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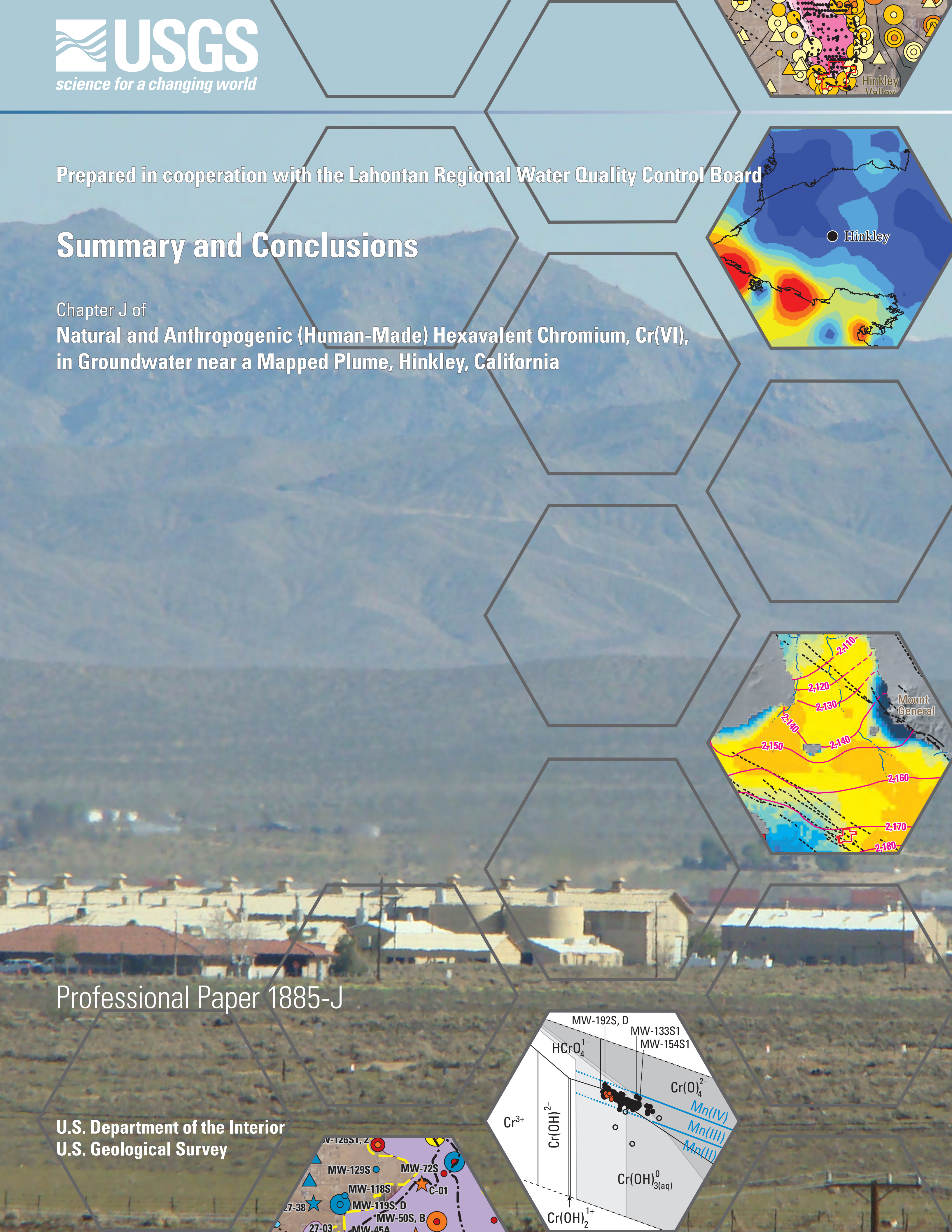

Prepared in cooperation with the Lahontan Regional Water Quality Control Board

Summary and Conclusions

Chapter J of

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

Professional Paper 1885-J

U.S. Department of the Interior
U.S. Geological Survey

Front cover

Hexavalent chromium concentrations in water from monitoring and domestic wells.

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.

Groundwater-level contours and depth to water during predevelopment (pre-1930) conditions.

Redox potential as a function of pH for wells sampled by the U.S. Geological Survey.

Summative-scale scores and summative-scale hexavalent chromium plume extent in Hinkley and Water Valleys.

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

By John A. Izbicki, Krishangi D. Groover, Whitney A. Seymour, David M. Miller,
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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)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ounce, avoirdupois (oz)	0.00003527	milligram (mg)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

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).

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

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

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of chemical constituents in solids are given in milligrams per kilogram (mg/kg).

Tritium concentrations are given in tritium units (TU).

Ohm-meters is a measure of electrical resistivity used to describe the resistance of geologic materials to an electric current.

Redox, a combination of the words reduction and oxidation, refers to chemical processes in which one substance or molecule gains an electron (is reduced and its oxidation state is decreased) and another loses an electron (is oxidized and its oxidation state is increased). The processes of oxidation and reduction occur simultaneously and cannot occur independently.

Isotopes are atoms of an element having the same number of protons but a different number of neutrons within the atomic nucleus. This difference may cause differences in the physical and chemical behavior of less abundant isotopes to the more commonly abundant isotope that can be used to understand the physical movement of water or constituents dissolved in water within the environment. Isotopic abundances are commonly expressed as ratios of the isotope of interest to the more abundant isotope in a sample to the ratio of those isotopes in a standard. The values are expressed in delta notation as part per thousand differences between the isotopic ratios in the sample and standard. Some isotopes are stable and do not change (decay) over time; other isotopes are unstable (radioactive) and change (decay) into different elements or isotopes over time. Radiogenic isotopes are produced by the decay of unstable (radioactive) isotopes.

A type-1 statistical error is a term used to describe a false positive. A false positive is the mistaken rejection of a null hypothesis even though it’s true. In a courtroom setting, a type I error would correspond to convicting an innocent defendant. A type-II statistical error is a term used to describe a false negative. A false negative is the failure to reject a hypothesis that is actually false. In a courtroom setting, a type II error would correspond to acquitting a guilty defendant. The probability of making a type-I or a type-II statistical error in a statistical test is controlled by the value of the significance criteria α for type-I errors and β for type-II errors.

Tons per square inch (equal to 1.406 kilograms per millimeter squared) is a unit of pressure used to describe the resistance of geologic materials to penetration during the cone penetration test.

Abbreviations

Cr(III)	trivalent chromium having an oxidation state of +3
Cr(t)	total chromium
Cr(VI)	hexavalent chromium having an oxidation state of +6
Eh	redox potential
EPA	U.S. Environmental Protection Agency
Fe	Iron
Fe(II)	ferrous iron having an oxidation state of +2
GAMA	Groundwater Ambient Monitoring Assessment
HCBSM	Hinkley Chromium Background Study Model
ICP-MS	inductively coupled plasma-mass spectrometry
IRP	Independent Review Panel
IRZ	in situ reactive zone
LRL	laboratory reporting level
MCL	maximum contaminant level
Mn	manganese
Mn(III)	manganese having an oxidation state of +3
Mn(IV)	manganese having an oxidation state of +4
N	nitrogen
NMR	nuclear magnetic resonance
NO_3	nitrate
PCA	principal component analysis
per mil	parts per thousand ratios of the sample to a standard value
PG&E	Pacific Gas and Electric Company
pmc	percent modern carbon
pXRF	portable (handheld) X-ray fluorescence
Q4 2015	October–December 2015
R^2	coefficient of determination
RWQCB	Regional Water Quality Control Board
SRL	study reporting level
TU	tritium units
TWG	technical working group
USGS	U.S. Geological Survey
UTL_{95}	upper 95-percent tolerance limit
ybp	years before present

Summary and Conclusions

By John A. Izbicki, Krishangi D. Groover, Whitney A. Seymour, David M. Miller, John G. Warden, and Laurence G. Miller

Executive Summary

Chromium concentrations in rock and aquifer material in Hinkley and Water Valleys in the Mojave Desert, 80 miles northeast of Los Angeles, California, are generally low compared to the average chromium concentration of 185 milligrams per kilogram (mg/kg) in the average bulk continental crust. Chromium concentrations in felsic, coarse-textured “Mojave-type” deposits, composed of Mojave River stream (alluvium) and lake-margin (beach) deposits sourced from the Mojave River, are as low as 5 mg/kg, with a median concentration of 23 mg/kg in aquifer materials adjacent to the screened intervals of sampled wells. The most abundant chromium-containing mineral within aquifer materials in Hinkley and Water Valleys is magnetite. Magnetite is resistant to weathering, and about 90 percent of chromium remains within unweathered mineral grains. However, chromium-containing hornblende diorite and basalt are present in surrounding uplands, and chromium-containing actinolite is present within some aquifer materials.

Although geologic abundance of chromium is clearly important, hexavalent chromium, Cr(VI), concentrations in alkaline oxic groundwater are related to additional factors. Hexavalent chromium concentrations in groundwater are influenced by a combination of processes including (1) mineralogy and the weathering rates of chromium-containing minerals; (2) texture of aquifer deposits; (3) accumulation of chromium weathered from minerals within surface coatings on mineral grains; (4) oxidation of accumulated trivalent chromium ,Cr(III) to Cr(VI) in the presence of manganese oxides (Mn oxides), including the abundance and oxidation states of those Mn oxides; (5) pH-dependent desorption of chromium from coatings on the surfaces of mineral grains into groundwater during appropriate aqueous geochemical conditions; and (6) age (time since recharge) of groundwater. The pH of groundwater increases with groundwater age (time since recharge) as a result of silicate weathering, and desorption of Cr(VI) from aquifer deposits increases with increasing pH as long as groundwater remains oxic. In the absence of the detailed geologic, geochemical, and hydrologic data collected as part of this study, pH-dependent sorption, evaluated as the Cr(VI) occurrence probability at the measured pH, is an effective indicator of natural or anthropogenic Cr(VI).

The Pacific Gas and Electric Company (PG&E) Hinkley compressor station is used to compress natural gas as it is transported through a pipeline from Texas to California. Between 1952 and 1964, cooling water containing Cr(VI) was discharged to unlined ponds and released into groundwater in unconsolidated aquifers. The extent of groundwater containing evidence of at least some anthropogenic Cr(VI) was 5.5 square miles (mi^2) and was estimated using a summative scale incorporating geologic, geochemical, and hydrologic data collected from more than 100 wells between March 2015 and November 2017. The summative-scale Cr(VI) plume extent is larger than the 2.2 mi^2 extent of the October–December 2015 (Q4 2015) regulatory Cr(VI) plume but is smaller than the 8.3 mi^2 maximum mapped extent of Cr(VI) greater than the interim regulatory Cr(VI) background concentration of 3.1 micrograms per liter (µg/L). The summative-scale Cr(VI) plume is within felsic, low-chromium aquifer material deposited by the Mojave River described as Mojave-type deposits and is within the area covered by the PG&E monitoring well network.

Background Cr(VI) concentrations were calculated using the computer program ProUCL 5.1 as the upper 95-percent tolerance limit, $UTL_{95,}$ using data from wells outside the summative-scale Cr(VI) plume extent collected between April 2017 and March 2018. The overall UTL_{95} for undifferentiated, unconsolidated deposits in the eastern and western subareas and the northern subarea upgradient of the Mount General fault in Hinkley Valley was 3.8 µg/L; this value is similar to the overall UTL_{95} value of 3.9 µg/L calculated for Mojave-type deposits in Hinkley and Water Valleys, and is similar to the maximum Cr(VI) concentration of older groundwater in contact with Mojave-type deposits of 3.6 µg/L.

In most cases the overall UTL_{95} value may be an acceptable Cr(VI) background value near the Cr(VI) plume margin; however, UTL_{95} values for the various subareas in Hinkley and Water Valleys provide greater resolution of Cr(VI) background that may be important for some purposes. The UTL_{95} values for undifferentiated, unconsolidated deposits in the eastern, western, and northern subareas upgradient of the Mount General fault were 2.8, 3.8, and 4.8 µg/L, respectively. The UTL_{95} value of 2.8 µg/L for wells screened in undifferentiated, unconsolidated deposits in the eastern subarea is important for plume management because the Hinkley compressor station and most of the summative-scale Cr(VI) plume are within the eastern subarea. A UTL_{95} value of 2.3 µg/L was calculated for Mojave-type deposits downgradient from the Hinkley compressor station. This value represents Cr(VI) concentrations that may have been present in that part of the aquifer had Cr(VI) not been released from the Hinkley compressor station, and it reflects coarser textured deposits in this area and the proximity of those deposits to recharge areas along the Mojave River that results in younger (post-1952), less alkaline groundwater than in wells farther downgradient. This value may be a suitable metric for Cr(VI) cleanup goals within the Cr(VI) plume after regulatory updates. A separate UTL_{95} value of 5.8 µg/L was calculated for mudflat/playa deposits and older groundwater near Mount General in the eastern subarea. The UTL_{95} values calculated for undifferentiated, unconsolidated deposits in the northern subarea downgradient from the Mount General fault and in Water Valley, including lacustrine (lake) deposits and material eroded from basalt and Miocene deposits, were 9.0 and 6.4 µg/L, respectively.

Hexavalent chromium concentrations in more than 70 domestic wells sampled between January 27 and 31, 2016, ranged from less than the study reporting level of 0.1–4.0 µg/L, with a median concentration of 1.2 µg/L. Hexavalent chromium concentrations in water from domestic wells did not exceed UTL_{95} values within subareas where the wells were located. Water from 47 percent of domestic wells sampled between January 27 and 31, 2016, had arsenic, uranium, or nitrate concentrations above a maximum contaminant level.

Anthropogenic Cr(VI) within groundwater downgradient from the Hinkley compressor station is treated by PG&E using bioremediation by adding ethanol as a reductant within a volume of aquifer known as the in situ reactive zone (IRZ). Laboratory microcosm studies showed that Cr(VI) is rapidly reduced to Cr(III) with additions of ethanol. Reduced Cr(III) is sorbed and is sequestered into crystalline iron and manganese oxides on the surfaces of mineral grains within the microcosms during a period of several months. Trivalent chromium was reoxidized back to Cr(VI) within 2 weeks of return to oxic (oxygen present) conditions within the microcosms. As much as 10 percent of added Cr was oxidized to Cr(VI) in microcosms prepared using recent Mojave River aquifer material, and as much as 20 percent of added Cr was oxidized to Cr(VI) in microcosms prepared using older Mojave River aquifer material. Less Cr(VI) (less than 3 percent of Cr added before reduction) was released to the aqueous phase, and this release occurred following longer time periods of oxygen exposure. Sequestration of chromium with manganese oxides during reduction facilitates reoxidation of Cr(III) to Cr(VI) under oxic conditions. Future maintenance of anoxic (oxygen absent) conditions would ensure continued sequestration of chromium as Cr(III) within IRZ treated portions of the Cr(VI) plume.

Although Cr(VI) within the summative-scale Cr(VI) plume may have an anthropogenic history associated with releases from the Hinkley compressor station, Cr(VI) concentrations less than the UTL_{95} values for the various subareas may not require regulatory attention. The regulatory Cr(VI) plume can be updated using the UTL_{95} values calculated as part of this study. The updated regulatory Cr(VI) plume extent would lie within the summative-scale Cr(VI) plume extent. The authority to establish regulatory Cr(VI) background values, clean-up goals, and future site management practices resides with the Lahontan Regional Water Quality Control Board.

J.1. Introduction

The Pacific Gas and Electric Company (PG&E) Hinkley compressor station (fig. J.1), in the Mojave Desert, 80 miles (mi) northeast of Los Angeles, California (fig. J.2), is used to compress natural gas as it is transported through a pipeline from Texas to California. Between 1952 and 1964, cooling water was treated with a compound containing hexavalent chromium, Cr(VI), to prevent corrosion of machinery within the compressor station. Cooling water containing Cr(VI) was discharged to unlined ponds and released into groundwater in unconsolidated aquifers downgradient from the Hinkley compressor station. Since 1964, cooling-water management practices have been used that do not contribute chromium to groundwater.

Pacific Gas and Electric Company informed the Lahontan Regional Water Quality Control Board (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 2010, site cleanup was projected to require between 10 and 95 years and was expected to cost between \$36 and \$176 million depending on the Cr(VI) cleanup goal selected (Haley and Aldrich, Inc., 2010; Pacific Gas and Electric Company, 2011). A 2007 study funded by PG&E estimated the natural Cr(VI) background to be 3.1 micrograms per liter (µg/L; CH2M Hill, 2007), and this concentration was adopted as the interim Cr(VI) background concentration for regulatory purposes by the Lahontan RWQCB (Lahontan Regional Water Quality Control Board, 2008).

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

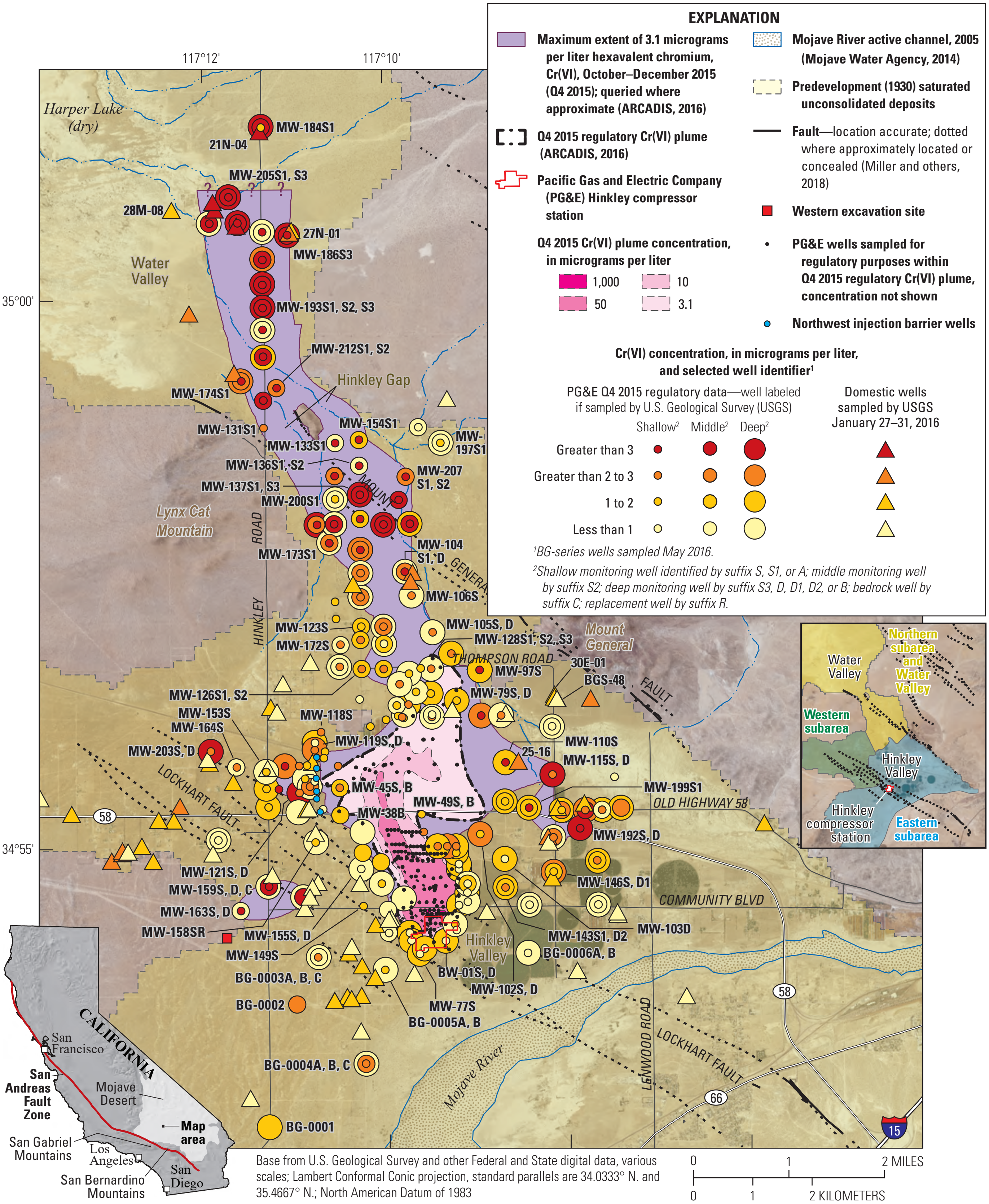
In October–December 2015 (Q4 2015), the regulatory Cr(VI) plume extended about 3 mi downgradient from the historical release location within the Hinkley compressor station, while groundwater having Cr(VI) concentrations greater than 3.1 µg/L was present through Hinkley Gap into Water Valley, more than 8 mi north of the Hinkley compressor station (fig. J.2; ARCADIS, 2016). In response to limitations associated with the 2007 study methodology and an apparent increase in the mapped extent of the plume between 2008 and 2012, the Lahontan RWQCB (Lahontan Regional Water Quality Control Board, 2012) agreed that the 2007 background-concentration study be updated. The U.S. Geological Survey (USGS) was requested to do the updated Cr(VI) background study.

J.1.1. Aqueous Geochemistry of Chromium

Chromium may be present in groundwater as reduced trivalent chromium, Cr(III), or as oxidized Cr(VI) (Rai and Zachara, 1984; Guertin and others, 2004). Trivalent chromium is the predominant form of chromium in acidic, reduced groundwater (Rai and Zachara, 1984; Ball and Nordstrom, 1998). Hexavalent chromium is the predominant form of chromium in alkaline, oxic groundwater (Rai and Zachara, 1984; Ball and Nordstrom, 1998). In the past, Cr(VI) in groundwater was considered evidence of anthropogenic (human-made) contamination (Hem, 1959), but Cr(VI) has been recognized as naturally occurring in alkaline, oxic groundwater (Robertson, 1975. 1991; Ball and Izbicki, 2004; Izbicki and others, 2008).

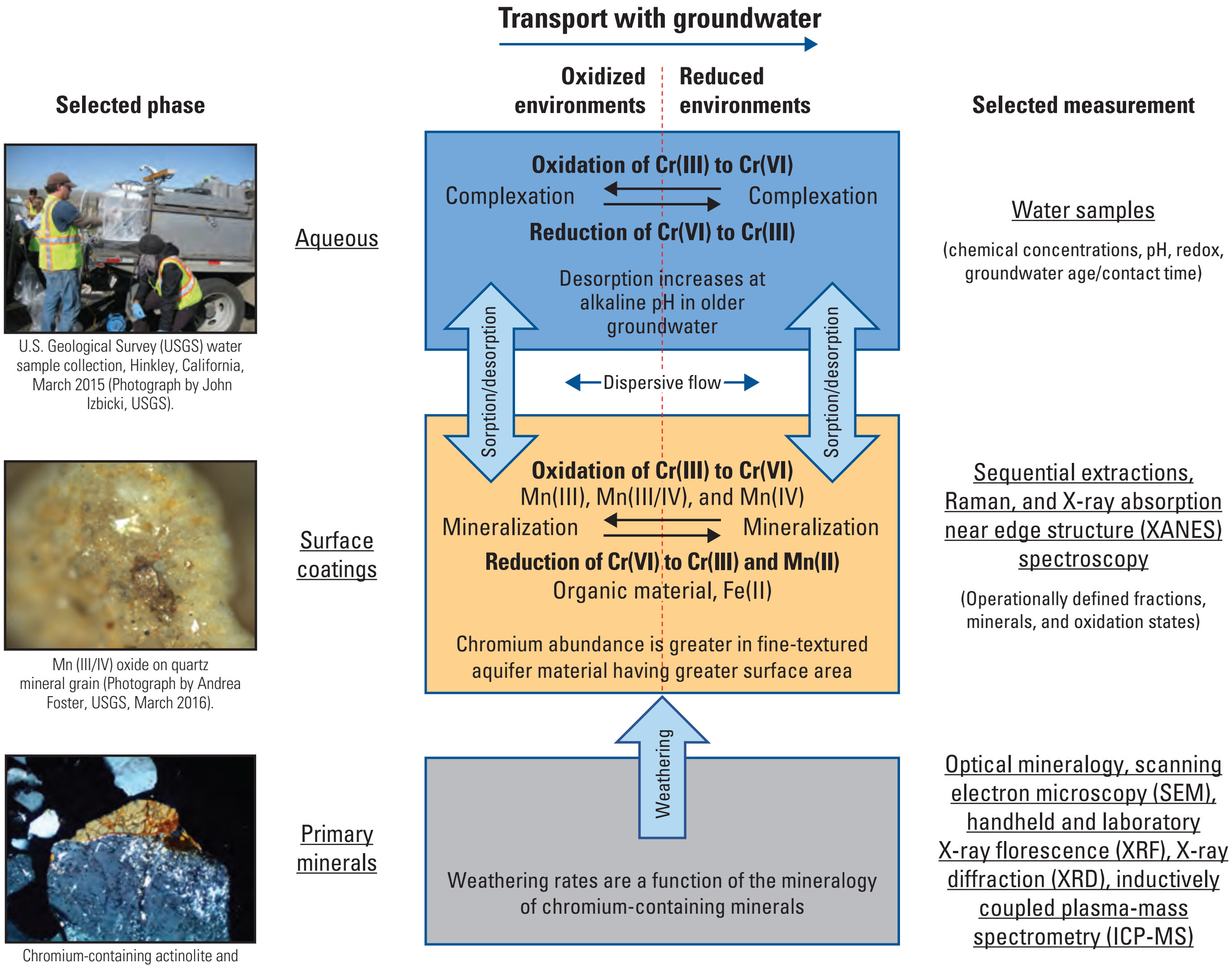
Trivalent chromium is an essential micronutrient. Hexavalent chromium is a carcinogen if inhaled (Daugherty, 1992; Agency for Toxic Substances and Disease Registry, 2012) and may be a carcinogen if ingested (Sedman and others, 2006; Beaumont and others, 2008). The U.S. Environmental Protection Agency (2019) does not have a maximum contaminant level (MCL) for Cr(VI) in drinking water but does have a MCL of 100 µg/L for total chromium, Cr(t). The California MCL for Cr(t) is 50 µg/L (State Water Resources Control Board, 2017). The cost of treatment was not considered during development of the 2014 California MCL for Cr(VI) of 10 µg/L, and the MCL was withdrawn in August 2017. The California MCL for Cr(t) is being used for regulation of drinking water supplies until a new California MCL for Cr(VI) is developed (State Water Resources Control Board, 2017).

Natural Cr(VI) concentrations in alkaline, oxic groundwater pumped for public supply can exceed MCLs developed for the protection of public health in some geologic and hydrologic settings within California (Chung and others, 2001; Ball and Izbicki, 2004; Dawson and others, 2008; Izbicki and others, 2008, 2012, 2015; Morrison and others, 2009; Mills and others 2011; Manning and others, 2015; McClain and others, 2016; Hausladen and others, 2018), the southwestern United States (Robertson, 1975, 1991), and elsewhere in the world (Oze and others, 2007; Kazakis and others, 2015) where chromium abundance in rock and soils is high. In addition to chromium abundance in geologic material, natural Cr(VI) concentrations in groundwater are influenced by a combination of processes including (1) mineralogy and the weathering rates of chromium-containing minerals; (2) texture of aquifer deposits; (3) accumulation of chromium weathered from minerals within surface coatings on mineral grains; (4) oxidation of accumulated Cr(III) to Cr(VI) in the presence of manganese oxides (Mn oxides), including the abundance and oxidation states of those Mn oxides; (5) pH-dependent desorption of chromium from coatings on the surfaces of mineral grains into groundwater during appropriate aqueous geochemical conditions; and (6) age (time since recharge) of groundwater (Richard and Bourg, 1991; Kotaś and Stasicka, 2000; Izbicki and others, 2008; Ščančar and Milačič, 2014; fig. J.3).



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

Figure J.2. Hexavalent chromium concentrations in water from monitoring wells sampled by Pacific Gas and Electric Company for regulatory purposes, October through December 2015, and from domestic wells sampled by the U.S. Geological Survey, January 2016, Hinkley and Water Valleys, western Mojave Desert, California. Data are available in chapter E (appendix E.1, table E.1.1) and U.S. Geological Survey (2021).



U.S. Geological Survey (USGS) water sample collection, Hinkley, California, March 2015 (Photograph by John Izbicki, USGS).

Mn (III/IV) oxide on quartz mineral grain (Photograph by Andrea Foster, USGS, March 2016).

Chromium-containing actinolite and metamorphic mineral grain (Photograph by Krishangi Groover, USGS, January 2017).

Modified from Izbicki and others (2008) and Ščančar and Milačič (2014).

[Cr(III), trivalent chromium; Cr(VI), hevavalent chromium; Fe(II), ferrous iron; Mn(II), manganese-2 oxide; Mn(III), manganese-3 oxide; Mn(IV), manganese-4 oxide; Mn(III/IV), mixed manganese-3 and manganese-4 oxide]

Figure J.3. Conceptual model of processes controlling mineral weathering and hexavalent chromium, Cr(VI), concentrations in groundwater in the presence of oxide coatings on the surfaces of mineral grains.

After chromium has weathered from mineral grains, it typically must oxidize to Cr(VI) before it can desorb from those grains and enter groundwater. During natural conditions, chromium oxidation commonly occurs in the presence of Mn oxides, including Mn(III) (Nico and Zasoski, 2000); Mn(III)/(IV) (Oze and others, 2007); and Mn(IV) oxides (Schroeder and Lee, 1975). Oxidation of Cr(III) to Cr(VI) is enhanced in fine-textured aquifer material and in older slow-moving groundwater, where diffusive transport of reactants to reactive Mn oxides on mineral grains facilitates oxidation (Hausladen and others, 2019). Once oxidized, Cr(VI) on the surfaces of mineral grains is potentially mobile into oxic groundwater under alkaline pH. Desorption of Cr(VI) from mineral grains increases in alkaline water until about pH 9.0 when almost all Cr(VI) is desorbed (Xie and others, 2015). In settings having an abundance of easily weathered chromium-containing minerals and reactive Mn oxides, Cr(VI) may occur naturally in groundwater at concentrations of concern for public health (Izbicki and others, 2008; Morrison and others, 2009; Mills and others, 2011). In areas having comparatively low geologic abundance of chromium, Cr(VI) may be present in groundwater at concentrations of concern for public health as contact time with aquifer materials, weathering of minerals within those materials, oxidation of Cr(III) to Cr(VI), and pH increases along groundwater flowpaths—as long as oxic conditions persist within groundwater (Izbicki and others, 2008, 2015; Manning and others, 2015).

Microbially mediated reduction of Cr(VI) to Cr(III) may occur in the presence of ferrous iron, Fe(II), and organic material (Oze and others, 2007) and may be inhibited in the presence of nitrate (Izbicki, 2008). Abiotic reduction of Cr(VI) to Cr(III) also can occur in the presence of Fe(II) at pH greater than 5.6 and in the presence of hydrogen sulfide at lower pH (Fendorf and others, 2000).

J.1.2. Hydrologic Setting

Hinkley Valley occupies about 62 square miles (mi^2) and contains about 36 mi^2 of unconsolidated deposits that were saturated under predevelopment (pre-1930) conditions (fig. J.2). Unconsolidated deposits in Hinkley and Water Valleys consist of locally derived material and material eroded from the San Bernardino Mountains to the south and San Gabriel Mountains to the southwest, transported to the area by the Mojave River. The most productive aquifers in Hinkley and Water Valleys are composed primarily of unconsolidated “Mojave-type” deposits consisting of alluvium and lake margin (beach) deposits sourced from the Mojave River (Miller and others, 2018, 2020a). Locally derived alluvium and weathered bedrock also are used for domestic supply in some areas. On the basis of differences in geology and hydrology, Hinkley Valley was divided into eastern, western, and northern subareas; the study area also included Water Valley to the north of Hinkley Valley (fig. J.2).

The eastern subarea is closest to recharge areas along the Mojave River. Mojave-type deposits in this area are commonly less than 160 feet (ft) thick and overlie fine-textured lacustrine (lake) deposits described as “blue clay” in drillers’ and geologists’ logs (ARCADIS and CH2M Hill, 2011). Deposits above the blue clay compose the upper aquifer. Fine-textured deposits, described as “brown clay,” are interspersed throughout the upper aquifer and, in places, are confining units that separate the upper aquifer into shallow and deep zones (ARCADIS and CH2M Hill, 2011). Mudflat/playa deposits sourced from the Mojave River are present at land surface near Mount General and at depth within the eastern subarea. These deposits also are commonly described as brown clay in drillers’ and geologists’ logs. The western subarea consists of Mojave-type deposits, overlying groundwater-discharge deposits, lacustrine deposits, and weathered bedrock (CH2M Hill, 2013; Miller and others, 2018, 2020a). The northern subarea consists of Mojave River alluvium overlying fine-textured lacustrine and mudflat/playa deposits sourced from the Mojave River and from local materials (Stantec, 2013; Miller and others, 2018, 2020a). Aquifers within Water Valley are composed of lake-margin deposits sourced from the ancestral Mojave River along the margins of Harper (dry) Lake that overlie and interfinger with locally derived alluvium (Miller and others, 2018, 2020a). Partly consolidated Miocene (5.3–23 million years old) deposits underlie part of the western subarea, and locally derived alluvium containing weathered material eroded in part from Miocene deposits east of the study area is present within parts of the northern subarea downgradient from the Mount General fault and in Water Valley.

Groundwater recharge occurs primarily from intermittent streamflow in the Mojave River. Large streamflows greater than about 5,000 cubic feet per second (ft^3/s) occur on average once every 5–7 years (Lines, 1996; Stamos and others, 2001; Seymour, 2016). In some years recharge from the Mojave River can exceed 100,000 acre-feet (acre-ft; Lines, 1996; Stamos and others, 2001; Jacobs Engineering Group, Inc., 2019). During predevelopment conditions, groundwater flow was from the Mojave River north toward Hinkley Gap into Water Valley (fig. J.4) where groundwater discharged by evaporation along the margins of Harper (dry) Lake (Thompson, 1929). The Lockhart fault impedes groundwater flow in Hinkley Valley (Stamos and others, 2001; Jacobs Engineering Group, Inc., 2019); less is known about the effect of the Mount General fault on groundwater flow. The Lockhart and Mount General faults consist of numerous mapped strands (Miller and others, 2018, 2020a).

Since the early 1950s, water-level declines were as much as 60 ft in wells near the Hinkley compressor station as a result of agricultural pumping (Stone, 1957; California Department of Water Resources, 1967; Seymour and Izbicki, 2018; fig. J.4). As a consequence of water-level declines, saturated Mojave-type deposits in much of the western and northern subareas are a thin veneer, commonly less than 10 ft thick, overlying weathered bedrock in the western subarea (CH2M Hill, 2013) and fine-textured lacustrine and mudflat/playa deposits in the northern subarea (Stantec, 2013). Many monitoring wells in the western subarea are completed partly or entirely in weathered bedrock, and many monitoring wells in the northern subarea are completed partly or entirely in fine-textured lacustrine and mudflat/playa deposits. Younger Mojave-type deposits in much of Hinkley Valley and lake-margin deposits in much of Water Valley were formerly, extensively pumped for agricultural supply and were largely above the water table at the time of this study (2015–18; Stamos and others, 2001; Miller and others, 2018, 2020a). As a result of groundwater development, irrigation return, and to a lesser extent septic discharges, were important components of recharge at the time of this study (Stamos and others, 2001; Jacobs Engineering Group, Inc., 2019).

The Hinkley compressor station and most of the Q4 2015 regulatory Cr(VI) plume are within the eastern subarea (ARCADIS, 2016). In Q4 2015, the regulatory Cr(VI) plume extended 3 mi downgradient from the historical discharge location within the Hinkley compressor station (fig. J.2; ARCADIS, 2016). However, the actual extent of Cr(VI) associated with the release was uncertain; Cr(VI) concentrations in water from wells greater than the interim regulatory background of 3.1 µg/L were present as far downgradient as Water Valley, more than 8 mi north of the Hinkley compressor station (fig. J.2; ARCADIS, 2016).

Groundwater monitoring for Cr(VI) began in the late 1980s (Ecology and Environment, Inc., 1988), remediation of Cr(VI) began in 1992, and clean-up was projected to require 10–95 years in 2010 (Haley and Aldrich, Inc., 2010; Pacific Gas and Electric Company, 2011). Monitoring wells installed for regulatory purposes by PG&E were most commonly identified by the prefix MW, with sites numbered sequentially in the order they were drilled. Shallower wells at a site, commonly screened across or just below the water table, were identified with the suffix S or S1. Deeper wells were identified with the suffix D, D1, or D2; or with the suffix S2 or S3 if a hydrologically important clay layer was not present. Older monitoring wells were identified with the suffixes A or B for shallower or deeper wells, respectively. The suffix C was used for MW wells penetrating bedrock or consolidated material, and the suffix R was used if a well was destroyed and subsequently replaced. Wells installed by PG&E as part of the USGS Cr(VI) background study were identified with the prefix BG. The BG sites were numbered sequentially in the order they were permitted, and wells at each BG site were identified from shallowest to deepest with the suffixes A, B, or C. Although drilling methods changed over time and in response to site conditions, most monitoring wells were drilled with auger rigs. For most wells drilled after 2011, core material was available from near the water table to the bottom of the borehole, often to below the depth of the deepest well at a site.

J.1.3. Purpose and Scope

The purpose of the USGS background study was to estimate background Cr(VI) concentrations in groundwater upgradient, downgradient, near the margins, and within the footprint of the mapped PG&E Cr(VI) plume in Hinkley, California. The scope of the study included eight tasks (table J.1; Izbicki and Groover, 2016, 2018) discussed in chapter A within this professional paper.

Geologic, geochemical, and hydrologic data collected as part of this study (Tasks 1–3 in table J.1) were used to develop metrics within a summative scale (table J.2) to address the question “What is the area of groundwater containing anthropogenic Cr(VI) associated with releases from the Hinkley compressor station?” (Task 6 in table J.1). Hexavalent chromium concentrations in water from wells outside the area containing anthropogenic Cr(VI) from the Hinkley compressor station were used to estimate background Cr(VI) concentrations in different parts of Hinkley and Water Valleys (Task 7 in table J.1). Hydrologic data, including predevelopment water-levels, groundwater recharge and discharge, aquifer properties, and groundwater movement across the Lockhart fault (Task 4 in table J.1), were collected to support updates to an existing groundwater-flow model by PG&E consultants (Jacobs Engineering Group, Inc., 2019). Groundwater chemistry data, including groundwater-age data, were compared with particle-tracking data computed from the updated groundwater-flow model (Jacobs Engineering Group, Inc., 2019) to understand differences in the conceptualization of the groundwater system and the extent of anthropogenic Cr(VI) in groundwater underlying Hinkley Valley developed from geochemical data and from hydraulic data (Task 5 in table J.1; Izbicki and Groover, 2018). Laboratory microcosm experiments were used to evaluate the fate of chromium during and after in situ reduction, a mitigation measure that has been used in Hinkley Valley to reduce Cr(VI) to Cr(III) and remove chromium from groundwater (Task 8 in table J.1).

Wells sampled as part of this study were selected by the USGS in collaboration with a technical working group (TWG) composed of Hinkley community members, the Independent Review Panel (IRP) Manager (Project Navigator, Ltd.), the Lahontan RWQCB, PG&E, and consultants for PG&E. The selected wells represent a mutually agreed upon, spatially distributed set of wells covering a range of geologic, geochemical, and hydrologic settings within and near the Q4 2015 regulatory Cr(VI) plume.

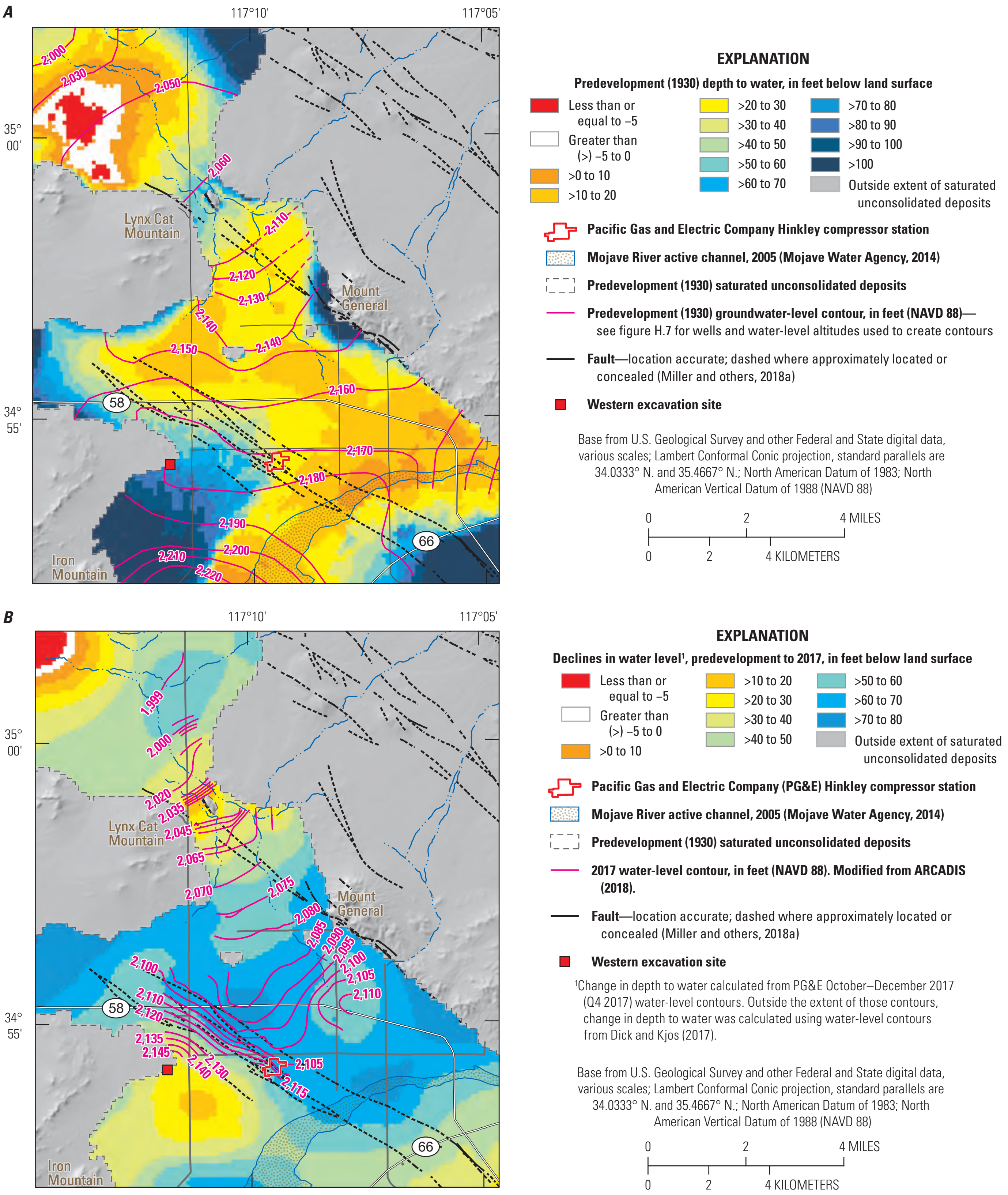
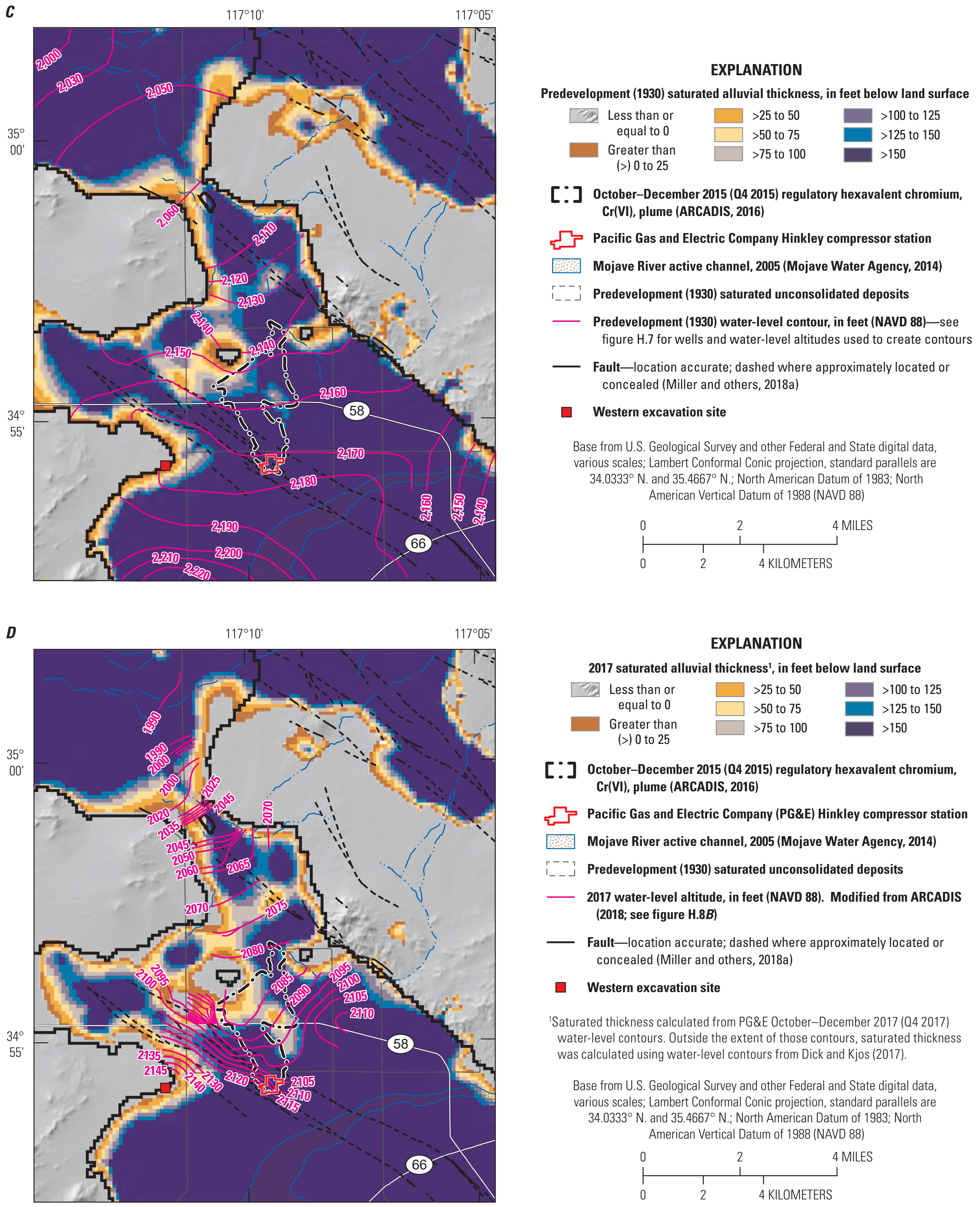


Figure J.4. Groundwater-level contours and depth to water during *A*, predevelopment (pre-1930) conditions, *B*, the change in water levels between predevelopment and 2017 conditions, *C*, the predevelopment thickness of saturated alluvium, and *D*, the saturated thickness of saturated alluvium at the time of this study, Hinkley and Water Valleys, western Mojave Desert, California. Data are available in ARCADIS (2018), U.S. Geological Survey (2021), and appendix H.1 (table H.1.2).



EXPLANATION

Predevelopment (1930) saturated alluvial thickness, in feet below land surface

- Less than or equal to 0
- Greater than (>) 0 to 25
- >25 to 50
- >50 to 75
- >75 to 100
- >100 to 125
- >125 to 150
- >150

October–December 2015 (Q4 2015) regulatory hexavalent chromium, Cr(VI), plume (ARCADIS, 2016)

Pacific Gas and Electric Company Hinkley compressor station

Mojave River active channel, 2005 (Mojave Water Agency, 2014)

Predevelopment (1930) saturated unconsolidated deposits

Predevelopment (1930) water-level contour, in feet (NAVD 88)—see figure H.7 for wells and water-level altitudes used to create contours

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

Western excavation site

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; North American Vertical Datum of 1988 (NAVD 88)

0 2 4 MILES

0 2 4 KILOMETERS

EXPLANATION

2017 saturated alluvial thickness[1], in feet below land surface

- Less than or equal to 0
- Greater than (>) 0 to 25
- >25 to 50
- >50 to 75
- >75 to 100
- >100 to 125
- >125 to 150
- >150

October–December 2015 (Q4 2015) regulatory hexavalent chromium, Cr(VI), plume (ARCADIS, 2016)

Pacific Gas and Electric Company (PG&E) Hinkley compressor station

Mojave River active channel, 2005 (Mojave Water Agency, 2014)

Predevelopment (1930) saturated unconsolidated deposits

2017 water-level altitude, in feet (NAVD 88). Modified from ARCADIS (2018; see figure H.8*B*)

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

Western excavation site

[1] Saturated thickness calculated from PG&E October–December 2017 (Q4 2017) water-level contours. Outside the extent of those contours, saturated thickness was calculated using water-level contours from Dick and Kjos (2017).

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; North American Vertical Datum of 1988 (NAVD 88)

0 2 4 MILES

0 2 4 KILOMETERS

Figure J.4.—Continued

Table J.1. Tasks and questions addressed by the U.S. Geological Survey background hexavalent chromium, Cr(VI), study, Hinkley and Water Valleys, western Mojave Desert, California.

[Modified from Izbicki and Groover (2016, 2018)]

Task number and description	Where discussed	Purpose
1: Evaluation of existing data	Chapter D	Identify areas near the mapped Cr(VI) plume having Cr(VI) concentration trends of concern to the study.
2: Analyses of rock and alluvium	Chapters B and C	Determine if there are naturally occurring geologic sources of chromium in aquifer deposits.
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 Hinkley compressor station.
4: Evaluation of local hydrogeologic conditions	Chapter H	Determine how differences in local geohydrology within the western, northern (including Water Valley), and eastern (including the plume and upgradient area) subareas influence the movement of groundwater and anthropogenic (human-made) Cr(VI) from the Hinkley compressor station.
5: Evaluation of groundwater movement	Appendix H.2	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.
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 Pacific Gas and Electric Company (PG&E) compressor station and areas that contain Cr(VI) from other sources.
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 Hinkley compressor station.
8: Fate of chromium during and after in situ reduction	Chapter I	Determine if Cr(VI) reduced to trivalent chromium, Cr(III), through additions of ethanol within the in situ reductive zone (IRZ) may reoxidize or if Cr(VI) is permanently removed from groundwater.

Table J.2. Summative-scale questions used to determine the extent of anthropogenic (human-made) and natural hexavalent chromium, Cr (VI), Hinkley and Water Valleys, western Mojave Desert, California.

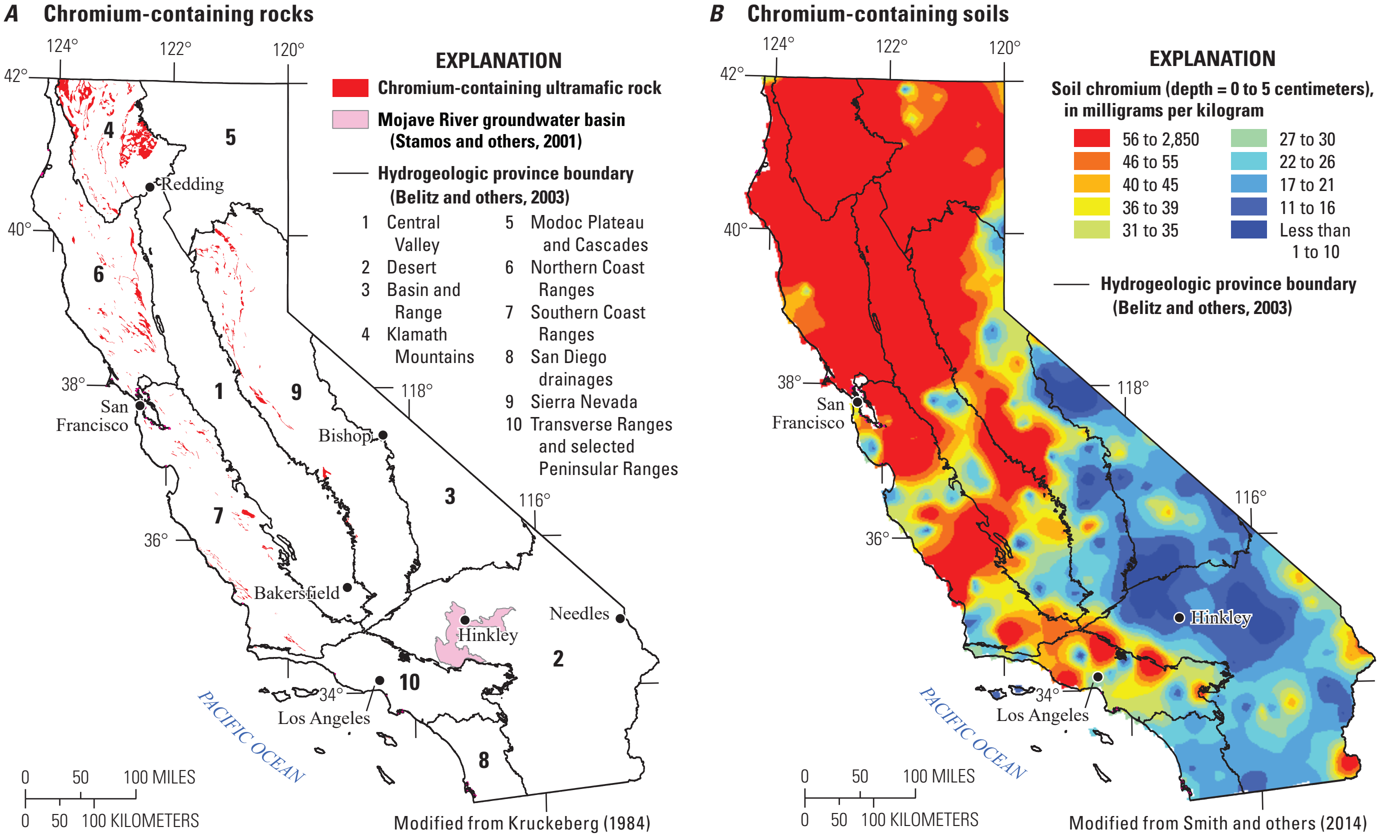
[Items in the scale are formulated as questions requiring a binary, yes or no, answer. A score of −1 is consistent with a natural source. A score of 1 is consistent with an anthropogenic source. **Abbreviations**: USGS, U.S. Geological Survey; PG&E, Pacific Gas and Electric Company; mg/kg, milligrams per kilogram; HXRF, handheld X-ray fluorescence; GAMA, Groundwater Ambient Monitoring and Assessment]

	Item	Data source	Chapter where data are discussed	Answer and score	
				Yes	No
	Geologic questions				
1	Are geologic materials at the well screen fine-textured (predominately silt or finer)?	USGS lithologic descriptions of core material (PG&E lithologic descriptions from well logs or drillers logs used if core material was not available)	Chapters B, C, and E	−1	1
2	Do geologic materials at the well screen contain more than 85 mg/kg chromium?	Portable HXRF measurements of core material	Chapter B	−1	1
3	Do geologic materials at the well screen contain more than 970 mg/kg manganese?	Portable HXRF measurements of core material	Chapter B	−1	1
	Geochemical questions				
4	Are Cr(VI) concentrations trended upward or downward, or have no trend, with time?	Regulatory Cr(VI) data collected between July 2012 and June 2017, interpreted with Kendall's Tau	Chapter D	1	−1
5	Is there an excess of Cr(VI) with respect to pH, with the probability of natural Cr(VI) occurrence at the measured pH less than 30 percent?	pH-dependent sorption evaluated on the basis of pH and Cr(VI) concentrations in California-wide GAMA data	Chapter E	1	−1
6	Is there an excess of Cr(VI) with respect to other trace elements?	Principal component analyses (PCA) of Cr(VI), arsenic, vanadium, uranium, iron, and manganese	Chapter E	1	−1
	Hydrologic questions				
7	Was the water recharged from the Mojave River?	delta Oxygen-18 ($\delta^{18}O$) and delta Deuterium (δD) data	Chapter F	1	−1
8	Does the water contain some fraction (at least 10 percent) "modern" water and a carbon-14 activity greater than 85-percent modern carbon?	Tritium, helium-3, helium-4, and carbon-14 data	Chapter F	1	−1

J.2. Chromium and Selected Element Concentrations in Rock, Surficial Alluvium, and Core Material

Chromium and other selected trace-element concentrations in rock, surficial alluvium, and core material (including core material adjacent to the screened intervals of wells sampled as part of this study) were measured using portable (handheld) X-ray fluorescence (pXRF). These results are presented in chapter B within this professional paper.

Chromium concentrations in rock and surficial alluvium in Hinkley and Water Valleys are generally low compared to elsewhere in California (fig. J.5) and compared to the average chromium concentration in the average bulk continental crust of 185 milligrams per kilogram (mg/kg; Reimann and de Caritat, 1998). Locally, chromium concentrations are as high as 530 mg/kg in mafic hornblende diorite that crops out along the western margin of Hinkley Valley in Iron Mountain, and the concentrations are as high as 295 mg/kg in surficial alluvium eroded from hornblende diorite (Groover and Izbicki, 2018). Other chromium-containing rocks in the area are either (1) not consistently high in chromium; (2) have limited areal extent; or (3) in the case of basalt, are present only in Water Valley. In contrast, chromium concentrations within actinolite and fuchsite (chromium-mica) in mafic rock within the San Gabriel Mountains, 40 mi southwest of the study area, (fig. J.2) were as high as 8,600 mg/kg. Chromium-containing actinolite was identified in older Mojave River deposits within Hinkley Valley.



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 J.5. Chromium concentrations in *A*, rock and *B*, soil in California. Modified from Kruckeberg (1984); Smith and others (2014).

Chromium concentrations in core material adjacent to the screened intervals of more than 100 wells sampled as part of the USGS Cr(VI) background study ranged from less than the study reporting level (SRL) of 5 to 410 mg/kg, with a median concentration of 23 mg/kg. Chromium concentrations in core material were lower in the eastern subarea and higher in the western and northern (including Water Valley) subareas. Chromium concentrations were higher in silt and finer textured material and lower in coarser textured material. Chromium concentrations in core material adjacent to the screened interval of sampled wells were log-normally distributed until about 85 mg/kg, with 3 percent of chromium concentrations greater than 85 mg/kg (fig. J.6*A*). Manganese can oxidize Cr(III) to Cr(VI) (Schroeder and Lee, 1975). Similar to Cr, Mn concentrations in core material also are associated with silt and finer textured material and were log-normally distributed until about 970 mg/kg, with 5 percent of Mn concentrations greater than 970 mg/kg (fig. J.6*B*).

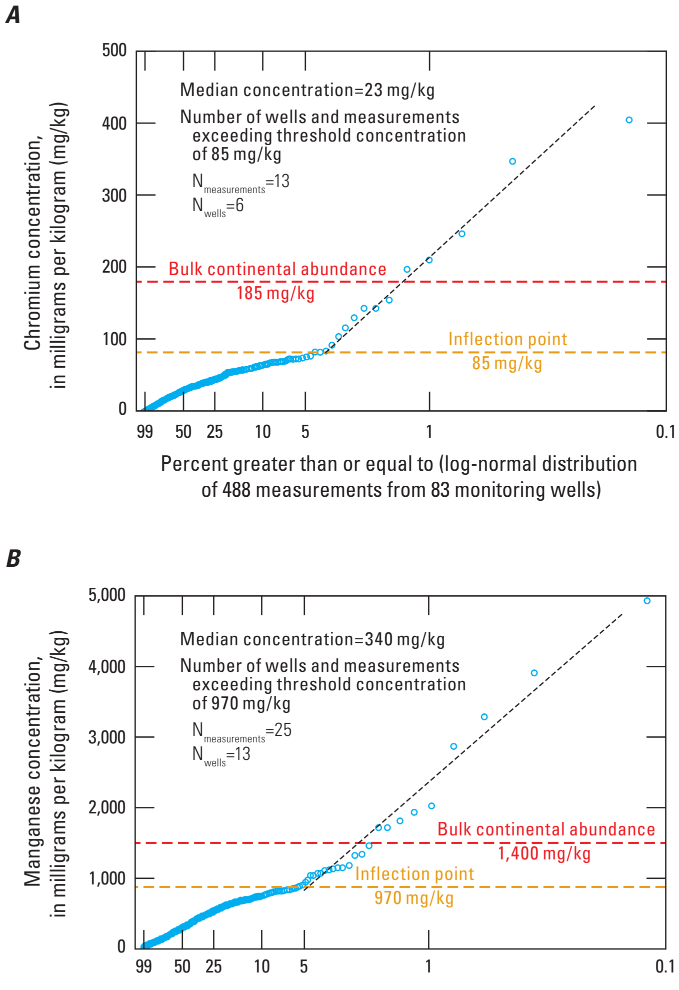


Figure J.6. Distribution of *A,* chromium and *B,* manganese in core material adjacent to the screened interval of sampled wells, Hinkley and Water Valleys, California. Data are available in Groover and Izbicki (2018).

Principal component analyses (PCA) of 18 elements within surficial alluvium, rock, and core material measured using pXRF showed distinct elemental assemblages associated with (1) recent and older Mojave River alluvium and Mojave-type lake-margin (beach) deposits, (2) alluvium eroded from mafic rock including hornblende diorite that crops out on Iron Mountain along the western margin of Hinkley Valley, (3) alluvium eroded from felsic volcanic and hydrothermal rock that crops out on Mount General along the eastern margin of Hinkley Valley, and (4) mudflat/playa and other fine-textured deposits, including material with visually abundant iron- (Fe) and Mn-oxide coatings. The elemental assemblage of older Mojave River alluvium is more mafic than recent Mojave River alluvium. Older Mojave River alluvium contains a higher abundance of Fe, Mn, and Cr eroded from mafic rock in the San Gabriel Mountains and contains a lower abundance of potassium and rubidium eroded from felsic rock in the San Bernardino Mountains (Groover and Izbicki, 2019). As a result of these differences, chromium concentrations within Mojave-type deposits are higher in the western subarea of Hinkley Valley and in parts of the eastern subarea upgradient from the Lockhart fault than within Mojave-type deposits elsewhere in the study area. Mudflat/playa deposits contain higher concentrations of most trace elements measured, including chromium, than other deposits in part because of their fine texture and increased surface area for sorption of these elements to the surfaces of mineral grains. Materials with visually abundant Fe- and Mn-oxide coatings also contain higher concentrations of most trace elements measured, including chromium, compared to similar texture deposits that lack visually abundant oxide coatings.

On the basis of PCA results, most sampled wells completed in Mojave-type deposits did not show shifts in elemental composition attributable to admixtures of local mafic or other source materials. Where present, admixtures did not generally result in increased chromium concentrations in core material adjacent to the screened intervals of sampled wells. However, chromium concentrations as high as 155 mg/kg in core material adjacent to the screened interval of well MW-186S3 in Water Valley are attributable to admixtures of local basalt.

Chromium concentrations greater than 85 mg/kg, and Mn concentrations greater than 970 mg/kg in core material adjacent to the screened interval of sampled wells, were selected for use as metrics (threshold values) within the summative scale developed to identify natural and anthropogenic Cr(VI) in water from wells (questions 2–3 in table J.2). Most Cr and Mn concentrations greater than threshold values were present in silt or finer textured material, and texture also was selected as a metric to identify natural and anthropogenic Cr(VI) in water from wells (question 1 in table J.2). However, chromium concentrations greater than the threshold value of 85 mg/kg were present in sand-textured Mojave River alluvium, having visibly abundant accumulations of secondary Fe- and Mn-oxide coatings on mineral grains in core material adjacent to the screened interval of well MW-128S1 near the leading edge of the Q4 2015 regulatory Cr(VI) plume.

J.3. Chromium in Minerals and Selected Aquifer Materials

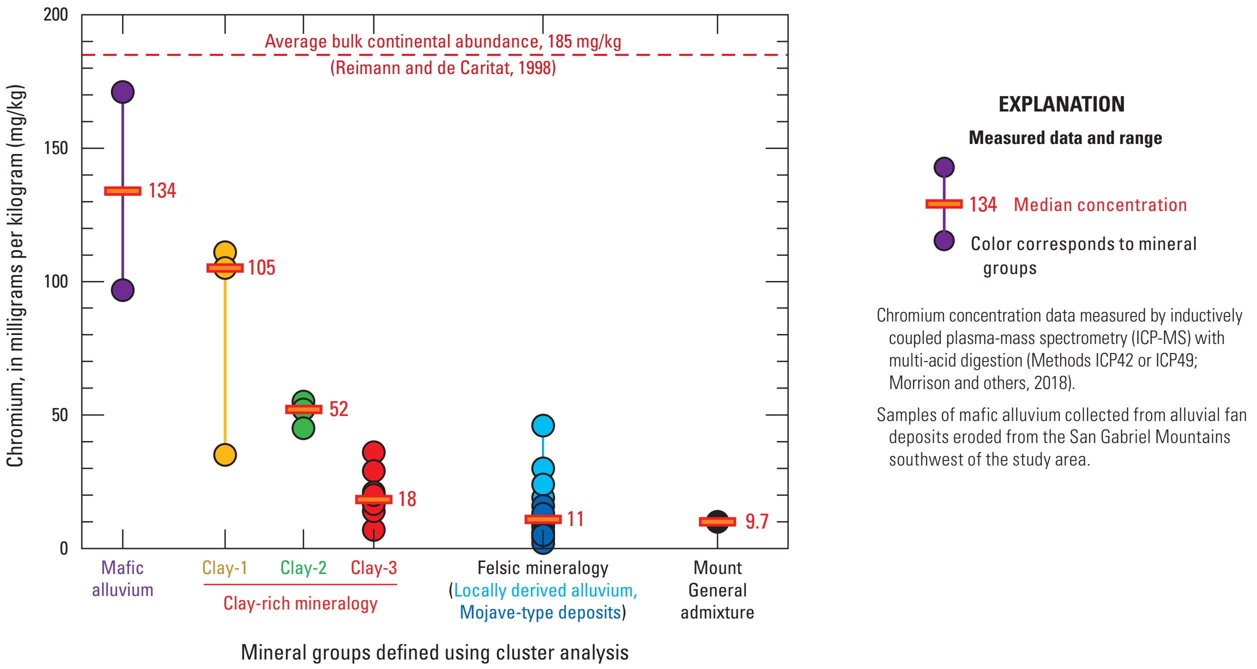
Chromium composition and mineralogy of selected aquifer materials, aquifer materials sorted by particle size and density (Morrison and others, 2018), and the chemical composition of coatings within operationally defined fractions extractable from the surfaces of mineral grains (Chao and Sanzolone, 1989; Wenzel and others, 2001), are presented in chapter C within this professional paper. These data were collected to support interpretations developed on the basis of pXRF data (chapter B).

Chemical analyses of surficial alluvium and core material by inductively coupled plasma-mass spectrometry (ICP-MS) are generally considered to be higher quality (more accurate and precise) than analyses by pXRF. Chromium concentrations measured using ICP-MS with multi-acid digestion (Taggart, 2002; Morrison and others, 2018) for 34 samples of surficial alluvium and core material ranged from 2 to 110 mg/kg, with a median concentration of 14 mg/kg. Chromium concentrations were lowest in coarse-textured Mojave River alluvium, with a median concentration of 6 mg/kg. For comparison, two samples collected as part of this study from alluvial fan deposits eroded from mafic rock in the San Gabriel Mountains west of the study area were as high as 170 mg/kg. Chromium concentrations measured by ICP-MS were similar to concentrations in the same materials measured by pXRF, on the basis of least-squares regression analysis with coefficient of determination (R^2=0.97).

Quartz and feldspar were the most abundant minerals in unconsolidated deposits that compose aquifers in Hinkley and Water Valleys, especially within recent and older Mojave River deposits. The chromium-containing amphiboles actinolite and hornblende were identified optically in older Mojave River alluvium and in locally derived alluvium eroded from Iron Mountain, respectively. Minerals identified by X-ray diffraction clustered in six groups from generally higher to lower chromium concentrations (fig. J.7). Higher chromium concentrations were measured in samples from mafic alluvial fan deposits eroded from the San Gabriel Mountains and from three clay-rich mineral groups associated with (1) weathered rock from Iron Mountain, (2) lacustrine deposits in the western subarea and mudflat/playa deposits in the northern subarea, and (3) granitic, felsic materials. Lower chromium concentrations were measured in samples having a lower clay mineral content and a felsic mineral composition eroded from locally derived alluvium or transported to Hinkley Valley by the Mojave River (fig. J.7). Mudflat/playa deposits and brown clay sampled within the eastern subarea contained few clay minerals and were composed of fine-textured felsic minerals transported to Hinkley Valley by the Mojave River. One sample containing metamorphic mineral admixtures from Mount General clustered by itself and had a low chromium concentration of 9.7 mg/kg.

Samples were sorted by density to isolate the “heavy-mineral” fraction having a specific gravity greater than 3.32. Minerals within the heavy-mineral fraction were identified using optical techniques, X-ray diffraction, and scanning electron microscopy with energy dispersive X-ray spectroscopy. Chromium concentrations within the heavy-mineral fraction were as high as 1,250 mg/kg. Most chromium within the heavy-mineral fraction was substituted within magnetite mineral grains less than 100 micrometers in diameter (very fine sand and finer texture material). Chromite, the most abundant chromium-containing mineral globally (Reimann and de Caritat, 1998), was not identified within the heavy-mineral fraction of core material from wells in Hinkley or Water Valleys. Magnetite was less abundant in locally derived and Miocene materials than in Mojave River alluvium and was not identified in weathered hornblende diorite bedrock. Chromium was not commonly detected in the “light-mineral” fraction having a specific gravity less than 2.85, and chromium within clay-rich mineral groups (fig. J.7) does not appear to be substituted within the interlayers of clay minerals.

Admixtures from various source terrains were identified in some core material on the basis of optical, X-ray diffraction, and scanning electron microscopy data. These included (1) basaltic minerals in MW-154S1 in the northern subarea, (2) metamorphic minerals eroded from Mount General in fine-textured materials from MW-192 and surficial mudflat/playa deposits in the eastern subarea near Mount General, and (3) metamorphic minerals from Iron Mountain in the western subarea. Although basaltic and metamorphic rock eroded from Iron Mountain may contribute chromium to aquifer material, rocks that crop out on Mount General are commonly low in chromium and unlikely to contribute chromium to aquifer material.



Chromium concentration data measured by inductively coupled plasma-mass spectrometry (ICP-MS) with multi-acid digestion (Methods ICP42 or ICP49; Morrison and others, 2018).

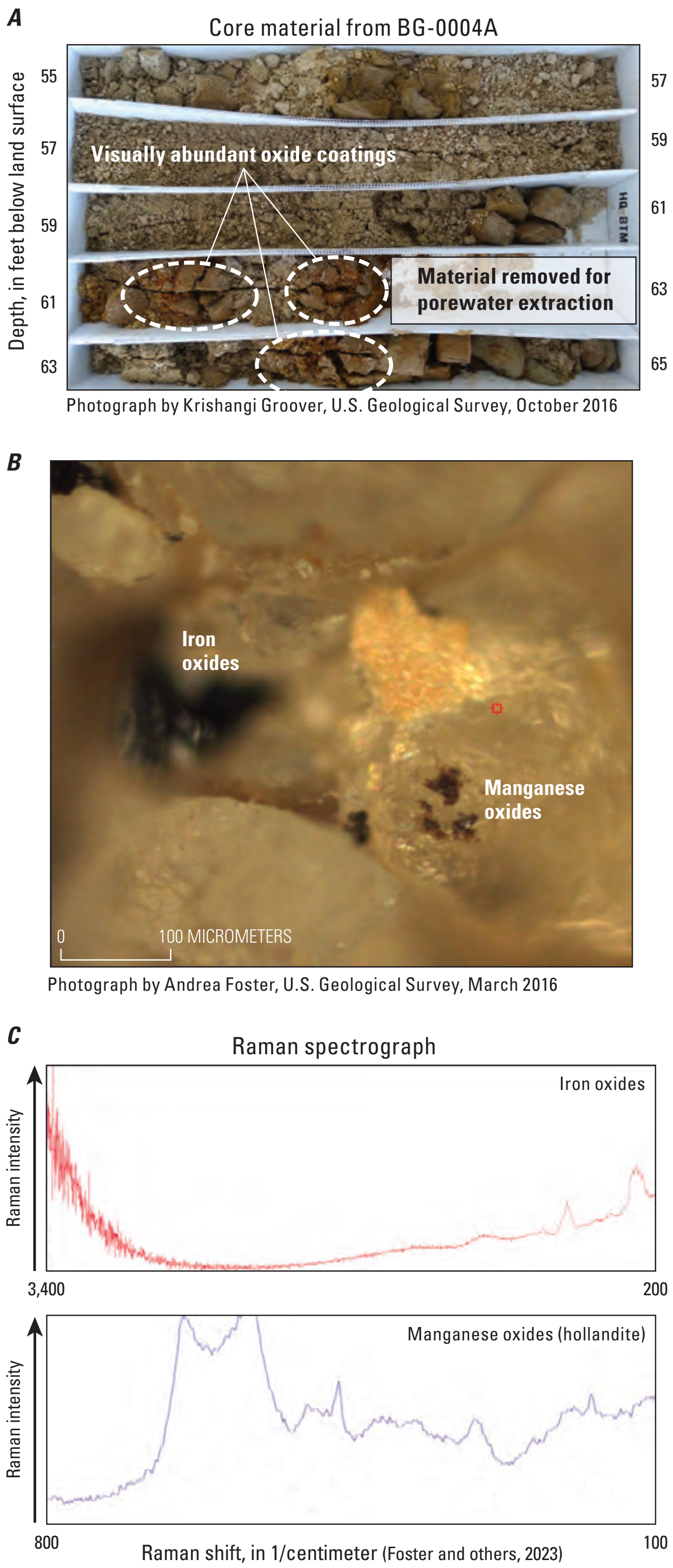
Samples of mafic alluvium collected from alluvial fan deposits eroded from the San Gabriel Mountains southwest of the study area.

Figure J.7. Chromium concentrations in selected samples of surficial alluvium and core material, grouped by mineralogy, Hinkley and Water Valleys, and the Sheep Creek fan, western Mojave Desert, California. Data are from Morrison and others (2018).

Extensive mineral weathering, including dissolution pits and weathering rinds, was identified optically in Miocene materials underlying unconsolidated deposits in the western subarea of Hinkley Valley, and extensive mineral weathering was identified in alluvium within Water Valley containing material eroded from Miocene rock east of the study area. Almost all magnetite present within mudflat/playa deposits penetrated by well MW-154S1 had weathered to hematite. Manganese substituted within magnetite likely weathered to highly oxidative Mn(IV) oxides which may readily oxidize Cr(III) to Cr(VI).

Comparison of ICP-MS data and sequential extraction data (Chao and Sanzolone, 1989; Wenzel and others, 2001) show that less than 10 percent of chromium was extractable from mineral grains. More than 90 percent of chromium in aquifer material within Hinkley and Water Valleys was not extractable and resides within unweathered mineral grains. Most extractable chromium was within the strong acid (4-normal nitric acid) extractable fraction. Extractable chromium concentrations were higher in fine-textured material, weathered hornblende diorite, and extensively weathered Miocene deposits. In contrast, 22 percent of arsenic and 24 percent of uranium was extractable and presumably was weathered from mineral grains. Extractable arsenic and uranium concentrations were higher in fine-textured aquifer material than in coarse-textured material.

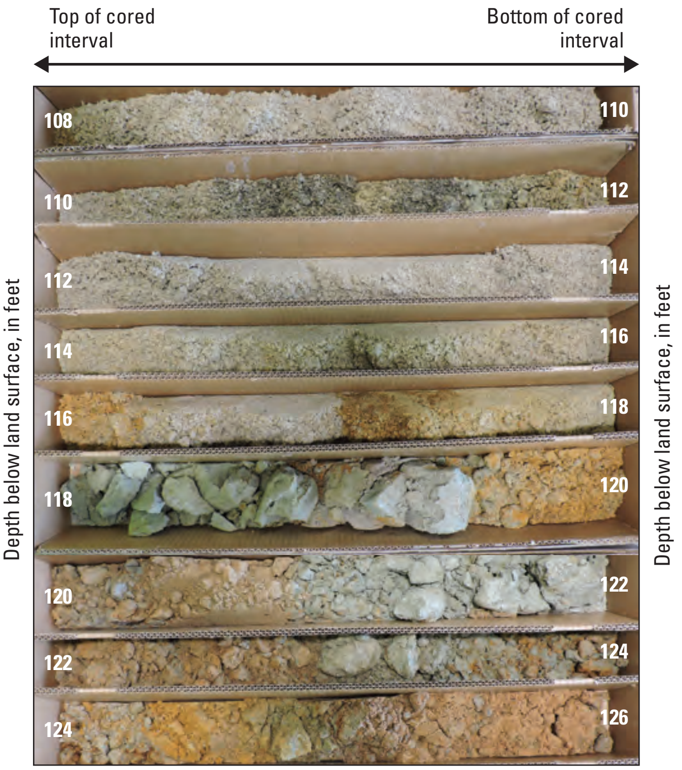
Visually abundant Fe- and Mn-oxide accumulations were observed in core material near geologic and lithologic contacts and near the water table from a number of sites in Hinkley and Water Valleys (fig. J.8; Foster and others, 2023). These visually abundant oxide accumulations may be associated with redox contrasts near geologic and lithologic contacts and near the water table. Large Fe- and Mn-oxide accumulations also were observed in core material at a number of sites within the Q4 2015 regulatory Cr(VI) plume, including SA-RW-48 about 0.3 mi downgradient from the Hinkley compressor station (fig. J.9). Similar large oxide accumulations were not observed at sites outside the Q4 2015 regulatory Cr(VI) plume. These large oxide accumulations resulted from reactions between aquifer material and water with high concentrations of Cr(VI), a strong oxidant, as groundwater containing anthropogenic Cr(VI) moved downgradient from the Hinkley compressor station through the aquifer. Although composed of felsic Mojave River deposits, chromium concentrations extracted within the weakly sorbed fraction from the surface of mineral grains at SA-RW-48 were the highest measured as part of this study, exceeding Cr(VI) concentrations in weathered hornblende diorite bedrock and weathered Miocene deposits. The data indicate that at least some anthropogenic chromium released from the Hinkley compressor station has reacted with aquifer materials and is sorbed on the surfaces of those materials. Much of this anthropogenic chromium is weakly sorbed and potentially highly mobile into groundwater.



Photograph by Krishangi Groover, U.S. Geological Survey, October 2016

Photograph by Andrea Foster, U.S. Geological Survey, March 2016

Figure J.8. Oxides within core material at BG-0004A, 64 feet below land surface: *A*, photograph of core material, *B*, photograph of quartz mineral grain with iron- and manganese-oxide coatings, and *C*, Raman spectrographs for iron- and manganese-oxide coatings on quartz mineral grain, Hinkley Valley, western Mojave Desert, California.



Photograph by Krishangi Groover, U.S. Geological Survey, March 2017

Figure J.9. Oxides on core material from SA-RW-48 within the October–December 2015 (Q4 2015) regulatory hexavalent chromium, Cr(VI), plume downgradient from the Hinkley compressor station, Hinkley Valley, western Mojave Desert, California.

The distribution of chromium by particle size, mineral density, and the extractable (sorbed) fraction was examined for selected wells completed in (1) weathered hornblende diorite bedrock underlying the western subarea, (2) Miocene deposits underlying the western subarea and locally derived alluvium in Water Valley that was partly eroded from Miocene deposits to the east, (3) secondary oxidized alluvium present near the water table and near lithologic or geologic contacts, and (4) mudflat/playa deposits in the eastern and northern subareas. Brown clay and mudflat/playa deposits in the eastern subarea near Mount General have a low-chromium, felsic mineralogy similar to Mojave River deposits and do not contain high concentrations of chromium, although highly oxidative Mn(IV) oxides within these materials may facilitate oxidation of Cr(III) to Cr(VI). Chemical and mineralogic data did not indicate high natural abundance, unusual mineralogy, or unusual sorptive properties for chromium in unconsolidated deposits within Mojave River alluvium at sites downgradient from the “western excavation site” in the western subarea.

Inductively coupled plasma-mass spectrometry, mineralogic, and sequential extraction data presented in chapter C within this professional paper are more expensive to collect and analyze than pXRF data presented in chapter B within this professional paper. Consequently, these data were not measured on core material from every well sampled as part of the USGS Cr(VI) background study. Although interpretations derived from ICP-MS, mineralogic, and sequential extraction data are consistent with interpretations derived from pXRF data, these data were not used to develop metrics within the summative scale used to identify natural and anthropogenic Cr(VI) in water from wells.

J.4. Analyses of Regulatory Water-Quality Data

Pacific Gas and Electric Company has monitored groundwater near Hinkley for Cr(VI) and other constituents since the late 1980s (Ecology and Environment, Inc., 1988). By June 2017, more than 20,000 samples had been collected and analyzed for Cr(VI) for regulatory purposes. Trends in Cr(VI) concentration data are presented in chapter D within this professional paper.

Most Cr(VI) regulatory samples were analyzed using the U.S. Environmental Protection Agency (EPA) Method 218.6 (U.S. Environmental Protection Agency, 1994) with a laboratory reporting level (LRL) of 0.2 µg/L. Between July 2012 and December 2015, selected samples were analyzed for low-level Cr(VI) concentrations using a modified version of EPA Method 218.6 with a LRL of 0.06 µg/L. Field-blank and duplicate data collected during this period indicated a SRL equal to the LRL of 0.2 µg/L for Cr(VI) analyses by EPA Method 218.6 and a SRL of 0.12 µg/L for low-level Cr(VI) analyses, with a precision of 0.09 µg/L at a concentration of 3.1 µg/L or about 3 percent. Low-level regulatory Cr(VI) analyses were no longer done by PG&E for regulatory purposes after implementation of a new Cleanup and Abatement Order in December 2015 (Lahontan Regional Water Quality Control Board, 2015).

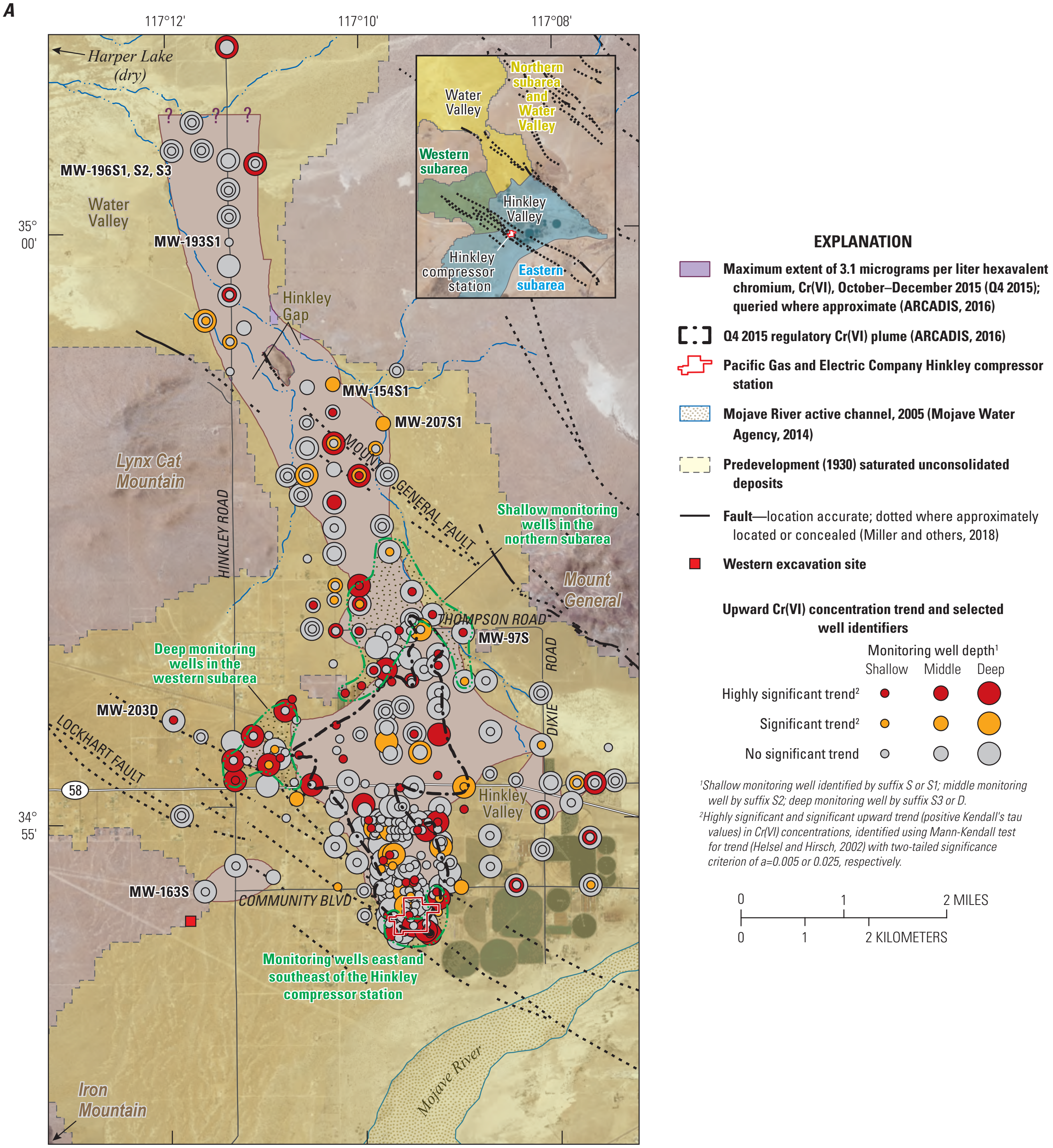
Hexavalent chromium concentration trends were calculated using the Mann-Kendall test for trends (Kendall, 1938; Mann, 1945; Helsel and Hirsch, 2002; Helsel and others, 2020) for more than 560 monitoring wells between July 2012 and June 2017. Selection of the July 2012 through June 2017 period allowed the largest number of wells having the greatest spatial coverage during a single period to be evaluated for trends. Hexavalent chromium concentration trends represent hydrologic conditions and groundwater-management activities during this period. The Mojave River did not flow during the period tested for Cr(VI) concentration trends and groundwater recharge from the river did not occur between 2012 and 2017. Water levels generally declined between 2012 and 2017 as a result of agricultural pumping and the lack of recharge from the Mojave River. In addition, the July 2012 through June 2017 period includes most of the March 2015 through November 2017 period of data collection for this study.

Upward Cr(VI) concentration trends (fig. J.10*A*) were present in 102 monitoring wells near the Q4 2015 regulatory Cr(VI) plume and throughout Hinkley and Water Valleys. Upward trends indicate that the Cr(VI) plume southeast of the Hinkley compressor station, within strands of the Lockhart fault and near the leading edge of the regulatory Cr(VI) plume within the northern subarea, may have expanded between 2012 and 2017. Expansion of the Cr(VI) plume southeast of the Hinkley compressor station triggered a regulatory investigation in 2018 (ARCADIS, 2018; Lahontan Regional Water Quality Control Board, 2018). However, upward Cr(VI) concentration trends commonly associated with declining water levels were widely distributed outside the Q4 2015 regulatory Cr(VI) plume (fig. J.10*A*). These widely distributed upward Cr(VI) concentration trends may be associated with natural Cr(VI) sources including movement of Cr(VI)-containing groundwater from weathered bedrock, fine-textured deposits, or secondarily oxidized material distributed throughout aquifer deposits.

Downward Cr(VI) concentration trends (fig. J.10*B*) were present in 146 monitoring wells. Downward trends were largely within the Q4 2015 regulatory Cr(VI) plume and can be attributed to remediation activities downgradient from the Hinkley compressor station.

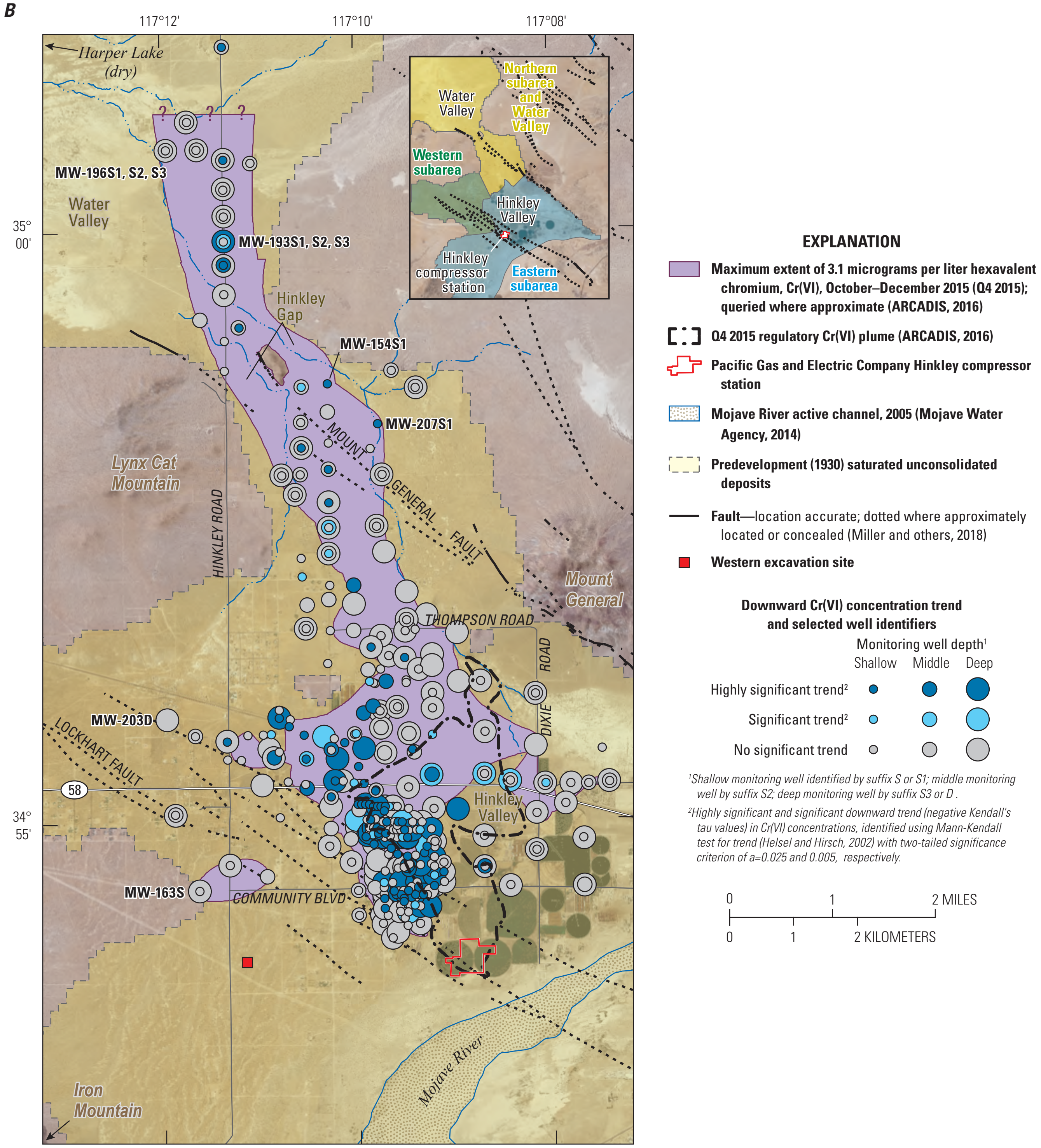
Hexavalent chromium concentration trends calculated for 219 domestic wells between July 2012 and June 2017 showed upward Cr(VI) concentration trends in 8 domestic wells and downward trends in 21 domestic wells clustered within former residential areas west of the Q4 2015 regulatory Cr(VI) plume (fig. J.11). Pumping from domestic wells decreased between 2012 and 2017 as the population of Hinkley declined as a result of land purchases by PG&E near the margin of the regulatory Cr(VI) plume. Under regulatory guidance from the Lahontan Regional Water Quality Control Board (2013), and assuming nearby monitoring wells were available for sample collection, PG&E destroyed abandoned domestic wells on property they purchased within Hinkley and Water Valleys, so continued monitoring of destroyed domestic wells was not possible.

Hexavalent chromium concentration trends (including upward, downward, and no trend) for wells sampled as part of this study were used as metrics within the summative-scale analyses (question 4 in table J.2) to define the extent of anthropogenic and natural Cr(VI) within Hinkley and Water Valleys. The July 2012 through June 2017 period selected for analysis of Cr(VI) concentration trends includes most of the March 2015 through November 2017 period of data collection for this study.



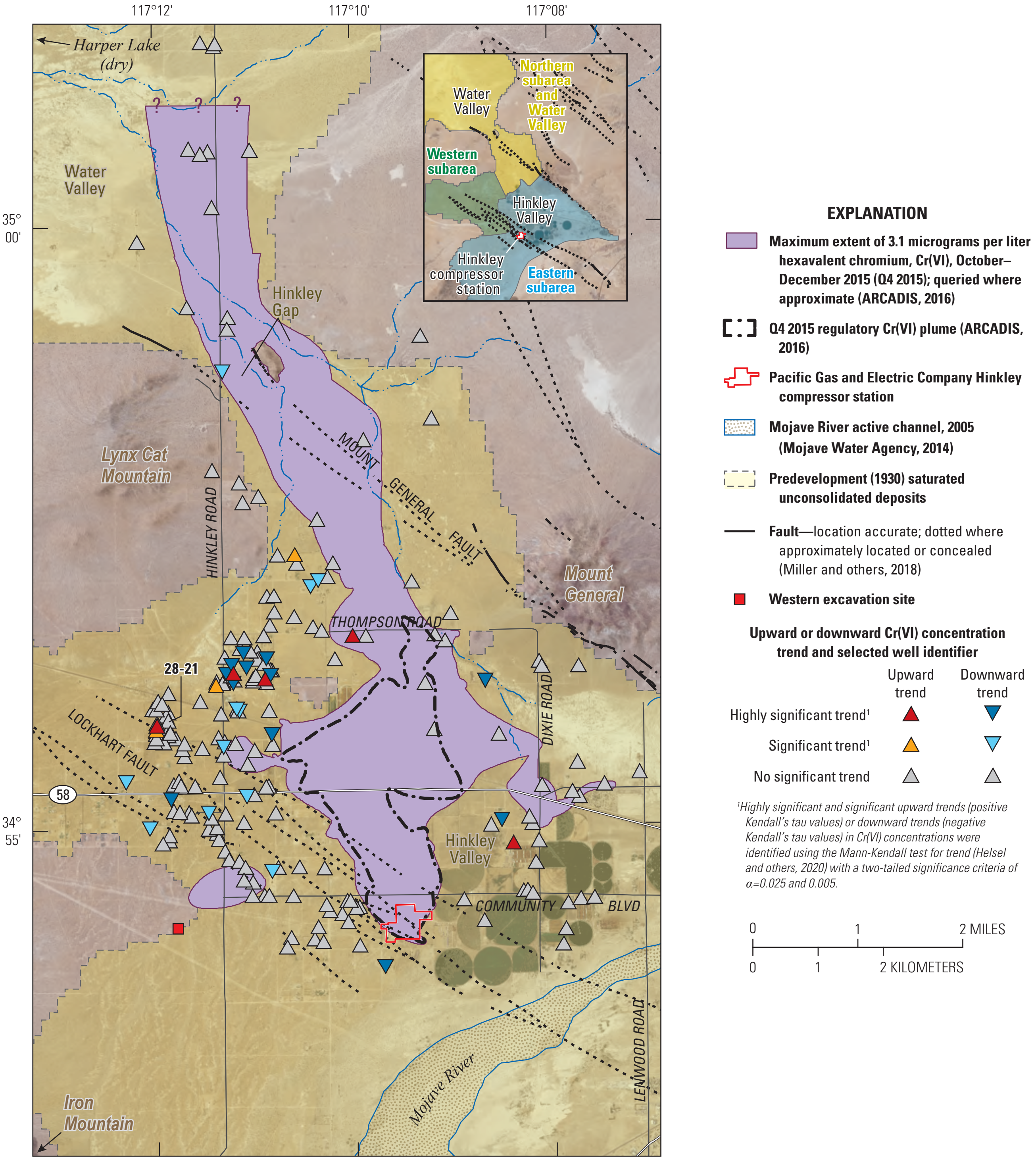
Base from U.S. Geological Survey and other Federal and State digital data, various scales; Lambert Conformal Conic projection, standard parallels are 34.0333° N. and 35.4667° N.; North American Datum of 1983

Figure J.10. Wells having statistically significant *A*, upward and *B*, downward hexavalent chromium, Cr(VI), concentration trends, Hinkley and Water Valleys, California, July 2012 through June 2017. Statistics were calculated from data submitted by Pacific Gas and Electric Company for regulatory purposes, accessed January 12, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/. Data are available in chapter D (appendix D.1, table D.1.3), and calculated statistics are available in appendix D.1, table D.1.4.



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

Figure J.10.—Continued



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

Figure J.11. Domestic wells having statistically significant upward or downward hexavalent chromium, Cr(VI), concentration trends, Hinkley and Water Valleys, California, July 2012 through June 2017. Statistics were calculated from data submitted by Pacific Gas and Electric Company for regulatory purposes, accessed January 12, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/. Data are available in chapter D (appendix D.1, table D.1.5), and calculated statistics are available in appendix D.1, D.1.6.

J.5. Groundwater Chemistry and Hexavalent Chromium

Water samples collected as part of this study from more than 100 wells between March 2015 and November 2017 were analyzed for field parameters, major ions, nutrients, and selected trace elements including Cr(VI) and Cr(t). These results are presented in chapter E within this professional paper.

To ensure comparable Cr(VI) data, sample collection methods, equipment, and analytical procedures used in this study were as similar as possible to methods and equipment used by PG&E to collect data for regulatory purposes. However, regulatory data were collected using a modified low-flow method in which one-casing volume was purged from monitoring wells before sample collection. In contrast, three-casing volumes were purged from wells before USGS sample collection, and a larger volume of water was required for sample analyses collected as part of this study than was required for regulatory samples. In addition, water levels were monitored during USGS purging and sample collection, and pumping rates were adjusted to ensure (where possible) water levels did not fall within the screened interval of the sampled well. These field protocols resulted in the removal of larger quantities of water in sampled wells, often at lower pumping rates requiring longer pumping times, than regulatory data collection. Differences in well purging and sample collection protocols resulted in Cr(VI) concentrations in samples collected as part of this study that were on average about 9 percent lower than Cr(VI) concentrations in PG&E regulatory samples. Differences were generally greater in low-yielding wells.

Hexavalent chromium concentrations were analyzed at the same commercial laboratory used to analyze PG&E regulatory data by ion chromatography using a modified version of EPA Method 218.6 (U.S. Environmental Protection Agency, 1994) having a LRL of 0.06 µg/L and for samples collected as part of this study having a SRL of 0.10 µg/L. Hexavalent chromium concentrations also were field speciated using cation exchange resins (Ball and McCleskey, 2003) with subsequent analyses at the USGS Redox Chemistry Laboratory by graphite furnace atomic absorption spectroscopy using EPA Method 7010 (U.S. Environmental Protection Agency, 2007). Results obtained using these methods were similar based on linear regression analysis (R^2=0.97). For consistency with regulatory data, Cr(VI) data analyzed by ion-chromatography are most commonly presented within this professional paper. However, field-speciation data for Cr(VI) and Cr(t) were used to calculate redox potential because of the lower SRL for Cr(t) for those analyses. Field-speciation data also were reported for Cr(VI) in porewater analyses because sample volume was insufficient for analyses of porewater by ion chromatography. Hexavalent chromium data analyzed on site in a mobile USGS field laboratory using ion chromatography are reported for samples from more than 70 domestic wells collected between January 25 and 31, 2016. On-site analyses enabled interested residents to follow water collected from their wells to the mobile lab, where it was analyzed in their presence—minimizing local stakeholder uncertainty associated with delays in laboratory analyses and tracking analytical data.

Water from most sampled wells was alkaline and oxic. Water from wells in the shallow zone of the upper aquifer within the eastern subarea and the southern part of the northern subarea was affected by irrigation return with specific conductance values as high as 4,790 microsiemens per centimeter (µS/cm) and nitrate as nitrogen (NO_3 as N) concentrations as high as 36 milligrams per liter (mg/L). Irrigation return water was present in wells downgradient from the mapped Q4 2015 regulatory Cr(VI) plume as far as wells MW-105S and MW-123S1 (fig. J.2), but high specific conductance values and nitrate concentrations associated with irrigation return were not widely present within the northern subarea. The data are consistent with water-level data (Stone, 1957; California Department of Water Resources, 1967) showing that groundwater pumping reversed the water-level gradient between the eastern and northern subareas within Hinkley Valley between 1953 and 1982 (Jacobs Engineering Group, Inc., 2019), thereby limiting the movement of water containing irrigation return to the north. Reversal of water-level gradients also may have limited movement of Cr(VI) released from the Hinkley compressor station into the northern subarea during this period.

Hexavalent chromium concentrations in water from sampled wells ranged from less than the SRL of 0.10 to 2,500 µg/L. The highest concentrations were in water from well MW-208S within the Q4 2015 regulatory Cr(VI) plume less than 0.25 mi downgradient from the Hinkley compressor station (fig. J.2). Data within the Q4 2015 regulatory Cr(VI) plume were collected to obtain end-members representative of anthropogenic Cr(VI). Consistent with regulatory data, the highest Cr(VI) concentrations within the Q4 2015 regulatory Cr(VI) plume remain near the source area just downgradient from the Hinkley compressor station more than 65 years after the initial release. Well MW-208S is within strands of the Lockhart fault, which may limit downgradient movement of Cr(VI)-containing groundwater in this area.

The highest Cr(VI) concentration outside the Q4 2015 regulatory Cr(VI) plume was 11 µg/L in water from well MW-154S1 completed in mudflat/playa deposits within the northern subarea; regulatory Cr(VI) concentrations in water from well MW-154S1 have been as high as 20 µg/L. Other high Cr(VI) concentrations outside the Q4 2015 regulatory Cr(VI) plume include 10 µg/L in water from well MW-163S completed in Mojave-type deposits in the western subarea downgradient from the western excavation site; 8.9 µg/L in water from well MW-203D (March 2015) completed in partly consolidated Miocene deposits underlying the western subarea; and 8.8 µg/L in water from well MW-133S1 completed in mudflat/playa deposits in the northern subarea near well MW-154S1 (fig. J.2). The highest Cr(VI) concentration outside the mapped Q4 2015 regulatory Cr(VI) plume in the eastern subarea was 3.9 µg/L in water from well MW-192S completed in Mojave-type deposits near mudflat/playa deposits near Mount General. Hexavalent chromium concentrations in Water Valley were as high as 5.1 µg/L in water from well MW-193S2 completed in clay-textured local alluvium containing material eroded partly from Miocene deposits east of the study area.

The redox potential in water from sampled wells (fig. J.12) was calculated from the Cr(III)/Cr(VI) redox couple using the computer program PHREEQC (Parkhurst and Appelo, 2013), updated with thermodynamic data from Ball and Nordstrom (1998). Hexavalent chromium concentrations in water from most wells were distributed in a narrow redox (Eh) and pH band within the overlapping Cr(IV), as $CrO_4^{2-}{}_{(aqueous)}$, and trivalent manganese, as $Mn(III)_{(solid)}$, stability fields (Hem, 1963). Water from wells MW-133S1 and MW-154S1 completed in carbonate-rich mudflat/playa deposits in the northern subarea and water from wells MW-192S and MW-192D near felsic, carbonate-rich mudflat/playa deposits in the eastern subarea near Mount General approached the more oxic $Mn(IV)_{(solid)}$ stability field (fig. J.12). Most Mn oxides on the surfaces of mineral grains in Hinkley and Water Valleys examined by Raman spectroscopy or by X-ray absorption near-edge structure analysis appear to be Mn(III/IV) oxides (chapter C). In contrast, similar analyses of Mn nodules from carbonate-rich mudflat/playa deposits show the presence of Mn(IV) oxides, consistent with the more oxidative redox potential of water from wells completed within those materials. However, Cr(VI) concentrations in porewater pressure-extracted from felsic Mn(IV)-containing deposits at site MW-192 did not exceed 3.3 µg/L; porewater does not appear to be a source of high Cr(VI) concentrations in water from wells MW-192S and MW-192D, although porewater may be a source of arsenic, uranium, and vanadium in water from wells within the study area.

The pH of water from sampled wells ranged from 6.9 in water-table wells near recharge areas along the Mojave River to 9.4 in deeper wells farther downgradient in the northern subarea. In natural conditions, Cr(VI) is present at higher concentrations in alkaline water than in neutral or slightly acidic water. Izbicki and others (2015) evaluated Cr(VI) concentrations and pH in water from more than 900 public supply wells across California sampled as part of the Groundwater Ambient Monitoring Assessment (GAMA) Program and developed a set of curves showing the Cr(VI) occurrence probability with pH in oxic groundwater. For the purposes of this study, curves developed by Izbicki and others (2015) were updated using smaller increments of 0.3 pH units (fig. J.13). The updated curves show a consistent monotonic increase in Cr(VI) concentrations with increases in pH and provide a method to evaluate the probability of Cr(VI) occurrence in native (uncontaminated) water from wells at the measured pH.

The Cr(VI) occurrence probability at the measured pH in water from most monitoring wells sampled by PG&E between October and December 2015, within the footprint of the Q4 2015 regulatory Cr(VI) plume, was 10 percent or less (fig. J.14*A*). The Cr(VI) occurrence probability at the measured pH in most wells outside the Q4 2015 regulatory Cr(VI) plume was 30 percent or greater. Hexavalent chromium occurrence probabilities of 30 percent or greater were interpreted as natural on the basis of their distribution outside the Q4 2015 regulatory Cr(VI) plume. Hexavalent chromium occurrence probabilities for wells sampled as part of this study also show a low probability of natural occurrence (less than 10 percent) in (1) water from wells within the Q4 2015 regulatory Cr(VI) plume (2) water from wells within the eastern subarea crossgradient from the Hinkley compressor station and upgradient from the Q4 2015 regulatory Cr(VI) plume, (3) water from shallow wells in the northern subarea just downgradient from the Q4 2015 regulatory Cr(VI) plume, and (4) water from wells downgradient from the western excavation site in the western subarea (fig. J.14*A*). In the absence of the detailed geologic, geochemical, and hydrologic data collected as part of this study, pH-dependent sorption, evaluated as the Cr(VI) occurrence probability at the measured pH of less than 10 percent, is an effective indicator of anthropogenic Cr(VI).

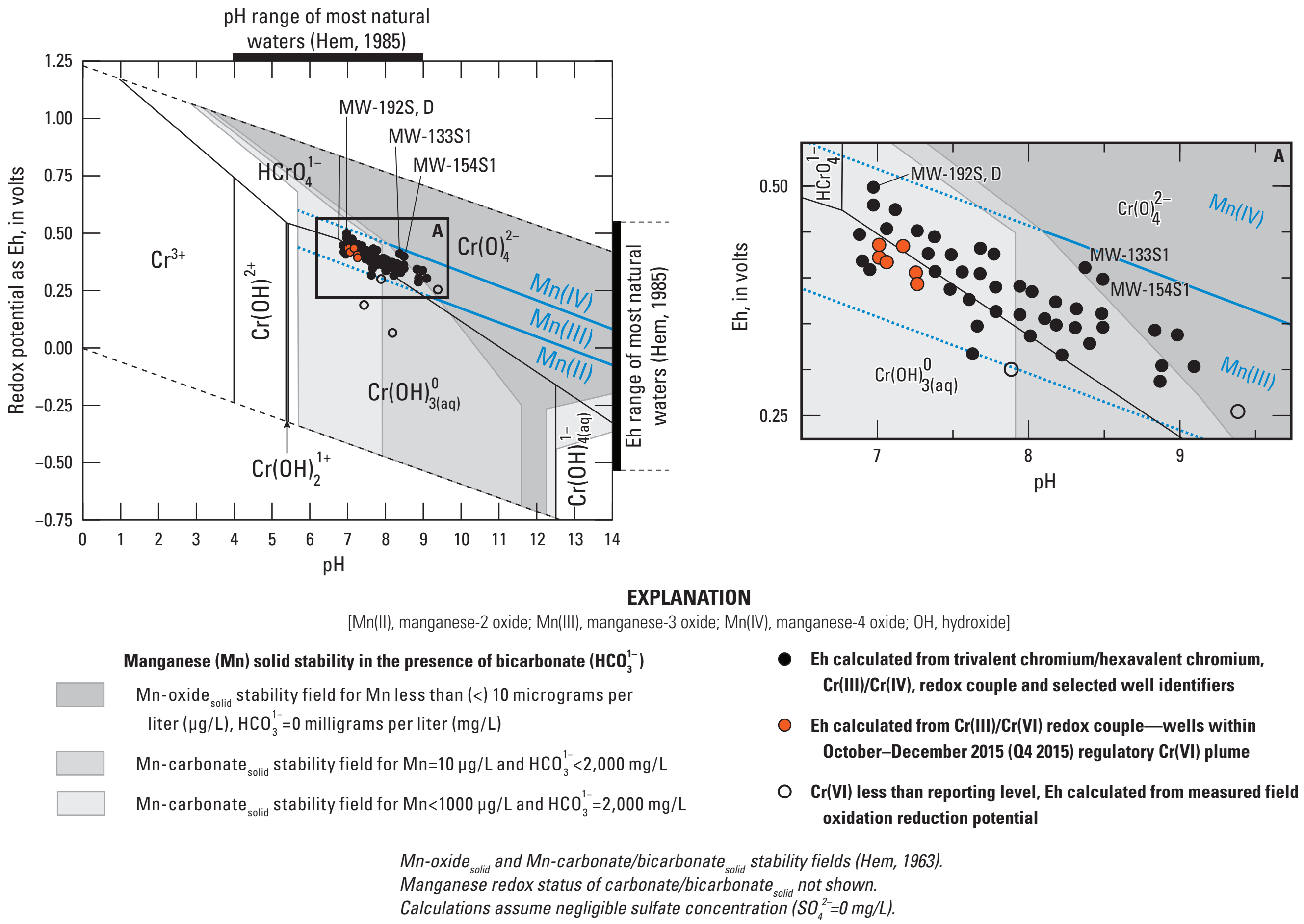


Figure J.12. Redox potential as a function of pH, for wells sampled as part of the U.S. Geological Survey hexavalent chromium, Cr(VI), background study, Hinkley and Water Valleys, western Mojave Desert, California, March 2015 through November 2017. Data are available in chapter E (appendix E.1, table E.1.1) and U.S. Geological Survey (2021).

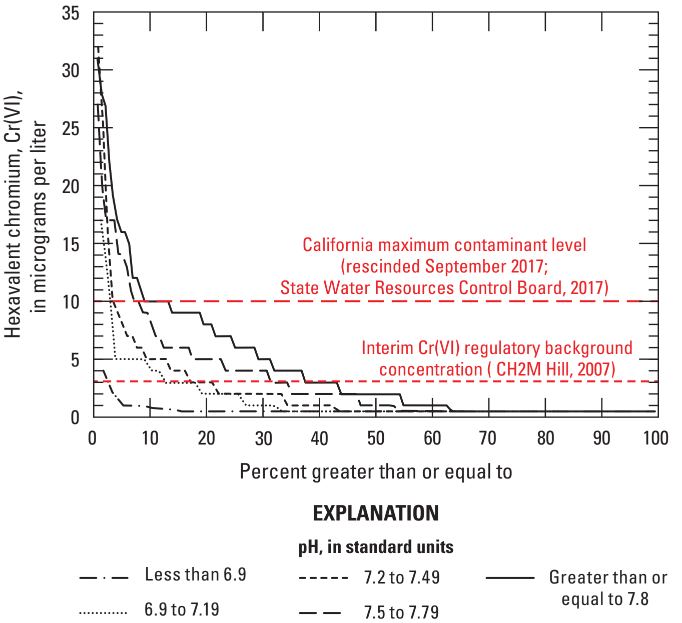
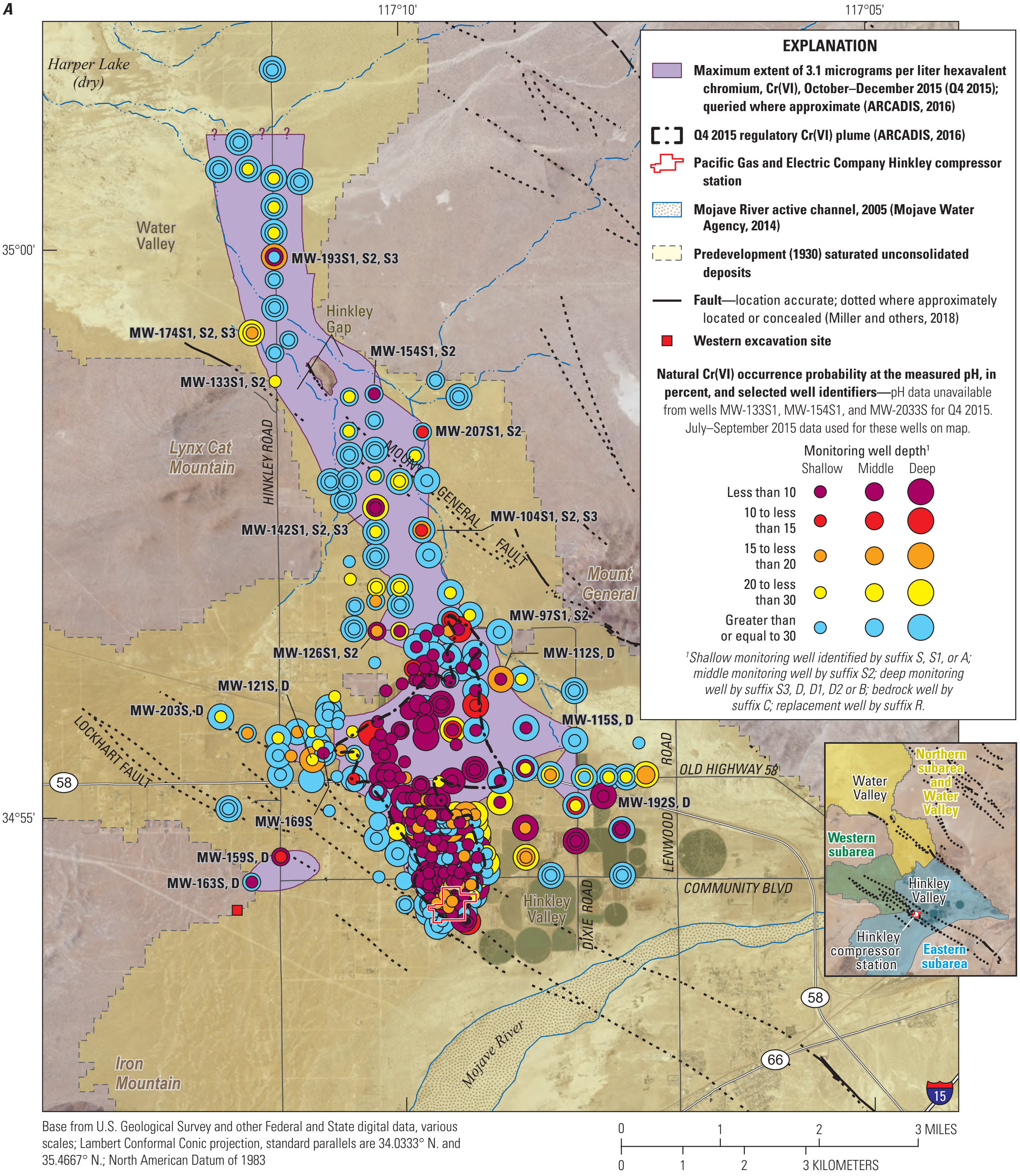


Figure J.13. Cumulative probability of hexavalent chromium, Cr(VI), concentration as a function of pH in water from public-supply wells in California. Modified from Groundwater Ambient Monitoring Assessment (GAMA) Program Priority Basin Project data, 2004–14 (Izbicki and others, 2015). Data are available in U.S. Geological Survey (2021).



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

Figure J.14. Probability of the hexavalent chromium, Cr(VI), occurrence at the measured pH in water from selected wells: A, Pacific Gas and Electric Company (PG&E) data, October–December 2015 (Q4 2015), and B, U.S. Geological Survey (USGS) data, March 2015 through 2017, Hinkley and Water Valleys, western Mojave Desert, California. Pacific Gas and Electric Company data are available at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/; U.S. Geological Survey data are available in U.S. Geological Survey (2021).

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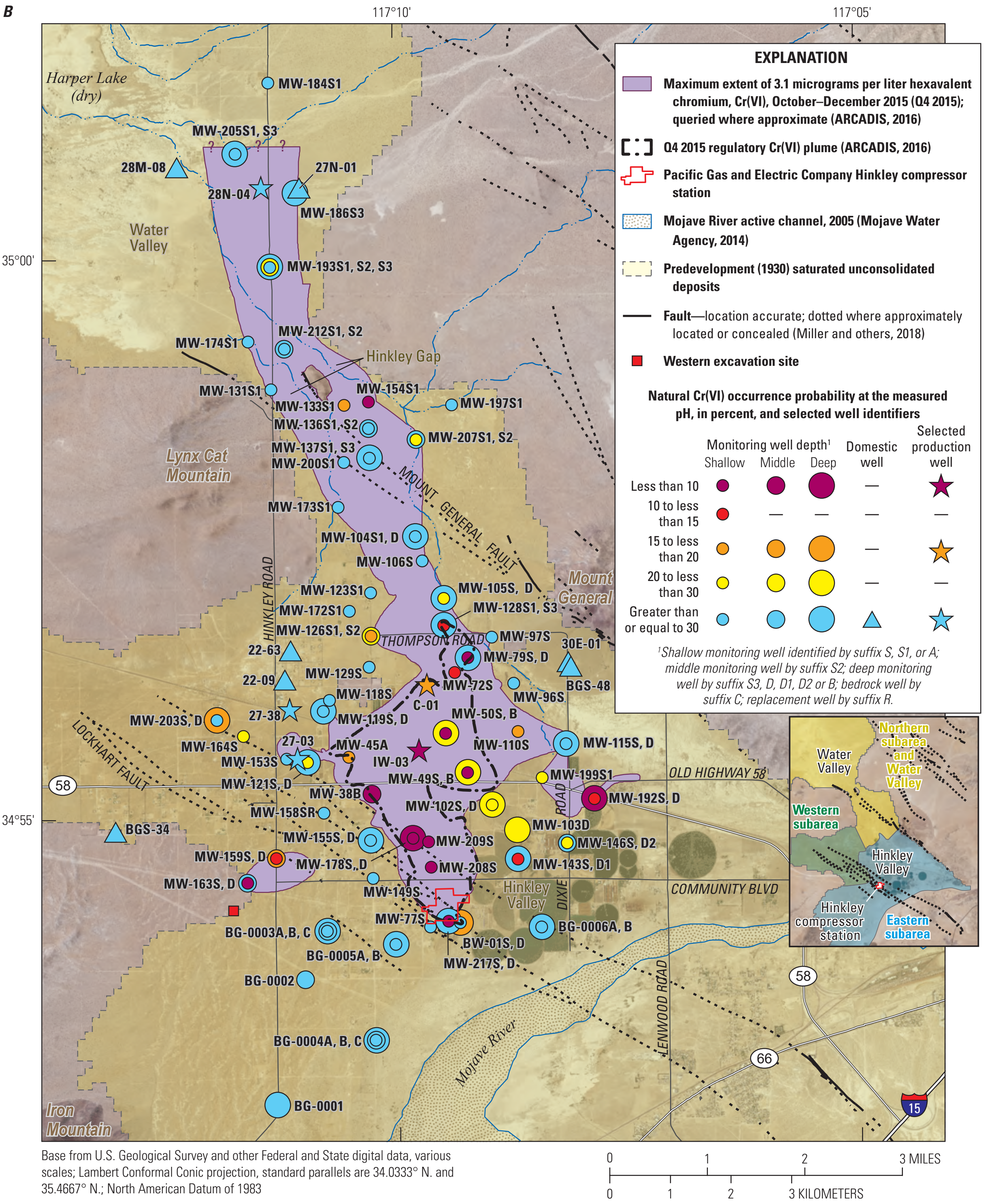


Base from U.S. Geological Survey and other Federal and State digital data, various scales; Lambert Conformal Conic projection, standard parallels are 34.0333° N. and 35.4667° N.; North American Datum of 1983

Figure J.14.—Continued

Concentrations of five selected trace elements (arsenic, iron, manganese, uranium, and vanadium) were measured along with Cr(VI) in water from wells sampled by the USGS between March 2015 and November 2017. Arsenic and vanadium form negatively charged oxyanions and uranium forms complexes with carbonates that are soluble in alkaline, oxic groundwater, and have aqueous geochemistry, in some respects, similar to Cr(VI). Arsenic concentrations in water from sampled wells were as high as 1,030 µg/L, uranium concentrations were as high as 114 µg/L, and vanadium concentrations were as high as 530 µg/L. Approximately 27 percent of sampled wells exceeded the MCLs of 10 and 30 µg/L for arsenic and for uranium, respectively (U.S. Environmental Protection Agency, 2019). There is no MCL for vanadium; however, 10 percent of sampled wells exceeded the notification level of 50 µg/L for vanadium in drinking water (State Water Resources Control Board, 2019). Releases from the Hinkley compressor station contributed Cr(VI) to groundwater; arsenic, uranium, and vanadium concentrations in water from wells in Hinkley and Water Valleys are not related to those releases.

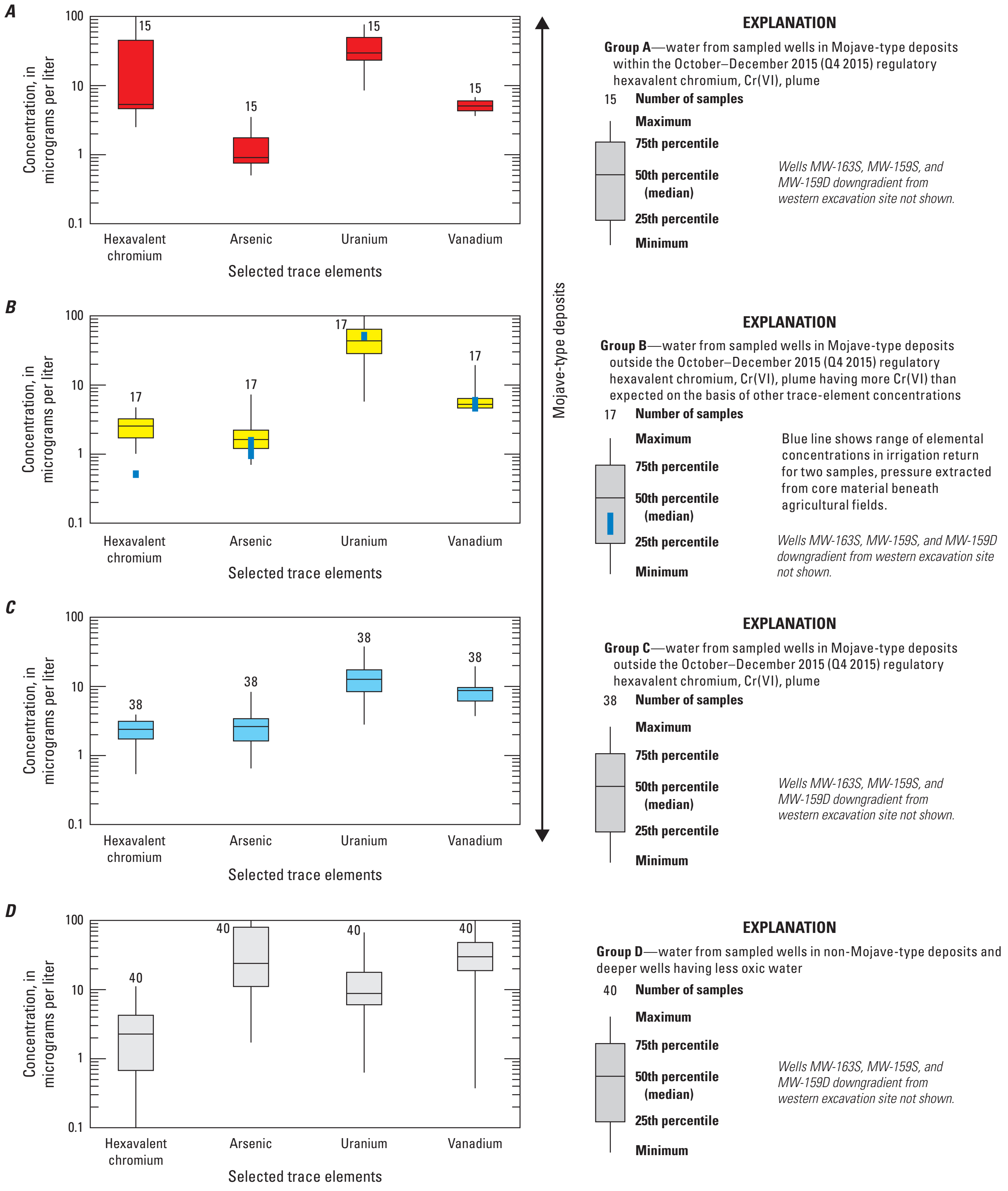
Trace-element concentrations in water from wells result from the (1) combined effects of geology, mineral weathering, and aqueous geochemistry—including redox potential, and pH-dependent sorption of arsenic and vanadium oxyanions and uranium complexes in oxic groundwater; (2) irrigation return; and (3) additions of anthropogenic Cr(VI) associated with releases from the Hinkley compressor station. Hexavalent chromium concentrations in irrigation return water are low and would result in a decrease in Cr(VI) abundance compared to the other trace elements measured. Additions of anthropogenic Cr(VI) from the Hinkley compressor station would result in an increase in the abundance of Cr(VI) compared to the other trace elements measured. Principal component analysis was used to evaluate these differences.

On the basis of PCA results, water samples from wells were divided into four groups (fig. J.15). The first three groups were composed of wells completed in Mojave-type deposits and included (1) group A, water from wells within the Q4 2015 regulatory Cr(VI) plume; (2) group B, water from wells outside the Q4 2015 regulatory Cr(VI) plume with increased concentrations of Cr(VI) compared to other trace elements measured; and (3) group C, water from wells outside the Q4 2015 regulatory Cr(VI) plume that do not show increased concentrations of Cr(VI) compared to other trace elements measured. Principal component analysis results for groups A and B show increased Cr(VI) concentrations compared to the other trace elements measured that are consistent with the presence of anthropogenic Cr(VI), whereas PCA results for group C do not show increased concentrations of Cr(VI) compared to other trace elements measured and are not consistent with the presence of anthropogenic Cr(VI). The fourth group, group D, included water from wells completed in non-Mojave-type deposits or deeper wells in Mojave-type deposits having less oxic water (lower redox potential values) and higher Fe or Mn concentrations. Water from wells within group B was present (1) within the eastern subarea crossgradient from the Hinkley compressor station and upgradient from the mapped Q4 2015 regulatory Cr(VI) plume and (2) within the northern subarea downgradient from the leading edge of the mapped Q4 2015 regulatory Cr(VI) plume (fig. J.16).

Hexavalent chromium concentrations in more than 70 domestic wells in Hinkley and Water Valleys sampled between January 27 and 31, 2016, ranged from less than the SRL of 0.1 to 4 µg/L, with a median concentration of 1.2 µg/L. Hexavalent chromium concentrations were generally within ranges expected for uncontaminated groundwater given their pH and trace-element composition. By the time of this study, PG&E purchased most land overlying and near the Q4 2015 regulatory Cr(VI) plume. After the land was purchased, unused domestic wells were destroyed following guidance from the Lahontan Regional Water Quality Control Board (2013). As a consequence, domestic wells in former residential areas within the community of Hinkley, having Cr(VI) concentrations as high as 8.6 µg/L, were not available for sample collection as part of this study.

Arsenic concentrations in water from sampled domestic wells in Hinkley and Water Valleys were as high as 300 µg/L, with 39 percent of sampled domestic wells exceeding the MCL of 10 µg/L. Uranium concentrations were as high as 62 µg/L, with 8 percent of sampled domestic wells exceeding the MCL of 30 µg/L. Vanadium concentrations were as high as 150 µg/L, with 9 percent of sampled domestic wells exceeding the notification level of 50 µg/L. In addition, nitrate concentrations were as high as 18 mg/L NO_3 as N, with 10 percent of sampled domestic wells exceeding the MCL of 10 mg/L NO_3 as N. Water from 47 percent of domestic wells sampled between January 27 and 31, 2016, had arsenic, uranium, or nitrate concentrations above an MCL.

Hexavalent chromium occurrence probability calculated from Cr(VI) and pH data and PCA results describing Cr(VI) and other trace-element concentrations were used within the summative scale to evaluate the occurrence of natural and anthropogenic Cr(VI) (questions 5 and 6 in table J.2). Similar to Cr(VI), concentrations of arsenic, uranium, and vanadium in oxic water are largely controlled by pH-dependent sorption. Consequently, interpretations of plume extent based on Cr(VI) occurrence probability at the measured pH and the PCA of trace-element concentrations are similar.



Group A—water from sampled wells in Mojave-type deposits within the October–December 2015 (Q4 2015) regulatory hexavalent chromium, Cr(VI), plume

Wells MW-163S, MW-159S, and MW-159D downgradient from western excavation site not shown.

Group B—water from sampled wells in Mojave-type deposits outside the October–December 2015 (Q4 2015) regulatory hexavalent chromium, Cr(VI), plume having more Cr(VI) than expected on the basis of other trace-element concentrations

Blue line shows range of elemental concentrations in irrigation return for two samples, pressure extracted from core material beneath agricultural fields.

Wells MW-163S, MW-159S, and MW-159D downgradient from western excavation site not shown.

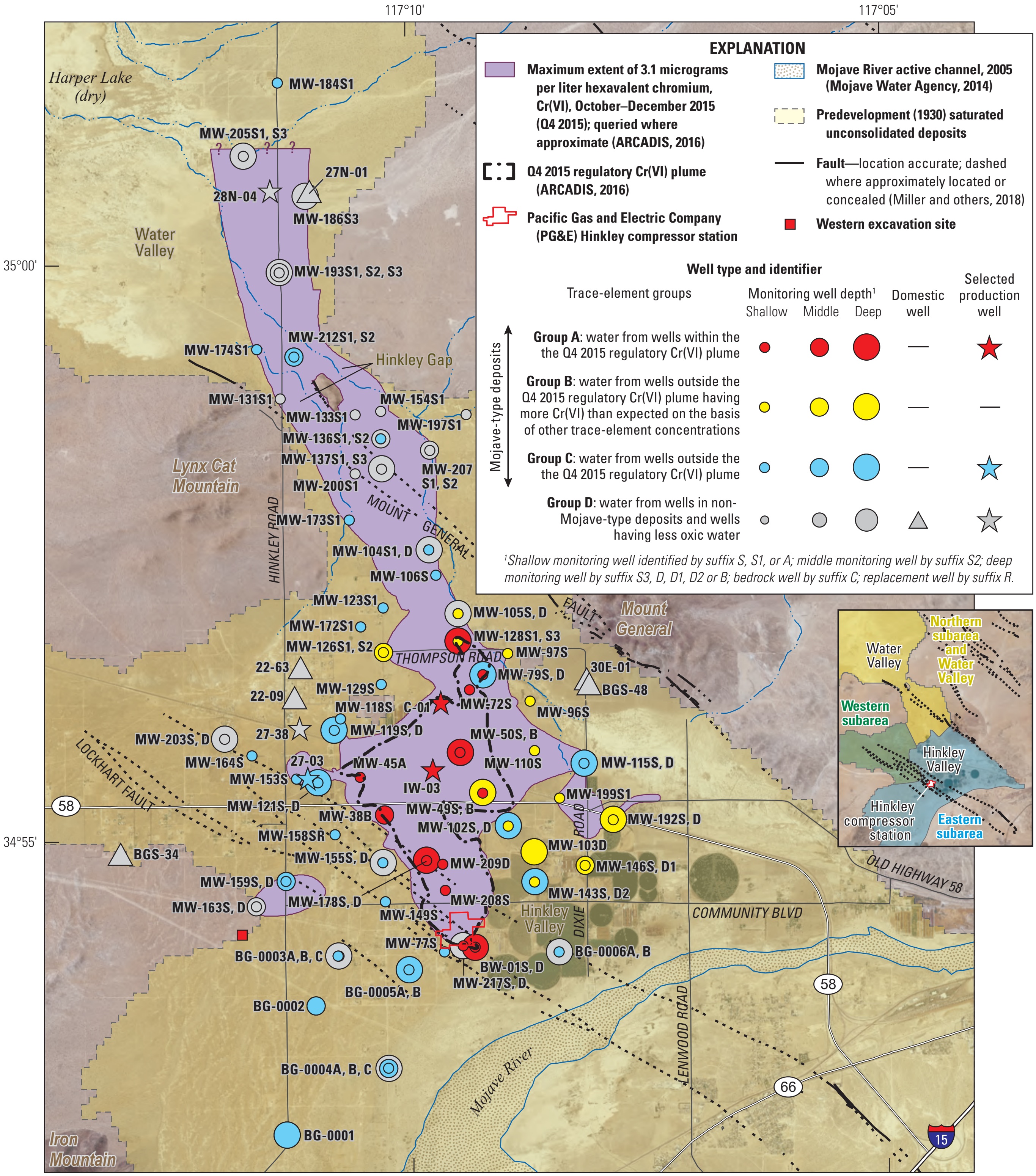
Group C—water from sampled wells in Mojave-type deposits outside the October–December 2015 (Q4 2015) regulatory hexavalent chromium, Cr(VI), plume

Wells MW-163S, MW-159S, and MW-159D downgradient from western excavation site not shown.

Group D—water from sampled wells in non-Mojave-type deposits and deeper wells having less oxic water

Wells MW-163S, MW-159S, and MW-159D downgradient from western excavation site not shown.

Figure J.15. Selected oxyanion concentrations in water from wells completed *A*, within the Q4 2015 (October–December 2015) regulatory hexavalent chromium, Cr(VI), plume; *B*, outside the plume in Mojave-type deposits impacted by irrigation return and having excess Cr(VI); *C*, outside the plume in other Mojave-type deposits; and *D*, in non-Mojave-type deposits or deposits yielding less oxic water, Hinkley and Water Valleys, western Mojave Desert, California, March 2015 through November 2017. Data are available in chapter E (appendix E.1, table E.1.1) and U.S. Geological Survey (2021).



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

Figure J.16. Water-quality groups estimated from principal component analysis (PCA) scores calculated for selected trace-element data, Hinkley and Water Valleys, western Mojave Desert, California, March 2015 through November 2017. Statistics calculated from data available in chapter E (appendix E.1, table E.1.1) and U.S. Geological Survey (2021).

J.6. Environmental Tracers and Groundwater Age

A suite of environmental tracers, including tracers of groundwater age, were analyzed in water samples collected from more than 100 wells in Hinkley and Water Valleys between March 2015 and November 2017. These data were used to characterize the source, movement, and age of groundwater within and near the Q4 2015 regulatory Cr(VI) plume and to identify chemical reactions and environmental processes occurring in native and anthropogenic groundwater and are discussed in chapter F within this professional paper.

The stable oxygen and hydrogen isotope compositions of water, delta oxygen-18 and delta deuterium, were used to identify water recharged by infiltration of streamflow in the Mojave River (fig. J.17). Streamflow in the river originates as runoff from winter precipitation near Cajon Pass, a low-altitude gap in the San Bernardino and San Gabriel Mountains 40 mi south of the study area. The delta oxygen-18 and delta deuterium composition of Mojave River water is heavier (has more of the heavier isotopes of oxygen and hydrogen with less negative values) than precipitation at higher altitudes within those mountains and is heavier than winter precipitation within Hinkley and Water Valleys (Izbicki, 2004). Not all water recharged from the Mojave River passed near the Hinkley compressor station, but all water containing anthropogenic Cr(VI) from the Hinkley compressor station would have been recharged from the Mojave River.

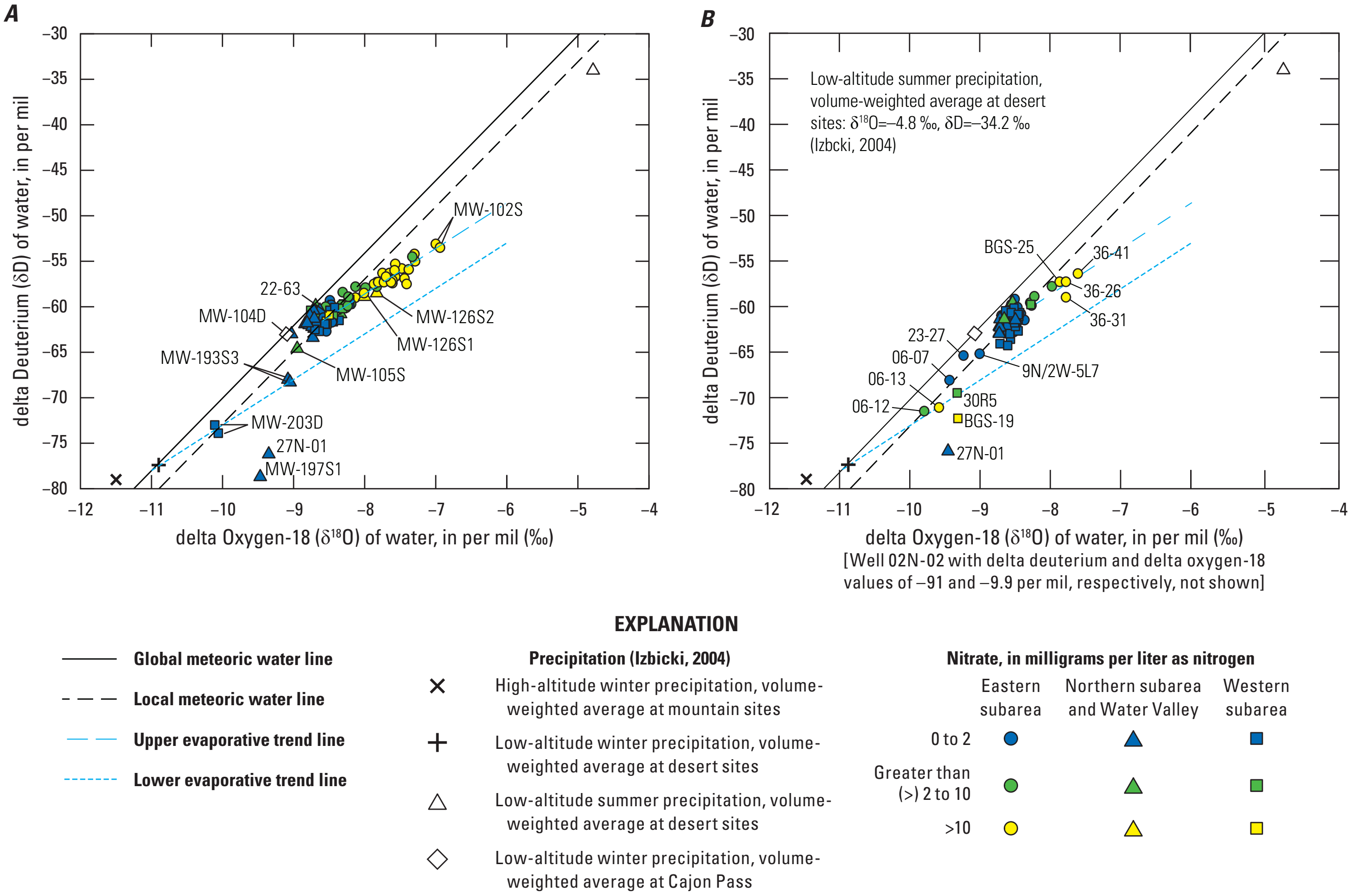


Figure J.17. Values of delta oxygen-18 as a function of delta deuterium in water from *A*, wells sampled March 2015 through November 2017 and *B*, selected domestic wells sampled January 27–31, 2016, Hinkley and Water Valleys, western Mojave Desert, California. Data are available in chapter E (appendix E.1, tables E.1.1, E.1.3.) and U.S. Geological Survey (2021).

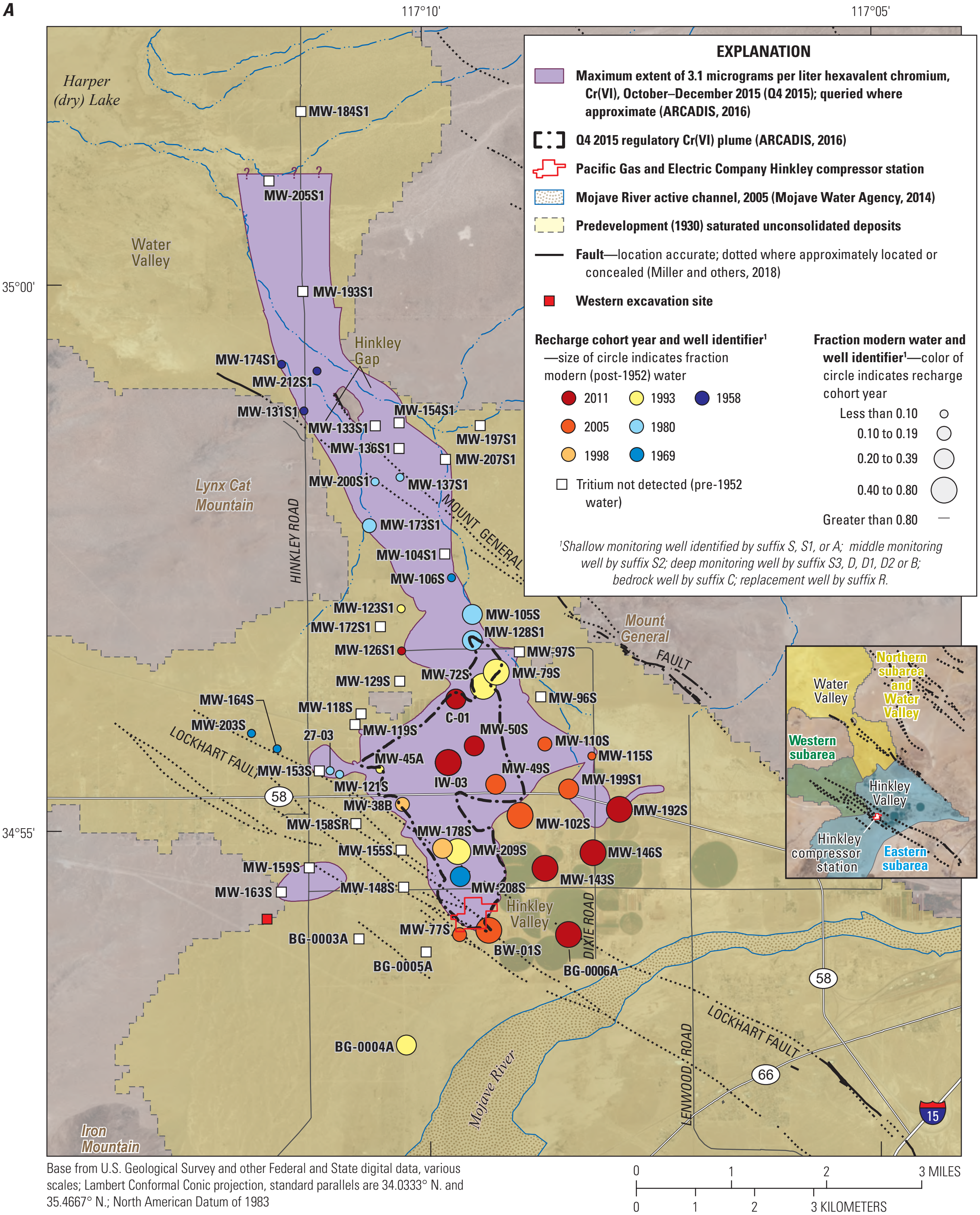
Water from most sampled wells was recharged by infiltration of surface flows within the Mojave River, and Mojave River sourced recharge water was present throughout Hinkley and Water Valleys. Water from well MW-203D completed in Miocene deposits underlying the western subarea, well MW-197S1 near the margin of the aquifer within the northern subarea, and wells MW-193S3 and 27N-01 in Water Valley is isotopically lighter (more negative) than Mojave River water (fig. J.17). Water from these wells was recharged from sources other than the Mojave River and would not have passed near the Hinkley compressor station. Additionally, water from these wells may have been recharged at a time in the geologic past when the climate was cooler and wetter from recharge sources that are not active under the climatic conditions at the time of this study. In March 2015, Cr(VI) concentrations in water from well MW-203D were 8.9 µg/L, and concentrations in regulatory samples from this well have been as high as 10 µg/L. On the basis of the delta oxygen-18 and delta deuterium compositions of water from well MW-203D, Cr(VI) concentrations in water from that well are not associated with releases from the Hinkley compressor station.

Water having delta oxygen-18 and delta deuterium values consistent with evaporation and irrigation return plots to the right of the Global Meteoric Water Line along an evaporative trend line (fig. J.17). Highly evaporated irrigation return water was not present farther than about 1 mi downgradient from the Q4 2015 regulatory Cr(VI) plume. Groundwater pumping for agricultural purposes created a local pumping depression in the northern part of the eastern subarea beginning in the early 1950s (Stone, 1957; California Department of Water Resources, 1967). This pumping depression existed until the early 1990s when groundwater-level declines limited agricultural pumping. While present, the pumping depression limited movement of groundwater impacted by irrigation return downgradient from the eastern subarea into the northern subarea, and it also may have limited the downgradient movement of groundwater containing anthropogenic Cr(VI) released from the Hinkley compressor station.

Recharge temperature and the amount of excess air entrapped in groundwater at the time of recharge were estimated from groundwater dissolved-gas (nitrogen gas and the noble gases neon and argon) concentrations using the computer program DGMETA (Jurgens, 2019). During predevelopment, before water-level declines resulting from agricultural pumping, dissolved-gas data indicate that most groundwater recharge originated from infiltration of warm, sustained streamflows in the Mojave River through a comparatively thin unsaturated zone. After the onset of agricultural activity and pumping induced groundwater-level declines, recharge temperatures became cooler and excess air concentrations increased, consistent with rapid infiltration of winter streamflows through a thicker unsaturated zone. Recharge temperature and excess air data were used in DGMETA calculations for estimation of groundwater age.

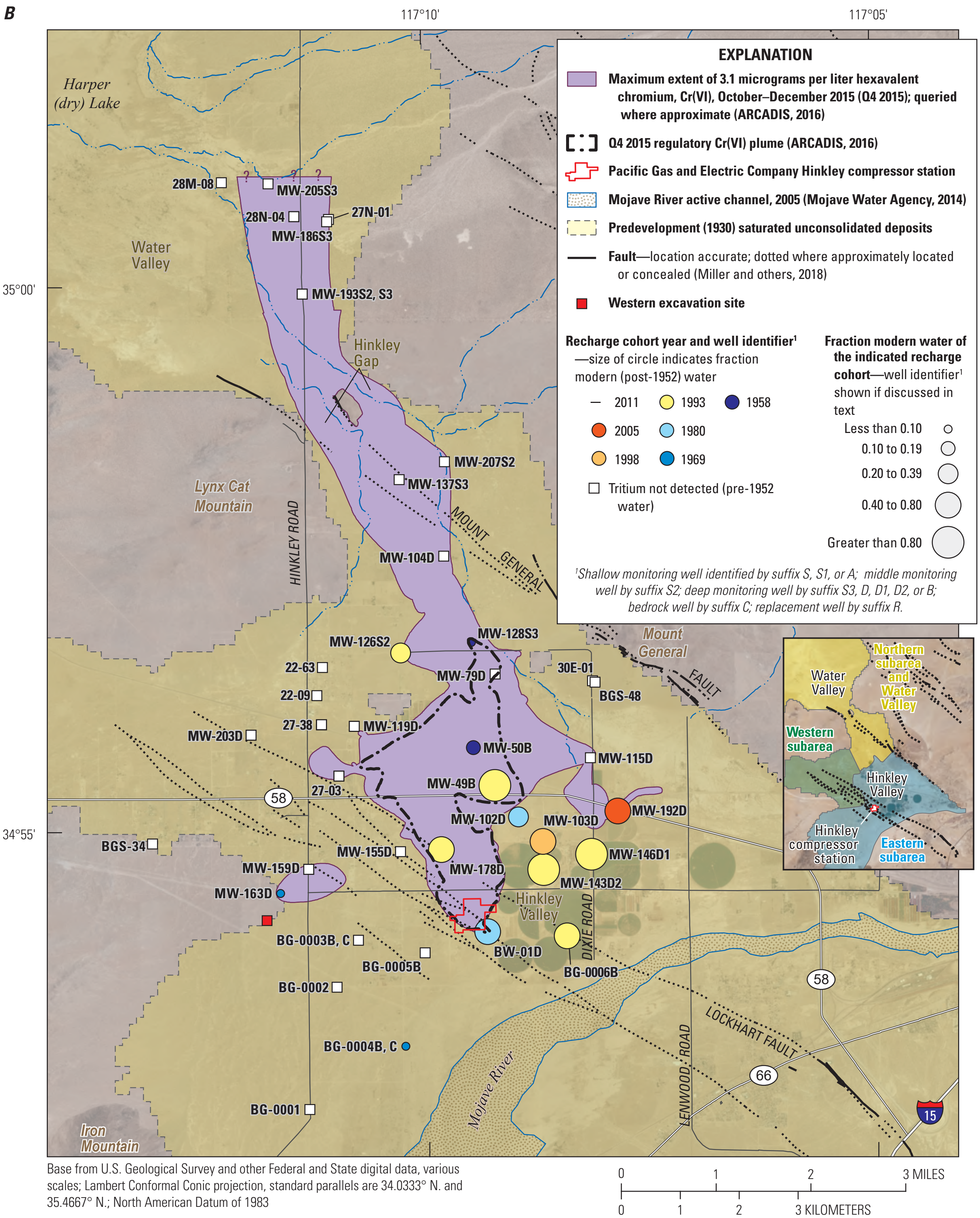
Tritium, a radioactive isotope of hydrogen, has a half-life of 12.3 years (Lucas and Unterweger, 2000). Although naturally occurring, tritium concentrations in groundwater increased as a result of atmospheric testing of nuclear weapons beginning in 1952. Tritium was measured by helium in-growth (Clarke and others, 1976) with an LRL of 0.01 tritium unit (TU) (Sültenfuß and others, 2009) and an SRL of 0.05 TU. Tritium recharged from the Mojave River before 1952 would have decayed to concentrations less than the SRL by 2015. The fraction of post-1952 groundwater and the age of the post-1952 fraction was calculated from the radioactive decay of tritium and its accumulated decay product helium-3, using the computer program DGMETA (Jurgens, 2019). DGMETA also was used to quantify helium in a sample that originated from different sources within the aquifer (Schlosser and others, 1989).

Tritium was detected in water from 51 percent of sampled wells and was detected as far downgradient as well MW-174S1, in the southern part of Water Valley more than 7 mi from the Mojave River. Tritium concentrations were higher, groundwater ages were younger, and fractions of post-1952 water yielded by wells were higher near recharge areas along the Mojave River (fig. J.18*A*). Groundwater ages increased downgradient from the river and with depth (fig. J.18*B*), and the fraction of post-1952 water decreased downgradient and with depth. Analogous to interpretations from oxygen-18 and delta deuterium values, not all post-1952 water recharged from the Mojave River passed near the Hinkley compressor station, but most water containing anthropogenic Cr(VI) from the Hinkley compressor station would have been post-1952 water recharged from the Mojave River. Some water containing anthropogenic Cr(VI) that was released from the Hinkley compressor station in 1952 would have infiltrated to the water table and mixed with groundwater already present within the aquifer; consequently, anthropogenic Cr(VI) may be present slightly in advance of the post-1952 tritium front. Agricultural pumping has lowered groundwater levels as much as 60 ft near the Hinkley compressor station since 1952 (Stone, 1957; California Department of Water Resources, 1967). As a result of this pumping, some groundwater containing tritium and anthropogenic Cr(VI) has been removed from the aquifer.



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

Figure J.18. Recharge cohorts and fraction of post-1952 water in *A,* shallow wells and *B*, deep wells, Hinkley and Water Valleys, western Mojave Desert, California, November 2015 through March 2017. Values are available in chapter F (appendix F.2, table F.2.1) and were calculated from data available in chapter E (appendix E.1, table E.1.1) and U.S. Geological Survey (2021).



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

Figure J.18.—Continued

Carbon-14, having a half-life of 5,730 years (Godwin, 1962), also was analyzed to estimate the age of water from wells. Similar to tritium, carbon-14 is naturally occurring, and carbon-14 activities in groundwater also increased as a result of atmospheric testing of nuclear weapons beginning in 1952. With the exception of 1958, the Mojave River was largely dry between 1952 and 1969—the period spanning both Cr(VI) releases and the highest tritium concentrations in precipitation. Only a small amount of recharge occurred between 1952 and 1969, and tritium associated with recharge after 1969 decreased to lower levels. Although commonly used to evaluate the age of older groundwater, carbon-14 activities in precipitation associated with nuclear weapons testing did not decrease as rapidly as tritium concentrations, and carbon-14 may be a more sensitive and easily detected tracer of post-1952 groundwater in the study area than tritium.

Carbon-14 activities in water from sampled wells ranged from 8.9 to 127 percent modern carbon (pmc; fig. J.19). Carbon-14 activities greater than 100 pmc indicate post-1952 water impacted by the atmospheric testing of nuclear weapons. The distribution of carbon-14 activities was similar to the distribution of tritium, with higher activities near the Mojave River and lower activities farther downgradient and in deeper wells. Unlike tritium, carbon-14 activities are affected by reactions that may occur during groundwater recharge and with aquifer materials; when compared with the carbon-14 activity of recently recharged water elsewhere in the Mojave Desert, post-1952 groundwater was present in water from wells as far downgradient as MW-174S1 in Water Valley. In some areas, large differences in groundwater age were present with depth, and post-1952 water overlies older water having low carbon-14 activities (fig. J.19).

Water from 24 sampled wells had unadjusted carbon-14 ages greater than 5,000 years before present (ybp), with the oldest water in well MW-104D having an unadjusted carbon-14 age of more than 20,000 ybp. Unadjusted carbon-14 ages do not account for reactions that occur during groundwater recharge or with aquifer material and assume only radioactive decay; unadjusted carbon-14 ages are commonly younger than actual groundwater ages. Older groundwater was present in water from (1) most deeper wells within the northern subarea and Water Valley, (2) well MW-203D completed in Miocene deposits in the western subarea, (3) wells 30-E01 and BGS-48 completed in locally derived alluvial fan deposits along the flanks of Mount General, and (4) well BG-0004C upgradient of the Lockhart fault near the Mojave River (fig. J.19). Water from wells MW-155S and MW-155D within strands of the Lockhart fault to the northwest of the Hinkley compressor station was older than water on the upgradient and downgradient sides of the fault (fig. J.19), consistent with limited movement of groundwater through the Lockhart fault.

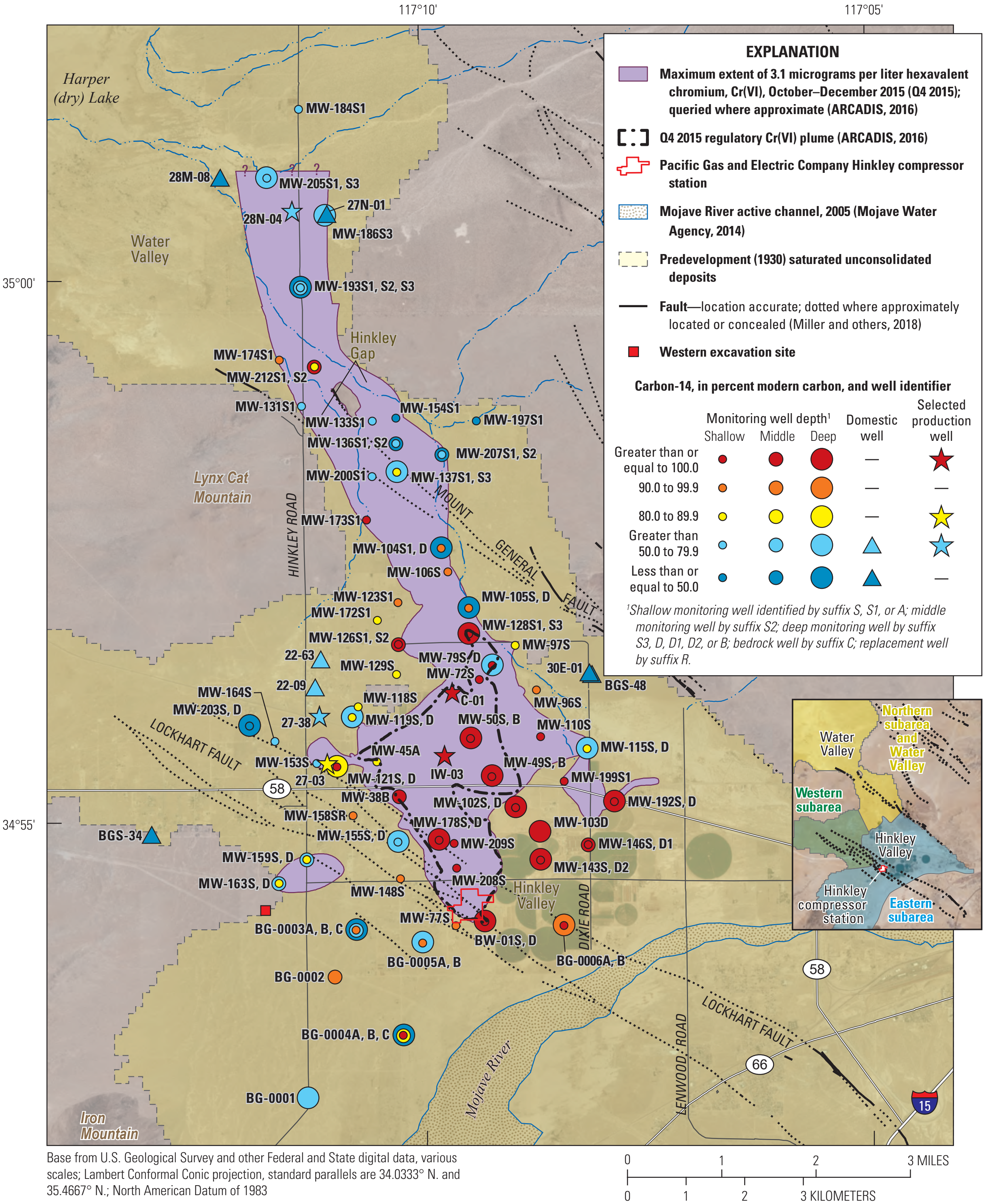
Hexavalent chromium concentrations in older groundwater in contact with Mojave-type deposits were as high as 3.5 µg/L in water from well MW-115D in the eastern subarea and as high as 3.6 µg/L in water from well MW-137S3 in the northern subarea (fig. J.19). These concentrations may represent an upper limit on Cr(VI) concentrations in groundwater within Mojave-type deposits that likely approximates background Cr(VI) concentrations in the study area.

Strontium-87/86 ratios and delta chromium-53 compositions are influenced by reactions between aquifer materials and water. These isotopes provide information on rock, minerals, and geologic material that water has contacted within an aquifer and on processes controlling concentrations of these elements in groundwater.

The strontium-87/86 ratios in water from sampled wells ranged from 0.70744 to 0.71085. Radiogenic strontium-87/86 ratios greater than 0.70950 were associated with felsic Mojave-type-deposit aquifer material. Non-radiogenic strontium-87/86 ratios less than 0.70950 are associated with Miocene volcanic activity in the Mojave Desert (Glazner and O’Neil, 1989). Non-radiogenic strontium-87/86 ratios were present in water from wells completed in partly consolidated Miocene deposits underlying the western subarea and in locally derived alluvium eroded in part from Miocene rock east of the study area. Some minerals within deposits containing Miocene materials are highly weathered (chapter C), and these weathered minerals can contribute Cr(VI) to water from wells.

The delta chromium-53 values in water from sampled wells ranged from near 0 to 2.8 per mil (parts per thousand ratios of the sample to a standard value). Chromium isotope values were near 0 per mil in water from wells having the highest Cr(VI) concentrations within the Q4 2015 regulatory Cr(VI) plume downgradient from the Hinkley compressor station. High delta chromium-53 values, consistent with reduction of Cr(VI) released from the Hinkley compressor station through reactions with aquifer materials, also were present within the Q4 2015 regulatory Cr(VI) plume. Reduced Cr(VI) accumulated as Cr(III) within oxide coatings on aquifer materials within the plume extent. Reduction of Cr(VI) in oxic groundwater was demonstrated to occur under environmental conditions upgradient from the Hinkley compressor station (chapter F) and in experimental microcosms prepared as part of this study (chapter I). However, delta chromium-53 data were not diagnostic of anthropogenic Cr(VI) at the concentrations of interest near the plume margins.

The delta oxygen-18 and delta deuterium; tritium, including tritium/helium-3 groundwater ages and fraction of post-1952 water; and carbon-14 data were used within the summative scale to identify natural and anthropogenic Cr(VI) in water from wells (questions 7 and 8 in table J.2). Strontium-87/86 ratios and delta chromium-53 values were not used within the summative scale but were used to confirm interpretations of natural and anthropogenic Cr(VI) in water from sampled wells and geochemical processes occurring within aquifers underlying Hinkley and Water Valleys.



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

Figure J.19. Measured carbon-14 activities in water from wells, Hinkley and Water Valleys, western Mojave Desert, California, March 2015 through November 2017. Data are available in chapter E (appendix E.1, table E.1.1) and U.S. Geological Survey (2021).

J.7. Evaluation of Natural and Anthropogenic (Human-Made) Hexavalent Chromium

Geologic, geochemical, and hydrologic data from more than 100 wells collected between March 2015 and November 2017 were interpreted using a summative scale to define the extent of anthropogenic Cr(VI) within chapter G within this professional paper. The 3-year period of data collection used to estimate the summative-scale Cr(VI) plume extent was incorporated in the study design to allow for interpretation and review of data as it was collected, with earlier data informing the collection of later data.

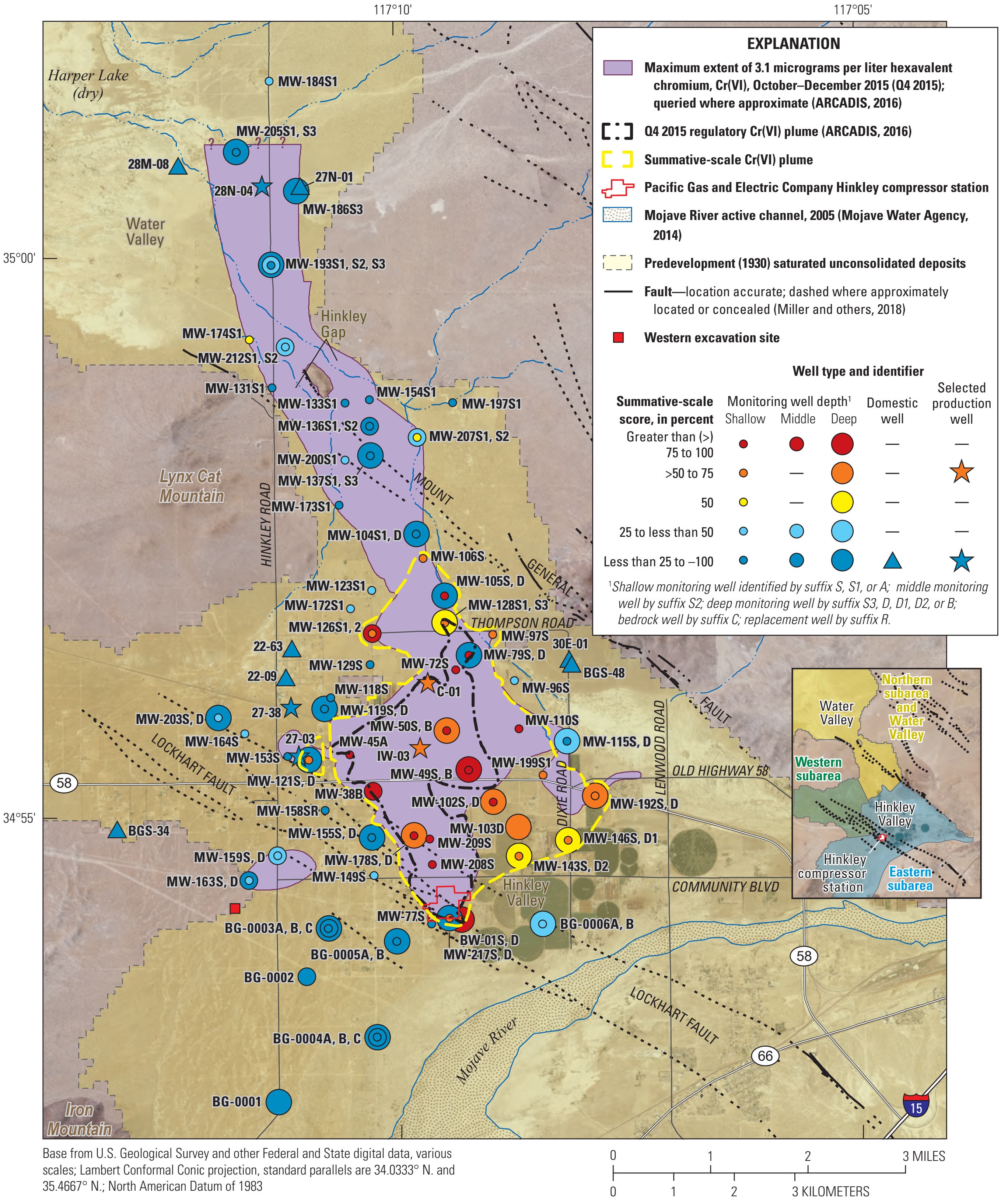
The summative scale consisted of eight questions requiring binary (yes or no) answers for each sampled well (table J.2). The questions were intended to (1) provide a transparent framework for data interpretation in which all stakeholders participated; (2) provide unbiased interpretation of data traceable to numerical measurements; (3) provide a framework in which geologic, hydrologic, and geochemical data would be interpreted collectively; and (4) consolidate different types of data into a simple, easy-to-understand interpretation. When data from each well are scored using the questions and metrics within the summative scale, all stakeholders would score each well the same way and would draw the same summative-scale Cr(VI) plume extent (fig. J.20).

Scores for each question in the summative scale were summed to create a single value for each sampled well ranging from −8 to 8. High-magnitude positive scores were consistent with anthropogenic Cr(VI), and high-magnitude negative scores were consistent with natural Cr(VI). However, sampled wells were selected with input from the TWG for reasons other than their ultimate inclusion within the summative scale. Consequently, it was not possible to collect data to score every question within the scale for every sampled well. To address this issue, summative-scale scores were evaluated as the percent of the total possible score for each well, with scores ranging from −100 to 100 percent for natural and anthropogenic Cr(VI), respectively. After the scores were compiled, the summative-scale Cr(VI) plume was drawn to include scores greater than 50 percent—the lowest-magnitude positive percent score that produced a coherent/mappable plume extent (fig. J.20).

The areal extent of the summative-scale Cr(VI) plume was 5.5 mi^2 (fig. J.20). The summative-scale Cr(VI) plume was within unconsolidated Mojave-type deposits consisting of felsic, low-chromium alluvium and lake-margin (beach) deposits sourced from the Mojave River (Mojave-type deposits). The summative-scale Cr(VI) plume was within the area covered by the PG&E monitoring well network. The summative-scale Cr(VI) plume is larger than the 2.2 mi^2 extent of the Q4 2015 regulatory Cr(VI) plume but smaller than the 8.3 mi^2 maximum mapped extent of Cr(VI) concentrations greater than the interim regulatory Cr(VI) background of 3.1 µg/L (ARCADIS, 2016). Hexavalent chromium in water from several deeper wells within the footprint of the Q4 2015 regulatory Cr(VI) plume had summative-scale scores of 50 percent and were identified as natural on the basis of the summative-scale analysis (fig. J.20). The summative-scale Cr(VI) plume extent was consistent with mineralogic and geochemical data collected as part of the USGS Cr(VI) background study that were not used within the summative scale.

Hexavalent chromium data from wells outside the summative-scale Cr(VI) plume collected between April 2017 and January 2018 were used to calculate Cr(VI) background concentrations in different parts of Hinkley and Water Valleys. The 1-year period (four quarters) of data collection was incorporated in the study design (Izbicki and Groover, 2016) to ensure a uniform and complete set of data were available for each well for calculation of Cr(VI) background, thereby addressing one of the limitations of the 2007 PG&E Cr(VI) background study (Lahontan Regional Water Quality Control Board, 2012). Hexavalent chromium background concentrations may be used for (1) plume management and estimation of the Cr(VI) plume margins, (2) establishment of cleanup goals within the Cr(VI) plume, and (3) understanding of Cr(VI) concentrations within unconsolidated deposits in parts of Hinkley and Water Valleys away from the regulatory Cr(VI) plume margins. Data used to calculate Cr(VI) background concentrations were comparable to regulatory data collected by PG&E and were not affected by differences in sample collection methodology with USGS data discussed in chapter F within this professional paper. The Cr(VI) background calculations are discussed in chapter G within this professional paper.

Background Cr(VI) concentrations in groundwater were calculated using the computer program ProUCL 5.1 (Singh and Maichle, 2015), as the upper 95-percent tolerance limit, UTL_{95}. The UTL_{95} is used by the EPA to describe background concentrations at contaminant sites. The UTL_{95} controls for Type-I (false positive) and Type-II (false negative) statistical errors in estimates of background. The UTL_{95} values were calculated for data from wells completed (screened) in Mojave-type deposits sampled as part of this study and for wells completed in undifferentiated, unconsolidated deposits sampled for regulatory purposes. For statistical reasons related to the independence of individual quarterly measurements and to ensure enough data were available for analysis, UTL_{95} values calculated from the median of quarterly measurements for wells completed in undifferentiated, unconsolidated deposits are reported in the following paragraphs.



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

Figure J.20. Summative-scale scores and summative-scale hexavalent chromium plume extent, Hinkley and Water Valleys, western Mojave Desert, California, March 2015 through November 2017. Summative-scale scores were calculated from data available in chapter E (appendix E.1, table E.1.1), Groover and Izbicki (2018), and U.S. Geological Survey (2021). Selected data and scores are available in chapter G (appendix G.1, table G.1.1).

For undifferentiated, unconsolidated deposits near the summative-scale Cr(VI) plume margin in the eastern and western subareas and in the northern subarea upgradient of the Mount General fault, the UTL_{95} values were 2.8, 3.8, and 4.8 µg/L, respectively (table J.3; fig. J.21). These values can be used to update the regulatory Cr(VI) plume extent and are suitable for management of Cr(VI) concentrations near the plume margins. An overall UTL_{95} value of 3.8 µg/L also was calculated for undifferentiated, unconsolidated deposits in the eastern and western subareas and in the northern subarea upgradient from the Mount General fault in Hinkley Valley; this value is similar to the overall UTL_{95} value of 3.9 µg/L calculated for Mojave-type deposits in Hinkley and Water Valleys, and is similar to the maximum Cr(VI) concentration of 3.6 µg/L in older groundwater in contact with Mojave-type deposits.

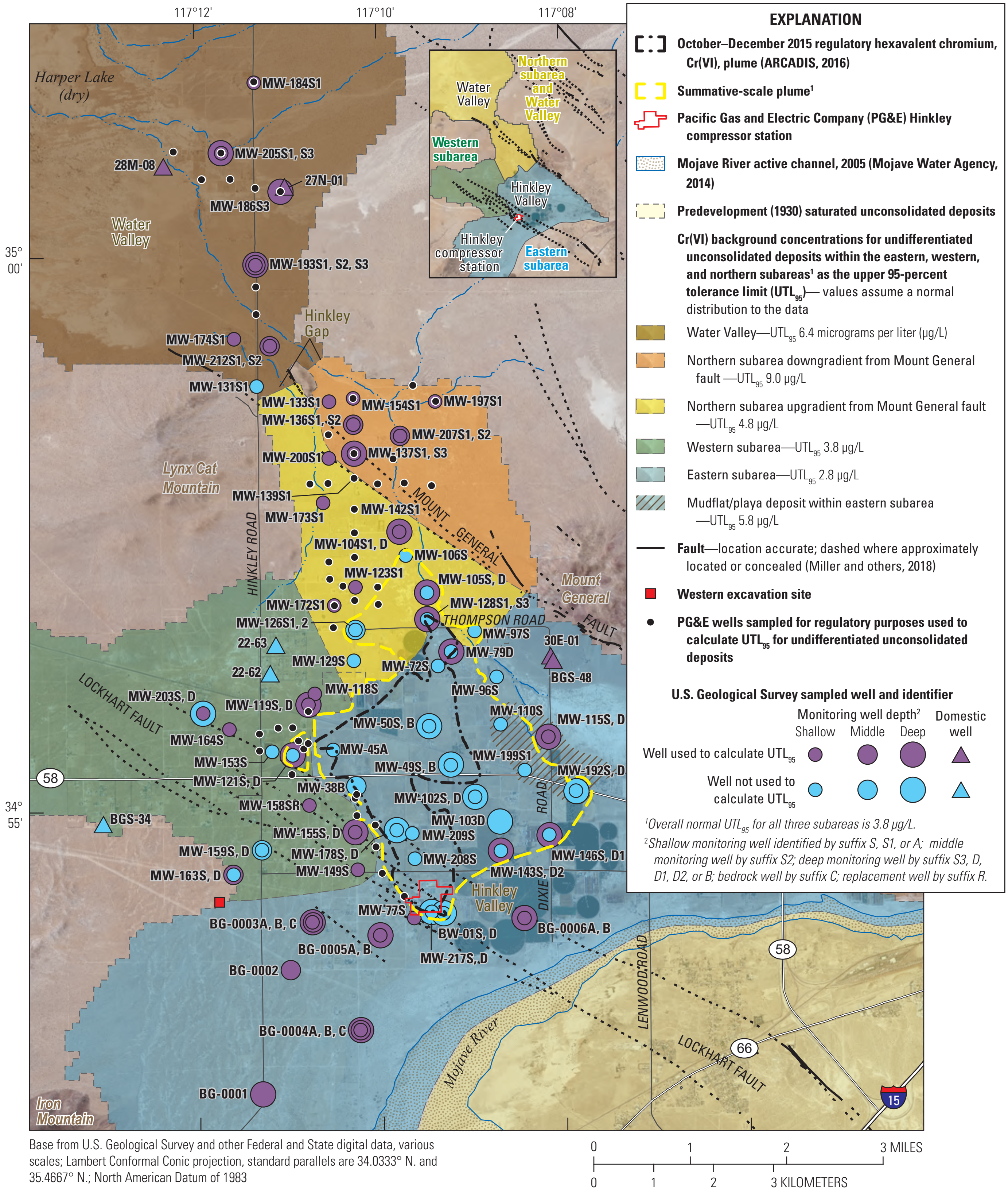
The overall UTL_{95} value may be an acceptable Cr(VI) background value to define and manage the Cr(VI) plume margin within the summative-scale Cr(VI) plume extent. However, UTL_{95} values for the various subareas provide greater resolution of Cr(VI) background that may be important in some areas.

The Cr(VI) UTL_{95} value of 2.8 µg/L calculated for the eastern subarea reflects low chromium concentrations in young (post-1952) groundwater in Mojave-type deposits in that area. Most of the summative-scale Cr(VI) plume is within the eastern subarea and this value is highly relevant for plume management. For example, the UTL_{95} value of 2.8 µg/L would have identified increases in anthropogenic Cr(VI) concentrations measured east and southeast of the Hinkley compressor station during an 8-year dry period with no flow in the Mojave River from 2011 to 2019 (ARCADIS, 2018; Lahontan Regional Water Quality Control Board, 2018), earlier than the overall UTL_{95} value of 3.8 µg/L. Within the eastern subarea, a separate UTL_{95} value of 5.8 µg/L (fig. J.21) was calculated for water within mudflat/playa deposits and older groundwater near Mount General. Although porewater extraction data indicate that felsic mudflat/playa deposits in the eastern subarea are a potential source of natural Cr(VI), they are not a plausible source of Cr(VI) concentrations in the eastern portion of the Q4 2015 regulatory Cr(VI) plume as high as 16 µg/L in water from wells sampled as part of this study or as high as 20 µg/L in regulatory data. The UTL_{95} value estimated for Mojave-type deposits in the eastern subarea downgradient from the Hinkley compressor station was 2.3 µg/L. This value reflects Cr(VI) concentrations that may have been present in that part of the aquifer if Cr(VI) had not been released from the Hinkley compressor station and may be a suitable metric for Cr(VI) cleanup goals within the Cr(VI) plume extent after regulatory updates. The value of 2.3 µg/L was lower than UTL_{95} values elsewhere in Hinkley Valley because of the geologic specificity of the data used for the calculation that represents coarser textured Mojave-type deposits in this area and the proximity of those deposits to recharge areas along the Mojave River that results in younger, less alkaline groundwater than in wells farther downgradient.

A UTL_{95} value of 4.8 µg/L was calculated for water from wells completed in undifferentiated, unconsolidated deposits in the northern subarea upgradient from the Mount General fault. This value is higher than the UTL_{95} for Mojave-type deposits in the northern subarea and the overall UTL_{95} value. The higher UTL_{95} value accounts for the presence of wells that are screened in Mojave-type deposits and the underlying mudflat/playa and lacustrine deposits. In 2018, concentrations of Cr(VI) in water from some wells, downgradient from the summative-scale Cr(VI) plume in undifferentiated, unconsolidated deposits in the northern subarea upgradient from the Mount General fault, equaled or exceeded the overall normal UTL_{95} value but did not exceed the Cr(VI) UTL_{95} value of 4.8 µg/L in this area. Additionally, the higher value provides for possible increases in Cr(VI) concentrations if water levels in this area continue to decline and the fraction of water yielded from wells partly screened in underlying deposits increases.

The UTL_{95} values calculated for undifferentiated, unconsolidated deposits in the northern subarea downgradient from the Mount General fault and in Water Valley were 9.0 and 6.4 µg/L, respectively (fig. J.21). Anthropogenic Cr(VI) was not present in these areas and subsurface geology differs from upgradient areas in Hinkley Valley, and data from these areas were not included in the calculation of the overall UTL_{95} (table J.3). These values can be used to identify unusual Cr(VI) concentrations in those areas. By chance alone some Cr(VI) concentrations in water from some wells will exceed UTL_{95} values. For example, in March 2015 Cr(VI) concentrations in water from well MW-154S1 were 11 µg/L and exceeded the UTL_{95} value for the northern subarea downgradient from the Mount General fault; regulatory Cr(VI) concentrations in water from well MW-154S1 have been as high as 20 µg/L.

Hexavalent chromium concentrations in more than 70 domestic wells sampled between January 27 and 31, 2016, ranged from less than the SRL of 0.1 to 4 µg/L, with a median concentration of 1.2 µg/L. The highest Cr(VI) concentration was in water from well 21N-04, the farthest north well sampled in Water Valley and the well farthest downgradient from the Hinkley compressor station. Hexavalent chromium concentrations in water from well 21N-04 exceeded the overall UTL_{95} value of 3.8 µg/L for the study area but were less than the UTL_{95} value for Water Valley. Several domestic wells in the eastern subarea were within the summative-scale Cr(VI) plume extent in the eastern subarea; however, water from these wells did not exceed the Cr(VI) UTL_{95} value of 2.8 µg/L for the eastern subarea. No domestic wells in the western or northern subarea upgradient from the Mount General fault exceeded the Cr(VI) UTL_{95} values of 3.8 and 4.8 µg/L for those areas, respectively; however, water from some monitoring wells in those areas exceeded the overall UTL_{95} value of 3.8 µg/L.



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

Figure J.21. Upper 95-percent tolerance limit for hexavalent chromium concentrations in water from wells screened in undifferentiated, unconsolidated deposits in the eastern, western, and northern subareas of Hinkley Valley and in Water Valley, western Mojave Desert, California, April 2017 through March 2018. Values were calculated from data submitted for regulatory purposes by Pacific Gas and Electric Company, accessed January 12, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/ and data from U.S. Geological Survey (2021). Data are available in chapter G (appendix G.2, table G.2.2).

Table J.3. Upper 95-percent tolerance limits, UTL_{95}, for hexavalent chromium, Cr(VI), in groundwater within undifferentiated, unconsolidated deposits in the eastern, western, and northern subareas of Hinkley and Water Valleys, western Mojave Desert, California, April 2017 through March 2018.

[Values were calculated from data submitted for regulatory purposes by Pacific Gas and Electric Company, accessed January 12, 2018, at https://www.waterboards.ca.gov/lahontan/water_issues/projects/pge/. Data are available from U.S. Geological Survey (2021) and in chapter G (appendix G.2, tables G.2.1, G.2.2). Background Cr(VI) concentrations calculated as the UTL_{95} using the computer program ProUCL (Singh and Maichle, 2015). The number of wells is the number of wells used in the calculation. The median of four measurements collected quarterly was used for each well. **Abbreviation**: µg/L, micrograms per liter]

Number of wells	Cr(VI) UTL_{95}, in µg/L	Maximum Cr(VI), in µg/L	Modeled distribution
Eastern subarea[1]			
24	2.8	3.6	Normal
Western subarea			
27	3.8	3.8	Normal
Northern subarea (upgradient of the Mount General fault)[2]			
30	4.8	4.0	Normal
Overall (Eastern, western, and northern subareas upgradient of the Mount General fault)			
81	3.8	4.0	Normal

[1] A separate UTL_{95} value of 3.8 µg/L was calculated for unconsolidated deposits near mudflat/playa deposits in the eastern subarea near Mount General. A UTL_{95} value of 2.3 µg/L was calculated for Mojave-type deposits within the updated regulatory Cr(VI) plume downgradient from the Hinkley compressor station.

[2] Separate UTL_{95} values of 9.0 and 6.4 µg/L were calculated for the northern subarea downgradient from the Mount General fault and for Water Valley.

The regulatory Cr(VI) plume extent is updated quarterly. The process involves PG&E and regulators with input from the local community and other stakeholders and is beyond the scope of this professional paper. Some Cr(VI) concentrations within the summative-scale Cr(VI) plume are less than the UTL_{95} values for their respective subareas and may not require regulatory attention, and an updated regulatory Cr(VI) plume would lie within the summative-scale Cr(VI) plume. For example, although anthropogenic Cr(VI) was indicated by the summative-scale analysis, Cr(VI) concentrations in water from wells MW-105S, MW-106S, MW-126S1, and MW-126S2 near the leading edge of the summative-scale Cr(VI) plume in the northern subarea did not exceed the UTL_{95} value of 4.8 µg/L; and between May 2017 and April 2018, the median Cr(VI) concentration in water from well MW-121S near the leading edge of the summative-scale Cr(VI) plume in the western subarea did not exceed the UTL_{95} value of 3.8 µg/L. Similarly, Cr(VI) concentrations in water from most wells in the eastern subarea outside the Q4 2015 regulatory Cr(VI) plume but within the summative-scale Cr(VI) plume extent did not exceed the UTL_{95} value of 2.8 µg/L for the eastern subarea. Wells MW-99S, MW-110S, and MW-192D in the eastern subarea near mudflat/playa deposits near Mount General had higher Cr(VI) concentrations, but concentrations were less than the UTL_{95} value of 5.8 µg/L for water associated with mudflat/playa deposits and older groundwater in that area and concentrations did not exceed the overall UTL_{95} value of 3.8 µg/L. Conversely, water from wells MW-97S and MW-128S1 near the leading edge of the Q4 2015 regulatory Cr(VI) plume in the northern subarea having Cr(VI) concentrations of 6.7 and 6.4 µg/L, respectively, exceeded the UTL_{95} value of 4.8 µg/L for that part of the northern subarea in January 2018 (the latest data considered as part of this study) and would likely be included in an updated Cr(VI) regulatory plume for that period.

The UTL_{95} values calculated as part of this study provide scientifically defensible background Cr(VI) concentrations that differ with local geologic, geochemical, and hydrologic conditions. The UTL_{95} values may be used for (1) plume management and estimation of the Cr(VI) plume margins, (2) establishment of cleanup goals within the Cr(VI) plume, and (3) understanding of Cr(VI) concentrations within unconsolidated deposits in parts of Hinkley and Water Valleys away from the plume margins. Limitations and biases associated with the UTL_{95} values are discussed in chapter G within this professional paper. The UTL_{95} values presented within this professional paper are not background Cr(VI) concentrations for regulatory purposes, and the authority to establish regulatory Cr(VI) background values, clean-up goals, and future site management practices resides with the Lahontan RWQCB.

J.8. Predevelopment Water Levels, Local Recharge, and Selected Hydrologic Properties of Aquifer Materials

Hydrologic and geophysical data were collected to provide information for updates to an existing groundwater-flow model of Hinkley Valley (ARCADIS and CH2M Hill, 2011) by PG&E consultants (Jacobs Engineering Group, Inc., 2019). These data are discussed in chapter H within this professional paper.

A predevelopment groundwater-level map (1930), drawn using water-level measurements collected as early as 1918, shows groundwater movement from recharge areas along the Mojave River to evaporative discharge areas near the margin of Harper (dry) Lake in Water Valley. Depth to water ranged from near land surface along the Mojave River to above land surface near Harper (dry) Lake, consistent with flowing wells in that area during predevelopment conditions. Predevelopment depths to water in much of Hinkley Valley downgradient from the Lockhart fault were less than 20-ft below land surface (bls), and predevelopment depths to water near the Hinkley compressor station were about 27 ft bls. Water-level declines from predevelopment as a result of agricultural pumping were as much as 60 ft near the Hinkley compressor station by 2016.

Average annual precipitation in Hinkley and Water Valleys is about 4.3 inches per year (in/yr) on the valley floor and does not exceed 6 in/yr in the surrounding mountains. Potential evaporation exceeds 59 in/yr throughout the area. Areal recharge from infiltration of precipitation on the valley floor and mountain block recharge from infiltration of precipitation in uplands surrounding Hinkley and Water Valleys are negligible. Recharge to Hinkley and Water Valleys as infiltration of runoff from upland drainages was estimated to average 64.7 acre-ft/yr, with additional recharge from two large drainages south of the Mojave River. In most years, runoff from upland drainages does not occur; in years when it does occur, local runoff to Hinkley Valley was estimated to average 296 acre-feet (acre-ft). In contrast, average recharge as infiltration of streamflow from the Mojave River is between 13,400 and 17,100 acre-ft/yr. Most recharge occurs from large streamflows in the Mojave River that occur every 5–7 years. In some years, recharge to Hinkley Valley from the Mojave River may exceed 100,000 acre-ft (Stamos and others, 2001; Jacobs Engineering Group, Inc. 2019).

Hydraulic-conductivity values estimated from slug-test data from 95 monitoring wells ranged from less than 0.1 to 680 feet per day (ft/d; Groover and others, 2021). Where shallower and deeper wells were tested at the same site, hydraulic conductivity decreased with depth at 70 percent of sites. Hydraulic-conductivity values estimated from nuclear magnetic resonance (NMR) data collected within the screened interval from 10 selected wells were highly correlated with hydraulic conductivity from slug-test data for those wells based on least-squares regression analysis (R^2=0.98). Median NMR hydraulic-conductivity values for Mojave-type deposits including Mojave River alluvium and lake-margin deposits were 71 and 15 ft/d, respectively; median values for local fan and weathered bedrock were 6 and 9 ft/d, respectively. Hydraulic conductivity, estimated from NMR data, for formerly saturated deposits overlying the water table at the time of this study were as high as 300 ft/d near the Hinkley compressor station (fig. J.22). Downgradient from the Hinkley compressor station, formerly saturated deposits had a hydraulic conductivity of about 180 ft/d, which is higher than the saturated materials at those sites. Consistent with NMR data, cone penetration test data show coarse-textured material in formerly saturated deposits above the water table (at the time of this study) near the Hinkley compressor station, within the Q4 2015 regulatory Cr(VI) plume, throughout the northern subarea, and near Hinkley Gap.

The Lockhart fault impedes groundwater flow in Hinkley Valley and influences the shape of the Q4 2015 regulatory Cr(VI) plume. Surficial and subsurface disruption of unconsolidated deposits was mapped by Miller and others (2020a). Groundwater-flow directions near the Lockhart fault measured using horizontal point-velocity probes were deflected to the northwest from directions estimated on the basis of water-level data on the upgradient side of the fault. Carbon-14 activities for wells MW-155S and MW-155D within splays of the fault were 63 and 49 pmc, with unadjusted carbon-14 ages of 5,600 and 3,500 ybp, respectively. Post-1952 groundwater containing tritium and high concentrations of anthropogenic Cr(VI) were present in water from wells along the downgradient side of the Lockhart fault, consistent with limited movement of groundwater across the fault. Well MW-208S, having a Cr(VI) concentration of 2,500 µg/L, the highest Cr(VI) concentration measured as part of this study, is within splays of the Lockhart fault less than 0.25 mi downgradient from the Hinkley compressor station, and the Lockhart fault may act to impede the downgradient movement of anthropogenic Cr(VI) within water in this area.

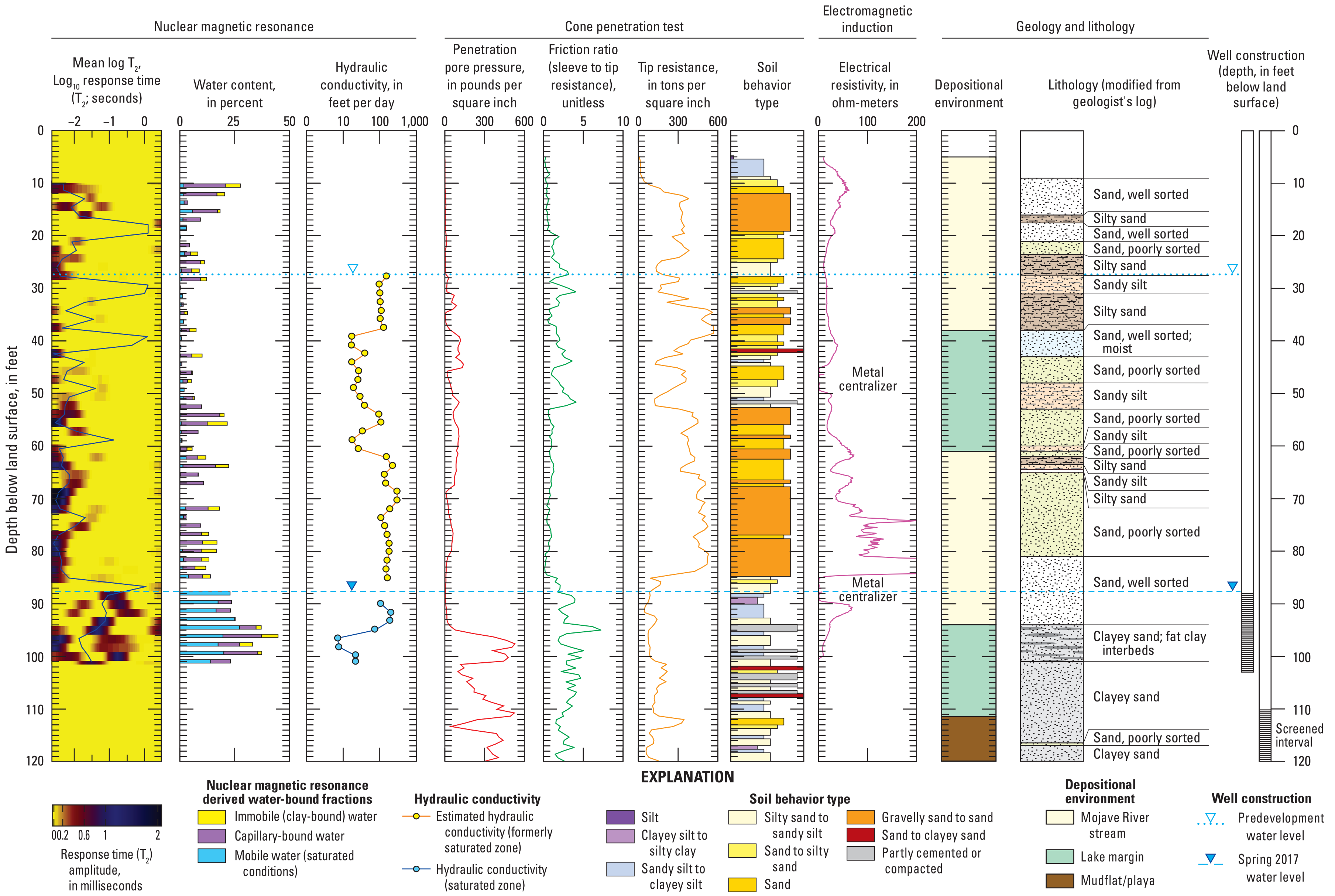


Figure J.22. Geophysical data collected at monitoring well site MW-217, Hinkley Valley, western Mojave Desert, California, March through May 2017. Geophysical log data are available in U.S. Geological Survey (2019); geologic provenance data are available in Miller and others (2020); geologists log from (Christopher Maxwell, Stantec, written commun., 2017); and hydraulic conductivity values for formerly saturated deposits were estimated using nuclear magnetic resonance geophysical log data from Groover and others (2021).

Coupled well-bore flow and depth-dependent water-quality data showed that water was yielded to wells C-01 and IW-03 within the Q4 2015 regulatory Cr(VI) plume through thin, permeable layers within the aquifer (fig. J.23). Lake-margin (beach) deposits penetrated by these wells within the upper unit of the upper aquifer system are areally extensive, hydraulicly well connected, and have hydraulic conductivities as high as 250 ft/d; hydraulic conductivities in these upper layers were greater than permeable units at depth. Collectively, well-bore flow data showed high permeability deposits at the water table that may have allowed transport of Cr(VI) downgradient when releases from the Hinkley compressor station first occurred. Well-bore flow data from well 27-03 in the western subarea near the summative-scale Cr(VI) plume margin showed comparatively uniform flow from the aquifer into the well with depth throughout the screened interval of the well. Well-bore flow data from well 27-38 (the former Hinkley School well) showed almost all water yielded to the well at depth from consolidated bedrock, with little water yielded from overlying unconsolidated deposits. Well-bore flow data from well 27N-04 in Water Valley showed almost all water was yielded from permeable Mojave-type lake-margin deposits near the water table, with almost no water yielded from underlying local alluvium.

The updated groundwater-flow model of Hinkley Valley, known as the Hinkley Chromium Background Study Model (HCBSM; Jacobs Engineering Group, Inc., 2019) is based on the understanding that PG&E and their consultants have of the groundwater-flow system in Hinkley and Water Valleys developed from their interpretation of water-level and hydraulic data. Differences between measured groundwater age, Cr(VI) regulatory data, and HCBSM particle-simulation data are discussed in chapter H within this professional paper (appendix H.2). These differences may be attributed to (1) conceptual differences in aquifer properties within the shallow and deep zones of the upper aquifer, (2) conceptual differences in groundwater movement between the western and northern subareas as groundwater levels declined as a result of agricultural pumping beginning in the early 1950s, (3) simulation of specific yield within the HCBSM outside of literature published ranges, and (4) conceptual differences in groundwater flow across the Lockhart fault. Differences between measured groundwater-age data, and Cr(VI) regulatory data, and HCBSM particle-simulation data were not reconciled within the timeframe of this study; consequently, the HCBSM was not used to iteratively evaluate and refine the summative-scale Cr(VI) plume extent as proposed in the study design (Izbicki and Groover, 2016, 2018). The HCBSM is not a USGS product and does not incorporate understanding of the groundwater-flow system supported by chemical, groundwater-age, and aquifer property data developed as part of this study.

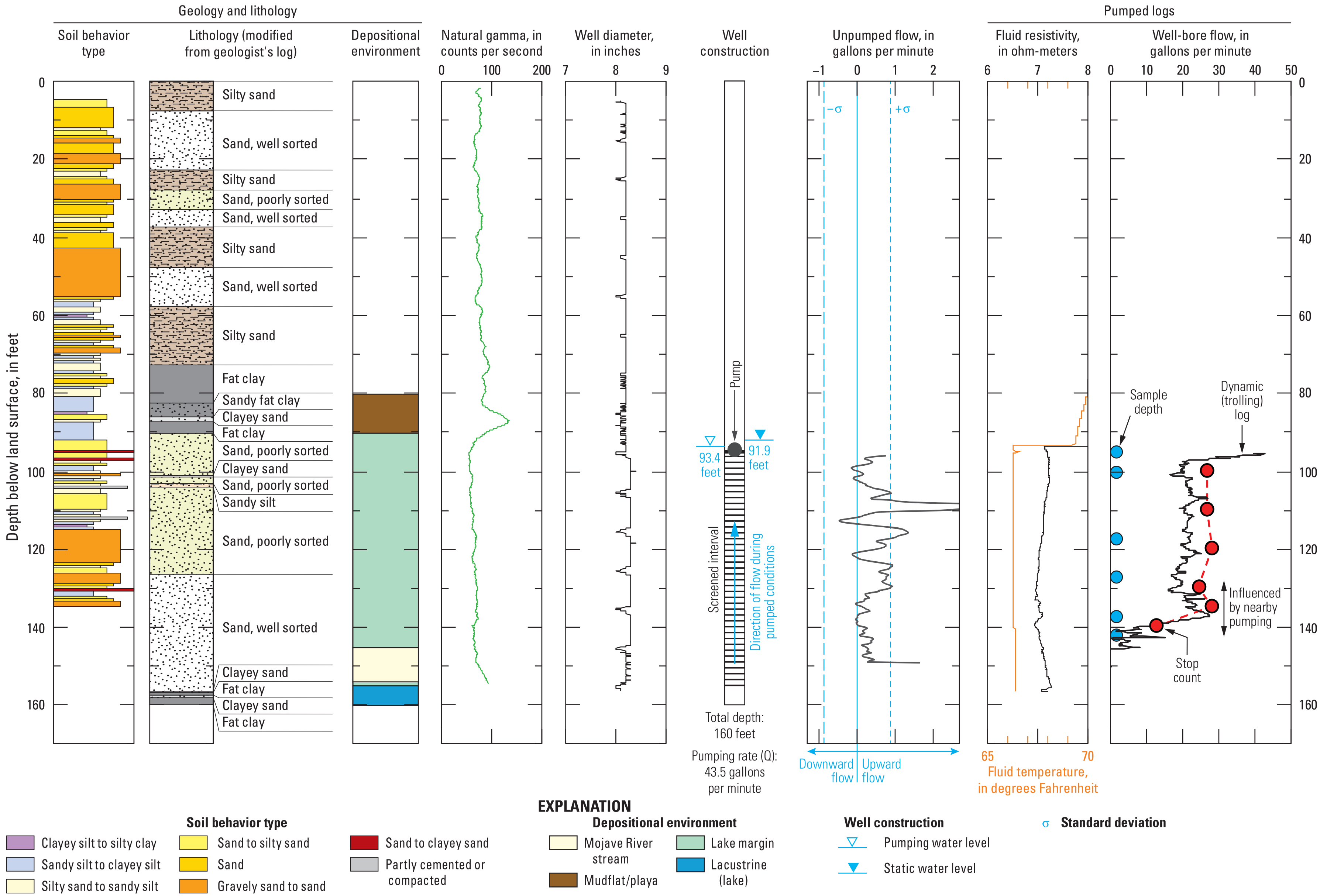


Figure J.23. Selected well-bore flow and other geophysical data collected under unpumped and pumped conditions from the Pacific Gas and Electric Company (PG&E) well IW-03, State well number 10N/3W-26L34S, Hinkley Valley, western Mojave Desert, California, November 30 through December 4, 2015. Geophysical log data and well construction information from video log data are available in U.S. Geological Survey (2019); geologic provenance data are available in Miller and others (2020); geologists log from (Christopher Maxwell, Stantec, written commun., 2017); and water chemistry data are available in U.S. Geological Survey (2019, 2021).

J.9. Sequestration and Re-Oxidation of Chromium in Experimental Microcosms

Anthropogenic Cr(VI) within groundwater is treated by PG&E using bioremediation by injecting ethanol as a reductant into a volume of aquifer known as the in situ reactive zone (IRZ; chapter A). This treatment reduces Cr(VI) to Cr(III) that is rapidly sequestered by sorption onto aquifer materials and by co-precipitation within Fe- or Mn-bearing minerals that form in place as reduction proceeds. Mitigation of anthropogenic Cr(VI) is projected to require 10–95 years (Haley and Aldrich, Inc., 2010; Pacific Gas and Electric Company, 2011), at which time ethanol injections will likely cease. This projection assumes that Cr(VI) removal is permanent and that no Cr(III) will oxidize back to Cr(VI) in the event of changing aqueous geochemical conditions, should oxic groundwater recharged from the Mojave River reenter the IRZ. Laboratory microcosm experiments, discussed within chapter I within this professional paper, were done to investigate the process of reductive sequestration and the potential for re-oxidation of Cr(III) to Cr(VI).

To evaluate the sequestration of Cr(VI) within groundwater to aquifer materials during reduced (oxygen absent) conditions, laboratory microcosms were prepared with fresh core material collected from sites within the aquifer up-gradient of the Cr(VI) regulatory plume using (1) recent Mojave River alluvium from site BG-0004 from 53 to 61.2 ft bls and (2) older Mojave River alluvium from site BG-0005 from 104 to 114.5 ft bls. Additional microcosms were prepared from core material collected within the Q4 2015 regulatory Cr(VI) plume from site SA-SB-01 from 103 to 108 ft bls. Control microcosms within the reduction experiments were prepared using artificial substrates consisting of cleaned quartz sand and Fe-coated sand. Unfiltered Mojave River groundwater and an added isotopic tracer of chromium-50 were reduced within the microcosms using ethanol and examined during a period of 2 years. During this time, repeated additions of diluted ethanol were added as needed to maintain reduced conditions within the microcosms within appropriate ranges, to avoid sulfate-reducing or methanogenic conditions, and to mimic field conditions. A total of 215 microcosms were prepared.

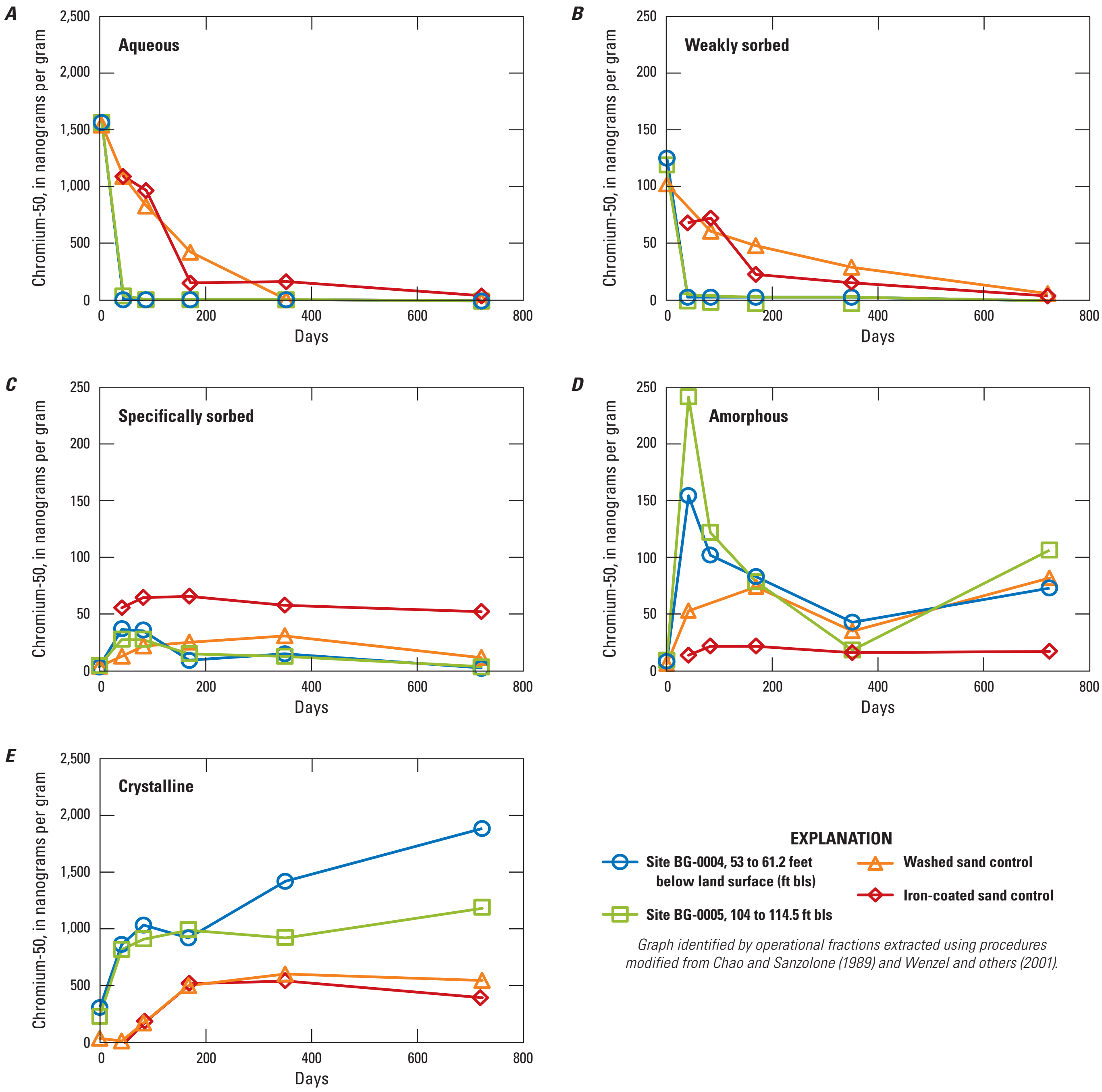
Analysis of chromium-50, Fe, and Mn obtained during sequential extractions of microcosms harvested at various times showed that some aqueous Cr was sorbed to mineral grain surfaces within hours, and incorporation of reduced Cr(III) into amorphous and crystalline solid phases occurred during the next few months (fig. J.24). Amorphous Cr-bearing phases included Fe and Mn (oxy)-hydroxides and organic matter. By the end of the 2-year experiment, most of the chromium-50 tracer resided within the crystalline phase. Synchrotron studies (bulk and micro-X-ray absorption spectroscopy) of solids indicated that Cr within the crystalline phase was associated with mixed valence Fe oxides such as magnetite and Fe/Mn oxides such as jacobsite. Manganese was spatially co-located with Cr during the later stages of reduction.

To evaluate the potential for re-oxidation of Cr(III) to Cr(VI), additional batch microcosms were prepared from fresh core material from sites BG-0004 and BG-0005. Microcosms were first reduced for 1 year, then subsequently exposed to air and allowed to oxidize for up to 2 years (fig. J.25). Control microcosms within the reoxidation experiments were prepared using artificial substrates composed of cleaned quartz sand coated with (1) pure Fe and Mn oxides, (2) with oxide mixtures approximating the natural Fe and Mn oxide ratio of Fe/Mn=50, and (3) with oxide mixtures approximating twice and half the natural ratio of Fe and Mn oxides, respectively. A total of 192 microcosms were prepared.

Hexavalent chromium was released during oxidation of all site and control materials. The amount of Cr(VI) released, and when it was released, differed between site materials and artificial substrates. Recent Mojave River deposits produced the least Cr(VI) during reoxidation, whereas older Mojave River deposits, which contained more Mn, produced more Cr(VI) during reoxidation; similarly, artificial substrates containing more Mn produced more Cr(VI) during reoxidation. Most Cr(VI) remained sorbed to aquifer solids within the microcosms, although Cr(VI) was detected within the aqueous phase within the microcosms.

Even though Cr(III) is sequestered during reduced conditions within crystalline oxides, co-location of Cr with Mn oxides during the later stages of reduction influences the susceptibility of Cr(III) to reoxidize to Cr(VI) under oxic conditions. Initial increases in Cr(VI) within 0–56 days of the onset of reoxidation indicate the time required for Mn oxides to form in proximity to sequestered Cr(III); microbes then mediate Mn(II) oxidation to form Mn(III) or Mn(IV) oxides, and Cr(III) is subsequently oxidized by these biogenic Mn-oxides. Microcosm results are consistent with previous studies that show Cr(III) is oxidized to Cr(VI) in the presence of Mn oxides (Schroeder and Lee, 1975; Nico and Zasoski, 2000; Oze and others, 2007).

Reoxidation of Cr(III) to Cr(VI) in study microcosms increases as sorbed Mn oxides increase. As much as 10 percent of the Cr added to microcosms containing recent Mojave River material (having less Mn) and 20 percent of the added Cr added to microcosms containing older Mojave River material (having more Mn) was reoxidized from Cr(III) to Cr(VI). Less Cr(VI) (less than 3 percent of Cr added before reduction) was released to the aqueous phase, and this release occurred following longer periods of oxygen exposure.



Graph identified by operational fractions extracted using procedures modified from Chao and Sanzolone (1989) and Wenzel and others (2001).

Figure J.24. Time-series of the median (n=2) amount of chromium-50 recovered in each of five operationally defined phases or fractions by sequential extractions of materials during 2 years of reduction: A, aqueous; B, weakly sorbed; C, specifically sorbed; D, amorphous; and E, crystalline. Note the 10 times higher scale for chromium-50 recovered in the aqueous phase *A* and strong acid extract *E*. Data are available in Miller and others (2020b).

Aqueous Cr(VI) concentrations measured within study microcosms are potentially, environmentally significant relative to background Cr(VI) concentrations calculated as part of this study. Although it is difficult to make a direct comparison between microcosm results and environmental data, release of Cr(VI) to groundwater has been reported in treated (reduced) groundwater after exposure to oxic conditions in environmental settings (Slejko and others, 2019). The experimental microcosm data indicate that maintenance of anoxic conditions within the IRZ would ensure sequestration of chromium on aquifer solids as Cr(III), thereby preventing re-oxidation to Cr(VI) and subsequent mobilization into groundwater.

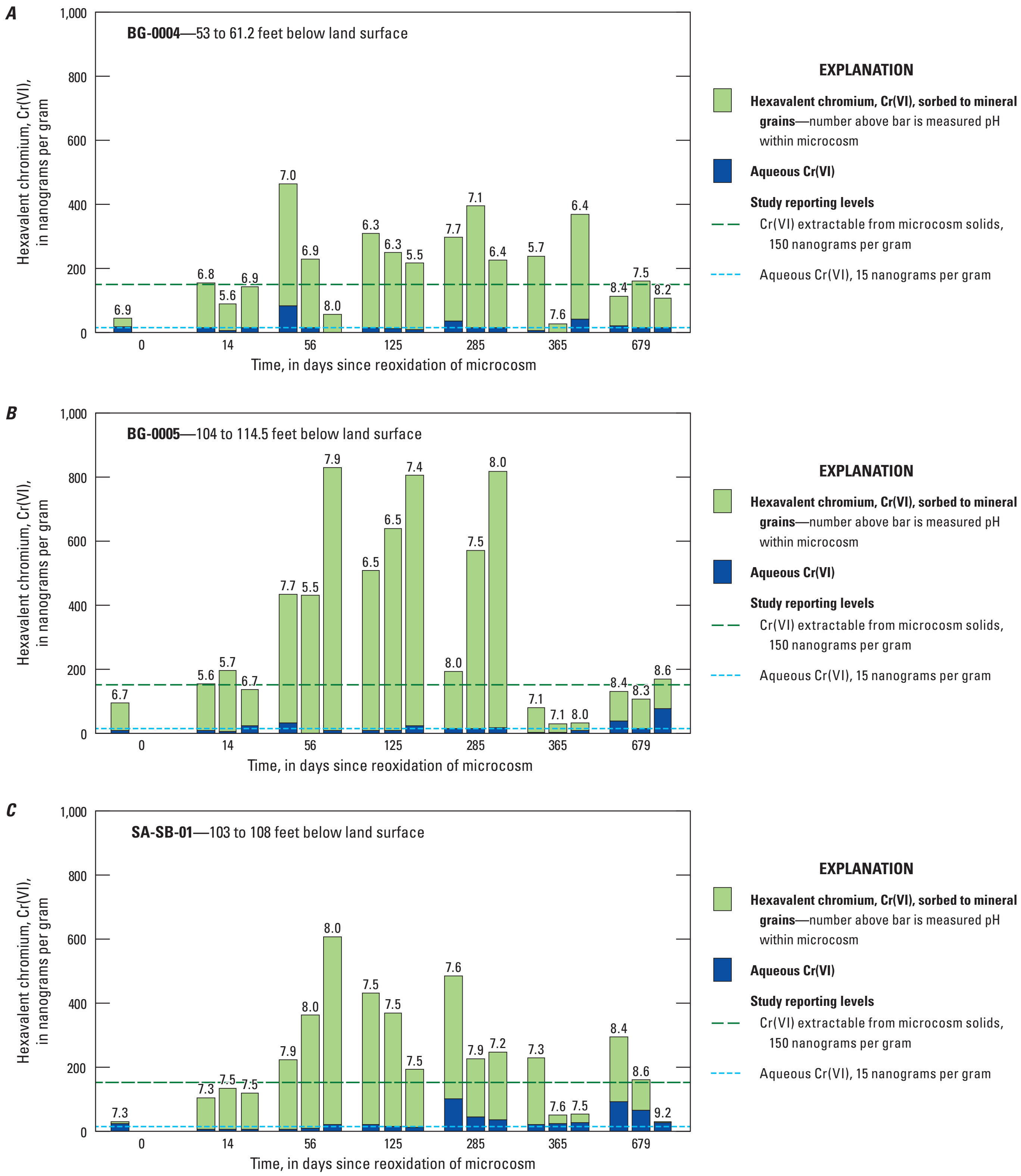


Figure J.25. Hexavalent chromium, Cr(VI), recovered at selected times during 2 years of reoxidation of site materials at *A*, BG-0004, *B*, BG-0005, and *C*, SA-SB-01, which were previously reduced for more than 1 year in the presence of 3,000 nanograms per gram (ng/g) added Cr(VI). Numbers above the bars indicate the pH of the aqueous phase at the time of sampling. Blue bars represent individual analyses of aqueous Cr(VI) at the time of separation from the solid phase. Blue-dashed lines represent the aqueous Cr(VI) reporting level. Green bars represent individual analyses of the amount of Cr(VI) released following alkaline digestion of the solid phase. Green-dashed lines represent the solid-phase Cr(VI) reporting level. Data are available in Miller and others (2020b).

J.10. Relevance, Limitations, and Uses of Hexavalent Chromium Background Study Results

A 2007 PG&E funded study estimated the Cr(VI) background concentration in Hinkley Valley to be 3.1 µg/L (CH2M Hill, 2007). This concentration was adopted as the interim Cr(VI) background concentration for regulatory purposes by the Lahontan RWQCB (Lahontan Regional Water Quality Control Board, 2008). In response to limitations associated with the 2007 study methodology and an apparent increase in the mapped extent of the Cr(VI) plume between 2008 and 2012, the Lahontan RWQCB (Lahontan Regional Water Quality Control Board, 2012) agreed that the 2007 background Cr(VI) study be updated.

The purpose of the updated study was to estimate background Cr(VI) concentrations in groundwater upgradient, downgradient, near the margins, and within the footprint of the mapped PG&E Cr(VI) plume in the upper aquifer underlying Hinkley Valley, California (Izbicki and Groover, 2016). The study identified geologic, geochemical, and hydrologic processes that contribute Cr(VI) to water from wells, estimated the extent of anthropogenic Cr(VI), and calculated background Cr(VI) concentrations from wells outside the area of anthropogenic Cr(VI). In addition, experimental data were collected to evaluate the in situ reduction of Cr(VI) to Cr(III) used by PG&E to remove Cr(VI) from groundwater within the plume.

J.10.1. Processes that Contribute Natural Hexavalent Chromium to Groundwater

Chromium concentrations in rock and aquifer deposits within Hinkley Valley are regionally low compared to the average chromium concentration of 185 mg/kg in the average bulk continental crust (Reimann and de Caritat, 1989). In the past, Cr(VI) in groundwater was considered a priori evidence of anthropogenic contamination (Hem, 1959). In recent years, natural Cr(VI) in groundwater has been identified and widely studied. However, detailed study of geologic conditions and processes that control natural Cr(VI) occurrence in areas having low geologic abundance of chromium are rare in the literature. Geologic, geochemical, and hydrologic processes that control concentrations of natural Cr(VI) in alkaline oxic groundwater within Hinkley Valley likely are important in a range of other geologic, geochemical, and hydrologic settings; however, the influence of these processes on Cr(VI) concentrations in groundwater may be difficult to discern in areas having a high geologic abundance of chromium.

In Hinkley Valley, geologic, geochemical, and hydrologic processes that contribute Cr(VI) to groundwater operate at the mineral grain and hydrologic scale. Most chromium in aquifer materials in Hinkley and Water Valleys is substituted within magnetite mineral grains. Magnetite is resistive to weathering, and about 90 percent of chromium remains within unweathered mineral grains. More easily weathered chromium-containing actinolite (eroded from the San Gabriel Mountains and transported to Hinkley Valley by the Mojave River) and hornblende (eroded from Iron Mountain along the western margin of Hinkley Valley) are present in Mojave-type deposits within Hinkley Valley. Basalt fragments (within unconsolidated deposits in Water Valley) and weathered Miocene materials (within unconsolidated deposits in parts of the northern subarea downgradient from the Mount General fault and in Water Valley) also contribute chromium to unconsolidated materials.

Chromium that has weathered from primary minerals is sorbed on the surfaces of mineral grains. Sorption is a function of surface area, with surface area and sorption increasing as particle-size decreases. As mineral grains become increasingly fine-textured, diffusive transport processes dominate, facilitating oxidation of Cr(III) to Cr(VI) in the presence of Mn oxides. Calcareous fine-textured mudflat/playa deposits in Hinkley and Water Valleys have abundant Mn(IV) oxides within visible Mn nodules and dendritic surface structures. Visually abundant Fe and Mn(III/IV) oxides were observed on the surfaces of mineral grains that have accumulated near the water table, near geologic and lithologic contacts, and near redox boundaries within aquifer deposits. Iron oxides within these deposits provide sorption sites and a reservoir for storage of chromium weathered from mineral grains where oxidation of Cr(III) to Cr(VI) can occur in the presence of Mn oxides.

Once oxidized to Cr(VI), desorption of Cr(VI) from sorption sites on the surfaces of mineral grains increases with increasing pH. Oxyanion-forming trace elements including arsenic and vanadium and uranium complexes with carbonate also have pH-dependent sorptive properties similar in some respects to Cr(VI).

J.10.2. Estimated Extent of Anthropogenic Hexavalent Chromium in Groundwater

Data from more than 100 wells sampled by the USGS between March 2015 and November 2017 were used to evaluate the extent of anthropogenic Cr(VI). Sampled wells were selected by the USGS, with input from a TWG composed of Hinkley community members, the IRP Manager, the Lahontan RWQCB, PG&E, and consultants for PG&E. Sampled wells represent a mutually agreed upon, spatially distributed set of wells covering a range of geologic, geochemical, and hydrologic settings within Hinkley and Water Valleys. Sampled wells were most commonly selected on the basis of high Cr(VI) concentrations or upward Cr(VI) concentration trends. As a consequence, wells selected for sample collection have a positive (high) bias. However, this bias ensured that wells having high Cr(VI) concentrations, important to the estimation of the extent of anthropogenic Cr(VI) and Cr(VI) background, were sampled as part of this study.

The areal extent of anthropogenic Cr(VI) released from the Hinkley compressor station was estimated using a summative-scale approach that incorporated data addressing geologic, geochemical, and hydrologic processes identified as part of this study. The summative scale was used to (1) provide a transparent framework for data interpretation in which all stakeholders participated; (2) provide unbiased interpretation of data traceable to numerical measurements; (3) provide a framework that enabled geologic, geochemical, and hydrologic data to be considered collectively; and (4) consolidate different types of data into a simple, easy-to-understand interpretation. Questions within the summative scale were developed to address measurable components of the geologic, geochemical, and hydrologic processes that control Cr(VI) concentrations in groundwater. When data from each well are scored using the questions and metrics within the summative scale, all stakeholders would score each well the same way and would draw the same summative-scale Cr(VI) plume extent.

The questions within the summative scale are not definitive of all processes controlling aqueous Cr(VI) concentrations in groundwater, and a different study design may have collected different data and developed different questions and metrics for use within the scale. Of the processes addressed by questions within the summative scale, pH-dependent sorption of Cr(VI), evaluated as the natural Cr(VI) occurrence probability at the measured pH, was the most relevant. Hexavalent chromium and pH are measured in regulatory samples of water from wells in Hinkley Valley; in the absence of the detailed geologic, geochemical, and hydrologic data collected as part of this study, the Cr(VI) occurrence probability at the measured pH can be used to identify natural and anthropogenic Cr(VI).

Hydraulic-gradient data were not used in the summative scale because the gradients may have changed as a result of pumping and recharge during the period after release of Cr(VI) from the Hinkley compressor stations and because of concerns that Cr(VI) may have been released at locations within the study area other than the Hinkley compressor station, including possible releases at the western excavation site in the western subarea (Lahontan Regional Water Quality Control Board, 2014). A numerical groundwater-flow model of Hinkley and Water Valleys (ARCADIS and CH2M Hill, 2011) was updated by PG&E consultants (Jacobs Engineering Group, Inc., 2019) with the intent of addressing physical and hydraulic constraints on groundwater flow and Cr(VI) movement downgradient from the Hinkley compressor station (chapter H, appendix H.2). The updated groundwater-flow model was not used to iteratively evaluate and refine the summative-scale Cr(VI) plume extent as proposed in the study design (Izbicki and Groover, 2016, 2018) because of differences between measured groundwater-age data and Cr(VI) regulatory data, and model particle-simulation data. Chemical and mineralogic data did not indicate high natural abundance, unusual mineralogy, or unusual sorptive properties for chromium in core material from sites downgradient from the western excavation site; Cr(VI) within this area was considered anthropogenic for the purposes of this professional paper.

The areal extent of the summative-scale Cr(VI) plume was 5.5 mi^2. The summative-scale Cr(VI) plume lies within unconsolidated Mojave-type deposits composed of alluvium and lake-margin deposits sourced from the Mojave River; these deposits are low in chromium. Additionally, the summative-scale Cr(VI) plume is within the area covered by the PG&E monitoring well network. The summative-scale Cr(VI) plume is larger than the 2.2 mi^2 extent of the Q4 2015 regulatory Cr(VI) plume but smaller than the 8.3 mi^2 maximum mapped extent of Cr(VI) greater than the interim regulatory Cr(VI) background of 3.1 µg/L.

The summative-scale Cr(VI) plume includes wells identified as containing anthropogenic Cr(VI) on the basis of the summative-scale analysis. However, the summative-scale Cr(VI) plume does not define the Cr(VI) plume extent for regulatory purposes. Hexavalent chromium concentrations outside the summative-scale Cr(VI) plume extent were used to calculate background Cr(VI) concentrations.

J.10.3. Background Hexavalent Chromium Concentrations in Groundwater

Background Cr(VI) concentrations near the margins of the Cr(VI) plume can be used for regulatory and management purposes, including (1) updating the extent of the regulatory Cr(VI) plume and plume management, (2) establishing Cr(VI) cleanup goals, and (3) identifying unusual Cr(VI) concentrations away from the regulatory Cr(VI) plume. Hexavalent chromium data from wells screened within undifferentiated, unconsolidated deposits outside the summative-scale Cr(VI) plume were used to calculate Cr(VI) background concentrations.

Hexavalent chromium background concentrations were calculated as the $\mathrm{UTL}_{95,}$ using the computer program ProUCL 5.1 using data collected between April 2017 and March 2018. The 1-year period (four quarters) of data collection was incorporated in the study design (Izbicki and Groover, 2016) to ensure a uniform and complete set of data were available for each well for calculation of Cr(VI) background, thereby addressing one of the limitations of the 2007 PG&E Cr(VI) background study.

An overall UTL_{95} value of 3.8 µg/L was calculated for Cr(VI) in undifferentiated, unconsolidated deposits within the eastern and western subareas and the northern subarea upgradient from the Mount General fault in Hinkley Valley. In most cases, the overall UTL_{95} value may be acceptable for use as a regulatory Cr(VI) background value near the plume margin to define and manage the Cr(VI) plume; however, UTL_{95} values for the various subareas in Hinkley and Water Valleys provide greater resolution of Cr(VI) background that may be important for some purposes. The UTL_{95} values of 2.8, 3.8, and 4.8 µg/L were calculated for Cr(VI) in undifferentiated, unconsolidated deposits in the eastern and western subareas and the northern subarea upgradient from the Mount General fault, respectively (table J.3). If greater precision is required for regulatory purposes near the summative-scale Cr(VI) plume margin, the UTL_{95} value of 2.8 µg/L may be useful to track plume expansion in the eastern subarea near the Hinkley compressor station during dry periods. The UTL_{95} value of 2.8 µg/L for the eastern subarea does not account for high natural Cr(VI) concentrations associated with mudflat/playa deposits and older alkaline groundwater near Mount General, and a separate UTL_{95} value of 5.8 µg/L was calculated for wells in that part of the eastern subarea. The UTL_{95} value of 4.8 µg/L may be used to evaluate Cr(VI) concentrations in the northern subarea upgradient from the Mount General fault where monitoring wells are often completed in Mojave-type deposits and in underlying mudflat/playa and lacustrine deposits that contain more chromium.

The UTL_{95} value for Mojave-type deposits downgradient from the Hinkley compressor station of 2.3 µg/L is an estimate of Cr(VI) concentrations that may have been present in that part of the aquifer if Cr(VI) had not been released from the Hinkley compressor station. This UTL_{95} value is lower than values elsewhere in Hinkley Valley because of the geologic specificity for coarser-textured Mojave-type aquifer materials and the proximity to recharge areas along the Mojave River that results in younger, less alkaline (near-neutral pH) groundwater. This UTL_{95} value may be a suitable metric for Cr(VI) cleanup goals within the regulatory Cr(VI) plume extent after regulatory updates. The UTL_{95} values calculated for undifferentiated deposits in the northern subarea downgradient from the Mount General fault and in Water Valley were 9.0 and 6.4 µg/L, respectively. These values define background Cr(VI) concentrations in these areas farther downgradient from the summative-scale and regulatory Cr(VI) plume margins.

Between April 2011 and March 2019, the regulatory Cr(VI) plume extent was updated quarterly. Regulatory Cr(VI) plume updates are a regulatory process done with input from PG&E, the local community, and other stakeholders. Updating the regulatory Cr(VI) plume extent was beyond the scope of the USGS background study; however, UTL_{95} values presented within this professional paper are intended to inform the process of updating the regulatory Cr(VI) plume. An updated regulatory Cr(VI) plume would likely be encompassed by the summative-scale Cr(VI) plume extent. Although identified as anthropogenic by the summative-scale analysis, some Cr(VI) concentrations within the summative-scale Cr(VI) plume are less than UTL_{95} values for their respective subareas and may not require regulatory attention.

The UTL_{95} values were used to evaluate Cr(VI) concentrations in domestic wells within Hinkley and Water Valleys. Hexavalent chromium concentrations in more than 70 domestic wells sampled between January 27 and 31, 2016, did not exceed 4 µg/L in Hinkley and Water Valleys. Samples were analyzed on site in a USGS mobile laboratory so that interested residents could follow water collected from their wells to the mobile laboratory and directly observe the laboratory analysis in real time. Hexavalent chromium concentrations were generally within ranges expected for uncontaminated groundwater based on their pH and trace-element composition. Domestic wells in former residential areas within the community of Hinkley, having Cr(VI) concentrations as high as 8.6 µg/L, had been destroyed by PG&E under guidance from the Lahontan RWQCB and were not available for sample collection.

Water from 39 percent of domestic wells sampled between January 21 and 31, 2016, had arsenic concentrations greater than the MCL for arsenic of 10 µg/L, with maximum concentrations as high as 300 µg/L. Water from 47 percent of domestic wells sampled had arsenic, uranium, or nitrate concentrations above an MCL.

The UTL_{95} values calculated as part of this study provide scientifically defensible background Cr(VI) concentrations that differ with local geologic, hydrologic, and geochemical conditions within the different subareas of Hinkley and Water Valleys at the time of this study. Background Cr(VI) concentrations calculated as part of this study are not indicative of predevelopment Cr(VI) concentrations that may have been present within groundwater in Hinkley and Water Valleys. The UTL_{95} values presented within this professional paper are not background Cr(VI) concentrations for regulatory purposes. The authority to establish regulatory Cr(VI) background concentrations, clean-up goals, and future site management practices resides with the Lahontan Regional Water Quality Control Board.

J.10.4. In Situ Reduction of Hexavalent Chromium to Trivalent Chromium

Anthropogenic Cr(VI) within groundwater downgradient from the Hinkley compressor station is treated by PG&E using bioremediation by adding ethanol as a reductant in a volume of aquifer known as the IRZ. Microcosm studies showed that Cr(VI) was rapidly reduced to Cr(III) with additions of ethanol. During a period of several months, reduced Cr(III) was sorbed and sequestered into crystalline Fe- and Mn-oxide solid phases on the surfaces of mineral grains within the microcosms. Within 2 weeks of reoxidation, Cr(III) began to be reoxidized back to Cr(VI) within the microcosms. Sequestration of chromium with Mn oxides on sorption sites on the surfaces of mineral grains influences the potential for Cr(III) to re-oxidize back to Cr(VI) once oxic conditions are reestablished within the microcosms.

Microcosm studies do not incorporate the effect of advective groundwater flow on the sequestration and reoxidation of Cr(VI) within the IRZ. However, microcosm studies indicate that maintenance of anoxic (oxygen absent) conditions within the IRZ may ensure sequestration of chromium on aquifer solids as Cr(III) and prevent re-oxidation of Cr(III) to Cr(VI) and subsequent mobilization into groundwater.

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