺
Parameter estimation			☺

After subsidence



Simulation Limitations & Challenges

- Limitations
 - Assumption of 1D vertical stress/strain
 - Earth fissures
 - SUB and SUB-WT features are independent
- Challenges
 - Combining SUB/SUB-WT
 - Robust simulation of 3D stresses/strains
 - Inelastic compaction is a nonlinear process

Central Valley Hydrologic Model

**recent updates
focusing on subsidence**

**Claudia Faunt, Michelle Sneed,
and Jon Traum**

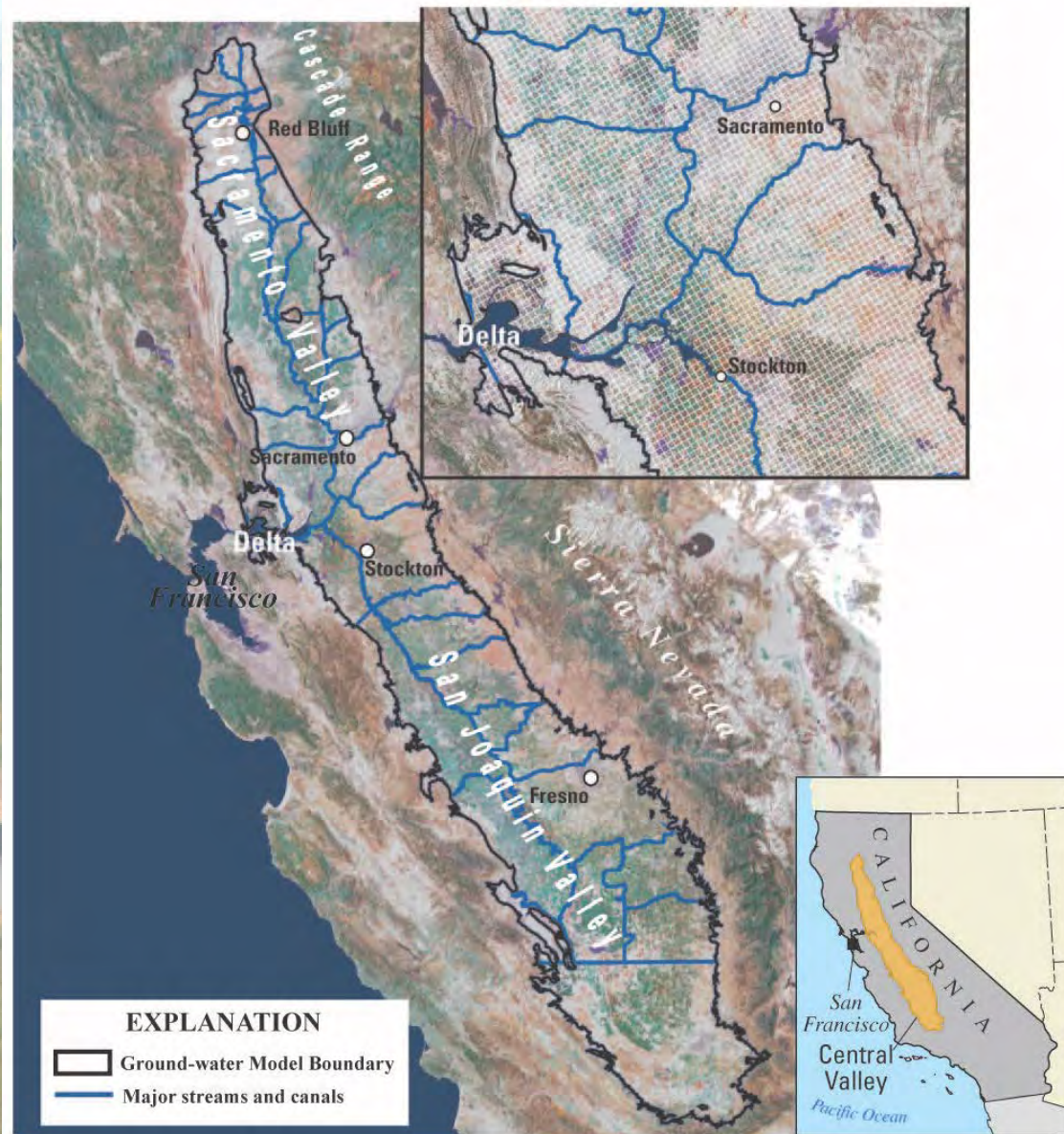
U.S. Geological Survey



<http://ca.water.usgs.gov/projects/central-valley/>

Central Valley Hydrologic Model

- ▶ 20,000 square miles
- ▶ Approximately 20 % of the Nation's groundwater pumpage is from the Central Valley aquifer system
- ▶ Focus on groundwater availability and changes in storage
- ▶ Developed for USGS Groundwater Resources Program
 - In consultation with CA-DWR
 - Updates in conjunction with Reclamation



CVHM – emphasis on groundwater availability and changes in storage

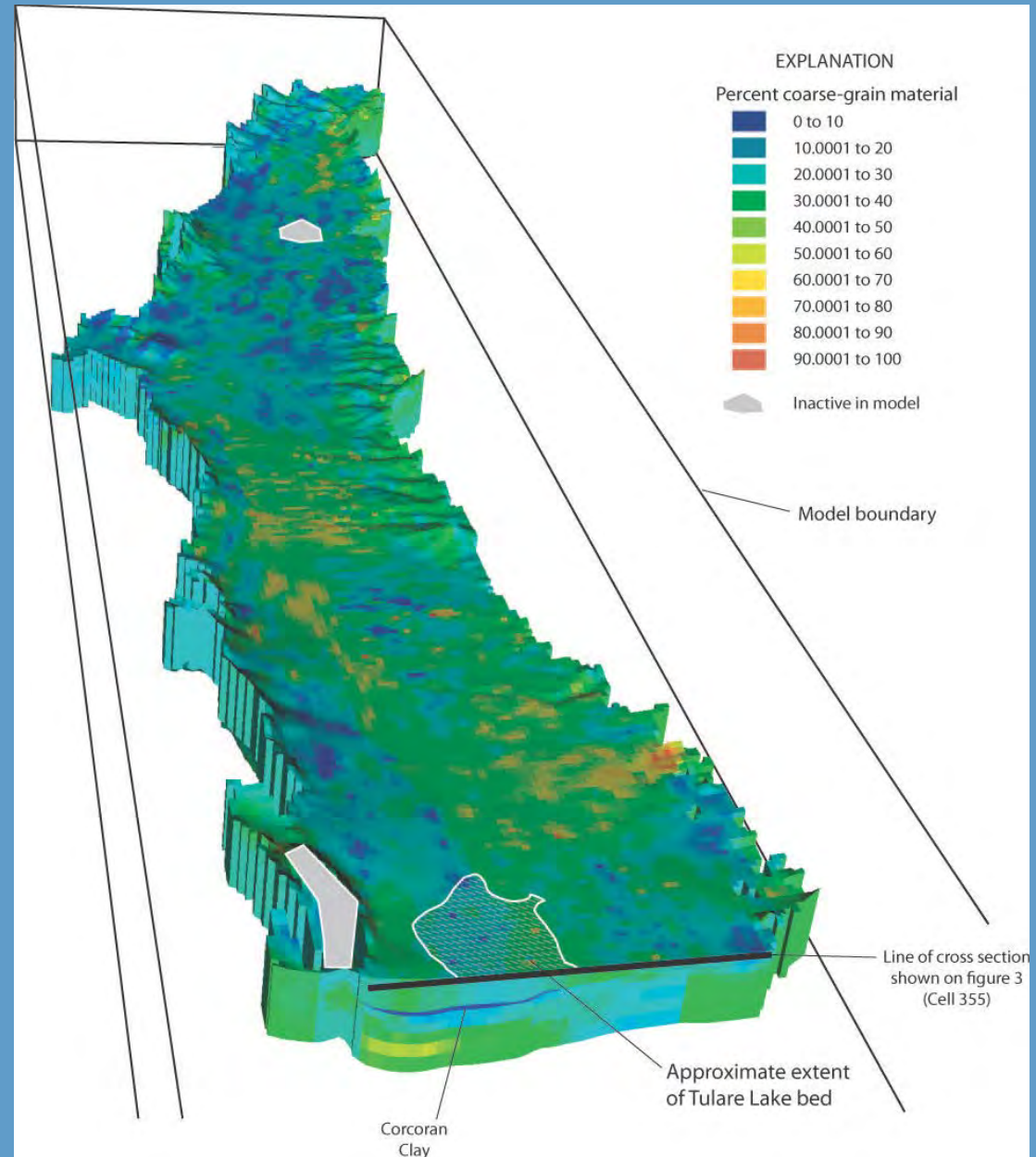
Objectives:

- **TEXTURE ANALYSIS:** Describe the sediment characteristics of the aquifer system to estimate hydraulic properties.
- **FARM PROCESS:** Develop an approach for systematically estimating water budget components for an aquifer system in an area dominated by irrigated agriculture.
- **GROUNDWATER MODEL:** Develop a model of the Central Valley aquifer system *capable of being accurate* at scales relevant to water management decisions.

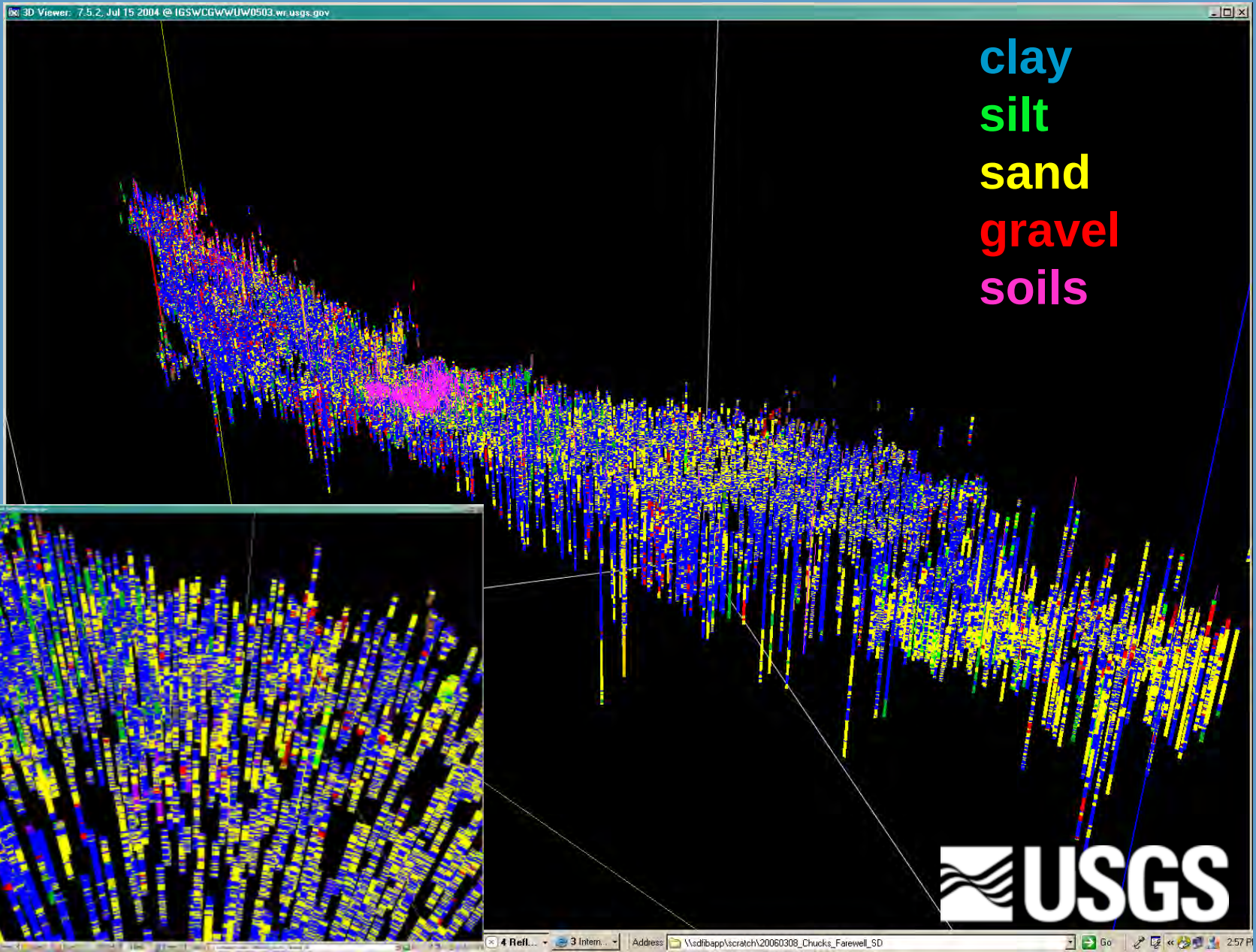
Texture Analysis:

3D model

- Based on 8,500 drillers logs
- Interpolated to one-mile spatial grid at 50 foot depth intervals
- Coarse near river channels
- Finer in low energy environments (Corcoran Clay)



Central Valley well logs - lithology



Farm Process:

- Systematic approach for estimating water-budget components
- Based on:
 - the consumptive use of water by plants
 - available surface-water deliveries

Pumping not metered

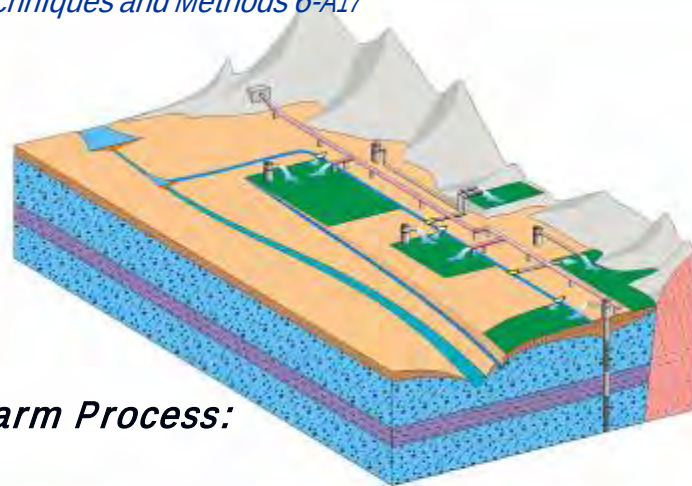


SIMULATING IRRIGATED AGRICULTURE WITH MODFLOW



By Schmid, Wolfgang, Hanson, R.T., Maddock III, T.M., and Leake, S.A.

USGS Techniques and Methods 6-A17

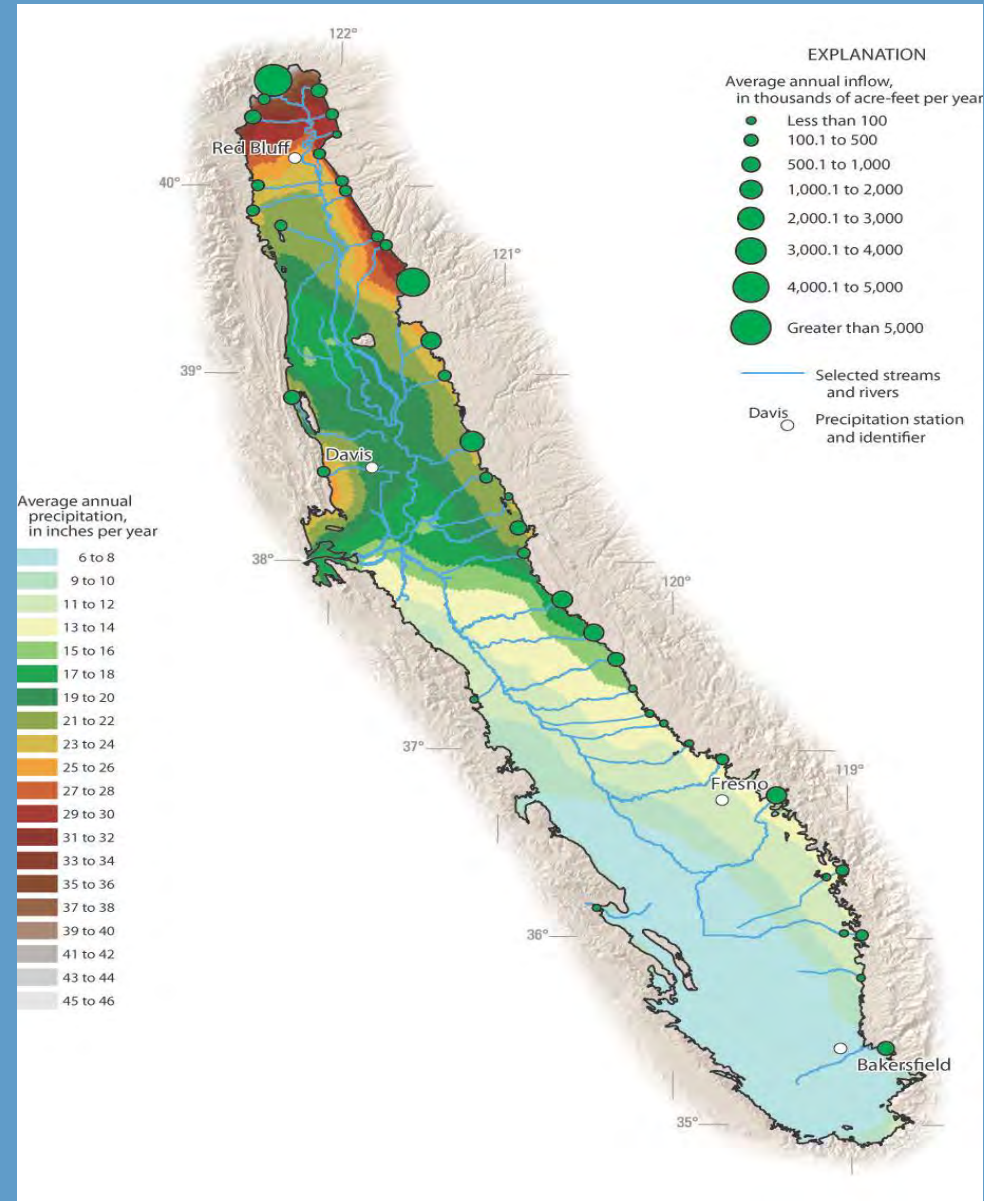
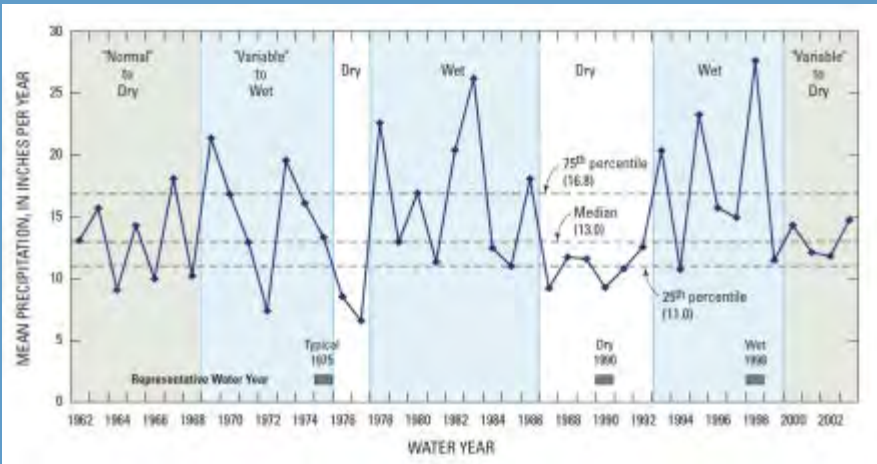


The Farm Process:

*FULLY COUPLED LAND USE—SURFACE-
WATER FLOW—GROUNDWATER FLOW*

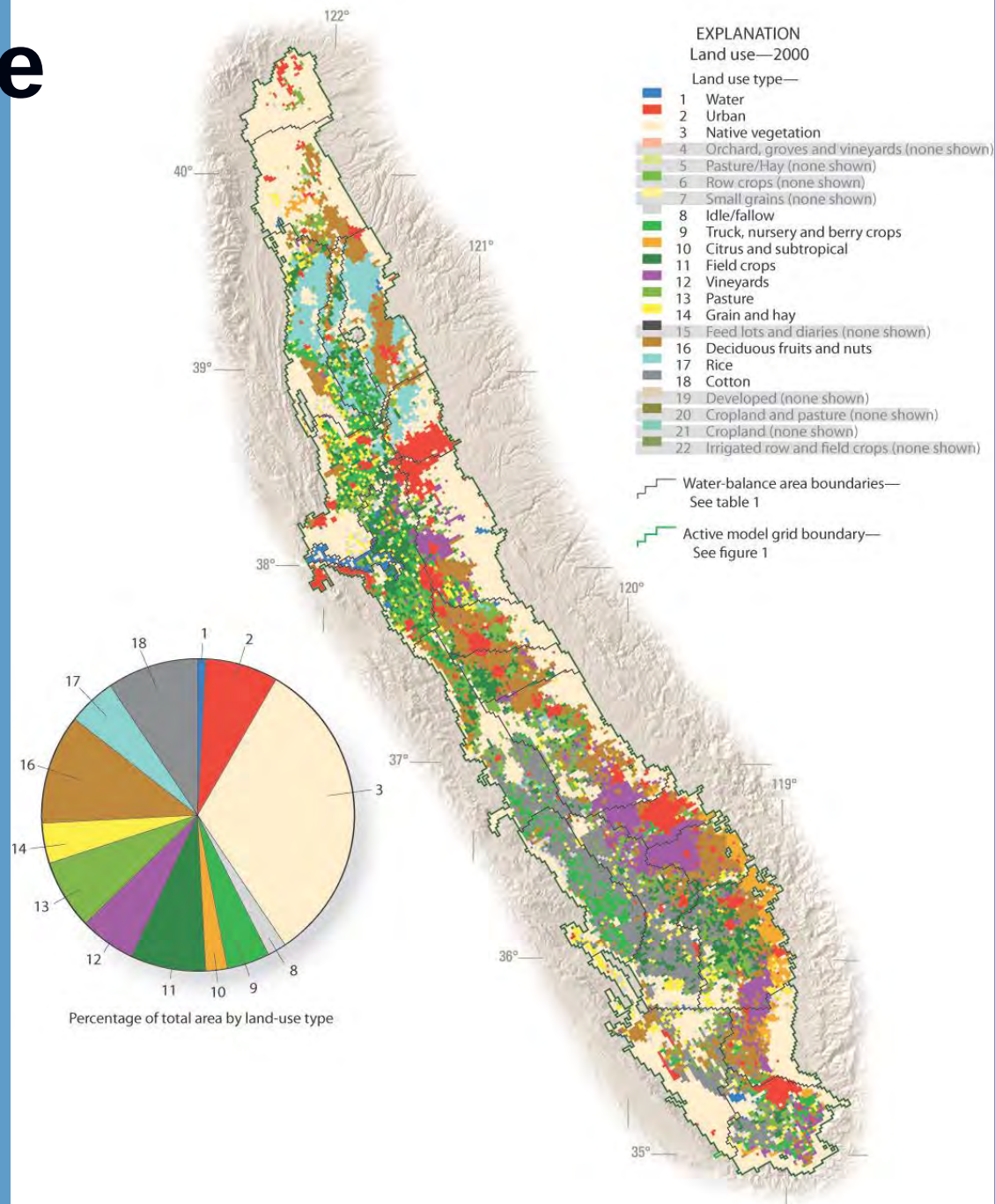
Climate: Precipitation and Inflows

- Vary Geographically
- Vary with Time
 - Annually
 - Seasonally

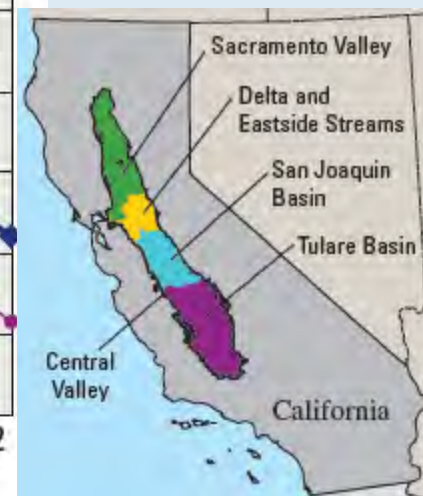
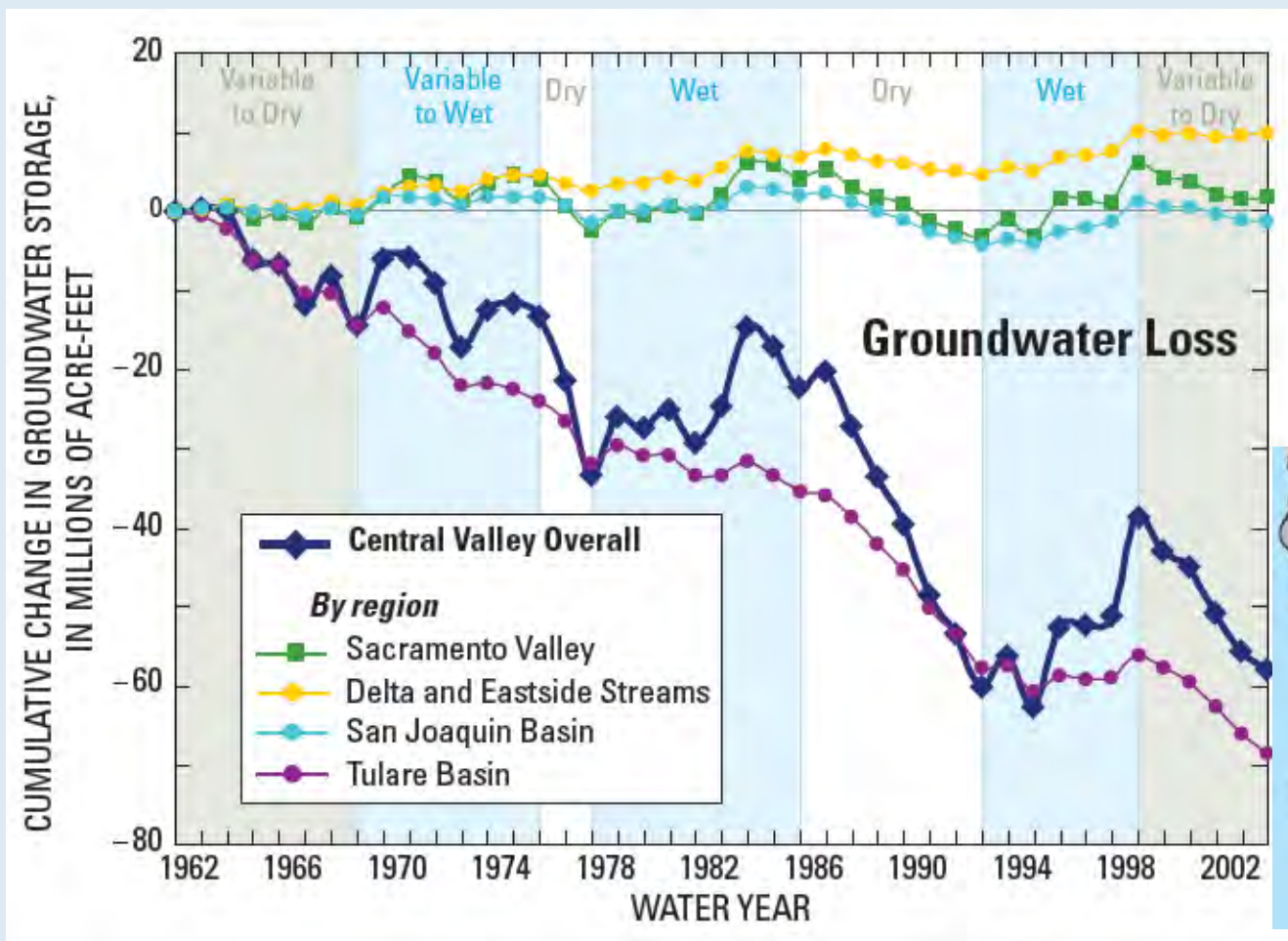


Water-balance regions and Landuse

- 21 regions
 - CA-DWR collaboration
- 1962-2003
- Landuse categories:
 - Urban
 - Native
 - Crops

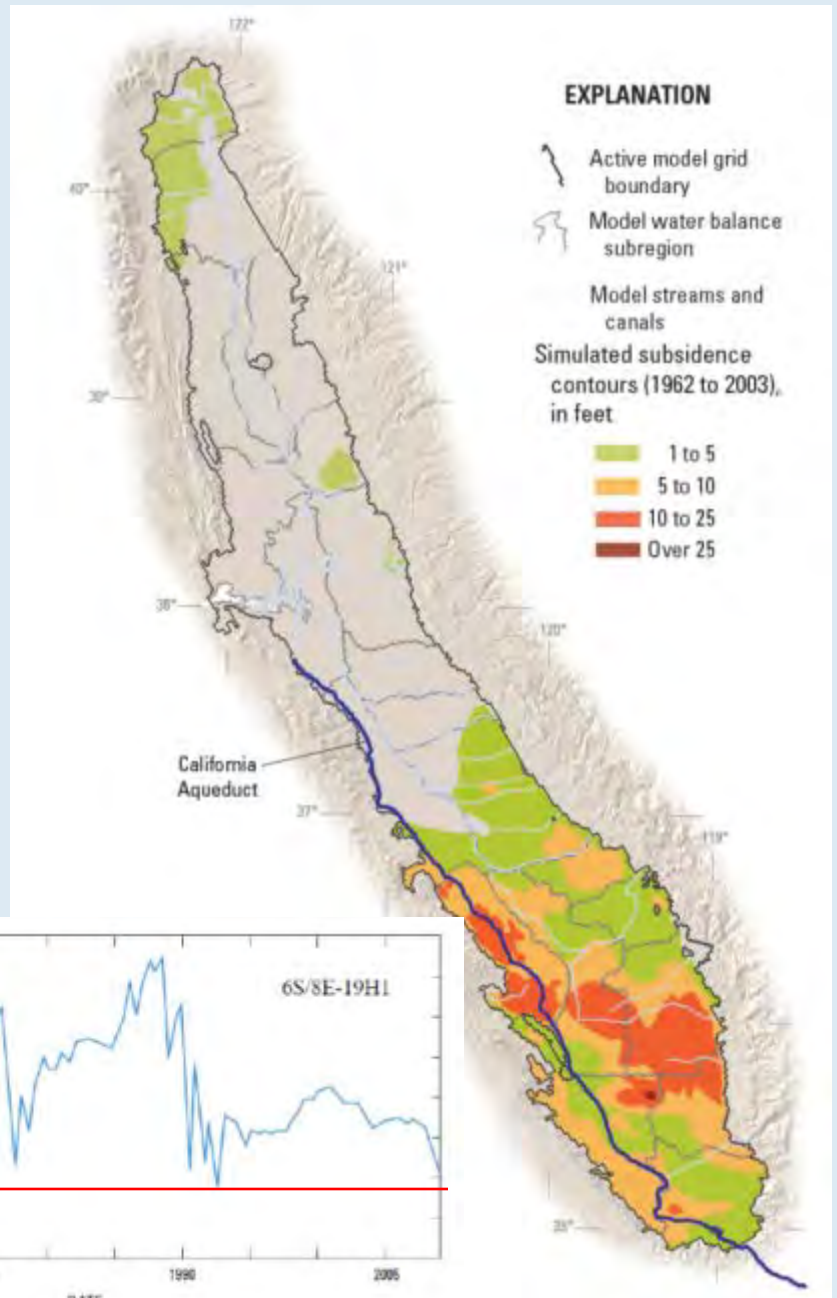
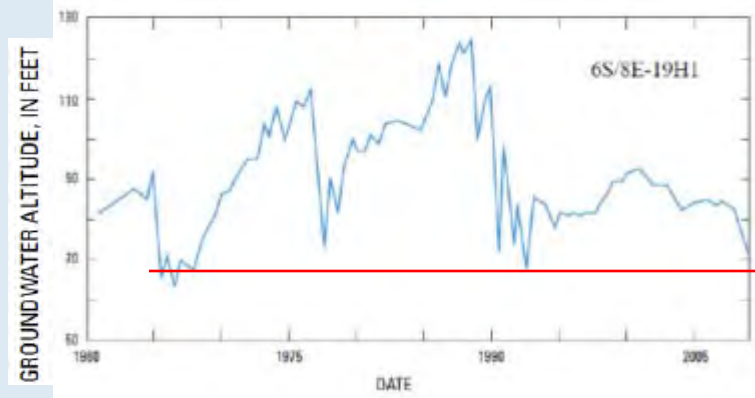


Change in Storage with time



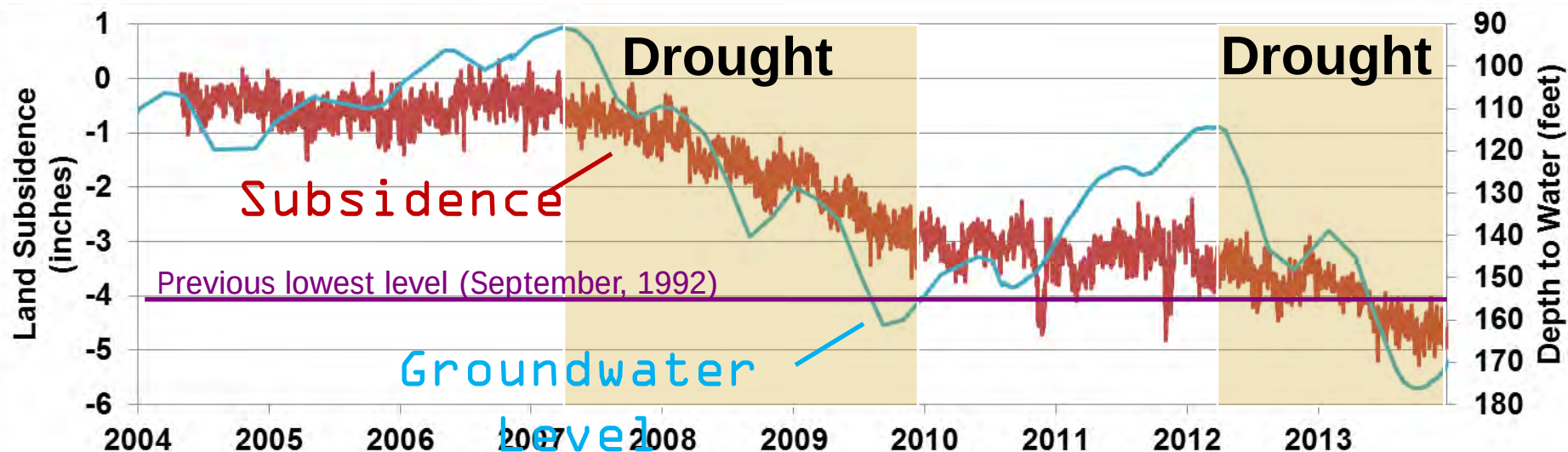
Subsidence:

- In 1960s, groundwater pumping caused water levels to decline
- Water-level declines cause compaction of fine-grained deposits, which results in subsidence
- Surface-water deliveries since the late 1960s have reduced the dependence on groundwater
- Recently water levels were again reaching their historic lows and subsidence renewed
- Management constraint



Recent Subsidence

- ▶ Renewed subsidence concern during 2007-09 drought, and now, the current drought
 - Reduced surface water importation
 - More reliance on the groundwater resources
 - Not just a problem during droughts for some areas without surface-water access



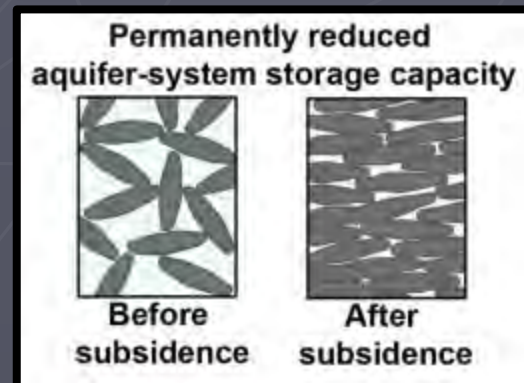
Subsidence Damages Natural Resources and Infrastructure

► Flood Protection and Infrastructure

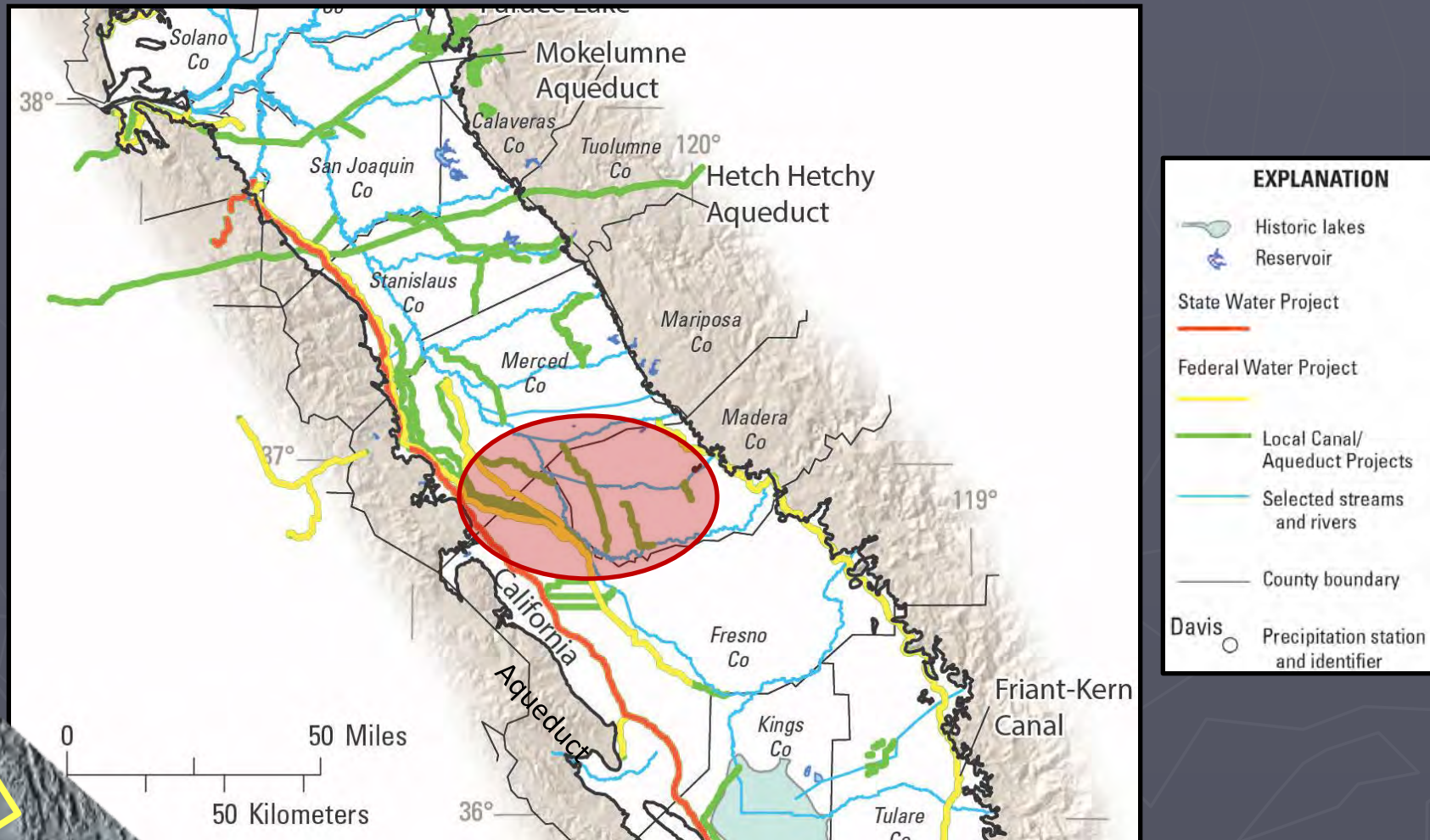
- Damage to water conveyance systems and other infrastructure
 - Reduced conveyance capacity and freeboard, panel damage; water surface and liner misalignment; erosion/deposition in unlined channels
 - Roads, rails, bridges, pipelines, wells, etc.

► Natural resources

- Reduces aquifer-system storage capacity
- Impacts to wetland, riparian, and aquatic ecosystems
- Restricted land uses



Federal, State, and Local Water Infrastructure in the Impacted Area



Modified from Faunt, 2009

Updates and Refinements to CVHM

► Model Code Changes

► Data Updates

- Extend the model simulation period
 - through 2009 (Reclamation)
 - through 2013 (USGS drought funding)
- Update land use
- Update surface water delivery data
- Increase the resolution in western San Joaquin Valley

► Recalibration

► Preliminary Results

► Working to incorporate current drought

Model Code Changes

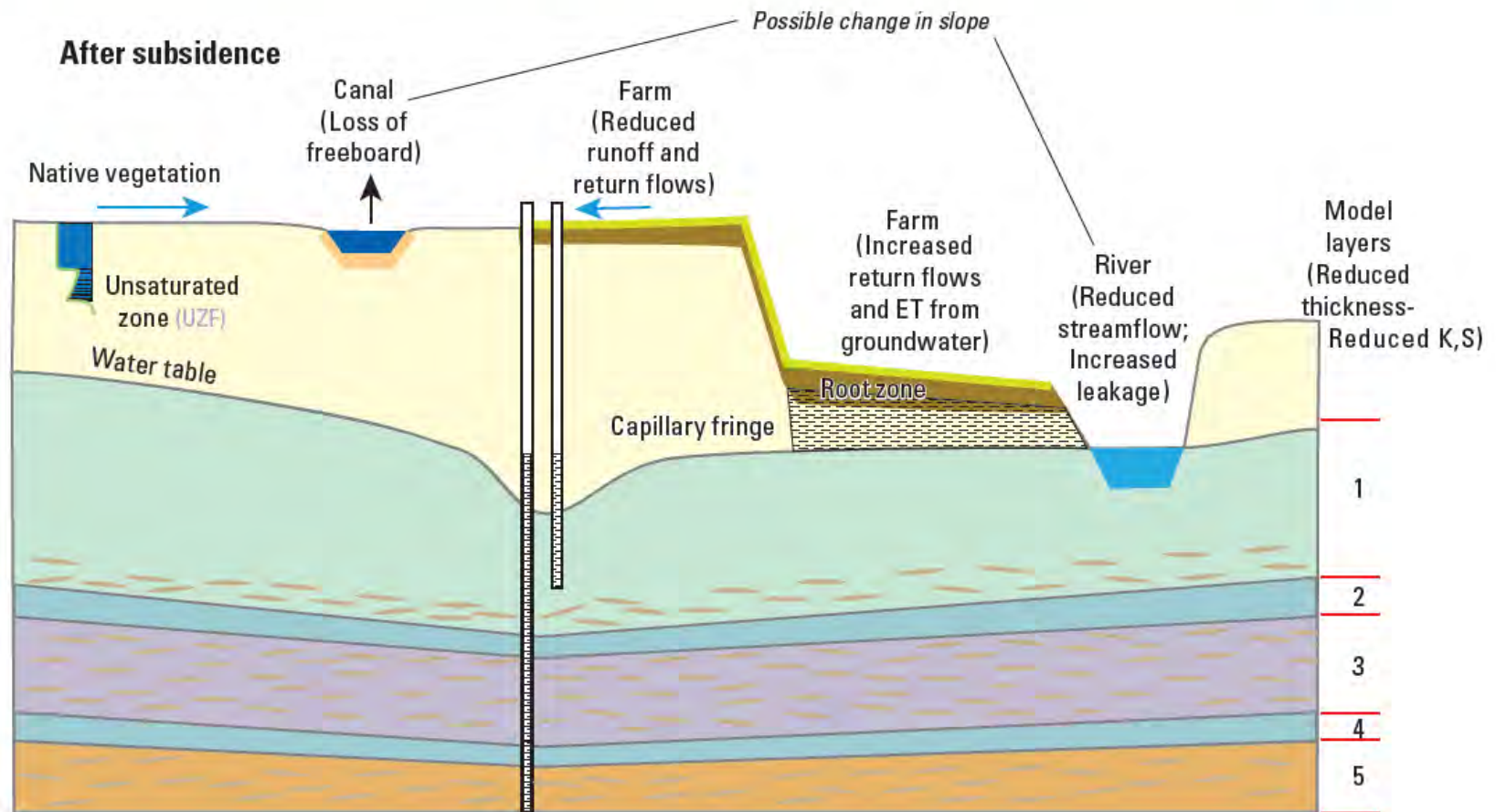
- **MODFLOW and CVHM** updated to include:
 - (1) more accurate details in the timing of the subsidence by incorporating delay beds,
 - (2) separation of the inelastic and elastic portions of subsidence in the SUB package, and
 - (3) changes in land-surface altitudes caused by subsidence - deformable layers
 - (4) Simulation of water table (NWT solver)
 - (5) Adjustable sub-regions through time

Landscape processes

Farm Process (FMP)
Streamflow Routing Package (SFR)
Surface-Water Routing Process (SWR)

Subsurface processes

Layer-Property Flow Package (LPF)
Subsidence Package (SUB)
Multi-Node Well Package (MNW)
Unsaturated-Zone Flow Package (UZF)



Updates and Refinements to CVHM

► Model Code Changes

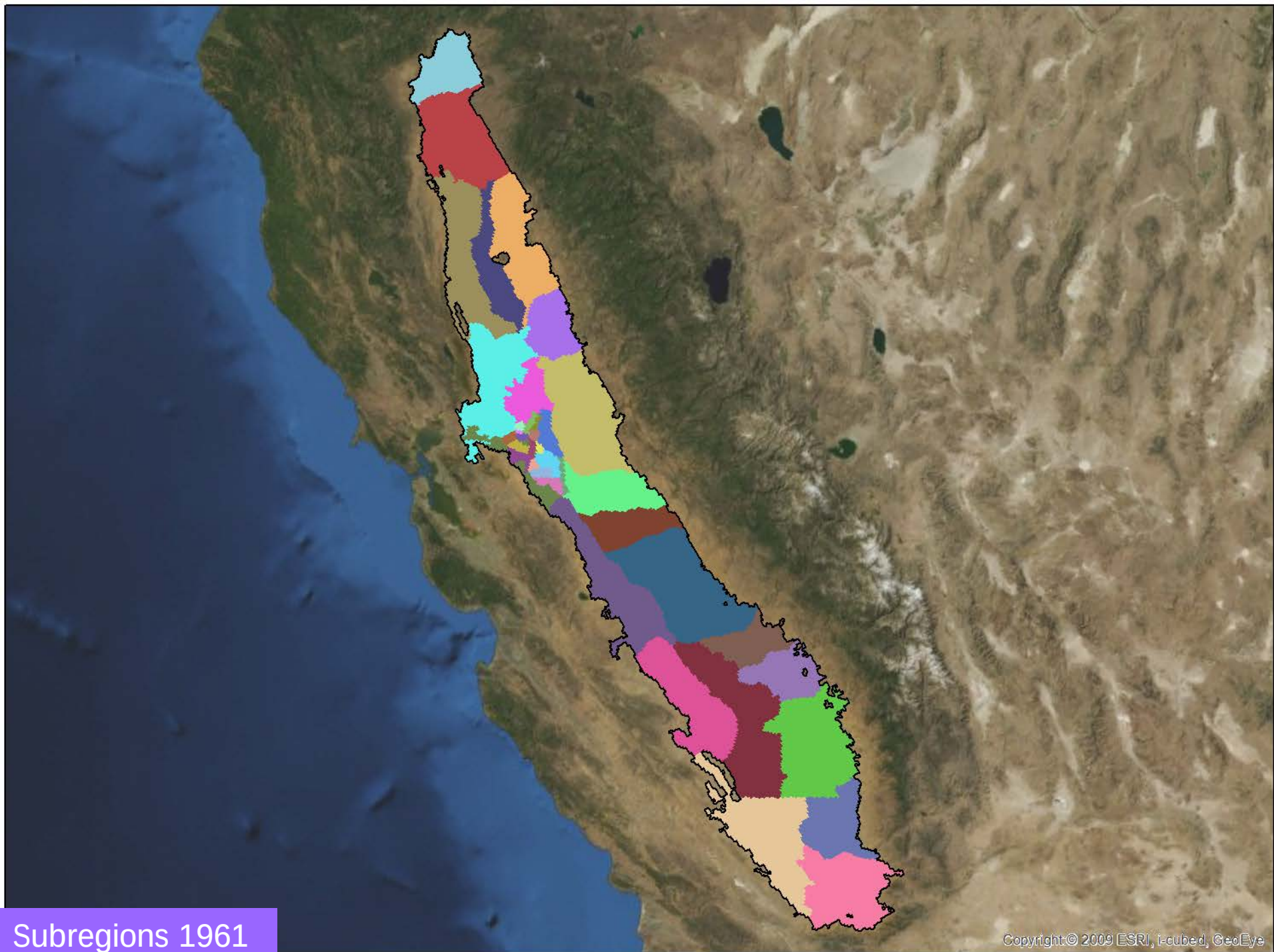
► Data Updates

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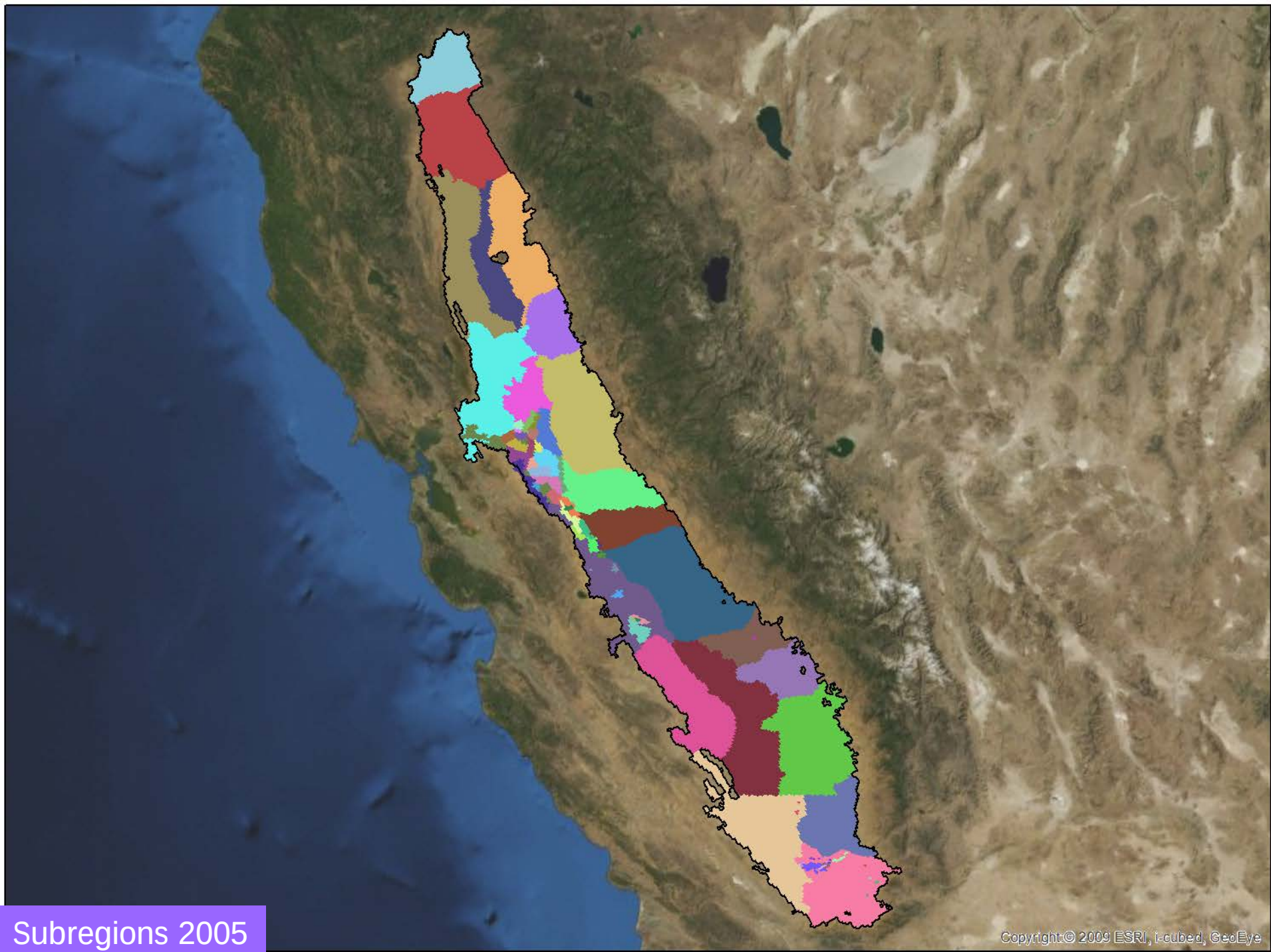
► Recalibration

► Preliminary Results

► Working to incorporate current drought



Subregions 1961



Subregions 2005

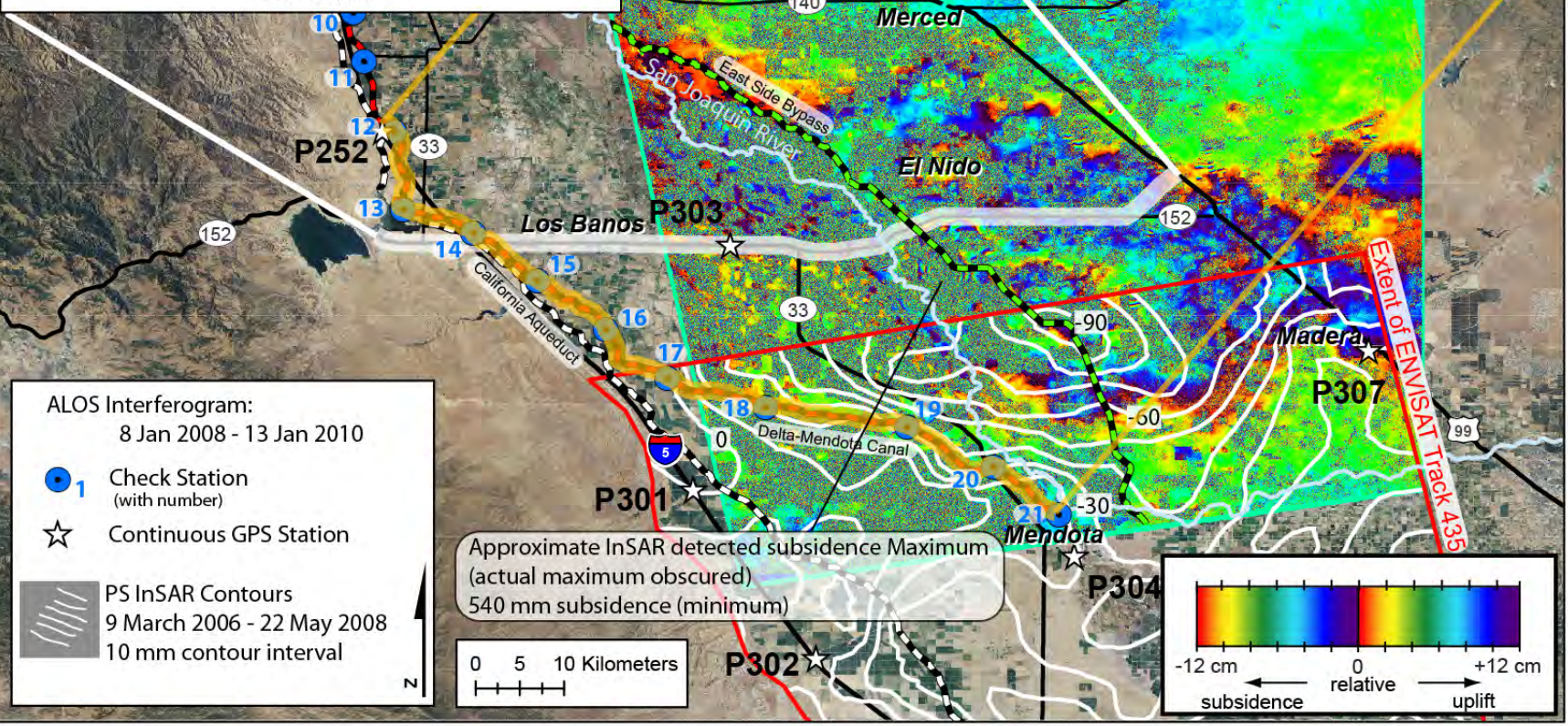
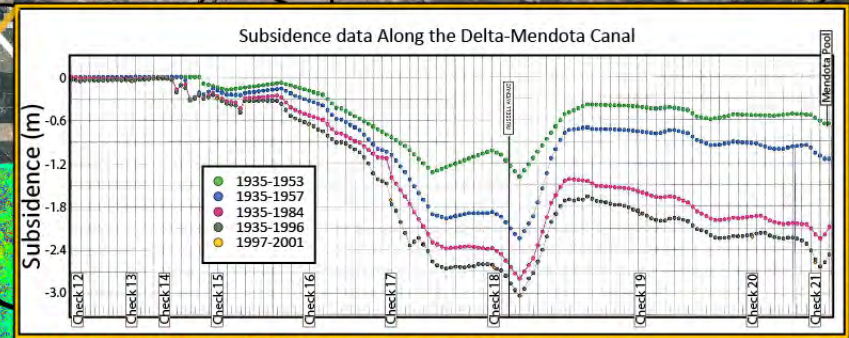
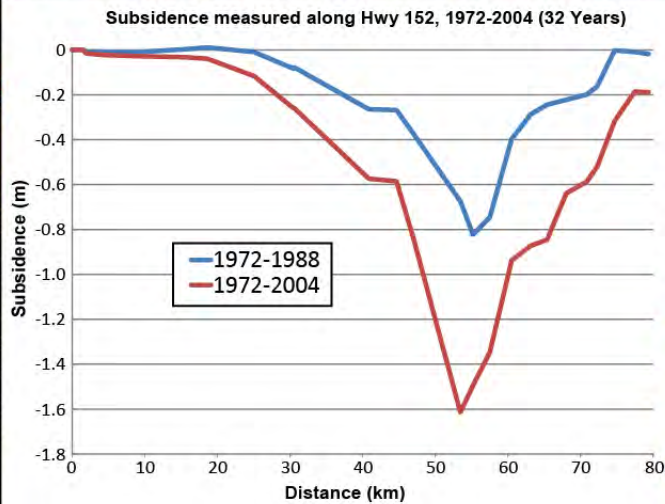
Constraining Subsidence Simulations: 1961-present

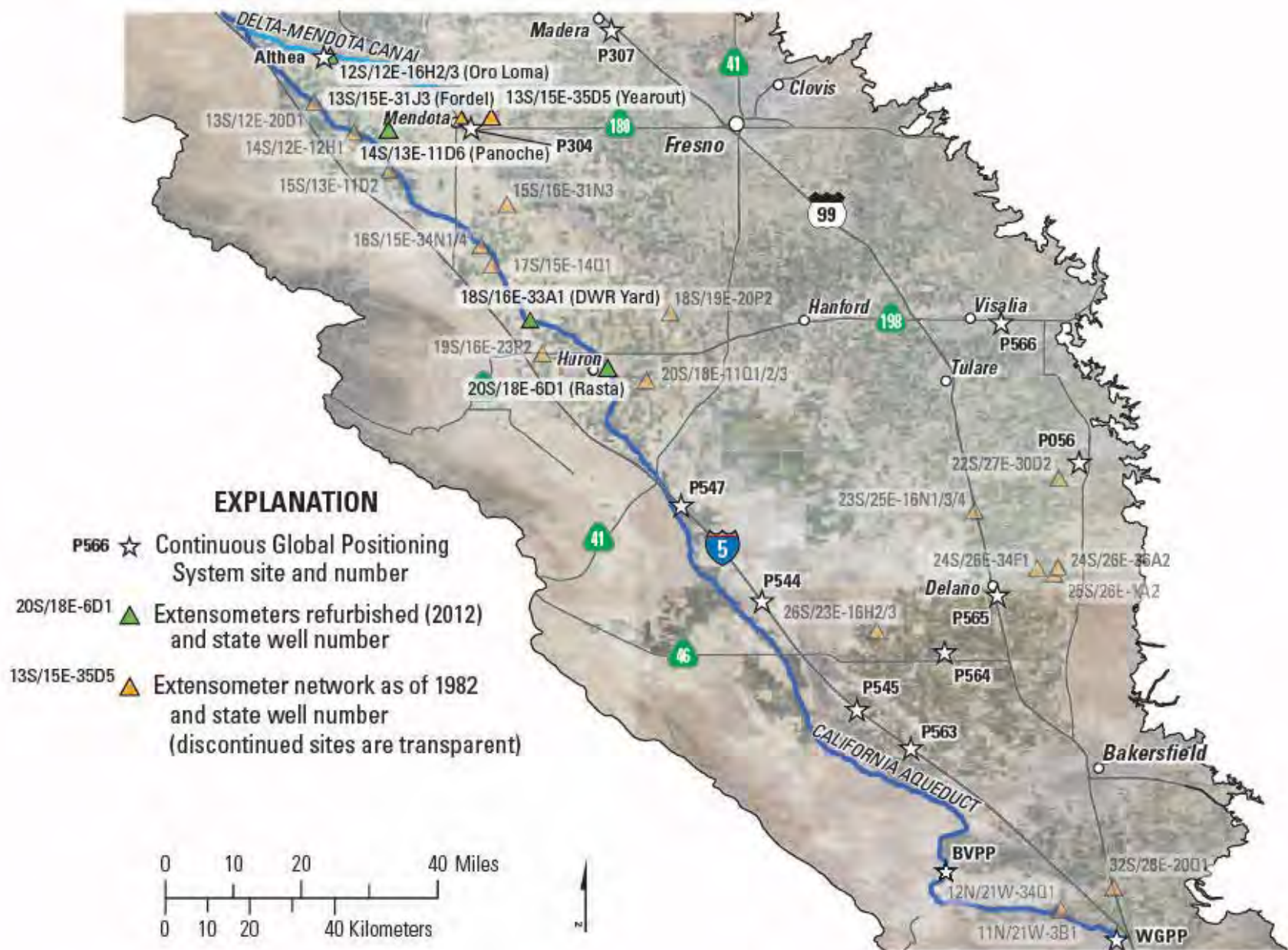
► Historical

- Leveling Surveys
 - Mostly along roads and water conveyance routes
- Extensometers
 - 24 (most south of Hwy 152)

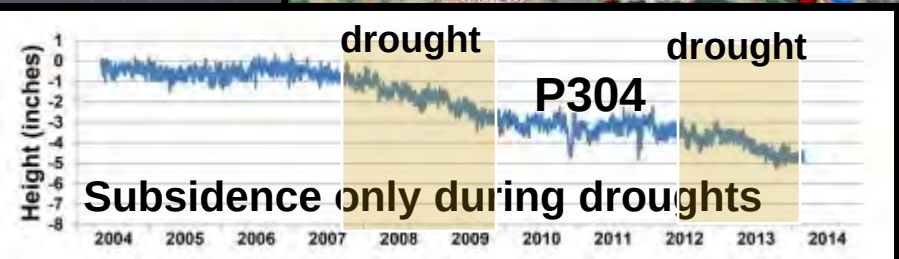
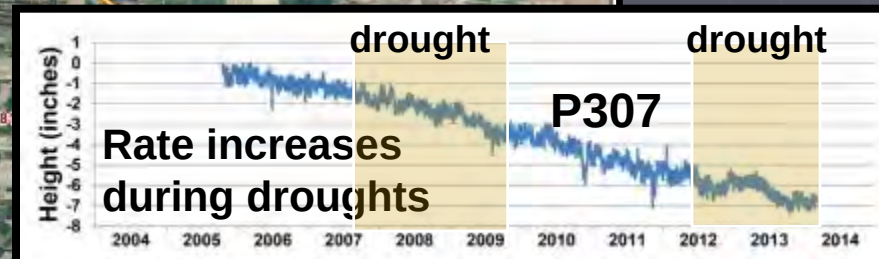
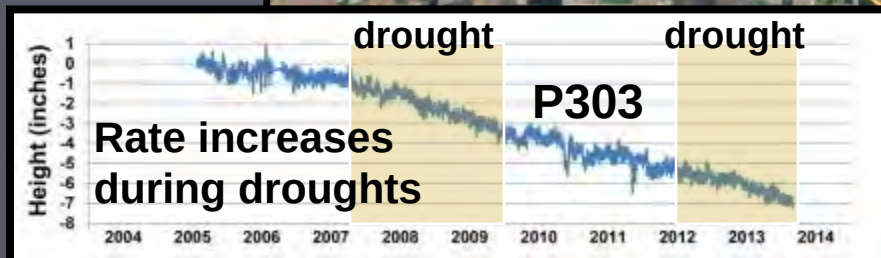
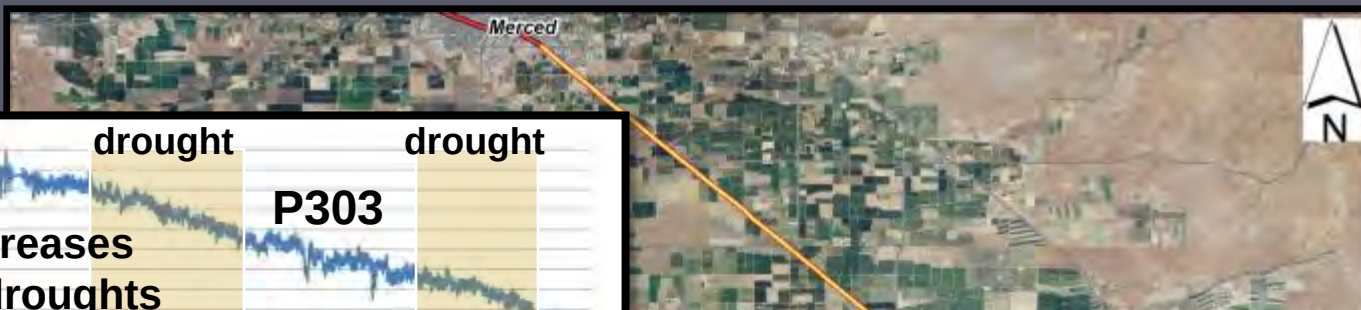
► Recent

- GPS Surveys
- Continuous GPS
 - 27 sites on valley floor
- InSAR
 - 83 C-band images (2 tracks) using PSInSAR
 - Small baseline (<560 m); short temporal separation <13 months; kriged
 - 15 L-band images (4 tracks) using conventional InSAR

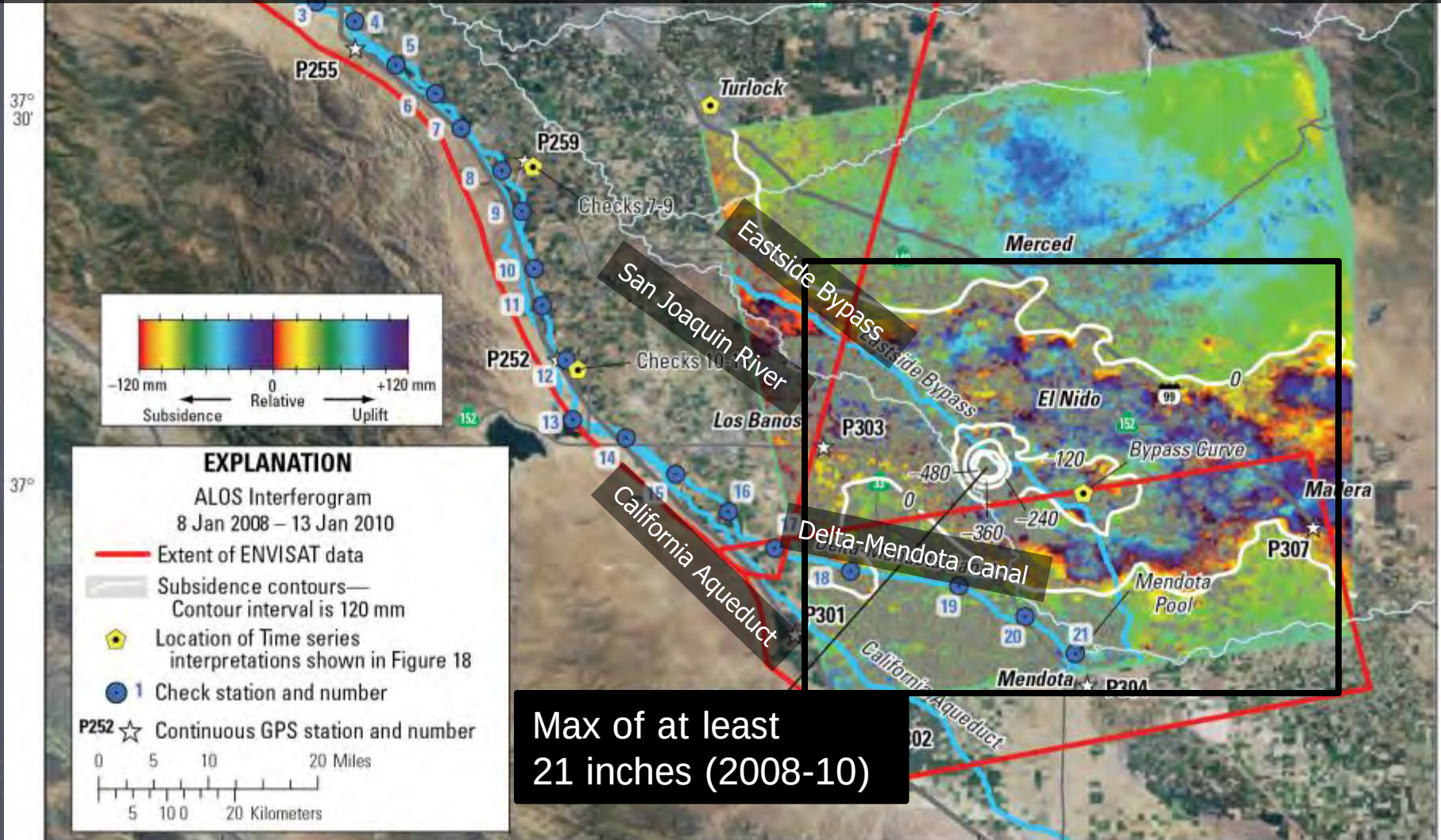




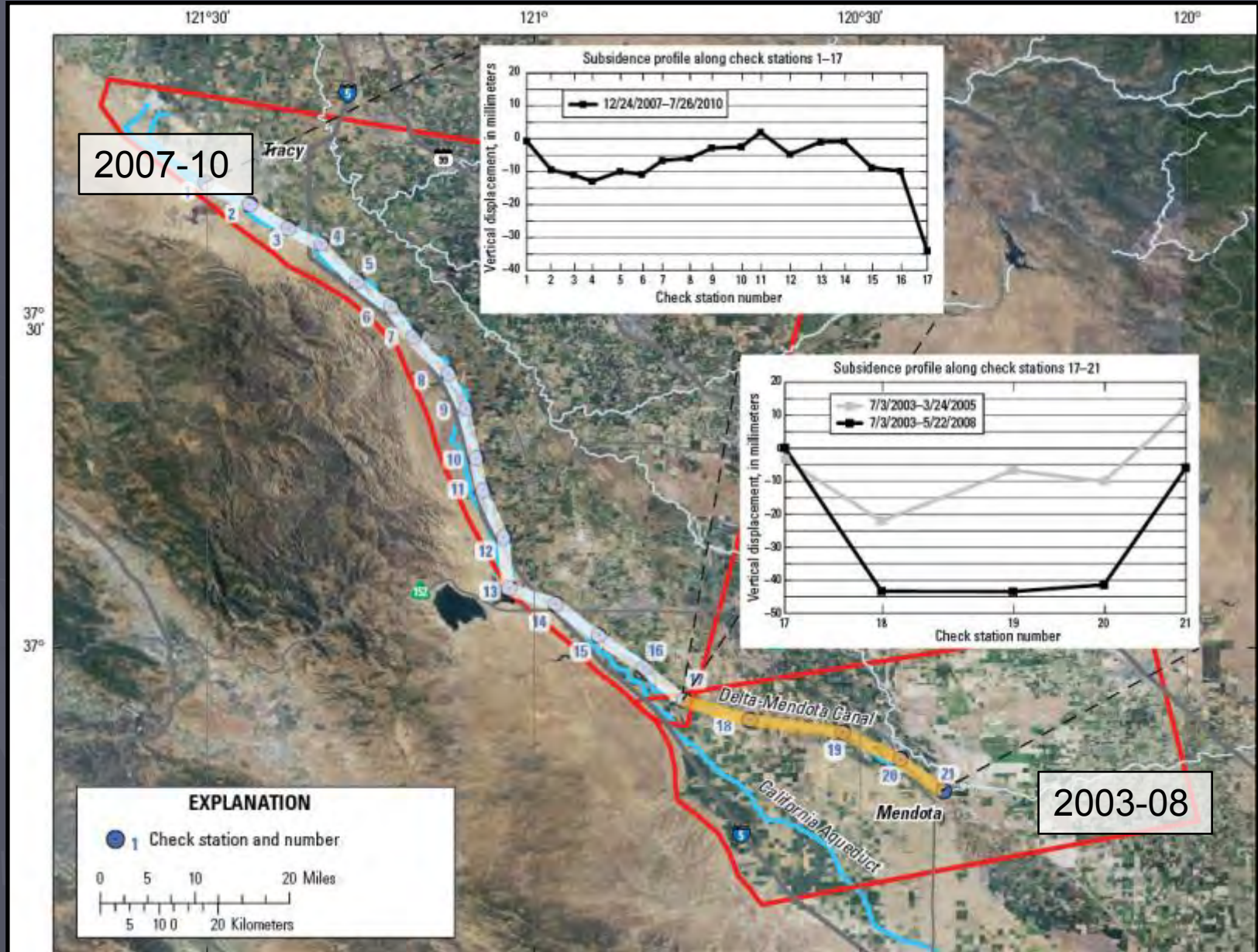
GPS Subsidence Measurements



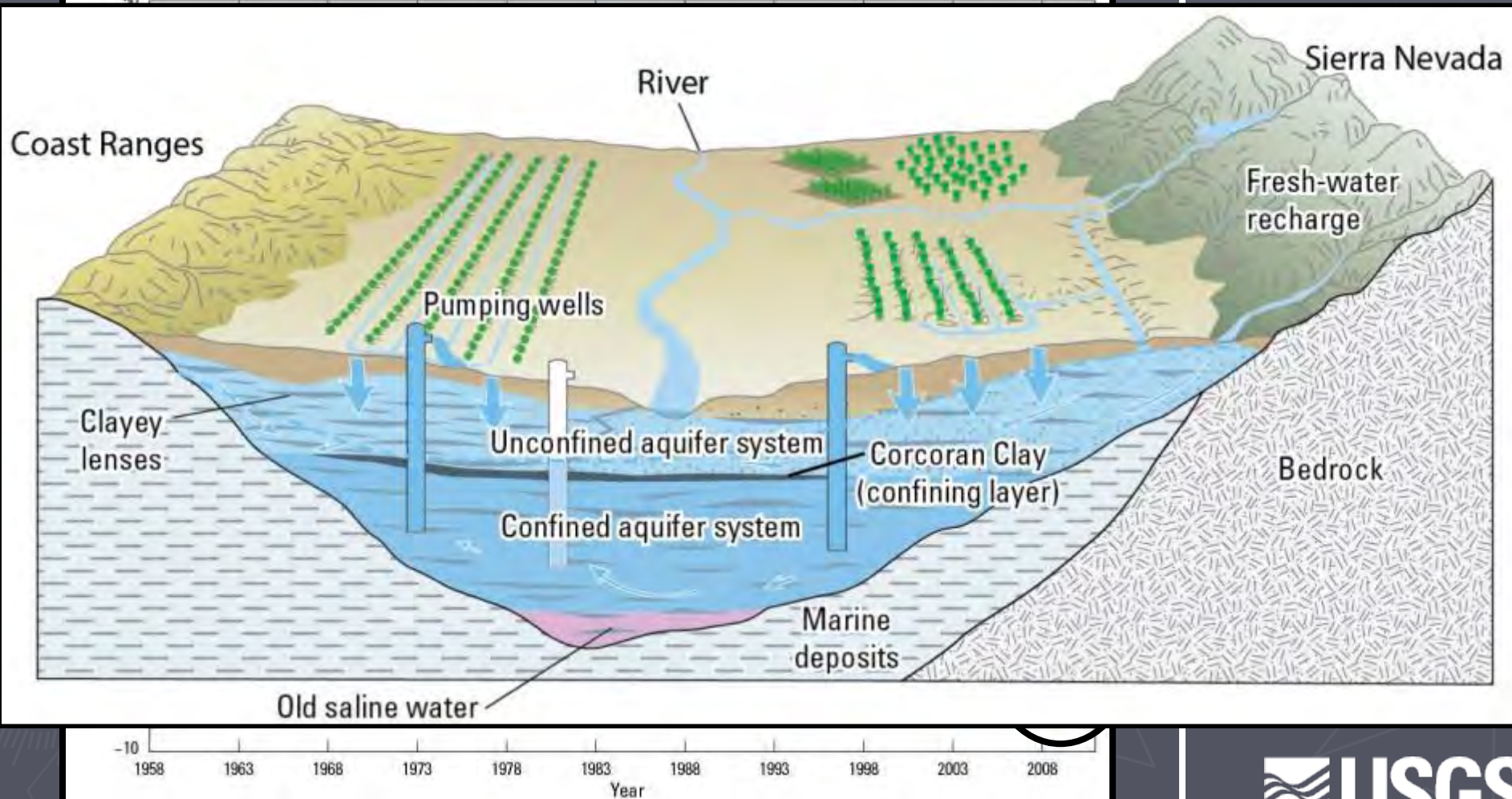
InSAR Subsidence Measurements: Maximum Subsidence Area near El Nido, between Eastside Bypass and San Joaquin River



Subsidence along the DMC

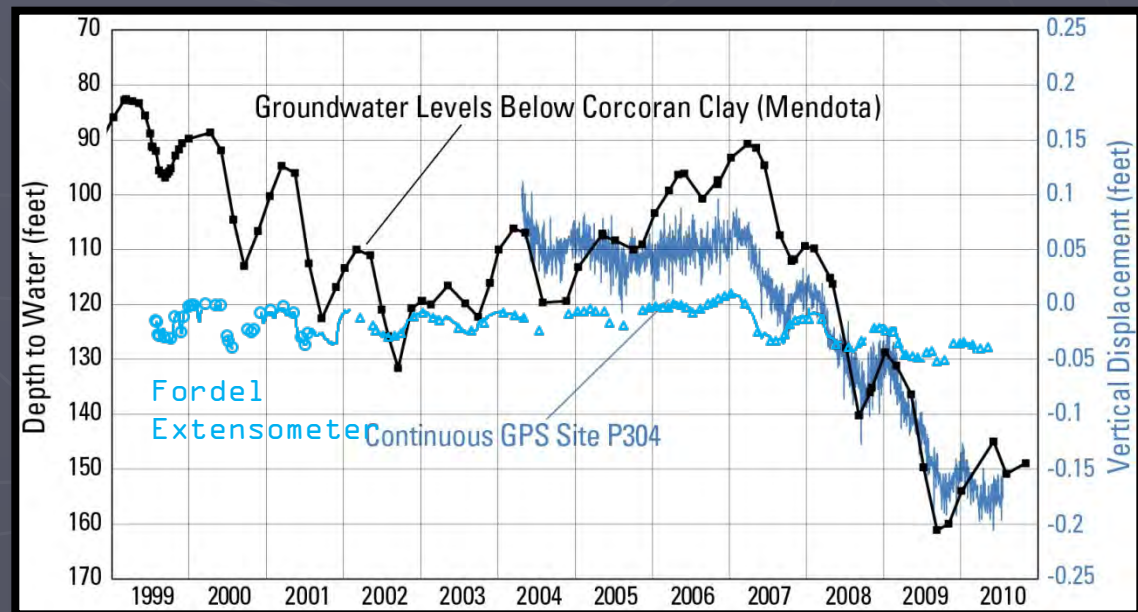


Water levels in the Shallow and Deep Systems Declined 2007-10



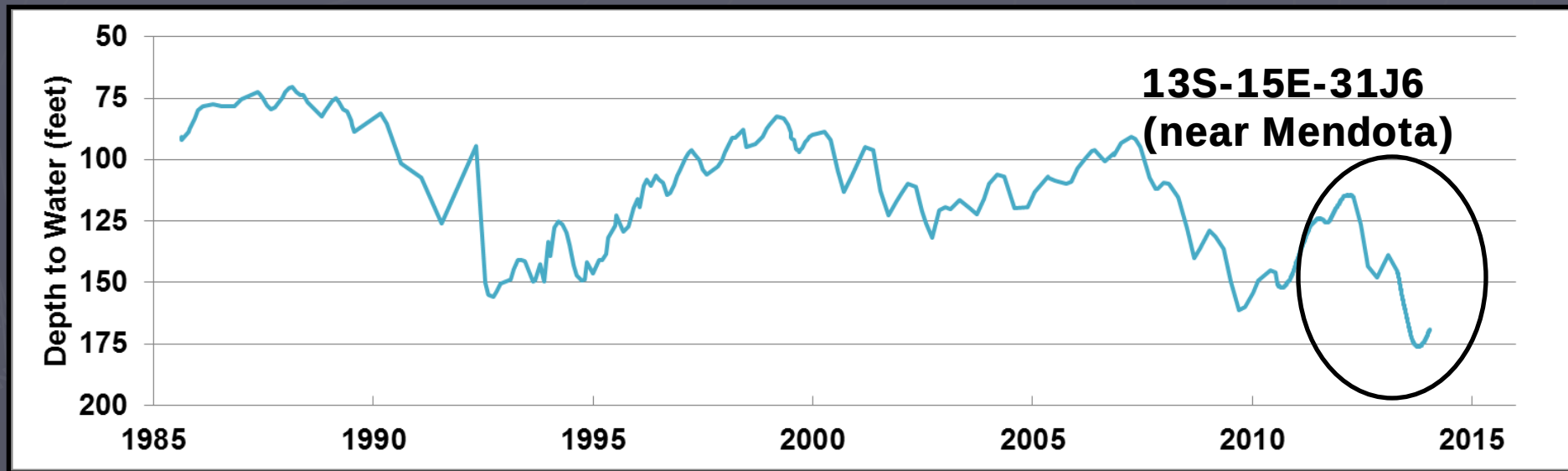
Where is subsidence happening?

- ▶ In some areas, most of the compaction has occurred below the Corcoran Clay
 - GPS, extensometer, leveling, and water-level data
 - 1-D modeling

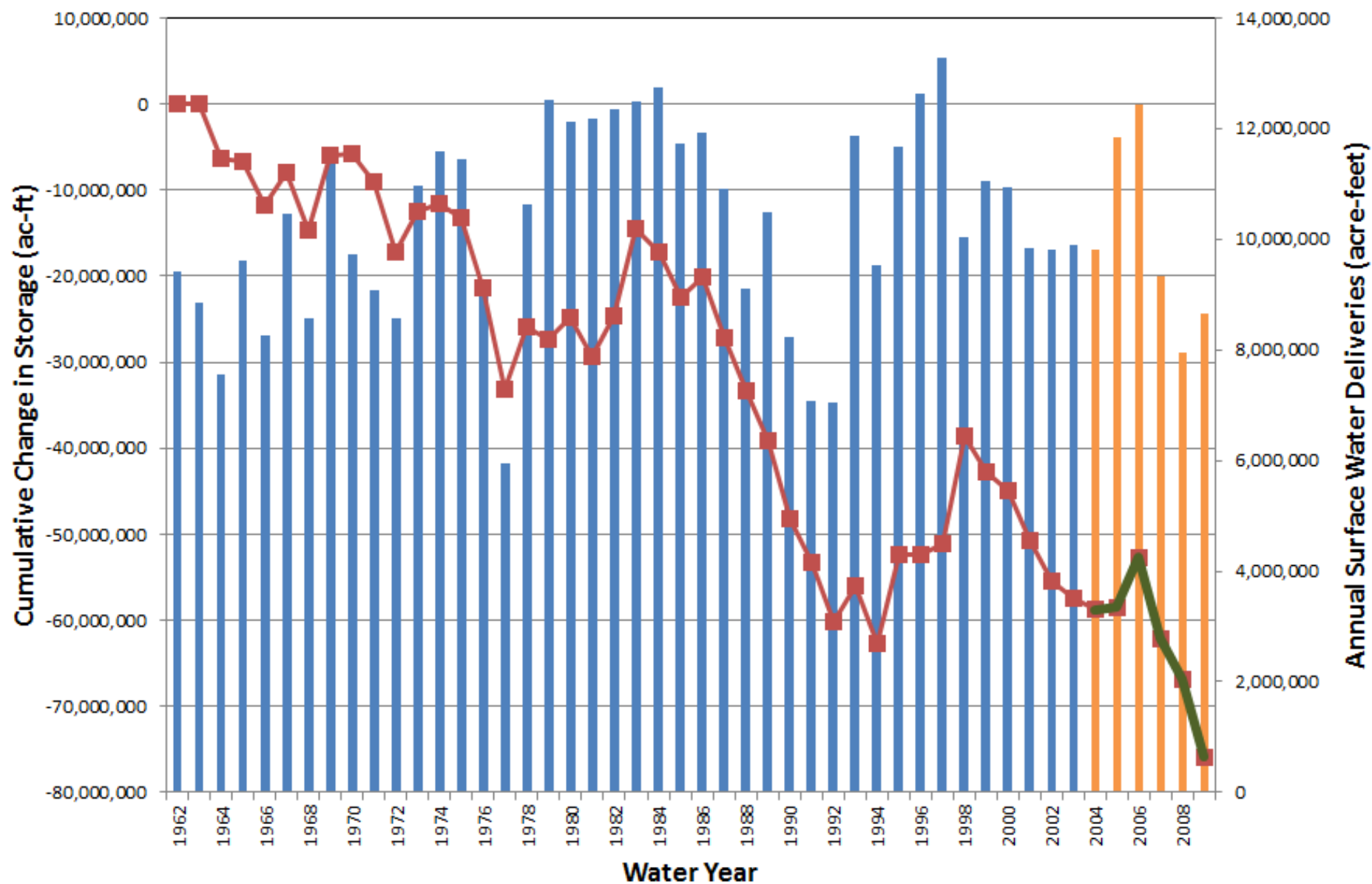


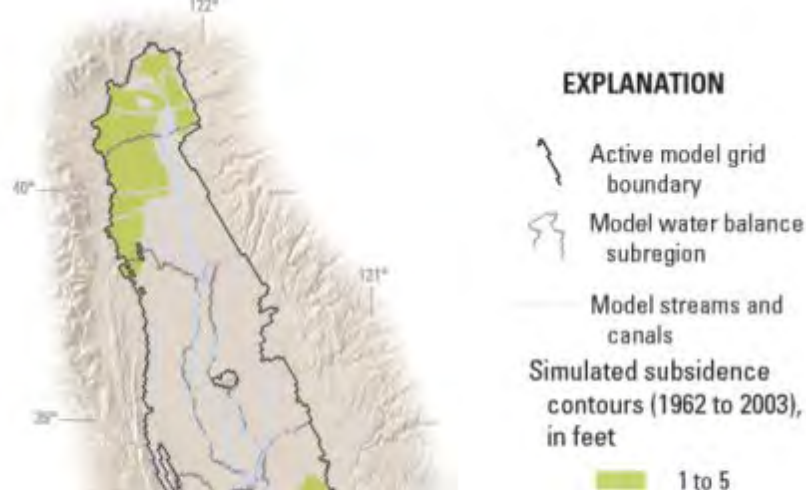
- ▶ Implication: CC not particularly important for simulating historical subsidence, but important for future scenarios

Groundwater Levels Continue to Decline

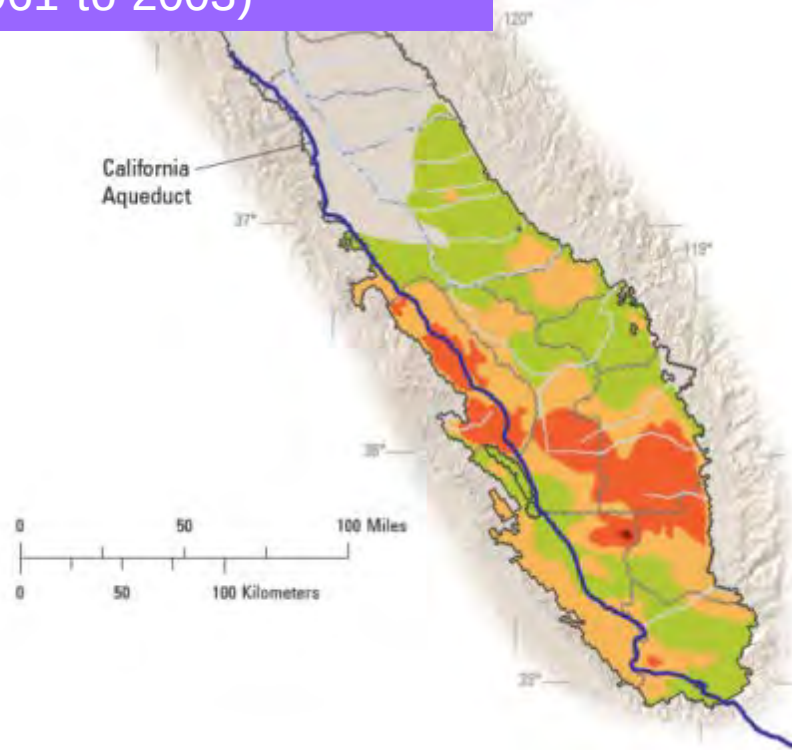


Cumulative Change in Storage and Annual Surface Water Deliveries

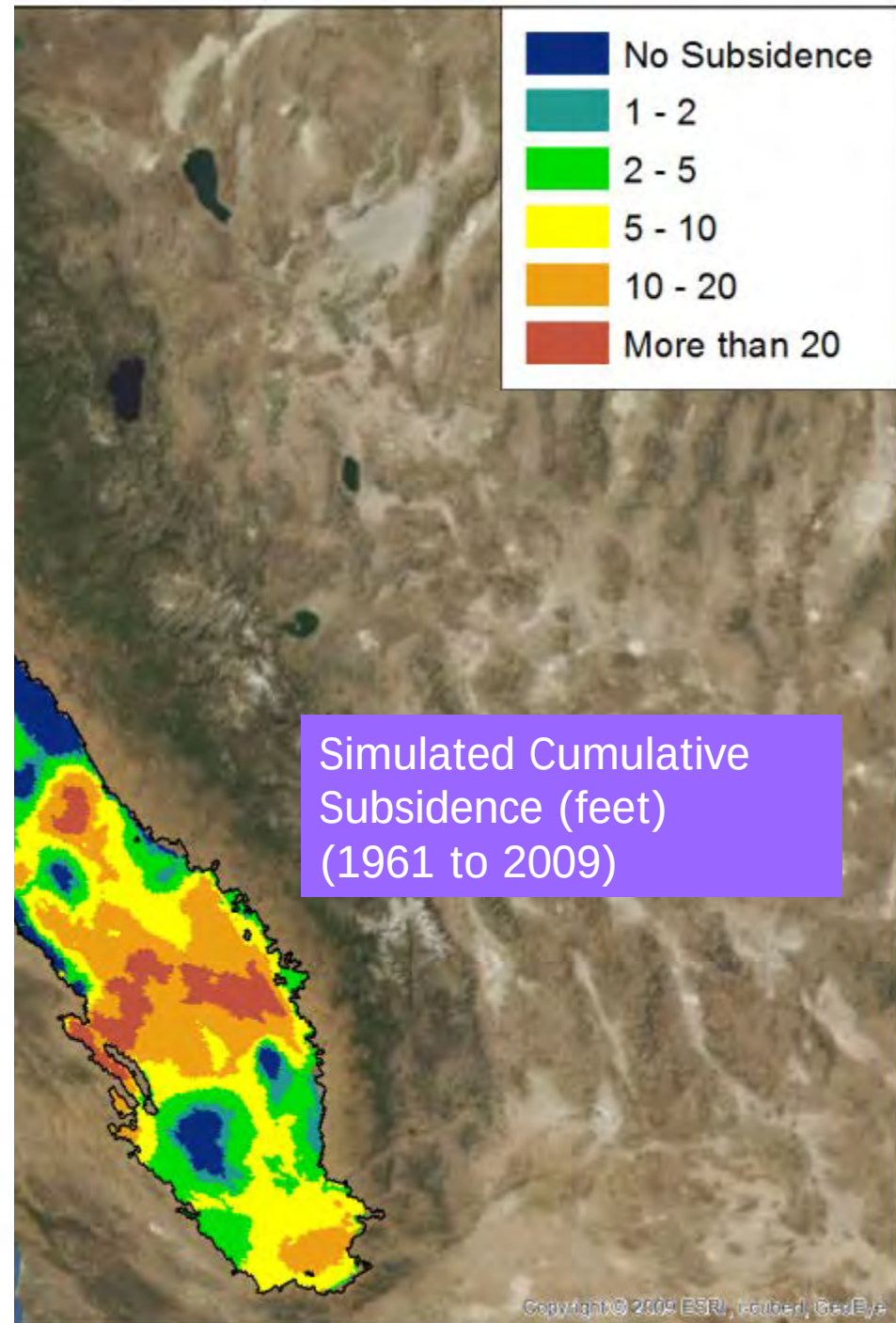


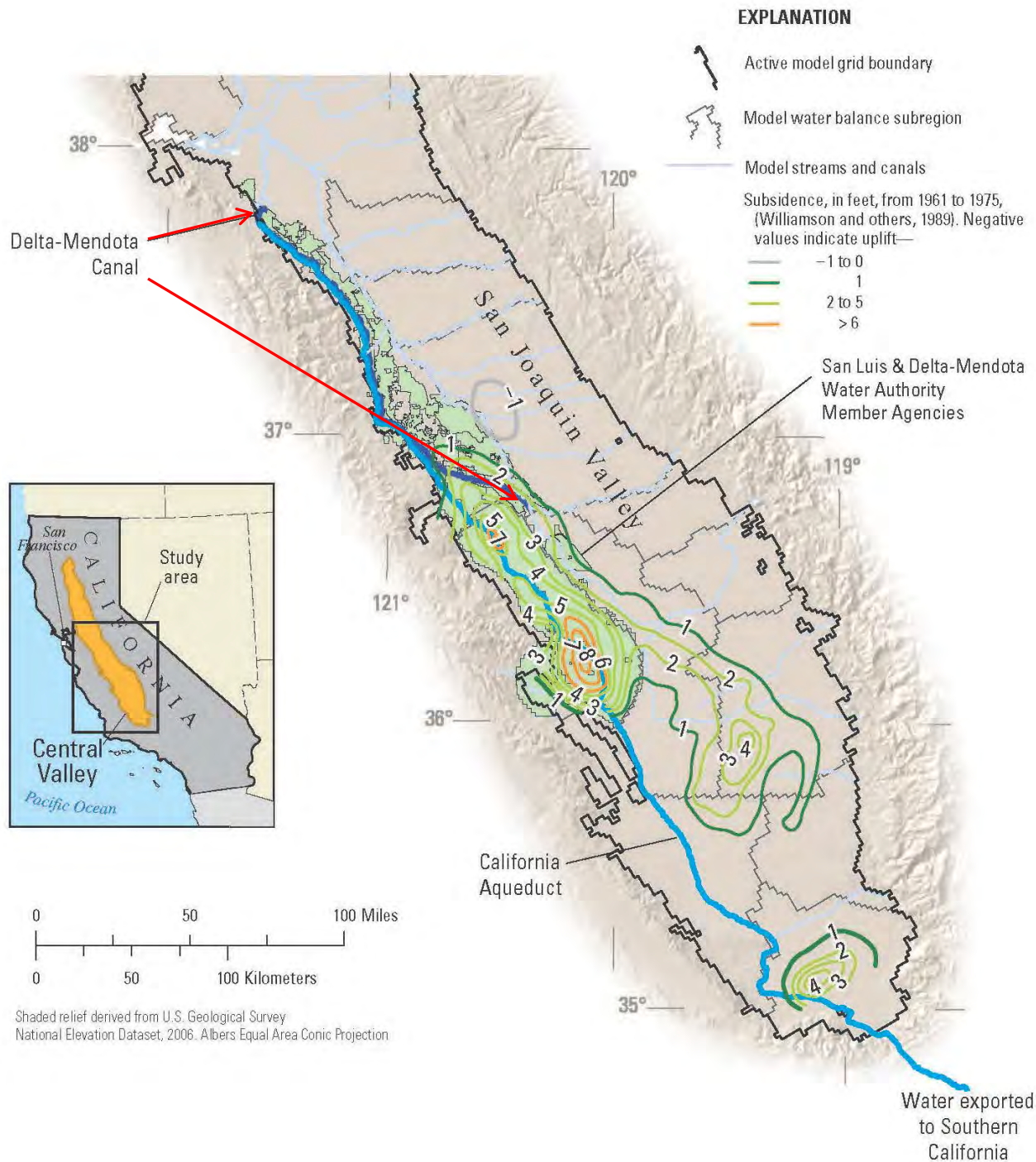


Simulated Cumulative Subsidence (feet) (1961 to 2003)



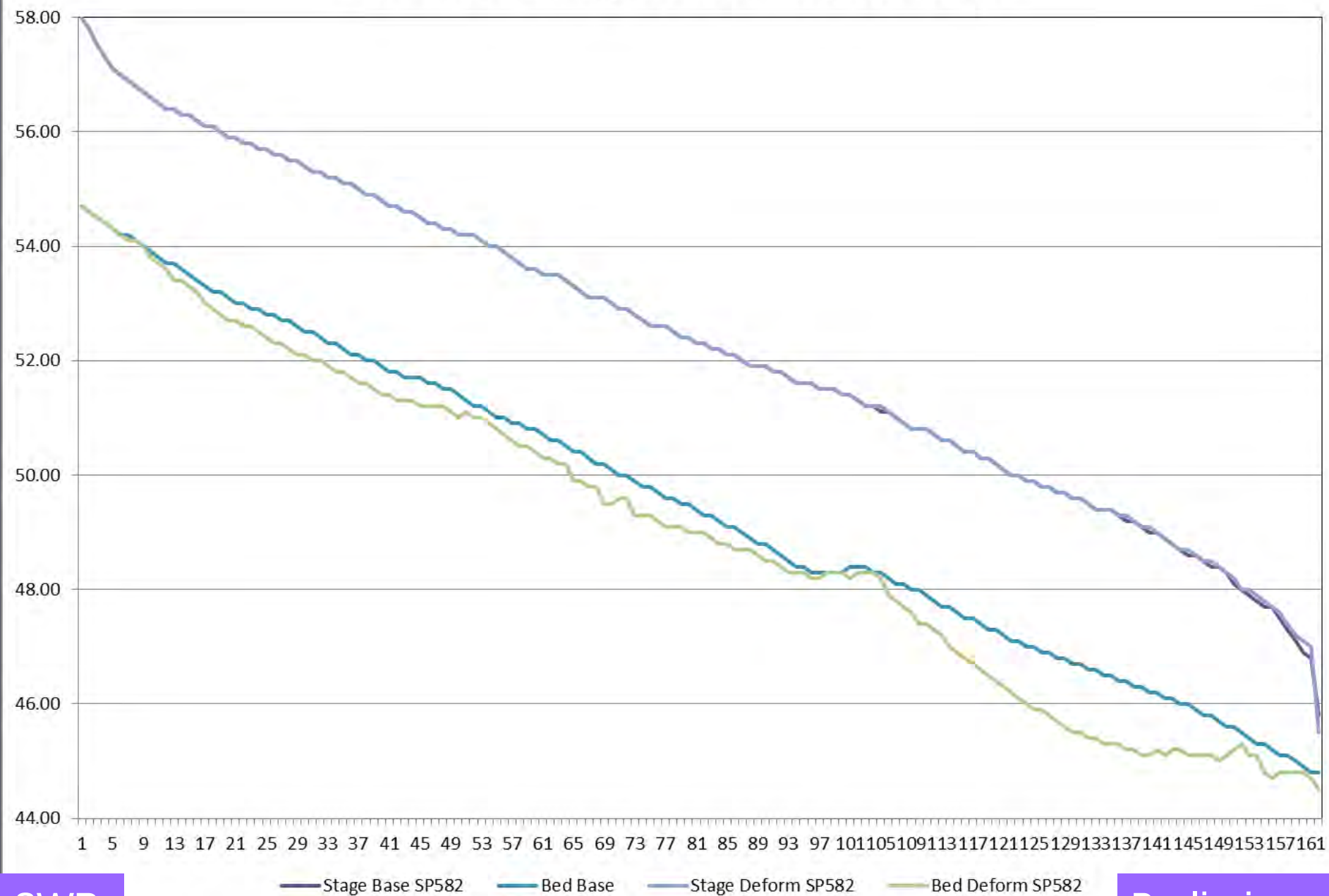
Simulated Cumulative Subsidence (feet) (1961 to 2009)





Example of Simulated
Sublink Deformation
along Delta Mendota
Canal from CVHM2
Model using MF-OWHM

Subsidence along DMC April 1961 - September 2009



Key Information for Resource Assessment

► Update data sets

- land use
- water levels
- surface water deliveries
- subsidence rates

► Update CVHM through present

- provides a detailed analysis of changes in hydrologic system and subsidence
- helps us better understand water resources and the interaction of groundwater with subsidence

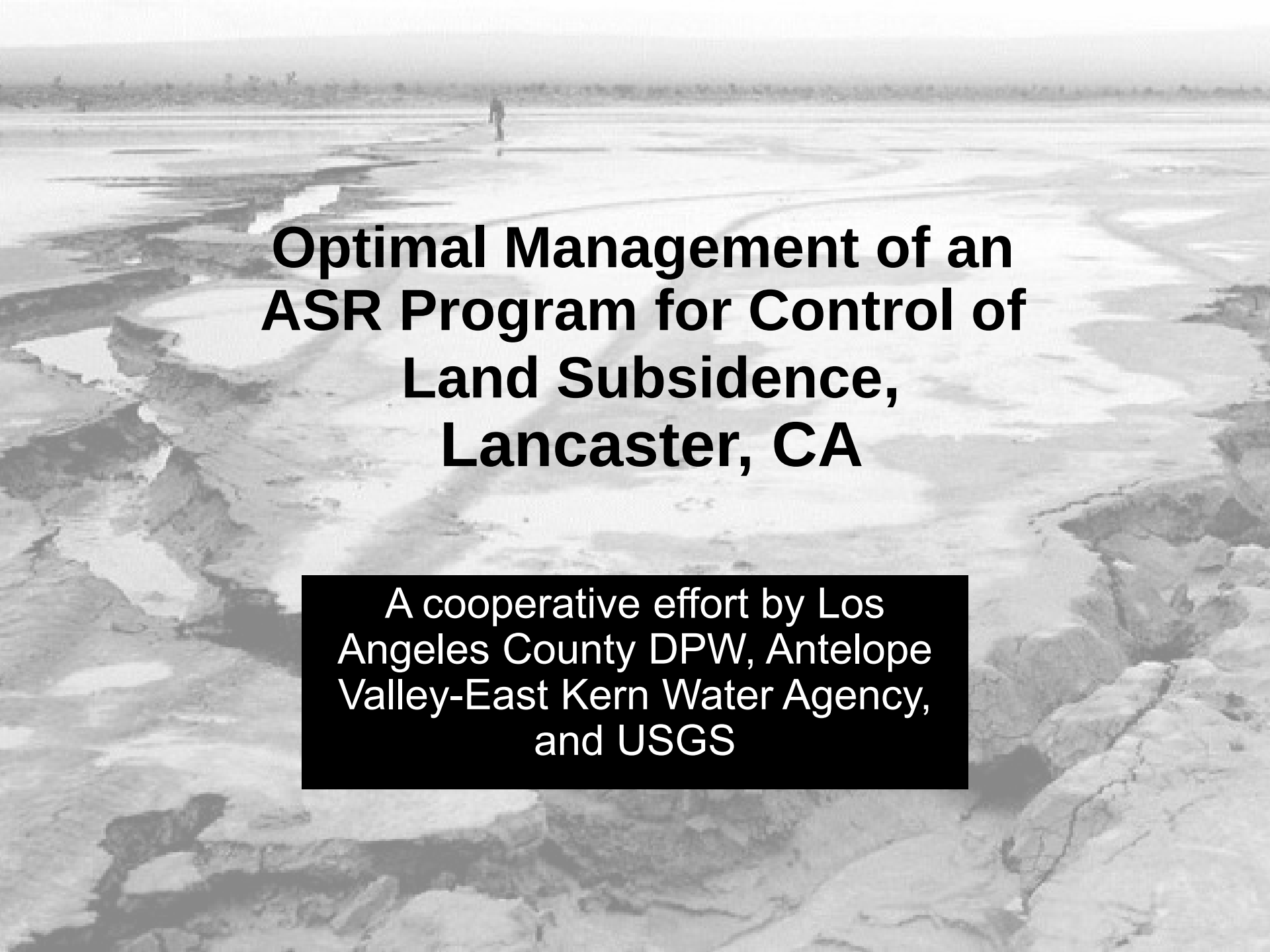
Future

CVHM is a useful tool to forecast information based on alternative scenarios

- ▶ Predict groundwater elevations and subsidence
- ▶ Simulate scenarios including
 - Extended drought/Climate change
 - Reduced surface water deliveries
 - Pumping (Reclamation)
 - Artificial Recharge
- ▶ Provide boundary conditions for local scale models (SJRR)

Long-term monitoring of water levels and subsidence is needed to track groundwater conditions

- ▶ Groundwater levels in the context of historical levels
- ▶ Track groundwater levels and subsidence in shallow and deep systems separately



Optimal Management of an ASR Program for Control of Land Subsidence, Lancaster, CA

A cooperative effort by Los
Angeles County DPW, Antelope
Valley-East Kern Water Agency,
and USGS

USGS Contributors

Steve Phillips

Carl Carlson

Loren Metzger

Brian Bergamaschi

Miranda Fram

Roger Fujii

James Howle

Kelly Goodwin

Devin Galloway

Michelle Sneed

Kenneth Hudnut

Josh Berghouse

Marti Ikehara

Nancy King

Bedrock
Alluvium
Playas

KERN COUNTY
LOS ANGELES COUNTY

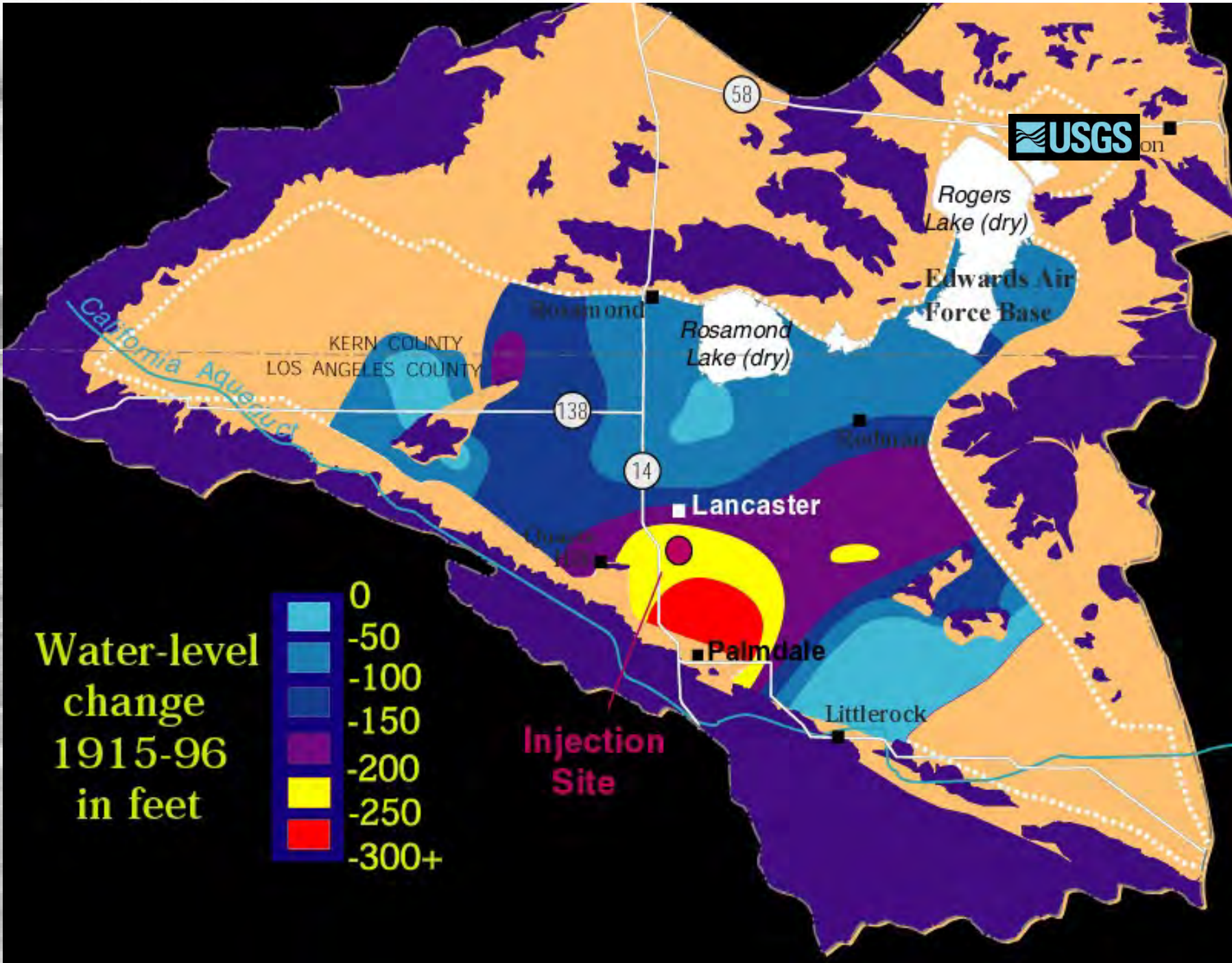
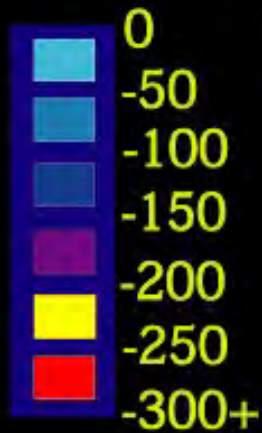
California
Aqueduct

Injection
Site



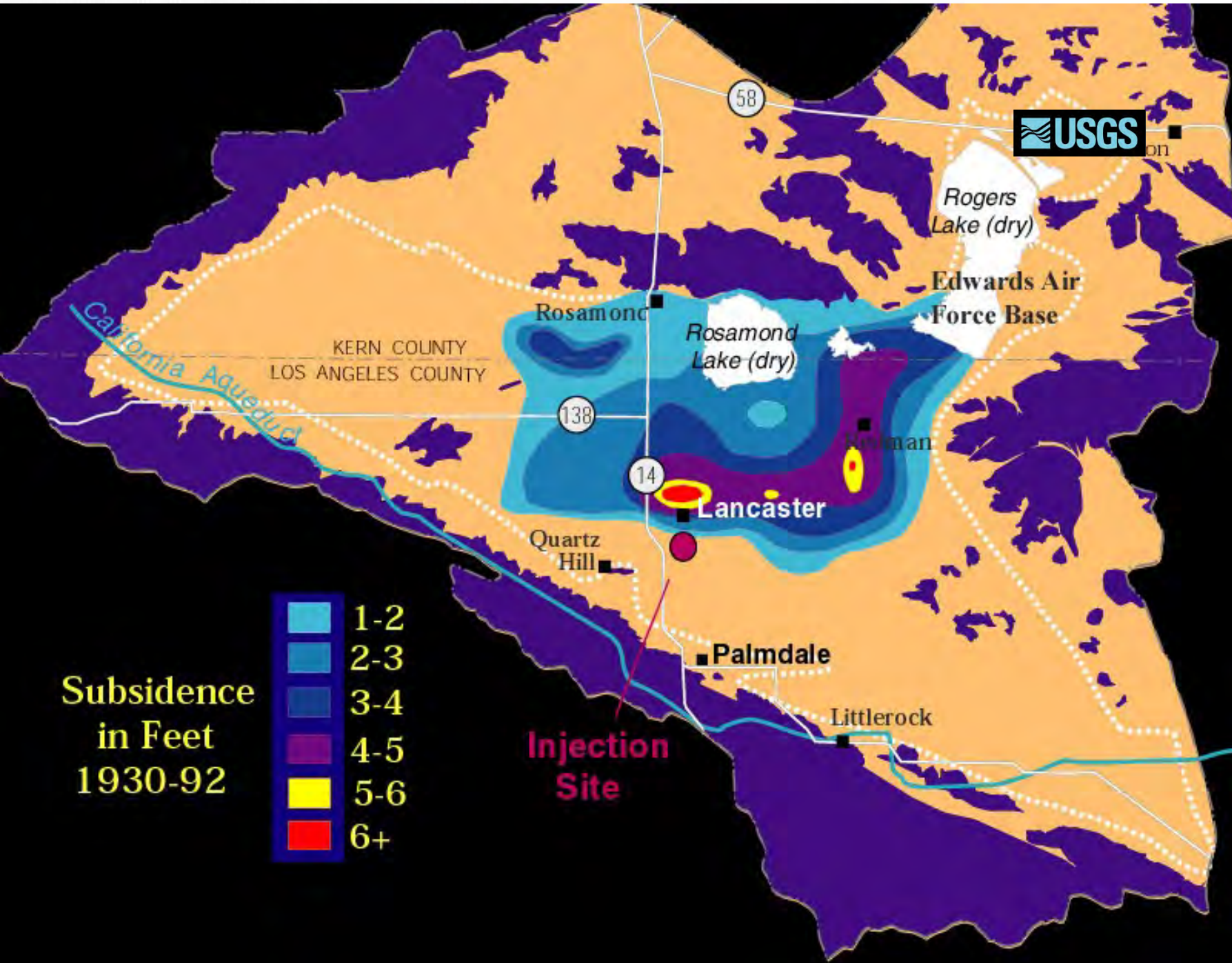


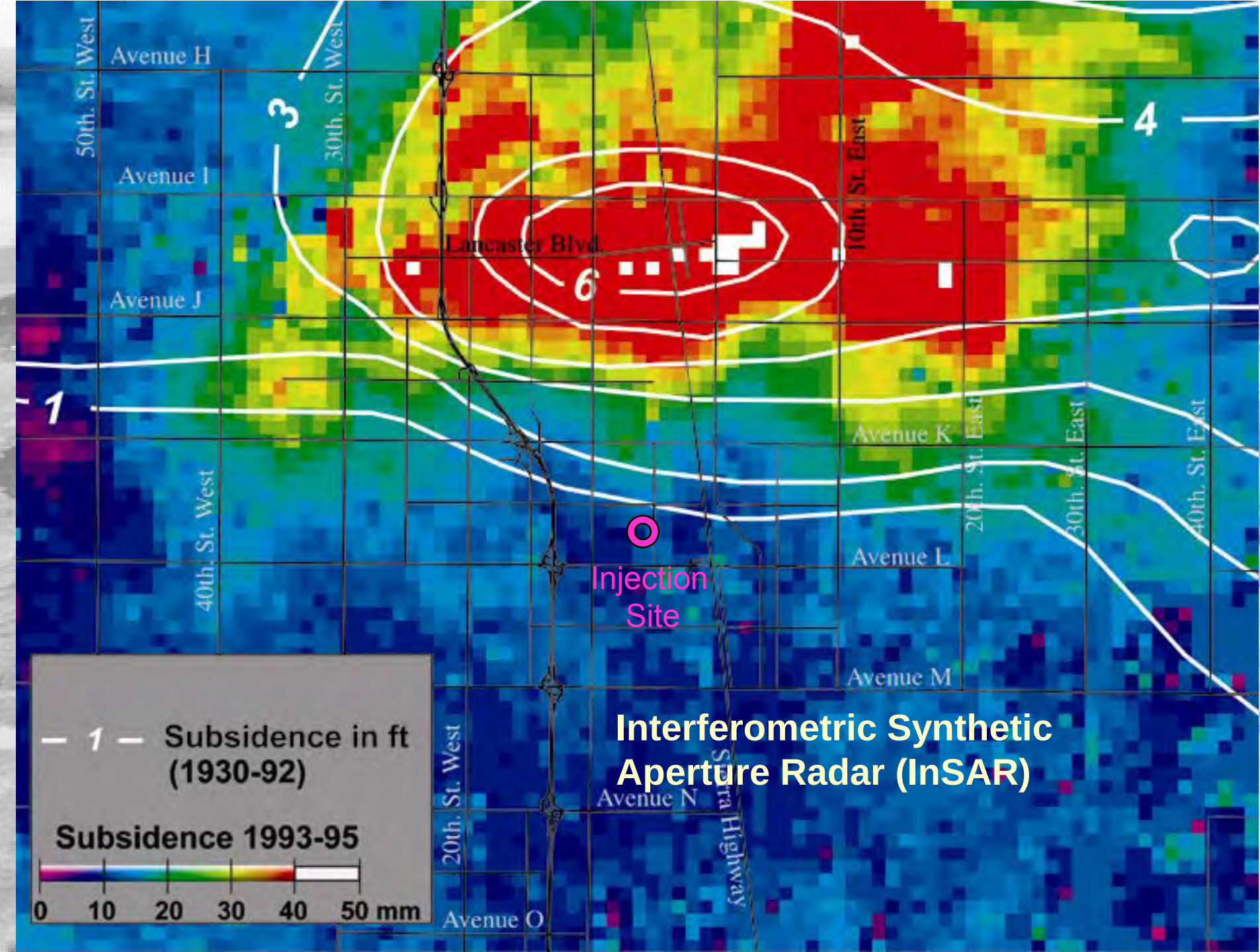
Water-level
change
1915-96
in feet

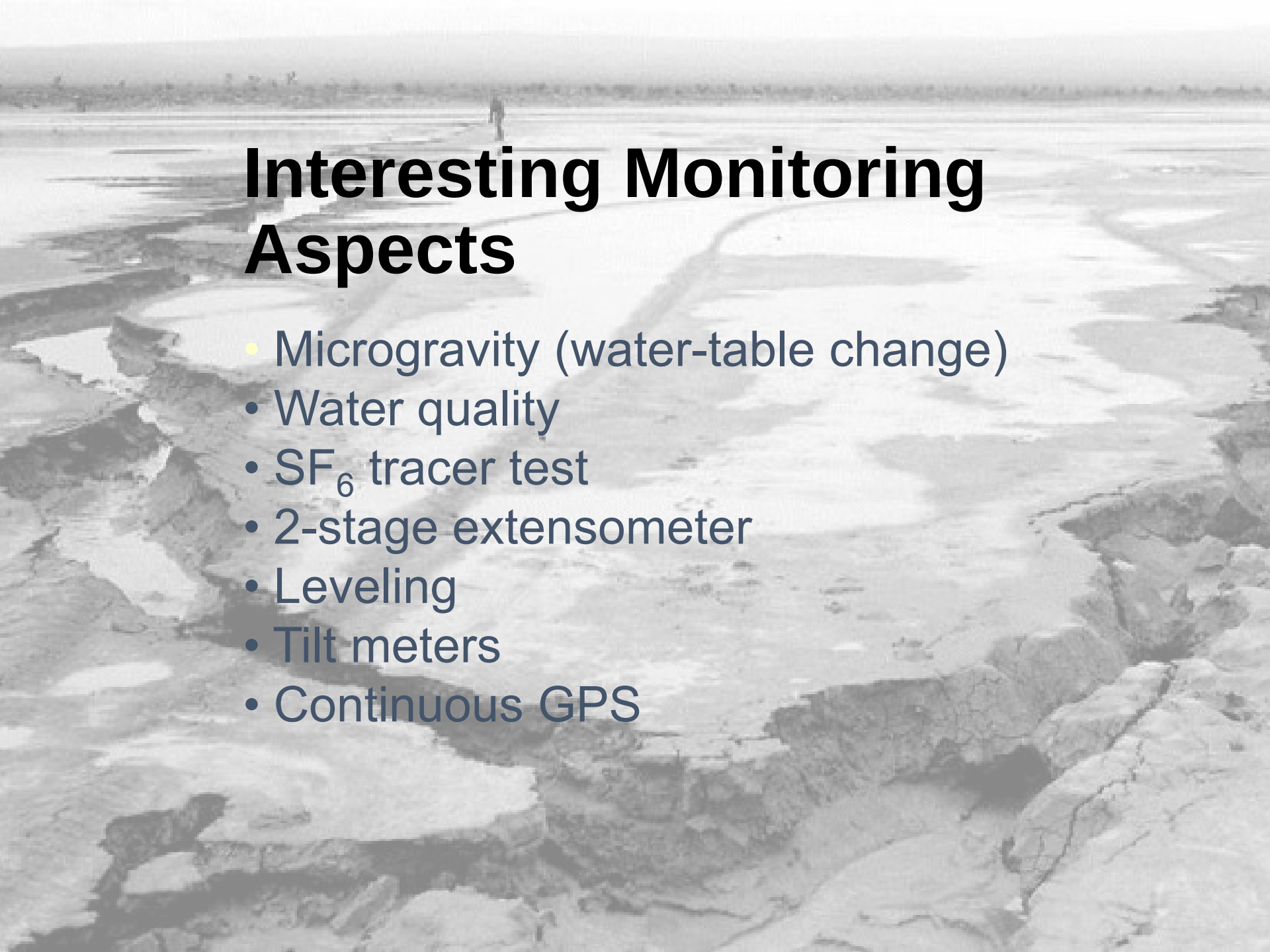




**Subsidence
in Feet
1930-92**

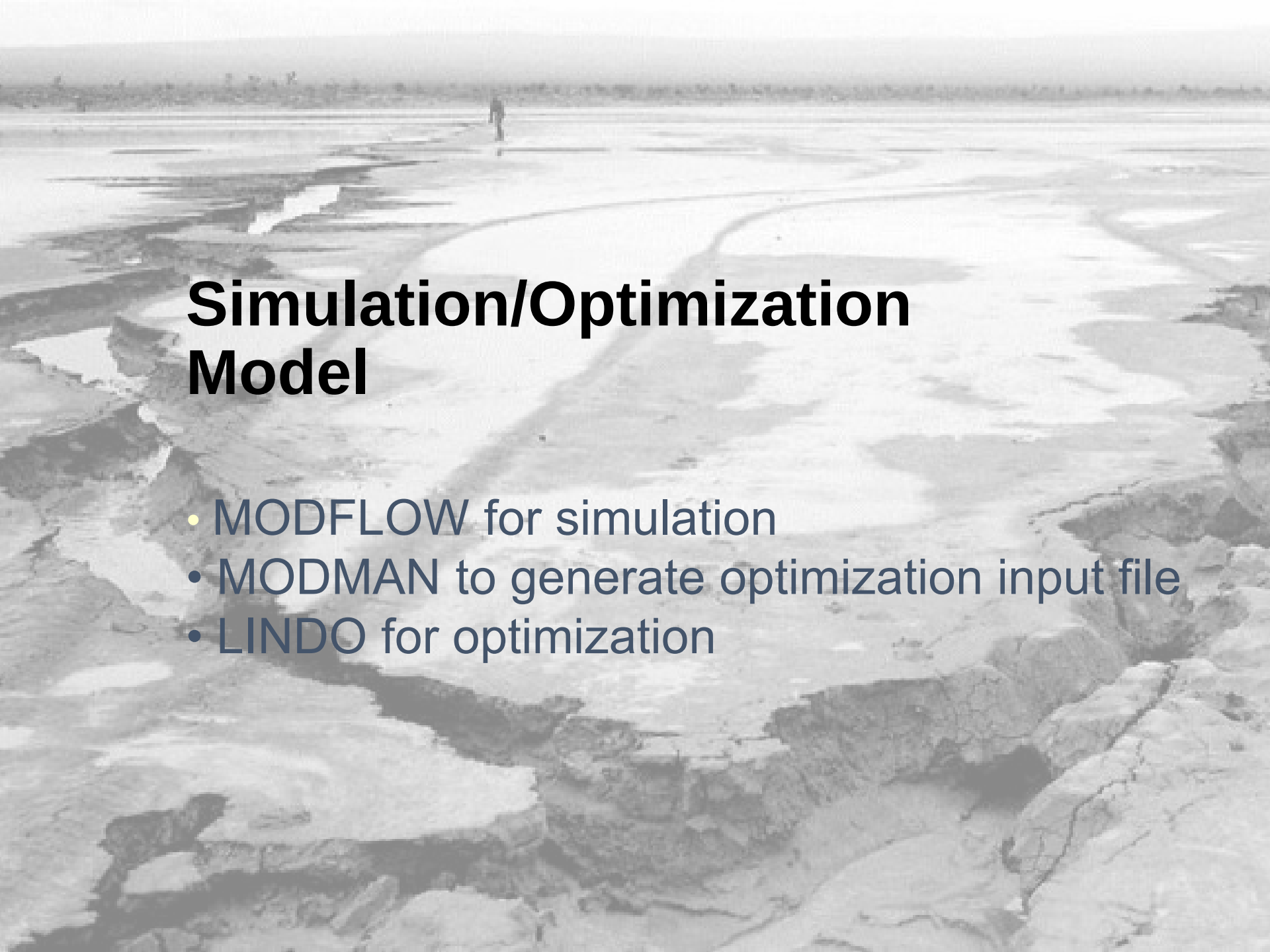






Interesting Monitoring Aspects

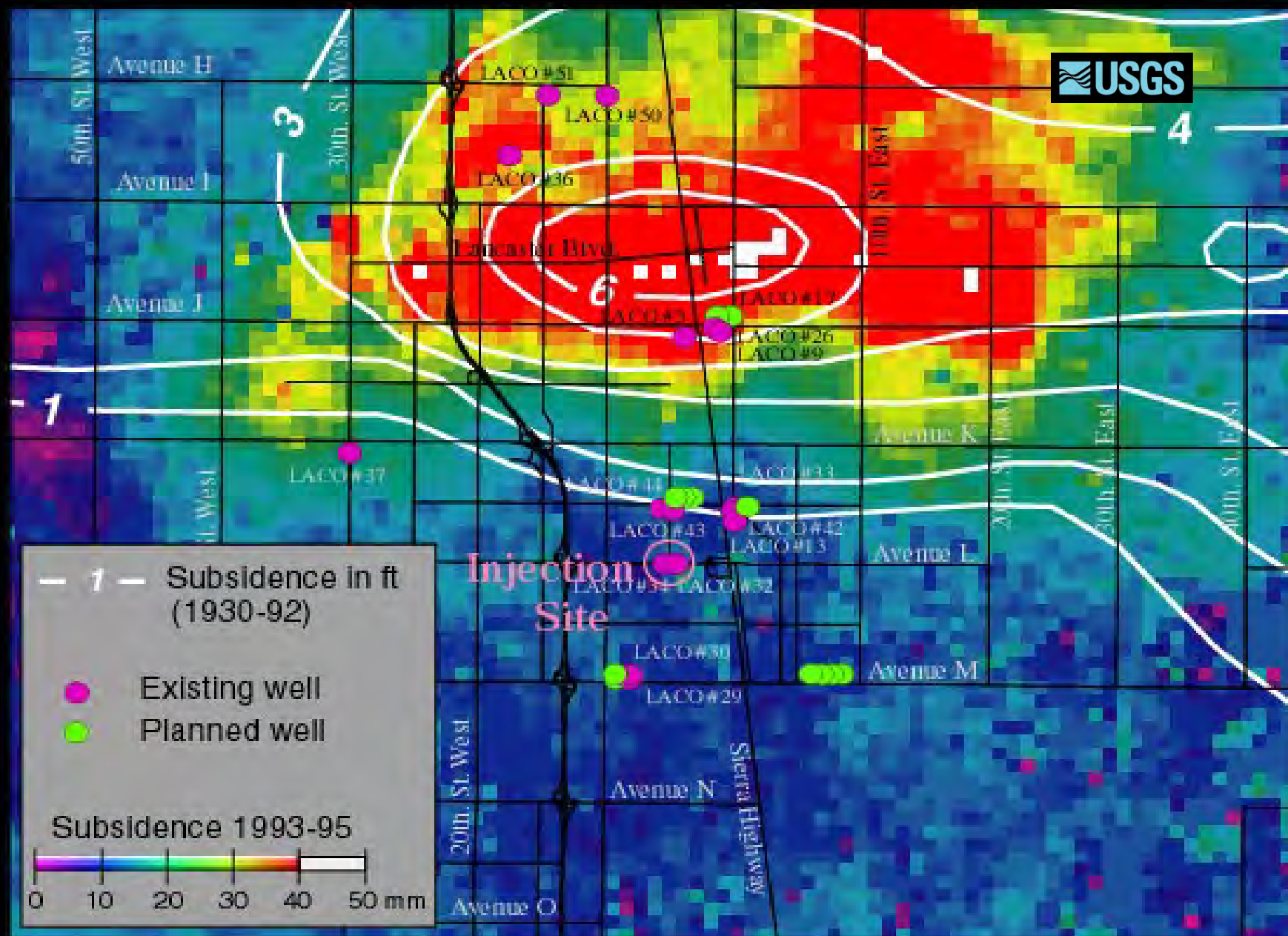
- Microgravity (water-table change)
- Water quality
- SF₆ tracer test
- 2-stage extensometer
- Leveling
- Tilt meters
- Continuous GPS



Simulation/Optimization Model

- MODFLOW for simulation
- MODMAN to generate optimization input file
- LINDO for optimization

Optimization of Injection Program



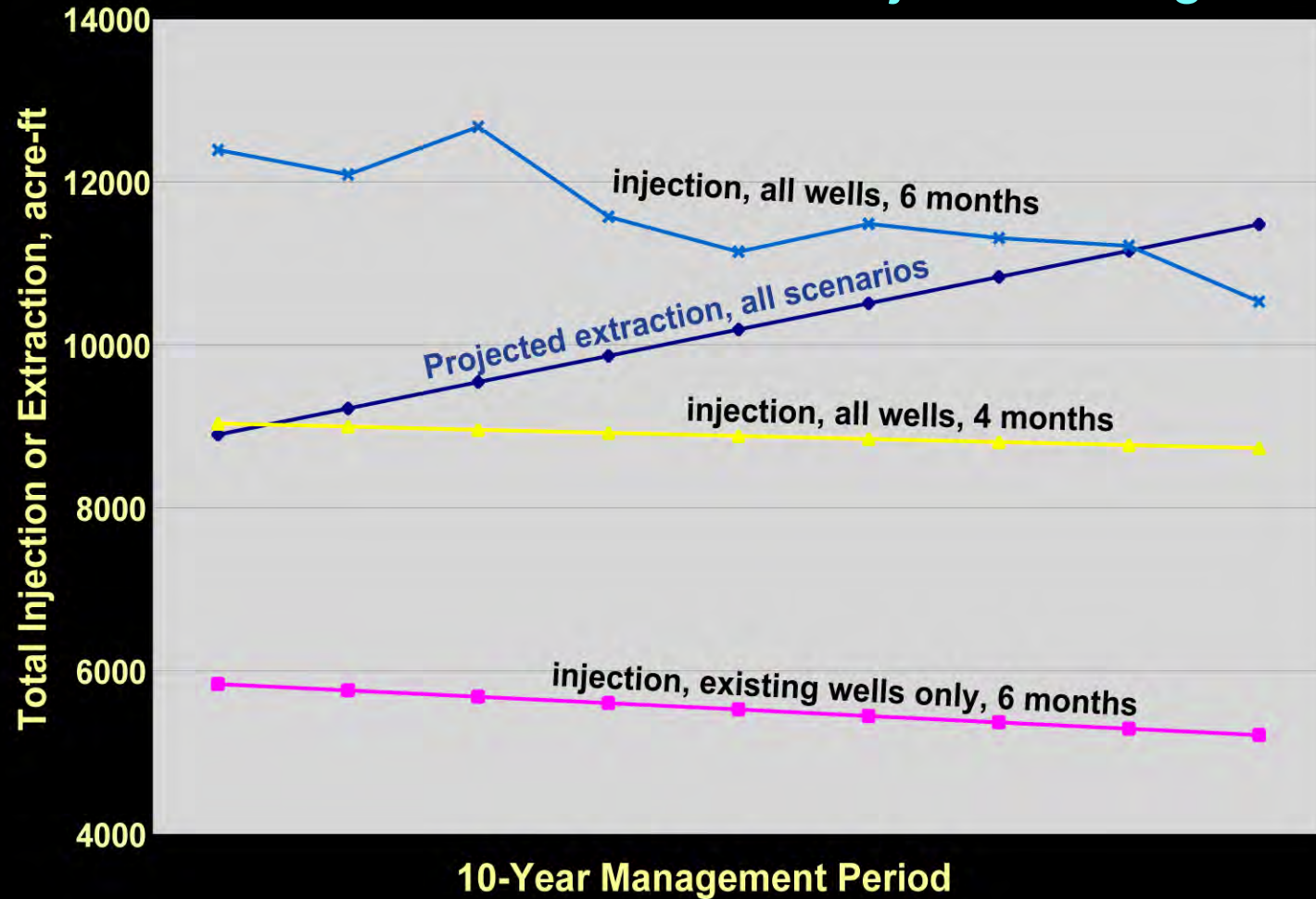
Objective Function

Maximize minimum head

subject to these constraints:

- Land subsidence (minimum head)
- Well injection/extraction capacities
- Must meet demand (projected growth)
- No injection during summer
- Economic (limited additional wells)
- Etc.

Potential Effectiveness of Injection Program



Post-study, there were 13+ active ASR wells in the Lancaster area, which helped to meet peak demands in the summer months & helped to address subsidence.





Thank You!