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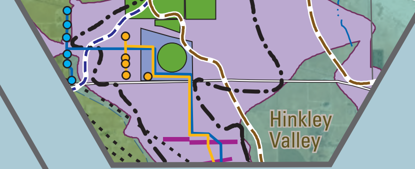
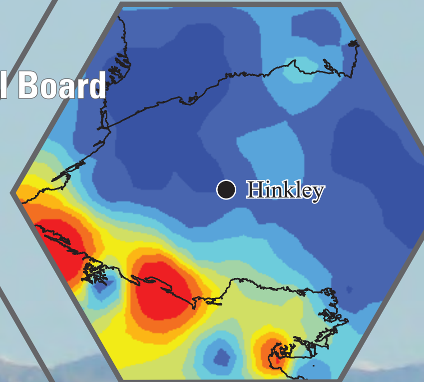
Prepared in cooperation with the Lahontan Regional Water Quality Control Board

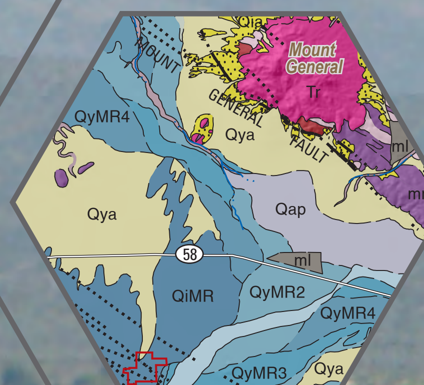
Introduction to Study Area Hydrogeology, Chromium Sources, Site History, and Purpose of Study

Chapter A of

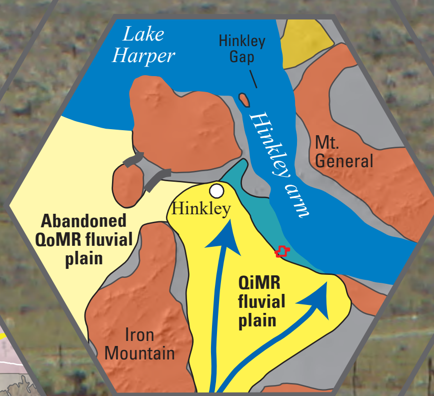
Natural and Anthropogenic (Human-Made) Hexavalent Chromium, Cr(VI), in Groundwater near a Mapped Plume, Hinkley, California







Professional Paper 1885-A



U.S. Department of the Interior
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Front cover

Map showing facilities installed by Pacific Gas and Electric Company.

Chromium concentrations in soil near Hinkley, California.

Background photograph: Pacific Gas and Electric Company (PG&E) compressor station, Hinkley, California, March 2009. Photograph by Steven Perry, ARCADIS, Inc., courtesy of PG&E.

Surficial geology of Hinkley and Water Valleys, western Mojave Desert, California

Simplified geologic history of consolidated deposits 500,000 years before present

Location of study area and surrounding features

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The authors thank the many people involved in the design and implementation of this study including the staff of the Lahontan RWQCB, the staff of PG&E and their consultants, and the staff of Project Navigator, Ltd. The authors also acknowledge and thank the many involved community members who allowed access to their properties for sample collection, and who collectively donated thousands of hours on behalf of the local community in support of this project and for resolution of other issues related to anthropogenic hexavalent chromium, Cr(VI), within the Hinkley area.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
Volume		
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
Mass		
microgram (µg)	0.00000003527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Below land surface (bls) is the datum used to describe depth.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L); concentrations in solid materials are given in milligrams per kilogram (mg/kg). Kiloannum is a thousand years before present.

Abbreviations

ATU	agricultural treatment unit
Cr(III)	trivalent chromium having an oxidation state of +3
Cr(VI)	hexavalent chromium having an oxidation state of +6
ECSZ	Eastern California Shear Zone
IRZ	in situ reactive zone
LTU	lant treatment unit
PG&E	Pacific Gas and Electric Company
RWQCB	Regional Water Quality Control Board
SCRIA	South Central Re-Injection Area
USGS	U.S. Geological Survey
UTL_{95}	upper 95-percent tolerance limit

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Abstract

Between 1952 and 1964, hexavalent chromium, Cr(VI), was released into groundwater from the Pacific Gas and Electric Company (PG&E) Hinkley compressor station in the Mojave Desert 80 miles (mi) northeast of Los Angeles, California. Remediation began in 1992, and in 2010, site cleanup was projected to require between 10 and 95 years and was expected to cost between $36 and $176 million. A 2007 PG&E study estimated the natural Cr(VI) background in groundwater in Hinkley Valley to be 3.1 micrograms per liter (µg/L). This concentration was used for interim regulatory purposes by the Lahontan Regional Water Quality Control Board (RWQCB). In the fourth quarter (October–December) 2015, the regulatory Cr(VI) plume extended about 3.0 mi downgradient from the release location within the Hinkley compressor station, while groundwater having Cr(VI) concentrations greater than 3.1 µg/L was present more than 8 mi downgradient. Although rocks and minerals in the area are naturally low in chromium, alluvium eroded from the San Gabriel Mountains and transported to Hinkley Valley by the Mojave River, and locally small exposures of mafic rock, including hornblende diorite and basalt, may contribute Cr(VI) to groundwater. In response to limitations of the PG&E 2007 Cr(VI) background study's methodology, uncertainty in the natural Cr(VI) background concentration, and an increase in the mapped extent of groundwater having Cr(VI) concentrations greater than the interim regulatory background of 3.1 µg/L, the Lahontan RWQCB concluded that the 2007 PG&E background Cr(VI) study should be updated. The purpose of the updated study is to estimate background Cr(VI) concentrations in groundwater within the upper aquifer upgradient, downgradient, near the margins, and within the footprint of the PG&E Cr(VI) plume in Hinkley, California. The scope of the study included eight tasks; results from those tasks are presented in the chapters within this professional paper.

A.1. Introduction

The Pacific Gas and Electric Company (PG&E) Hinkley compressor station (fig. A.1), in the Mojave Desert 80 miles (mi) northeast of Los Angeles, California (fig. A.2*A*), is used to compress natural gas as it is transported through a pipeline from Texas to California. Between 1952 and 1964, cooling water used at the Hinkley compressor station was treated with a compound containing hexavalent chromium, Cr(VI), to prevent corrosion of machinery within the compressor station. Cooling-tower water was discharged to unlined ponds, releasing Cr(VI) into groundwater in the underlying unconsolidated aquifer (Lahontan Regional Water Quality Control Board, 2013). Since 1964, cooling-water management practices have been used that do not release Cr(VI) into groundwater.

Figure A.1. Pacific Gas and Electric Company (PG&E) compressor station, Hinkley, California, March 2009. (Photograph by Steven Perry, ARCADIS, Inc., courtesy of PG&E, used with permission.)

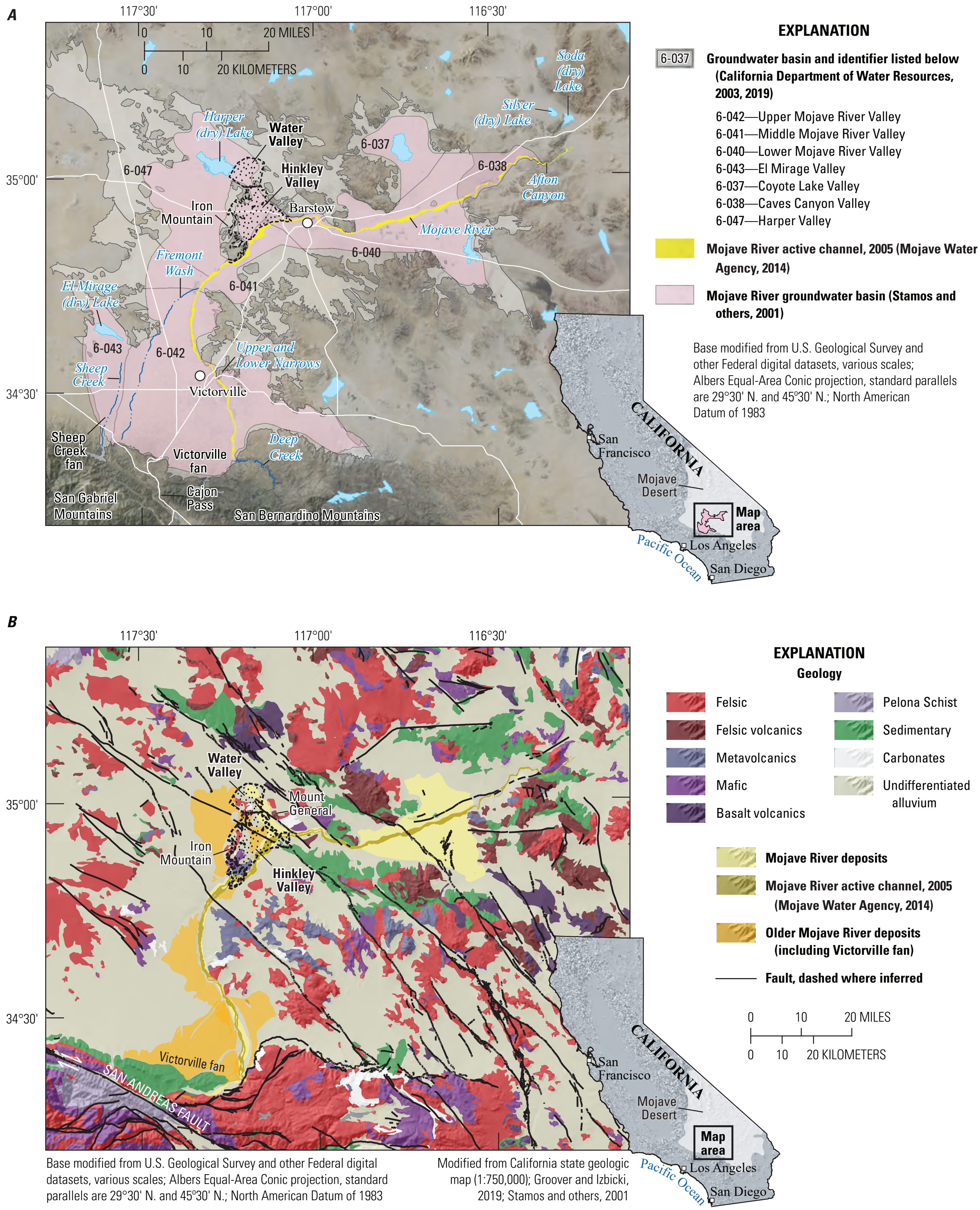


Figure A.2. *A,* Location of study area and *B,* generalized surficial geology within the western Mojave Desert, California.

In 2007, a PG&E study of the background concentration of Cr(VI) in groundwater estimated the average Cr(VI) concentration in the Hinkley area to be 1.2 micrograms per liter (µg/L), with a 95-percent upper-tolerance limit (UTL_{95}) of 3.1 µg/L (CH2M Hill, 2007). The 3.1 µg/L UTL_{95} was adopted by the Lahontan Regional Water Quality Control Board (RWQCB) as the maximum background concentration used to map the Cr(VI) plume extent for regulatory purposes (Lahontan Regional Water Quality Control Board, 2008). In response to limitations of the PG&E study's methodology (Lahontan Regional Water Quality Control Board, 2011), and to an increase in the mapped extent of groundwater having Cr(VI) concentrations greater than 3.1 µg/L between 2008 and 2012, the Lahontan RWQCB (Lahontan Regional Water Quality Control Board, 2012a) concluded that the 2007 PG&E background Cr(VI) concentration study be updated. The U.S. Geological Survey (USGS) was requested by the Lahontan RWQCB to complete an updated background study of Cr(VI) concentrations in Hinkley and Water Valleys.

Maps of groundwater levels and Cr(VI) concentrations in groundwater prepared for regulatory purposes beginning in August 2006 are available at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/archive.html (accessed February 21, 2018). Predevelopment and 2015 water-level maps are provided in chapter H of this professional paper (figs. H.7, H.8). Regulatory orders, studies, and other information pertaining to the PG&E Hinkley compressor station Cr(VI) cleanup are available at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/ (accessed March 6, 2018).

The purpose of this chapter is to provide background information on the regional and local hydrogeology, the regional occurrence of chromium, and the history of Cr(VI) releases and cleanup at the PG&E Hinkley compressor station. This chapter concludes with an outline of the purpose and scope of the multichapter U.S. Geological Survey (USGS) background Cr(VI) concentration professional paper.

A.2. Hydrogeology

The study area is within the Mojave River drainage in the western Mojave Desert, southern California (fig. A.2*A*). Regional changes in the hydrogeology of the Mojave River system over the past several million years have enabled deposition of material eroded from the San Bernardino and San Gabriel Mountains to be transported more than 40 mi into the desert by the Mojave River to Hinkley and Water Valleys. The distribution of these materials influences the natural occurrence of Cr(VI) in groundwater within Hinkley and Water Valleys.

A.2.1. Regional Hydrogeologic Setting

The Mojave River drainage is 2,120 square miles (mi^2). Altitudes within the Mojave River drainage range from 1,500 to 8,500 feet (ft). Precipitation ranges from slightly more than 4 inches per year (in/yr; 110 millimeters per year, mm/yr), near Barstow in the central part of the study area, to almost 40 in/yr (1,000 mm/yr), in the higher altitudes of the San Bernardino and San Gabriel Mountains to the southwest (fig. A.2*A*; Stamos and others, 2001; Flint and Flint, 2007). Most precipitation falls during the winter months, and a winter snowpack commonly develops at the higher altitudes of the San Bernardino and San Gabriel Mountains.

The Mojave River drainage is within the Eastern California Shear Zone (ECSZ; Dokka and Travis, 1990). Folding and uplift within the ECSZ over the past 10 million years disrupted surface drainage patterns. By the late Pliocene (5.6 to 2.6 million years before present), ancestral river systems that formerly drained toward the Pacific Ocean were internally drained to topographically closed structural basins (Cox and others, 2003). With the shift to internal drainage and drier climatic conditions associated with uplift of the San Gabriel and San Bernardino Mountains, alluvial material eroded from those mountains advanced into the Mojave Desert. This shift in drainage created a distinctive stratigraphy of alluvium deposited by south-flowing streams sourced from the desert mountains, overlain by wetland and lacustrine deposits, and finally overlain by the braided stream deposits from the north-flowing ancestral Mojave River (Cox and others, 2003). Mojave River deposits are recognized by their arkosic composition (Cox and others, 2003) and distinctive rounded quartzite pebbles (Cyr and others, 2015).

The Mojave River drains a topographically closed basin that extends more than 120 mi from the San Bernardino and San Gabriel Mountains to its terminus at Silver (dry) Lake, north of Afton Canyon (fig. A.2*A*; Thompson, 1929). The river is a geologically recent feature, less than 3.3 million years old (Cox and others, 2003), that has its source in the San Bernardino Mountains near Cajon Pass. Cajon Pass is a low altitude gap between the San Bernardino and San Gabriel Mountains, created 3 to 5 million years ago by geologic movement along the San Andreas Fault (Meisling and Weldon, 1989; Cox and others, 2003). As a result of movement along the fault, the source area contributing alluvium to the Mojave River changed over recent geologic time—with mafic chromium-containing alluvium eroded from the San Gabriel Mountains within older Mojave River alluvium deposited more than 500,000 years ago (Cox and others, 2003) and felsic alluvium eroded from the San Bernardino Mountains within younger Mojave River alluvium (Groover and Izbicki, 2019).

Moist air from the Pacific Ocean can enter the Mojave Desert through Cajon Pass and precipitate without passing over the higher altitudes of the coastal mountains (Izbicki, 2004). Large winter flows greater than 5,000 cubic feet per second (ft^3/s), with some peak streamflows exceeding 60,000 ft^3/s, occur in the Mojave River on average every 5 to 7 years (fig. A.3). These large flows result from a combination of precipitation near the pass, rain-on-snow at higher altitudes within the mountains, and snowmelt (Lines, 1996; Stamos and others, 2001; Seymour, 2016) and can extend the entire length of the river from the mountain front to Afton Canyon and Silver (dry) Lake. With the exception of occasional large flows, the Mojave River is dry along most of its length, except where groundwater discharge maintains perennial streamflow. Flow in perennial reaches along the Mojave River, such as the Upper and Lower Narrows near Victorville and near Afton Canyon, has decreased in recent years, while flow along other formerly perennial reaches has ceased entirely, and wetland areas along the river have dried as a result of declining groundwater levels resulting from groundwater pumping (Lines, 1996; Stamos and others, 2001).

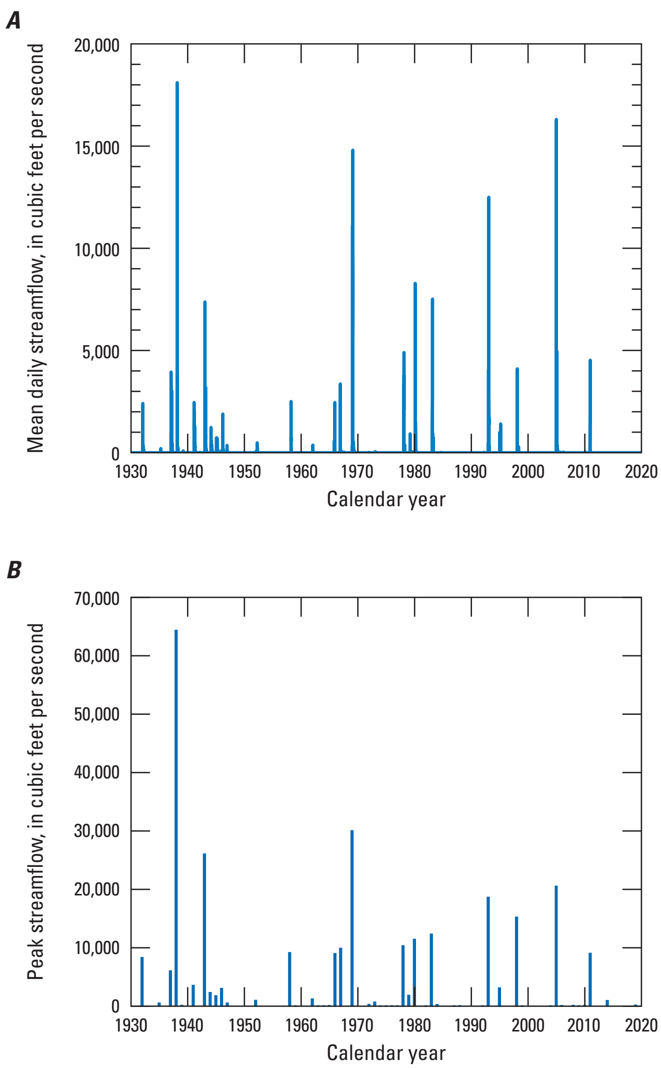


Figure A.3. *A,* Mean daily streamflow and *B,* annual peak streamflow in the Mojave River at Barstow, California (10262500), January 1, 1930, to December 31, 2018. Data are available in U.S. Geological Survey (2018).

With the exception of short reaches of the Mojave River where groundwater discharges at land surface and some streams in the higher altitudes of the San Bernardino and San Gabriel Mountains, there are no perennial streams in the Mojave River drainage, and groundwater is the only dependable source of water supply. California Department of Water Resources (2003, 2019) groundwater basins within the Mojave River drainage include the Upper, Middle, and Lower Mojave River Valley groundwater basins and the topographically closed El Mirage Valley, Coyote Lake Valley, and parts of the Harper Valley groundwater basins (fig. A.2*A*). The most productive aquifer within the Mojave River drainage is the floodplain aquifer along the length of the Mojave River (Stamos and others, 2001; California Department of Water Resources, 2003, 2019). The floodplain aquifer is commonly less than 0.5 to 1 mi wide and typically less than 200 ft thick (Stamos and others, 2001). The occasional large flows in the Mojave River account for almost all the groundwater recharge to the floodplain aquifer (Lines, 1996; Stamos and others, 2001; Izbicki, 2004; Izbicki and Michel, 2004; Seymour, 2016), with most groundwater in the floodplain aquifer recharged after the onset of atmospheric nuclear weapons testing beginning in 1952 (Izbicki and Michel, 2004).

The floodplain aquifer is surrounded and underlain by a regional aquifer composed of older Mojave River alluvium (3.3 million to 500,000 years old) and alluvium eroded from desert mountains. Groundwater recharge to the regional aquifer occurs primarily at the front of the San Bernardino and San Gabriel Mountains, with only small amounts of recharge from lower-altitude mountains within the area (Stamos and others, 2001; Izbicki, 2004). As a consequence, groundwater within the regional aquifer is much older than groundwater in the floodplain aquifer, and in many cases, groundwater in the regional aquifer was recharged under cooler and wetter climatic conditions many thousands of years before present (Izbicki and Michel, 2004).

Shallow lakes were present in the western Mojave Desert during the Pleistocene (2.5 million to 11,700 years before present; Enzel and others, 2003). Some playas, such as Harper (dry) Lake, are remnants of those lakes, and some areas may contain lacustrine (lake) deposits at depth. Lacustrine deposits associated with these lakes are commonly fine-grained, organic-rich, reducing environments.

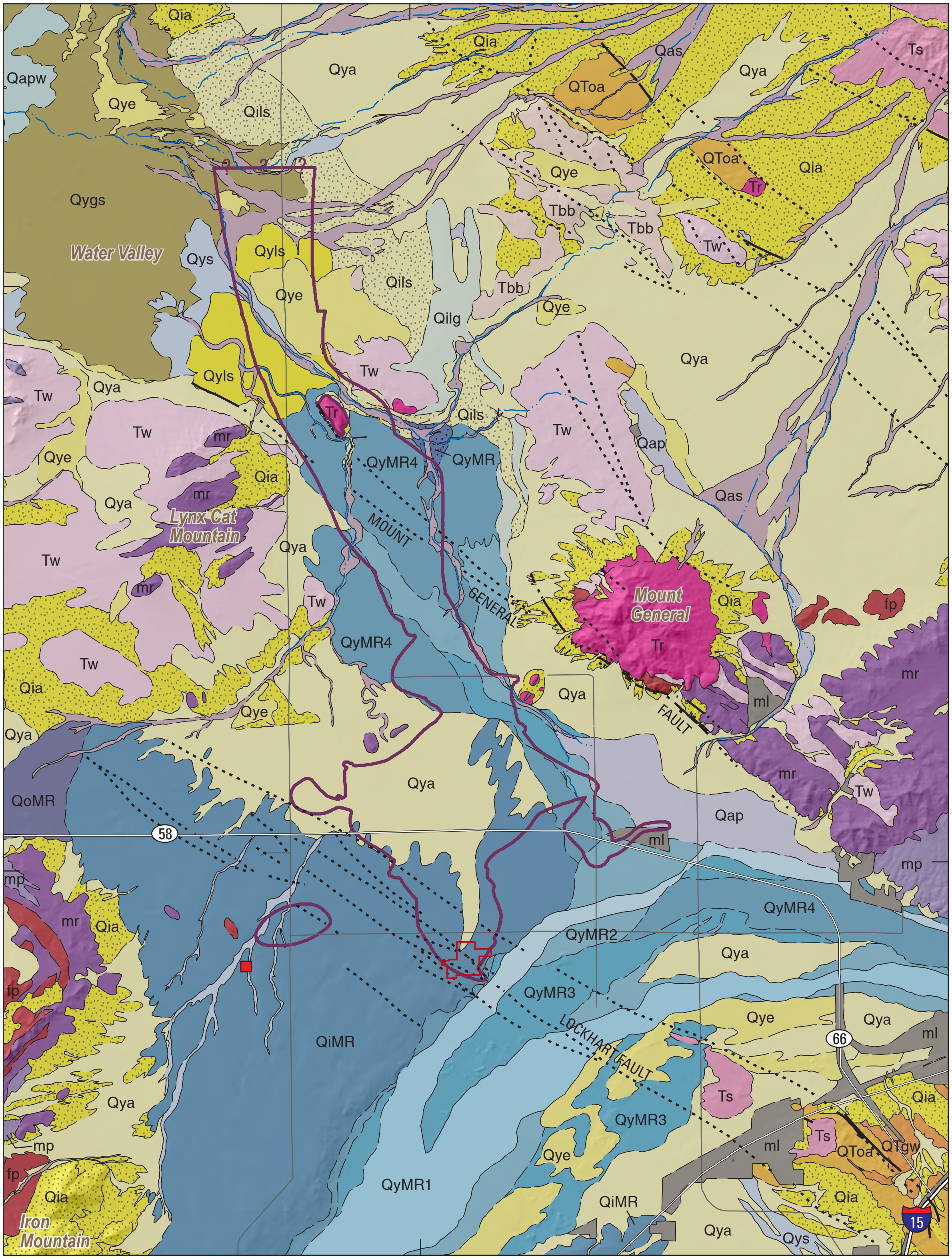
A.2.2. Local Hydrogeologic Setting

Hinkley Valley, within the Middle and Lower Mojave Valley and Harper Valley groundwater basins (California Department of Water Resources, 2003, 2019), is approximately 62 mi^2 and contains 36 mi^2 of unconsolidated deposits that were saturated during predevelopment (1930) conditions. Bedrock in Hinkley Valley consists of felsic plutonic (granite) and related intrusive plutons, sheets, and dikes (Dibblee, 1960a, b; Boettcher, 1990; Fletcher and others, 1995; Fletcher and others, 2002), with exposures of mafic plutonic (diorite and gabbro) rock near the south end of Iron Mountain and Mount General (fig. A.4). Older rocks predating these intrusive rocks include marble, quartzite, and metavolcanic rocks present as pendants, and wallrocks associated with plutons. These older rocks have been altered to varying degrees by metamorphism. Additionally, some rocks that crop out on Mount General have been altered by hydrothermal processes. Partly consolidated deposits consisting of early Miocene (5.3 to 23 million years before present) lacustrine, alluvial fan, rock-avalanche deposits, and locally derived Tertiary alluvium overlie bedrock. These Miocene continental deposits are interspersed with lavas ranging from dacite to rhyolite. Younger (Pliocene) basalt is exposed at land surface and interspersed with late Tertiary alluvium in the Water Valley area.

Unconsolidated deposits overlying bedrock occupy 36 mi^2 within Hinkley Valley. Within Hinkley Valley, and Water Valley to the north (fig. A.4), unconsolidated deposits include deposits sourced from the Mojave River (“Mojave-type” deposits including Mojave River stream and lake margin deposits), and lake, mudflat/playa, groundwater-discharge deposits, and locally derived alluvial material (table A.1; Miller and others, 2018, 2020). In the subsurface, geologic materials and depositional provenance were described as part of this study on the basis of physical, chemical, and paleontological examination of core material from more than 200 wells installed by PG&E as part of groundwater remediation (Miller and others, 2018; 2020). In most cases, geologic provenance was unambiguously assigned to Mojave-type deposits and other materials by physical examination of lithic grains within core material, including the degree of rounding of coarse sand grains. It was not always possible to uniquely identify older Mojave stream deposits from more recent Mojave stream deposits on the basis of physical examination of core material. Physical descriptions and provenance of selected core material were summarized by Groover and Izbicki (2018).

In the geologic framework model developed as part of this study (Miller and others, 2018), the ancestral Mojave River flowed west of Iron Mountain and reached Pleistocene Lake Harper about 750 to 630 kilo-annum (ka; one ka is 1,000 years before present) and entered Hinkley Valley about 600 to 475 ka (Cox and others, 2003) along two paths: (1) first through the gap between Lynx Cat and Iron Mountains and (2) later south of Iron Mountain in the southwest end of Hinkley Valley (Miller and others, 2018; 2020). Arrival of the ancestral Mojave River to the area created and maintained Lake Harper, which grew in size and flooded parts of Hinkley Valley—creating a shallow arm of water extending south of the PG&E compressor station (fig. A.5*A*). Deposition of fine-grained, lacustrine deposits within the shallow lake formed the “blue clay,” an important confining unit throughout much of the valley. Ash deposits within the blue clay, as thick as 7 ft, were identified on the basis of their chemical composition as Lava Creek B material (Miller and others, 2018, 2020) that originated from an eruption in Yellowstone about 630 ka (Matthews and others, 2015). As Mojave River deposits accumulated west of Iron Mountain, overflow of the river through the gap between Lynx Cat and Iron Mountains deposited an alluvial fan that grades from coarse-grained to finer-grained downslope (fig. A.5*A*). The fan increased in size with time and prograded across the valley toward the shallow Hinkley arm of Lake Harper. Groundwater discharge along the toe of the fan sustained wetlands where fine-textured, calcite-rich groundwater discharge deposits accumulated over weathered bedrock and older partly consolidated deposits.

With continued accumulation of Mojave River deposits west of Iron Mountain, overflow of the river into Hinkley Valley south of Iron Mountain built a fluvial wedge in the south part of Hinkley Valley (fig. A.5*B*). With time, fluvial and delta deposits prograded across the nearly flat valley toward Lake Harper, burying older deposits, the preexisting drainage system, and the older alluvial fan deposits (Miller and others, 2020). Eventually, the ancestral Mojave River eroded through fluvial deposits south of Iron Mountain to form a canyon along the course of the Mojave River. The fluvial plain in the southern portion of Hinkley Valley was abandoned. Where present at land surface, these deposits, as much as 100 ft above the active channel of the Mojave River, have a distinctive hummocky, “inverted stream channel” topography. Fine-grained overbank deposits across the nearly flat valley floor were deposited by the Mojave River around this time and compose part of another important confining unit within Hinkley Valley known as the “brown clay” (Miller and others, 2020). The brown clay is distributed areally and vertically throughout alluvial and lacustrine deposits in the valley, apparently migrating to the east and north over time, with deposition of similar materials continuing in flat-lying portions of the valley until the time of this study (2015–18). Not all brown clays within Hinkley Valley are sufficiently thick to be hydrologically important confining layers.



Base from U.S. Geological Survey and other Federal and State digital data, various scales; Lambert Conformal Conic projection, standard parallels are 34.0333° N. and 35.4667° N.; North American Datum of 1983

0 1 2 MILES
0 1 2 KILOMETERS

Surficial geology from Miller and others, 2020

Figure A.4. Surficial geology of Hinkley and Water Valleys, western Mojave Desert, California. Modified from Miller and others (2018).

EXPLANATION

Surficial Deposits

Made Land

ml — Made land (Recent)

Stream Deposits

Qas — Active stream channel deposits (Holocene)

Qys — Young stream deposits (Holocene)

Qya — Young alluvial fan deposits (Holocene to latest Pleistocene)

Qia — Intermediate alluvial fan deposits (late to middle Pleistocene)

QToa — Gravel (early Pleistocene to Pliocene)

Eolian Deposits

Qye — Young eolian sand deposits (Holocene)

Mojave River Deposits

QyMR — Young Mojave River deposits, undifferentiated (Holocene)

QyMR1 — Young Mojave River deposits, unit 1 (latest Holocene)

QyMR2 — Young Mojave River deposits, unit 2 (late Holocene)

QyMR3 — Young Mojave River deposits, unit 3 (middle Holocene)

QyMR4 — Young Mojave River deposits, unit 4 (early Holocene and latest Pleistocene)

QiMR — Intermediate Mojave River deposits (middle to late Pleistocene)

QoMR — Older Mojave River deposits (early Pleistocene)

Playa, Groundwater-Discharge, and Lacustrine Deposits

Qap — Active playa deposits (latest Holocene)

Qapw — Active playa-margin wetland deposits (latest Holocene)

Qygs — Young wetland deposits (late Holocene)

Qyls — Young lacustrine sand deposits (latest Pleistocene)

Qils — Intermediate lacustrine sand deposits (late Pleistocene)

Qilg — Intermediate lacustrine gravel deposits (late Pleistocene)

QTgw — Groundwater-discharge wetland deposits (early Pleistocene to Pliocene)

Rock Units

Pliocene volcanic rock

Tbb — Black Mountain Basalt (Pliocene)

Miocene sedimentary rock

Ts — Sandstone and siltstone (Miocene)

Bedrock

Tr — Rhyolite (Miocene)

Tw — Waterman Hills granite (Miocene)

mp — Mafic plutonic rocks (Mesozoic)

fp — Felsic plutonic rocks (Mesozoic)

mr — Metamorphic rocks (Neoproterozoic?, Paleozoic, and Mesozoic)

Maximum extent of 3.1 micrograms per liter hexavalent chromium, Cr(VI), October–December 2015 (Q4 2015); queried where approximate (ARCADIS, 2016a)

Pacific Gas and Electric Company Hinkley compressor station

Contact—location accurate; dashed where approximately located

Fault—location accurate; dotted where approximately located or concealed (Miller and others, 2018)

Western excavation site

Figure A.4.—Continued

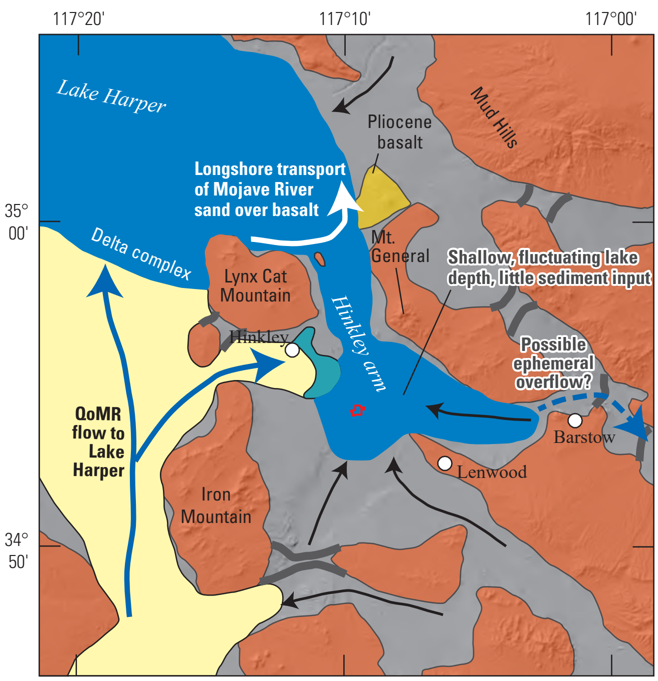
Table A.1. Classification of core material from Pacific Gas and Electric Company (PG&E) monitoring wells and criteria used to assign depositional provenance and depositional environment, Hinkley and Water Valleys, western Mojave Desert, California.

[Modified from Miller and others, 2018, 2020. **Abbreviations**: m, meter; $CaCO_3$, calcium carbonate]

Classification	Criteria
	Provenance
Mojave type	Arkose with quartzite lithic grains; rounded to well-rounded grains.
Local alluvial fan	Lithics similar to local bedrock; angular to subangular grains dominate.
Uncertain	Grain size is medium sand and finer; lithics and rounding not distinctive.
	Depositional environment
	Mojave type
Mojave River stream	Coarse stream channel deposits are poorly sorted, crudely bedded; lacks fossils. Color is orange to brown. Soils common in upper 2–6 m of section; less common 6–12 m; rare below.
Lake margin	Moderately to well-sorted sand and silt with sparse gravelly sand interbeds at most; thin bedded to laminated; commonly mica rich; grain size and color vary from bed to bed; sparse fossils indicate shallow lake environment. May represent fluvial delta, beach, and nearshore lake deposits, or playa-margin deposits. Color is white to gray, tan to pale tan, and rich brown.
	Non-Mojave type
Local alluvial fan	Poorly sorted, vaguely bedded gravel and sand of local provenance; commonly several soils within sequence; lacks fossils. Color is yellow-brown to red-brown. Sequences overlying bedrock are characterized by weathered bedrock materials interspersed with thin beds of sand; may indicate pediment deposits.
Lake (lacustrine)	Clay and silt to very fine sand, thinly bedded to laminated; commonly rippled; generally not calcareous; fossils indicate shallow lake environment. Color is gray, green, olive, tan, and white; commonly ranges to brown near base and top. Commonly diatomaceous. No evidence of dropstones.
Mudflat/playa	Fine sand to silt and clay; mostly poorly sorted with admixture of coarse and very coarse sand grains; sand grains floating in mud very common. Rare mudcracks and thin stream sheetflow beds taken to indicate playa environment. Calcareous nodules and zones of manganese-oxide stain are common; sparse fossils indicate shallow lake environment. Color is brown and orangish brown.
Groundwater discharge	Calcium-carbonate-rich sediment, typically with alluvial fan lithics and sand grains floating in a fine sand to silt composed of detrital grains and carbonate material. Very poorly sorted overall. Sand and pebble grains uniformly coated by $CaCO_3$. Color is pale gray or pale tan to white.

After eroding through fluvial deposits south of Iron Mountain, the ancestral Mojave River eventually flowed through Hinkley Valley past Barstow to create and maintain Lake Manix from about 500 to 24 ka (Reheis and others, 2012; fig. A.5*C*). During this interval, the ancestral Mojave River would occasionally change course and flow through Hinkley Valley toward Lake Harper. Garcia and others (2014) demonstrated that Hinkley and Water Valleys held multiple lakes fed by the Mojave River between approximately 40–45 ka and revised early estimates that the lakes were as young as 25 ka (Meek, 1999). During intervals when the ancestral Mojave River flowed north toward Lake Harper, coarse-grained Mojave stream material was deposited along a south to north axis through the valley toward Hinkley Gap (fig. A.5*C*). In general, these Mojave stream deposits are continuous in the north-south direction and lack soils or other evidence of extended episodic deposition. In addition to active stream-channel deposits, they include fine-grained material deposited along the margins of active channels in floodplains or oxbow lakes (Cox and others, 2003). Mojave stream deposits that are finer-grained, moderately well sorted, and thinly bedded were interpreted to represent low-energy stream depositional environments near deltas or lake margins and include well-sorted beach (or aeolian) deposits. Locally derived alluvial fan material eroded from Iron Mountain, Mount General, and Lynx Cat Mountain surrounds the Mojave-type deposits, and small amounts of these materials are occasionally mixed within the margins of the Mojave-type deposits.

A



Historical geology from Miller and others (2020)

750,000 to 630,000 years before present:

Older Mojave River deposits, QoMR (oriented east-west in Hinkley Valley) arrived in Hinkley Valley about 750,000 to 600,000 years before present. Deep lake persisted at least until 630,000 years before present based on presence of Lava Creek B ash.

EXPLANATION

Mojave River alluvium

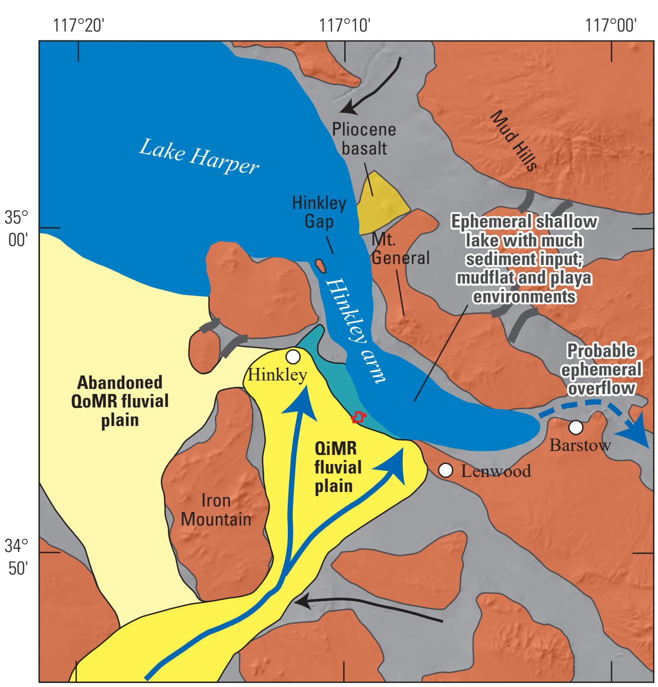
- QoMR—Older Mojave River deposits (early Pleistocene)
- **Lake**
- **Bedrock**
- **Pliocene basalt**
- **Locally derived alluvium**
- **Delta/wetland**—groundwater discharge deposits
- **Pacific Gas and Electric Company Hinkley compressor station**
- **Topographic divide**
- **Mojave River flow**
- **Local stream flow**

0 2 4 6 8 10 MILES

0 2 4 6 8 10 KILOMETERS

Base from U.S. Geological Survey and other Federal digital data, various scales; Universal Transverse Mercator (UTM) projection, zone 11; North American Datum of 1983

B



Historical geology from Miller and others (2020)

500,000 years before present:

Intermediate Mojave River deposits QiMR (oriented northeast-southeast in Hinkley Valley) broke through south of Iron Mountain about 500,000 years before present. Carbonate-rich groundwater discharge deposits formed at the toe of the alluvial fans.

EXPLANATION

Mojave River alluvium

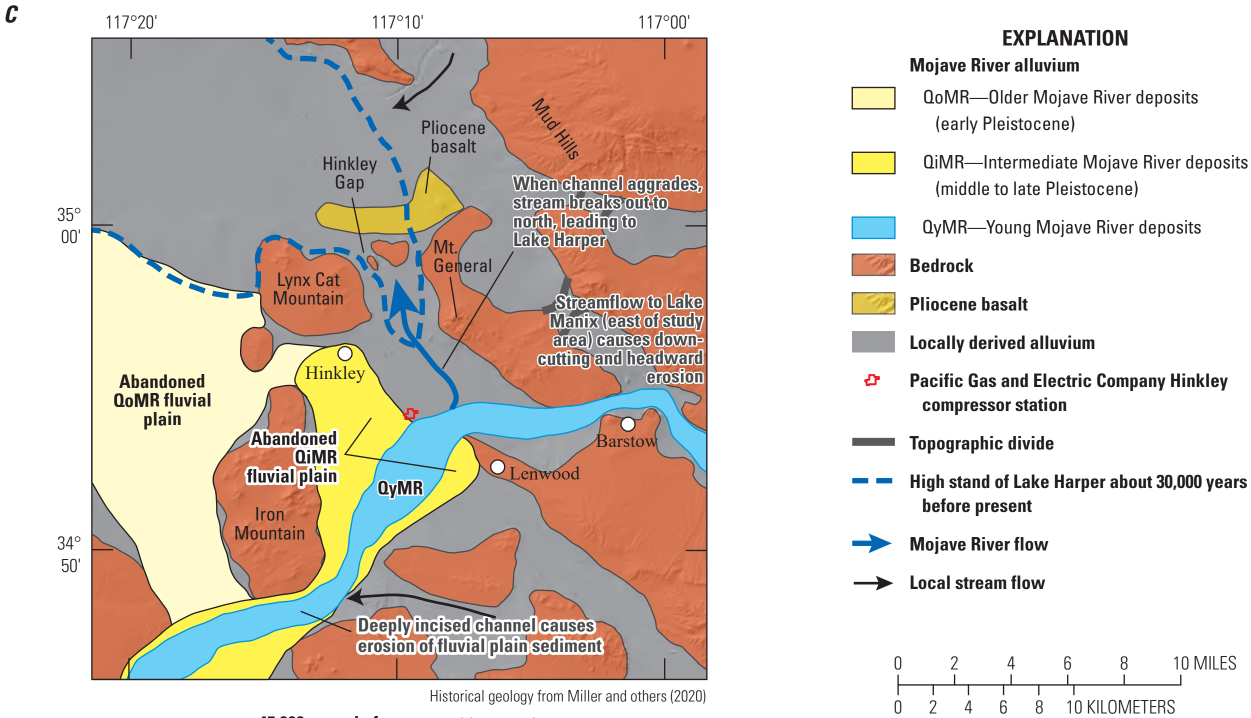
- QoMR—Older Mojave River deposits (early Pleistocene)
- QiMR—Intermediate Mojave River deposits (middle to late Pleistocene)
- **Lake**
- **Bedrock**
- **Pliocene basalt**
- **Locally derived alluvium**
- **Delta/wetland**—groundwater discharge deposits
- **Pacific Gas and Electric Company Hinkley compressor station**
- **Topographic divide**
- **Mojave River flow**
- **Local stream flow**

0 2 4 6 8 10 MILES

0 2 4 6 8 10 KILOMETERS

Base from U.S. Geological Survey and other Federal digital data, various scales; Universal Transverse Mercator (UTM) projection, zone 11; North American Datum of 1983

Figure A.5. Simplified geologic history of unconsolidated deposits *A,* 750,000 to 630,000 years before present, *B,* 500,000 years before present, and *C,* 45,000 years before present to recent, Hinkley and Water Valleys, western Mojave Desert, California. Modified from Miller and others (2018, 2020).



Historical geology from Miller and others (2020)

45,000 years before present to recent:
Recent to young Mojave River deposits (oriented north-south) filled Hinkley Valley. Deposits changed from Mojave River stream to transgressing/regressing shallow lake margin to mudflat/playa deposits from south to north.

Base from U.S. Geological Survey and other Federal digital data, various scales; Universal Transverse Mercator (UTM) projection, zone 11; North American Datum of 1983

Figure A.5.—Continued

The geologic materials described by Miller and others (2018, 2020) constitute important hydrologic units identified by PG&E and their consultants (Jacobs Engineering Group, Inc., 2019). Throughout much of Hinkley Valley, unconsolidated deposits are composed of an upper and lower aquifer separated by lake deposits consisting of blue clay. The blue clay is blue because it is reduced (does not contain oxygen). The blue clay is commonly less than 160 ft below land surface and may be up to 100 ft thick near the Mojave River (ARCADIS and CH2M Hill 2011; CH2M Hill, 2013; Jacobs Engineering Group, Inc., 2019). Below the blue clay are unconsolidated lower aquifer deposits composed primarily of locally derived alluvium. These deposits are as thick as 600 ft near the Mojave River and thin to the north (Huff and others, 2002; Miller and others, 2020). The blue clay terminates against shallow bedrock in the western part of Hinkley Valley (Jacobs Engineering Group, Inc., 2019), and alluvial deposits composing the upper aquifer in this area overlie weathered bedrock or groundwater discharge deposits. The upper aquifer is composed of Mojave-type deposits consisting of Mojave River stream and lake margin deposits and is divided into shallow and deep zones separated by brown clay (ARCADIS and CH2M Hill, 2011; CH2M Hill, 2013). The brown clay is up to 50 ft thick in the northern part of the eastern subarea (fig. A.6). Although brown clay is present throughout alluvial deposits in Hinkley Valley, it is not an important hydrologic unit within the upper aquifer in much of the area.

Subsurface geologic conditions differ in the northern parts of Hinkley Valley, along the margins of the valley where locally derived alluvial material interfingers with alluvium sourced from the Mojave River, and in Water Valley. In the northern subarea (fig. A.6), coarse-grained Mojave River stream and lake margin deposits overlie generally fine-grained mudflat/playa and lake deposits (Stantec, 2013). Mojave River stream deposits extend into Water Valley where well-sorted lake margin deposits (beach deposits) associated with high stands of Lake Harper compose permeable water-yielding deposits. Locally derived alluvial material is present along the margins of Mount General and throughout Water Valley. In Water Valley, local alluvium was eroded, in part, from fine-grained Miocene continental deposits within the Mud Hills (fig. A.5) to the east and commonly contains basaltic fragments.

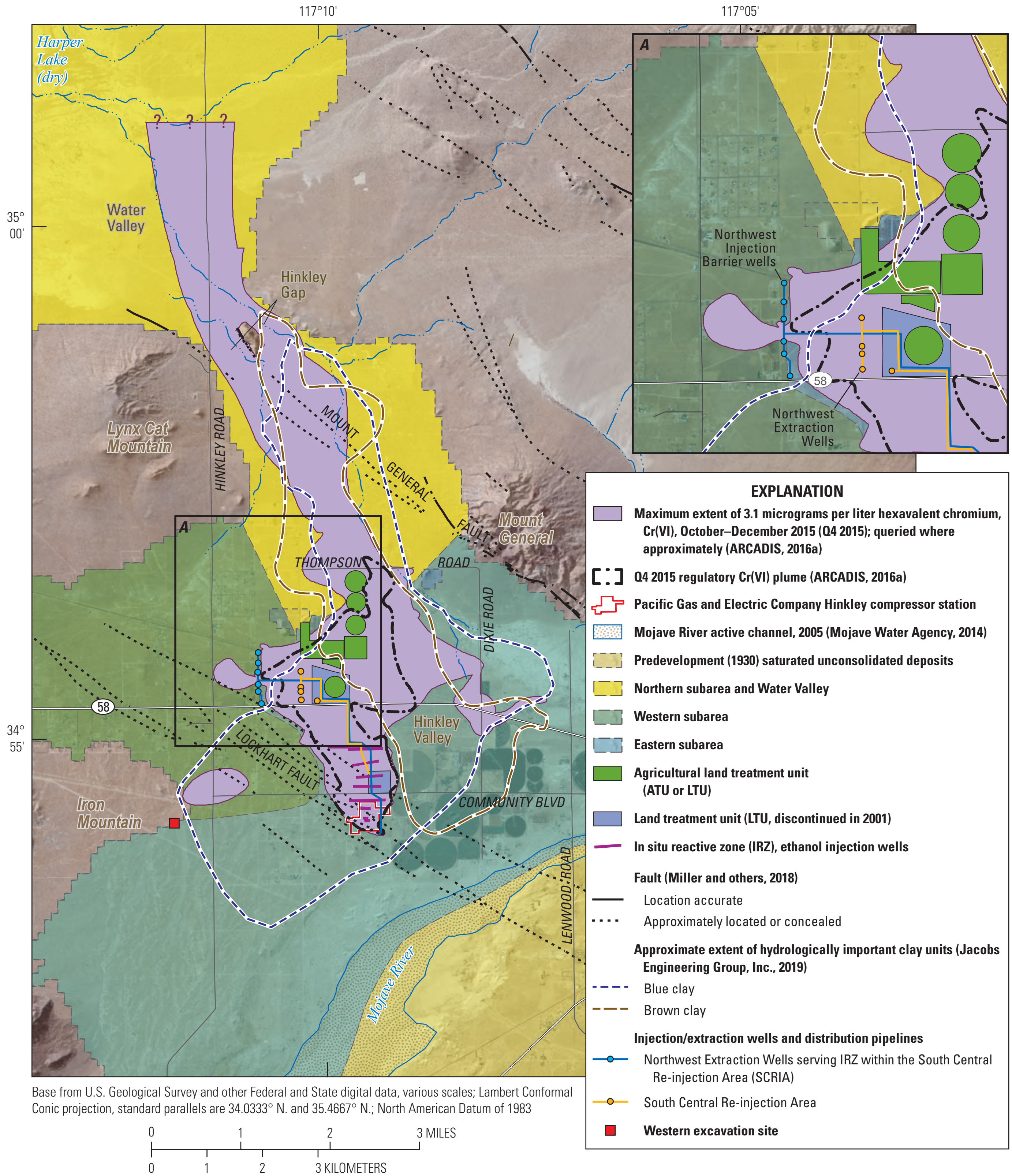


Figure A.6. Facilities installed by Pacific Gas and Electric Company (PG&E) to remediate hexavalent chromium, Cr(VI), in groundwater, Hinkley Valley, western Mojave Desert, California. Data from PG&E in December 2016 are available within annual reports for the Hinkley site published by PG&E consultants at https://geotracker.waterboards.ca.gov/profile_report?global_id=SL0607111288.

During predevelopment conditions, groundwater recharge in Hinkley Valley and much of Water Valley was almost entirely from the Mojave River, with only small amounts of recharge as infiltration from local streams and negligible recharge from infiltrating precipitation (Stamos and others, 2001). Recharge from the Mojave River is episodic, occurring as infiltration from large flows (greater than about 5,000 ft^3/s) that typically occur once every 5 to 7 years (fig. A.3). During predevelopment conditions, groundwater movement within Hinkley Valley was from recharge areas along the Mojave River toward Hinkley Gap into Water Valley, where groundwater discharged by evaporation in wetlands along the southeast margin of Harper (dry) Lake (Thompson, 1929). Movement along the right-lateral Lockhart and Mount General faults within Hinkley and Water Valleys offset unconsolidated deposits (Miller and others, 2018, 2020). The Lockhart fault impedes groundwater flow, whereas the effect of the Mount General fault on groundwater movement is less certain (Miller and others, 2007); both faults consist of numerous mapped strands (Miller and others, 2018, 2020).

Water-level declines as a result of groundwater pumping for agriculture began in the early 1950s (Stone, 1957; Stamos and others, 2001). In 2015, water levels beneath the Hinkley compressor station were as much as 60 ft below predevelopment levels (Seymour and Izbicki, 2018). Formerly saturated coarse-grained deposits throughout Hinkley and Water Valleys became unsaturated as a result of water-level declines, and only thin lenses of Mojave-type deposits remained saturated in parts of the western subarea downgradient from the Lockhart fault and in the northern subarea. Water-level declines as a result of agricultural pumping resulted in adjudication of the groundwater basin in 1996 and a court-ordered reduction in pumping (California Superior Court, 1996), with additional litigation continuing until 2002.

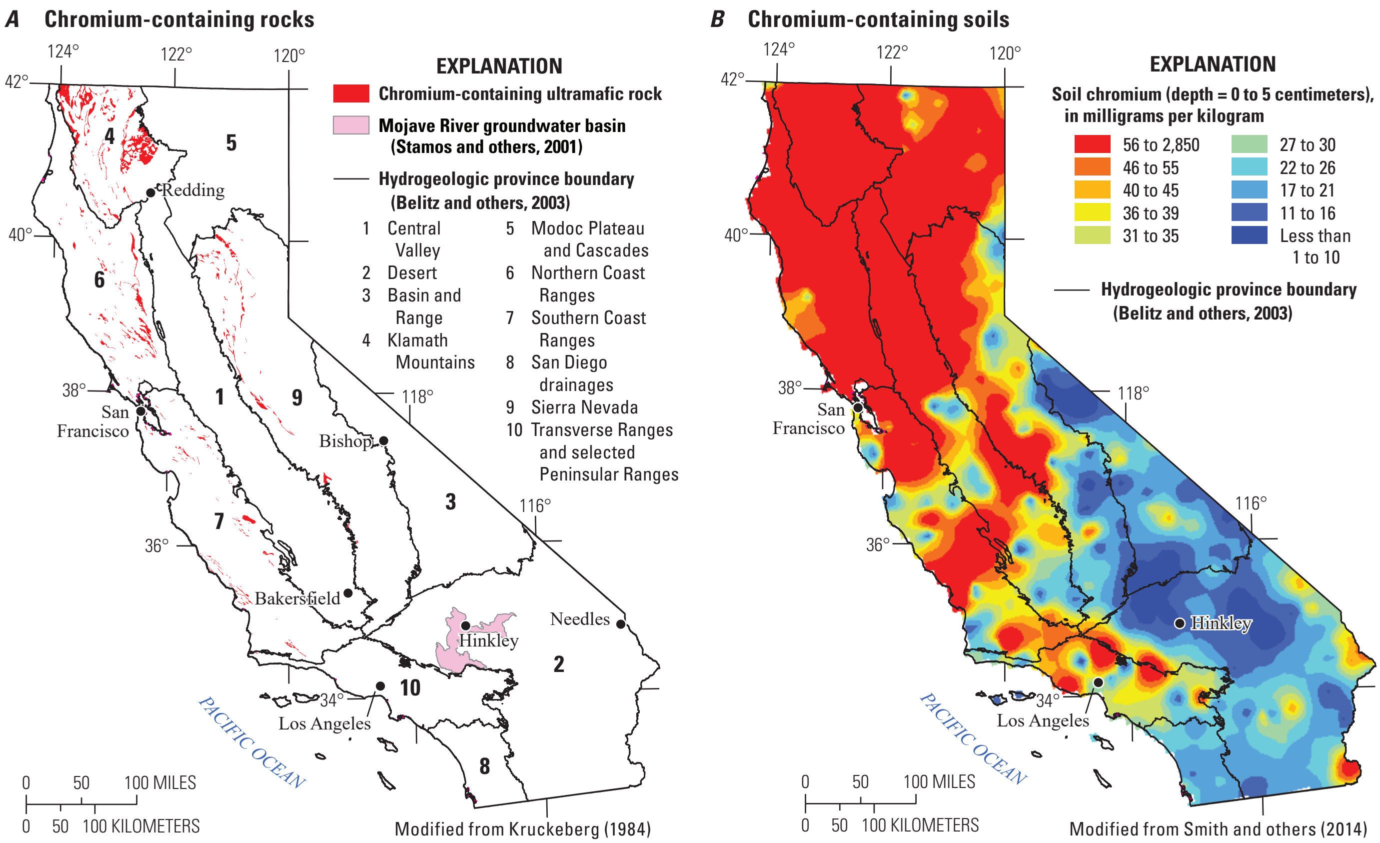
A.3. Chromium in Rock and Alluvium within the Mojave River Drainage

Naturally occurring chromium is commonly associated with mafic and ultramafic rock (Reimann and de Caritat, 1998). With the exception of chromium-containing mafic rock in the San Gabriel Mountains and small areas of mafic, chromium-containing rock within the Mojave River drainage, the region is naturally low in chromium (Kruckeberg, 1984; Smith and others, 2014; fig. A.7).

Movement along the San Andreas Fault over the past several million years created Cajon Pass and the Mojave River. This movement transported mafic rocks, including the Pelona Schist within the San Gabriel Mountains, to the northwest (Meisling and Weldon, 1989; Cox and others, 2003) and changed the source area contributing alluvium to the Mojave River (Cox and others, 2003; Izbicki and others, 2008). The greenschist facies within the Pelona Schist contains chromium-bearing minerals, including actinolite and fuchsite (chromium-mica), which have chromium concentrations as high as 4,000 and 8,600 milligrams per kilogram (mg/kg), respectively (Groover and Izbicki, 2018). As a consequence, older Mojave River deposits (QoMR; fig. A.5*A*) were eroded at a time when the San Gabriel Mountains contributed alluvium directly to the ancestral Mojave River. This older alluvium contained more mafic material, with a higher fraction of chromium-bearing minerals with higher chromium concentrations than more recent Mojave River deposits (QiMR or QyMR; Groover and Izbicki, 2019). These older deposits are exposed at land surface over a large area of the regional aquifer, extending nearly to Barstow into Hinkley and Water Valleys (fig. A.2*B*; Cox and others, 2003; Miller and others, 2018, 2020).

The Mojave River groundwater basin (fig. A.2) includes large alluvial fan complexes eroded from the San Gabriel Mountains known as the Victorville and the Sheep Creek fans (Meisling and Weldon, 1989; Miller and Bedford, 2000; Stamos and others, 2001). These alluvial fans were deposited by streams that were tributaries to the Mojave River in the geologic past. The Victorville fan was beheaded and separated from the San Gabriel Mountains as a result of geologic movement along the San Andreas Fault and subsequent erosion by streams draining toward the Pacific Ocean through Cajon Pass about 1 million years ago. Although mafic rock from the San Gabriel Mountains no longer directly contributes alluvium to the Mojave River from this area, reworking of alluvial material from the Victorville fan contributes material to recent Mojave River alluvium. Surface drainage and transport of mafic alluvium from the San Gabriel Mountains through Sheep Creek to the Mojave River occurred until the Sheep Creek fan extended to the north, creating the topographically closed El Mirage (dry) Lake about 8,000 years ago; however, groundwater movement from this area to the regional aquifer continues (Stamos and others, 2001). Recent work showed that erosion of Victorville fan deposits and alluvium from Fremont Wash (the former downstream reach of Sheep Creek wash) contributed mafic alluvium to the Mojave River in the geologic past but only provided small (insignificant) amounts of mafic, chromium-containing alluvium to the Mojave River at the time of this study (2015–18; Groover and Izbicki, 2019).

Locally within Hinkley and Water Valleys, small exposures of mafic rocks are present, including hornblende diorite and gabbro at Iron Mountain and Mount General (Boettcher, 1990; Boettcher and Walker, 1993) and basalts in Water Valley. Older alluvium from the ancestral Mojave River, potentially containing mafic material, locally derived alluvium from mafic terrains, and weathered mafic rock, also are present.



Base 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

Base 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

Figure A.7. Chromium concentrations in *A*, rock and *B*, soil in California. Modified from Kruckeberg (1984); Smith and others (2014).

A.4. Site History

Between 1952 and 1964, cooling water used at the PG&E Hinkley compressor station was treated with a compound containing chromium to prevent corrosion of machinery within the compressor station. The cooling-tower waste was discharged to unlined ponds, resulting in the release of Cr(VI) to soil and groundwater in the underlying unconsolidated aquifer (Lahontan Regional Water Quality Control Board, 2013). Since 1965, cooling-water management practices have been used that do not contribute chromium to groundwater.

The Pacific Gas and Electric Company informed the Lahontan RWQCB of Cr(VI) releases from the Hinkley compressor station in 1987 (Lahontan Regional Water Quality Control Board, 1987), and groundwater monitoring began at the site in the late 1980s (Ecology and Environment, Inc., 1988). In 1996, Cr(VI) release from the Hinkley compressor station resulted in a $333 million settlement against PG&E (Anderson, and others v. PG&E, Superior Court for the County of San Bernardino, Barstow Division, File BCV 00300). At the time, this was the largest settlement in a direct-action lawsuit in United States history.

Estimates of the mass of Cr(VI) released from the Hinkley compressor station between 1952 and 1964 are uncertain. However, the mass of Cr(VI) in groundwater within the mapped plume downgradient from the Hinkley compressor station in January 2011 was estimated to be 4,700 pounds (lbs; Lahontan Regional Water Quality Control Board, 2013). For comparison, 300 mi east at the PG&E Topock compressor station, built at the same time along the same natural gas line as the Hinkley compressor station and presumably operated in a similar manner, 8,700 lbs of chromium were removed from groundwater between August 2005 and October 2014 (CH2M Hill, 2014a), and more than 24,300 lbs of chromium were estimated to remain in groundwater within the mapped plume at the Topock site (CH2M Hill, 2014b). In the initial disclosure of Cr(VI) releases from the Hinkley compressor station, PG&E estimated 144,000,000 gallons (gal) of cooling water containing Cr(VI) were released from the Hinkley compressor station between 1952 and 1964 (Lahontan Regional Water Quality Control Board, 1987). Documents filed as part of the 1996 legal action (Anderson, and others v. PG&E, Superior Court for the County of San Bernardino, Barstow Division, File BCV 00300) estimated that as much as 370,000,000 gal of cooling water may have been released into groundwater. Assuming industrial practices commonly used at that time, concentrations of Cr(VI) in chromium-based corrosion inhibitors used in cooling water would have ranged from 10 milligrams per liter (mg/L), the minimum required to inhibit corrosion, to 30 mg/L (U.S. Environmental Protection Agency, 1993), and the mass of Cr(VI) released at Hinkley compressor station would have ranged from about 12,000 to 36,000 or 31,000 to 93,000 lbs, depending on the initial volume of cooling water released at the site. Although these values are largely uncertain, they exceed the estimated mass of Cr(VI) within groundwater of 4,700 lbs (Lahontan Regional Water Quality Control Board, 2013) and are within the range of Cr(VI) releases at the PG&E Topock compressor station site.

In the fourth quarter (October–December) of 2015, PG&E acknowledged a Cr(VI) plume in the upper aquifer extending 3.0 mi downgradient from the release location within the Hinkley compressor station, while groundwater having Cr(VI) concentrations greater than 3.1 µg/L was present more than 8 mi downgradient (fig. A.6; ARCADIS, 2016a). Small amounts of Cr(VI) were present within the lower aquifer system as a result of flow through unused or abandoned wells, or as a result of groundwater movement near the margins of the blue clay driven by vertical hydraulic gradients induced by pumping from deeper wells (ARCADIS, 2016b).

Groundwater flow at the site is nominally to the north, but the mapped plume downgradient from the compressor station trends to the northwest along the downgradient side of the Lockhart fault. Although Cr(VI) generally moves freely with groundwater, the highest Cr(VI) concentrations within the mapped plume, in excess of 1,000 µg/L, remain less than 3,000 ft from the source area within the Hinkley compressor station more than 65 years after the initial release (ARCADIS, 2016a). Andrews and Neville (2003) suggested that mobilization of Cr(VI) from the unsaturated zone by rising water levels resulting from implementation of the Mojave Basin Area Adjudication (Riverside County Superior Court, 1996) and subsequent reduction in agricultural pumping may be responsible for high Cr(VI) concentrations near the compressor station. Other explanations also are possible, including slow movement of groundwater containing anthropogenic Cr(VI) downgradient from the compressor station because of (1) low hydraulic conductivity within saturated deposits beneath the source area or (2) splays of the Lockhart fault that impede groundwater flow. Alternatively, estimates of the mass of Cr(VI) in the groundwater within the regulatory Cr(VI) plume may not accurately indicate the total mass of Cr(VI) released from the site. It is possible that some of the Cr(VI) released between 1952 and 1964, when water levels were higher and highly permeable deposits above the water table at the time of this study (2015–18) were saturated, may have moved with groundwater farther downgradient from the Hinkley compressor station than indicated by the regulatory Cr(VI) plume maps. Much of the Cr(VI) released from the Hinkley compressor station may have been removed from the aquifer by agricultural pumping as water levels declined.

Remediation of Cr(VI) began in 1992 with land application of Cr(VI)-containing groundwater to irrigate crops (fig. A.6; Haley and Aldrich, Inc., 2010). This treatment strategy was designed to reduce soluble Cr(VI) to insoluble trivalent chromium, Cr(III), with subsequent removal of Cr(III) occurring within the crop root zone. Irrigated acreage to treat Cr(VI) increased in 1998. These land treatment units (LTUs) were closed in 2001 as a result of concern over the possible release of atmospheric aerosols containing chromium during irrigation (Lahontan Regional Water Quality Control Board, 2001). During their operation, land application at the LTU sites removed about 1,550 lbs of Cr(VI) (Alisto Engineering Group, 2001; Haley and Aldrich, Inc., 2010). In 2004, agricultural treatment units (ATUs) designed to minimize aerosol production came online, and land application of Cr(VI)-containing water to agricultural land resumed (CH2M Hill, 2005); expansion of these facilities continued until 2013 (ARCADIS, 2018).

In 2007, in situ reduction of soluble Cr(VI) to insoluble Cr(III) through the injection of organic carbon substrates within in situ reactive zones (IRZ) began (ARCADIS, 2008; fig. A.6). Lactate, initially used as the carbon substrate, was replaced by ethanol as the carbon source by May 2009 (Pacific Gas and Electric Company, 2009). In situ reduction of Cr(VI) to Cr(III) produced byproducts, including arsenic and manganese, in treated groundwater, which were subsequently regulated by the Lahontan Regional Water Quality Control Board (2012b).

In 2009, a series of extraction wells known as the Northwest Extraction Wells were installed to supply injection water to the IRZs as part of the SCRIA (South Central Re-Injection Area; fig. A.6). In 2010, a series of freshwater injection wells known as the Northwest Injection Barrier (CH2M Hill, 2009) were installed to limit expansion of the mapped plume toward residential areas in the western part of Hinkley Valley (fig. A.6).

Between 2001 and 2017, 803 lbs of Cr(VI) were removed by the various agricultural treatment units and the Northwest Extraction Wells, and 2,528 pounds of Cr(VI) were estimated to have been reduced in situ to Cr(III) and removed from groundwater (ARCADIS, 2018). Approximately 1,400 pounds of Cr(VI) released from the Hinkley compressor station were estimated to remain in groundwater in 2017 (ARCADIS, 2018). Remediation activities at the site are summarized in greater detail in ARCADIS (2018).

Proposed remediation alternatives were first presented to the Lahontan RWQCB by PG&E in January 2011 (Haley and Aldrich, Inc., 2010). Site cleanup using the preferred alternative presented in March 2011 was projected to require 10 to 95 years and cost between $36 and $176 million depending on the Cr(VI) cleanup goal (Haley and Aldrich, Inc., 2010; Pacific Gas and Electric Company, 2011).

A.5. Purpose and Scope of the USGS Hexavalent Chromium Background Study

The USGS was requested by the Lahontan RWQCB to complete an updated background study of Cr(VI) concentrations in Hinkley and Water Valleys. The purpose of the USGS hexavalent chromium, Cr(VI), background study was to estimate background Cr(VI) concentrations in groundwater within the upper aquifer system underlying Hinkley and Water Valleys upgradient, downgradient, near the margins, and within the footprint of the mapped PG&E Cr(VI) plume in the upper aquifer underlying Hinkley, California. This professional paper focuses on anthropogenic Cr(VI) in groundwater released from the Hinkley compressor station and background Cr(VI) concentrations within the upper aquifer in the eastern, western, and northern subareas within Hinkley Valley and within Water Valley (fig. A.6). First, to make estimates of Cr(VI) background, the study evaluated the extent of anthropogenic Cr(VI) in groundwater near the PG&E plume and addressed the question: "What is the area of groundwater containing anthropogenic Cr(VI) associated with releases from the Hinkley compressor station?" Second, Cr(VI) concentrations in water from wells outside the area containing anthropogenic Cr(VI) were then used to estimate natural Cr(VI) concentrations in different parts of Hinkley and Water Valley. Background Cr(VI) values calculated as part of this study are not background Cr(VI) concentrations for regulatory purposes, and the authority to establish regulatory values resides solely with the Lahontan Regional Water Quality Control Board.

The scope of the study included eight tasks (table A.2) described by Izbicki and Groover (2016 and 2018). Field-data collection began in March 2015 and was completed in January 2018.

Table A.2. Tasks and questions addressed by the U.S. Geological Survey background hexavalent chromium, Cr(VI), study in Hinkley and Water Valleys, western Mojave Desert, California, January 2015 to December 2019.

[Modified from Izbicki and Groover, 2016, 2018. **Abbreviations**: Cr(VI), hexavalent chromium; PG&E, Pacific Gas and Electric Company; IRZ, in situ reactive zone]

Task		Where discussed	Purpose
Task 1	Evaluation of existing data.	Chapter D	Identify areas near the mapped Cr(VI) plume having water quality of concern to the study.
Task 2	Analyses of rock and alluvium.	Chapters B and C	Determine if there are naturally occurring geologic sources of chromium in aquifer deposits.
Task 3	Analyses of chemical and environmental tracers in water from wells.	Chapters E and F	Determine the chemical and isotopic (including other environmental tracers) composition of water from selected wells throughout the study area—with respect to (1) the sources and chemical processes controlling Cr(VI) occurrence and (2) the source, movement, and age of the groundwater relative to the timing of Cr(VI) releases from the PG&E compressor station.
Task 4	Evaluation of local hydrogeologic conditions.	Chapter H	Determine how differences in local geohydrology within the eastern (including the regulatory plume and upgradient areas), western, and northern subareas of Hinkley Valley and Water Valley influence the movement of groundwater and anthropogenic (human-made) Cr(VI) from the compressor station.
Task 5	Evaluation of groundwater movement.	Chapter H	Evaluate how changing hydrologic conditions in the study area through time influence the movement of water and Cr(VI) through aquifers underlying Hinkley and Water Valleys.
Task 6	Evaluation of the occurrence of natural and anthropogenic Cr(VI).	Chapter G	Identify areas within the aquifer containing human-made Cr(VI) from releases at the PG&E compressor station and areas that contain Cr(VI) from other sources.
Task 7	Estimation of background Cr(VI) concentrations.	Chapter G	Estimate background Cr(VI) in parts of the study area not affected by discharges from the PG&E compressor station.
Task 8	Fate of chromium during and after in situ reduction.	Chapter I	Determine if chromium within the IRZ may reoxidize or if Cr(VI) is permanently removed from groundwater.

The following chapters within this professional paper present results for tasks addressed by the USGS Cr(VI) background study (table A.2). Chapters B and C discuss elemental composition and mineralogy of rock, unconsolidated material, and surface coatings on mineral grains (Task 2). Chapters D and E discuss the Cr(VI) and chemical composition of water from wells sampled by PG&E for regulatory purposes and as part of this study (Tasks 1 and 3, respectively). Chapter F discusses the stable water isotopic composition (delta deuterium and delta oxygen-18), age-dating parameters (tritium, helium-3, carbon-14, and industrial gases), strontium isotopes, and chromium isotopes in water from wells sampled as part of this study (Task 3). Chapter G discusses the extent of anthropogenic Cr(VI) estimated on the basis of data presented in chapters B through F using a summative-scale approach (Task 6) and provides estimates of background Cr(VI) concentrations within the various subareas of Hinkley Valley and in Water Valley (Task 7). Chapter H discusses the local hydrologic setting, including predevelopment water-levels, aquifer properties, and groundwater movement across faults (Task 4). Appendix H.2 compares groundwater chemistry and age-dating data used to define the mapped summative-scale Cr(VI) plume with particle-tracking results from an updated groundwater-flow model prepared in support of the study by PG&E consultants (Jacobs Engineering Group, Inc., 2019; Task 5). Chapter I discusses laboratory results estimating the fate of chromium during and after in situ reduction (Task 8). Chapter J summarizes important results from the study and provides information on the limitations and uses of those results.

A.6. References Cited

Alisto Engineering Group, 2001, Annual report evaluation of corrective action for year 2000–2001: Pacific Gas and Electric Company, Hinkley Compressor Station, Hinkley, Calif.: San Francisco, Calif., Pacific Gas and Electric Company, prepared by Alisto Engineering Group, Walnut Creek, Calif., [variously paged].

Andrews, C.B., and Neville, C.J., 2003, Ground water flow in a desert basin—Challenges of simulating transport of dissolved chromium: Groundwater, v. 41, no. 2, p. 219–226. [Available at https://doi.org/10.1111/j.1745-6584.2003.tb02585.x.]

ARCADIS, 2008, Fourth quarter 2007 monitoring report for the central area in situ remediation pilot study: San Francisco, Calif., Pacific Gas and Electric Company, prepared by ARCADIS, Oakland, Calif., RC000699, [variously paged], accessed November 27, 2018, at https://documents.geotracker.waterboards.ca.gov/esi/uploads/geo_report/3207217156/SL0607111288.PDF.

ARCADIS, 2016a, Annual cleanup status and effectiveness report (January to December 2015) Pacific Gas and Electric Company, Hinkley Compressor Station, Hinkley, California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by ARCADIS, Oakland, Calif., RC000699, [variously paged], accessed February 2016, at https://documents.geotracker.waterboards.ca.gov/esi/uploads/geo_report/9395357131/SL0607111288.PDF.

ARCADIS, 2016b, Updated conceptual site model and background chromium concentrations for lower aquifer report, Hinkley Compressor Station, Hinkley, California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by ARCADIS, Oakland, Calif., RC000699.0142, [variously paged], accessed November 28, 2018, at https://geotracker.waterboards.ca.gov/esi/uploads/geo_report/9069337844/SL0607111288.pdf.

ARCADIS, 2018, Annual cleanup status and effectiveness report (January to December 2017) Hinkley Compressor Station, Hinkley California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by ARCADIS, Oakland, Calif., RC000699, [variously paged], accessed November 27, 2018, at https://geotracker.waterboards.ca.gov/esi/uploads/geo_report/4949047982/SL0607111288.pdf.

ARCADIS and CH2M Hill, 2011, Development of a groundwater flow and solute transport model, appendix G *of* Haley and Aldrich., Inc, Addendum #3 to the feasibility study Pacific Gas and Electric Company Hinkley compressor station, Hinkley, California: San Francisco, Calif., Pacific Gas and Electric Company, [variously paged], accessed September 4, 2019, at https://geotracker.waterboards.ca.gov/esi/uploads/geo_report/2112934887/SL0607111288.pdf.

Belitz, K., Dubrovsky, N.M., Burow, K., Jurgens, B., Johnson, T., 2003, Framework for a ground-water quality monitoring and assessment program for California. U.S. Geological Survey Water Resources Investigation Report 2003–4166, 78 p., accessed June 23, 2021, at http://pubs.usgs.gov/wri/wri034166/.

Boettcher, S.S., 1990, Geologic map of Iron Mountain: Geological Society of America Digital Map and Chart Series 19, scale 1:12,000. [Available at https://www.geosociety.org/maps/1990-boettcher-ironmountain/?WebsiteKey=a5b62ffc-18e7-49eb-b75a-db5406bdc7ea.]

Boettcher, S.S., and Walker, J.D., 1993, Geologic evolution of Iron Mountain, central Mojave Desert, California: Tectonics, v. 12, no. 2, p. 372–386. [Available at https://doi.org/10.1029/92TC02423.]

California Department of Water Resources, 2003, California's groundwater: California Department of Water Resources Bulletin 118, 7 p., accessed November 20, 2018, at https://water.ca.gov/Programs/Groundwater-Management/Bulletin-118.

California Department of Water Resources, 2019, California's groundwater—Basin boundary modifications: California Department of Water Resources Bulletin 118, accessed June 12, 2019, at https://water.ca.gov/Programs/Groundwater-Management/Bulletin-118.

California Superior Court, 1996, City of Barstow v. City of Adelanto: case no. 208568, Judgement after trial, 140 p., accessed November 18, 2019, at https://www.mojavewater.org/wp-content/uploads/2022/04/20220119_Stipulation_Hu.pdf.

CH2M Hill, 2005, Annual monitoring report Desert View Dairy land treatment unit, Hinkley, California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by CH2M Hill, Oakland, Calif., [variously paged], accessed November 27, 2018, at https://geotracker.waterboards.ca.gov/esi/uploads/geo_report/5186680436/SL0607111288.pdf.

CH2M Hill, 2007, Groundwater background study report: Hinkley compressor station, Hinkley, Calif.: San Francisco, Calif., Pacific Gas and Electric Company, prepared by CH2M Hill, Oakland, Calif., [variously paged], accessed January 12, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/docs/2007_background_study_report.pdf.

CH2M Hill, 2009, Well completion report for northwest interim remediation project, Pacific Gas and Electric Company, Hinkley Compressor Station, Hinkley, California: prepared by CH2M Hill, Oakland, Calif., [variously paged], accessed August 22, 2018, at https://geotracker.waterboards.ca.gov/esi/uploads/geo_report/1239488005/SL0607111288.pdf.

CH2M Hill, 2013, Framework for evaluation of background chromium in the upper aquifer of Hinkley Valley, Pacific Gas and Electric Company, Hinkley Compressor Station, Hinkley, California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by CH2M Hill, Oakland, Calif., [variously paged], accessed November 27, 2018, at https://documents.geotracker.waterboards.ca.gov/esi/uploads/geo_report/2601029872/SL0607111288.PDF.

CH2M Hill, 2014a, Third quarter 2014 monitoring report for interim measure no. 3 groundwater treatment system, Pacific Gas and Electric Company compressor station, Needles, California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by CH2M Hill, Oakland, Calif., [variously paged], accessed June 30, 2017, at https://dtsc-topock.com/sites/default/files/IM3_3Q2014_Report_Final_10-15-14.pdf.

CH2M Hill, 2014b, Basis of design report/per-final (90%) design submittal for the final groundwater remedy, Pacific Gas and Electric Company Topock compressor station, Needles, California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by CH2M Hill, Oakland, Calif., [variously paged], accessed June 30, 2017, at https://dtsc-topock.com/sites/default/files/90percent_BOD_MainTextTablesFigures_090814.pdf.

Cox, B.F., Hillhouse, J.W., and Owen, L.A., 2003, Pliocene and Pleistocene evolution of the Mojave River, and associated tectonic development of the Transverse Ranges and Mojave Desert, based on borehole stratigraphy studies and mapping of landforms and sediments near Victorville, California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and paleohydrology of the Mojave and southern Great Basin Deserts—Boulder, Colorado: Geological Society of America Special Paper 368, p. 1–42. [Available at https://doi.org/10.1130/0-8137-2368-X.1.]

Cyr, A.J., Miller, D.M., and Mahan, S.A., 2015, Paleodischarge of the Mojave River, southwestern United States, investigated with single-pebble measurements of ^{10}Be: Geosphere, v. 11, no. 4, p. 1158–1171. [Available at https://doi.org/10.1130/GES01134.1.]

Dibblee, T.W., Jr., 1960a, Geologic map of the Barstow quadrangle, San Bernardino County, California: U.S. Geological Survey Mineral Investigations Field Studies Map MF–233, scale 1:62,500, accessed November 26, 2018, at https://doi.org/10.3133/mf233.

Dibblee, T.W., Jr., 1960b, Geologic map of the Hawes quadrangle, San Bernardino County, California: U.S. Geological Survey Mineral Investigations Field Studies Map MF–226, scale 1:62,500, accessed November 26, 2018, at https://doi.org/10.3133/mf226.

Dokka, R.K., and Travis, C.J., 1990, Late Cenozoic strike-slip faulting in the Mojave Desert, California: Tectonics, v. 9, no. 2, p. 311–340. [Available at https://doi.org/10.1029/TC009i002p00311.]

Ecology and Environment, Inc., 1988, Hinkley compressor station groundwater remediation project site characterization report, October 14, 1988: San Francisco, Calif., Pacific Gas and Electric Company, prepared by Ecology and Environment, Inc., San Francisco, Calif., 164 p.

Enzel, Y., Wells, S.G., and Lancaster, N., 2003, Late Pleistocene lakes along the Mojave River, southeast California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and Paleohydrology of the Mojave and southern Great Basin deserts: Boulder, Colo., Geological Society of America, p. 61–77. [Available at https://doi.org/10.1130/0-8137-2368-X.61.]

Fletcher, J.M., Bartley, J.M., Martin, M.W., Glazner, A.F., and Walker, J.D., 1995, Large-magnitude continental extension—An example from the central Mojave metamorphic core complex: Geological Society of America Bulletin, v. 107, no. 12, p. 1468–1483. [Available at https://doi.org/10.1130/0016-7606(1995)107<1468:LMCEAE>2.3.CO;2.]

Fletcher, J.M., Miller, J.S., Martin, M.W., Boettcher, S.S., Glazner, A.F., and Bartley, J.M., 2002, Cretaceous arc in the Mojave block—Profound crustal modification that controlled subsequent tectonic regimes, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., eds., Geologic evolution of the Mojave Desert and southwestern Basin and Range: Geological Society of America Memoir 195, p. 19–41. [Available at https://doi.org/10.1130/0-8137-1195-9.131.]

Flint, L.E., and Flint, A.L., 2007, Regional analyses of groundwater recharge, chap. B *of* Stonestrom, D.A., Constantz, J., Ferre, T.P.A., and Leake, S.A., eds., Ground-water recharge in the arid and semiarid southwestern United States: U.S. Geological Survey Professional Paper 1703, p. 29–60, accessed July 8, 2019, at https://doi.org/10.3133/pp1703B.

Garcia, A.L., Knott, J.R., Mahan, S.A., and Bright, J., 2014, Geochronology and paleoenvironment of pluvial Harper Lake, Mojave Desert, California, USA: Quaternary Research, v. 81, no. 2, p. 305–317. [Available at https://doi.org/10.1016/j.yqres.2013.10.008.]

Groover, K.D., and Izbicki, J.A., 2018, Field portable X-ray fluorescence and associated quality control data for the western Mojave Desert, San Bernardino County, California: U.S. Geological Survey data release, accessed November 29, 2018, at https://doi.org/10.5066/P9CU0EH3.

Groover, K.D., and Izbicki, J.A., 2019, Selected trace-elements in alluvium and rocks, western Mojave Desert, southern California: Journal of Geochemical Exploration, v. 200, p. 234–248, accessed July 8, 2019, at https://doi.org/10.1016/j.gexplo.2018.09.005.

Haley and Aldrich, Inc., 2010, Feasibility study, Pacific Gas and Electric Company Hinkley compressor station, Hinkley, California, Addendum 3: San Francisco, Calif., Pacific Gas and Electric Company, prepared by Haley and Aldrich, San Diego, Calif., [variously paged], accessed November 27, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/fsr083010.html.

Huff, J.A., Clark, D.A., and Martin, P., 2002, Lithologic data and ground-water data for the Mojave River ground-water basin—Centro subarea, appendix D *of* Huff, J.A., Clark, D.A., and Martin, P., Lithologic and ground-water data for monitoring sites in the Mojave River and Morongo ground-water basins, San Bernardino County, California, 1992–1998: U.S. Geological Survey Open-File Report 2002–354. [Available at https://doi.org/10.3133/ofr02354.]

Izbicki, J.A., 2004, Source and movement of ground water in the western part of the Mojave Desert, southern California, USA: U.S. Geological Survey Water-Resources Investigations Report 2003–4313, 36 p., accessed November 20, 2018, at https://doi.org/10.3133/wri034313.

Izbicki, J.A., and Groover, K.D., 2016, A plan for study of natural and man-made hexavalent chromium, Cr(VI), in groundwater near a mapped plume, Hinkley, California: U.S. Geological Survey Open-File Report 2016–1004, 12 p., accessed November 28, 2018, at https://doi.org/10.3133/ofr20161004.

Izbicki, J.A., and Groover, K.D., 2018, Natural and man-made hexavalent chromium, Cr(VI), in groundwater near a mapped plume, Hinkley, California—Study progress as of May 2017, and a summative-scale approach to estimate background Cr(VI) concentrations: U.S. Geological Survey Open-File Report 2016–1004, 28 p., accessed November 28, 2018, at https://doi.org/10.3133/ofr20181045.

Izbicki, J.A., and Michel, R.L., 2004, Movement and age of ground water in the western part of the Mojave Desert, southern California, USA: U.S. Geological Survey Water-Resources Investigations Report 2003–4314, 42 p., accessed November 20, 2018, at https://doi.org/10.3133/wri034314.

Izbicki, J.A., Ball, J.W., Bullen, T.D., and Sutley, S.J., 2008, Chromium, chromium isotopes and selected trace elements, western Mojave Desert, USA: Applied Geochemistry, v. 23, no. 5, p. 1325–1352, accessed September 10, 2018, at https://doi.org/10.1016/j.apgeochem.2007.11.015.

Jacobs Engineering Group, Inc., 2019, Groundwater flow modeling to support the Hinkley chromium background study, San Bernardino County, California: San Francisco, Calif., Pacific Gas and Electric Company, prepared by Jacobs Engineering Group, Redding, Calif., project no. 706888CH, [variously paged], accessed March 24, 2020, at https://geotracker.waterboards.ca.gov/view_documents?global_id=T10000010367&enforcement_id=6411598, with appendixes A through H, at https://geotracker.waterboards.ca.gov/view_documents?global_id=T10000010367&enforcement_id=6411607.

Kruckeberg, A.R., 1984, California serpentines—Flora, vegetation, geology, soils, and management problems: Berkeley, University of California Press, Ltd., 180 p.

Lahontan Regional Water Quality Control Board, 1987, Cleanup and abatement order, no. 6-87-160: South Lake Tahoe, Calif., California Regional Water Quality Control Board, Lahontan Region, 3 p., accessed June 30, 2017, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/cao/docs/refs/2_6_87_160.pdf.

Lahontan Regional Water Quality Control Board, 2001, Cleanup and abatement order, no. CAO 6-01-50, cease nuisance conditions by airborne hexavalent chromium: South Lake Tahoe, Calif., California Regional Water Quality Control Board, Lahontan Region.

Lahontan Regional Water Quality Control Board, 2008, Staff report—Background chromium study Pacific Gas and Electric Company Compressor Station: South Lake Tahoe, Calif., California Regional Water Quality Control Board, Lahontan Region, [variously paged], accessed November 20, 2018, at http://www.swrcb.ca.gov/rwqcb6/water_issues/projects/pge/docs/backgroundstudy_pge8_08.pdf.

Lahontan Regional Water Quality Control Board, 2011, Scientific peer review of PG&E's 2007 groundwater background study report: South Lake Tahoe, Calif., California Regional Water Quality Control Board, Lahontan Region, [variously paged], accessed February 21, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/review.html.

Lahontan Regional Water Quality Control Board, 2012a, Staff report summary and discussion—Peer review of Pacific Gas and Electric Company's 2007 groundwater chromium background study report: South Lake Tahoe, Calif., California Regional Water Quality Control Board, Lahontan Region, 59 p., accessed March 3, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/docs/encl_1.pdf.

Lahontan Regional Water Quality Control Board, 2012b, Investigative order no. R6V-2012-0060—Byproduct plume monitoring in IRZ areas, Pacific Gas and Electric Company (PG&E), Hinkley Compressor Station, San Bernardino County, Calif.: South Lake Tahoe, Calif., California Regional Water Quality Control Board, Lahontan Region, [variously paged], accessed November 20, 2018, at https://geotracker.waterboards.ca.gov/regulators/deliverable_documents/7292661905/r6v_2012_0060.pdf.

Lahontan Regional Water Quality Control Board, 2013, Final environmental impact report—Comprehensive groundwater cleanup strategy for historical chromium discharges from PG&E's Hinkley Compressor Station, San Bernardino County: South Lake Tahoe, Calif., California Regional Water Quality Control Board, Lahontan Region, [variously paged], accessed November 20, 2018, at https://www.waterboards.ca.gov/rwqcb6/water_issues/projects/pge/docs/feir/vol1_intro.pdf.

Lines, G.C., 1996, Ground-water and surface-water relations along the Mojave River, southern California: U.S. Geological Survey Water-Resources Investigations Report 95–4189, 43 p., accessed November 20, 2018, at https://doi.org/10.3133/wri954189.

Matthews, N.E., Vázquez, J.A., and Calvert, A.T., 2015, Age of the Lava Creek supereruption and magma chamber assembly at Yellowstone based on $^{40}Ar/^{39}Ar$ and U–Pb dating of sanidine and zircon crystals: Geochemistry, Geophysics, Geosystems, v. 16, no. 8, p. 2508–2528, accessed August 14, 2016, at https://doi.org/10.1002/2015GC005881.

Meek, N., 1999, New discoveries about the late Wisconsin history of the Mojave River system, *in* Reynolds, R.E., and Reynolds, J., eds., Tracks along the Mojave—A field guide from Cajon Pass to the Calico Mountains and Coyote Lake: Redlands, Calif., San Bernardino County Museum Association Quarterly, v. 46, no. 3, p. 113–117.

Meisling, K.E., and Weldon, R.J., 1989, Late Cenozoic tectonics of the northwestern San Bernardino Mountains, southern California: Geological Society of America Bulletin, v. 101, no. 1, p. 106–128. [Available at https://doi.org/10.1130/0016-7606(1989)101<0106:LCTOTN>2.3.CO;2.]

Miller, D.M., and Bedford, D., 2000, Geologic map database of the El Mirage Lake Area, San Bernardino and Los Angeles Counties, California: U.S. Geological Survey Open-File Report 2000–222, accessed November 11, 2018, at https://pubs.usgs.gov/of/2000/0222/pdf/of00-222_5a.pdf.

Miller, D.M., Dudash, S.L., Green, H.L., Lidke, D.J., Amoroso, L., Phelps, G.A., and Schmidt, K.M., 2007, A new Quaternary view of northern Mojave Desert tectonics suggests changing fault patterns during the late Pleistocene, *in* Miller, D.M., and Valin, Z.C., eds., Geomorphology and tectonics at the intersection of Silurian and Death Valleys, southern California: U.S. Geological Survey Open-File Report 2007–1424, p. 157–171, accessed November 27, 2018, at https://doi.org/10.3133/ofr20071424.

Miller, D.M., Haddon, E.K., Langenheim, V.E., Cyr, A.J., Wan, E., Walkup, L.C., and Starratt, S.W., 2018, Middle Pleistocene infill of Hinkley Valley by Mojave River sediment and associated lake sediment—Depositional architecture and deformation by strike-slip faults, *in* Miller, D.M., ed., The Mojave River from sink to source: The 2018 Desert Symposium Field Guide and Proceedings, April 2018, accessed November 27, 2018, at http://www.desertsymposium.org/2018%20DS%20Against%20the%20Current.pdf.

Miller, D.M., Langenheim, V.E., and Haddon, E.K., 2020, Geologic map and borehole stratigraphy of Hinkley Valley and vicinity, San Bernardino County, California: U.S. Geological Survey Scientific Investigations Map 3458,. [Available at https://doi.org/10.3133/sim3458.]

Mojave Water Agency, 2014, Geospatial library: Mojave Water Agency web page, accessed May 22, 2014, at https://www.mojavewater.org/data-maps/geospatial-library/.

Pacific Gas and Electric Company, 2009, Request to increase the discharge volume for ethanol source area in-situ remediation project, PG&E Hinkley Compressor Station, Hinkley, Calif.: San Francisco, Calif., Pacific Gas and Electric Company, 2 p., accessed November 27, 2018, at https://geotracker.waterboards.ca.gov/regulators/deliverable_documents/1980183243/pge_hinkley_enclsr1_070809.pdf.

Pacific Gas and Electric Company, 2011, Addendum #2 to the feasibility study: San Francisco, Calif., Pacific Gas and Electric Company, [variously paged], accessed May 7, 2020, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/docs/addndm2.pdf.

Reheis, M.C., Bright, J., Lund, S.P., Miller, D.M., Skipp, G., and Fleck, R.J., 2012, A half-million-year record of paleoclimate from the Lake Manix core, Mojave Desert, California: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 365–366, p. 11–37. [Available at https://doi.org/10.1016/j.palaeo.2012.09.002.]

Reimann, C., and de Caritat, P., 1998, Chemical elements in the environment: Berlin, Germany, Springer-Verlag, 398 p. [Available at https://doi.org/10.1007/978-3-642-72016-1.]

Riverside County Superior Court, 1996, Judgement after trial—Mojave Basin Area Adjudication—city of Barstow, et al v. city of Adelanto, et al—Riverside County Superior Court Case No. 208568: Riverside County Superior Court, 140 p., accessed October 25, 2022, at https://www.watereducation.org/sites/main/files/file-attachments/final_judgment.pdf?1474673523.

Seymour, W., 2016, Hydrologic and geologic controls on groundwater recharge along the Mojave River floodplain aquifer: San Diego, Calif., San Diego State University, master's thesis, 73 p., accessed November 20, 2018, at https://digitallibrary.sdsu.edu/islandora/object/sdsu%3A1599.

Seymour, W., and Izbicki, J.A., 2018, Pre-development water-levels in the Centro area of the Mojave River groundwater basin, *in* Miller, D.M., ed., Against the current—The Mojave River from sink to source: The 2018 Desert Symposium Field Guide and Proceedings, p. 165, April 2018, accessed November 27, 2018, at http://www.desertsymposium.org/2018%20DS%20Against%20the%20Current.pdf.

Smith, D.B., Cannon, W.F., Woodruff, L.G., Solano, F., and Ellefsen, K.J., 2014, Geochemical and mineralogical maps for soils of the conterminous United States: U.S. Geological Survey Open-File Report 2014–1082, 386 p., accessed June 11, 2019, at https://doi.org/10.3133/ofr20141082.

Stamos, C.L., Martin, P., Nishikawa, T., and Cox, B.F., 2001, Simulation of ground-water flow in the Mojave River basin, California: U.S. Geological Survey Water Resources-Investigations Report 2001–4002, ver. 3, 129 p., accessed November 20, 2018, at https://doi.org/10.3133/wri014002.

Stantec, 2013, Compliance with provision 1.C of Cleanup and abatement order R6V-2008-0002-A4 and requirements of Investigation order R6V-2013-0029: San Francisco, Calif., Pacific Gas and Electric Company, prepared by Stantec, Lafayette, Calif., [variously paged]. [Available at https://geotracker.waterboards.ca.gov/esi/uploads/geo_report/8126426041/SL0607111288.pdf.]

Stone, R.S., 1957, Ground-water reconnaissance in the western part of the Mojave Desert, California, with particular respect to the boron content of well water: U.S. Geological Survey Open-File Report 57–107, 102 p., accessed April 11, 2019, at https://doi.org/10.3133/ofr57107.

Thompson, D.G., 1929, The Mohave Desert region, California, a geographic, geologic, and hydrologic reconnaissance: U.S. Geological Survey Water Supply Paper 578, 759 p., accessed November 20, 2018, at https://doi.org/10.3133/wsp578.

U.S. Environmental Protection Agency, 1993, Chromium emissions from industrial process cooling towers—Background information for proposed standards: Research Triangle Park, N.C., Office of Air Quality Planning and Standards, EPA-453/R-93-022, 241 p.

U.S. Geological Survey, 2018, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed December 31, 2018, at https://doi.org/10.5066/F7P55KJN.

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