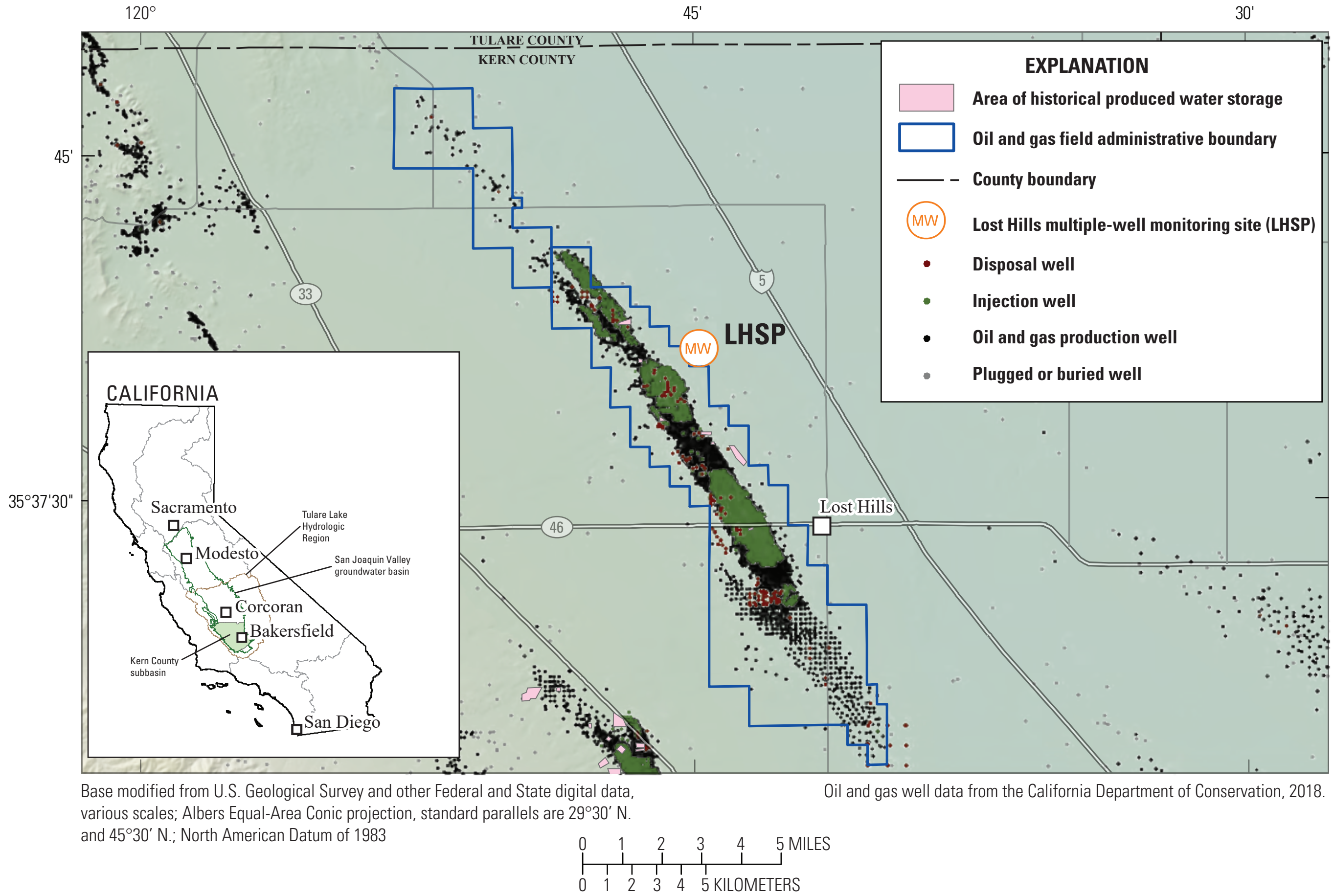
Prepared in cooperation with California State Water Resources Control Board

Multiple-Well Monitoring Site Adjacent to the Lost Hills Oil Field, Kern County, California

The U.S. Geological Survey (USGS), in cooperation with the California State Water Resources Control Board, is evaluating several questions about oil and gas development and groundwater resources in California, including (1) the location of groundwater resources; (2) the proximity of oil and gas operations and groundwater and the geologic materials between them; (3) evidence for or against fluids from oil and gas sources in groundwater; and (4) the pathways or processes responsible when fluids from oil and gas sources are present in groundwater (U.S. Geological Survey, 2019). As part of this evaluation, the USGS installed a multiple-well monitoring site in the southern San Joaquin Valley near Lost Hills, California, adjacent to the Lost Hills oil field (fig. 1). Data collected at the Lost Hills multiple-well monitoring site (LHSP) provide information about the geology, hydrology, geophysics, and geochemistry of the aquifer system, thus enhancing understanding of relations between adjacent groundwater and the Lost Hills oil field in an area where there is little groundwater data. This report presents construction information for the LHSP and initial geohydrologic data collected from the site.

Figure 1. Location of Lost Hills multiple-well monitoring well site (LHSP) and selected other wells in relation to the Lost Hills oil field, Kern County, California.



Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Oil and gas well data from the California Department of Conservation, 2018.

Study Area

The LHSP is in the Kern County subbasin of the San Joaquin Valley groundwater basin situated on the southern end of the Tulare Lake Hydrologic Region (California Department of Water Resources, 2016; fig. 1). The LHSP is approximately 1,400 feet (ft) east and downgradient from the Lost Hills oil and gas field administrative boundary.

Primary water-bearing units that comprise the major aquifers on the west side of the Tulare Lake region include alluvial and river sediments of Holocene age, older alluvium and terrace deposits of Pleistocene age, and Pliocene-Pleistocene-age Tulare Formation (Woodring, 1940; California Department of Water Resources, 2015).

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Most groundwater studies of the Central Valley define hydrogeologic units—aquifers and confining layers, rather than stratigraphic units (Faunt, 2009). At the LHSP, the stratigraphic units are defined; therefore, the aquifer system is discussed as the alluvial and Tulare aquifer systems even though they function regionally as a single water-yielding unit. Numerous lenses of fine-grained sediments are distributed throughout the San Joaquin Valley; these generally constitute more than 50 percent of the total thickness of the valley fill (Faunt, 2009). Faunt (2009) also noted that sediments in the western part of the San Joaquin Valley are generally finer-grained than sediments located to the east.

The primary confining unit in the aquifer system of the Tulare Lake Hydrologic Region is the Corcoran Clay (Frink and Kues, 1954) and its equivalent, the E-clay of Croft (1972). For the purposes of this brief discussion, the Corcoran Clay and the Corcoran Clay equivalent are simply referred to as the Corcoran Clay. The Corcoran Clay underlies approximately the western two thirds of the San Joaquin Valley extending from the southern edge of the valley, near Kern Lake (not shown), to north of Modesto (Faunt, 2009). The Corcoran Clay is thicker in an area between Lost Hills and Corcoran, located about 35 miles (mi) to the north, and may be as thick as 200 ft approximately 14 mi north of Lost Hills (Faunt, 2009). The Corcoran Clay is between 272 and 338 feet below land surface (ft bls) at the LHSP. Locally, Faunt (2009) and Gillespie and others (2019b) show the western edge of the clay is generally coincident with the eastern edge of the Lost Hills oil and gas field.

The LHSP location was selected to provide better information regarding vertical and lateral changes in groundwater gradients and water quality of the alluvial and Tulare aquifer system. The site is located east of the Lost Hills field and downgradient from the intensively developed oil field where the potential presence of oil-field fluids in overlying and adjacent groundwater zones exist either from naturally existing oil and gas shows in aquifers in proximity to oil fields or resulting from a range of historical and current oil and gas development activities. These activities include surface spills, leakage of produced water from disposal ponds, injection of fluids into the subsurface for enhanced recovery and produced-water disposal, and potential introduction of preferential pathways through leaky or improperly abandoned oil and gas wells or test holes (Davis and others, 2018a; Gillespie and others, 2019b).

The land surface and confining clay layers slope downward gradually from the Lost Hills oil field toward the LHSP borehole (Gillespie and others, 2019b). The LHSP is approximately 4,500 ft from the nearest active oil well, 4,500 ft from the nearest active steam flood well (injection of steam for enhanced recovery of oil), 6,000 ft from the nearest produced water disposal well, and 7,000 ft from the nearest water flood well (injection of produced water for enhanced recovery of oil). There is a high concentration of oil-production activities near the LHSP. Activities within 2 mi to the south and west of the LHSP include 22 water-disposal wells, 1,020 steam-flood wells, and 22 water-flood wells that are active, inactive, or new; 1,480 oil- or gas-production wells that are active, inactive, or new; 832 wells that are plugged or buried; and 3 areas where produced water-storage ponds have been or are currently located (California Department of Conservation, 2018).

Drilling and Well Installation

The LHSP pilot borehole, with a diameter ranging from 8 $^{1}/_{2}$ to 7 $^{5}/_{8}$ inches, was drilled to a depth of 1,880 ft bls during March 2018 using direct mud-rotary drilling techniques. Drill cuttings were collected throughout the drilling process and analyzed (along with notes from the on-site geologist) to summarize the lithology (fig. 2) following the procedures described by Everett and others (2013). To assist in the identification of lithologic and stratigraphic units, geophysical logging of the borehole was done before well construction using techniques described by Keys and MacCary, 1971; Shuter and Teasdale, 1989; Keys, 1990; and Kenyon and others, 1995. Geophysical logs completed at the site include caliper, natural gamma, resistivity (16- and 64-inch), spontaneous potential (SP), electromagnetic induction (conductivity), full wave sonic (delta-T), and Nuclear Magnetic Resonance (NMR) porosity (fig. 2). Logging in the small-diameter pilot hole was advantageous because it allowed for higher-quality logs to be collected than in the larger diameter holes. Well-screen and filter-pack intervals were selected based on the geophysical and lithologic data. The pilot hole was then reamed to increase the borehole diameter to allow for the construction of the five-well monitoring site. The deepest well (LHSP #1) was constructed with 2.5-inch-diameter polyvinyl chloride (PVC) casing to allow for future geophysical logging, and the shallower four wells were constructed with 2-inch-diameter PVC casing. The wells were installed with screened intervals from 1,780 to 1,800 (LHSP #1); 1,110 to 1,130 (LHSP #2); 700 to 720 (LHSP #3); 490 to 510 (LHSP #4); and 210 to 230 (LHSP #5) ft bls (fig. 2; table 1). A filter pack of #3 sand was installed around each screen, and a low-permeability bentonite grout was placed in the depth intervals between the filter packs to isolate each of the wells.

After construction was completed, the wells were developed by using airlifting and a surging technique with compressed air to remove drilling fluid and develop the filter pack surrounding each monitoring well. The field parameters that were recorded during the process include specific conductance, pH, water temperature, apparent color, and turbidity. Well development continued until no discernible drilling mud was present and field parameters were stabilized. The average flow rate and development time was used to estimate the total discharge and total purge volumes of the casing and sand pack (table 2). After well development, the turbidity of all wells, except LHSP #1, was below 10 nephelometric turbidity units (NTU; table 2). The higher turbidity in LHSP #1, 105 NTU, is assumed to be a result of the formation because the appearance of the water resembled the color of the clays and silts of the formation/cuttings samples collected during drilling.

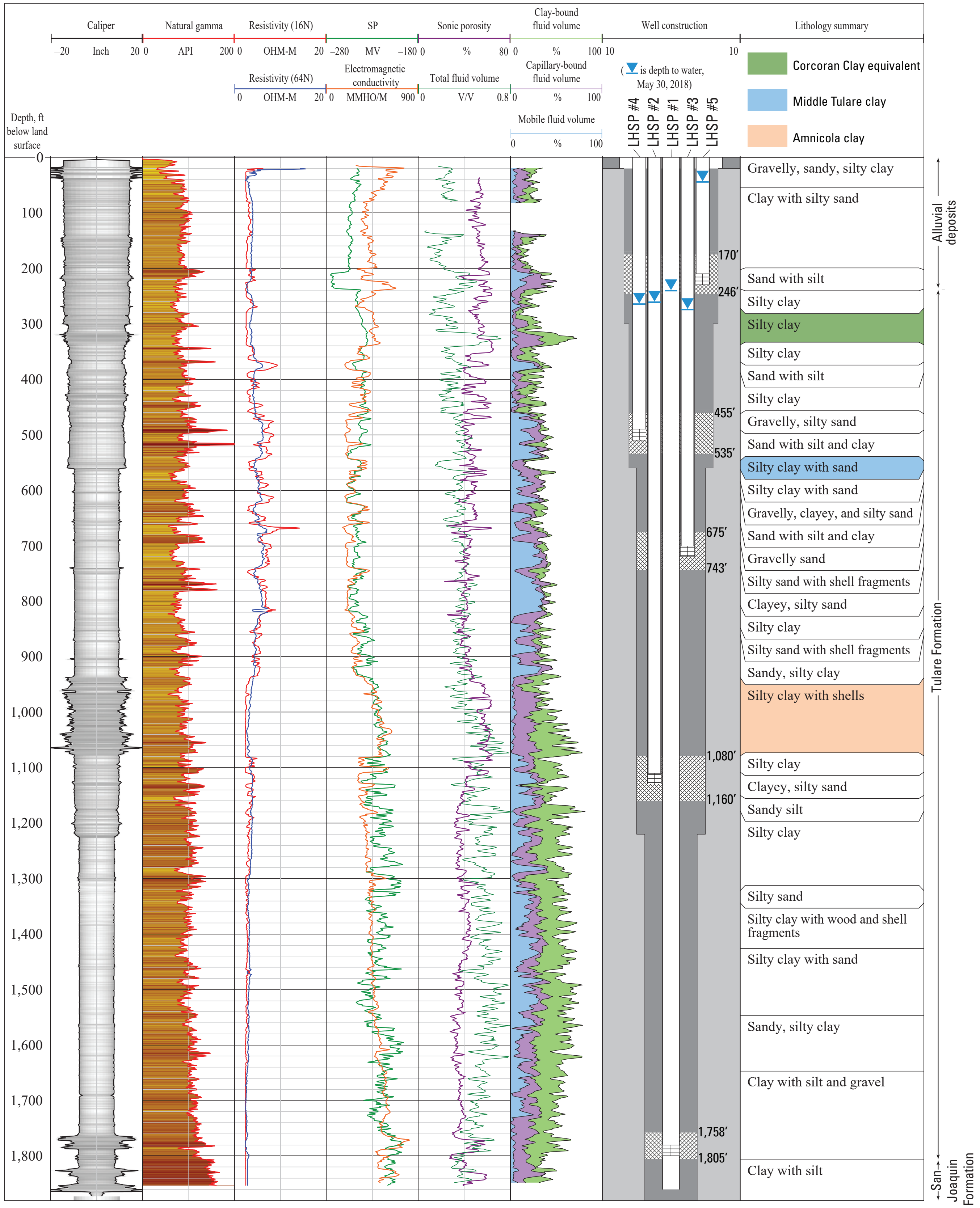

Figure 2. Well construction, summary lithology, and geophysical log data from Lost Hills multiple-well monitoring site (LHSP), Kern County, California. (**Abbreviations**: API, American Petroleum Institute units; RES, resistivity; SP, spontaneous potential; 16N, 16-inch normal; NMR, Nuclear Magnetic Resonance; OHM-M, ohm-meter; 64N, 64-inch normal; MV, millivolt; MMHO/M, millimho per meter; %, percent; V/V, volume per volume).

Table 1. Identification and construction information from Lost Hills multiple-well monitoring site (LHSP), Kern County, California.

[See figure 1 for well locations. Wells ordered from shallowest to deepest. The fifteen-digit U.S. Geological Survey (USGS) site identification number is used to uniquely identify the well. The common name is used throughout the report for quick reference. Land-surface datum (LSD) is a datum plane that is approximately at land surface at each well. The altitude of the LSD is described in feet above the North American Vertical Datum of 1988 (NAVD 88). **Abbreviations**: NWISWeb, National Water Information System Web site; ft, feet; ft bls, feet below land surface]

Common well name	USGS site identification number (hyperlinked to NWISWeb)	Altitude of LSD (ft above NAVD88)	Well diameter (inside, inches)	Depth to bottom of well (ft bls)	Depth to top of perforations (ft bls)	Depth to bottom of perforations (ft bls)
LHSP #5	354048119445005	272.55	1.94	230	210	230
LHSP #4	354048119445004	272.55	1.94	510	490	510
LHSP #3	354048119445003	272.55	1.94	720	700	720
LHSP #2	354048119445002	272.55	1.94	1,130	1,110	1,130
LHSP #1	354048119445001	272.55	2.32	1,860	1,780	1,800

Table 2. Well development and water-level data from Lost Hills multiple-well monitoring site (LHSP), Kern County, California.

[Wells ordered from shallowest to deepest. **Abbreviations**: ft bls, feet below land surface; gal/min, gallons per minute; gal, gallon; v/v, volume per volume; NTU, nephelometric turbidity units]

Common well name	Pre-development depth to water (ft bls)	Post development depth to water (ft bls) (5/30/18)	Average flow (gal/min)	Hours of development	Estimated total discharge (gal)	Purge per casing volume (v/v)	Purge per sand pack volume (v/v)	Post development turbidity (NTU)
LHSP #5	43.26	44.15	6.3	28	9,200	307	34	5.4
LHSP #4	264.41	264.83	5.0	6	1,100	29	5.6	2.2
LHSP #3	277.08	276.82	6.5	14	6,900	97	49	6.8
LHSP #2	261.86	261.41	7.1	30	11,200	81	58	2.7
LHSP #1	222.80	219.73	1.3	208	12,600	32	65	105

Geology

The lithology at the site consists of unconsolidated terrestrial deposits of gravels, sands, silts, and clays (fig. 2) in the alluvial deposits and the Tulare Formation, and marine silts and clays of the underlying San Joaquin Formation. The lithology at this location is primarily fine grained and is consistent with observations by Page (1983) that the Tulare Formation along the western edge of the southern San Joaquin Valley is fine grained, particularly at depth. The contact between the alluvial deposits and the Tulare Formation is thought to be at 237 ft bls based on changes in color of the sediment from light yellowish brown to olive gray and an abrupt change in the SP log; however, as noted by Wood and Davis (1959), it is difficult to distinguish the alluvial deposits from the upper Tulare in this region. The depths to the top and bottom contacts of the several prominent clay layers underlying the LHSP are more apparent based on characteristic shifts in borehole geophysical logs observed across the area (Gillespie and others, 2019b) and are identified as (all depths ft bls) Corcoran Clay equivalent, 272–338 ft; middle Tulare clay, 547–562 ft; and Amnicola clay, 938–1,079 ft. The base of the Tulare Formation is estimated at 1,807 ft bls based on borehole log interpretation (Gillespie and others, 2019a).

Shell and wood fragments were observed at several depths (fig. 2). Shell fragments observed between 693 and 860 ft bls were too small to identify by using photographs of type shells but are thought to be *Anodonta*. Shells observed between 938 and 1,079 ft bls were identified as *Amnicola* based on descriptions of Woodring and others (1940). Shell fragments observed between 1,344 and 1,426 ft bls were not identified.

Hydrology

Aquifer Tests

The hydraulic conductivity of the aquifer material adjacent to the screened interval was estimated from pneumatic slug tests completed on each of the wells. Compressed nitrogen gas (N_2) was used to depress the water level in the well by using a pressure regulator and well-head apparatus following procedures similar to Leap (1984) and Greene and Shapiro (1995). Induced declines in water levels were hundreds of feet above the perforations so that no nitrogen gas entered the formation through the perforations. Multiple tests were generally completed in each well, and average values are shown in table 3. Aquifer properties analysis was completed using AQTESOLV software (Duffield, 2007) and the Kansas Geological Survey (KGS) Model package for overdamped slug tests in partially penetrating wells in a confined aquifer (Hyder and others, 1994).

Table 3. Summary results of slug tests from Lost Hills multiple-well monitoring site (LHSP), Kern County, California.

[Wells ordered from shallowest to deepest. **Abbreviations**: ft bls, feet below land surface; ft, feet; lbs/in^2, pounds per square inch; ft/day, feet per day; KGS, Kansas Geological Survey]

Common well name	Screened section (ft bls)	Static water level at start of test (ft bls)	Static water level at end of test (ft bls)	Change in static water level during test (ft)	Method of analysis	Pressures (lbs/in^2)	Number of tests included in average	Hydraulic conductivity (ft/day)
LHSP #5	210–230	44.15	44.16	–0.01	KGS Model	5, 10	3	4
LHSP #4	490–510	264.83	264.86	–0.03	KGS Model	5, 10	3	1
LHSP #3	700–720	276.82	276.86	–0.04	KGS Model	5, 10	3	6
LHSP #2	1,110–1,130	261.41	261.45	–0.04	KGS Model	5, 10	4	4
LHSP #1	1,780–1,800	219.73	219.74	–0.01	KGS Model	5	1	0.02

Hydraulic conductivity estimates ranged from 0.02 foot per day (ft/day; LHSP #1) to 6 ft/day (LHSP #3; table 3; Everett and others, 2019). The deepest well, LHSP #1, is completed in silty clay at the base of the Tulare Formation where a low hydraulic conductivity is expected. The values in overlying wells were in the range of values expected for sand with gravel, silt, and clay, although the value at LHPSP #4 of 1 ft/day was at the low end of typical values (Heath, 1983).

Water Levels

Water-level data collected included periodic discrete manual measurements and hourly data recorded by downhole pressure transducers. Methods described by Cunningham and Schalk (2011) were used to collect and quality-assure the water-level records. The data were analyzed to identify vertical water-level gradients, which indicate direction and variability of potential groundwater flow between aquifer layers and responses to factors such as recharge and local groundwater withdrawal.

The vertical water-level gradients at the site calculated from multiple discrete water-level measurements collected on May 30, 2018 (table 2), indicated that groundwater should flow downward from the top and upward from the bottom toward the middle of the Tulare aquifer system. The groundwater gradient was downward to a depth of approximately 600 ft with a maximum gradient of –0.788 foot per foot (ft/ft) between LHSP #5 and LHSP #4. Between 600 and 1,800 ft, the gradient was upward with a maximum of 0.062 ft/ft between LHSP #1 and LHSP #2 (fig. 3). The steep gradient between LHSP #5 and LHSP #4 indicates that the Corcoran Clay equivalent, which separates these two wells, is an effective aquitard separating overlying and underlying aquifer layers at this location. Before installation of the LHSP, there were no available data on vertical profiles of groundwater flow across the full thickness of the alluvial and Tulare aquifer system near the Lost Hills oil field.

Water-level changes that happened over time were used to help determine the degree of hydraulic interaction between aquifer layers that are restricted by confining clay layers. The change in water level for each well relative to May 31, 2018, at 3:00 p.m. Pacific daylight time (PDT) was calculated (fig. 4). During the period between May 31, 2018, and January 30, 2019, a water-level rise of 10 ft was observed in LHSP #1, the deepest well, and a slight rise of about 1.5 ft was observed in LHSP #5, the shallowest well. A slight decline of 1.5 ft was observed in LHSP #2 during the same period. Between May 31, 2018, and mid-November 2018, declines of approximately 7.5 and 11.0 ft were observed in LHSP #3 and LHSP #4. After December 1, 2018, water levels in both wells rose through the period of record. The decline and recovery observed in LHSP #3 and LHSP #4 is expected for aquifer layers affected by seasonal groundwater withdrawals, which could be regional or local. Water levels typically decline in the summer due to increased water use and groundwater withdrawal, and they recover in the winter in correlation with decreased withdrawal and increased recharge from precipitation. Larger summer declines and earlier recovery of water levels in LHSP #4 compared to LHSP #3 indicated that the layer in the

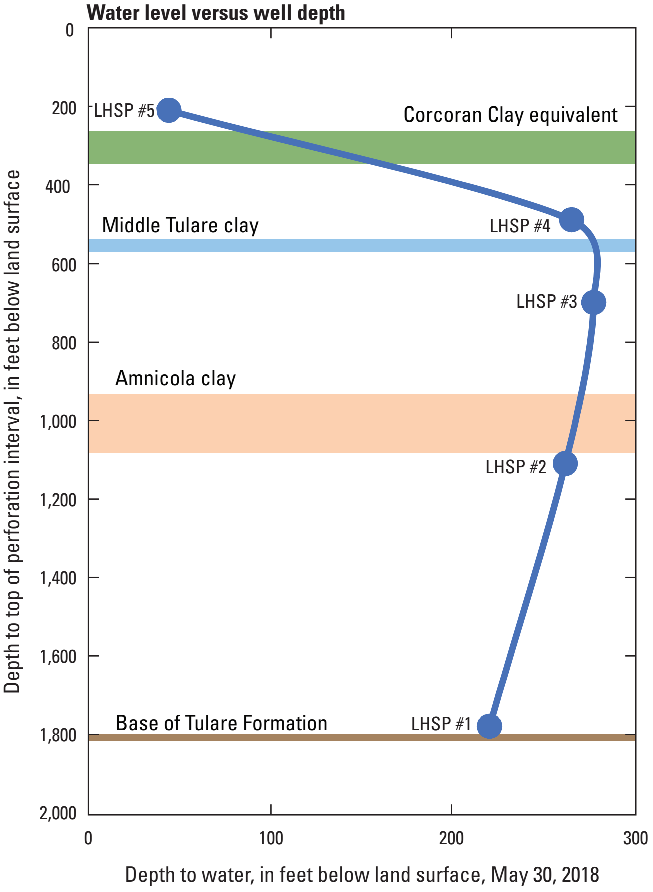

Figure 3. Vertical flow gradient at Lost Hills multiple-well monitoring well site (LHSP), Kern County, California.

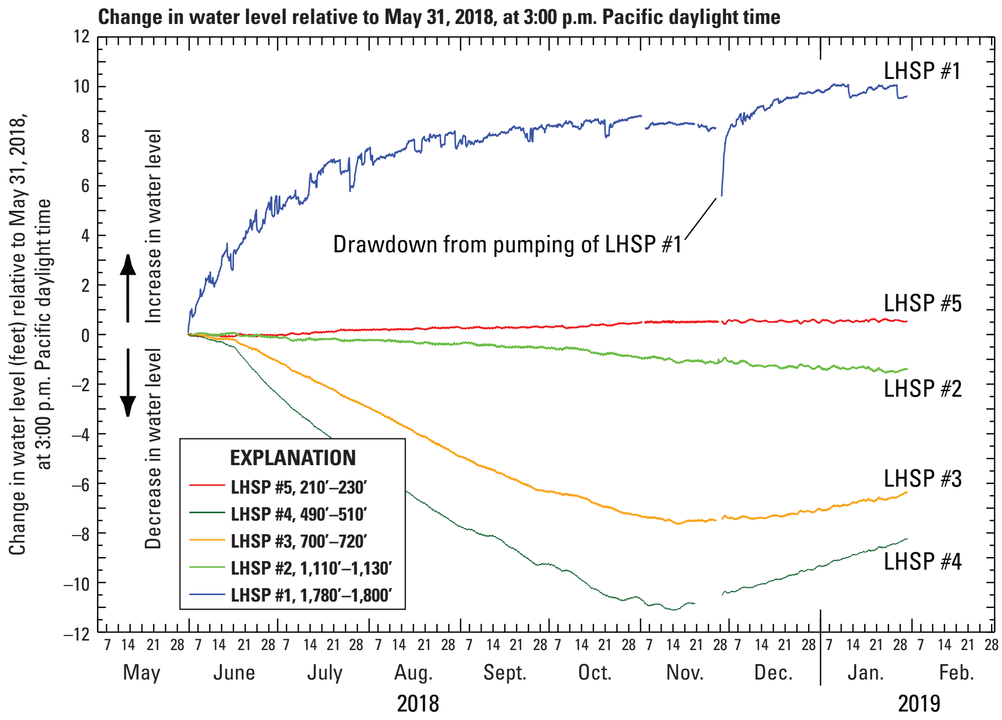

Figure 4. Change in water level relative to May 31, 2018, observed in wells at the Lost Hills multiple-well monitoring well site (LHSP), Kern County, California.

upper part of the Tulare aquifer system is more strongly affected by groundwater pumping than is the middle part. The smaller declines and lack of recovery of water levels through the period of record for well LHSP #2 indicated that the layer in the lower part of the Tulare aquifer system could have a delayed response to groundwater pumping in overlying layers. The monotonic increases in LHSP #5, above the Corcoran Clay equivalent, indicated that this shallow aquifer layer is not affected by groundwater pumping and could have limited hydraulic connection to aquifer layers below the Corcoran Clay equivalent. The pattern of increased water levels observed in well LHSP #1 and short-term fluctuations over time differed from the observations of wells LHSP #2–5, indicating that water levels at the bottom of the Tulare aquifer system are responding to different hydrologic stresses than the overlying layers. These stresses may include upgradient oil-field activities (injection, steam or water flooding, or pumping) to the southwest. The short-term fluctuations of ½ to 1 foot in water level could be indicative of upgradient pumping or injection activity or that the well is in a relatively low permeability layer that is highly responsive to changes in aquifer conditions. The approximate 3-foot drop and subsequent recovery in water level observed in LHSP #1 in late November 2018 was a result of drawdown and recovery associated with pumping of this well for water-quality sampling. Further analysis of water levels over time in comparison with oil-field activities, such as pumping and injection, are needed to help determine the hydrologic stresses affecting water levels at the base of the Tulare aquifer system.

Geochemistry

To delineate the chemical characteristics and source of the groundwater, samples were collected from each well in accordance with the protocols established by the USGS National Field Manual (U.S. Geological Survey, variously dated) and analyzed for major-ion chemistry; minor and trace elements; nutrients; radium isotopes; dissolved organic carbon and organic carbon characteristics; volatile organic compounds; low molecular weight organic acids; concentrations and isotopic values of light hydrocarbon gases; the stable isotopes of hydrogen (deuterium) and oxygen (oxygen-18) in water; boron, strontium, and lithium isotopes; carbon (carbon-13) in dissolved inorganic carbon and carbon-14 activities; noble and atmospheric gases; and groundwater-age tracers tritium and sulfur hexafluoride.

The collection and analysis procedures are further described by Dillon and others (2016), Davis and others (2018b), and Wright and others (2019). Sampling began in November 2018, 6 months after well development was completed, and was done in February 2019. Results for many analytes were not available at the time this report was prepared (April 2019). Consequently, results of water-quality samples are not discussed in this report other than the distribution of total dissolved solids (TDS).

Most of the aquifer system to the base of the Tulare Formation had TDS of less than 10,000 mg/L. The water samples from the LHSP wells had total dissolved solids concentrations ranging from 3,400 (LHSP #3) to 13,200 (LHSP #5) mg/L residue on evaporation at 180 degrees Celsius (table 4). Total dissolved solids were calculated at multiple depths from the geophysical logs using the algorithm developed by Bateman and Konen (1977; fig. 5), and the TDS data are available from Gillespie and others (2019a). Total dissolved solids measured from groundwater samples collected from the wells confirmed that the calculated estimates from the geophysical logs are reasonable. Total dissolved solids calculations at selected depths shown on figure 5 indicate that TDS values were higher near the surface and at depth, exceeding 10,000 mg/L in some zones above 410 ft and below 1,680 ft bls, and the lowest TDS values were between 3,000 and 5,000 mg/L in zones between 500 and 900 ft bls.

Accessing Data

The data presented in this report can be accessed using the USGS National Water Information System (NWIS) web page (NWISWeb) at https://waterdata.usgs.gov/nwis/. All discrete water-level measurements and the daily maximum, minimum, and median values for all time-series water-level data for sites presented in this report are available through the USGS NWISWeb. In digital copies of this report, the site identification numbers (table 1) presented in the tables are hyperlinked directly to the data on NWISWeb. Any updates applied to data presented in this report after publication will be available on NWISWeb.

Table 4. Water-quality indicators (field parameters) and total dissolved solids in samples collected from Lost Hills multiple-well monitoring site (LHSP), Kern County, California.

[Wells ordered from shallowest to deepest. The five-digit U.S. Geological Survey (USGS) parameter code below the constituent name is used to uniquely identify a specific constituent or property. *Threshold type*: SMCL-CA, California Department of Public Health secondary maximum contaminant level; SMCL-US, U.S. Environmental Protection Agency secondary maximum contaminant level. **Abbreviations**: mg/L, milligrams per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; na, not available; <, less than; >, greater than; *, value above threshold level]

Common well name	Dissolved oxygen, field (mg/L) (00300)	pH, field (standard units) (00400)	Water temperature, field (°C) (00010)
Threshold type	na	SMCL-US	na
Threshold level	na	<6.5–8.5>	na
LHSP #5	0.058	7.2	23.6
LHSP #4	0.071	7.3	25.7
LHSP #3	0.139	7.6	25.5
LHSP #2	0.070	7.1	25.8
LHSP #1	0.137	6.6	24.7

Common well name	Specific conductance, field (µS/cm at 25 °C) (00095)	Alkalinity, lab (mg/L as $CaCO_3$) (29801)	Total dissolved solids (mg/L) (70300)
Threshold type	SMCL-CA	na	SMCL-US
Threshold level	[1]900 (1,600)	na	500
LHSP #5	*17,200	158	*13,200
LHSP #4	*5,940	187	*4,050
LHSP #3	*5,380	474	*3,400
LHSP #2	*10,400	180	*6,180
LHSP #1	*22,800	535	*13,800

[1] The SMCL-CA for specific conductance has recommended lower and upper threshold values. The upper value is shown in parentheses.

Geophysical logs can be accessed through the USGS GeoLog Locator portal (https://webapps.usgs.gov/GeoLogLocator). Sites with available geophysical logs can be searched by the USGS site identification number (table 1) or can be located using the interactive map. Lithologic samples, shaker and sieve, collected during the drilling of the multiple-completion monitoring wells are archived at the USGS office in San Diego, California. Photos of the shaker and sieve samples (along with the full descriptions and notes recorded by the site hydrologist) can be accessed through the USGS GeoLog Locator. Formal requests for access to samples, field notes, or bench notes can be directed to the U.S. Geological Survey California Water Science Center.

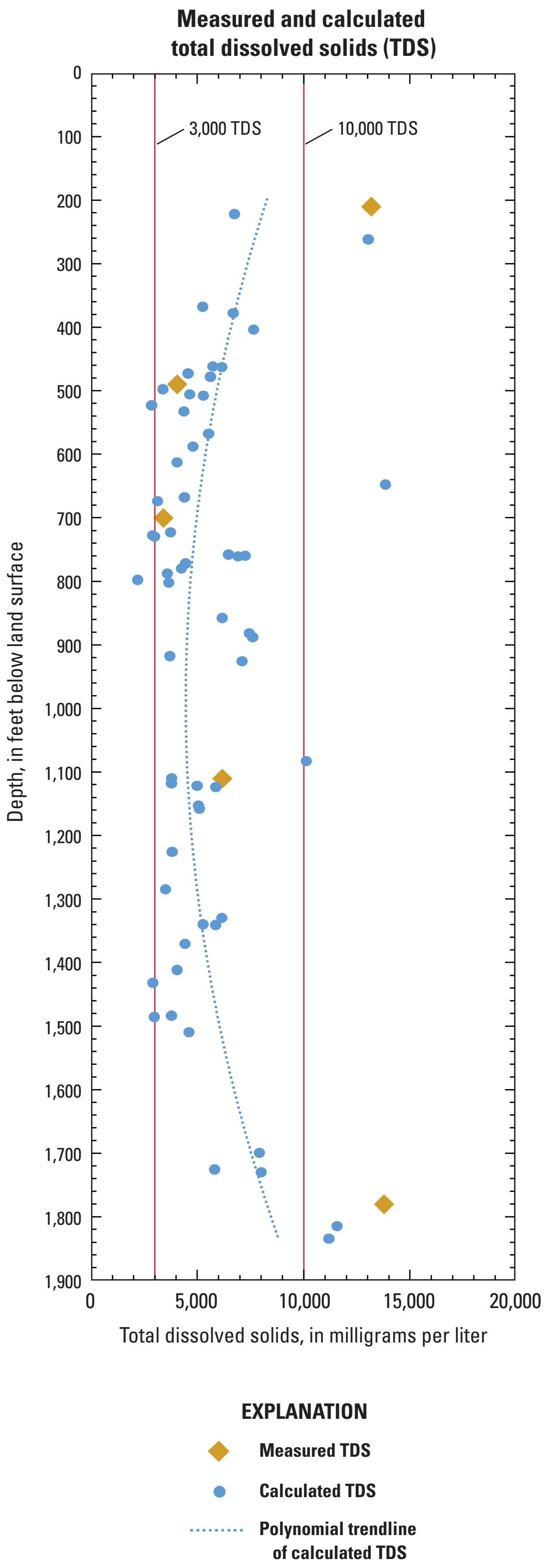

Figure 5. Measured and calculated total dissolved solids (TDS) for selected depths at Lost Hills multiple-well monitoring well site (LHSP), Kern County, California. Calculations based on the Bateman and Konen Equation (1977).

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References Cited

Bateman, R.M., and Konen, C.E., 1977, The log analyst and the programmable pocket calculator: Society of Petrophysicists and Well Log Analysts, v. 18, no. 5, p. 3–10.

California Department of Conservation, 2018, Oil and gas online data: Division of Oil, Gas, and Geothermal Resources, accessed February 20, 2018, at https://www.conservation.ca.gov/dog/Online_Data/Pages/Index.aspx.

California Department of Water Resources, 2015, California's groundwater update 2013—A compilation of enhanced content for California water plan: California Department of Water Resources, accessed November, 26, 2018, at https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Docs/Update2013/GroundwaterUpdate/Californias-Groundwater-Update-2013--Tulare-Lake-Regional-Report.pdf.

California Department of Water Resources, 2016, Bulletin 118 interim update 2016: California Department of Water Resources, accessed September 26, 2018, at https://water.ca.gov/Programs/Groundwater-Management/Bulletin-118.

Croft, M.G., 1972, Subsurface geology of the late Tertiary and Quaternary water-bearing deposits of the southern part of the San Joaquin Valley, California: U.S. Geological Survey Water Supply Paper 1999–H, 29 p., https://doi.org/10.3133/wsp1999H.

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods 1–A1, 151 p., https://doi.org/10.3133/tm1A1.

Davis, T.A., Landon, M.K., and Bennett, G.L., 2018a, Prioritization of oil and gas fields for regional groundwater monitoring based on a preliminary assessment of petroleum resource development and proximity to California's groundwater resources: U.S. Geological Survey Scientific Investigations Report 2018–5065, 115 p., https://doi.org/10.3133/sir20185065.

Davis, T.A., Teunis, J.A., McCarlson, A.J., Seitz, N.O., and Johnson, J.C., 2018b, Water chemistry data for samples collected at groundwater and surface-water sites near the Lost Hills and Belridge oil fields, November 2016–September 2017, Kern County, California: U.S. Geological Survey data release, https://doi.org/10.5066/F7NS0T5M.

Dillon, D.B., Davis, T.A., Landon, M.K., Land, M.T., Wright, M.T., and Kulongoski, J.T., 2016, Data from exploratory sampling of groundwater in selected oil and gas areas of coastal Los Angeles County and Kern and Kings Counties in southern San Joaquin Valley, 2014–15—California oil, gas, and groundwater project (ver. 1.1, October 2017): U.S. Geological Survey Open-File Report 2016–1181, 24 p., https://doi.org/10.3133/ofr20161181.

Duffield, G.M., 2007, AQTESOLV for Windows version 4.5 user's guide: Reston, Va., HydroSOLVE, Inc., 529 p., https://hwbdocuments.env.nm.gov/Los%20Alamos%20National%20Labs/General/37764.pdf.

Everett, R.R., Gibbs, D.R., Hanson, R.T., Sweetkind, D.S., Brandt, J.T., Falk, S.E., and Harich, C.R., 2013, Geology, water-quality, hydrology, and geomechanics of the Cuyama Valley groundwater basin, California, 2008–12: U.S. Geological Survey Scientific Investigations Report 2013–5108, 62 p., https://doi.org/10.3133/sir20135108.

Everett, R.R, Ledbetter, B.J., and Rodriguez, O., 2020, Aquifer test data for multiple-well monitoring site (LHSP), Kern County, California: U.S. Geological Survey data release, https://doi.org/10.5066/P9LGXIN8.

Faunt, C.C., ed., 2009, Groundwater availability of the Central Valley aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p., https://doi.org/10.3133/pp1766.

Frink, J.W., and Kues, H.A., 1954, Corcoran Clay—A Pleistocene lacustrine deposit in San Joaquin Valley, California: American Association of Petroleum Geologists, v. 38, no. 11, p. 2357–2371, https://doi.org/10.1306/5CEAE0A0-16BB-11D7-8645000102C1865D.

Gillespie, J.M., Davis, T.A., Ball, L.B., Herrera, P.J., Wolpe, Z., Medrano, V., Bobbitt, M., and Stephens, M.J., 2019a, Geological, geochemical, and geophysical data from the Lost Hills and Belridge oil fields: U.S. Geological Survey data release, https://doi.org/10.5066/P90QH6CI.

Gillespie, J.M., Davis, T.A., Stephens, M.J., Ball, L.B., and Landon, M.K., 2019b, Groundwater salinity and the effects of produced water disposal in the Lost Hills–Belridge oil fields, Kern County, California: Environmental Geoscience, v. 26, no. 3, p. 73–96, http://archives.datapages.com/data/deg/2019/EG032019/eg18009/eg18009.htm.

Greene, E.A., and Shapiro, A.M., 1995, Methods of conducting air-pressurized slug tests and computation of type curves for estimating transmissivity and storativity: U.S. Geological Survey Open-File Report 95–424, 43 p., https://doi.org/10.3133/ofr95424.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water Supply Paper 2220, 86 p., https://doi.org/10.3133/wsp2220.

Hyder, Z., Butler, J.J., Jr., McElwee, C.D., and Liu, W., 1994, Slug tests in partially penetrating wells: Water Resources Research, v. 30, no. 11, p. 2945–2957, https://doi.org/10.1029/94WR01670.

Kenyon, B., Kleinberg, R., Straley, C., Gubelin, G., and Morriss, C., 1995, Nuclear magnetic resonance imaging—Technology for the 21st Century: Oilfield Review, v. 7, no. 3, p. 19–33.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E2, 150 p., https://doi.org/10.3133/twri02E2.

Keys, W.S., and MacCary, L.M., 1971, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E1, 126 p., https://doi.org/10.3133/twri02E1.

Leap, D.I., 1984, A simple pneumatic device and technique for performing rising water level slug tests: Ground Water Monitoring and Remediation, v. 4, no. 4, p. 141–146, https://doi.org/10.1111/j.1745-6592.1984.tb00905.x.

Page, R.W., 1983, Geology of the Tulare Formation and other continental deposits, Kettleman City area, San Joaquin Valley, California, with a section on ground-water management considerations and use of texture maps: U.S. Geological Survey Water-Resources Investigations Report 83–4000, 28 p., https://doi.org/10.3133/wri834000.

Shuter, E., and Teasdale, W.E., 1989, Application of drilling, coring, and sampling techniques to test holes and wells: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. F1, 97 p., https://doi.org/10.3133/twri02F1.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9, 2 v. [variously paged], https://water.usgs.gov/owq/FieldManual/.

U.S. Geological Survey, 2019, California oil, gas, and groundwater (COGG) program: accessed July 8, 2019, at https://ca.water.usgs.gov/projects/oil-gas-groundwater/index.html.

Wood, P.R., and Davis, G.H., 1959, Ground-water conditions in the Avenal–McKittrick area, Kings and Kern Counties, California: U.S. Geological Survey Water-Supply Paper 1457, 141 p., https://doi.org/10.3133/wsp1457.

Woodring, W.P., Stewart, R., and Richards, R.W., 1940, Geology of the Kettleman Hills oil field, California—Stratigraphy, paleontology, and structure: U.S. Geological Survey Professional Paper 195, 170 p., https://doi.org/10.3133/pp195.

Wright, M.T., McMahon, P.B., Landon, M.K., and Kulongoski, J.T., 2019, Groundwater quality of a public supply aquifer in proximity to oil development, Fruitvale oil field, Bakersfield, California: Applied Geochemistry, v. 106, p. 82–95, https://doi.org/10.1016/j.apgeochem.2019.05.003.

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