Owens Valley Groundwater Basin Land Subsidence Technical Memorandum

Prepared for

Owens Valley Groundwater Authority

OWENS VALLEY GROUNDWATER AUTHORITY

Prepared by

DBS&A

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Project #DB18.1418.00

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Certification

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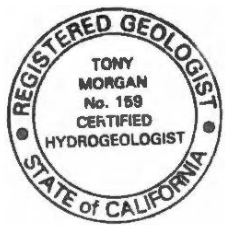

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1. Introduction

Daniel B. Stephens & Associates, Inc. (DBS&A) has prepared this Owens Valley Groundwater Basin Land Subsidence Evaluation Technical Memorandum (Tech Memo) for the Owens Valley Groundwater Authority (OVGA or Agency) and is under contract to prepare a Groundwater Sustainability Plan (GSP or Plan) under the Sustainable Groundwater Management Act (SGMA) of 2014.

Land subsidence is one of six sustainability indicators defined in the SGMA legislation. This document will provide 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.

The subsidence evaluation has been summarized, as appropriate, for each of the proposed management areas (Figure 1-1) in the basin:

- Tri Valley / Fish Slough;
- Owens Valley; and
- Owens Lake.

2. Background

Subsidence directly related to subsurface fluid extractions (e.g., groundwater and hydrocarbons) has been observed for several decades in California. Permanent compaction of fine-grained sediments occurs due to the increase in the effective stress caused by fluid removal. A detailed discussion of the geomechanics associated with subsidence is beyond the scope of this document; however, other publications describe the geomechanics associated with subsidence (e.g., Poland, 1984; Poland and Davis, 1969) and its effects (e.g., USGS, 1999, 2016).

The evaluation of subsidence for the Owens Valley basin in this document is based on review of the following lines of evidence:

- Previous investigations/evaluations;
- Geodetic surveys;
- Interferometric Synthetic Aperture Radar (InSAR) data; and

- GPS, extensometers and tiltmeters.

3. Previous Investigations/Evaluations

In 2014, California Department of Water Resources (DWR) prepared a report summarizing recent, historical, and estimated future subsidence potential for groundwater basins included in CA DWR Bulletin 118 (DWR, 2014). The stated intent of the document was to provide screening-level information with respect to subsidence. DWR lists Owens Valley basin with low potential for future subsidence. The ranking was determined from long-term water level trends (well records greater than 10 years) above historical lows and no documented subsidence.

The Inyo County and City of Bishop (2017) reports no documented subsidence in the county or City.

The County of Mono Regional Transportation Plan & General Plan Update (2015 Draft EIR), Mono County and the Town of Mammoth Lakes (2019), and https://www.monocounty.ca.gov/generalplan?tid=All&keys=subsidence reports that no subsidence has been documented due to fluid withdrawals.

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 (https://www.unavco.org/instrumentation/networks/status/nota).

Several CGPS stations are found near the basin (Figure 4-1) with surface elevation data extending back to about 2007. All stations (with the possible exception of P651) 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 4-1 shows locations of these CGPS stations, along with UNAVCO time-series graphs (Figure 4-2) 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 and outliers with a standard deviation greater than 20mm were removed. 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. CGPS stations surrounding Owens Valley basin are set on bedrock or weathered bedrock (UNAVCO). None of the CGPS stations show persistent evidence of subsidence (Figure 4-2).

In addition, LADWP has a series of ground-based GPS monitoring stations in the Owens Lake area (Table 4-1; Figure 4-3). Unfortunately, these data were not available for inclusion in this technical memorandum.

GPS Survey Station ID	GPS Station Type [1]	Sensitive Infrastructure to be Monitored and/or Location Rationale	Relative Location within Lakebed	Monitoring Plan
---	*New Survey Point*	LORP Pump Station	North-central	Collect ground-based GPS survey elevation point at GPS survey stations. Measure and record elevations once prior to pumping, then annually when pumping begins.
6532	Primary	DCM Mainline	Northeast	
7012	Primary	DCMs	Northern Brine Pool	
---	*New Survey Point*	Swansea/Highway 136	Northeast edge	
7016	Back-up	DCMs	North-northeast Brine Pool	
6527	Primary	Mainline	Central northeast	
---	*New Survey Point*	Keeler/Highway 136	Central northeast edge	
6523	Back-up	Mainline	Eastern	
---	*New Survey Point*	DCMs (thickest section of clays)	Eastern central	
6521	Primary	Mainline (thickest section of clays)	Eastern	
6518	Primary	Mainline (thickest section of clays)	Central east-southeast	
7007	Primary	DCMs (thickest section of clays)	Southeast Brine Pool	
7010	Primary	DCMs (thickest section of clays)	Central southeast	
6513	Back-up	Mainline	Central southeast	
---	*New Survey Point*	Rio Tinto Facilities (thickest section of clays)	Southern Brine Pool	
6508	Primary	DCMs (thickest section of clays)	South central	
6509	Back-up	Mainline (thickest section of clays)	South central	
---	*New Survey Point*	Highway 190	Southeast edge	
7011	Primary	DCMs (thickest section of clays)	Southwest	
6503	Primary	DCMs (thickest section of clays)	Southwest	
7003	Primary	DCMs (thickest section of clays)	Southern	
---	*New Survey Point*	Highway 190 (thickest section of clays)	Southern edge	
7005	Back-up	DCMs (thickest section of clays)	Southern	
6501	Back-up	Mainline	Southwestern edge	
6372	Primary	Highway 395	Central northeast edge	
6371	Primary	Highway 395	Northeast edge	
6535	Back-up	DCMs	Northwest central	

[1] Back-ups sites will be considered if a primary site is unavailable for any reason; otherwise secondary sites will not be used for subsidence monitoring.

Table 4-1 LADWP GPS Elevation Monitoring Stations at Owens Lake (from LADWP, 2019)

5. Interferometric Synthetic Aperture (InSAR) Data

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 time from one measurement to the next, providing images that estimate ground surface elevation change. In an effort to assist with technical subsidence evaluations for GSP development, DWR contracted TRE Altamira Inc. (TRE) and National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) 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 representing average vertical movement per 100 square meter areas within the basins from June 13, 2015 to September 19, 2019. TRE also provided rasters (gridded datasets) interpolated from the point data representing annual vertical displacement and total 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. The study determined that InSAR data within California provided accurate vertical displacement measurements within +/-0.05 feet (+/-0.6 inch) (Towill, 2020).

Twenty-six representative sites (Figure 5-1) in the basin were selected to show the TRE-processed InSAR-based total vertical displacement data. The sites were chosen based on a special geographical characteristics and/or hydrogeological settings and were located in areas underlain by alluvium.

Time-series graphs showing total vertical displacement from the available TRE-processed InSAR datasets are shown in Figure 5-2. The values represent the vertical elevation change for the end date of the analyzed periods between points on the graph. 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 yearly land elevation change without seasonal variation. Vertical land surface elevation fluctuations recorded by the stations generally ranged between +0.05 feet and -0.05 feet throughout the basin. These values are less than the reliable instrumental resolution.

Three sites in the Owens Lake area (22, 23, and 24) have time series trends that show the land surface rising. At site 23 in the central portion of Owens Lake, the InSAR data suggests that the land surface has been rising since mid-2016. This apparent land surface rising may be a function actual elastic rebound of the ground associated with the recharge of the aquifers as the drought period was ending during the 2016-2019 timeframe. Elastic rebound was reported in the Owens

Lake area by previous investigators (Neponset Geophysical Corporation, 1999). Likewise, changes in land surface elevation could be attributed to land use shifts or man-made situations (e.g., construction activities), although none were reported in the Neponset study.

Sites 22 and 24 show slight increasing trends beginning in late 2019, but additional data are needed to determine if the trends are sustained. None of the measurement points indicate subsidence due to groundwater extraction is measurable.

6. Extensometers and Tiltmeters

Neponset Geophysical Corporation (1999) reported on a tiltmeter survey conducted in the northern part of Owens Lake playa. The study monitored land surface elevation changes during the performance of three short term groundwater pumping tests by the Great Basin Air Pollution Control District. Observations of land surface elevation changes were recorded while groundwater was pumped from a relatively shallow well (perforated from 143 to 230 feet below ground surface [bgs]) for 10 days, a deep well (perforated at 440-555 feet bgs) for 7 days, and when both wells were pumped concurrently for 23 days. The shallow and deep wells were pumped at approximately at 1,500 gallons/minute (gpm). The maximum measured deformation of 0.0363 feet (0.43 inches) was recorded when both the shallow and deep wells were pumped simultaneously, but resulted in only 0.0077 feet (0.09 inches) of net subsidence (inelastic subsidence) after recovery.

Los Angeles Department of Water Resources (LADWP) has proposed to install extensometers at two locations in the vicinity of Owens Lake (Figure 6-1) as part of their Owens Lake Groundwater Development Project. These locations were selected based on clay layers within the aquifers, vicinity to potential future pumping, and nearby infrastructure that could be affected by land subsidence. The extensometers have not yet been installed but could be useful monitoring points in the future.

7. Discussion

The potential for subsidence in Owens Valley basin has been evaluated for the GSP using multiple methods and data sources (Table 7-1).

Study/Investigator	Subsidence	Comments
Neponset Geophysical Corp (1999)	maximum subsidence of 0.0363 feet (0.43 inches) with 0.0077 ft (0.09 inches) of inelastic subsidence	23-day pumping test near Owens Lake
Geodetic Data	No recorded subsidence	Basin-wide data
Various Regional General Plans or Hazard Mitigation Plans	No recorded subsidence	
DWR, 2014	Low potential	Ranking for entire basin
InSAR	Less than +/-0.05 ft (land elevation changes less than instrumental resolution)	June 2015 – Sept 2019 study period / basin-wide data

Table 7-1 Summary of Subsidence Evaluations

Each of the proposed management areas has a slightly different susceptibility to subsidence that is rooted in a few key factors:

- The hydrostratigraphic setting (i.e., are the geologic units fine-grained); and
- Is the water level below, or projected to be below, the historic lows in the future?

In general, both of these factors must be present to initiate subsidence. If monitoring data or site-specific subsidence evaluations have been done, these can be used to support a subsidence susceptibility ranking.

Management Area	Hydro-stratigraphic Setting Susceptibility	Chronic Declines in Groundwater Levels	Geodetic / Extensometer / Tiltmeter Evidence of Subsidence	InSAR Evidence of Subsidence	Subsidence Susceptibility Ranking
Tri Valley & Fish Slough	Low	Yes	No	No	Low
Owens Valley	Low to Moderate	No	No	No	Low
Owens Lake	High	No	Yes	No	Moderate

Table 7-2 Summary of Subsidence Potential

Tri Valley / Fish Slough: The hydrogeologic setting in the Fish Slough and Tri-Valley management area is dominated by volcanics and alluvial fan sediments which are typically not susceptible to subsidence. Groundwater levels in this area are showing chronic declines with rates observed to be about 0.15 feet/year (Fish Slough) and 0.49 – 1.86 feet/year (Tri Valley) and are thought to be historic lows for this management area. The groundwater extractions in this management area are distributed throughout the area rather than being concentrated in small zones, so the effects of subsidence, if any, may be more area wide. Despite one of the necessary factors being present, there is no direct instrumental evidence of subsidence in the management area. Consequently, the potential for subsidence is considered low.

Owens Valley: The Owens Valley management area, in general, covers the flanks of the valley floor in the central portion of the basin (Figure 1-1). Alluvial fan deposits interbedded with basalt flows dominate the underlying geology with limited evidence of thick sequences of clays or fine-grained sediments that would be susceptible to subsidence. The southern portion of the management area may, in some locations, be underlain by fine-grained sediments/clays associated with ancestral Owens Lake when it was larger extending north of Independence. The groundwater levels in the management area are not displaying chronic declines and, similar to the Tri Valley/Fish Slough management area, groundwater extractions are distributed throughout the basin with the most concentrated zone of pumping located near population centers (e.g., City of Bishop). There is no direct instrumental evidence of subsidence in the management area, so the potential for subsidence is considered low. In the adjudicated portion of the Basin, the pumping stress is much greater and the presence of fine-grained sediments more common, but subsidence in this area also has not been reported.

Owens Lake: The Owens Lake management area is underlain by multiple aquifers separated by aquitards composed of lacustrine clays. This hydrogeologic setting is highly susceptible to subsidence, however, the lack of extensive groundwater extractions lowers the potential for the subsidence if the present pumping stress continues. There is no recent instrumental evidence of wide-spread subsidence, however, the Neoponset (1999) study did record subsidence with a relatively short-term (23 day) groundwater extraction test. The majority of the subsidence was elastic in nature. So, it is possible to have subsidence, and future groundwater extraction projects should consider the potential for those projects to initiate subsidence. As described in Section 6, LADWP has plans to install two extensometers in this management area to monitor if potential future groundwater extractions associated with their proposed project could initiate subsidence. Based on the hydrogeologic setting and demonstrated initiation of subsidence after only a short-term groundwater extraction test, the subsidence susceptibility ranking is moderate for this management area.

The generally moderate potential for subsidence to occur within the basin can be monitored by regularly reviewing the future InSAR data sets. DWR plans on continuing to provide InSAR subsidence data covering the groundwater basin, from which changes in ground surface elevation should be assessed on an annual basis under the GSP. These data sets are good monitoring tools that document subsidence (or the lack thereof) in arrears (i.e., data captures subsidence [or recovery] that has already happened), but are not suitable as early warning or real-time indicators of subsidence.

To monitor real-time subsidence or get early warnings, the installation of extensometers or additional CGPS stations within the areas underlain by alluvium/alluvial fan materials (i.e., not underlain by bedrock) would be required. Extensometers are complimentary to the CGPS and offer the added benefit of being able to be positioned in specific aquifers and develop hydrostratigraphically discrete measurements of subsidence. Future groundwater projects in the Owens Lake management area could be required to include real-time subsidence monitoring and be evaluated on a case-by-case basis to protect and sustainably manage the Basin.

Assessing potential future subsidence instigated by depressing groundwater water levels lower than the historical low value can be semi-quantitatively estimated by using analytical spreadsheet predictive tools (e.g., LRE, 2017) or the implementation of the subsidence module in future updates to groundwater flow models. At present, the need to use analytical spreadsheet tools or develop of new groundwater flow models are not warranted given the low subsidence potential and thus are outside of the scope of work for this GSP. But, the methods suggested herein could be considered in future updates to the GSP or if conditions or pumping stress changes.

8. Conclusions

After reviewing available historical reports, geodetic survey data, satellite imagery, and tiltmeter and groundwater level data, the Owens Valley basin has historically shown little to no subsidence related to groundwater withdrawal, even through multiple droughts and record low water levels. Prevention of future subsidence can be accomplished by maintaining water levels above historical lows. The overall potential for subsidence under the current groundwater management schemes is considered low; however, the geologic materials in the Owens Lake management area could be susceptible and future projects will be evaluated whether expanded or on the ground monitoring is necessary.

Groundwater extractions and/or exports from the basin are managed by various existing regulations, so the potential for over-pumping the aquifers and depressing water levels to elevations significantly below the historic low water levels (and therefore establishing conditions favorable for the initiation of subsidence) are unlikely. Changes in future land uses are not expected to result significantly greater demand for groundwater.

The recommended subsidence monitoring program can be divided into three phases:

Priority		Technique	Comments
I	In arrears	InSAR data	Low cost (data provided by others) / Good areal coverage
II	Real time or near real time	Extensometers / CGPS	Expensive to install / Ongoing maintenance costs / Site-specific data / Extensometers allow aquifer-specific measurements
III	Predictive, future subsidence	Analytical tools / subsidence groundwater flow module	Semi-quantitative results / Must have detailed lithologic data (e.g., borehole geophysical logs, well drillers reports)

Table 8-1 Recommended Subsidence Monitoring Program

It is recommended that the GSA use the InSAR data set as a primary monitoring tool for subsidence in the basin. DWR plans on continuing to provide InSAR subsidence data covering the groundwater basins, in which the OVGA will be able to monitor the changes each year. If the InSAR data identifies areas of subsidence or critical infrastructure are being impacted by subsidence, then Priority II monitoring techniques should be considered for implementation. As new groundwater models are being developed (e.g., Fish Slough and Tri-Valley management area) or the existing LADWP groundwater flow models are being updated, it is suggested that consideration be given to implementing the subsidence predictive modules associated with the model software.

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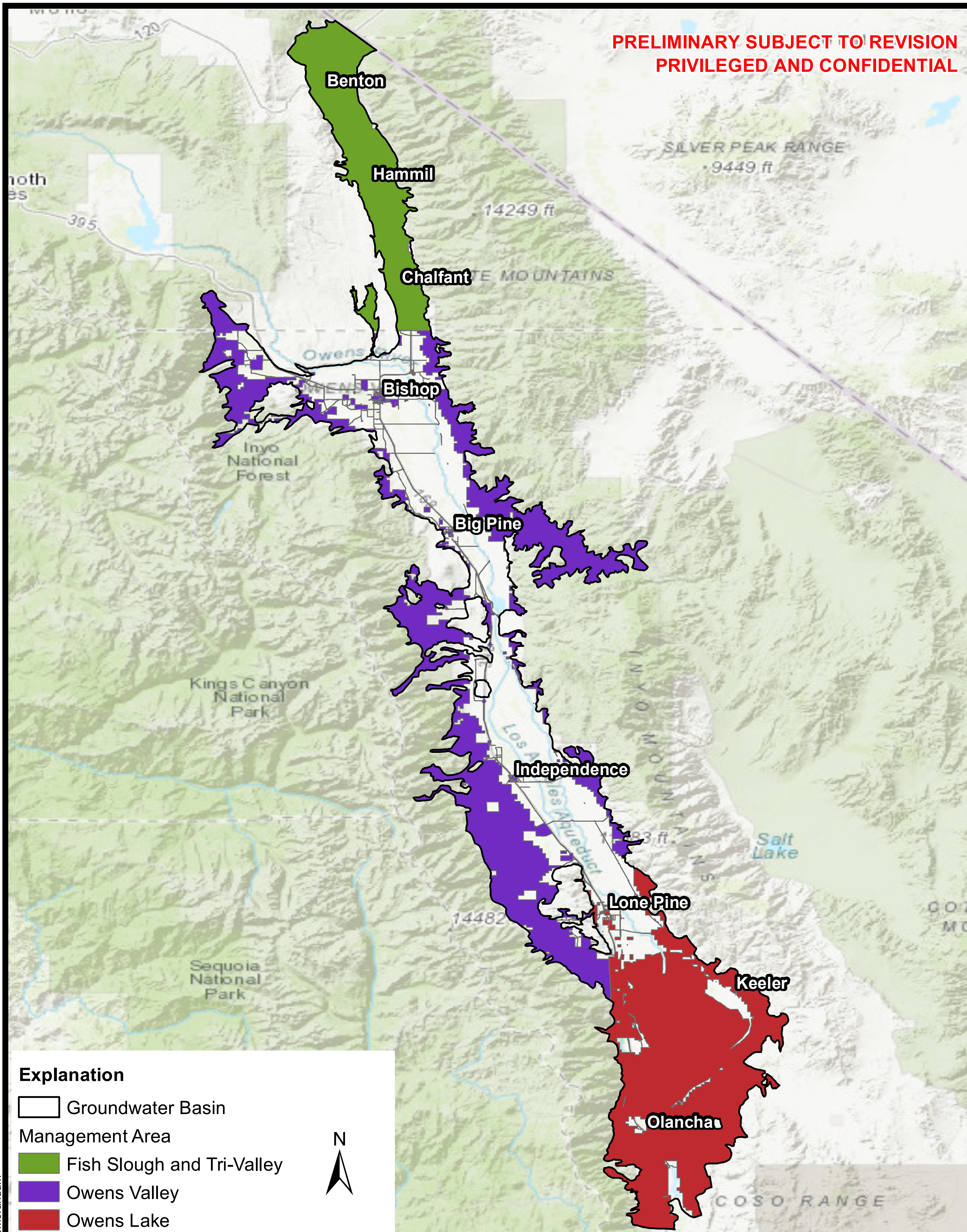
10. Figures and Tables



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Subsidence Technical Memorandum

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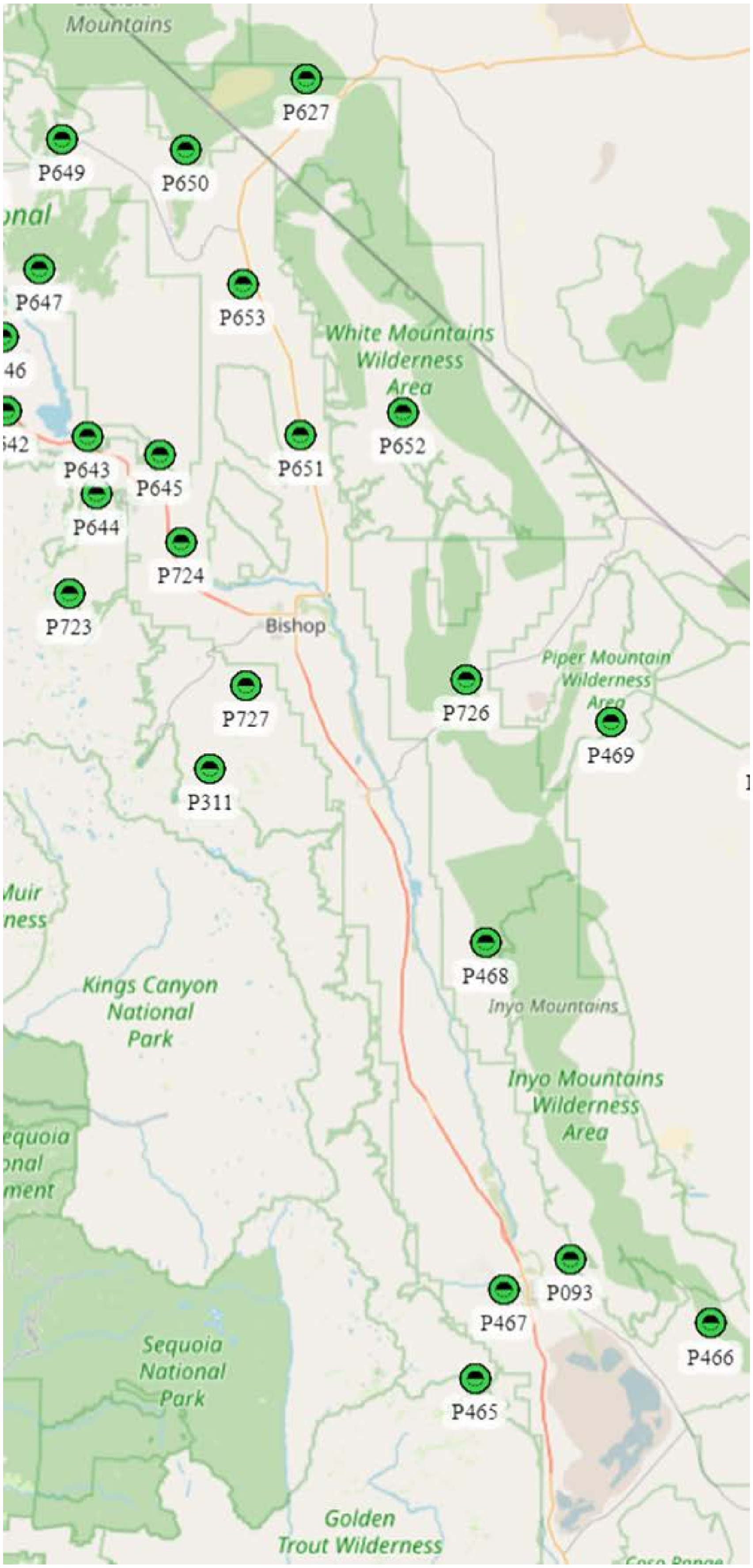
Owens Valley Basin GSP

GSP Management Areas

Figure 1-1



OWENS VALLEY BASIN GSP

Continuous Monitoring GPS Stations near Owens Valley Basin

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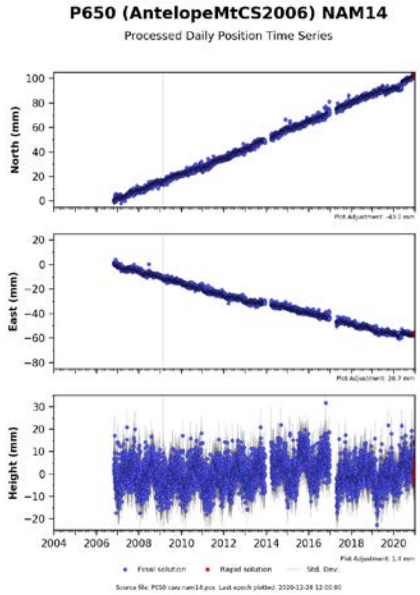
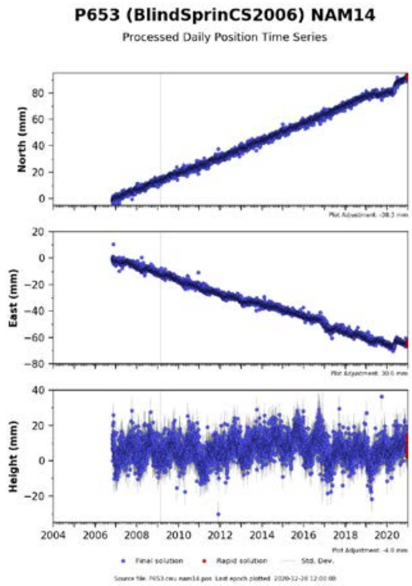
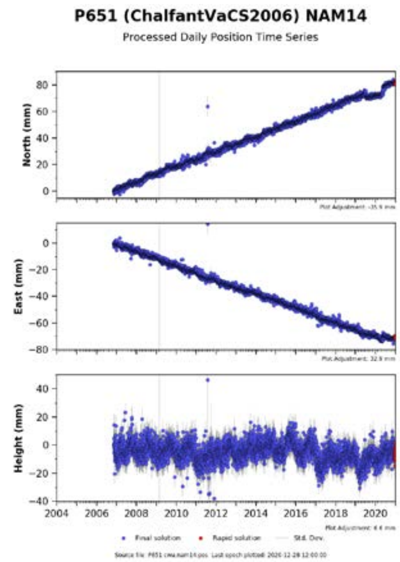
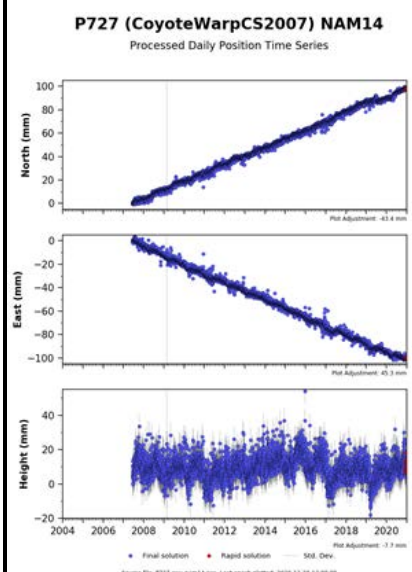
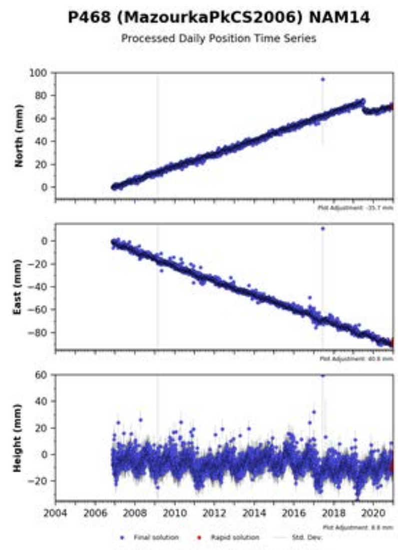
Figure 4-1

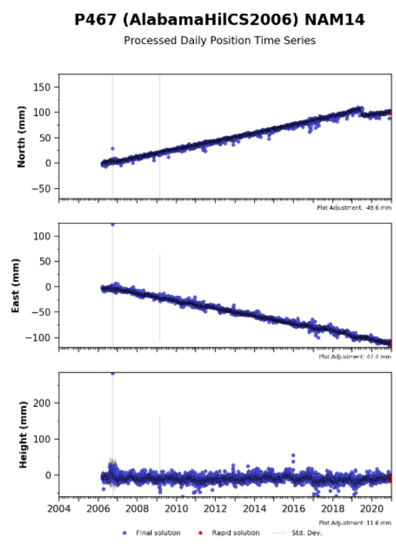


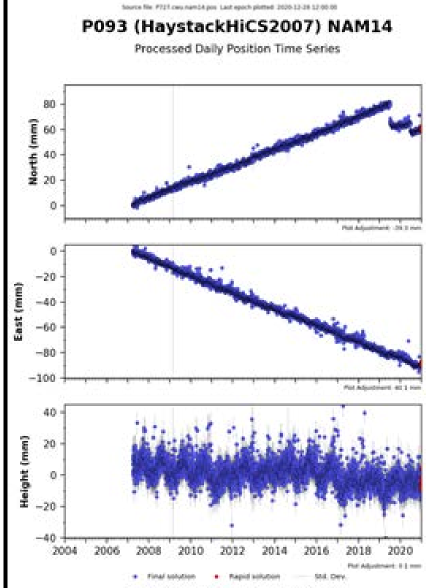


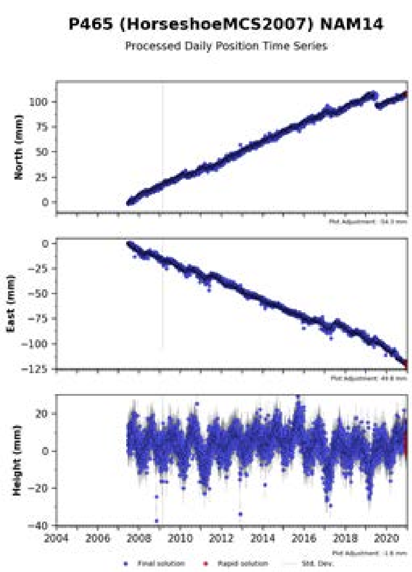












OWENS VALLEY BASIN GSP

Representative CGPS Time Series Data near Owens Valley Basin

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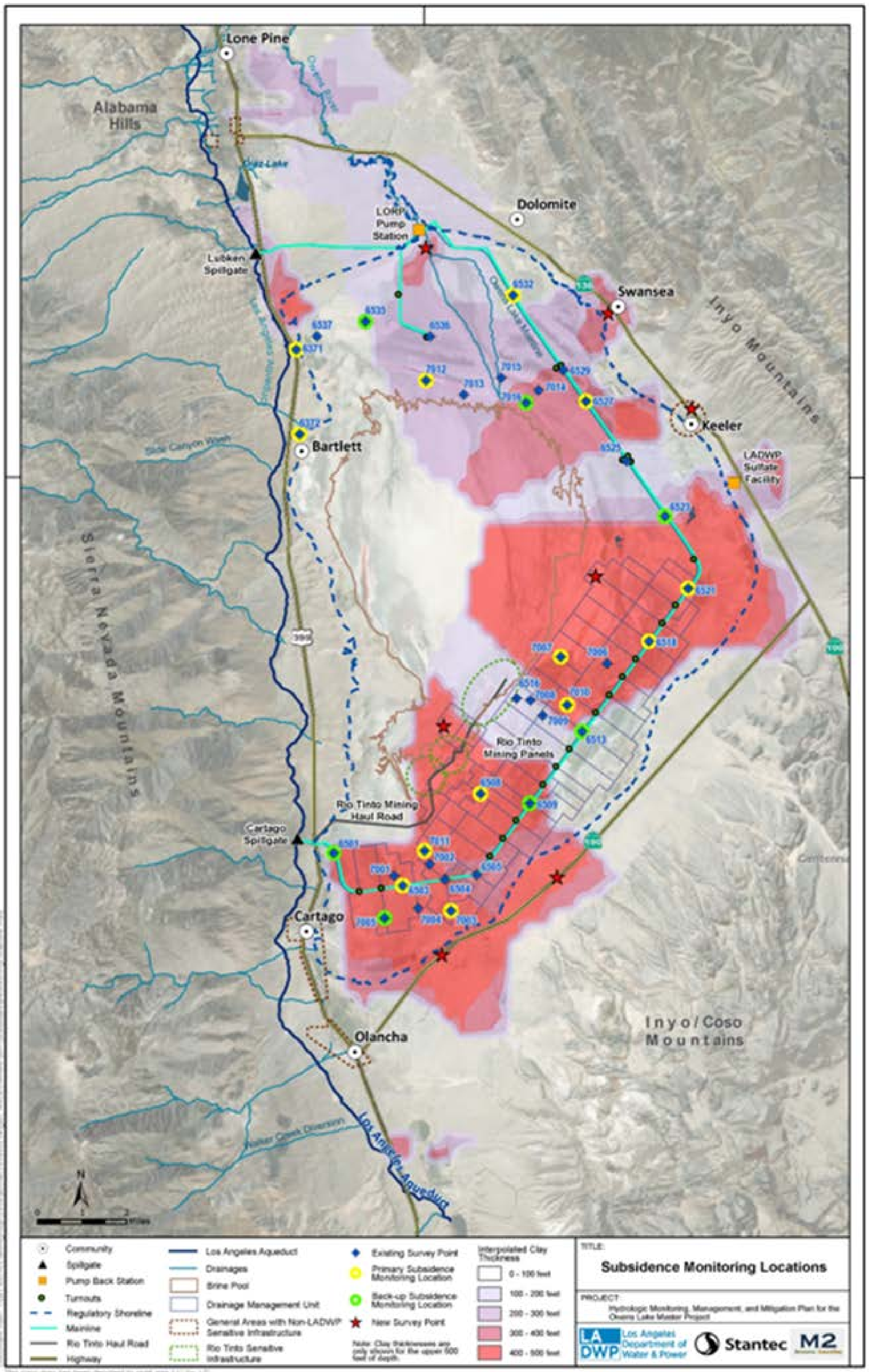
Figure 4-2



From LADWP (2019) Hydrologic Monitoring, Management, and Mitigation Plan for The Owens Lake Groundwater Development Program

OWENS VALLEY BASIN GSP

LADWP Subsidence Monitoring Stations near Owens Lake

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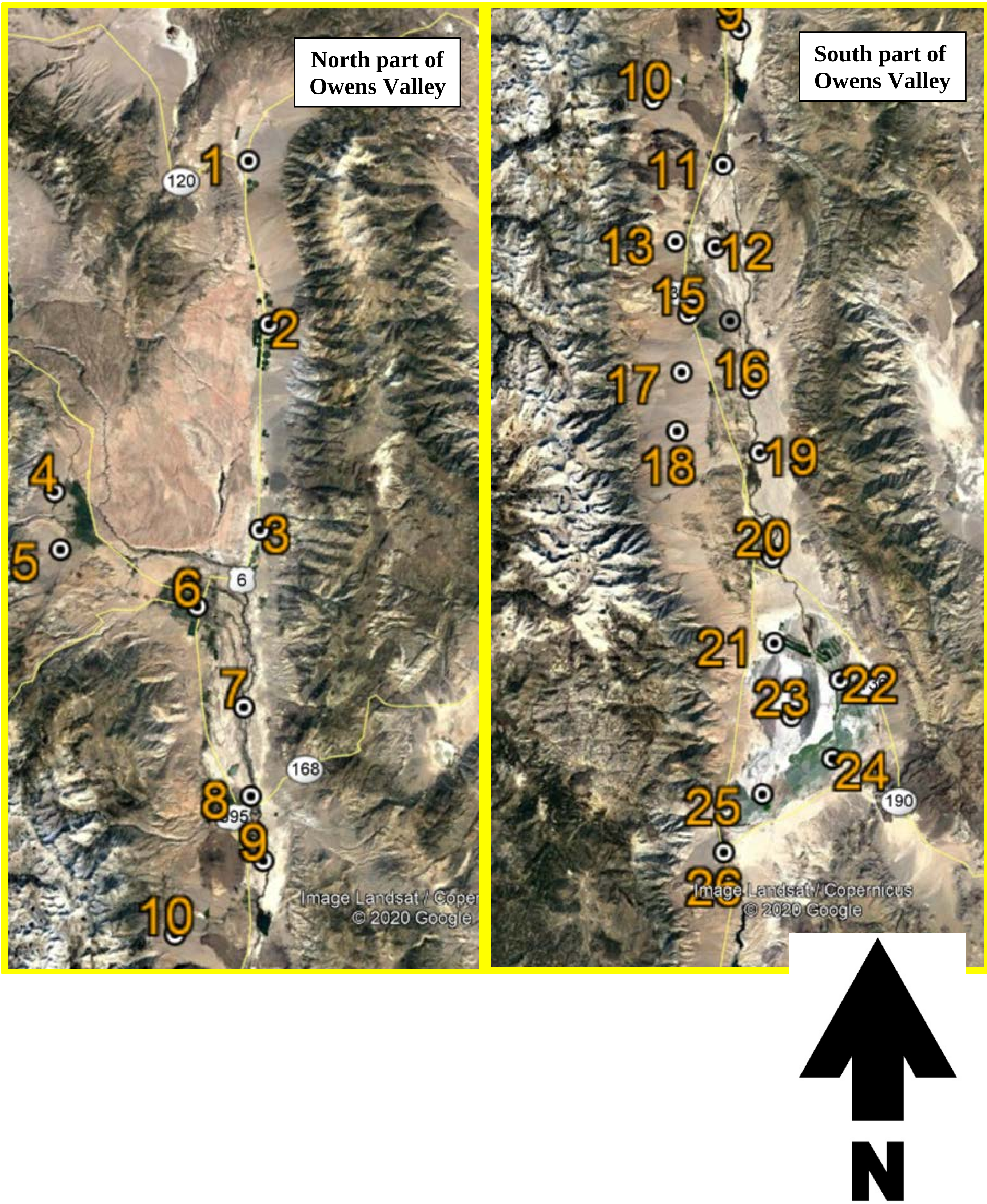
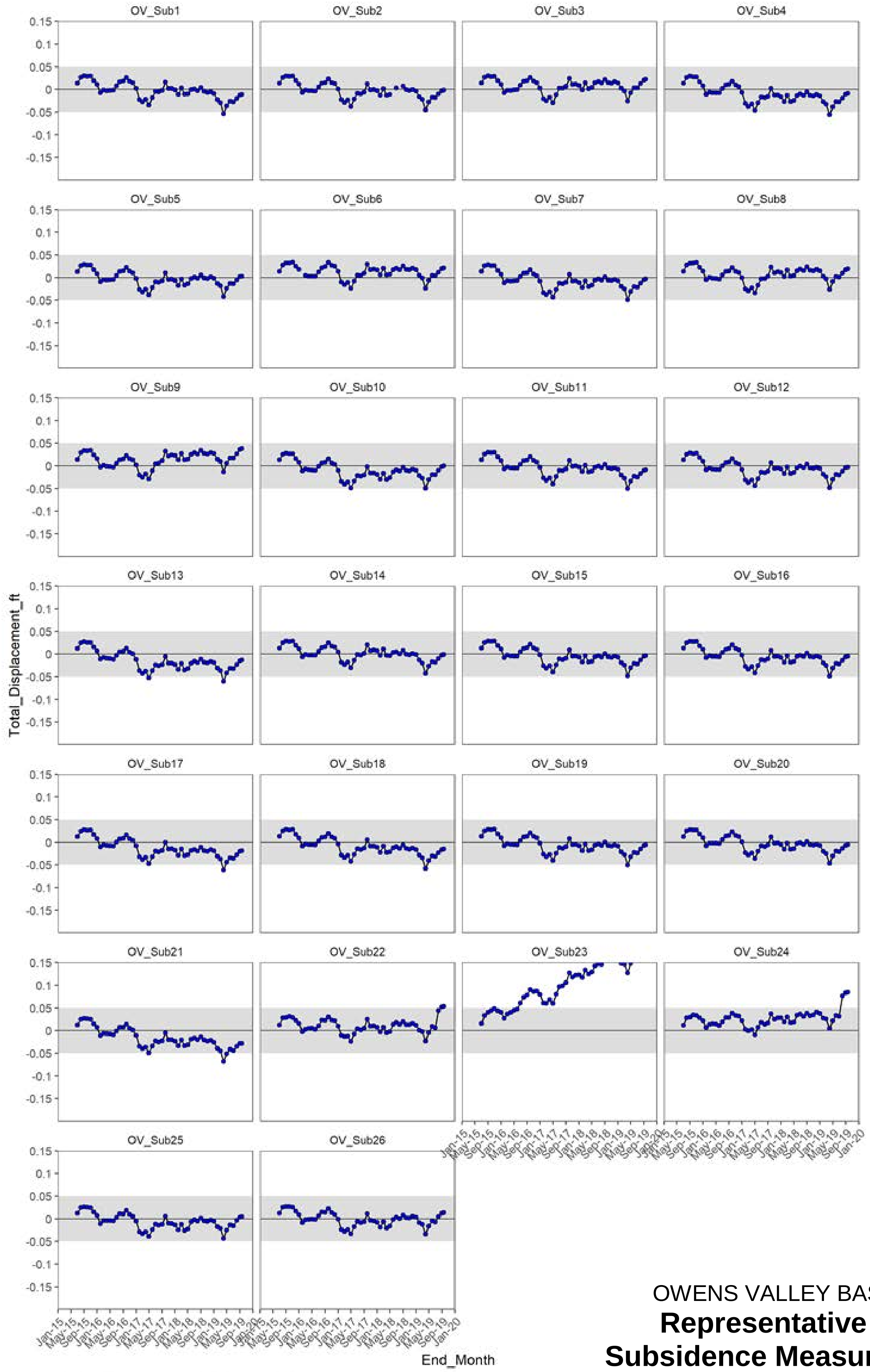
Figure 4-3



OWENS VALLEY BASIN GSP

Representative InSAR Subsidence Monitoring Points



OWENS VALLEY BASIN GSP
Representative InSAR Subsidence Measurement Points

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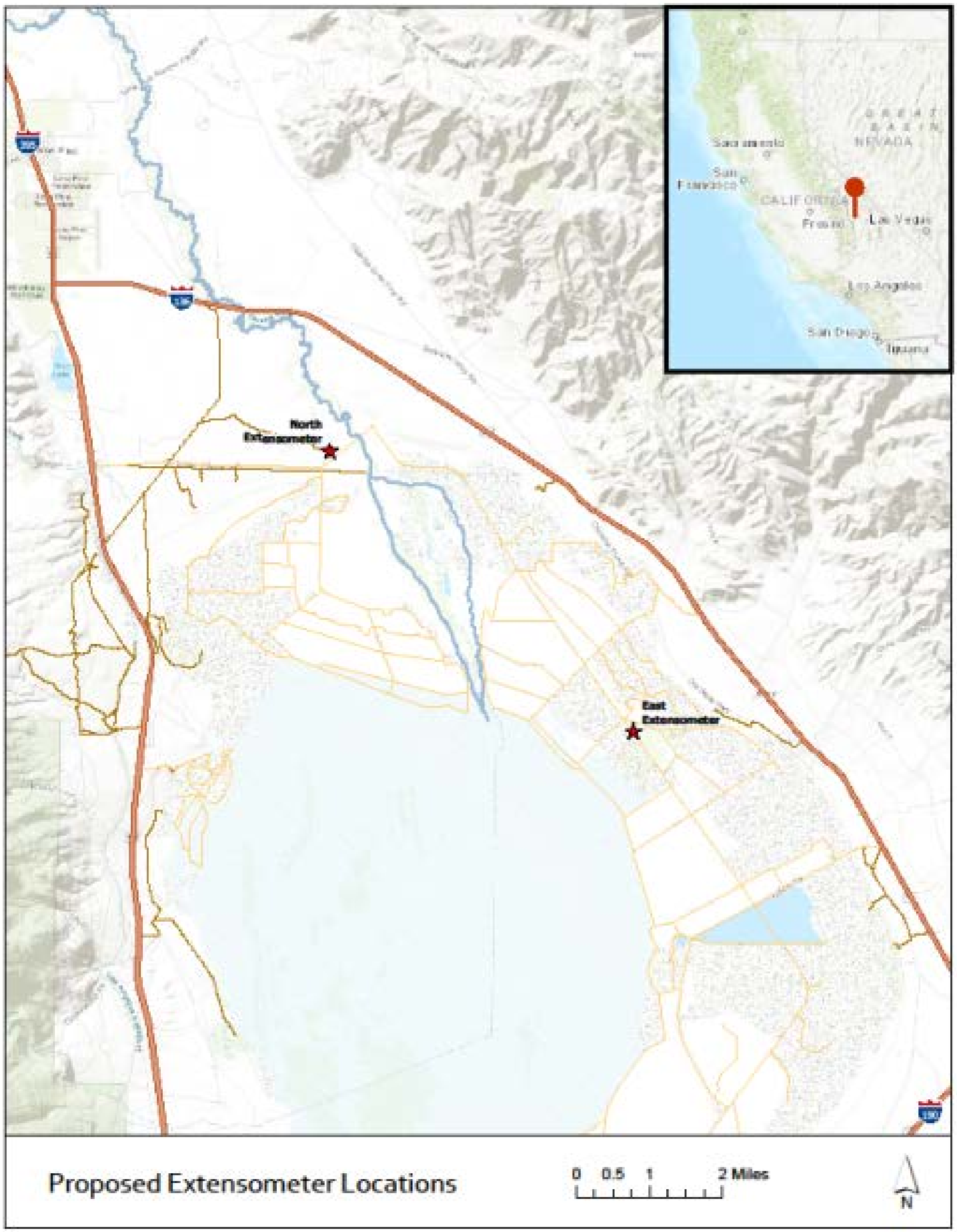
Figure 5-2



OWENS VALLEY BASIN GSP

LADWP Proposed Extensometer Installation Locations near Owens Lake

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Figure 6-1