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Fillmore and Piru Basins Land Subsidence Evaluation Technical Memorandum

Submitted to

Fillmore and Piru Basins Groundwater Sustainability Agency

Prepared by

DBS&A
Daniel B. Stephens & Associates, Inc.

a Geo-Logic Company

3916 State Street, Garden Suite
Santa Barbara, CA 93105
www.dbstephens.com
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DANIEL B. STEPHENS & ASSOCIATES, INC.

DRAFT

Kaelyn Schwartz, GIT
Staff Geologist
kschwartz@geo-logic.com
3916 State Street, Garden Suite
Santa Barbara, CA 93105

DRAFT

Tony Morgan, PG, CHG
Principal Hydrogeologist
tmorgan@geo-logic.com
3916 State Street, Garden Suite
Santa Barbara, CA 93105

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1. Introduction

Daniel B. Stephens & Associates, Inc. (DBS&A) has prepared this Fillmore and Piru Groundwater Basins Land Subsidence Evaluation Technical Memorandum (Tech Memo) for the Fillmore and Piru Basins Groundwater Sustainability Agency (FPBGSA or Agency) and is under contract to prepare their mandated Groundwater Sustainability Plans (GSP or Plan) under the Sustainable Groundwater Management Act (SGMA) of 2014. Although SGMA requires separate Plans to be prepared for each basin, Fillmore and Piru subbasins (hereafter referred to as "basins") are hydrogeologically connected and have historically been managed and monitored together. In keeping with this historical precedent, this tech memo has been prepared to cover both basins.

Land subsidence is one of six sustainability indicators defined in the SGMA legislation. This document provides a background discussion on inelastic land subsidence (subsidence), summaries of previous investigations, a review of current data sets (e.g., geodetic monitoring, interferometric synthetic radar), and an evaluation of subsidence susceptibility for both basins.

2. Background

Subsidence directly related to subsurface fluid extractions (e.g., groundwater and hydrocarbons) has been observed for several decades in California. Compaction of fine-grained sediments occurs due to the increase in the effective stress of overburden caused by fluid removal (i.e., lowering of groundwater levels), which reduces the volume of pore spaces between sediment grains (i.e., volume available for groundwater storage). For this evaluation, it is important to acknowledge the difference between inelastic and elastic subsidence in relation to changes in groundwater levels. Inelastic subsidence is interpreted to occur where land surface elevations do not recover following recovery of groundwater levels. On the other hand, elastic subsidence is that which land surface elevation does recover following rising groundwater levels. A detailed discussion of the geomechanics associated with subsidence can be found in Poland (1984) and Poland and Davis (1969) and its effects in USGS (1999, 2016). In the context of SGMA, the potential for inelastic subsidence is the primary concern because it is essentially irreversible (i.e., lost groundwater storage capacity).

Hanson (1995) proposed causal factors of subsidence in Ventura County could be groundwater extraction, hydrocarbon extraction (i.e., petroleum and natural gas), and tectonic movement. A detailed discussion of the steady increase of groundwater pumping in the basins since the late 1800's through the late 1980's is included in the Plan. Regional tectonic movement and surrounding hydrocarbon extraction areas are briefly discussed in this section. Although the basins are located in or near tectonically active and active hydrocarbon extraction areas, the purpose of this document is to address subsidence related to the lowering of groundwater levels.

Hydrocarbon extraction has occurred in Ventura County for many decades, however, subsidence related to oil and gas withdrawal specifically in the basins has not been historically observed or determined. Figure 1 shows well sites near the basins associated with hydrocarbon extraction as listed by California Geologic Energy Management Division's (CalGEM, formerly the Department of Oil, Gas and Geothermal Resources [DOGGR]). Active oil and gas production in the area occurs primarily outside of the basins with several hydrocarbon well fields located in the surrounding mountains. A few active wells of the Bardsdale and Shiells Canyon Oil Fields are located less than 0.25 miles inside of the southeastern Fillmore basin boundary. Three Holser Oil Field active wells are located just inside the Piru basin boundary in Holser Canyon (tributary east of Piru Creek). There are no reported instances of subsidence directly associated with hydrocarbon extraction areas within the basins or those well fields immediately adjacent to the basins.

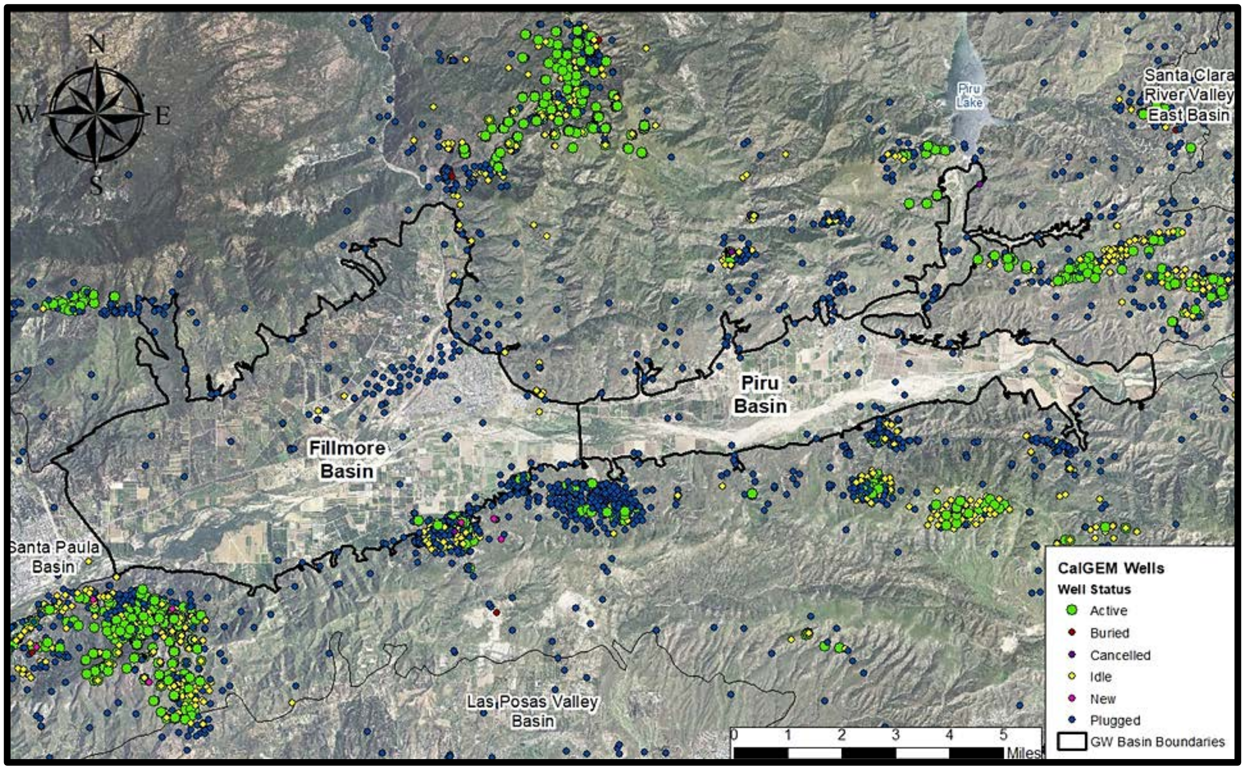

Figure 1: Fillmore and Piru basins area map showing CalGEM hydrocarbon extraction-related wells.

The basins are part of the tectonically active Transverse Ranges, where crustal shortening and rapid uplift rates have occurred for millions of years. Orme (1998) reports a broad range of 0.05 to 9 mm/year of long-term uplift for the coastal Transverse Ranges region. The basins consist of varying thicknesses of alluvium underlain primarily by the San Pedro Formation synclinal fold. Studies have estimated a maximum dip-displacement for the north basin-bounding San Cayetano reverse fault and south basin-bounding Oak Ridge fault to be 8.8 mm/year (about 0.03 feet/year) (Rockwell, 1988) and 12.5 mm/year (about 0.04 feet/year) (Yeats, 1988), respectively. Not only is the region's topography vertically affected by gradual long-term tectonic shifts, but the area is prone to earthquakes which can cause sudden land movements.

The evaluation of subsidence for the Fillmore and Piru basins in this document is based on review of the following lines of evidence:

- Previous investigations and reports;
- Geodetic surveys;
- Interferometric Synthetic Aperture Radar (InSAR) data;
- Analytical subsidence susceptibility evaluations.

3. Previous Investigations

Numerical groundwater flow modeling by Hanson et al. (2003) was used to estimate the timing and magnitude of historical subsidence in coastal Ventura County from 1891 through 1993. The use of a groundwater flow model to infer subsidence is not a direct measurement or observation of subsidence. Groundwater flow model estimated historical subsidence is a calculated value based on the geomechanical properties of the geologic material and the rate and magnitude of historical groundwater level change predicted by the model. Simulated subsidence was compared to select benchmarks on the South Oxnard Plain for subsidence model calibration. Hanson et al. (2003) stated the majority of the subsidence in their model domain occurred following the drought of the late 1920s and increase in agricultural pumping that occurred between the 1950's and 1993. The highest modeled subsidence was in the South Oxnard Plain and Las Posas Valley subareas where 3 and 5 feet was simulated, respectively (Figure 2). During the early development period from 1939 to 1960, subsidence occurred primarily in the upper aquifer system on the Oxnard Plain before pumping increased in the lower aquifer system from 1959 to 1993. The model indicates a maximum value of just over 0.1 feet (0.00098 ft/yr) of subsidence from 1891 to 1993 in the Fillmore basin and just over 0.25 feet (0.0024 ft/yr) in the eastern portion of the Piru Basin.

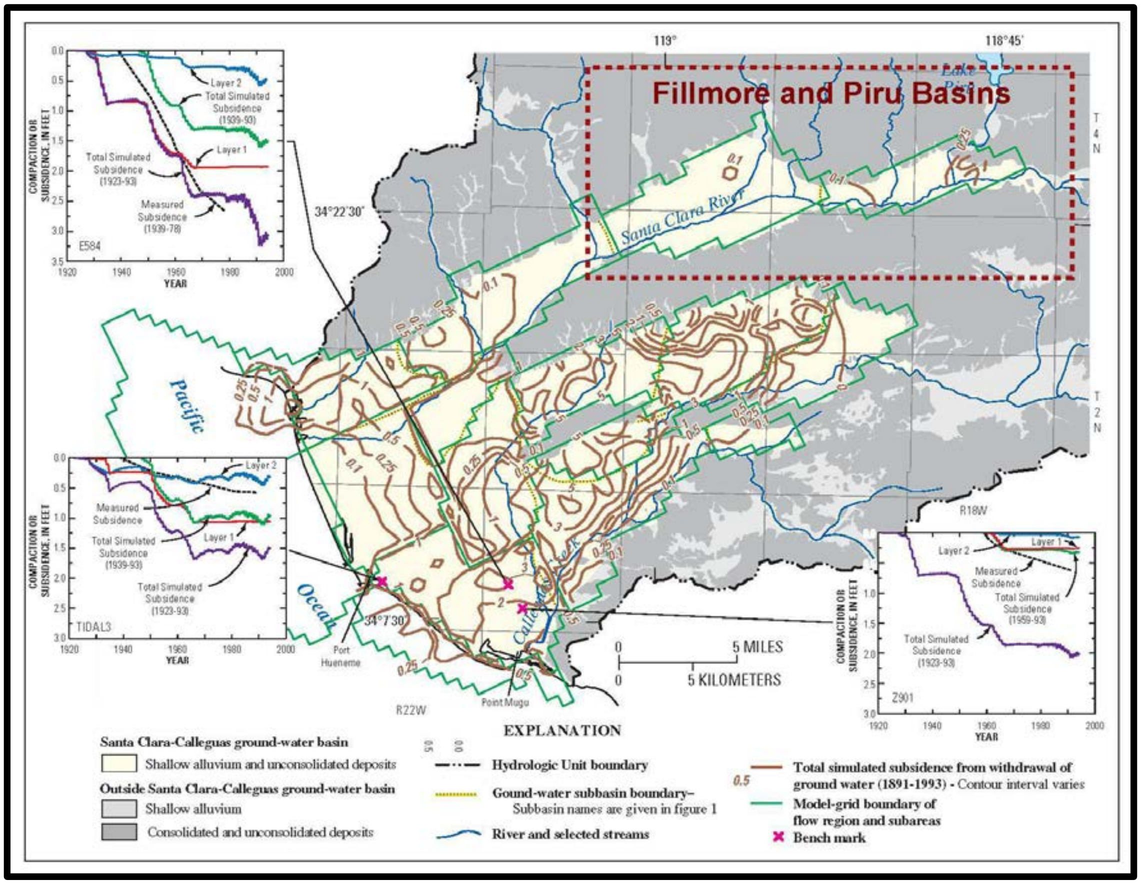

Figure 2: Simulated subsidence in the Santa Clara-Calleguas groundwater basin due to groundwater withdrawal from 1891 to 1993. Figure originally produced by Hanson et al. (2003).

Borchers (2014) summarizes results from the Hanson et al. (2003) study, solely focusing on areas of more significant subsidence (i.e. Oxnard Plain, Las Posas Valley, and South Pleasant Valley subbasins).

The 2013 Ventura County General Plan Hazards Appendix (Ventura County, 2013) contains a brief section and map showing the limits of subsidence zones. The zones were based on figures from the 1973 Hazards Appendix and have not been updated due to lack of geodetic data in these areas. Part of the zone extends along the Santa Clara River Valley, including the basins. The report states that sediment loading and groundwater level decline in the present Santa

Clara River course could lead to hydrocompaction (i.e., subsidence) and possible flooding in lower lands (Oxnard Plain) could occur. Ventura County recently produced a 2040 General Plan Environmental Impact Report (Ventura County, 2020), which provides a general statement and map showing the Santa Clara River Valley (including the basins), Oxnard Plain, and Las Posas Valley as part of the subsidence risk area caused by groundwater extraction.

In 2014, California Department of Water Resources (DWR) prepared a document summarizing recent, historical, and estimated future subsidence potential for groundwater basins included in CA DWR Bulletin 118 (DWR, 2014). The purpose of the document was to provide screening-level information with respect to subsidence. DWR lists Fillmore basin with low potential for future subsidence. The ranking was determined from less than 10 percent of wells with long term water level trends (well records longer than 10 years) with current water levels (2008-2014) at or below historical low spring levels and one active continuous GPS monitoring station (see Geodetic Surveys) that showed 0.03 feet of maximum decrease in ground elevation. The Piru basin had insufficient data to establish a subsidence ranking.

4. Geodetic Surveys

UNAVCO monitors continuously operating geodetic instrument networks, including Continuous Global Positioning Systems (CGPS) stations, that measure three-dimensional positions (generally every 15 or 30 seconds) of a point near earth's surface. Four CGPS stations are found near the basins (less than 5 miles away) with surface elevation data extending back to either 1999 or 2000. All four stations are mounted outside of the alluvial basins and in bedrock, suggesting any vertical movement is likely caused by tectonic movement rather than compaction of fine-grained materials due to groundwater withdrawal.

Figure 3 shows locations of these CGPS stations, along with UNAVCO time-series graphs displaying measured land displacement relative to the first measurement of each station. Data displayed in the time-series graphs are referenced to the North American tectonic plate (NAM14) reference frame. Outliers with a standard deviation greater than 20 mm (about 0.8 inches) were removed by UNAVCO. Long-term general vertical movement rate trends were determined by applying a line of best fit to each station's entire measured timeframe of data.

Three of the four CGPS stations surrounding Fillmore basin (KBRC, SOMT, and FMVT) are all set in weathered or poorly lithified sedimentary bedrock (UNAVCO) and show a long-term trend of approximately 0.003 mm/year (0.000009 feet/year) of downward vertical movement since December 2000. Just south of Lake Piru, CGPS station SFDM set in bedrock (UNAVCO) indicates a linear trend of 0.001 mm/year (0.000003 feet/year) of upward vertical movement since 1999. Looking on a smaller timescale, the four stations show similar seasonal upward and downward movement trends.

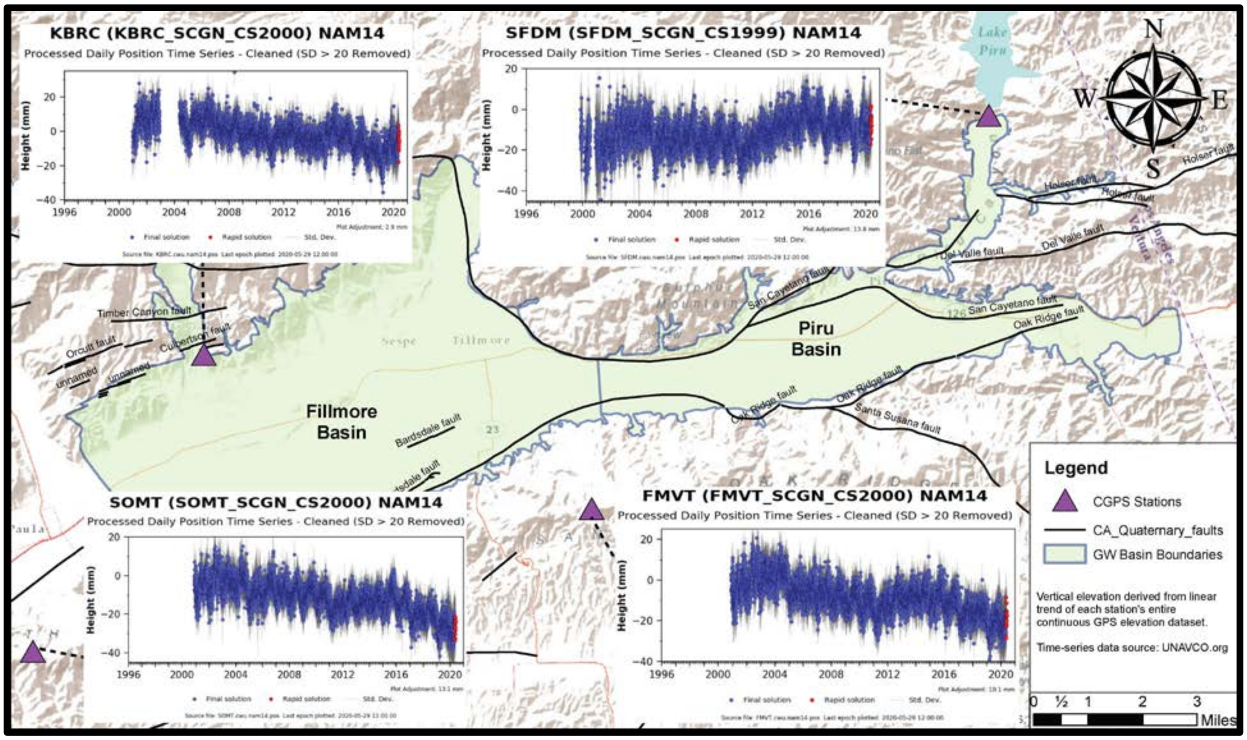

Figure 3: Map showing CGPS locations and vertical movement time-series data provided by UNAVCO.

Following the 1994 Northridge earthquake (magnitude 6.7), the USGS (1996) conducted a study to assess and restore geodetic infrastructure affected or damaged by land elevation changes caused by the earthquake. A geophysical model of permanent ground deformation, based on the geodetic infrastructure movement, was developed and benchmarks that differed +/- 1.2 inches (3 cm) from the model were considered anomalous (suggesting needed replacement).

The model required non-tectonic deformation (i.e., subsidence due to groundwater withdrawal) to be removed from measured elevation changes to infer deformation solely due to tectonic activity. Therefore, at least three pre-seismic surveys made between 1971 and 1989 were used to subtract the elevation changes from the 1994 measurements. The National Geodetic Survey (NGS) conducted leveling surveys along routes in areas affected by the earthquake, including routes cutting through the Fillmore and Piru basins (Figure 4).

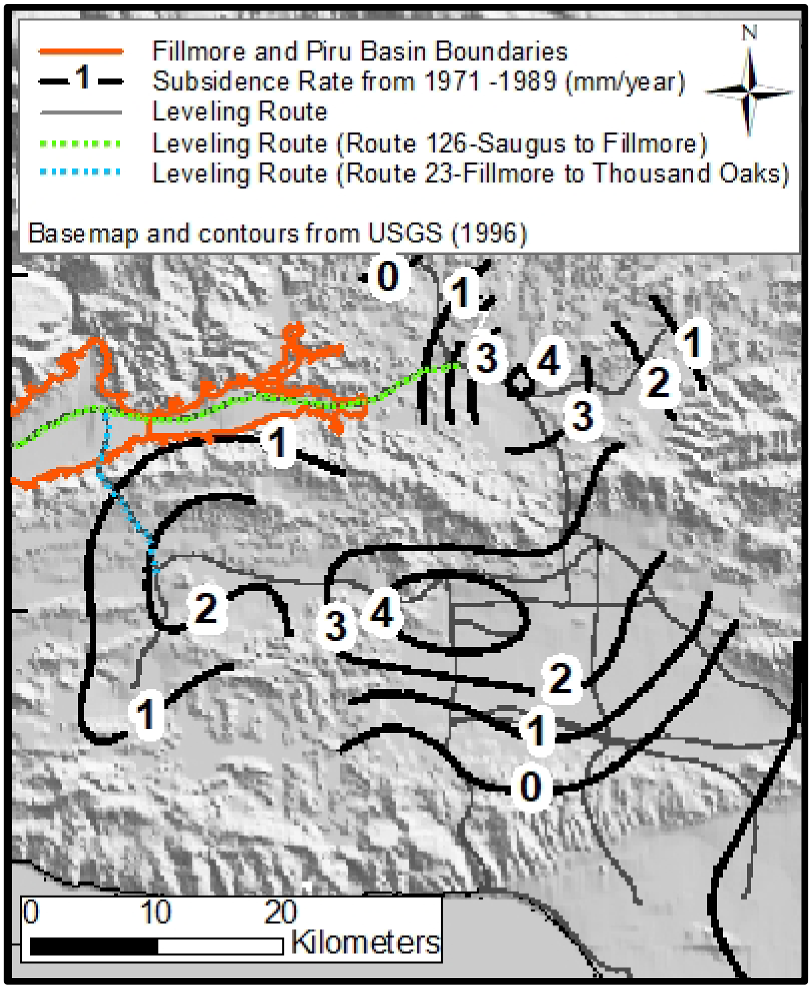

Figure 4: Map from USGS 1994 Northridge Earthquake report (USGS, 1996) showing NGS leveling routes and contours of measured pre-seismic subsidence rates (mm/year) from 1971 to 1989.

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Figure 4 includes subsidence rate contours that the USGS produced from the 1971 to 1989 pre-seismic surveys covering the Los Angeles Basin. Based on these contours, average subsidence rates in the Fillmore and Piru Basins were under 1 mm (0.003 feet) per year from 1971 to 1989. A comparison of 1975 and 1989 leveling surveys (pre-1994 Northridge earthquake) taken along Route 126 (Los Angeles Avenue) from Saugus to Fillmore determined 15 mm (0.05 feet) of cumulative subsidence over the 14-year period, with maximum subsidence of 60 mm (0.2 feet) occurring between the 1975 and 1978 surveys. The area of maximum subsidence was 20 km (12.4 miles) wide and centered around the Town of Piru. The rebound in ground elevation following 1978 could have been due to groundwater recharge or a systematic error in the 1978 survey. A survey along Route 23 (Moorpark Freeway) from Fillmore to Thousand Oaks determined a maximum subsidence of 8 mm (0.03 feet) at Fillmore between 1975 and 1989.

The final modeled coseismic uplift extent related to the 1994 Northridge earthquake is shown in Figure 5. Within the basins, only the very eastern portion of the Piru basin showed tectonic deformation related to the earthquake and fell within the 0 to 10 cm (less than 0.3 feet) zone of the coseismic uplift contours modeled by USGS.

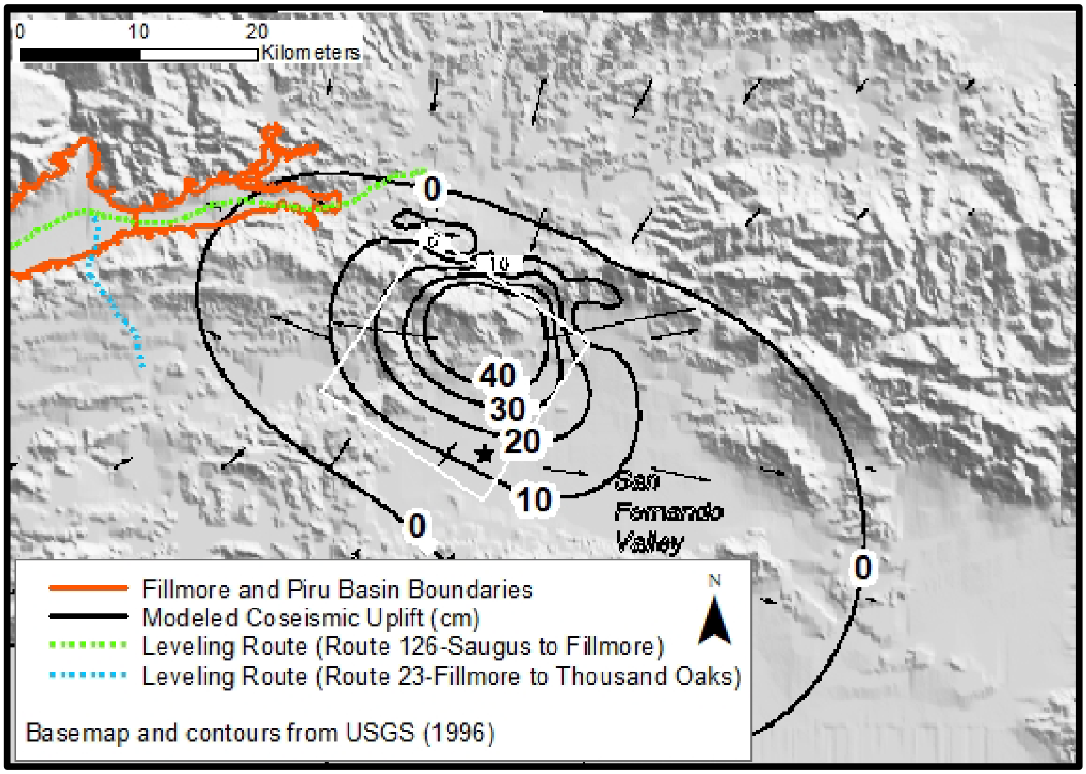


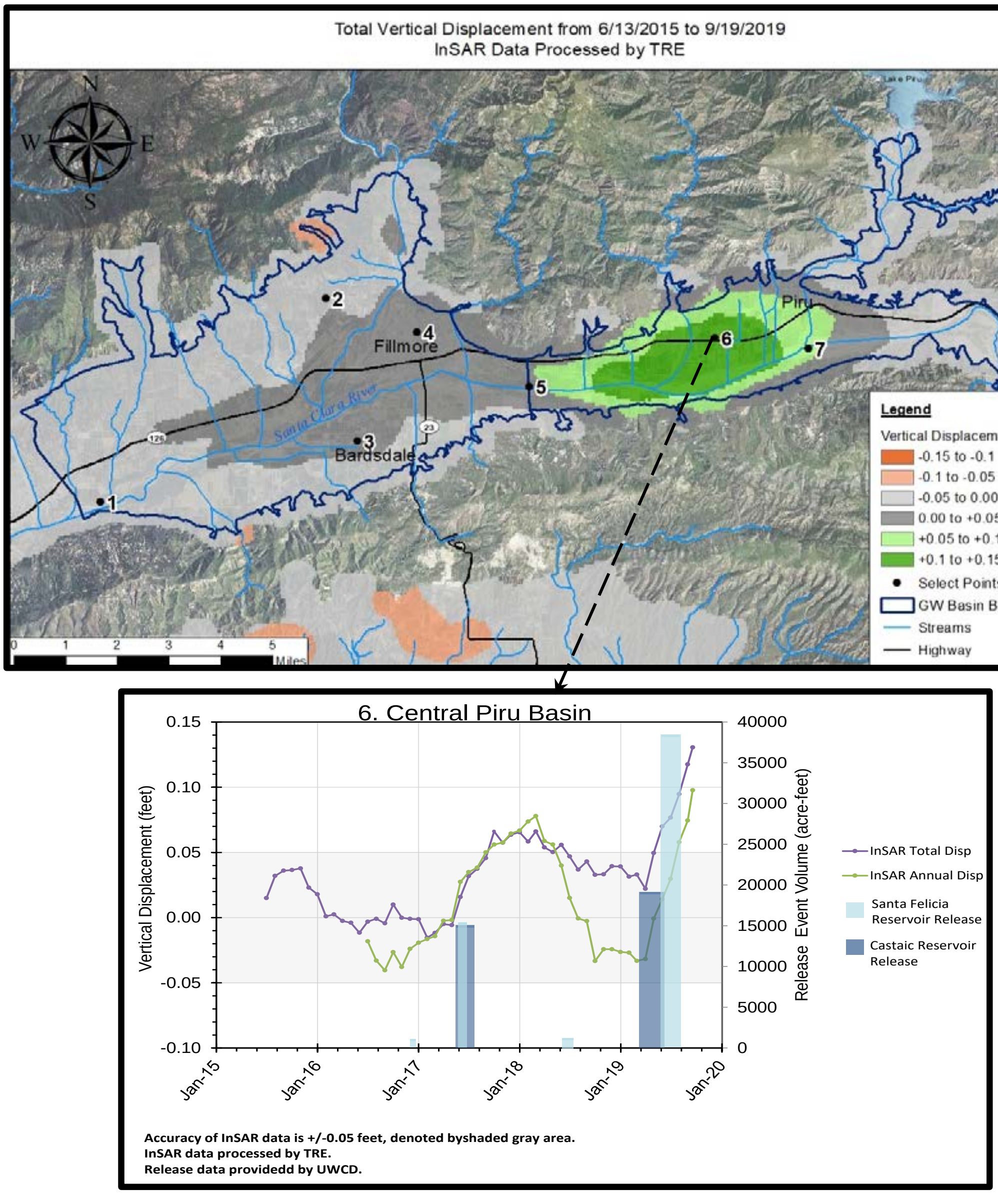
Figure 5: Map from USGS 1994 Northridge Earthquake report (USGS, 1996) modeled coseismic uplift related to the 1994 Northridge Earthquake in relation to the basin boundaries and NGS leveling routes surveyed in the basins.

5. Interferometric Synthetic Aperture (InSAR) Data

Interferometric Synthetic Aperture (InSAR) is a satellite-based remote sensing method used to map ground surface elevation change over large areas with high accuracy. Satellites emit electromagnetic pulses that produce measurements upon their return. These measurements are processed to create synthetic aperture radar images. The InSAR method calculates the change in elevation from one measurement to the next and presents the changes as raster images. To assist with quantitative subsidence evaluations for GSP development, DWR contracted TRE Altamira Inc. (TRE) to process InSAR data collected by the European Space Agency (ESA) Sentinel-1A satellite covering Bulletin 118 groundwater basins. The processed TRE InSAR datasets are available to the public on DWR's SGMA Map Viewer: (https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#landsub).

TRE processed InSAR point data (measured about every two weeks) to get values representing average monthly vertical movement per 100 square meter (about 1,000 square feet) areas within the basins from May 20, 2015 to September 1, 2019. TRE also provided rasters interpolated from the point data representing total and annual vertical displacement relative to June 13, 2015 (date entire CA study coverage began), both in monthly time steps. Towill Inc., contracted by DWR, conducted an accuracy study by comparing the InSAR vertical displacement data with CGPS data (including CPGS station, KBRC, mentioned in Section 4). The study (Towill, 2020) determined that InSAR data within California provided accurate vertical displacement measurements within 16 mm (+/-0.05 feet or +/-0.6 inch) at the 95% confidence interval.

Figure 6 shows TRE-processed InSAR data representing total vertical displacement in the basins over the longest available time period, June 13, 2015 through September 19, 2019. The Fillmore basin generally did not have vertical land movement that fell outside of the measurement accuracy range of +0.05 feet to -0.05 feet. The central portion of Piru basin shows uplift of up to 0.14 feet that extends westward from near the confluence of Piru Creek and SCR to the Piru-Fillmore basin boundary. This area spatially corresponds with the areas along the Santa Clara River where high surface water infiltration rates associated with natural runoff or man-made surface water enhancement projects (e.g., Article 21 Water, releases of water from Santa Felicia Dam). The areas of uplift above the minimum measurement accuracy are likely related to basin recharge (i.e., recovery of groundwater levels following the 2012-2016 drought), resulting in elastic recovery.



Accuracy of InSAR data is +/-0.05 feet, denoted byshaded gray area.
InSAR data processed by TRE.
Release data providedd by UWCD.

Figure 6: InSAR data processed by TRE showing total vertical displacement within the basins from June 13, 2015 to September 19, 2019. Time-series graph shows relationship of upward movement observed in InSAR data in relation to reservoir releases.

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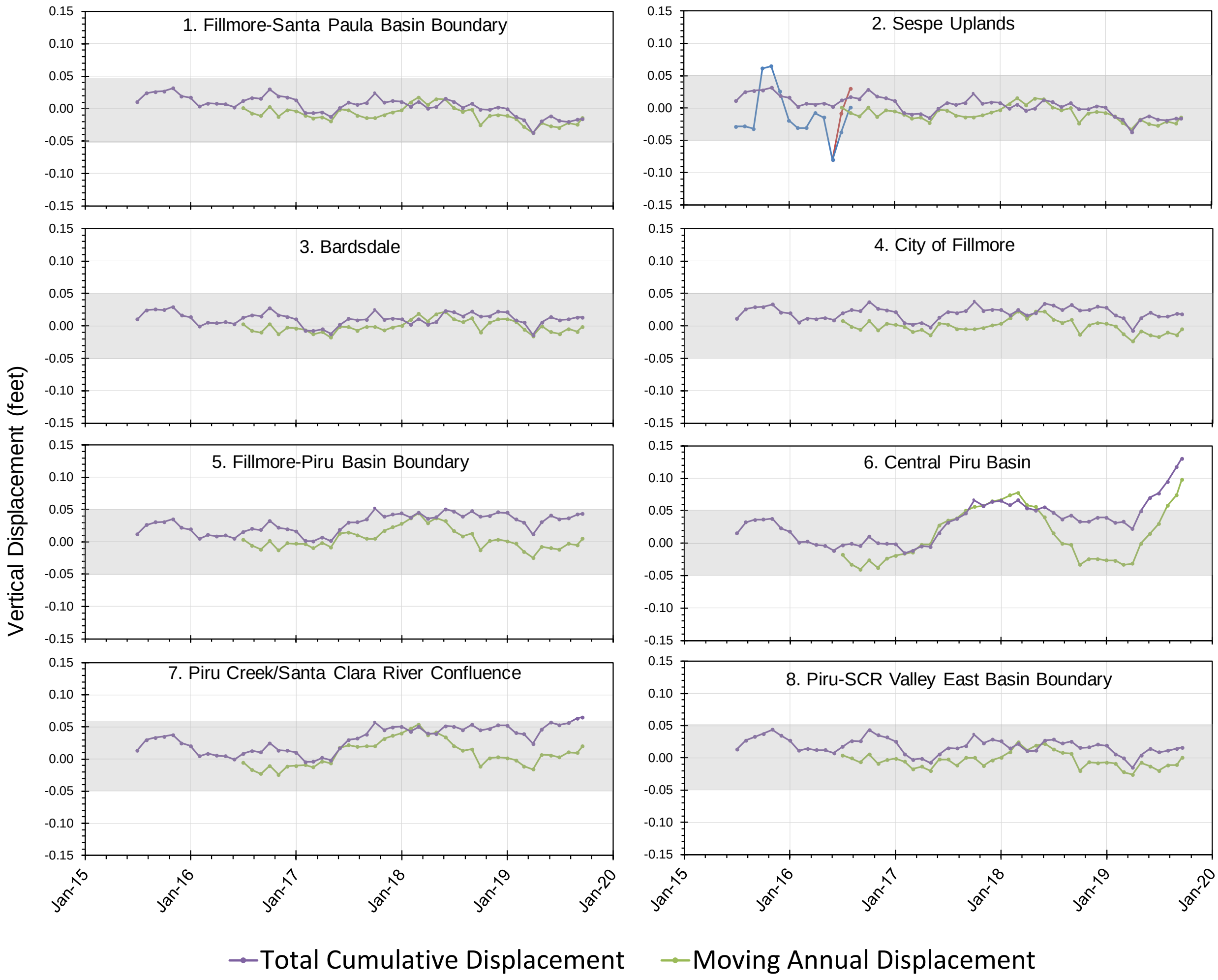
Eight points within the basins were chosen for vertical displacement time-series analysis based on special geographical characteristics and/or hydrogeological settings (e.g., likelihood of the area having significant thicknesses of fine-grained sediment, presence or absence of rising groundwater elevations, and general depths-to-groundwater). Locations of these points are shown on the maps in Figure 6 and described below:

1. Fillmore-Santa Paula Basin Boundary
2. Sespe Uplands
3. Bardsdale
4. City of Fillmore (Pole Creek Fan)
5. Fillmore-Piru Basin Boundary
6. Central Piru Basin
7. Piru Creek/Santa Clara River Confluence
8. Piru-SCR East Basin Boundary

Time-series graphs showing total and annual vertical displacement from the available TRE - processed InSAR datasets are shown in Figure 7. The values represent the vertical elevation change for the end date of the analyzed periods. Total displacement shows monthly cumulative departure change from a beginning reference date of June 13, 2015 for TRE data. Annual vertical displacement shows a monthly moving window representing displacement occurring within the past 12 months. Annual vertical displacement measurements allow analysis of annual land elevation change without seasonal variation.



Gray bar denotes measurement accuracy range of +0.05 to -0.05 feet (Towill, 2020).

Figure 7: Time-series graphs showing running annual and total land surface elevation changes derived from InSAR data processed by TRE for select points in the basins.

Figure 7 shows that the majority of the measured land elevation changes fall within the measurement accuracy range of +/-0.05 feet (grey bands on the plots). Quantitative interpretations of the land surface movement in the +/-0.05 feet range should be done with caution. However, general land surface movement trends can be seen in the InSAR data.

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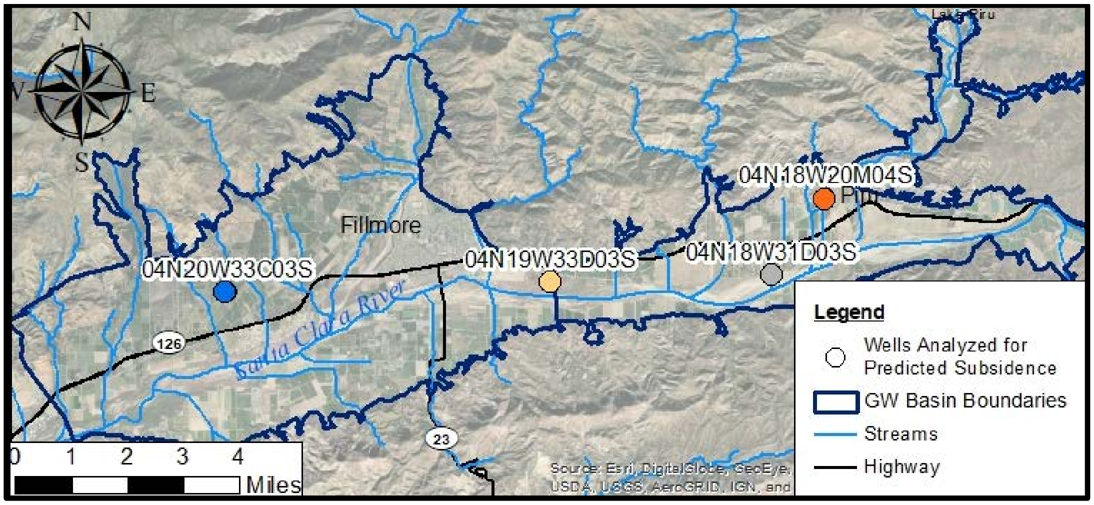
Fillmore basin locations 1 through 4 and Piru basin location 8 show a similar pattern of land elevation fluctuation within the accuracy range over the time span (i.e., no significant change in land surface). Locations 5 and 7 show a small jump in total vertical displacement of approximately 0.05 feet of uplift beginning in May 2017 and somewhat stabilizes by October 2017. Location 6 has a similar jump of about 0.07 feet from May to October 2017 and another jump of about 0.11 feet beginning in April 2019 to the end of the dataset (September 2019), corresponding with groundwater recharge efforts performed by UWCD, as mentioned earlier in this section. Overall, the InSAR data set does not suggest land surface movements in excess of the minimum resolution of this instrumental technique.

6. Future Potential Subsidence

The datasets and reports previously discussed in this document provide insight on historical subsidence, however, a prediction method is needed to project possible future subsidence for the basins. Potential subsidence is significantly influenced by fine-grained layer distribution, thickness and compressibility, amount and timing of water-level changes, and lowest historical water level. It is important to note that any significant predicted subsidence would not occur until water levels drop below historical lows. The UWCD-developed groundwater flow model (UWCD, 2021) was used to simulate future groundwater water elevations under moderately extreme climate change conditions (the central tendency 2070 Climate Change Factors [2070CF]). The simulated water level time-series allow the effect of general hydrologic conditions (e.g., wet versus dry conditions) to be compared over a multi-decadal timeframe (1986 through 2096). In order to assess the potential for future subsidence with groundwater declines, simulated future groundwater elevation time-series at select wells in the Fillmore and Piru basins were evaluated by comparing future water levels against estimated historical lows (Figure 8).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Lake Piru
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Piru
Fillmore
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Santa Clara River
23
0 1 2 3 4
Miles
Source: Esri, DigitalGlobe, GeoEye, USDA, USGS, AeroGRID, IGN, and
Legend
○ Wells Analyzed for Predicted Subsidence
GW Basin Boundaries
Streams
Highway

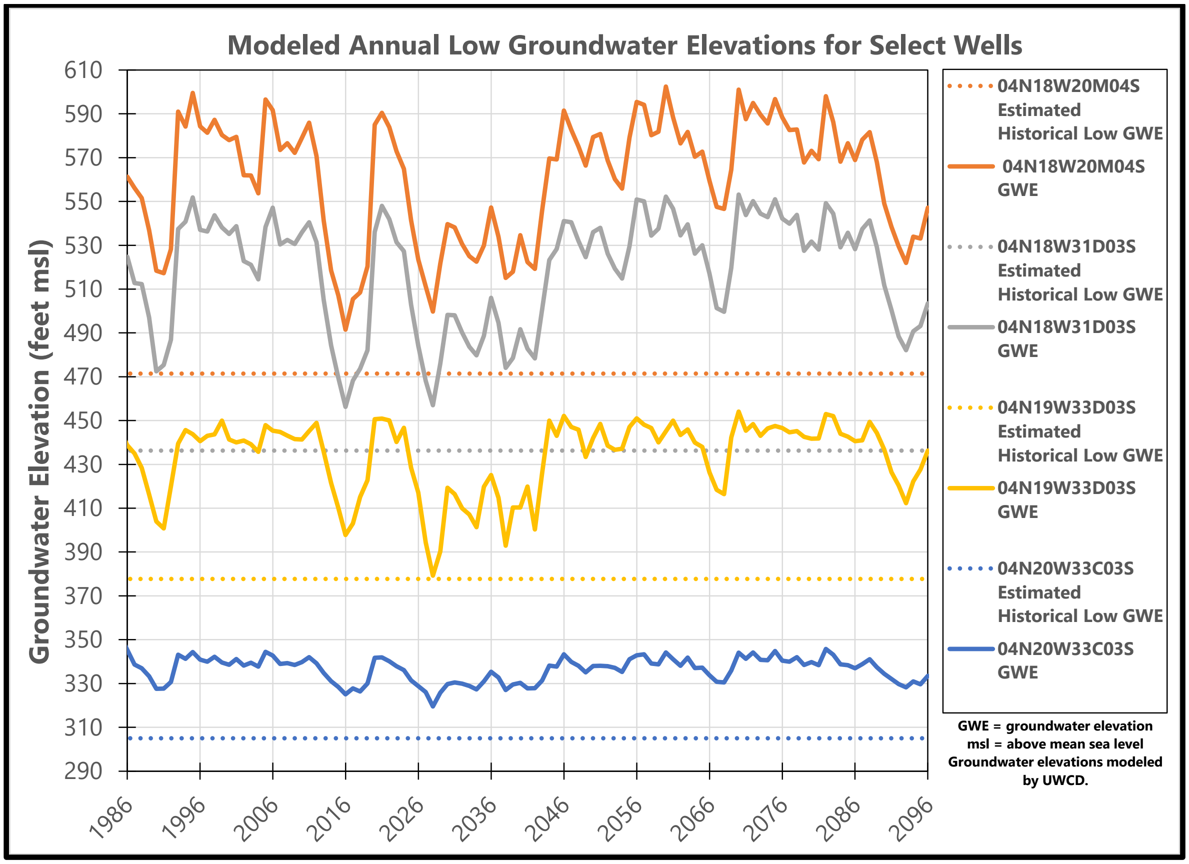

Figure 8: Map showing example wells locations used for analysis for potential future subsidence. Graphs represent modeled annual low water levels for the example wells, with their respective estimated historical low water levels

Simulated annual low water levels for the four example wells for the available model timeframe were used for the evaluation. In order to account for maximum historical lows anticipated prior to the modeled timeframe, the historical low water level was estimated to be 20 feet lower than the modeled 2016 drought water level. This historical low estimate was based on the review of wells with long-term water level records (e.g., back to the 1940s) that showed early drought levels generally measured about 20 feet lower than the measured 2016 drought low water levels.

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The hydrographs in Figure 8 reveal that the future water levels predicted by the 2070 climate change factor scenario (2020-2096) are functionally identical to those experienced during the historical period of record (1986-2019). The range between the minimum water levels during major drought periods and the maximum water levels during wet periods for the historic and future modeling timeframes are very similar. Additionally, the future simulated water levels do not decline to the elevation of the estimated historical low water levels. In the absence of future water levels below the estimated historical low water levels, it is unlikely that subsidence would be experienced at these well locations.

A basin-wide review of the relationship between the estimated historical low groundwater elevation and the low groundwater level predicted by the 2070 CF model scenario allows the determination of where in the basins the change in groundwater levels might initiate conditions susceptible to subsidence. Figure 9 shows that nearly all wells (for which the well construction details are known) are predicted to have future water levels shallower than the estimated historic low levels. This relationship suggests that it is unlikely that subsidence in either basin would be experienced in the future under the modeled climatic and groundwater extraction scenario.

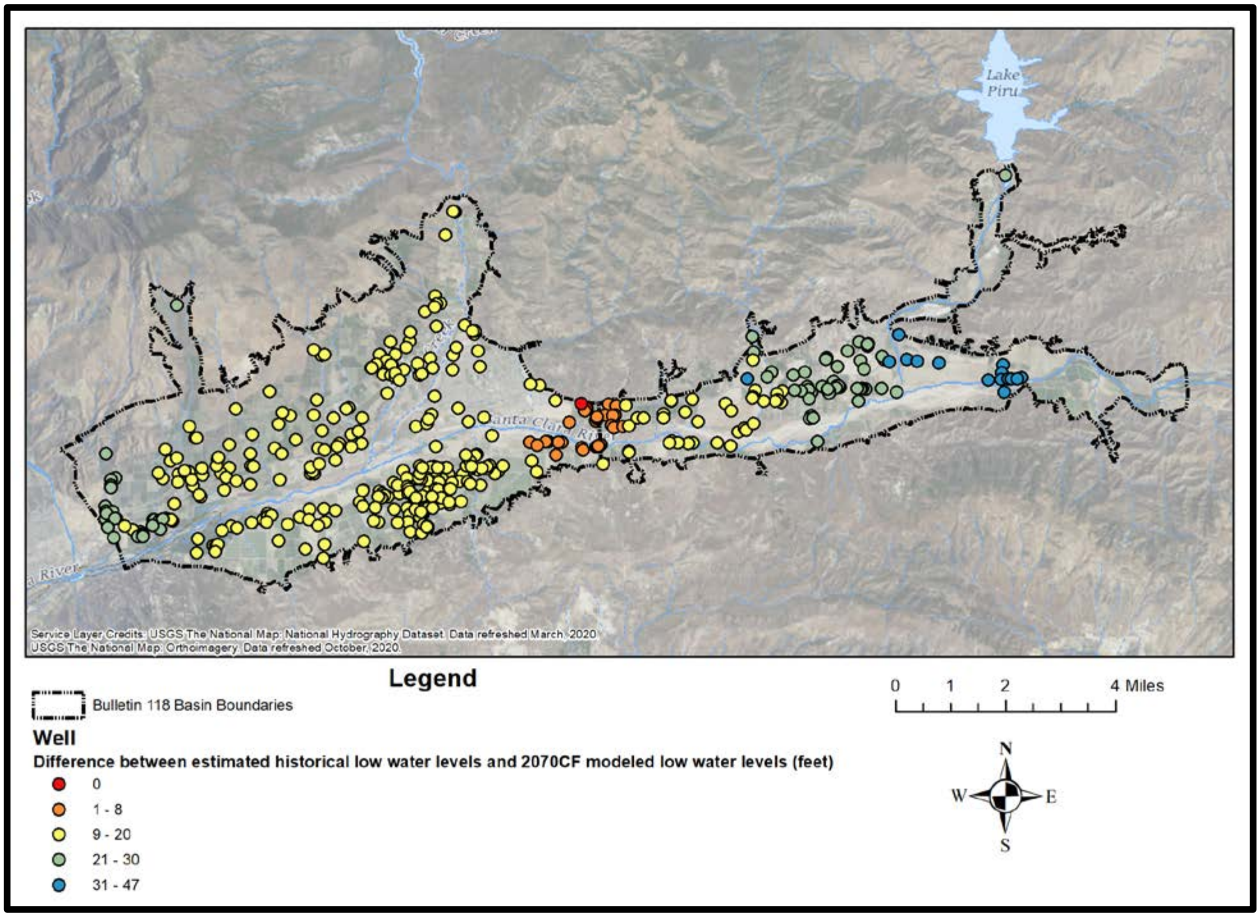

Figure 9: Difference between estimated historical low water level and 2070CF modeled low water levels

The water levels near the boundary between the Fillmore and Piru basins are typically some of the shallowest in the basins and the 2070CF modeled water levels are predicted to be less than 10 feet above the estimated historical low in this area. In general, the differences between the estimated historical low water level and the 2070CF modeled low water levels increase to the east and west away from the Fillmore-Piru basin boundary.

7. Discussion

The potential for subsidence in the Fillmore and Piru basins has been approached from multiple aspects and is summarized in Table 1.

Study/Investigator	Fillmore Basin	Piru Basin	Comments
USGS, 1996	maximum subsidence of 0.03 feet (8 mm, 0.6 mm/yr) near City of Fillmore	maximum subsidence zone up to 0.05 feet (15 mm, ~1 mm/year) around the Town of Piru	1975-1989 study period
Hanson, 2003	maximum value of just over 0.1 feet (0.00098 ft/yr) of subsidence	0.25 feet (0.0024 ft/yr) in the eastern portion of Piru Basin	1891 to 1993 study period
Ventura County, 2013 and 2020	Lies within subsidence hazard zone	Lies within subsidence hazard zone	No technical analyses conducted.
DWR, 2014	Low potential	Insufficient data	
InSAR	Less than +/-0.05 ft	Generally, less than +/- 0.05 ft except during periods of artificial recharge, then up to +0.14 ft of rebound in Piru basin	June 2015 – Sept 2019 study period
2070 Climate Change Modeling by UWCD	No subsidence anticipated	No subsidence anticipated	1986 to 2096 model timeframe

Table 1. Summary of Subsidence Evaluations

The susceptibility of each basin to subsidence is rooted in a few key factors:

- The hydrostratigraphic setting (i.e., do the geologic units contain fine-grained sediments); and
- If the water level is below, or projected to be below, the historic lows in the future.

In general, both of these factors must be present to initiate subsidence. Site-specific subsidence monitoring data (e.g., extensometer or tiltmeter) can be used, if available, to augment the hydrostratigraphic setting and water level data sets and develop a subsidence susceptibility ranking for the basins as summarized in Table 2 below.

Basin	**Hydro-stratigraphic Setting Susceptibility**	**Chronic Declines in Groundwater Levels**	**Geodetic / Extensometer / Tiltmeter Evidence of Subsidence**	**InSAR Evidence of Subsidence**	**Subsidence Susceptibility Ranking**
Fillmore	Low to Moderate	No	No	No	**Low**
Piru	Low	No	No	No	**Low**

Table 2. Summary of (Inelastic) Subsidence Potential

The hydrostratigraphic setting for the Fillmore basin is identified as Low to Moderate to reflect the greater amount of fine-grained alluvial sediments in the western portion of the basin compared to the eastern portion. As a contrast, the Piru basin hydrostratigraphic setting is dominated by coarse-grained materials and consequently assigned a Low value. Consideration of each of the input variables supports the assignment of an overall Low Subsidence Susceptibility Ranking for each basin.

8. Conclusion

This review of available historical reports, geodetic survey data, and satellite imagery (InSAR) indicates that the Fillmore and Piru basins have historically shown little to no subsidence related to groundwater withdrawal, even through multiple droughts and record low water levels.

The basins are located in a very tectonically active region that also has oil and gas extraction operations, which adds complexity to determination of the cause(s) of land elevation changes. Previous historical investigations covering the basins have primarily been inconclusive in determining actual rates or values of subsidence, due to lack of available data, and focus on a regional scale or areas of significant subsidence (i.e., Oxnard Plain). The following key takeaway points are:

- Multi-decadal historical datasets involving geodetic measurements and model simulations have revealed very low overall subsidence rates throughout the basins;

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- Recent InSAR data covering the 2015 to 2019 time period suggests little to no subsidence throughout the Fillmore basin, while rebound is observed in the Piru basin associated with elastic recovery related to recharge following a multi-year drought;
- Future water levels projected through 2096 in the UWCD 2070CF model do not go below historical lows, thereby minimizing the potential for subsidence.

The FPBGSA can use a variety of monitoring techniques for subsidence:

Water Levels: There is an extensive historical water level database in these basins and it is expected that a robust monitoring program will continue into the future. These datasets can be used to identify when, or if, the water levels are approaching the estimated historical low water levels. Based on historical and projected future groundwater level trends, the basins are at low risk for water level declines that would suppress water levels to elevations lower than the estimated historical lows.

Geodetic / InSAR data: The available geodetic and InSAR datasets are effective monitoring tools that document current and recent (e.g., within the past year) subsidence. The DWR plans on continuing to provide InSAR subsidence data covering the groundwater basins, allowing a low-cost method of the monitoring future land surface elevation changes. Prevention of future inelastic subsidence is reliant on maintaining water levels above historical lows.

Based on the review of these readily available data sets, the susceptibility ranking is considered Low for both the Fillmore and Piru basins.

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