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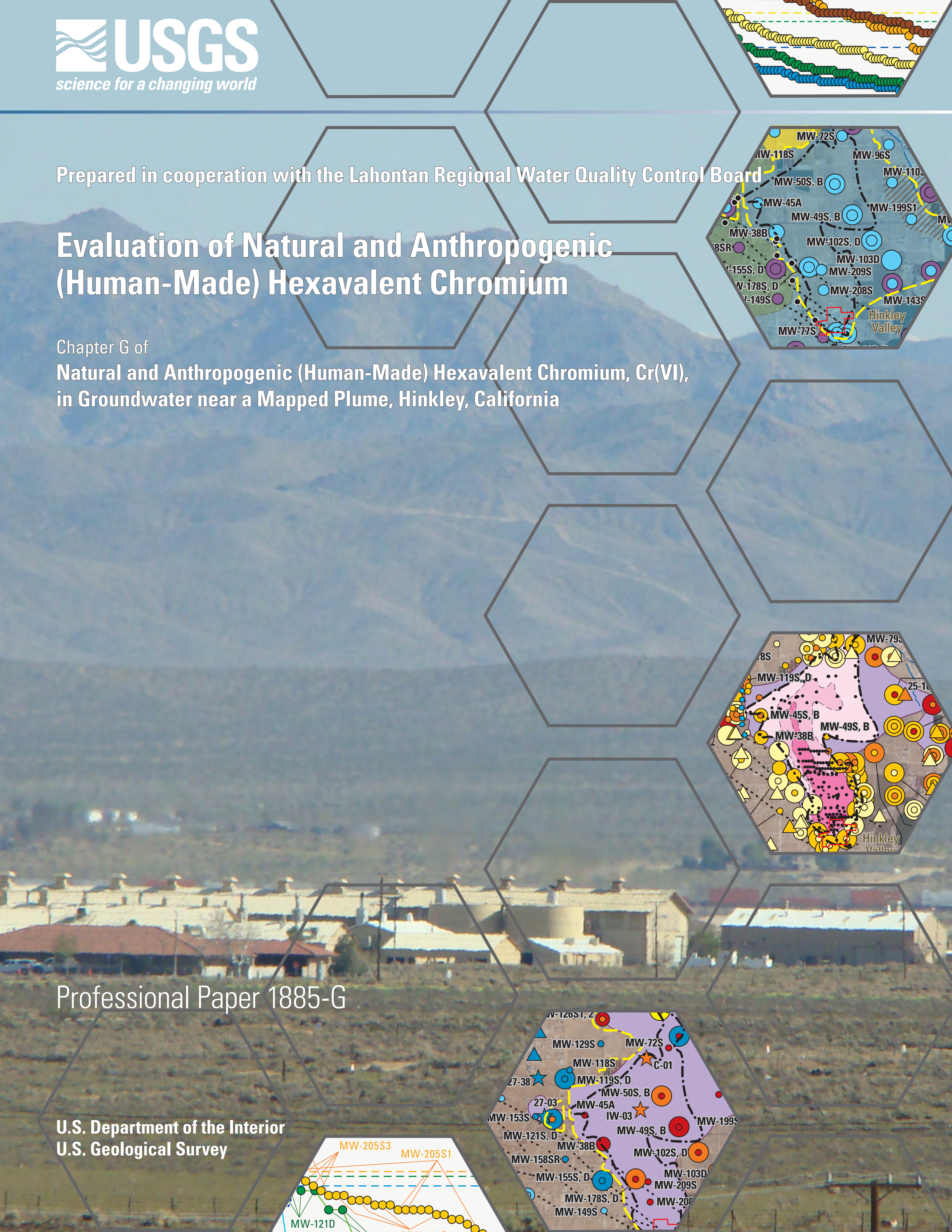


Prepared in cooperation with the Lahontan Regional Water Quality Control Board

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

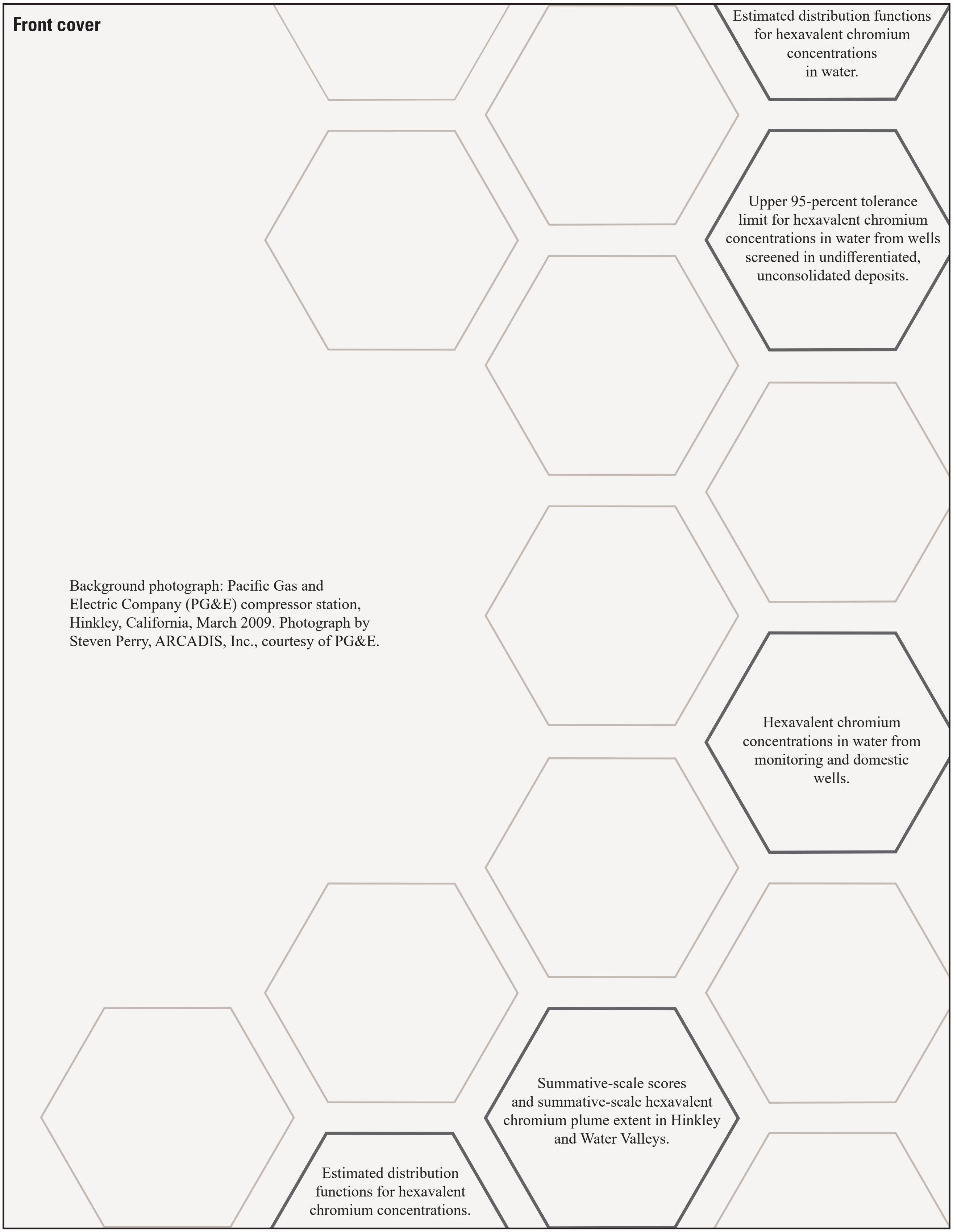
Chapter G of

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

Professional Paper 1885-G

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

Front cover



Estimated distribution functions for hexavalent chromium concentrations in water.

Upper 95-percent tolerance limit for hexavalent chromium concentrations in water from wells screened in undifferentiated, unconsolidated deposits.

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.

Hexavalent chromium concentrations in water from monitoring and domestic wells.

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

Estimated distribution functions for hexavalent chromium concentrations.

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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, John G. Warden, Krishangi D. Groover, and Whitney A. Seymour

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

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
micrometer (µm)	3.937×10^{-5}	inch (in.)
	Mass	
milligram (mg)	3.527×10^{-5}	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

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

$$°F = (1.8 \times °C) + 32.$$

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 professional paper, 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 solid materials are given in milligrams per kilogram (mg/kg).

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. Stable isotope values are commonly given in part per thousand (per mil) differences of the isotope ratio in the sample divided by the isotope ratio in a standard. Tritium is a radioactive isotope of hydrogen having a half-life of 12.3 years; tritium concentrations are given in tritium units (TU) where one tritium unit is one atom of tritium in 10^{18} atoms of hydrogen. Carbon-14 is a radioactive isotope of carbon having a half-life of 5,730 years; carbon-14 activities expressed as percent modern carbon (pmc), 100 pmc is 12.88 disintegrations per minute per gram of carbon. Carbon-14 ages are expressed as years before present (ybp) in archeology, geology, hydrology and other disciplines.

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.

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.

Abbreviations

α	significance criterion used for type-I statistical error
β	significance criterion used for type-II statistical error
Cr(III)	trivalent chromium having an oxidation state of +3
Cr(t)	total dissolved chromium
Cr(VI)	hexavalent chromium having an oxidation state of +6
LRL	laboratory reporting level
Mn	manganese
Mn(III)	manganese having an oxidation state of +3
Mn(IV)	manganese having an oxidation state of+4
PG&E	Pacific Gas and Electric Company
pXRF	handheld X-ray fluorescence
Q1 2018	January–March 2018
Q2 2017	April–June 2017
Q4 2015	October–December 2015
RWQCB	Regional Water Quality Control Board
SEM	scanning electron micrograph
SRL	study reporting level
SSA	summative-scale analysis
TWG	technical working group
USGS	U.S. Geological Survey
UTL_{95}	upper 95-percent tolerance limit
XANES	X-ray absorption near-edge structure
XRD	X-ray diffraction

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By John A. Izbicki, John G. Warden, Krishangi D. Groover, and Whitney A. Seymour

Abstract

Hexavalent chromium, Cr(VI), was released between 1952 and 1964 from the Pacific Gas and Electric Company (PG&E) Hinkley compressor station, in the Mojave Desert about 80 miles northeast of Los Angeles, California. Geologic, geochemical, and hydrologic data from more than 100 wells collected between March 2015 and November 2017 were interpreted using a summative-scale analysis to define the extent of anthropogenic (human-made) Cr(VI) in groundwater. The summative scale consisted of eight questions requiring binary (yes or no) answers for each sampled well. 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 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. When data from each well are scored using 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 areal extent of the summative-scale Cr(VI) plume was 5.5 square miles (mi^2); this is larger than the 2.2-mi^2 extent of the October–December 2015 (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 value of 3.1 micrograms per liter (µg/L). The summative-scale Cr(VI) plume is within the area covered by the PG&E monitoring well network and lies within “Mojave-type” deposits composed of low-chromium stream and near-shore lake deposits sourced from the Mojave River. The summative-scale Cr(VI) plume included all shallow wells within the footprint of the Q4 2015 regulatory Cr(VI) plume, but summative-scale scores indicate that anthropogenic Cr(VI) was not present in several wells within the footprint of the regulatory Cr(VI) plume that were screened within the deep zone of the upper aquifer. The summative-scale Cr(VI) plume extent was consistent with mineralogic and geochemical data collected as part of this study that were not used within the summative-scale analysis.

Data from wells outside the summative-scale Cr(VI) plume collected for regulatory purposes from April 2017 through March 2018 were used to estimate Cr(VI) background concentrations as the upper 95-percent tolerance limit (UTL_{95}) in different parts of Hinkley and Water Valleys. The UTL_{95} values were calculated using the computer program ProUCL 5.1 and are suitable for use by regulatory agencies in support of (1) updating the regulatory Cr(VI) plume extent and management of Cr(VI) near the plume margins, (2) establishing cleanup goals for Cr(VI) within the updated regulatory Cr(VI) plume, and (3) identifying unusual Cr(VI) concentrations outside the regulatory Cr(VI) plume. The nonparametric UTL_{95} values for wells screened in Mojave-type deposits in the eastern, western, and northern subareas of Hinkley Valley were 3.7, 3.9, and 4.0 µg/L, respectively. The normal UTL_{95} values for wells screened in undifferentiated, unconsolidated deposits in the eastern and western subareas and the northern subarea upgradient from the Mount General fault were 2.8, 3.8, and 4.8 µg/L, respectively. An overall normal UTL_{95} value of 3.8 µg/L was calculated for undifferentiated, unconsolidated deposits in these areas. This value is similar to the overall nonparametric UTL_{95} value of 3.9 µg/L calculated for Mojave-type deposits and similar to the maximum Cr(VI) concentration of older groundwater in contact with Mojave-type deposits of 3.6 µg/L. The provenance of most PG&E monitoring wells is not precisely known, and the UTL_{95} values for wells screened in undifferentiated, unconsolidated deposits in the different subareas may be more widely applicable for regulatory purposes than the UTL_{95} values for Mojave-type deposits.

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 most of the summative-scale Cr(VI) plume is within the eastern subarea. A UTL_{95} value of 5.8 µg/L was calculated for older (pre-1952) groundwater associated with 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 Cr(VI) plume downgradient from the Hinkley compressor station after regulatory updates. This lower value is consistent with neutral to slightly alkaline, younger (post-1952) groundwater within coarse-textured, low-chromium Mojave-type deposits in this area and may be a suitable metric for Cr(VI) cleanup goals. The UTL_{95} value of 4.8 µg/L for wells screened in undifferentiated, unconsolidated deposits in the northern subarea upgradient from the Mount General fault provides for possible increases in Cr(VI) concentrations if water levels continue to decline. Downgradient from the Q4 2015 regulatory Cr(VI) plume and the summative-scale Cr(VI) plume, UTL_{95} values of 9.0 and 6.4 µg/L were calculated for wells screened in undifferentiated, unconsolidated deposits in the northern subarea downgradient from the Mount General fault and for Water Valley, respectively, consistent with different geologic and geochemical conditions in these areas.

The UTL_{95} values calculated as part of this study provide scientifically defensible estimates of background Cr(VI) concentrations that differ with local geologic, geochemical, and hydrologic conditions in Hinkley and Water Valleys. The regulatory Cr(VI) plume extent can be updated on the basis of these values. The summative-scale Cr(VI) plume extent may contain wells having anthropogenic Cr(VI) concentrations less than the UTL_{95} values for their respective subareas that may not require regulatory attention, and an updated regulatory Cr(VI) plume extent may be less than the summative-scale Cr(VI) plume extent. The UTL_{95} values are not background Cr(VI) concentrations for regulatory purposes, and the authority to establish regulatory values resides solely with the Lahontan Regional Water Quality Control Board.

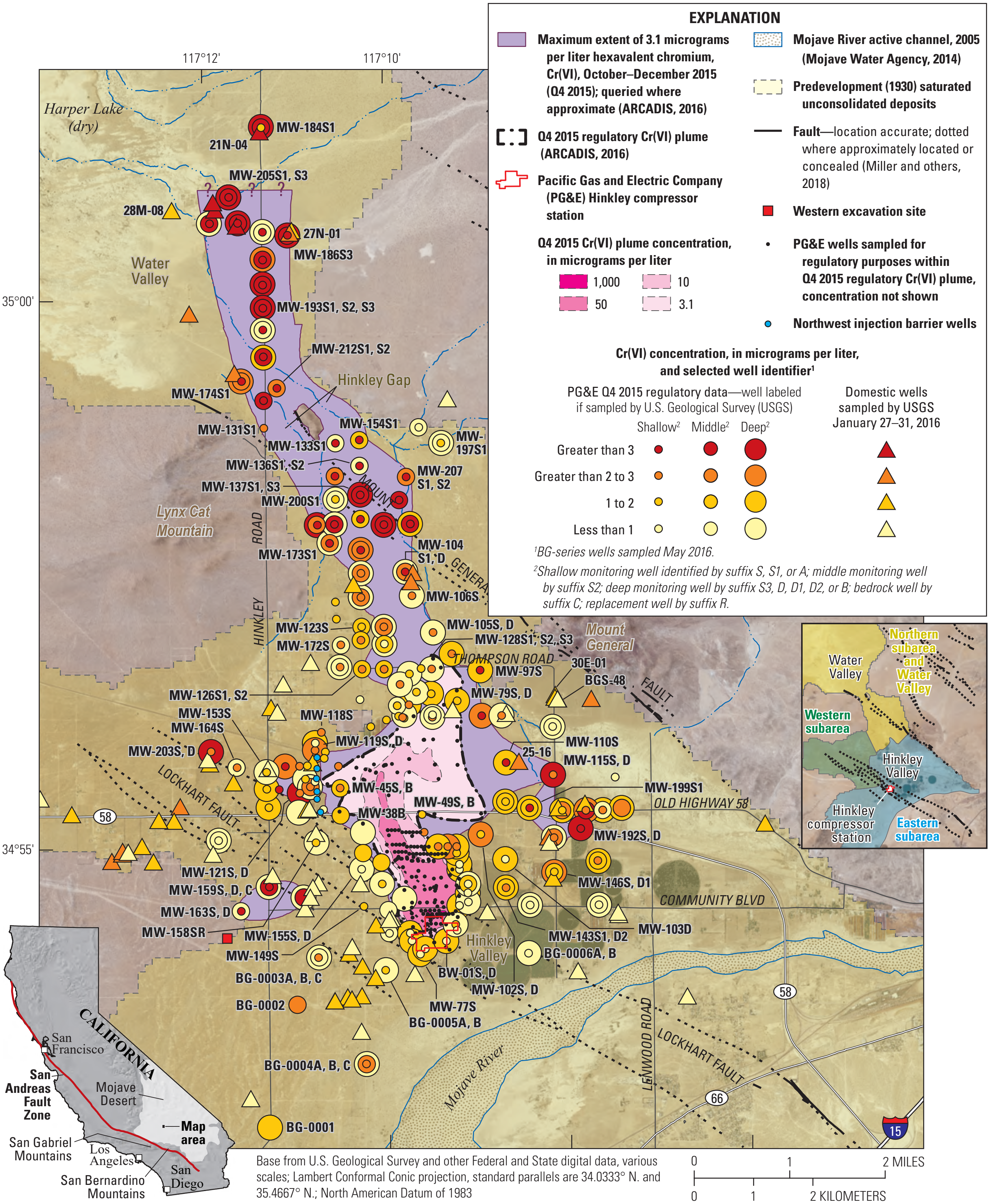
G.1. Introduction

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

In 2007, a PG&E study of the natural Cr(VI) concentrations in groundwater estimated average Cr(VI) concentrations in the Hinkley area to be 1.2 micrograms per liter (µg/L), with an upper 95-percent tolerance limit (UTL_{95}) of 3.1 µg/L (CH2M Hill, 2007). The 3.1-µg/L UTL_{95} was adopted by the Lahontan Regional Water Quality Control Board (RWQCB; Lahontan Regional Water Quality Control Board, 2008) as the interim regulatory background Cr(VI) value to map the plume extent and to guide Cr(VI) cleanup and remediation activities.

Maps prepared for regulatory purposes seemed to show rapid expansion of the extent of Cr(VI) concentrations greater than 3.1 µg/L in water from wells between 2010 and 2012 (chapter D, fig. D.2). By 2015, the mapped extent of Cr(VI) concentrations greater than 3.1 µg/L included discontinuous areas in the eastern, western, and northern subareas of Hinkley Valley and extended into Water Valley more than 8 mi downgradient from the Hinkley compressor station (fig. G.1). Changes in the mapped extent of Cr(VI) concentrations greater than 3.1 µg/L likely resulted from changes in the extent of the PG&E monitoring well network, as new wells in previously unsampled areas were installed through time, rather than changes in groundwater Cr(VI) concentrations. However, it was unclear if Cr(VI) in water from newer monitoring wells was associated with Cr(VI) released from the Hinkley compressor station or if Cr(VI) was naturally occurring in groundwater and predated releases from the Hinkley compressor station.

In response to the apparent increase in the extent of Cr(VI) concentrations greater than the interim regulatory background Cr(VI) concentration and to limitations associated with the methodology of the PG&E study, the Lahontan RWQCB (Lahontan Regional Water Quality Control Board, 2012) agreed that the 2007 PG&E background Cr(VI) study be updated. The U.S. Geological Survey (USGS) was requested by the Lahontan RWQCB to do the updated background study of Cr(VI) concentrations in Hinkley and Water Valleys. The study was done with input from 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 TWG met about quarterly during the study; annual updates were provided to the Hinkley community, and interim reports were published (Izbicki and Groover, 2016, 2018).



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 G.1. 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).

G.1.1. Site Description

Most geologic materials in Hinkley and Water Valleys are low in chromium (Smith and others, 2014); however, chromium is locally present in hornblende diorite in Iron Mountain, in basalt in Water Valley, and in alluvium eroded from those materials (chapter B, table B.3). Chromium concentrations in unconsolidated materials are higher in fine-textured silt and clay and lower in coarse-textured sand and gravel (chapter B, fig. B.8). Chromite, the most abundant chromium-containing mineral globally (Dixon and Weed. 1989), is highly resistant to weathering and not generally present in Hinkley and Water Valleys. Most chromium in Hinkley and Water Valleys is substituted for iron within magnetite (chapter C), which also is resistant to weathering. Some more easily weathered chromium-containing minerals, such as actinolite in older Mojave River deposits and hornblende in locally derived alluvium eroded from Iron Mountain, are present in Hinkley and Water Valleys (chapter C, figs. C.9*A,B*).

Hinkley Valley is about 62 square miles (mi^2) and contains about 36 mi^2 of unconsolidated deposits that were saturated under predevelopment conditions (chapter H, fig. H.8). Aquifers of interest in Hinkley Valley are composed primarily of unconsolidated "Mojave-type" deposits consisting of alluvium and lake-margin deposits sourced from the Mojave River (Miller and others, 2018, 2020). Aquifers consisting of locally derived alluvium and weathered bedrock also are important 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 (fig. G.1). 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 (chapter A, fig. A.6; ARCADIS and CH2M Hill, 2011; Jacobs Engineering Group, Inc., 2019; Miller and others, 2018, 2020). 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 (chapter A, fig. A.6; ARCADIS and CH2M Hill, 2011; Jacobs Engineering Group, Inc., 2019; Miller and others, 2018, 2020). Mudflat/playa deposits sourced from the Mojave River, present at land surface near Mount General and at depth in the eastern subarea, also are described as brown clay in drillers' and geologists' logs. The western subarea consists of Mojave-type deposits overlying groundwater-discharge deposits, fine-textured lacustrine deposits, or weathered bedrock (CH2M Hill, 2013; Miller and others, 2018, 2020). The northern subarea consists of Mojave-type deposits overlying fine-textured lacustrine and mudflat/playa deposits sourced from the Mojave River and from local materials (Stantec, 2013; Miller and others, 2018, 2020). Aquifers in Water Valley are composed of lake-margin deposits sourced from the ancestral Mojave River along the margins of Harper (dry) Lake (chapter A, fig. A.5) that overlie and interfinger with locally derived alluvium (Miller and others, 2018, 2020).

Recharge is primarily from intermittent flows in the Mojave River that occur on average once every 5 to 7 years (Lines, 1996; Stamos and others, 2001; Seymour, 2016). During predevelopment conditions, groundwater flow was from the Mojave River northward toward Hinkley Gap into Water Valley where groundwater discharged by evaporation along the margins of Harper (dry) Lake (chapter H, fig. H.8; Thompson, 1929). The Lockhart fault impedes groundwater flow in Hinkley Valley. Less is known about the effect of the Mount General fault on groundwater flow. Each fault consists of numerous mapped strands (Miller and others, 2018, 2020). Predevelopment (pre-1930) and 2018 water-level maps are provided in chapter H within this professional paper (chapter H, fig. H.8).

Measured water-level declines in wells as a result of agricultural pumping since the early 1950s were as great as 60 ft (chapter H, fig. H.8A; Stone, 1957; California Department of Water Resources, 1967; Seymour and Izbicki, 2018). As a consequence of water-level declines, saturated Mojave-type deposits in much of the western subarea are a thin veneer, commonly less than 10 ft thick, overlying fine-textured lacustrine deposits, groundwater-discharge deposits, or weathered bedrock (CH2M Hill, 2013). Similarly, saturated Mojave-type deposits in much of the northern subarea are a thin veneer overlying fine-textured lacustrine and mudflat/playa deposits (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 or mudflat/playa deposits. Younger Mojave-type deposits in much of Hinkley Valley and lake-margin deposits in much of Water Valley, formerly extensively pumped for agricultural supply, were largely above the water table at the time of this study (2017; chapter H, fig. H.8*B*; Miller and others, 2018, 2020; Jacobs Engineering Group, Inc., 2019). As a result of groundwater development, deep percolation of irrigation return water and, to a lesser extent, septic discharges are important components of recharge in Hinkley and Water Valleys (Stamos and others, 2001; Jacobs Engineering Group, Inc., 2019).

The Hinkley compressor station and most of the regulatory Cr(VI) plume are in the eastern subarea (fig. G.1). In October–December 2015 (Q4 2015), the regulatory Cr(VI) plume extended 3 mi downgradient from the historical discharge location within the Hinkley compressor station (fig. G.1) and the highest Cr(VI) concentrations in groundwater remained less than 3,000 ft downgradient from the release location within the Hinkley compressor station (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. G.1).

Remediation of Cr(VI) in Hinkley Valley began in 1992, and in 2010, cleanup was projected to require 10 to 95 years (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. Shallow 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 S2 or S3 if a hydrologically important intervening clay layer was not present. The suffix C was used for MW wells completed in consolidated rock, and the suffix R was added if the well is a replacement for a well that was destroyed. Older monitoring wells were identified with the suffixes A or B for shallower or deeper wells, respectively. 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 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. Core material was available for most wells drilled after 2011 from near the water table to the bottom of the borehole, commonly to below the depth of the deepest well at a site.

G.1.2. Purpose and Scope

The purpose of this chapter is to (1) estimate the extent of anthropogenic (human-made) Cr(VI) in the upper aquifer released from the Hinkley compressor station in Hinkley and Water Valleys and (2) calculate background Cr(VI) concentrations in the upper aquifer near and within the estimated Cr(VI) plume. The scope of the work included (1) use of a summative scale (Izbicki and Groover, 2016, 2018) to determine the extent of anthropogenic Cr(VI) released from the Hinkley compressor station; (2) analyses of the summative-scale results and comparison with other data collected as part of this study; and (3) calculation of Cr(VI) background concentrations in the eastern, western, and northern subareas in Hinkley Valley and in Water Valley. The summative-scale Cr(VI) plume extent and Cr(VI) background values were compared with data from domestic wells sampled as part of this study.

This chapter is presented in two parts: (1) the summative-scale development and (2) the Cr(VI) background calculations. First, the summative scale was developed to answer the question, “Is Cr(VI) in water from sampled wells natural or anthropogenic?” The summative scale and associated metrics included (1) physical and chemical data from more than 1,500 analyses of aquifer materials adjacent to the screened interval of sampled wells (chapters B and C); (2) Cr(VI) concentration trend data based on more than 10,000 Cr(VI) analyses from more than 550 wells collected for regulatory purposes by PG&E between July 2012 and June 2017 (chapter D); and (3) chemical and isotopic data, including groundwater age-dating constituents, from more than 100 sampled wells (chapters E and F). These wells were selected by the USGS with input from the TWG and were sampled between March 2015 and November 2017. The summative scale was refined with input from the TWG, and alternative formulations of the scale are presented. Results of the summative-scale analysis (SSA) were compared with other data collected as part of this study (chapters B through F) that were not included within the summative scale. Second, Cr(VI) background concentrations were estimated from data from wells outside the Cr(VI) summative-scale extent that were identified as natural. Separate Cr(VI) background calculations were made (1) for wells completed in Mojave-type deposits and (2) for wells completed in undifferentiated, unconsolidated geologic materials distributed throughout Hinkley and Water Valleys. The Cr(VI) background concentrations were compared to Cr(VI) concentrations in domestic wells sampled as part of this study.

G.2. Summative-Scale Analysis

A summative scale (Izbicki and Groover, 2016, 2018) was used to determine the extent of anthropogenic Cr(VI) associated with releases from the Hinkley compressor station and identify natural Cr(VI). The summative scale consisted of multiple items formulated as questions that addressed geologic, geochemical, and hydrologic criteria developed on the basis of data collected as part of the USGS Cr(VI) background study (table G.1).

Table G.1. Summative-scale questions used to determine the extent of anthropogenic (human-made) and natural hexavalent chromium, Cr(VI), in water from wells sampled as part of the U.S. Geological Survey Cr(VI) background study, 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, milligram per kilogram; 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, E	−1	1
2. Do geologic materials at the well screen contain more than 85 mg/kg chromium?	Portable (handheld) X-ray fluorescence measurements of core material.	Chapter B	−1	1
3. Do geologic materials at the well screen contain more than 970 mg/kg manganese?	Portable (handheld) X-ray fluorescence 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 using the Mann-Kendall test for trend (Helsel and others, 2020).	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 analysis 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 and delta deuterium data.	Chapter F	1	−1
8. Does the water contain measurable modern, post-1952, water (measurable tritium) and a carbon-14 activity greater than 84-percent modern carbon?	Tritium, helium-3, helium-4, and carbon-14 data.	Chapter F	1	−1

Geologic questions within the summative scale (table G.1) addressed chromium and manganese abundance and the texture of aquifer material adjacent to the screened interval of sampled wells. Manganese (Mn) abundance was included in the summative scale because manganese oxides, including manganese oxides having a valence of +3, +4, and mixed +3/+4 valances [Mn(III), Mn(IV) and Mn(III/IV), respectively], may oxidize trivalent chromium, Cr(III), to Cr(VI) under the appropriate geochemical conditions (Schroeder and Lee, 1975; Nico and Zasoski, 2000; Oze and others, 2007; Kazakis and others, 2015). Texture was included in the summative scale because chromium and manganese are more abundant on the surface coatings of fine-textured aquifer materials than coarser textured materials (chapter B, fig. B.8; chapter C, figs. C.6, C.15). In addition, fine-textured aquifer materials have low permeability that limits advective flow within pore fluids, thereby promoting diffusive processes that favor oxidation of Cr(III) to Cr(VI) in the presence of manganese oxides on the surfaces of mineral grains (Hausladen and others, 2019).

Geochemical questions within the summative scale (table G.1) addressed Cr(VI) concentration trends (chapter D, fig. D.5), pH-dependent sorption of Cr(VI) (chapter E, figs. E.17, E.18), and co-occurrence of Cr(VI) with selected trace elements (chapter E, figs. E.20, E.21). In Mojave-type deposits having similar felsic mineral composition, pH-dependent sorption of Cr(VI) and co-occurrence of Cr(VI) with other trace elements that have similar pH-dependent sorptive processes control the concentrations of Cr(VI) and other oxyanion-forming trace-elements in groundwater. High concentrations of Cr(VI) relative to the expected concentrations of Cr(VI) at the measured pH and relative to measured concentrations of selected oxyanion-forming trace elements, can be used to demonstrate that Cr(VI) in groundwater is from anthropogenic sources.

Hydrologic questions in the summative scale (table G.1) addressed the source and age of water from wells on the basis of the stable isotopes of water (delta oxygen-18 and delta deuterium; chapter F, figs. F.3, F.4) and the radioactive isotopes tritium (chapter F, figs. F.10, F.13) and carbon-14 (chapter F, fig. F.16). Releases of Cr(VI) from the Hinkley compressor station occurred between 1952 and 1964. Although not all groundwater recharged from the Mojave River during this period passed near the Hinkley compressor station and would be expected to contain anthropogenic Cr(VI), water containing anthropogenic Cr(VI) would have been recharged from the Mojave River during the post-1952 period and would likely contain tritium; substantially older (pre-1952) groundwater would not contain anthropogenic Cr(VI) released from the Hinkley compressor station. Large concentrations of tritium and carbon-14 were released into the environment as a result of the atmospheric testing of nuclear weapons beginning in 1952 (chapter F, fig. F.9). However, water containing tritium and having high carbon-14 activities associated with nuclear weapons testing was not present in groundwater in Hinkley Valley until after recharge from streamflow in the Mojave River in 1958, and most tritium-containing groundwater was recharged after large streamflows in 1969 (chapter F, fig. F.2; Stamos and others, 2001; Izbicki and Michel, 2004; Jacobs Engineering Group, Inc., 2019). The Cr(VI) released from the Hinkley compressor station beginning in 1952 would have initially mixed with slightly older groundwater and would have moved downgradient with that groundwater in advance of tritium-containing groundwater.

A threshold Cr(VI) concentration, effectively a Cr(VI) background, was not used as part of the summative scale, although Cr(VI) concentration data were used in calculations describing pH-dependent sorption of Cr(VI) and the co-occurrence of Cr(VI) with selected trace elements. The Cr(VI) background concentration in different parts of Hinkley and Water Valleys outside the summative-scale Cr(VI) plume extent is estimated in section "G.3 Calculation of Hexavalent Chromium Background Concentrations."

Hydraulic-gradient (water-level) data (chapter H, fig. H.8) were not used in the summative scale because of concern 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). Additionally, hydraulic gradients within the aquifer may have changed over time as a result of pumping and recharge, and water levels at the time of this study (2015–18) may not represent conditions within the aquifer during Cr(VI) releases from the Hinkley compressor station. Furthermore, hydraulic gradient data near the Lockhart fault may not adequately characterize movement of groundwater in that area since Cr(VI) releases occurred from the Hinkley compressor station (chapter H, fig. H.15). 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. Hydraulic data collected in support of model development are provided in chapter H within this professional paper, and the updated model results are compared to data collected as part of this study in chapter H within this professional paper (appendix H.2).

Each question within the summative scale required a binary (yes or no) answer for each sampled well. The answer was assigned a score. A score of +1 for a question within the scale represents data consistent with anthropogenic Cr(VI) released from the Hinkley compressor station; a score of −1 represents data inconsistent with anthropogenic Cr(VI). Data to support scoring for the summative-scale questions are presented in chapters B through F within this professional paper. Use of a summative scale to evaluate the areal extent of anthropogenic Cr(VI) released from the Hinkley compressor station was intended to

1. provide a transparent framework for data interpretation in which all stakeholders participated;
2. provide an unbiased interpretation of data that is traceable to numerical measurements and data;
3. provide a framework that enabled geologic, geochemical, and hydrologic data to be considered collectively; and
4. consolidate different types of data into simple, easy-to-understand figures and interpretations.

The questions and scoring metrics that compose the summative scale are intended to facilitate interpretation of data collected as part of the USGS Cr(VI) background study. A successful summative scale would identify high Cr(VI) concentrations within the regulatory Cr(VI) plume where stakeholders agree that anthropogenic Cr(VI) is present. A successful summative scale also would identify high Cr(VI) concentrations outside the regulatory Cr(VI) plume where stakeholders agree that natural Cr(VI) is present.

Scores for each question in the summative scale were summed to create a single value for each sampled well that may range from −8 to +8. High-magnitude negative scores were consistent with natural Cr(VI), and high-magnitude positive scores were consistent with anthropogenic Cr(VI). 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 answer and score every question within the scale for every sampled well. For example, core material was not available from older monitoring wells or from domestic wells, and handheld X-ray fluorescence (pXRF) data could not be collected for chromium or manganese concentrations in core material adjacent to the screened interval of those wells; however, texture could be evaluated from drillers' or geologists' logs if available. In addition, it was not possible to calculate Cr(VI) concentration trends for newer monitoring wells installed after 2014 because of insufficient data. To address these issues, summative-scale scores were evaluated as the percentage of the total possible score for each well, with scores that may range from −100 to +100 percent for natural and anthropogenic Cr(VI), respectively. In accordance with guidelines for the procedure established by Izbicki and Groover (2018), the summative-scale Cr(VI) plume was drawn around the lowest magnitude positive percentage score that produced a contiguous plume extent. Data used to assign the summative-scale scores for each well, the scores for each question within the summative scale for each well, and the summed score for each well (expressed as the summed value and as a percentage) are provided in appendix G.1 (table G.1.1).

The summative scale was initially described by Izbicki and Groover (2016). The summative-scale questions and scoring metrics were developed and refined with input from the TWG, and a preliminary version of the scale was published in 2018 (Izbicki and Groover, 2018). Subsequently, the summative-scale and scoring metrics were further refined and alternative summative scales developed with input from the TWG for use in this study.

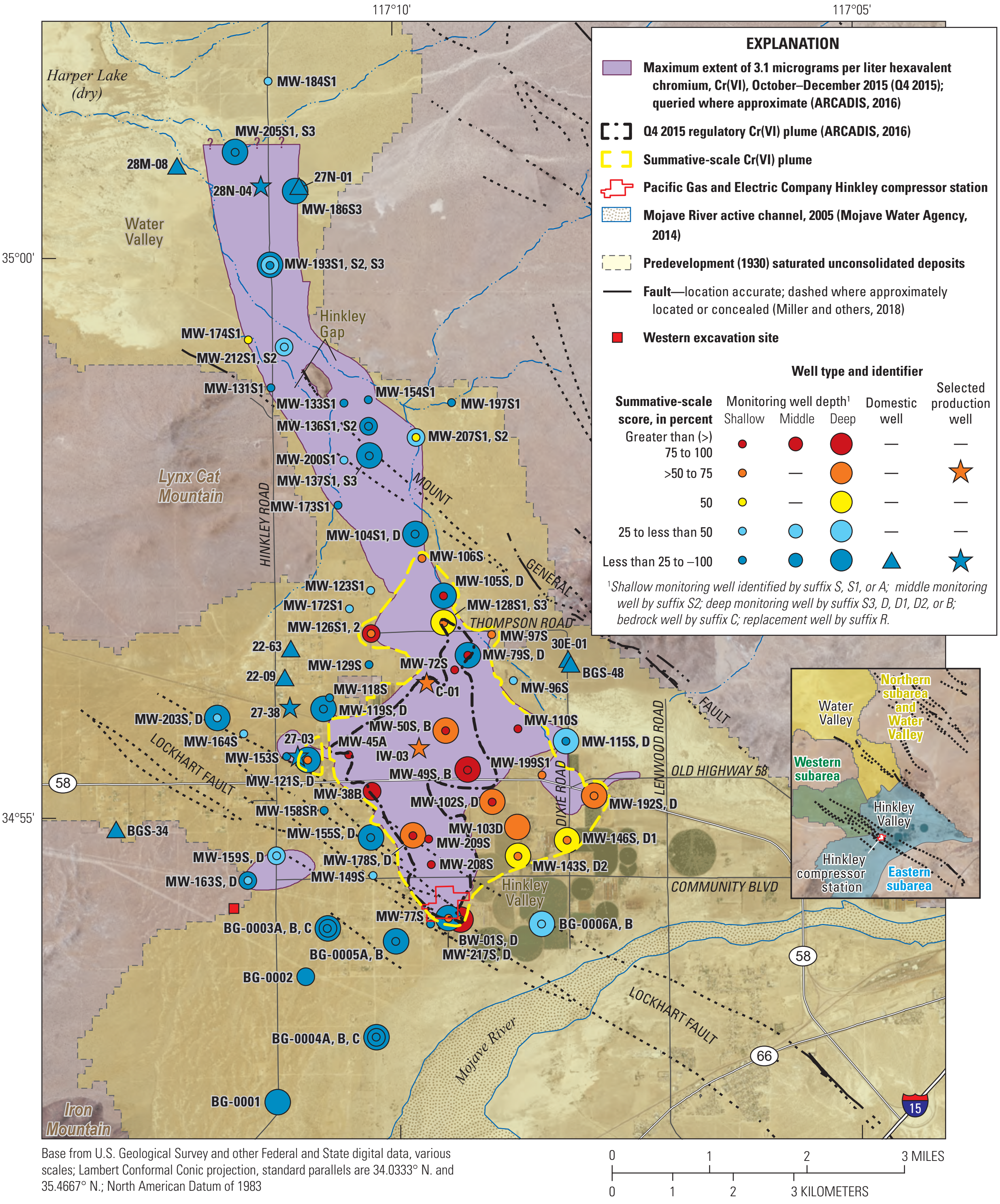
By design, the summative scale provides little discretion in interpretation of data collected as part of this study. When data collected from each well are scored using questions and metrics within the summative scale (table G.1), all stakeholders would score each well the same way and would include the same wells within the summative-scale Cr(VI) plume extent. Other data collected as part of this study, but not used as part of the summative scale, were used to verify results and increase understanding of anthropogenic and natural Cr(VI) occurrence in Hinkley and Water Valleys.

G.2.1. Extent of Anthropogenic (Human-Made) Hexavalent Chromium

The extent of anthropogenic Cr(VI) in water from wells was evaluated on the basis of the summative-scale results. The summative-scale Cr(VI) plume included wells sampled as part of this study having a summative-scale score greater than +50 percent (fig. G.2). Additional control on the summative-scale Cr(VI) plume margins was provided by PG&E regulatory pH and Cr(VI) data with a Cr(VI) occurrence probability of less than 10 percent (chapter E, fig. E.18*A*).

The extent of the summative-scale Cr(VI) plume was 5.5 mi^2 (fig. G.2). This is larger than the 2.2-mi^2 extent of the Q4 2015 regulatory Cr(VI) plume (ARCADIS, 2016) but smaller than the 8.3-mi^2 extent of Cr(VI) concentrations greater than the interim Cr(VI) background value of 3.1 µg/L (ARCADIS, 2016). The summative-scale Cr(VI) plume is within the area covered by the PG&E monitoring well network and is within Mojave-type deposits composed of alluvium and lake-margin deposits sourced from the Mojave River. These deposits are composed of materials that have low chromium and tend to be coarser textured and more permeable than locally derived alluvium, lacustrine, and mudflat/playa deposits (chapters B, C, and H).

The summative-scale Cr(VI) plume included wells MW-178S, MW-178D, MW-208S, and MW-209S (fig. G.2). These wells are less than 3,000 ft downgradient from the Hinkley compressor station, and water from these wells, sampled as part of this study, had Cr(VI) concentrations ranging from 50 to 2,500 µg/L. Three of these four wells, MW-178S, MW-208S, and MW-209S, had summative-scale scores of +100 percent (fig. G.2), and anthropogenic Cr(VI) from the Hinkley compressor station is accepted by stakeholders to be present in water from these wells.



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 G.2. 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 appendix G.1 (table G.1.1).

The footprint of the summative-scale Cr(VI) plume included five deep wells screened within the deep zone of the upper aquifer, MW-79D, MW-105D, MW-128S3, MW-143D2, and MW-146D1. Water from these five wells had Cr(VI) concentrations ranging from less than the study reporting level (SRL) of 0.1 to 1.8 µg/L and summative-scale scores of +50 percent or less (fig. G.2). On the basis of their summative-scale scores, water from these five wells does not contain anthropogenic Cr(VI) from the Hinkley compressor station. Water from two of these wells, MW-79D and MW-105D, had dissolved-oxygen concentrations less than the SRL of 0.2 milligram per liter (mg/L) and would not be expected to contain measurable Cr(VI). In contrast, water from wells MW-49B and MW-50B, also screened within the deep zone of the upper aquifer and within the footprint of the Q4 2015 regulatory Cr(VI) plume, had Cr(VI) concentrations of 1.6 and 2.8 µg/L, respectively, in March 2017. Water from these two wells had summative-scale scores of +100 and +67 percent, respectively, indicative of anthropogenic Cr(VI) from the Hinkley compressor station (fig. G.2). Consistent with an anthropogenic Cr(VI) source, Cr(VI) concentrations in water from well MW-50B increased to 8.2 µg/L by January 2018.

Most of the increase in the summative-scale Cr(VI) plume extent, compared to the Q4 2015 regulatory Cr(VI) plume, was in the eastern subarea. The summative-scale Cr(VI) plume in the eastern subarea included 2.5 mi^2 and nine sampled wells that were not within the Q4 2015 regulatory Cr(VI) plume (fig. G.2). Concentrations of Cr(VI) in water from these wells ranged from 1.4 to 4.1 µg/L between March 2015 and November 2017. Higher Cr(VI) concentrations, ranging from 3.8 to 4.1 µg/L, were measured in water from wells MW-110S, MW-192S, and MW-192D, that are associated with mudflat/playa deposits along the toe of the alluvial fan eroded from Mount General (chapter E, fig. E.11*B*). Regulatory Cr(VI) concentrations in water from these wells have been as high as 7.6, 4.4, and 5.0 µg/L, respectively. Although not diagnostic of anthropogenic Cr(VI), water from wells MW-110S, MW-192S, and MW-192D had Cr(VI) concentrations and delta chromium-53 values within the expected range of anthropogenic Cr(VI) released from the Hinkley compressor station that could not be explained by fractionation of chromium within local geologic materials or from older (pre-1952) groundwater in this area (chapter F, fig. F.26*A*).

The summative-scale Cr(VI) plume included well MW-121S in the western subarea (fig. G.2). Water from well MW-121S, sampled as part of this study in March 2015 and March 2017, had Cr(VI) concentrations of 2.0 µg/L and summative-scale scores of +75 percent during each sample (fig. G.2). Regulatory Cr(VI) concentrations in water from well MW-121S were as high as 11 µg/L shortly after the well was installed in August 2011, and anthropogenic Cr(VI) may have been present in water from well MW-121S at that time. Well MW-121S is west of the Northwest Injection Barrier (chapter A, fig. A.6) installed by PG&E to prevent movement of anthropogenic Cr(VI) toward residential areas within the community of Hinkley (CH2M Hill, 2009).

The summative-scale Cr(VI) plume extent in the northern subarea included 0.7 mi^2 and five sampled wells MW-97S, MW-105S, MW-106S, MW-126S1, and MW-126S2 that were not within the Q4 2015 regulatory Cr(VI) plume (fig. G.2). Concentrations of Cr(VI) in water from these five wells ranged from 1.7 to 4.7 µg/L, and the highest Cr(VI) concentration was in water from well MW-97S. Well MW-97S was sampled twice as part of this study; water from the well had a Cr(VI) concentration of 2.5 µg/L in March 2015 and the Cr(VI) concentration increased to 4.7 µg/L in November 2017. Well MW-97S would not have been included in the summative-scale Cr(VI) plume on the basis of the March 2015 data. Regulatory Cr(VI) concentrations in water from well MW-97S increased from 1.8 µg/L in February 2011, shortly after the well was installed, to as high as 7.0 µg/L in October 2016. Unlike most wells in Hinkley and Water Valleys, water levels in well MW-97S rose during the period tested to evaluate Cr(VI) concentration trends between July 2012 and June 2017 (chapter D, fig. D.9). Regulatory Cr(VI) concentrations in water from wells MW-105S, MW-106S, MW-126S1, and MW-126S2 have been as high as 2.9, 3.2, 4.8, and 1.5 µg/L, respectively. Despite comparatively low Cr(VI) concentrations, water from well MW-126S2 sampled in March 2015, had a summative-scale score of +100 percent (fig. G.2; appendix G.1, table G.1.1). Similar to well MW-97S, water levels in wells MW-105S, MW-106S, MW-126S1, and MW-126S2 also rose during the period tested to evaluate Cr(VI) concentration trends between July 2012 and June 2017 (chapter D). Water-level rises in all five of these wells were attributed to either propagation of recharge from the Mojave River or to changes in management practices (including pumping) used to control the Cr(VI) plume in this area (chapter D).

Water from wells within the summative-scale Cr(VI) plume extent had delta chromium-53 isotope compositions ranging from −0.13 to 2.8 per mil, with a median value of 1.0 per mil (chapter F). The lowest delta chromium-53 values are in water from wells having high Cr(VI) concentrations that represent the composition of Cr(VI) during the initial releases from the Hinkley compressor station. Low delta chromium-53 values ranging from 0.61 to 0.53 per mil also were measured in water from wells MW-143S and MW-146S near the plume margins in the eastern subarea, and a delta chromium-53 value of 0.52 per mil was present in water from well MW-106S, in the northern subarea. Most delta chromium-53 values within the margins of the Q4 2015 regulatory Cr(VI) plume were fractionated to higher values as a result of Cr(VI) reacting with aquifer materials as it moved downgradient from the Hinkley compressor station (chapter F, fig. F.22*B*). The low delta chromium-53 values in water from wells MW-106S, MW-143S, and MW-146S are not consistent with Cr(VI) released from the Hinkley compressor station that would have been fractionated within the aquifer to higher values as Cr(VI) concentrations decreased. On the basis of delta chromium-53 values, it is possible that wells MW-143S and MW-146S in the eastern subarea and well MW-106S in the northern subarea may have been incorrectly included within the summative-scale Cr(VI) plume extent by the SSA. Water levels in wells MW-143S and MW-146S declined below the screened interval of the well after July 2017; the wells were dry and not sampled for regulatory purposes after that time.

Water from wells MW-159S, MW-159D, and MW-163S, downgradient from the western excavation site, was not identified as anthropogenic on the basis of the SSA (fig. G.2; appendix G.1, table G.1.1). These wells are on the upgradient side of the Lockhart fault and upgradient from the Hinkley compressor station (fig. G.2). Concentrations of Cr(VI) in water from these wells ranged from 5.3 to 10 µg/L as part of this study. Regulatory Cr(VI) concentrations in water from wells MW-159S, MW-159D, and MW-163S have been as high as 6.4, 6.3, and 10 µg/L, respectively. The western excavation site, on property owned by PG&E, was used as an illegal disposal site by unknown parties. Anthropogenic constituents including diesel degradants, industrial compounds, and metals were present at the site and in groundwater downgradient from the site; however, Cr(VI) releases at the western excavation site have not been confirmed by regulatory agencies (Lahontan Regional Water Quality Control Board, 2014).

The western excavation site has a different hydrologic history from the Hinkley compressor station and is managed separately for regulatory purposes (Lahontan Regional Water Quality Control Board, 2014). The use of a summative scale designed to assess Cr(VI) releases from the Hinkley compressor station may not be appropriate at the western excavation site, and additional data provided in section “G.2.4.3.1 Wells Downgradient from the Western Excavation Site,” were used to evaluate Cr(VI) concentrations in groundwater in this area.

G.2.2. High Natural Hexavalent Chromium in Water from Wells

The presence of natural Cr(VI) in water from wells also was evaluated on the basis of the summative-scale results. Summative-scale scores ranged from 100 to −75 percent (appendix G.1, table G.1.1). Although no well scored −100 percent, the SSA identified wells in Hinkley and Water Valleys having high Cr(VI) concentrations that were not related to Cr(VI) releases from the Hinkley compressor station. The highest Cr(VI) concentrations outside the summative-scale Cr(VI) plume were measured in water from wells completed in mudflat/playa deposits in the northern subarea and partly consolidated Miocene deposits (23 to 5.3 million years old) in the western subarea.

Water from well MW-154S1 in the northern subarea, completed in fine-textured mudflat/playa deposits with manganese concentrations in core material greater than the summative-scale metric of 970 milligrams per kilogram (mg/kg; chapter B, fig. B.11*B*; Groover and Izbicki, 2018), had a Cr(VI) concentration of 11 µg/L in March 2015 and a summative-scale score of 0 percent (appendix G.1, table G.1.1). Regulatory Cr(VI) concentrations in water from well MW-154S1 have been as high as 20 µg/L. Although Cr(VI) concentrations in water from well MW-154S1 were the highest measured as part of this study outside the Q4 2015 regulatory Cr(VI) plume, well MW-154S1 was not included within the summative-scale Cr(VI) plume extent (fig. G.2). Similarly, water from well MW-133S1, also completed in fine-textured mudflat/playa deposits in the northern subarea with chromium concentrations in core material greater than the summative-scale metric of 85 mg/kg (chapter B, fig. B.11*A*; Groover and Izbicki, 2018), had a Cr(VI) concentration of 8.8 µg/L in March 2016 and a summative-scale score of 0 percent (appendix G.1, table G.1.1). Regulatory Cr(VI) concentrations in water from well MW-133S1 have been as high as 9.8 µg/L. Water from wells MW-154S1 and MW-133S1 did not contain tritium above the SRL of 0.05 tritium unit (TU) and had carbon-14 activities of 32- and 72-percent modern carbon (pmc), respectively, with unadjusted carbon-14 ages of more than 9,400 and 2,700 years before present (ybp), respectively, which predate Cr(VI) releases from the Hinkley compressor station.

Water from well MW-203D, completed in partly consolidated Miocene deposits underlying alluvium in the western subarea had a high-magnitude negative summative-scale score of −75 percent (fig. G.2; appendix G.1, table G.1.1). Concentrations of Cr(VI) in water from well MW-203D were 5.4 and 8.9 µg/L in March 2015 and March 2017, respectively. Concentrations of Cr(VI) in regulatory data from well MW-203D were as high as 10 µg/L but varied widely during the study (chapter D, fig. D.9), partly in response to the volume of water purged from the well before sample collection (chapter E, fig. E.5). Water from well MW-203D did not contain measurable tritium above the SRL of 0.05 TU and had a carbon-14 activity of 14 pmc, with an unadjusted carbon-14 age of more than 16,000 ybp, which predates Cr(VI) releases from the Hinkley compressor station.

Water from well MW-207S1, in the northern subarea downgradient from the Mount General fault, had Cr(VI) concentrations as high as 7.7 µg/L in March 2016; well MW-207S1 had a summative-scale score of +50 percent (fig. G.2; appendix G.1, table G.1.1) and was not included within the mapped summative-scale Cr(VI) plume extent. Although well MW-207S1 is completed in Mojave-type deposits (Groover and Izbicki, 2018; Miller and others, 2020), water from well MW-207S1 had a nonradiogenic strontium isotope (strontium-87/86) value consistent with the presence of Miocene material at that site (chapter F, fig. F.21). Although strontium-87/86 data were not included within the summative scale, weathering of minerals that compose Miocene materials (chapters C and F) may have contributed to high Cr(VI) concentrations in water from well MW-207S1. Water from well MW-207S1 did not contain measurable tritium and had a carbon-14 activity of 62 pmc, with an unadjusted carbon-14 age of 3,950 ybp, which predates releases from the Hinkley compressor station.

G.2.3. Alternative Summative-Scale Analyses

Not all questions within the summative scale precisely identified anthropogenic and natural Cr(VI) in water from wells. For example, although anthropogenic Cr(VI) from the Hinkley compressor station was released into groundwater recharged from the Mojave River, not all groundwater recharged from the Mojave River flowed near the Hinkley compressor station and would contain anthropogenic Cr(VI). Similarly, given the timing of Cr(VI) releases between 1952 and 1964, most anthropogenic Cr(VI) from the Hinkley compressor station would be associated with post-1952 groundwater; however, not all post-1952 groundwater flowed near the Hinkley compressor station and would contain anthropogenic Cr(VI). In addition, when scores for questions are summed, positive and negative scores within the SSA cancel each other, potentially obscuring the presence of anthropogenic Cr(VI) in water from wells completed in aquifer materials having fine texture, high chromium concentrations, or high manganese concentrations within aquifer solids that are associated with natural Cr(VI) (table G.1).

To address the lack of precision associated with some summative-scale questions, the questions were reformulated and separated into two alternative scales that more precisely identify anthropogenic Cr(VI) and natural Cr(VI) in water from wells (table G.2). Questions within the alternate scales were assigned values of +1 for a yes answer and 0 for a no answer to address the possibility that the −1 and +1 scoring for questions in the summative scale may obscure anthropogenic Cr(VI) in some settings. Similar to the SSA, scores for each question were summed to produce a single value for each well. Not every well had data to address every question within the alternative summative scales, and results were expressed as a percentage of the total possible score for each well.

Scores calculated using the two alternative summative scales were compared with results from the SSA. However, the summative-scale Cr(VI) plume extent (fig. G.2) was not modified on the basis of the alternative summative scales.

G.2.3.1. Presence of Anthropogenic Hexavalent Chromium

Three alternative summative-scale questions were used to address the presence of anthropogenic Cr(VI) in water from wells (table G.2). These questions are referred to as the “anthropogenic summative scale.” The questions within this scale were selected to be more specific to the presence of anthropogenic Cr(VI) than questions within the summative scale (table G.1).

Questions were scored +1 for answers consistent with anthropogenic Cr(VI) and 0 for answers not consistent with anthropogenic Cr(VI) (table G.2). Anthropogenic summative-scale scores for wells ranged from 0 to 3. Some wells had data to only score two questions, and results are expressed as a percentage of the total possible score at each well and scores ranged from 0 to 100 percent (appendix G.1, table G.1.1). Scores for the anthropogenic summative scale greater than +50 percent were interpreted as consistent with anthropogenic Cr(VI); thus, a single positive response for a well having data to only score two questions would result in an anthropogenic summative-scale score of +50 percent but would not result in an interpretation of anthropogenic Cr(VI).

Table G.2. Alternative 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.

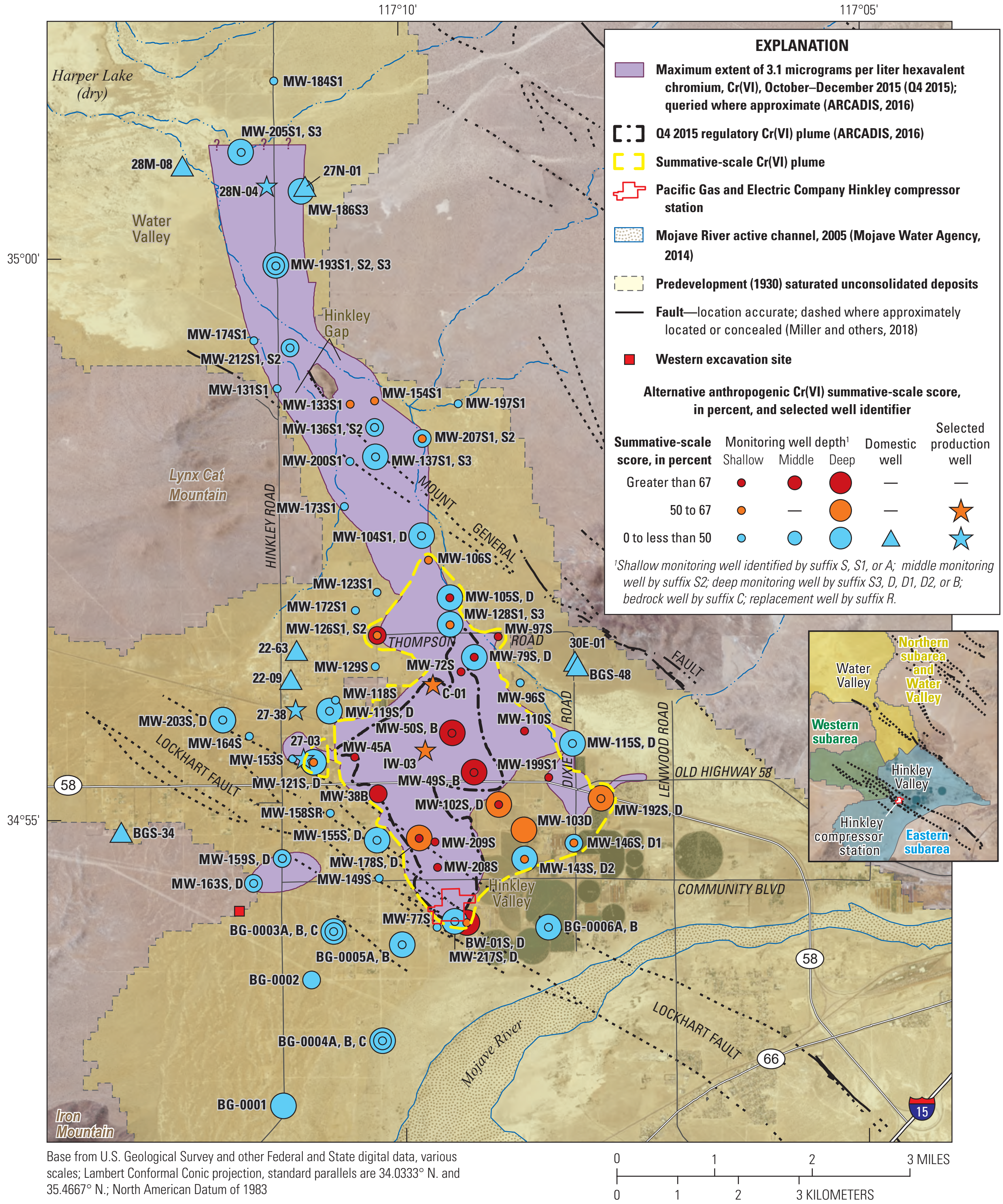
[Items in the scale are formulated as questions requiring a binary, yes or no, answer. For identification of anthropogenic Cr(VI), a score of 0 is consistent with a natural source and a score of 1 is consistent with an anthropogenic source. For identification of natural Cr(VI), a score of 0 is consistent with an anthropogenic source and a score of 1 is consistent with a natural source. **Abbreviations**: GAMA, Groundwater Ambient Monitoring and Assessment; mg/kg, milligram per kilogram]

Item	Data source	Chapter where data are discussed	Answer and score	
			Yes	No
Anthropogenic summative scale				
1. 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 using the Mann-Kendall test for trend (Helsel and others, 2020).	Chapter D	1	0
2. 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	0
3. Do geologic materials at the well screen contain more than 970 mg/kg of manganese?	Principal component analysis of Cr(VI), arsenic, vanadium, uranium, iron, and manganese.	Chapter E	1	0
Natural summative scale				
1. Is the Cr(VI) concentration consistent with the measured pH, with the probability of Cr(VI) occurrence greater than 30 percent?	pH-dependent sorption evaluated on the basis of pH and Cr(VI) concentrations in California-wide GAMA data.	Chapter E	1	0
2. Is the Cr(VI) concentration consistent with the concentrations of other trace elements?	Principal component analyses of Cr(VI), arsenic, vanadium, uranium, iron, and manganese.	Chapter E	1	0
3. Was water from the well recharged from local sources other than the Mojave River?	delta Oxygen-18 and delta deuterium data.	Chapter F	1	0
4. Does water from the well contain older groundwater without measurable tritium?	Tritium, helium-3, helium-4, and carbon-14 data.	Chapter F	1	0

Similar to the summative-scale results, wells within the Q4 2015 regulatory Cr(VI) plume had anthropogenic summative-scale scores greater than +50 percent, consistent with anthropogenic Cr(VI) (fig. G.3). Deeper wells MW-79D and MW-128S3, within the footprint of the Q4 2015 regulatory Cr(VI) plume, had anthropogenic summative-scale scores of less than +50 percent (appendix G.1, table G.1.1). Hexavalent chromium in water from these wells was not identified as anthropogenic within the SSA (fig. G.2). Most wells in the eastern subarea that were not included within the Q4 2015 regulatory Cr(VI) plume but were included within the summative-scale Cr(VI) plume, had anthropogenic summative-scale scores greater than +50 percent (fig. G.3). The exception is well MW-217S, which had an anthropogenic summative-scale score of +33 percent; however, water from well MW-217S had a probability of natural Cr(VI) occurrence at the measured pH of less than 10 percent and was likely correctly identified as anthropogenic on the basis of the SSA. Water from wells MW-143S and MW-146D1 in the eastern subarea, which had unfractionated delta chromium-53 values near 0 per mil and summative-scale scores of +75 percent, had anthropogenic summative-scale scores of +67 percent, consistent with the presence of anthropogenic Cr(VI) identified on the basis of the SSA.

Well MW-121S, in the western subarea west of the Northwest Injection Barrier (chapter A, fig. A.6; CH2M Hill, 2009), and well MW-106S, in the northern subarea near the leading edge of the summative-scale Cr(VI) plume, had anthropogenic summative-scale scores of +67 (fig. G.3), consistent with anthropogenic Cr(VI). As previously described, Cr(VI) in water from these wells was identified as anthropogenic on the basis of the SSA (fig. G.2; appendix G.1, table G.1.1) and regulatory Cr(VI) concentrations from wells MW-121S and MW-106S have been as high as 11 and 3.2 µg/L, respectively.

Wells MW-133S1, MW-154S1, and MW-207S1 in the northern subarea, downgradient from the summative-scale Cr(VI) plume and the Mount General fault, had Cr(VI) concentrations of 8.8, 11, and 7.7 µg/L, respectively, and had anthropogenic summative-scale scores of +67 percent (fig. G.3; appendix G.1, table G.1.1). Water from these wells did not contain measurable tritium at the SRL of 0.05 TU; had carbon-14 activities ranging from 72 to 32 pmc with unadjusted ages ranging from 2,700 to 9,400 ybp, which predate Cr(VI) releases from the Hinkley compressor station; and was unlikely to contain anthropogenic Cr(VI).



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 G.3. Alternative anthropogenic summative-scale scores for hexavalent chromium in water from wells, Hinkley and Water Valleys, western Mojave Desert, California, March 2015 through November 2017. 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 appendix G.1 (table G.1.1.).

G.2.3.2. Presence of Natural Hexavalent Chromium

Four alternative summative-scale questions were used to address the presence of natural Cr(VI) in water from wells (table G.2). These questions are referred to as the "natural summative scale." The questions are more specific to the presence of natural Cr(VI) than questions within the summative scale (table G.1). Questions were scored +1 for answers consistent with natural Cr(VI) and 0 for answers not consistent with natural Cr(VI) (table G.2). Natural summative-scales scores for wells ranged from 0 to 4 (appendix G.1, table G.1.1).

Geologic questions within the natural summative scale associated with high chromium or manganese concentrations in core material and fine texture are associated with higher natural Cr(VI) concentrations in groundwater (table G.1; chapter B, figs. B.8, B.11*A*, *B*). However, these questions were not used in the natural summative scale to ensure anthropogenic Cr(VI) in water from wells, having high natural chromium and manganese in geologic materials or fine texture, would not be scored as natural if anthropogenic Cr(VI) was present. Similar to the summative scale, scores for question 4 in the natural summative scale (table G.2), addressing the age (time since recharge) of groundwater, were calculated from tritium and carbon-14 data. However, a score of 1, indicating older (pre-1952) groundwater, was assigned for this question if tritium concentrations were less than the SRL of 0.05 TU and carbon-14 ages were less than 84 pmc. A score of 1 is consistent with older groundwater that does not contain any fraction of post-1952 water. This approach ensured that only older groundwater that predated releases from the Hinkley compressor station was scored a value of 1, consistent with natural chromium.

Natural summative-scale scores for wells ranged from 0 to 4 (appendix G.1, table G.1.1). Although all sampled wells had data to answer every question within the scale, results are expressed as a percentage of the total possible score at each well for consistency with previous analyses. A positive response to a question within the natural summative scale generally excluded anthropogenic Cr(VI), and a score of +25 percent or greater was interpreted as consistent with a natural source of Cr(VI). This scoring addressed some of the imprecision associated with the summative-scale questions (table G.1).

Most wells outside the footprint of the summative-scale Cr(VI) plume had natural summative-scale scores of +25 percent or greater, consistent with natural Cr(VI) (fig. G.4). Only water from wells MW-197S1, near the margin of the aquifer in the northern subarea downgradient from the Mount General fault, and MW-193S3, within Water Valley, scored +100 percent.

Although the natural summative-scale questions were formulated to identify natural Cr(VI), the distribution of these scores also provides information on the extent of anthropogenic Cr(VI). Wells within the Q4 2015 regulatory Cr(VI) plume and within the summative-scale Cr(VI) plume had scores of 0 percent (fig. G.4; appendix G.1, table G.1.1). Similar to summative-scale results, deep wells within the footprint of the Q4 2015 regulatory Cr(VI) plume, MW-79D and MW-128S3, had natural summative-scale scores greater than 0 percent that were consistent with natural Cr(VI) (fig. G.4). Well MW-121S, near the plume margin in the western subarea, with a history of regulatory Cr(VI) concentrations as high as 11 µg/L, had a natural summative-scale score of 0 percent, consistent with anthropogenic Cr(VI); well MW-121D at the same site had a natural summative-scale score of +25 percent, consistent with natural Cr(VI) (fig. G.4). In contrast, well MW-106S, near the leading edge of the summative-scale Cr(VI) plume in the northern subarea, had a natural summative-scale score of +25 percent, consistent with natural Cr(VI) (fig. G.4).

Wells MW-159S and MW-159D, downgradient from the western excavation site, had natural summative-scale scores of 0 percent consistent with anthropogenic Cr(VI) (fig. G.4; appendix G.1, table G.1.1). As previously described, the western excavation site on property owned by PG&E was used as an illegal disposal site by unknown parties. Although anthropogenic constituents have been identified in groundwater downgradient from the site, Cr(VI) releases at the western excavation site have not been confirmed by regulatory agencies (Lahontan Regional Water Quality Control Board, 2014).

G.2.4. Comparison of Summative-Scale Results with Data from Selected Wells

Summative-scale results for selected wells were compared with data collected as part of this study that were not included within the SSA. These data, provided in chapters B through F within this professional paper, are generally supportive of interpretations derived from the SSA (fig. G.2) and the alternative anthropogenic (fig. G.3) and natural (fig. G.4) SSAs. This discussion examines data from selected wells presented in chapters B through F within this professional paper that were not included within the summative-scale Cr(VI) plume, including (1) wells near the leading edge of modern (post-1952) groundwater, (2) wells in geologic materials associated with natural chromium (including visually abundant iron- and manganese-oxide coatings on the surfaces of mineral grains, mudflat/playa deposits, Miocene deposits, and weathered bedrock), and (3) wells that have no identifiable source of natural chromium able to explain high Cr(VI) concentrations in groundwater.

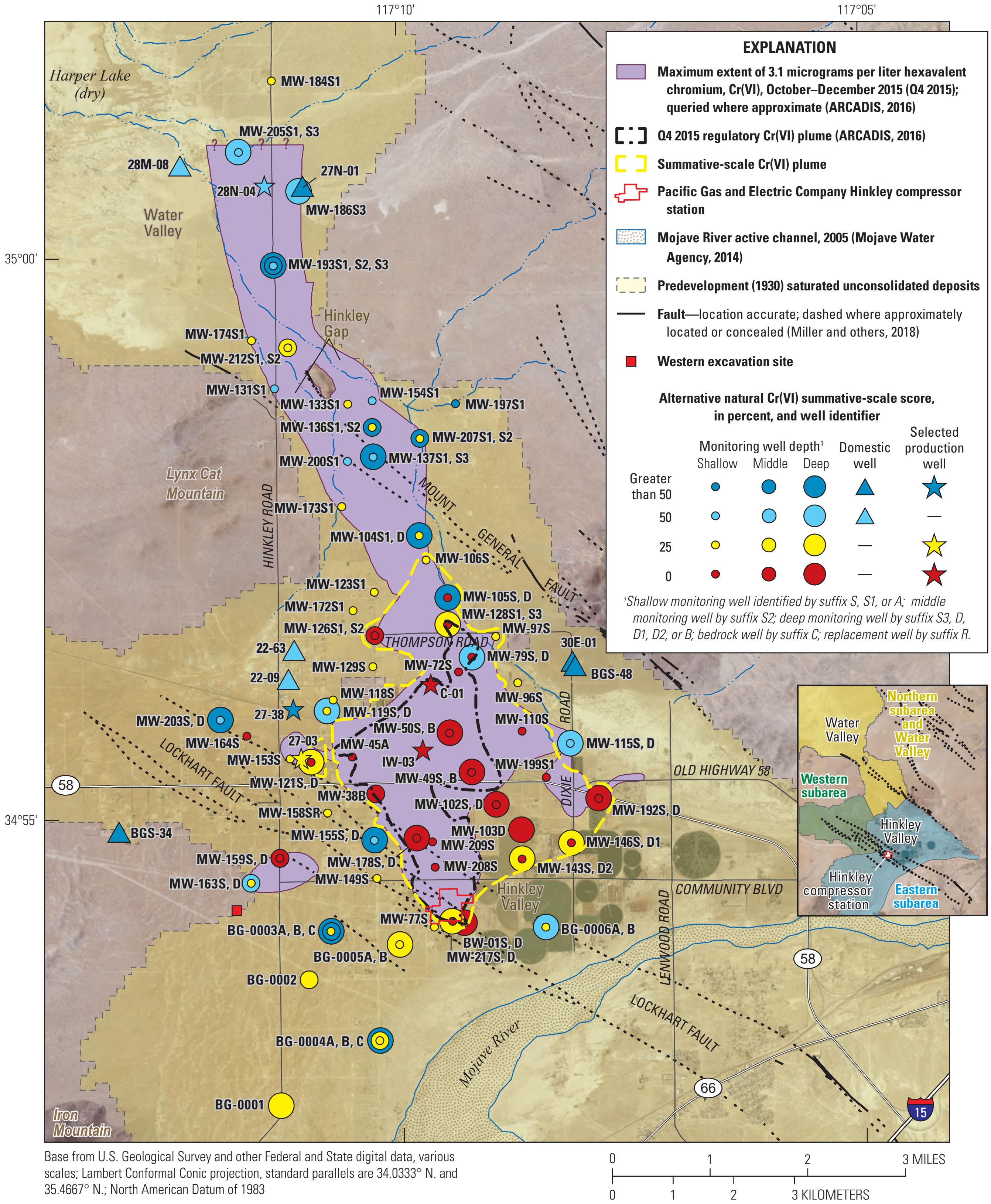


Figure G.4. Alternative natural summative-scale scores for hexavalent chromium in water from wells, Hinkley and Water Valleys, western Mojave Desert, California, March 2015 through November 2017. Scores were calculated from data available in chapter E (appendix E.1, table E.1.1), Groover and Izbicki (2018), and U.S. Geological Survey (2021). Selected data and scores are available in appendix G.1 (table G.1.1.)

G.2.4.1. Wells near the Leading Edge of Modern Groundwater

The leading edge of modern, younger (post-1952) groundwater was evaluated on the basis of tritium data (chapter F, fig. F.10). Tritium was measured for this study using helium ingrowth (Clarke and others, 1976) having a laboratory reporting level (LRL) commonly near 0.02 TU and a SRL of 0.05 TU (chapter F). Tritium for environmental studies is more commonly measured using techniques that have higher LRLs near 0.2 TU, and 22 wells sampled as part of this study had detectable tritium concentrations greater than the SRL that were less than 0.2 TU (appendix G.1, table G.1.1).

Given the timing of Cr(VI) releases from the Hinkley compressor station, interpretation of low tritium concentrations and the leading edge of post-1952 groundwater was concerning to stakeholders in the TWG. Concern is increased because anthropogenic Cr(VI) released from the Hinkley compressor station beginning in 1952 would have initially mixed with older groundwater and may be present in advance of the leading edge of tritium-containing groundwater. Incorrect hydrologic or geochemical interpretation of low tritium concentrations above the LRL or SRL may incorrectly identify the leading edge of post-1952 groundwater, and the leading edge of associated anthropogenic Cr(VI).

Carbon-14 data were used to support the interpretation of tritium data in question 8 of the summative scale (table G.1). A summative-scale score of +1, consistent with post-1952 water, was assigned for wells having detectable tritium concentrations less than 0.2 TU and carbon-14 activities greater than the initial activity at the time of recharge of 84 pmc, estimated for the western Mojave Desert (Izbicki and Michel, 2004). A summative-scale score of −1, consistent with older (pre-1952) water, was assigned for wells having detectable tritium concentrations less than 0.2 TU and carbon-14 activities less than or equal to 84 pmc.

No wells having tritium concentrations greater than 0.13 TU had carbon-14 activities less than 84 pmc (chapter F, fig. F.18). Half of the sampled wells (11 of 22 wells) having detectable tritium concentrations less than 0.2 TU had carbon-14 activities less than or equal to 84 pmc. This includes wells MW-164S, MW-203S, and 27-03 in the western subarea, and wells MW-131S and MW-200S1 downgradient from the Q4 2015 regulatory Cr(VI) plume in the northern subarea (appendix G.1, table G.1.1). Although, some post-1952 water is likely present in these wells, the wells were assigned a score of −1 for question 8 in the summative scale (table G.1), consistent with pre-1952 water. Small amounts of measurable tritium in water from these wells may result from small amounts of irrigation return, septic discharges, or (scant) local recharge.

Water samples from wells MW-123S1, MW-128S3, MW-137S1, and MW-174S1, in the northern subarea, having detectable tritium concentrations less than 0.2 TU and carbon-14 activities greater than 84 pmc were assigned scores of +1 for question 8, consistent with post-1952 water; however, on the basis of their summed scores, these wells were not included within the summative-scale Cr(VI) plume. In contrast, water samples from well MW-106S in the northern subarea and well MW-121S in the western subarea having detectable tritium concentrations of 0.15 and 0.06 TU, respectively, and carbon-14 activities of 95 and 87 pmc, respectively, were assigned scores of +1 for question 8. On the basis of their summed scores, these wells were included within the summative-scale Cr(VI) plume.

Water from well MW-174S1 in Water Valley, more than 6 mi downgradient from the Hinkley compressor station, had a tritium concentration of 0.17 TU in March 2016. Well MW-174S1 was the farthest downgradient well having detectable tritium and was estimated to contain 3-percent modern water with a tritium/helium-3 recharge date of 1958 (chapter F, appendix F.2, table F.2.1; fig. F.13*A*). In addition to measurable tritium, water from well MW-174S1 had a carbon-14 activity of 95 pmc, consistent with modern, post-1952 recharge, and was scored as +1 for question 8 in the summative scale (appendix G.1, table G.1.1). Carbon-14 activities in wells further downgradient in Water Valley did not exceed 50 pmc (chapter F, fig. F.16).

Water from well MW-174S1 had a Cr(VI) concentration of 3.1 μg/L in March 2016. However, the Cr(VI) concentration at the measured pH of 7.5 (question 5, table G.1) and trace-element composition in water from well MW-174S1 (question 6, table G.1) were consistent with Cr(VI) in native groundwater (chapter E, figs. E.18*B*, E.21). The summative-scale score for Cr(VI) in water from well MW-174S1 was +25 percent, and well MW-174S1 was not included within the summative-scale Cr(VI) plume (fig. G.2; appendix G.1, table G.1.1). Alternative anthropogenic and natural summative-scale scores for Cr(VI) in water from well MW-174S1 were +33 and +25 percent, respectively (figs. G.3, G.4; appendix G.1, table G.1.1), and the alternative summative-scale scores did not indicate anthropogenic Cr(VI).

Upgradient from well MW-174S1, water within much of the regulatory Cr(VI) plume has been affected by irrigation return from overlying agriculture. However, water from well MW-174S1 has major-ion (chapter E, figs. E.8, E.9) and delta oxygen-18 and delta deuterium isotope compositions (chapter F, fig. F.4) consistent with Mojave River recharge that does not contain large fractions of irrigation return water. Historical water-level data (Stone, 1957; California Department of Water Resources, 1967) indicate development of a pumping depression downgradient from the Hinkley compressor station that persisted until agricultural pumping declined in the early 1990s (Stamos and others, 2001; Jacobs Engineering Group, Inc., 2019). While present, this pumping depression may have limited the downgradient movement of groundwater containing irrigation return and anthropogenic Cr(VI) released from the Hinkley compressor station.

As described previously, not all water that originated from the Mojave River and not all water containing low concentrations of tritium recharged after 1952 passed near the Hinkley compressor station and would contain anthropogenic Cr(VI). Although it may be possible that small amounts of anthropogenic Cr(VI) are present in water from well MW-174S1 and other wells containing measurable tritium in the northern subarea downgradient from the summative-scale Cr(VI) plume, Cr(VI) co-occurrence with pH and Cr(VI) co-occurrence with other trace elements measured in those wells as part of this study and the summative-scale scores for these wells are within ranges expected for natural Cr(VI) (appendix G.1, table G.1.1).

G.2.4.2. Wells in Geologic Materials Associated with Natural Chromium

Data from wells penetrating aquifer material containing (1) visually abundant iron- and manganese-oxide coatings, (2) mudflat/playa deposits, (3) Miocene deposits, or (4) weathered bedrock that may have high concentrations of natural Cr(VI) are provided in chapters B through F within this professional paper. Although not included within the SSA, data for wells completed in these materials are summarized in this section and are consistent with summative-scale results for wells interpreted to contain natural Cr(VI).

G.2.4.2.1. Wells in Deposits Having Visually Abundant Iron and Manganese Oxides

Naturally occurring aluminum-, iron-, and manganese-oxide coatings are ubiquitous on mineral grains that compose aquifers. Although these coatings are generally less than 5 micrometers (µm) thick, they play an important role in the storage of chromium and other trace elements weathered from mineral grains before their release into groundwater (Izbicki and others, 2008; Ščančar and Milačič, 2014; chapters C and I). In addition, oxide coatings commonly provide a manganese-rich matrix that can facilitate oxidation of Cr(III) to Cr(VI) (Schroeder and Lee, 1975; Oze and others, 2007). Visually abundant iron- and manganese-oxide coatings much greater than 5 µm thick were observed on mineral grains in core material at redox boundaries near the water table, near geologic contacts, and in highly weathered Miocene materials (chapter C, fig. C.13).

Mojave-type deposits having visually abundant iron- and manganese-oxide coatings on the surfaces of mineral grains were examined in detail within core material adjacent to the screened interval of well BG-0004A (fig. G.1; chapter C, figs. C.19, C.20). Concentrations of Cr(VI) in water from well BG-0004A ranged from 2.3 to 3.1 µg/L between January 2016 and January 2018 (chapter E, appendix E.1, table E.1.1). At this well, pXRF analyses of core material having visually abundant oxide coatings at 64 ft below land surface (bls) indicated chromium concentrations as high as 38 mg/kg (Groover and Izbicki, 2018), with 22 percent of that chromium extractable from exchange sites on the surfaces of mineral grains and potentially mobile to groundwater (chapter C, appendix C.1, table C.1.1). In contrast, the chromium concentration in similarly textured core material at this site between 57 and 61 ft bls that was unaltered by oxide forming processes was 13 mg/kg, and less than 4 percent of that chromium was extractable from exchange sites on the surfaces of mineral grains and potentially mobile to groundwater (chapter C, fig. C.19). Manganese concentrations on core material having visually abundant oxide coatings on the surfaces of mineral grains from BG-0004A exceeded the summative-scale threshold of 970 mg/kg, whereas manganese concentrations on unaltered core material between 51 and 61 ft bls were less than 230 mg/kg (Groover and Izbicki, 2018). The distribution of extractable manganese was similar to distribution of extractable chromium (chapter C, appendix C.1, table C.1.1). Raman spectroscopy of oxide coatings from BG-0004A identified Mn(III/IV) oxides on the surfaces of mineral grains (chapter C, fig. C.20; Foster and others, 2023) that are able to oxidize Cr(III) to Cr(VI) (Schroeder and Lee, 1975; Oze and others, 2007).

It is likely that visually abundant iron- and manganese-oxide coatings on mineral grains within core material adjacent to the screened intervals of other wells near the water table, near geologic contacts, and in highly weathered materials have similar compositions that may contribute natural Cr(VI) to water from wells. For example, core material consisting of Mojave-type deposits from well MW-121D (fig. G.1) between 110 and 120 ft bls overlying weathered hornblende diorite bedrock in the western subarea contains visually abundant iron- and manganese-oxide coatings on the surfaces of mineral grains (chapter C, fig. C.13*B*) with chromium and manganese concentrations measured by pXRF as high as 118 and 1,040 mg/kg, respectively (Groover and Izbicki, 2018), that exceed summative-scale thresholds for the elements.

The presence of visually abundant iron- and manganese-oxide coatings was not used as part of the SSA because of the qualitative, descriptive nature of these features. Similarly, extractable Cr(VI) and manganese concentrations, or Raman spectrographic characterization of manganese oxides, were not used as part of the SSA because of the difficulty associated with making these measurements on core material from all sampled wells. Instead, the summative scale used pXRF data for chromium and manganese (Groover and Izbicki, 2018) to evaluate the effect of oxide coatings on the surfaces of mineral grains on Cr(VI) concentrations in water from wells (chapter B, figs. B.11*A*, *B*). These data were available for core material adjacent to the screened interval of most sampled wells. Chromium and manganese concentrations in core material adjacent to the screened intervals of sampled wells that exceed summative-scale thresholds of 85 and 970 mg/kg, respectively, are summarized in table B.4 in chapter B within this professional paper.

G.2.4.2.2. Wells in Mudflat/Playa Deposits in the Eastern Subarea

Mudflat/playa deposits are present and interspersed within aquifer material throughout much of Hinkley and Water Valleys (Miller and others, 2020). Active playas are present in Harper (dry) Lake and near the toe of alluvial fan deposits eroded from Mount General within Hinkley Valley. Mudflat/playa deposits in the eastern and northern subareas of Hinkley Valley differ in their composition with respect to chromium and in their potential to oxidize Cr(III) to Cr(VI).

Much of the increase in the summative-scale Cr(VI) plume extent compared to the Q4 2015 regulatory Cr(VI) plume was in the eastern subarea. The summative-scale Cr(VI) plume in the eastern subarea included an additional 2.5 mi^2 and nine wells sampled as part of this study that were not included in the Q4 2015 regulatory Cr(VI) plume (fig. G.2, appendix G.1, table G.1.1). Concentrations of Cr(VI) in water from most of these wells were less than 2.5 µg/L; however, Cr(VI) concentrations in water from wells MW-110S, MW-192S, and MW-192D, near fine-textured mudflat/playa deposits along the toe of the alluvial fan eroded from Mount General (fig. G.1), exceeded the interim regulatory Cr(VI) background concentration of 3.1 µg/L (chapter E, appendix E.1, table E.1.1). Summative-scale scores for these wells ranged from +75 percent for wells MW-192S and MW-192D to +100 percent for well MW-110S (fig. G.2; appendix G.1, table G.1.1), consistent with anthropogenic Cr(VI) from the Hinkley compressor station. Wells MW-192S and MW-192D are east of Dixie Road and outside the regulatory boundary established by the 2015 cleanup and abatement order (Lahontan Regional Water Quality Control Board, 2015); however, Cr(VI) concentrations in Hinkley Valley east of Dixie Road were evaluated as part of this study.

Chromium and manganese concentrations in core material adjacent to the screened intervals of wells MW-110S, MW-192S, and MW-192D are low and did not exceed 41 and 570 mg/kg, respectively, and most chromium and manganese concentrations in core material at these sites were less than 12 and 170 mg/kg, respectively (Groover and Izbicki, 2018). These concentrations are less than the summative-scale thresholds of 85 and 970 mg/kg for chromium and manganese, respectively (table G.1). Low chromium and manganese concentrations in core material from these wells are consistent with lithologic descriptions that identify these materials as sourced from the Mojave River (chapter A, table A.1; Miller and others, 2020) and with X-ray diffraction (XRD) data (chapter C, fig. C.10) that indicate these materials have a felsic Mojave-type mineralogy.

Scanning electron micrograph (SEM) with energy dispersive X-ray spectroscopy data (chapter C, fig. C.12*A*) and analyses of chromium within the heavy (specific gravity greater than 3.2) mineral fraction (chapter C, fig. C.23) indicated much of the chromium within mudflat/playa deposits within the eastern subarea remains within unweathered magnetite mineral grains. Magnetite is resistant to weathering, and chromium substituted within magnetite is largely unavailable to groundwater. Admixtures of local alluvium eroded from Mount General were not identified in core material adjacent to the screened interval of wells MW-110S, MW-192S, and MW-192D (Morrison and others, 2018; Miller and others, 2020), and the elemental composition of these materials was similar to the composition of felsic Mojave-type deposits (chapter B, fig. B.16).

Surficial mudflat/playa deposits in the eastern subarea near Mount General also are low in chromium and manganese despite their fine texture, and concentrations do not exceed 37 and 710 mg/kg, respectively (Groover and Izbicki, 2018). The XRD data indicated surficial mudflat/playa deposits in this area also are composed of fine-textured felsic minerals, rather than clay minerals present in mudflat/playa deposits elsewhere in Hinkley and Water Valleys, although some locally sourced material eroded from Mount General is evident in XRD data from surficial materials in this area (chapter C, fig. C.10).

Calcareous mudflat/playa deposits in Hinkley Valley were observed to contain manganese-oxide nodules and dendritic structures known as “dragon’s breath” (chapter C, fig. C.13*C*). The X-ray absorption near-edge structure (XANES) spectroscopy indicated highly oxidative Mn(IV) oxides within these materials (chapter C, fig. C.24). Consistent with XANES data, calculated redox values indicated Cr(VI) in water from wells MW-192S and MW-192D was near equilibrium with Mn(IV) oxides (chapter E, fig. E.15), rather than with the more common Mn(III/IV) oxides identified in core material associated with iron and manganese oxides at well BG-0004A (chapter C, fig. C.20). On the basis of these data, it is possible that fine-textured mudflat/playa deposits in this part of the eastern subarea may be highly oxidative and could contribute Cr(VI) to water from wells despite the low chromium concentrations of these materials.

To address the possibility that manganese-IV within mudflat/playa deposits could oxidize Cr(VI) from geologic materials low in chromium, test holes were drilled and porewater was pressure extracted from fresh core material near well site MW-192 (chapter E, table E.6). Concentrations of Cr(VI) in four samples of porewater from fine-textured deposits near well site MW-192 ranged from 0.4 to 3.3 µg/L (chapter E, table E.6). Some Cr(VI) concentrations in porewater were higher than expected at the measured pH given the low chromium concentrations in these materials, and oxidation of naturally occurring Cr(III) to Cr(VI) in mudflat/playa deposits in the eastern subarea is potentially enhanced by Mn(IV) oxides within those deposits. However, Cr(VI) concentrations measured in porewater are not high enough to explain Cr(VI) concentrations in water from wells MW-110S, MW-192S, and MW-192D.

Water from wells MW-110S, MW-192S, and MW-192D had circumneutral pH values, with high specific conductance and delta oxygen-18 and delta deuterium isotope compositions affected by evaporation of irrigation return water (chapter E, appendix E.1 table E.1.1; figs. E.16*B*, E.6*B*; chapter F, fig. F.4, respectively). Irrigation return contains low concentrations of Cr(VI), commonly less than 0.5 µg/L (chapter E, table E.6), and is not a likely source of Cr(VI). Groundwater containing Cr(VI) is applied to agricultural fields by PG&E to remove Cr(VI) within the root zone as irrigation return water infiltrates to the water table (chapter A, fig. A.6). In contrast, porewater pressure extracted from fine-textured core material at well site MW-192 had alkaline pH values, and low specific conductance and delta oxygen-18 and delta deuterium isotope compositions that were largely unaffected by evaporation and irrigation return water. Mass-balance calculations indicate it is not possible to obtain the Cr(VI) concentrations of water from wells MW-110S, MW-192S, and MW-192D through mixing with porewater.

Although not diagnostic of anthropogenic Cr(VI), water from wells MW-110S and MW-192D had Cr(VI) concentrations and delta chromium-53 compositions within the expected range of anthropogenic Cr(VI) released from the Hinkley compressor station that could not be explained by fractionation of chromium within local geologic materials or by fractionation of Cr(VI) within older (pre-1952) groundwater in this area (characterized by water from well MW-115D; chapter F, fig. F.26*A*). On the basis of summative-scale scores ranging from +75 to +100 percent (fig. G.2), Cr(VI) in water from wells MW-110S, MW-192S, and MW-192D was consistent with anthropogenic Cr(VI) released from the Hinkley compressor station.

Well MW-115D, also in the eastern subarea near Mount General (fig. G.2), is screened in coarse-textured Mojave-type deposits that have low chromium and manganese concentrations that do not exceed 18 and 380 mg/kg, respectively (Groover and Izbicki, 2018). Water from well MW-115D had a Cr(VI) concentration of 3.5 µg/L in March 2017, and regulatory Cr(VI) concentrations have been as high as 4.6 µg/L. These are the highest Cr(VI) concentrations measured in the eastern subarea outside the summative-scale Cr(VI) plume. Concentrations of Cr(VI) in water from well MW-115D in March 2017 were within the range expected for natural Cr(VI) in groundwater on the basis of the measured pH of 8.0 (chapter E, fig. E.18*B*) and measured trace-element concentrations (chapter E, fig. E.21).

Groundwater from well MW-115D is isolated from surface sources of recharge along the Mojave River by mudflat/playa deposits within the aquifer; water from well MW-115D does not have measurable tritium and has a carbon-14 activity of 81 pmc, with an unadjusted age of 1,750 ybp which predates releases from the Hinkley compressor station. This isolation has contributed to long contact times between groundwater and aquifer materials, promoting weathering of silicate minerals, and the development of alkaline groundwater with subsequent desorption of Cr(VI) from aquifer materials (chapter E, fig. E.17). In addition, the chemistry and delta oxygen-18 and delta deuterium isotope compositions of water from well MW-115D were unaffected by irrigation return and were similar to porewater compositions measured in mudflat/playa deposits in the eastern subarea (chapter F, fig. F.4). Although not diagnostic, delta chromium-53 data indicate that Cr(VI) in water from some wells in the eastern subarea near Mount General may have been contributed from older groundwater characterized by well MW-115D (chapter F, fig. F.26*A*). The summative-scale score for well MW-115D was +25 percent (fig. G.2; appendix G.1, table G.1.1), and unlike water from wells MW-110S, MW-192S, and MW-192D, Cr(VI) in water from well MW-115D was interpreted as natural.

G.2.4.2.3. Wells in Mudflat/Playa Deposits in the Northern Subarea

Fine-textured mudflat/playa deposits in the northern subarea differ from those in the eastern subarea near Mount General and are closely associated with lacustrine deposits distributed throughout aquifer materials in the northern subarea (Miller and others, 2018, 2020). Although the summative-scale Cr(VI) plume extent in the northern subarea is greater than the Q4 2015 regulatory Cr(VI) plume, it does not extend throughout the northern subarea. Wells that penetrate mudflat/playa and lacustrine deposits in the northern subarea downgradient from the Mount General fault that yield water with high Cr(VI) concentrations (fig. G.1; appendix G.1, table G.1.1) were not included within the summative-scale Cr(VI) plume (fig. G.2).

Concentrations of Cr(VI) in water from wells MW-133S1 and MW-154S1 (fig. G.1), completed in mudflat/playa deposits in the northern subarea downgradient from the Mount General fault, were 8.8 and 11 µg/L, respectively (appendix G.1, table G.1.1). Concentrations of Cr(VI) in water from well MW-154S1 were the highest sampled outside the Q4 2015 regulatory Cr(VI) plume as part of this study. Concentrations of Cr(VI) in regulatory data from wells MW-133S1 and MW-154S1 have been as high as 9.8 and 20 µg/L, respectively. Summative-scale scores for wells MW-133S1 and MS-154S1 were 0 percent (fig. G.2; appendix G.1, table G.1.1), and Cr(VI) concentrations were consistent with natural Cr(VI) on the basis of those scores.

In contrast to mudflat/playa deposits in the eastern subarea, chromium and manganese concentrations in core material adjacent to the screened interval of well MW-133S1 were as high as 85 and 840 mg/kg, respectively, and concentrations in well MW-154S1 were as high as 77 and 1,340 mg/kg, respectively (Groover and Izbicki, 2018). Chromium concentrations in core material equaled the summative-scale threshold of 85 mg/kg in well MW-133S1, and manganese concentrations exceeded the summative-scale threshold of 970 mg/kg in well MW-154S1 (table G.1).

In contrast to the eastern subarea, XRD data indicated mudflat/playa deposits in the northern subarea are composed of clay minerals, predominately chlorite with minor to trace amounts of smectite (chapter C, fig. C.10). Rapid oxidation of Cr(III) to Cr(VI) in the presence of manganese oxides associated with clay minerals was observed by Oze and others (2007). The SEM data collected on the heavy mineral fraction indicate magnetite was not present in core material from well MW-154S1 (Morrison and others, 2018), and finely disseminated magnetite that may have been present within the material at the time of deposition may have weathered to hematite (chapter C, fig. C.9*C*). Manganese substituted within magnetite commonly weathers to form highly oxidative Mn(IV) oxides (Dixon and Weed, 1989; Anthony and others, 2001). In addition, manganese-oxide nodules and dendritic structures known as “dragon’s breath,” similar to features observed in mudflat/playa deposits in the eastern subarea (chapter C), were noted in descriptions of core material collected at wells MW-133S1 and MW-154S1. The XANES spectra indicated highly oxidative Mn(IV) oxides within these materials (chapter C, fig. C.24). Calculated redox values indicate Cr(VI) in water from wells MW-133S1 and MW-154S1 are near equilibrium with Mn(IV) oxides, rather than with the more common Mn(III/IV) oxides (chapter E, fig. E.15).

To address the possibility that porewater from fine-textured mudflat/playa deposits could be a source of Cr(VI) to water from wells in the northern subarea, a test hole was drilled and porewater was pressure extracted from fresh core material near well site MW-154S1 (chapter E, table E.6). Concentrations of Cr(VI) in porewater extracted from two samples of core material collected below the water table did not exceed 1.3 µg/L (chapter E, table E.6), possibly because of locally reduced (gleied) conditions observed within the saturated core material. Conditions in the overlying unsaturated zone were more oxic, and the total dissolved chromium, Cr(t), concentration in porewater from unsaturated core material collected above the water table was 5.4 µg/L (chapter E, table E.6). It was not possible to extract enough water from the unsaturated core materials to analyze for Cr(VI). Although not as high as concentrations in water from wells MW-133S1 and MW-154S1, the Cr(t) concentration of 5.4 µg/L in porewater extracted from core material at well MW-154S1 was the highest porewater concentration measured in Hinkley and Water Valleys. Although not diagnostic of natural Cr(VI), Cr(VI) concentration and delta chromium-53 isotope composition data in water from wells MW-133S1, MW-154S1, and other wells indicate that chromium associated with lacustrine and mudflat/playa deposits may be a possible source of natural Cr(VI) in the northern subarea (chapter F, fig. F.26*C*).

Water from wells MW-133S1 and MW-154S1 was oxic and highly alkaline with pH values of 8.4 and 8.5, respectively (chapter E, appendix E.1, table E.1.1). Water samples did not contain measurable tritium at concentrations greater than the SRL of 0.05 TU; had carbon-14 activities of 72 and 32 pmc, respectively; and had unadjusted carbon-14 ages of 2,700 and more than 9,400 ybp, respectively, which predate Cr(VI) releases from the Hinkley compressor station. Geologic and geochemical conditions at wells MW-133S1 and MW-154S1, in the northern subarea downgradient from the Mount General fault, including aquifer mineralogy, oxic groundwater, strongly alkaline pH values, and older groundwater ages are consistent with summative-scale scores indicative of natural Cr(VI) in water from wells in this area (appendix G.1, table G.1.1).

G.2.4.2.4. Wells in Miocene Deposits

Miocene deposits (23 to 5.3 million years old) in Hinkley Valley consist of partly consolidated conglomerate and volcanic rock underlying Mojave-type deposits in the western subarea (Miller and others, 2020). Material reworked from Miocene sedimentary rock east of the study area (chapter B, fig. B.3) is present in unconsolidated deposits within the northern subarea of Hinkley Valley and in Water Valley; much of that Miocene material is highly weathered (chapter C, fig. C.9).

Concentrations of Cr(VI) in water from well MW-203D (fig. G.1), completed in Miocene deposits underlying the western subarea were 8.9 µg/L in March 2015 and 5.4 µg/L in March 2017 (chapter E, appendix E.1, table E.1.1); Cr(VI) concentrations in regulatory samples have been as high as 10 µg/L. Concentrations of Cr(VI) in regulatory data from well MW-203D decreased to less than the LRL of 0.06 µg/L by July 2014, and Cr(VI) concentrations varied widely as a result of sampling conditions, especially prior pumping (chapter E, fig. E.5).

Chromium and manganese concentrations in core material adjacent to the screened interval of well MW-203D were as high as 350 and 1,150 mg/kg (Groover and Izbicki, 2018), respectively, exceeding the summative-scale thresholds of 85 and 970 mg/kg, respectively (table G.1). Water from well MW-203D was oxic and highly alkaline with pH values as high as 8.3 (chapter E, appendix E.1, table E.1.1); measured Cr(VI) concentrations had a 15- to 20-percent probability of natural occurrence at the measured pH (chapter E, fig. E.18*B*). The delta oxygen-18 and delta deuterium data (chapter F, fig. F.3) indicate water from well MW-203D did not originate as recharge from the Mojave River, and low carbon-14 activities of 14 pmc indicated an unadjusted carbon-14 age of more than 16,000 ybp. On the basis of these data, Cr(VI) in water from well MW-203D could not have originated from releases at the Hinkley compressor station. Summative-scale scores for Cr(VI) in water from well MW-203D were −75 percent and were consistent with natural Cr(VI) (fig. G.2; appendix G.1, table G.1.1). No sampled well had a summative-scale score of −100 percent, and well MW-203D had the highest magnitude negative score of any well sampled in Hinkley or Water Valleys.

As a result of their geologic age, many Miocene materials have weathered more extensively than younger deposits in Hinkley Valley; consequently, a higher percentage of the chromium within these materials has weathered from minerals, is sorbed onto oxide coatings on the surfaces of mineral grains, and is potentially available to groundwater. In core material adjacent to the screened interval of well MW-203D, 27 percent of measured chromium was extractable from exchange sites on the surfaces of mineral grains and is potentially mobile to groundwater (chapter C, fig. C.18*A*; appendix C.1, table C.1.1), compared to a median of 10 percent in most other core materials (chapter C, fig. C.16). In addition, weathering of resistive magnetite to hematite was observed in Miocene materials (chapter C, fig. C.9). As magnetite weathers, manganese substituted within magnetite mineral grains weathers to the more oxidative Mn(IV) oxides (Dixon and Weed, 1989), rather than the more common Mn(III/IV) oxides, potentially facilitating oxidation of sorbed Cr(III) to Cr(VI). However, calculated redox values did not indicate Cr(VI) in water from wells MW-203D was near equilibrium with oxidative Mn(IV) oxides.

Although Miocene deposits were only penetrated by well MW-203D, unconsolidated deposits containing material reworked from Miocene deposits east of the study area were identified in Hinkley and Water Valleys on the basis of their low (nonradiogenic) strontium-87/86 ratio (chapter F, fig. F.21). The low strontium-87/86 ratio is the result of Miocene volcanism in the Mojave Desert area (Glazner and O'Neil, 1989) and differs from the higher (radiogenic) ratios in Mojave-type deposits eroded from granitic rock in the San Bernardino Mountains (DePaolo, 1981; Bataille and Bowen, 2012). Although chromium concentrations are not consistently high in Miocene materials, mineral grains eroded from Miocene source rock are more weathered than mineral grains in unconsolidated deposits elsewhere in Hinkley and Water Valleys (chapter C, fig. C.9*C*). These Mojave-type materials were eroded from source rock and deposited in Hinkley and Water Valleys less than 750,000 years ago; some shallower Mojave-type materials were deposited less than 45,000 years ago (Garcia and others, 2014; chapter A, fig. A.5).

Similar to materials at well MW-203D, unconsolidated deposits containing Miocene materials in core material adjacent to the screened interval of well MW-193S1 (fig. G.1) in Water Valley had 27 percent of the measurable chromium extractable from surface exchange sites and potentially mobile to groundwater (chapter C, fig, C.18*B*; appendix C.1, table C.1.1). Manganese concentrations extractable from surface exchange sites in core material adjacent to the screened interval of the deeper well at this site, MW-193S3, were the highest measured as part of this study and were 60 percent greater than manganese concentrations extractable from the next most manganese-enriched core materials (chapter C, appendix C.1, table C.1.1). High manganese concentrations on surface sorption sites may be highly reactive and may partly explain Cr(VI) concentrations as high as 150 µg/L in water from well MW-193S3 shortly after the well was drilled in July 2013, especially if this manganese was present as Mn(IV). Concentrations of Cr(VI) in water from well MW-193S3 decreased with time and were less than 0.5 µg/L when sampled as part of this study in March 2015 and March 2016, consistent with low dissolved-oxygen concentrations of 0.3 mg/L.

Because Miocene materials are older and mineral grains are often more weathered, these materials can contribute Cr(VI) to groundwater even if the chromium concentrations within aquifer materials are not especially high. Miocene materials are typically penetrated by deeper wells, and groundwater is commonly isolated from surface sources of recharge. This isolation has contributed to long contact times between groundwater and aquifer materials, promoting weathering of silicate minerals and development of alkaline groundwater with subsequent desorption of Cr(VI) from aquifer materials. Despite their potential usefulness in identifying Miocene materials where chromium weathered from mineral grains may be sorbed to surface exchange sites, readily oxidized, and potentially mobile to groundwater, strontium-87/86 data were not included within the SSA.

G.2.4.2.5. Wells in Weathered Bedrock

Consistent with regional studies (Smith and others, 2014), most bedrock in Hinkley and Water Valleys is low in chromium (chapter B, table B.3). Water in most bedrock wells in Hinkley Valley sampled as part of this study did not contain measurable dissolved oxygen at the SRL of 0.2 mg/L, and most Cr(VI) concentrations were near the SRL of 0.1 µg/L (chapter E, appendix E.1, table E.1.1). The Cr(VI) in water from most bedrock and weathered bedrock wells was scored as natural in the SSA (appendix G.1, table G.1.1).

In contrast to most bedrock wells, MW-153S in the western subarea (fig. G.1) was completed in weathered hornblende diorite (chapter B, fig. B.9). Hornblende diorite that crops out on Iron Mountain has chromium concentrations as high as 530 mg/kg (chapter B, table B.3). Core material adjacent to the screened interval of well MW-153S had chromium concentrations as high as 405 mg/kg and manganese concentrations as high as 4,940 mg/kg (Groover and Izbicki, 2018). These values exceeded the summative-scale threshold concentrations for chromium and manganese of 85 and 970 mg/kg, respectively (table G.1), and were the highest chromium and manganese concentrations measured in core material adjacent to the screened interval of a sampled well (Groover and Izbicki, 2018). Magnetite was not detected by SEM within heavy mineral separates in core material from well MW-153S (Morrison and others, 2018), and hornblende, which is more easily weathered than magnetite, was the primary chromium-containing mineral. Although only 14 percent of measured chromium was extractable from exchange sites on the surfaces of mineral grains (chapter C, fig. C.17), core material adjacent to the screened interval of well MW-153S had the highest concentration of extractable chromium outside the summative-scale Cr(VI) plume. Extractable concentrations were high because of the high chromium concentrations in core material.

Despite the high concentrations of chromium and manganese in core material and their potential availability to groundwater, the Cr(VI) concentration in water from well MW-153S was only 3.3 µg/L in March 2015. This concentration is only slightly greater than the 2007 interim regulatory Cr(VI) background concentration of 3.1 µg/L (CH2M Hill, 2007; Lahontan Regional Water Quality Control Board, 2008). However, regulatory Cr(VI) concentrations in water from well MW-153S have been as high as 7.6 µg/L. The summative-scale score for well MW-153S of −63 percent was consistent with natural Cr(VI) (appendix G.1, table G.1.1).

Water from well MW-153S was oxic with a dissolved-oxygen concentration of 6.6 mg/L (chapter E, appendix E.1, table E.1.1); the pH was 7.5, and measured Cr(VI) concentrations had a greater than 30-percent probability of natural occurrence at the measured pH (chapter E, fig. E.18*B*). Water from well MW-153S did not contain measurable tritium at the SRL of 0.05 TU and had a carbon-14 activity of 80 pmc (chapter E, appendix E.1, table E.1.1), consistent with recharge before Cr(VI) releases from the Hinkley compressor station and with summative-scale scores consistent with natural Cr(VI) sources. Concentrations of Cr(VI) in water from well MW-153S may represent an upper limit on natural Cr(VI) concentrations, controlled by pH, in water from wells in contact with hornblende diorite in the western subarea. These data indicate that in addition to chromium abundance in geologic materials, geochemical conditions within aquifers also controls natural Cr(VI) concentrations in water from wells.

Under conditions at the time of this study (2015–18), saturated unconsolidated deposits in much of the western subarea were a thin veneer (commonly less than 10 ft thick) overlying weathered bedrock. Weathering and redistribution of chromium from weathered hornblende diorite bedrock may have contributed chromium to visually abundant iron- and manganese-oxide coatings that have accumulated on the surfaces of mineral grains in shallower wells, including well MW-121D, completed in Mojave-type deposits (chapter C, fig. C.13*B*). Redistribution of chromium from weathered hornblende diorite bedrock to iron and manganese oxides that form naturally near geologic contacts may increase the mobility of chromium to groundwater in materials that would otherwise have low-chromium concentrations.

G.2.4.3. Wells That Do Not Have Identifiable Sources of High Natural Chromium

Most wells identified as containing natural Cr(VI) have identifiable sources of chromium in core material and aqueous geochemistry (including groundwater age) that can contribute to Cr(VI) in groundwater. Wells downgradient from the western excavation site in the western subarea and well MW-97S in the northern subarea have high Cr(VI) concentrations but do not have identifiable sources of chromium in core material or aqueous geochemistry that can contribute Cr(VI) to groundwater. These wells are described in the following sections.

G.2.4.3.1. Wells Downgradient from the Western Excavation Site

The western excavation site (fig. G.1), on property owned by PG&E, was used as an illegal disposal site by unknown parties. Anthropogenic constituents including diesel degradants, industrial compounds, and metals were present at the site and in groundwater downgradient from the site; however, Cr(VI) releases at the western excavation site have not been confirmed by regulatory agencies (Lahontan Regional Water Quality Control Board, 2014).

Concentrations of Cr(VI) in water from wells MW-159S, MW-159D, and MW-163S, downgradient from the western excavation site (fig. G.1), ranged from 5.3 to 10 µg/L in March 2015 and March 2017 (chapter E, appendix E.1, table E.1.1); regulatory Cr(VI) data from these wells were within similar ranges. Although not diagnostic of Cr(VI) sources, concentrations of Cr(VI) were highest in water from well MW-163S, closest to the western excavation site, and Cr(VI) concentrations and delta chromium-53 compositions in water from downgradient wells are consistent with fractionation of chromium in water from well MW-163S and mixing with water from well MW-158SR farther downgradient (chapter F, fig. F.26*B*). Despite high Cr(VI) concentrations, summative-scale scores for these wells were +25 percent, and the wells were not included within the summative-scale Cr(VI) plume (fig. G.2); however, alternative (natural) summative-scale scores for wells MW-159S and MW-159D were 0 percent and were consistent with anthropogenic Cr(VI) (fig. G.4; appendix G.1, table G.1.1). Concentrations of Cr(VI) in water from deeper wells downgradient from the western excavation site (including well MW-163D completed in lacustrine deposits) and well MW-159C (completed in granitic bedrock underlying wells MW-159S and MW-159D and not shown on fig. G.2) were less than the SRL of 0.1 µg/L. Water from these wells had dissolved-oxygen concentrations of less than the SRL of 0.2 mg/L (chapter E, appendix E.1, table E.1.1) and would not be expected to contain Cr(VI).

Water from wells MW-159S, MW-159D, and MW-163S, completed in older Mojave River alluvium, was oxic and alkaline with pH values ranging from 7.5 to 7.9. The probability of these measured Cr(VI) concentrations occurring naturally at the pH of water from wells MW-159S and MW-159D was between 10 and 20 percent, and the probability of the measured Cr(VI) concentrations occurring naturally at the pH of water from well MW-163S was less than 10 percent (chapter E, fig. E.17).

Concentrations of Cr(VI) in the nearest monitoring wells, BG-0002, BG-0003A, and BG-0003B, in older Mojave River alluvium upgradient from the western excavation site did not exceed 2.5 µg/L (fig. G.1), and the probability of the measured Cr(VI) concentrations occurring naturally at the pH of water from these wells was greater than 30 percent (chapter E, fig. E.18*B*). Similarly, Cr(VI) concentrations in water from 22 wells completed in older Mojave River deposits along the Mojave River upstream from Hinkley Valley do not exceed 4 µg/L (Metzger and others, 2015), and the probability of the measured Cr(VI) concentrations occurring naturally at the measured pH of water from these wells was greater than 30 percent.

The Mojave River entered Hinkley Valley south of Iron Mountain about 500,000 ybp (chapter A, fig. A.5). Chromium concentrations in Mojave-type deposits in the western subarea are commonly higher than concentrations elsewhere in Hinkley Valley (chapter B, fig. B.7) because of chromium-containing actinolite within these deposits (chapter C, fig. C.9*A*). Actinolite mineral grains eroded from the San Gabriel Mountains 40 mi to the southwest and transported to Hinkley Valley by the Mojave River (Groover and Izbicki, 2019) were rounded and showed evidence of weathering (chapter C, fig. C.9*A*). Chromium-containing hornblende also was identified in core material from wells downgradient from the western excavation site (chapter C, fig. C.9*B*). Hornblende mineral grains were angular and relatively unweathered, consistent with erosion, and limited transport from local sources within Iron Mountain. Older Mojave River alluvium from sites MW-159 and MW-163 contained trace amounts of unidentified opaque metamorphic minerals (chapter C, fig. C.9*B*), possibly associated with metavolcanics that crop out on the southern end of Iron Mountain. These materials do not contain high chromium concentrations (chapter B, table B.3).

Although chromium-containing actinolite and hornblende minerals were identified, chromium concentrations in core material adjacent to the screened intervals of wells MW-159S, MW-159D, and MW-163S were less than 30 mg/kg (chapter C, fig. C.26), and manganese concentrations in those same core materials did not exceed 464 mg/kg (Groover and Izbicki, 2018). Chromium and manganese concentrations in core material adjacent to the screened intervals of wells MW-159S, MW-159D, and MW-163S were below summative-scale thresholds of 85 and 970 mg/kg for chromium and manganese, respectively (table G.1). Test drilling at well MW-159C penetrated weathered granitic rock that had low chromium concentrations of 22 mg/kg, rather than weathered hornblende diorite that underlies much of the western subarea; bedrock knobs near the western excavation site also had similar low-chromium concentrations (chapter B, table B.3).

Most of the chromium in core material adjacent to the screened intervals of wells MW-159S and MW-163S, downgradient from the western excavation site, was within the heavy (dense) mineral fraction composed of magnetite mineral grains that are resistive to weathering (chapter C, fig. C.26). Additional core material analyzed at these sites had similar composition (Morrison and others, 2018). Less than 13 percent of the chromium in core material adjacent to the screened intervals of wells MW-159S and MW-163S was weathered from primary minerals and extractable from exchange sites on the surfaces of mineral grains, and potentially available to groundwater (chapter C, fig. C.26).

The western excavation site is managed separately from Cr(VI) releases at the Hinkley compressor station, and Cr(VI) releases at the site have not been confirmed by regulatory agencies (Lahontan Regional Water Quality Control Board, 2014). However, given the unusually high Cr(VI) concentrations in water from wells downgradient from the western excavation site and the absence of a plausible natural source of chromium for these high concentrations, Cr(VI) concentrations in water from wells MW-159S, MW-159D, and MW-163S were not used for the calculation of background Cr(VI) concentrations.

G.2.4.3.2. Well MW-97S in the Northern Subarea

Concentrations of Cr(VI) in water from well MW-97S (fig. G.1), sampled as part of this study, were 2.7 µg/L in March 2015 and increased to 4.7 µg/L in November 2017 (chapter E, appendix E.1, table E.1.1). This increase is consistent with upward Cr(VI) concentration trends in regulatory data in water from well MW-97S between July 2012 and June 2017 (chapter D, fig. D.9). Regulatory Cr(VI) concentrations in water from well MW-97S increased from 1.8 µg/L in February 2011, shortly after the well was installed, to as high as 7.0 µg/L in October 2016. Summative-scale scores for well MW-97S increased from +25 percent in March 2015 to +71 percent in November 2017 (appendix G.1, table G.1.1). The November 2017 score (shown in fig. G.2) was used to draw the summative-scale Cr(VI) plume extent, and Cr(VI) in water from well MW-97S was interpreted as anthropogenic for the purposes of calculation of background Cr(VI) concentrations.

Unlike most wells in Hinkley and Water Valleys, increasing Cr(VI) concentrations in water from well MW-97S were accompanied by increasing water levels (chapter D, fig. D.9). Specific conductance values in both samples from well MW-97S, 415 and 394 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C) in March 2015 and November 2017, respectively, were low (chapter E, appendix E.1, table E.1.1). Water from well MW-97S was apparently not affected by irrigation return and differed from water in nearby wells within the Q4 2015 regulatory Cr(VI) plume. Tritium was not detected in water from well MW-97S in March 2015, and the carbon-14 activity of 80 pmc indicates that water from the well was recharged before 1952. Tritium was not measured in November 2017, and carbon-14 activities were unchanged. Well MW-97S is the only well within the summative-scale Cr(VI) plume that does not contain post-1952 water having detectable tritium and would contain Cr(VI) released from the Hinkley compressor station prior to recharge from the Mojave River in 1958. Water from well MW-97S sampled in November 2017 containing Cr(VI) may represent the leading edge of Cr(VI) released from the Hinkley compressor station beginning in 1952.

Well MW-97S is completed primarily in fine-textured Mojave-type deposits and penetrated mudflat/playa deposits (Miller and others, 2020). These materials overlie weathered dacitic volcanic bedrock. Chromium concentrations in aquifer materials penetrated by well MW-97S were as high as 70 mg/kg but did not exceed the summative-scale threshold for chromium of 85 mg/kg; manganese concentrations were as high as 1,930 mg/kg and exceeded the summative-scale threshold for manganese of 970 mg/kg (chapter B, fig. B.11). Chromium concentrations in underlying dacitic rock in the study area have a median concentration of 28 mg/kg (chapter B, table B.3), and concentrations were less than the average continental chromium abundance of 185 mg/kg (Reimann and de Caritat, 1998). Concentrations of Cr(VI) in porewater pressure extracted from fresh core material near site MW-97 at a depth of 97 ft bls were 0.9 µg/L (chapter E, table E.6). A higher Cr(VI) concentration of 2.7 µg/L was extracted from core material collected at a depth of 82 ft bls in April 2018. This material would have been unsaturated in March 2015 when the well was first sampled as part of this study. The delta oxygen-18 and delta deuterium isotope composition of porewater at 82 ft bls was affected by evaporation (chapter E, table E.6) and was consistent with the delta oxygen-18 and delta deuterium composition of water in the Q4 2015 regulatory Cr(VI) plume. Additionally, changes in the trace-element assemblage in water from well MW-97S (chapter E, fig. E.20), consistent with anthropogenic Cr(VI) in water from well MW-97S, were measured between March 2015 and November 2017.

The SSA did not identify Cr(VI) in water from well MW-97S as anthropogenic in March 2015 but did identify Cr(VI) in water from this well as anthropogenic in November 2017. The presence of anthropogenic Cr(VI) in water from well MW-97S is consistent with low-chromium concentrations in geologic materials, including underlying dacitic rock at this site. Alternatively, it is possible that Cr(VI) in water from well MW-97S could be attributed to the poor sorption and high mobility of the chromate oxyanion at pH values as high as 9.0 in water from well MW-97S. Continued Cr(VI) regulatory data collection accompanied by field measurements of specific conductance and pH may provide additional information on the source of Cr(VI) in water from well MW-97S.

G.2.5. Limitations and Use of Summative-Scale Results

The SSA identified natural and anthropogenic Cr(VI) in water from wells in a wide range of geologic and geochemical settings in Hinkley and Water Valleys for the period March 2015 through November 2017. Results of the SSA included wells within the Q4 2015 regulatory Cr(VI) plume and excluded deeper wells MW-79D and MW-128S3 within the footprint of the Q4 2015 regulatory Cr(VI) plume. The summative-scale Cr(VI) plume included 5.5 mi^2 of Hinkley Valley and lies within Mojave-type deposits. The extent of the summative-scale Cr(VI) plume included an additional 2.5 mi^2 in the eastern subarea and 0.7 mi^2 in the northern subarea not included within the Q4 2015 regulatory Cr(VI) plume. For comparison, the maximum mapped extent of groundwater having a Cr(VI) concentration greater than the interim Cr(VI) background concentration of 3.1 µg/L was 8.3 mi^2 (ARCADIS, 2016).

Areas outside the Q4 2015 regulatory Cr(VI) plume that were included within the summative-scale Cr(VI) plume were included largely on the basis of geochemical questions within the summative scale that addressed pH-dependent sorptive processes for Cr(VI) and other trace elements (table G.1, questions 5 and 6). On the basis of these questions, some wells having water with a slightly acidic to neutral pH in the eastern subarea and having Cr(VI) concentrations less than the 3.1 µg/L regulatory Cr(VI) background value, were included within the summative-scale Cr(VI) plume. Conversely, some wells having alkaline water in the western and northern subareas of Hinkley Valley and in Water Valley and having Cr(VI) concentrations greater than 3.1 µg/L that otherwise would have been identified as anthropogenic, were not included within the summative-scale Cr(VI) plume. Differences in sorption of Cr(VI), and other trace elements, with pH are well founded from a geochemical basis, and of all the questions within the scale, question 5 is potentially the most relevant for decision makers. Both Cr(VI) and pH are measured quarterly as part of regulatory data collection and can be used in the future to provide information on the natural or anthropogenic source of Cr(VI) in water from wells in the absence of the geologic, lithologic, chemical, and isotopic data collected as part of this study.

Summative-scale scores were consistent with other mineralogic and geochemical data collected as part of this study that were not included within the SSA. However, limitations in the summative-scale approach result from well selection, the formulation and precision of questions within the scale, and the metrics and procedures used to score answers to those questions.

Wells were selected for sample collection as part of this study in consultation with the TWG. Consultation with the TWG ensured wells important to local stakeholders were included in this study; however, the selection process resulted in a positive bias toward a selection of wells having higher Cr(VI) concentrations or upward concentration trends in favor of wells having lower Cr(VI) concentrations or downward concentration trends. Additionally, wells were often selected for reasons other than their eventual inclusion within the summative scale. As a result of the well selection process, it was not possible to collect data to answer and score every question within the summative scale, for every sampled well. For example, core material was not available from older monitoring wells drilled before 2011 or from domestic wells, and handheld X-ray fluorescence (pXRF) data could not be collected for chromium or manganese concentrations in core material adjacent to the screened interval of those wells; however, texture could be evaluated from drillers' or geologists' logs if available. In addition, it was not possible to calculate Cr(VI) concentration trends for newer monitoring wells installed after 2014 because of insufficient data. Although not all sampled wells had data to answer every question within the summative scale, data availability did not preclude the use of the summative scale to evaluate data collected as part of this study; 68 percent of sampled wells had data to answer all questions within the summative scale, and 96 percent of sampled wells had data to answer six of the eight questions within the scale.

Questions within the summative scale (table G.1) were formulated on the basis of data that could be readily collected at a large number of wells to answer those questions; consequently, the questions that compose the scale are not necessarily inclusive of all data that could have been collected or inclusive of all metrics that may discriminate between anthropogenic and natural Cr(VI) in groundwater. A different study design may have collected different data that may have supported inclusion of different questions within a summative scale. For example, the most relevant predictor of Cr(VI) concentrations in groundwater measured as part of this study may be the concentration of chromium sorbed on the surfaces of mineral grains, especially within the mobile weakly sorbed, specifically sorbed, and amorphous extractable fractions (Chao and Sanzolone, 1989; Wenzel and others, 2001; chapter C, appendix C.1, table C.1.1). Similarly, Raman and XANES spectroscopy describing the surface properties of sorbed materials on the surfaces of mineral grains collected as part of this study, especially the oxidation state of manganese oxides, may be relevant predictors of Cr(VI) concentrations in groundwater. However, these data could not be collected from core material for the large number of wells sampled as part of this study. The descriptor "visually abundant iron and manganese oxides" used to describe these surface coatings was too qualitative for inclusion within the summative scale, and oxide coatings within core materials may not have been consistently described for use in this study (Groover and Izbicki, 2018).

The pXRF measurements collected as part of this study (Groover and Izbicki, 2018), include elemental concentrations within mineral grains; the pXRF measurements also include the chromium and manganese concentrations of oxide coatings on the surfaces of mineral grains. Although somewhat imprecise, these metrics were included within questions 2 and 3 of the summative scale. A more precise metric describing the effect of sorbed materials on the surfaces of mineral grains on aqueous Cr(VI) concentrations in groundwater was provided probabilistically by question 5 within the summative scale, which addressed the occurrence of Cr(VI) in groundwater relative to the measured pH of water from sampled wells (chapter E, fig. E.17). In contrast to pH controls on aqueous Cr(VI) concentrations, almost all water from wells in Hinkley and Water Valleys was oxic, and measures of the redox status of sampled wells, such as oxidation-reduction potential or dissolved-oxygen concentrations, were not included within the summative scale developed for this study. In a different setting, questions addressing the redox status of groundwater may be important.

Some questions within the summative scale were imprecise with respect to the origin of natural or anthropogenic Cr(VI) in water from wells. For example, although all groundwater containing anthropogenic Cr(VI) would have originated as recharge from the Mojave River, not all groundwater recharged from the Mojave River passed near the Hinkley compressor station and would contain anthropogenic Cr(VI). Similarly, although groundwater containing anthropogenic Cr(VI) would largely have been recharged after 1952 and would contain tritium, not all tritium-containing groundwater passed near the Hinkley compressor station, and not all tritium-containing groundwater would contain anthropogenic Cr(VI). Alternative anthropogenic and natural formulations of the summative scale (table G.2) were developed to address imprecision associated with groundwater-source and -age data.

The metrics used to establish threshold values to answer questions within the summative scale were quantitative and established from analyses of data presented in chapters B through F within this professional paper. All stakeholders using the questions and metrics within the summative scale would score each well the same way and would draw the same summative-scale Cr(VI) plume extent; however, not all stakeholders may choose to use the same metrics for each question, even when using the same data. For example, the threshold values for chromium and manganese abundance in core material of 85 and 970 mg/kg, respectively, for questions 2 and 3 of the summative scale (table G.1) were selected from identifiable features within a log-normal data distribution using a standard approach from the literature (chapter B, fig. B.11*A*, *B*). It also may have been defensible to use literature values for the average bulk continental abundance of chromium and manganese of 185 and 1,400 mg/kg, respectively (Reimann and de Caritat, 1998), as the threshold values for questions 2 and 3 within the summative scale; resulting in fewer wells scored as having high natural chromium or manganese concentrations in core material.

Finally, the +1 and −1 scoring for questions within the summative scale may obscure anthropogenic Cr(VI) in some settings. Alternative anthropogenic and natural formulations of the summative scale addressed scoring issues associated with the summative scale.

Additional analyses may reveal additional questions and metrics for those questions that could improve the SSA and produce a different summative-scale Cr(VI) plume extent. For example, strontium-87/86 isotope data used to evaluate summative scale results could have been formulated into a question within the summative scale to evaluate the presence of Miocene material that may have weathered to release Cr(VI) to groundwater on the basis of nonradiogenic strontium-87/86 ratios in water from wells. In contrast, delta chromium-53 isotope data used to evaluate reductive fractionation of anthropogenic Cr(VI) within the Q4 2015 regulatory Cr(VI) plume and the fractionation of chromium from selected natural endmembers, would likely prove too complex for a simple binary analysis within a summative scale.

Aquifer materials, including chromium-containing minerals and chromium sorbed to the surfaces of mineral grains, and groundwater are a single system, and scores for questions within the summative scale are not strictly independent measures of natural or anthropogenic Cr(VI) occurrence in groundwater. For example, three questions within the summative scale (table G.1, questions 1, 2, and 3) address geologic aspects of aquifer materials that may affect Cr(VI) occurrence in groundwater. Scores for these questions are not independent; chromium and manganese within aquifer materials are positively correlated (chapter B, fig. B.12), and concentrations of both elements are significantly higher in silt and finer textured material than in coarser sand textured material (chapter B, fig. B.8). Presumably, wells such as MW-121D, completed in fine-textured aquifer material having chromium and manganese concentrations greater than their respective summative-scale threshold values, would be more likely to have natural Cr(VI) than wells completed in material lacking one or more of these metrics. Similarly, hydrologic and geochemical questions also are not strictly independent. Water from wells with older groundwater also has alkaline pH as a result of long contact times with aquifer materials and weathering of silicate minerals (table G.1, questions 5 and 8). Summative-scale scores for wells such as MW-203D, completed in partly consolidated weathered Miocene deposits underlying the western subarea, with a pH of 8.3, a carbon-14 activity of 14 pmc, and an unadjusted age of more than 16,000 ybp, are consistent with natural Cr(VI) concentrations as high as 10 µg/L.

The SSA identified natural and anthropogenic Cr(VI) in water from wells in a wide range of geologic, geochemical, and hydrologic settings in Hinkley and Water Valleys; however, the summative-scale Cr(VI) plume does not define the extent of anthropogenic Cr(VI) for groundwater management or regulatory purposes. Wells outside the summative-scale Cr(VI) plume (fig. G.2) were used to estimate background Cr(VI) concentrations in section “G.3 Calculation of Hexavalent Chromium Background Concentrations.” Some Cr(VI) concentrations within the summative-scale Cr(VI) plume are low and, although they may contain Cr(VI) released from the Hinkley compressor station, they may not require regulatory attention. An updated regulatory Cr(VI) plume would likely exclude wells having Cr(VI) concentrations less than the background values and would have a smaller extent than the summative-scale Cr(VI) plume.

G.3. Calculation of Hexavalent Chromium Background Concentrations

Data from wells outside the summative-scale Cr(VI) plume extent were used to calculate Cr(VI) background concentrations in Hinkley and Water Valleys. The Cr(VI) background concentrations can be used to inform regulatory decision making regarding (1) updating the regulatory Cr(VI) plume extent and management of Cr(VI) near the plume margins, (2) establishing cleanup goals within the Cr(VI) plume, and (3) improving understanding of natural Cr(VI) concentrations in the different hydrogeologic settings within Hinkley and Water Valleys. The Cr(VI) background concentrations differ in different areas of Hinkley and Water Valleys because of local differences in geology, geochemistry, and hydrology (Izbicki and Groover, 2016). Consequently, in addition to an overall Cr(VI) background concentration, separate Cr(VI) background concentrations were estimated for different areas in Hinkley and Water Valleys.

G.3.1. Methods

The Cr(VI) summative-scale plume lies within Mojave-type deposits in Hinkley Valley. Consequently, the Cr(VI) background concentrations were initially calculated from Cr(VI) data collected from wells completed (screened) in Mojave-type deposits outside the mapped summative-scale Cr(VI) plume extent that were sampled as part of the USGS Cr(VI) background study in the eastern, western, and northern subareas in Hinkley Valley and in Water Valley (fig. G.2). Wells screened in Mojave-type deposits were identified on the basis of their primary provenance and depositional environment (chapter A, table A.1) described by Miller and others (2020; appendix G.1, table G.1.1). Sampled wells were selected with input from the TWG and represent a mutually agreed upon, spatially distributed set of wells covering a range of geologic, geochemical, and hydrologic settings near the PG&E regulatory Cr(VI) plume. These wells have the most complete set of independent geologic, chemical, and isotopic data available.

Additional Cr(VI) background calculations were done using Cr(VI) data collected for regulatory purposes from wells completed in unconsolidated deposits without regard for the provenance or depositional environment in which the well is completed. This dataset included additional wells having suitable Cr(VI) data and is larger than the dataset for Mojave-type deposits; consequently, the results are statistically more robust but have less geologic specificity than Cr(VI) background values calculated for Mojave-type deposits.

G.3.1.1. Data Collection

Data for Cr(VI) background calculations were collected quarterly from Q2 2017 (April–June 2017) through Q1 2018 (January–March 2018) by (1) PG&E from monitoring wells sampled for regulatory purposes (ARCADIS, 2018a, 2019) and (2) the USGS from monitoring wells installed as part of this study and from selected domestic wells (U.S. Geological Survey, 2021). 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). Estimation of Cr(VI) background over periods longer than 1 year would incorporate upward or downward Cr(VI) concentration trends into the data (chapters D and E), complicating the interpretation of Cr(VI) background concentrations. The four quarterly measurements from each well represent a clustered sample design; the consequences of that design are described in section “G.3.1.2 Statistical Approach.”

Wells were sampled according to procedures used by PG&E to collect regulatory data described in chapter E within this professional paper. Water from wells was analyzed for field parameters (including water temperature, dissolved oxygen, specific conductance, and pH), Cr(VI), and Cr(t) (ARCADIS, 2018a, 2019; U.S. Geological Survey, 2021). By design, samples were not affected by the pumping of larger volumes of water required for the more complete chemical and isotopic analyses (including age-dating constituents) of samples collected as part of this study between March 2015 and November 2017 (chapters E and F).

Samples of Cr(VI) and Cr(t) were filtered and preserved onsite and delivered by courier for analysis within 24 hours at the same commercial laboratory used by PG&E for regulatory analyses. The Cr(VI) analyses were done by ion chromatography, Method 218.6 (U.S. Environmental Protection Agency, 1994b), having an LRL of 0.20 µg/L. Low-level analysis for Cr(VI), using a modified version of U.S. Environmental Protection Agency Method 218.6 having an LRL of 0.06 µg/L, was used for samples collected by the USGS. The Cr(t) analyses were done by inductively coupled plasma-mass spectrometry, Method 200.8 (U.S. Environmental Protection Agency, 1994a). The Cr(t) data were not used for calculation of Cr(VI) background values.

Precision and accuracy estimated from 170 field replicates and 55 field blanks collected by PG&E for regulatory purposes between April 2017 and March 2018 were similar to values estimated for PG&E data between March 2015 and November 2017 (chapter E); the SRL for regulatory data was equal to the LRL of 0.2 µg/L, and the precision was about 6 percent at the mean value of 4.2 µg/L. The Cr(VI) data used to calculate background values are comparable to data collected by PG&E for regulatory purposes.

G.3.1.2. Statistical Approach

The Cr(VI) background concentrations were calculated as the upper 95-percent tolerance limit (UTL_{95}) using the computer program ProUCL 5.1 (Singh and Maichle, 2015). The UTL_{95} is the value below which 95 percent of the concentrations are expected to fall with 95-percent confidence (Singh and Singh, 2015). ProUCL compares measured data to normal, lognormal, and gamma distributions (fig. G.5*A*) and estimates the UTL_{95} value from statistical metrics for those distributions. ProUCL provides results of statistical tests that describe which distribution(s), if any, fit the measured data, while also controlling for type-I (false positive) and type-II (false negative) statistical errors at levels specified by the user. For the purposes of the Cr(VI) background calculations, type-I and type-II errors were controlled at a significance criterion of α=0.05 and β=0.05, respectively. ProUCL also estimates the UTL_{95} value using nonparametric methods that do not assume a distribution for the data and uses bootstrap approximation (Efron and Tibshirani, 1993) to control type-II errors for nonparametric UTL_{95} estimates. ProUCL provides an estimate of the type-II error obtained without bootstrap approximation and the amount of data that would be needed to control type-II errors at the specified significance criteria without bootstrap approximation. These estimates provide an understanding of how many additional data would be required to improve confidence in the UTL_{95} estimate. The user decides on the basis of results from statistical tests included in ProUCL which distributional fit, or nonparametric method, is appropriate for estimates of the UTL_{95} value.

Water from most wells was oxic, and only a few wells had Cr(VI) concentrations less than the SRL. Concentrations of Cr(VI) less than the SRL were associated with reduced groundwater, where Cr(VI) is reduced to Cr(III) and removed from groundwater. This differs from nondetections (“less than” values) for many other constituents in which the constituent may be present but was not detected using available analytical techniques. Simple substitution of nondetect values with a single low value of 0.001 µg/L was used for the calculation of UTL_{95}. The UTL_{95} was insensitive to the low value selected as long as a nonzero value was used. Alternative approaches that estimate the statistical distribution of nondetect values (Singh and others, 2006; Daniel, 2015) were not used in this study.

ProUCL controls for type-I and type-II statistical errors, and UTL_{95} values are higher than values for the upper 95-percent confidence limit (Neter and Wasserman, 1974) that only controls for type-I errors. Because ProUCL controls for type-I and type-II errors, users can be 95-percent confident that 95 percent of the background Cr(VI) concentrations in Hinkley and Water Valleys are less than the UTL_{95} value. However, given enough data, some natural Cr(VI) concentrations would exceed the Cr(VI) UTL_{95} value by chance alone.

The clustered sample design used for background data collection, in which four data points were collected from each well between Q2 2017 and Q1 2018, affected the calculation of UTL_{95} values. The summative-scale Cr(VI) plume lies within low-chromium Mojave-type deposits. Initially, the UTL_{95} value for each subarea was calculated for sampled wells screened within Mojave-type deposits outside the summative-scale Cr(VI) plume extent using all four quarterly data points; however, given the clustered sample design, these four measurements are not strictly independent and are potentially correlated. In ProUCL, the effect of the clustered sample design and the correlation of quarterly data from sampled wells was to overestimate the sample size. This overestimation yields lower values for UTL_{95} estimates fit to normal, lognormal, or gamma model distributions and may overestimate control of type-II errors for nonparametric UTL_{95} values; consequently, UTL_{95} values for wells completed in Mojave-type deposits within each subarea were calculated using the median value from each well.

The U.S. Environmental Protection Agency (2009) recommends that at least 10 data points be used to estimate UTL_{95} values, and some agencies recommend as many as 20 data points be used (Connecticut Department of Energy and Environmental Protection, 2014; Idaho Department of Environmental Quality, 2014). Not all subareas had enough median values from quarterly samples to robustly estimate the UTL_{95} values for Mojave-type deposits, although there were enough data to estimate the overall UTL_{95} value for Mojave-type deposits in Hinkley and Water Valleys.

To address data limitations, Cr(VI) UTL_{95} values also were estimated from the median of quarterly regulatory data collected from Q2 2017 through Q1 2018 from other available PG&E monitoring wells. Although drillers’ and geologists’ logs are available, the provenance of drill cuttings (Mojave-type deposits, including stream and lake-margin deposits sourced from the Mojave River, versus non-Mojave-type deposits, including lacustrine, local alluvium, mudflat/playa, and groundwater-discharge deposits) from these additional wells was not described as part of this study by Miller and others (2020). These additional regulatory wells are described as completed in “undifferentiated, unconsolidated deposits.” Although the regulatory dataset has more data points and UTL_{95} values are more robustly estimated, these values have less geologic specificity than the UTL_{95} values calculated for Mojave-type deposits.

Results of the various calculations were compared and contrasted to select appropriate UTL_{95} values for background Cr(VI) in water from wells in individual subareas in Hinkley and Water Valleys. This approach is consistent with guidance from the U.S. Environmental Protection Agency (2009) that states the user is responsible for selection of appropriate fits to model distributions.

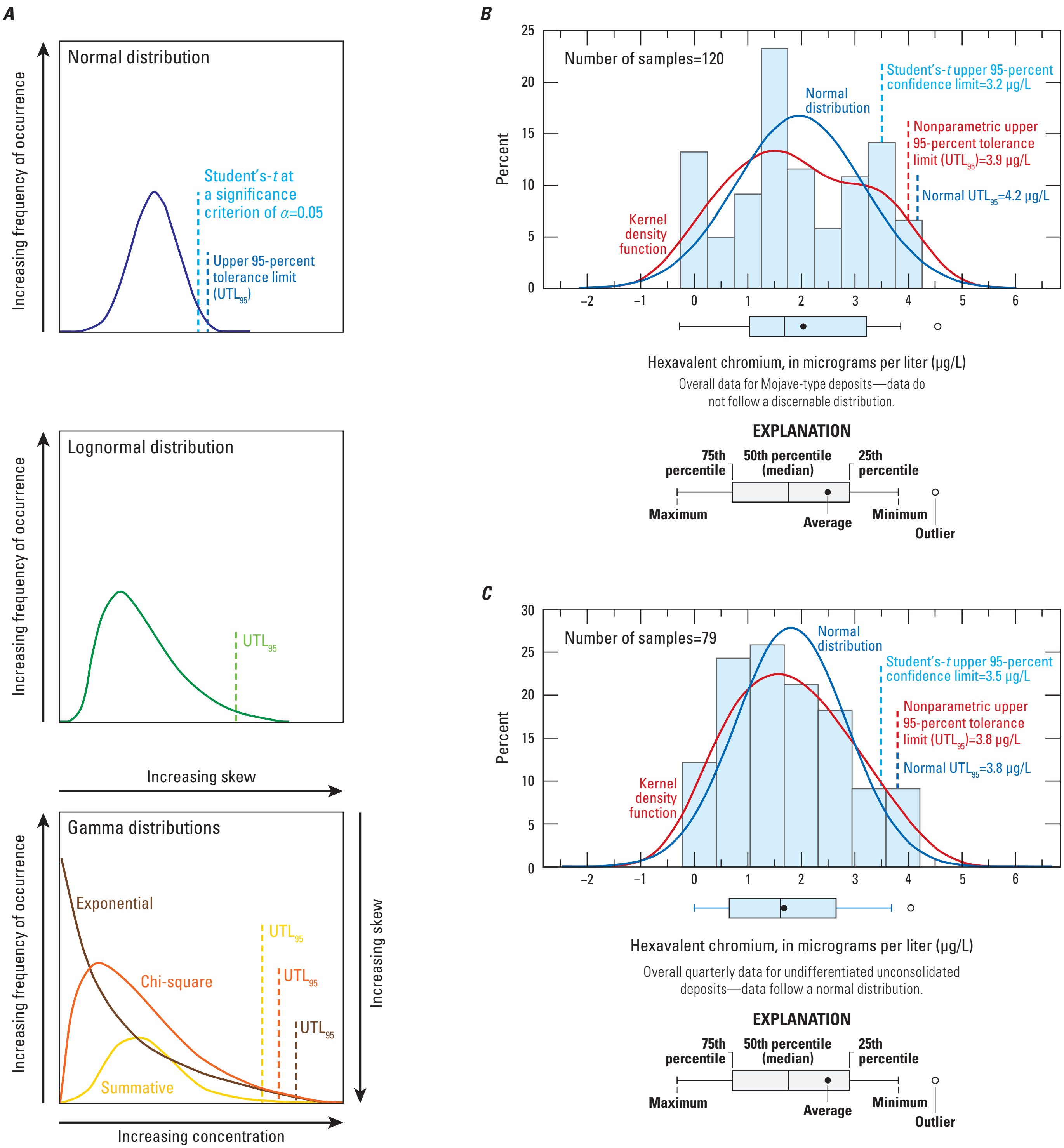


Figure G.5. Upper 95-percent tolerance limits for different data distributions, Hinkley and Water Valleys, western Mojave Desert, California, April 2017 through March 2018. *A*, selected probability density functions; *B*, measured data with a nonparametric distribution; *C*, measured data approximately fit to the normal distribution. Upper 95-percent tolerance limits were calculated from data in ARCADIS (2018a, 2019) and U.S. Geological Survey (2021).

G.3.2. Hexavalent Chromium Background Concentrations for Mojave-Type Deposits

The mapped summative-scale Cr(VI) plume lies within Mojave-type deposits in Hinkley Valley (fig. G.2); therefore, Cr(VI) UTL_{95} values were initially calculated for water from wells completed in Mojave-type deposits in the eastern, western, and northern (including Water Valley) subareas using quarterly data from Q2 2017 through Q1 2018 (table G.3). Concentrations of Cr(VI) in water from 29 wells ranged from less than 0.2 to 4.0 µg/L (fig. G.6), and the median concentration was 1.9 µg/L. Data used to calculate the UTL_{95} values for Mojave-type deposits in Hinkley and Water Valleys are provided in appendix G.2 (table G.2.1).

The nonparametric Cr(VI) UTL_{95} values calculated from quarterly data for Mojave-type deposits in the eastern, western, and northern (including Water Valley) subareas were 3.7, 3.9, and 4.0 µg/L, respectively, with an overall nonparametric UTL_{95} value of 3.9 µg/L (table G.3). Control of type-II errors for nonparametric UTL_{95} values without bootstrap approximation ranged from 70 to 90 percent; data availability in the eastern and western subareas would need to almost double to control type-II error at β=0.05 without bootstrap approximation (table G.3). A nonparametric UTL_{95} value of 2.3 µg/L was calculated from quarterly data from selected wells (table G.3) for Mojave-type deposits downgradient from the Hinkley compressor station. This value reflects background Cr(VI) concentrations in coarse-textured, low-chromium Mojave-type deposits containing neutral to slightly alkaline, post-1952 groundwater in this area and may be a suitable metric for Cr(VI) cleanup goals within the regulatory Cr(VI) plume after its extent has been updated. The data did not fit normal, lognormal, or gamma distributions. Although UTL_{95} values for the different subareas are similar, the distributions of concentration data in the eastern and western subareas were significantly different from the generally higher distribution of concentrations in the northern subarea on the basis of the Kolmogorov-Smirnov *D*-statistic (Arnold and Emerson, 2011) at a significance criterion of α=0.05 (fig. G.6).

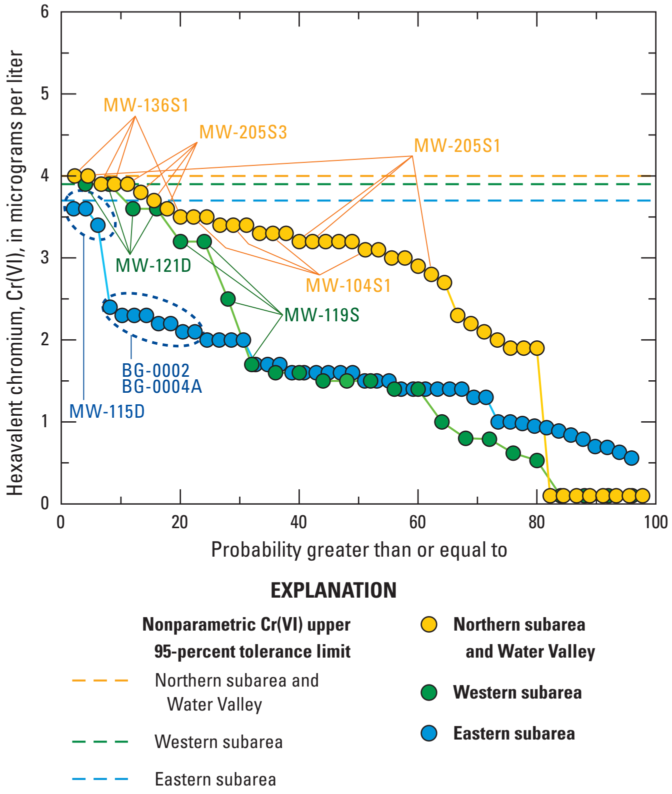
The Cr(VI) UTL_{95} values also were calculated from the median of quarterly data. The normal UTL_{95} value calculated for the eastern subarea was 3.8 µg/L. The western subarea did not have enough data to robustly estimate the UTL_{95} value. Data in the northern subarea did not fit a normal distribution and had a nonparametric Cr(VI) UTL_{95} value of 4.0 µg/L. The values for the eastern and northern subareas are similar to nonparametric UTL_{95} values estimated from quarterly data. The overall nonparametric Cr(VI) UTL_{95} value estimated from the median of the quarterly data of 3.9 µg/L was the same as the nonparametric UTL_{95} value estimated from quarterly data (table G.3).

Table G.3. Upper 95-percent tolerance limit for hexavalent chromium, Cr(VI), background concentrations in water from wells screened in Mojave-type deposits in the eastern, western, and northern subareas (including Water Valley), 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/ and data from U.S. Geological Survey (2021). Data are available in appendix G.2 (table G.2.1).

[Mojave-type deposits include Mojave River alluvium and near-shore lake deposits sourced from the Mojave River. The upper 95-percent tolerance limit (UTL_{95}), calculated using quarterly data from selected wells using the computer program ProUCL 5.1 (Singh and Maichle, 2015), except the overall UTL_{95} value, which also was calculated from the median of quarterly data from selected wells. Type-I error is the probability of a false positive at the specified confidence level. Type-II error is the probability of a false negative at the specified confidence level. **Abbreviations**: µg/L, microgram per liter]

Subarea	Number of samples	Number of wells	UTL_{95}, in µg/L	Maximum Cr(VI), in µg/L	Model distribution	Confidence associated with type-II error without bootstrap approximation, in percent	Number of samples to control type-II error at 95-percent confidence without bootstrap approximation
Eastern[1]	48	12	3.7	3.7	Nonparametric	70	93
Western	24	6	3.9	3.9	Nonparametric	71	59
Northern	44	11	4.0	4.0	Nonparametric	90	59
Updated regulatory Cr(VI) plume extent	52	13	2.3	2.4	Nonparametric	74	93
Overall	116	29	3.9	4.0	Nonparametric	84	153
	29	29	3.9	3.9	Nonparametric	79	59

[1] Background concentrations of Cr(VI) in the eastern subarea reflect Cr(VI) concentrations in mudflat/playa deposits penetrated by wells MW-115S and MW-115D near Mount General. These deposits do not reflect Cr(VI) concentrations in Mojave-type deposits elsewhere in the eastern subarea that do not exceed 2.3 µg/L and would have a (nonparametric) UTL_{95} of 2.4 µg/L if wells MW-115S and MW-115D were not included in the calculation.



Date distributions in the eastern and western subareas are significantly different from the data distribution in the northern subarea on the basis of the Kolmogorov-Smirnov *D*-statistic (Arnold and Emerson, 2011) at a significance criterion of α=0.05.

Figure G.6. Estimated distribution functions for hexavalent chromium concentrations for quarterly samples of water from wells completed in Mojave-type deposits from selected areas in Hinkley and Water Valleys, western Mojave Desert, California, April 2017 through March 2018. Estimated distribution functions 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 appendix G.2 (table G.2.1).

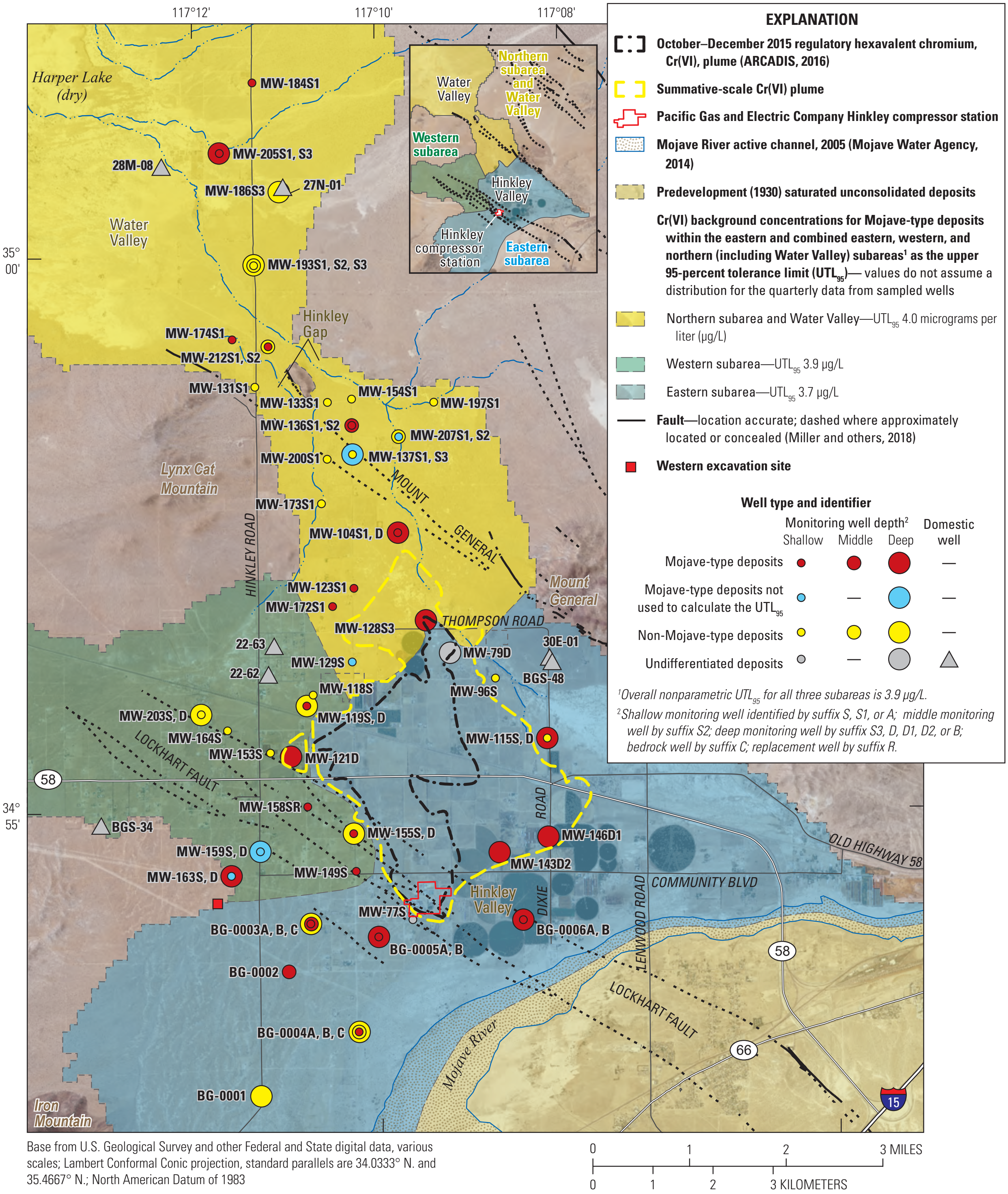
More than 100 wells were sampled and analyzed for a range of chemical and isotopic constituents, including age-dating constituents, as part of the USGS Cr(VI) background study. To the extent possible, core material adjacent to the screened interval of sampled wells was described and analyzed for chromium, manganese, and other trace elements. These data represent the most complete independent set of data available to assess the extent of anthropogenic and natural Cr(VI) in Hinkley and Water Valleys. Details of UTL_{95} calculations in the various subareas in Hinkley and Water Valleys, including descriptions of wells and geologic, geochemical, and hydrologic conditions that control UTL_{95} values in each subarea, are provided in the following sections.

G.3.2.1. Eastern Subarea

In the eastern subarea, 22 wells sampled as part of the USGS Cr(VI) background study were outside the summative-scale Cr(VI) plume (fig. G.7). Data from 12 wells completed in Mojave-type deposits were selected for calculation of UTL_{95} values (appendix G.2, table G.2.1). Concentrations of Cr(VI) in 48 samples collected quarterly from these wells from Q2 2017 through Q1 2018 ranged from 0.56 to 3.7 µg/L (fig. G.6; appendix G.2, table G.2.1), and the median concentration was 1.6 µg/L. The nonparametric Cr(VI) UTL_{95} value for Mojave-type deposits in the eastern subarea calculated on the basis of quarterly data was 3.7 µg/L (table G.3).

Concentrations of Cr(VI) used to calculate the UTL_{95} value in the eastern subarea were highest in water from well MW-115D (fig. G.6). Water from well MW-115D differs from water in most other sampled wells completed in Mojave-type deposits in the eastern subarea in that it does not contain measurable tritium and has a carbon-14 activity of 81 pmc (chapter E, appendix E.1, table E.1.1), with an unadjusted age of 1,750 ybp. Water from well MW-115D is isolated from surface sources of recharge along the Mojave River by intervening mudflat/playa deposits. Concentrations of Cr(VI) in water from wells elsewhere in the eastern subarea do not exceed 2.3 µg/L, and the highest concentrations are in water from wells BG-0002 and BG-0004A (fig. G.6; appendix G.2, table G.2.1). Core material adjacent to the screened intervals of wells BG-0002 and BG-0004A contains visually abundant iron- and manganese-oxide coatings on the surfaces of mineral grains that have developed naturally near the water table and near redox boundaries associated with contacts between different geologic materials (chapter C, fig. C.13*A,B*). Concentrations of Cr(VI) in water from other sampled wells in Mojave-type deposits in the eastern subarea did not exceed 2 µg/L. If data from MW-115D are not considered, the nonparametric UTL_{95} value for the eastern subarea would be 2.3 µg/L. This value may be more representative of conditions and processes responsible for natural Cr(VI) in groundwater in the eastern subarea where mudflat/playa deposits are not present.

Concentrations of Cr(VI) in 40 quarterly samples from 10 wells completed in non-Mojave-type or undifferentiated, unconsolidated deposits in the eastern subarea collected from Q2 2017 through Q1 2018 ranged from less than 0.2 to 2.8 µg/L, and the median concentration was 1.3 µg/L. The highest Cr(VI) concentrations were in water from well MW-96S, completed in weathered quartz diorite bedrock. Concentrations of Cr(VI) in water from well MW-115S, completed in mudflat/playa deposits near Mount General, were as high as 2.1 µg/L. The median Cr(VI) concentration in non-Mojave-type deposits in the eastern subarea was not significantly different from the median Cr(VI) concentration for Mojave-type deposits in that area of 1.6 µg/L on the basis of the median test (Neter and Wasserman, 1974) at a significance criterion of α=0.05.



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 G.7. Nonparametric upper 95-percent tolerance limit for hexavalent chromium background concentrations in water from wells screened in Mojave-type deposits in the eastern, western, and northern (including Water Valley) subareas, 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/ and data from U.S. Geological Survey (2021). Data are available in appendix G.2 (table G.2.1).

Chromium associated with mudflat/playa deposits and older groundwater isolated from surficial sources of groundwater recharge are potential sources of natural Cr(VI) in the eastern subarea near Mount General. Mudflat/playa deposits in this part of the eastern subarea are highly felsic with low chromium concentrations. Most chromium within these deposits is present within unweathered magnetite mineral grains (chapter C, fig. C.12), and Cr(VI) concentrations in porewater pressure extracted from mudflat/playa deposits in the eastern subarea did not exceed 3.3 µg/L (chapter E, table E.6). Water from wells such as MW-115D is isolated from surface sources of recharge along the Mojave River by mudflat/playa deposits within the aquifer. This isolation contributes to long contact times between groundwater and aquifer materials that promote weathering of silicate minerals and development of alkaline conditions with subsequent desorption of Cr(VI) from aquifer materials, as long as groundwater remains oxic. Concentrations of Cr(VI) in water from well MW-115D from Q2 2017 through Q1 2018 were as high as 3.7 µg/L (appendix G.2, table G.2.1), and concentrations in regulatory samples have been as high as 4.6 µg/L. Data collected as part of this study indicate that although Cr(VI) from mudflat/playa deposits and older groundwater is locally important, these sources are not high enough to explain Cr(VI) concentrations in regulatory samples from wells along the eastern margin of the Q4 2015 regulatory Cr(VI) plume as high as 20 µg/L.

G.3.2.2. Western Subarea

In the western subarea, 19 wells sampled as part of the USGS Cr(VI) background study were outside the summative-scale Cr(VI) plume (fig. G.7). Data from six wells completed in Mojave-type deposits were selected for calculation of UTL_{95} values. The number of wells was limited by the thin saturated thickness (commonly less than 10 ft thick) within Mojave-type deposits overlying weathered bedrock in much of the western subarea downgradient from the Lockhart fault. Concentrations of Cr(VI) in 24 samples collected quarterly from these wells from Q2 2017 through Q1 2018 ranged from 0.2 to 3.9 µg/L (fig. G.6; appendix G.2, table G.2.1), and the median concentration was 1.5 µg/L. The nonparametric Cr(VI) UTL_{95} value for Mojave-type deposits in the western subarea calculated on the basis of quarterly data was 3.9 µg/L (table G.3). The normal Cr(VI) UTL_{95} value for Mojave-type deposits in the western subarea was not robustly estimated because of the small number of data points available to fit to a normal distribution.

Concentrations of Cr(VI) used to calculate the nonparametric UTL_{95} value in the western subarea were highest in water from well MW-121D (fig. G.6). Well MW-121D is completed in Mojave-type deposits having visually abundant iron- and manganese-oxide coatings on the surfaces of mineral grains (chapter C, fig. C.13*B*). Chromium and manganese concentrations as high as 120 and 1,040 mg/kg, respectively (chapter B, table B.4), that exceed their respective summative-scale threshold concentrations of 85 and 970 mg/kg (table G.1), were measured on mineral grains within deposits penetrated by well MW-121D. Below these materials, well MW-121D penetrates lacustrine and groundwater-discharge deposits that overlie weathered hornblende diorite bedrock having chromium concentrations as high as 410 mg/kg (Groover and Izbicki, 2018; Miller and others, 2020). The next highest Cr(VI) concentrations in the western subarea were in water from well MW-119S (fig. G.6), completed in Mojave-type deposits containing abundant caliche overlying weathered mafic bedrock similar to well MW-121D (Groover and Izbicki, 2018). Concentrations of Cr(VI) in water from well MW-119S increased monotonically from 1.7 to 3.2 µg/L between April 2017 and March 2018 (well MW-119S was resampled by PG&E in Q4 2017 [October–December 2017] and Q1 2018, and lower values for Cr(VI) were reported for regulatory purposes). Water from other sampled wells in Mojave-type deposits in the western subarea had Cr(VI) concentrations of less than 2 µg/L (fig. G.6; appendix G.2, table G.2.1) and were similar to concentrations in water from most wells in Mojave-type deposits within the eastern subarea.

Concentrations of Cr(VI) in water from wells MW-159S, MW-159D, and MW-163S, completed in Mojave-type deposits downgradient from the western excavation site (fig. G.7) and ranging from 7 to 10 µg/L between Q2 2017 and Q1 2018, were not used to calculate the UTL_{95} value for the western subarea. Water from these wells contains anthropogenic compounds associated with the site, although Cr(VI) releases at the western excavation site have not been identified by regulatory agencies (Lahontan Regional Water Quality Control Board, 2014). Examination of core material from these wells (chapter C, fig. C.26; Groover and Izbicki, 2018; Morrison and others, 2018) did not indicate high chromium concentrations in aquifer solids, unusual chromium-containing mineralogy, high-chromium concentrations on the surfaces of mineral grains, or aqueous geochemistry including strongly alkaline pH (chapter E, fig. E.18) or older groundwater age (chapter F, fig. F.16) that would contribute to high natural Cr(VI) concentrations in groundwater.

Concentrations of Cr(VI) in water from well MW-121S completed in Mojave-type deposits ranging from 2.3 to 3.7 µg/L between Q2 2017 and Q1 2018 (appendix G.2, table G.2.1) also were not used to calculate the UTL_{95} value. Well MW-121S was within the summative-scale Cr(VI) plume extent (fig. G.2). In the past, regulatory Cr(VI) concentrations in water from well MW-121S have been as high as 11 µg/L.

Concentrations of Cr(VI) in 28 samples from 7 wells completed in non-Mojave-type deposits in the western subarea collected from Q2 2017 through Q1 2018 ranged from 0.2 to 6.5 µg/L, and the median concentration was 2.5 µg/L. The median concentration in non-Mojave-type deposits in the western subarea was statistically different from the median concentration in Mojave-type deposits in that area of 1.5 µg/L on the basis of the median test (Neter and Wasserman, 1974) at a significance criterion of α=0.05. Landowner permission could not be obtained to sample domestic wells 22-09, 22-63, and BGS-34 during this period, and data from these domestic wells are not included in the range or median values for non-Mojave-type deposits in the western subarea.

Concentrations of Cr(VI) in non-Mojave-type deposits in the western subarea were highest in water from well MW-203D. Hexavalent chromium concentrations in water from well MW-203D, completed in partly consolidated Miocene deposits, ranged from 2 to 6.6 µg/L between April 2017 and March 2018. Miocene deposits are between 23 and 5.3 million years old and are more weathered than overlying, younger Mojave-type deposits (chapter C, fig. C.9*D*) that were eroded from source rock less than 750,000 years ago (chapter A, fig. A.5). In addition, water from well MW-203D was strongly alkaline with pH values as high as 8.3, did not contain measurable tritium, and had a carbon-14 activity of 14 pmc (chapter E, appendix E.1, table E.1.1) corresponding to an unadjusted groundwater age of more than 16,000 ybp. Concentrations of Cr(VI) in regulatory data from well MW-203D were as high as 10 µg/L in October 2013, shortly after the well was drilled, and have varied widely through time (chapter D, fig. D.9).

Concentrations of Cr(VI) in water from well MW-153S, completed in weathered hornblende diorite having chromium concentrations in core material as high as 405 mg/kg (the highest measured in core material adjacent to a well sampled as part of this study), ranged from 3.4 to 3.9 µg/L between April 2017 and March 2018. Water from well MW-153S was alkaline with pH values near 7.5, did not contain measurable tritium, and had a carbon-14 activity of 80 pmc (chapter E, appendix E.1, table E.1.1), corresponding to an unadjusted age of 1,850 ybp, which predates releases from the Hinkley compressor station.

Chromium associated with visually abundant iron- and manganese-oxide coatings that have developed on the surfaces of mineral grains within Mojave-type deposits near redox boundaries associated with geologic contacts seem to be the highest source of natural Cr(VI) in Mojave-type deposits in the western subarea. Many of the wells used for background Cr(VI) calculations in the western subarea have complex provenance and lithology similar to well MW-121D and MW-119S, which includes visually abundant iron- and manganese-oxide coatings on the surfaces of mineral grains in close proximity to weathered mafic chromium-containing bedrock or partly consolidated Miocene deposits (Miller and others, 2020).

G.3.2.3. Northern Subarea, Including Water Valley

In the northern subarea and Water Valley, 28 wells sampled as part of the USGS Cr(VI) background study were outside the summative-scale Cr(VI) plume (fig. G.7). Data from 11 wells completed in Mojave-type deposits were selected for calculation of UTL_{95} values. Concentrations of Cr(VI) in 44 samples collected quarterly from these wells from Q2 2017 through Q1 2018 ranged from less than 0.2 to 4.0 µg/L (fig. G.6; appendix G.2, table G.2.1), and the median concentration was 3.2 µg/L. Well MW-129S, completed in Mojave-type deposits, was not sampled during this period because of an oversight. Concentrations of Cr(VI) in water from well MW-129S were 0.93 µg/L in March 2016, and concentrations in regulatory samples from well MW-129S have not exceeded 1.1 µg/L. The nonparametric Cr(VI) UTL_{95} value calculated for Mojave-type deposits in the northern subarea including Water Valley on the basis of these data was 4.0 µg/L (table G.3).

Concentrations of Cr(VI) used to calculate the UTL_{95} value in the northern subarea and Water Valley were highest in water from well MW-136S1, downgradient from the Mount General fault, and in water from wells MW-205S1 and MW-205S3, in Water Valley (fig. G.6). Concentrations of Cr(VI) in water from these wells were as high as 4.0 µg/L from Q2 2017 through Q1 2018 (appendix G.2, table G.2.1). Although these wells are completed in Mojave-type deposits, geologic, geochemical, and hydrologic conditions downgradient from the Mount General fault and in Water Valley differ from conditions closer to the summative-scale Cr(VI) plume margin. Concentrations of Cr(VI) in quarterly samples collected from well MW-104S1 ranging from 3.1 to 3.5 µg/L between April 2017 and March 2018 (fig. G.6; appendix G.2, table G.2.1) may be more representative of conditions closer to the summative-scale Cr(VI) plume margin.

The Cr(VI) concentrations in water from two wells completed in Mojave-type deposits in the northern subarea, MW-137S3 and MW-207S1, were not used to calculate the UTL_{95} value for that area. Concentrations of Cr(VI) in water from well MW-137S3 increased monotonically from 1.7 to 6.7 µg/L between Q2 2017 and Q1 2018 (not shown on fig. G.6). The Cr(VI) concentration of 3.6 µg/L in water from well MW-137S3 in March 2015 was previously identified as unusual (chapter E) on the basis of its strongly alkaline pH of 9.1 and low dissolved-oxygen concentration of 0.2 mg/L. Concentrations of Cr(VI) above 0.2 µg/L are not expected in low dissolved oxygen, reduced groundwater. Dissolved-oxygen concentrations remained less than 0.5 mg/L and pH remained strongly alkaline (9.0 or greater) as Cr(VI) concentrations increased between Q2 2017 and Q1 2018. Although completed in Mojave-type deposits (Groover and Izbicki, 2018; Miller and others, 2020), water from well MW-207S1 had a nonradiogenic strontium isotope (strontium-87/86) value of 0.708995, consistent with water in contact with Miocene deposits rather than the Mojave-type deposits at that site (chapter F, fig. F.21).

Concentrations of Cr(VI) in 56 quarterly samples from 14 wells in non-Mojave-type deposits or undifferentiated, unconsolidated deposits in the northern subarea and Water Valley from Q2 2017 through Q1 2018 ranged from less than 0.2 to 9.4 µg/L, and the median concentration was 3.6 µg/L. The median Cr(VI) concentration in non-Mojave-type deposits in the northern subarea including Water Valley was significantly different from the median concentration in Mojave-type deposits in that area of 3.2 µg/L on the basis of the median test (Neter and Wasserman. 1974) at a significance criterion of α=0.10 (probability, p=0.08). Data from well MW-131S were not included because the well went dry after two samples were collected. The highest Cr(VI) concentrations were in water from wells MW-133S1 and MW-154S1, completed in mudflat/playa deposits downgradient from the Mount General fault. These deposits are widespread in the northern subarea and commonly contain high concentrations of chromium and manganese, with manganese in the form of highly oxidative Mn(IV) oxides (chapter E, fig. E.15). Concentrations of Cr(VI) as high as 4.7 µg/L were measured in water from well MW-193S2, completed in locally derived alluvium in Water Valley that was partly eroded from Miocene deposits east of the study area, and concentrations as high as 4.2 µg/L were measured in water from well MW-186S3 in Water Valley, completed in locally derived alluvium with admixtures of basalt (Miller and others, 2020).

Chromium associated with lacustrine and mudflat/playa deposits seems to be the most typical source of natural Cr(VI) in the northern subarea, consistent with delta chromium-53 isotope data in water from wells in this area (chapter F, fig. F.26*C*). As a result of water-level declines from pumping and the thin saturated thickness of Mojave-type deposits in the northern subarea, many wells used for background calculations in the northern subarea partly penetrate these materials. Additional sources of natural Cr(VI) in Water Valley include basalt (chapter B, table B.3) and materials eroded from Miocene sedimentary rock east of the study area (chapter F, fig. F.21) within locally derived alluvium. Generally alkaline pH values in water from wells in the northern subarea and Water Valley (chapter E, fig. E.16) facilitate desorption of Cr(VI) from aquifer materials into groundwater.

G.3.2.4. Within the Regulatory Hexavalent Chromium Plume

The summative-scale Cr(VI) plume is within Mojave-type deposits. Groundwater within the summative-scale Cr(VI) plume has a near-neutral to slightly alkaline pH, contains tritium, and contains post-1952 recharge from the Mojave River. Mojave-type deposits in the area tend to be thick, coarse-textured, and contain low-chromium concentrations (Groover and Izbicki, 2018). Background Cr(VI) concentrations were estimated as the UTL_{95} values for the aquifer within the summative-scale Cr(VI) plume to determine Cr(VI) concentrations that may have been present in this area if releases from the Hinkley compressor station had not occurred. These estimates may inform the establishment of cleanup goals within the regulatory Cr(VI) plume after it has been updated.

Concentrations of Cr(VI) in water from 14 wells (appendix G.2, table G.2.1) outside the mapped summative-scale Cr(VI) plume extent in the eastern and western subareas completed in Mojave-type deposits were used to calculate the UTL_{95} value for the summative-scale mapped plume extent. Water from selected wells contained measurable tritium or had carbon-14 activities greater than 84 pmc, consistent with recently recharged (post-1952) groundwater, and had near-neutral to slightly alkaline pH, consistent with younger water that has not reacted extensively with silicate minerals within the aquifer. The Cr(VI) concentrations in water from wells having older groundwater, such as MW-115D, were not used to calculate the UTL_{95} value. Similarly, the Cr(VI) concentrations in water from wells downgradient from the summative-scale Cr(VI) plume in the northern subarea were not used to calculate the UTL_{95} value because of geologic, geochemical, and hydrologic changes that occurred in the northern subarea. Concentrations of Cr(VI) in 56 samples collected quarterly from the selected wells from Q2 2017 through Q1 2018 ranged from 0.56 to 2.4 µg/L (appendix G.2, table G.2.1), and the median concentration was 1.5 µg/L. The nonparametric UTL_{95} value was 2.3 µg/L (table G.3). This value estimates Cr(VI) background concentrations in water from wells within the regulatory Cr(VI) plume downgradient from the Hinkley compressor station if Cr(VI) had not been released into groundwater. This UTL_{95} value may inform cleanup and remediation goals for groundwater in Mojave-type deposits in Hinkley Valley.

The highest Cr(VI) concentrations used to calculate the UTL_{95} value within the summative-scale Cr(VI) plume were in water from wells BG-0002 and BG-0004A. As described previously, core material from these wells contains visually abundant iron- and manganese-oxide coatings developed near the water-table interface and near redox boundaries associated with contacts between different geologic materials (chapter C, fig. C.13*B*). Naturally occurring iron- and manganese-oxide coatings are ubiquitous on mineral grains that compose the aquifers, and these oxide coatings play an important role in the storage of chromium and its oxidation from Cr(III) to Cr(VI) before its release into groundwater.

G.3.3. Hexavalent Chromium Background Concentrations for Undifferentiated, Unconsolidated Deposits

Control of type-II errors for nonparametric Cr(VI) UTL_{95} values, without bootstrap approximation, calculated from quarterly data for wells in Mojave-type deposits ranged from 70 to 90 percent (table G.3); however, given the clustered sample design, quarterly values from sampled wells were correlated and not statistically independent. There were not enough data to calculate normal Cr(VI) UTL_{95} values from the uncorrelated median of quarterly data for wells in Mojave-type deposits in each subarea in Hinkley and Water Valleys, although there were enough data to estimate the overall normal UTL_{95} value for Mojave-type deposits of 3.8 µg/L (table G.3). Additional data may improve the UTL_{95} estimates for the subareas in Hinkley and Water Valleys.

For regulatory purposes, PG&E collects Cr(VI) data from a large number of monitoring wells in Hinkley and Water Valleys not sampled as part of the USGS Cr(VI) background study. Although the number of wells sampled by PG&E for regulatory purposes and sample collection frequency were reduced as part of the 2015 cleanup and abatement order (Lahontan Regional Water Quality Control Board, 2015), more than 120 wells outside the summative-scale Cr(VI) plume were sampled quarterly by PG&E from Q2 2017 through Q1 2018 in the eastern, western, and northern subareas of Hinkley Valley and in Water Valley. Regulatory Cr(VI) data from these wells (ARCADIS, 2018a, 2019) have SRLs and precision values similar to data collected as part of the USGS Cr(VI) background study. Although detailed well construction and lithologic data are available for these additional monitoring wells, these wells lack geologic provenance and depositional environment data (chapter A, table A.1) used to identify wells completed in Mojave-type and non-Mojave-type deposits (Miller and others, 2018, 2020). Consequently, these additional wells are described as completed in undifferentiated, unconsolidated deposits.

Regulatory data collected by PG&E from more than 120 wells completed in undifferentiated, unconsolidated deposits outside the summative-scale Cr(VI) plume from Q2 2017 through Q1 2018 were used to calculate Cr(VI) UTL_{95} values in the eastern, western, and northern subareas of Hinkley Valley and in Water Valley (appendix G.2, table G.2.2). For these calculations, (1) UTL_{95} values for wells near mudflat/playa deposits in the eastern subarea were calculated separately and (2) the northern subarea was divided, on the basis of differences in geology, geochemistry, and hydrology, into areas upgradient and downgradient from the Mount General fault and Water Valley. Values of UTL_{95} for wells in these areas were calculated separately. Concentrations of Cr(VI) in water from wells completed in weathered bedrock and partly consolidated Miocene deposits were not used in these calculations. Although these calculations use more data and have greater statistical power, they lack the geologic specificity of Cr(VI) UTL_{95} values calculated for Mojave-type deposits.

Concentrations of Cr(VI) in 324 samples collected quarterly from 81 wells in undifferentiated, unconsolidated deposits in the eastern and western subareas and the northern subarea upgradient from the Mount General fault in Hinkley Valley from Q2 2017 through Q1 2018 ranged from less than 0.2 to 4.2 µg/L (figs. G.8*A*, *B*), and the median concentration was 1.7 µg/L. Data used to calculate UTL_{95} values for these areas are provided in appendix G.2 (table G.2.2). Quarterly data and the median of the quarterly data for wells completed in Mojave-type deposits did not fit lognormal or gamma distributions but consistently fit normal distributions.

The normal Cr(VI) UTL_{95} values calculated from the median of quarterly data from sampled wells in the eastern and western subareas and in the northern subarea upgradient from the Mount General fault were 2.8, 3.8, and 4.8 µg/L, respectively, with an overall normal UTL_{95} value of 3.8 µg/L (table G.4). The areas for which the normal UTL_{95} values apply are shown in figure G.9. The normal UTL_{95} value in the eastern subarea is lower and the normal UTL_{95} value in the northern subarea upgradient of the Mount General fault is larger than the nonparametric UTL_{95} values estimated for Mojave-type deposits in these areas (table G.3). As a consequence of water-level declines resulting from agricultural pumping, Mojave-type deposits throughout the northern subarea are a thin veneer (commonly less than 10 ft thick) overlying lacustrine and mudflat/playa deposits. The higher normal UTL_{95} value in the northern subarea upgradient from the Mount General fault results from the thin saturated thickness of Mojave-type deposits and the resulting monitoring well network design, and the lack of geologic specificity associate with these calculations in which many wells are completed partly or entirely in underlying non-Mojave-type deposits.

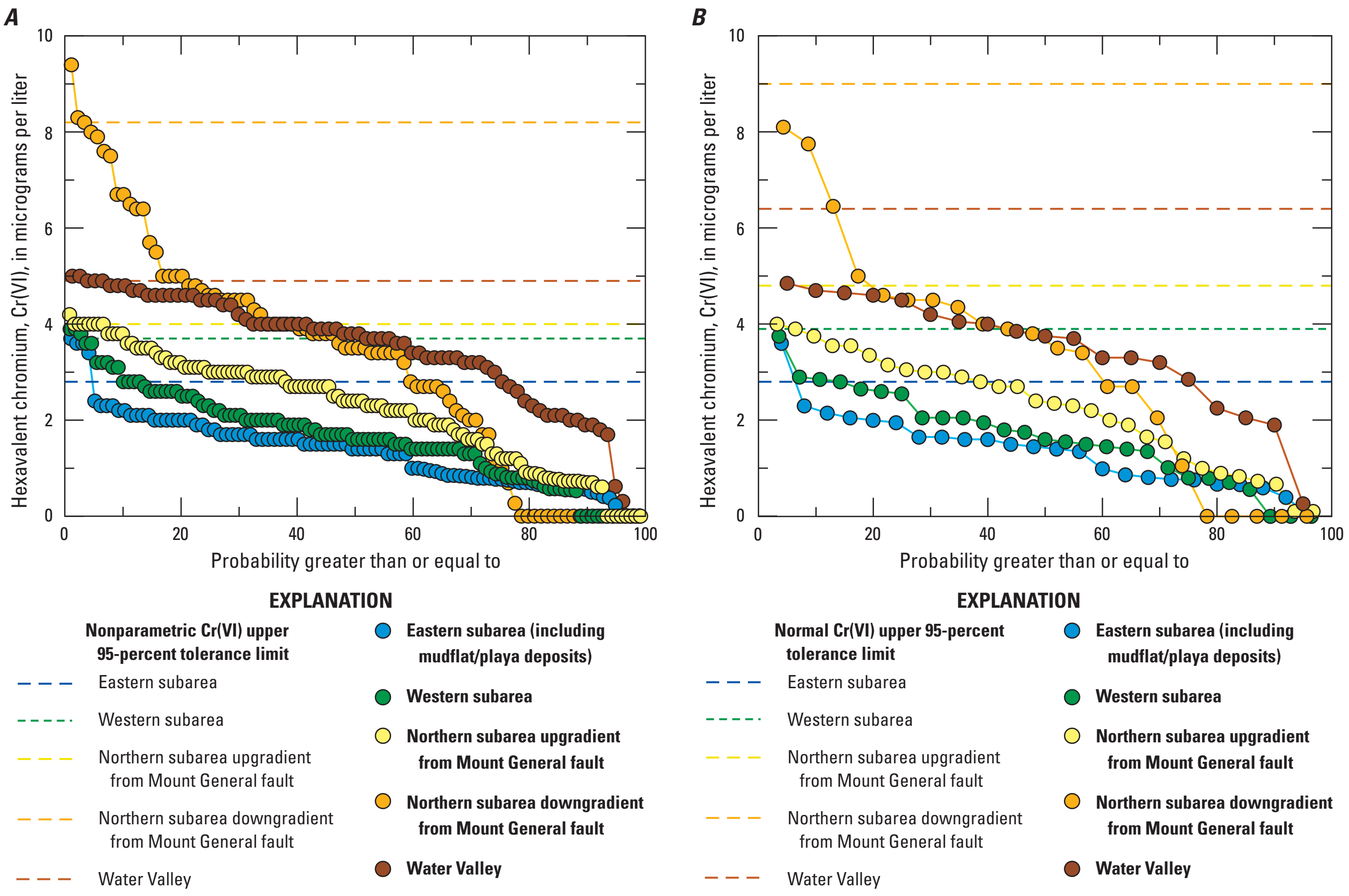


Figure G.8. Estimated distribution functions for hexavalent chromium concentrations in water from wells completed in undifferentiated, unconsolidated deposits for selected areas in Hinkley and Water Valleys, western Mojave Desert, California, April 2017 through March 2018. *A*, quarterly data and *B*, the median of quarterly data. 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 appendix G.2 (table G.2.2.).

A separate UTL_{95} value was calculated for mudflat/playa deposits (including Mojave-type deposits isolated from surface sources of recharge by mudflat/playa deposits) in the eastern subarea using data from wells MW-115S, MW-115D, BG-0004C, and BG-0003C (appendix G.2, table G.2.2). For calculation of the normal UTL_{95} value, data were supplemented with Cr(VI) porewater data extracted from selected depths at well site MW-192 near Mount General (chapter E, table E.6). Porewater data from discrete depths at site MW-192 were treated as independent values for the purpose of this calculation. The normal UTL_{95} value of 5.8 µg/L for mudflat/playa deposits in the eastern subarea was calculated from eight values (four median values from wells and four porewater values). This calculation used fewer than the U.S. Environmental Protection Agency (2009) recommendation of 10 data points, and the normal UTL_{95} value for mudflat/playa deposits in the eastern subarea near Mount General is poorly estimated; additional data would likely improve this estimate.

Separate normal UTL_{95} values calculated for the northern subarea downgradient from the Mount General fault and Water Valley were 9.0 and 6.4 µg/L, respectively (table G.4). The higher UTL_{95} values reflect geologic, geochemical, and hydrologic differences in these areas compared to that part of the northern subarea upgradient from the Mount General fault and closer to the summative-scale Cr(VI) plume.

The nonparametric Cr(VI) UTL_{95} value for Mojave-type deposits within an updated regulatory Cr(VI) plume downgradient from the Hinkley compressor station of 2.3 µg/L (table G.3) was not recalculated. The Cr(VI) plume lies within Mojave-type deposits, and the geologic specificity of the nonparametric UTL_{95} value is appropriate for this area. The UTL_{95} value of 2.3 µg/L may be a suitable metric for cleanup goals within the regulatory Cr(VI) plume after regulatory updates.

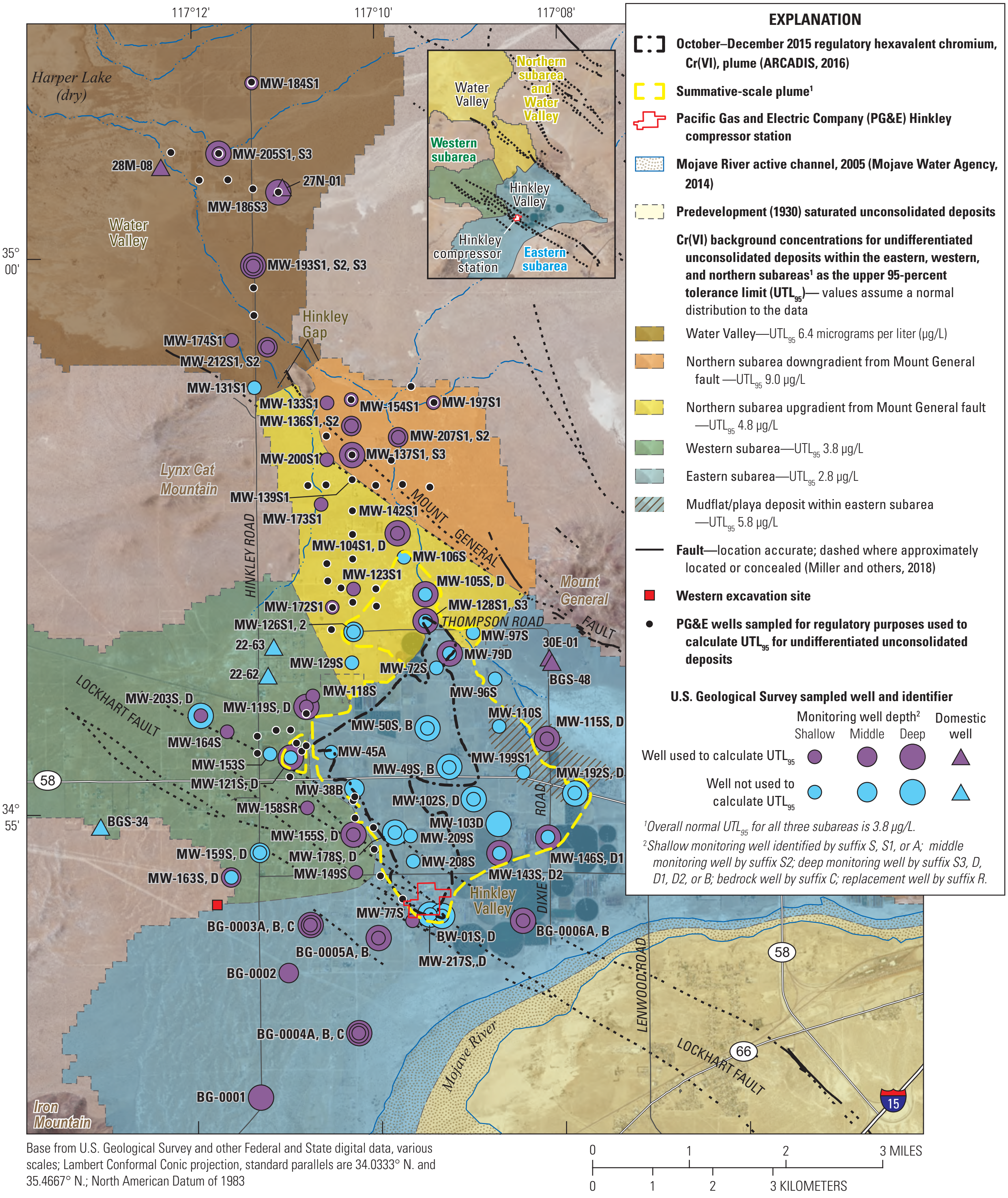
Table G.4. Upper 95-percent tolerance limit for hexavalent chromium, Cr(VI), background concentrations in water from wells screened in undifferentiated, unconsolidated deposits in the eastern, western, and northern subareas of Hinkley Valley and in Water Valley, western Mojave Desert, California, April 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 appendix G.2 (table G.2.2.)

[The upper 95-percent tolerance limit (UTL_{95})calculated using the computer program ProUCL 5.1 (Singh and Maichle, 2015). Data used for calculation: Quarterly, four values collected between April 2017 and March 2018; Median, median of four values collected between April 2017 and March 2018. Type-I error is the probability of a false positive at the specified confidence level. Type-II error is the probability of a false negative at the specified confidence level. **Abbreviations**: µg/L, microgram per liter, —, no data or not calculated]

Data used for calculation	Number of samples	Number of wells	UTL_{95}, in µg/L	Maximum Cr(VI), in µg/L	Model distribution	Confidence associated with type-II error without bootstrap approximation, in percent	Number of samples to control type-II error at 95-percent confidence without bootstrap approximation
Eastern subarea							
Quarterly	80	20	2.3	2.4	Nonparametric	91	93
Median	20	20	2.8	2.3	Normal	—	—
Eastern subarea (mudflat/playa deposits)							
Quarterly	6	4	3.7	3.7	Nonparametric	56	59
Median	8	[1]8	5.8	3.6	Normal	—	—
Western subarea							
Quarterly	108	27	3.7	3.9	Nonparametric	91	124
Median	27	27	3.8	3.8	Normal	—	—
Northern subarea (upgradient from Mount General fault)							
Quarterly	120	30	4.0	4.2	Nonparametric	86	153
Median	30	30	4.8	4.0	Normal	—	—
Northern subarea (downgradient from Mount General fault)							
Quarterly	88	22	8.2	9.4	Nonparametric	82	124
Median	22	22	9.0	8.1	Normal	—	—
Water Valley							
Quarterly	76	19	4.9	5.0	Nonparametric	90	93
Median	19	19	6.4	4.9	Normal	—	—
Overall (eastern and western subareas and the northern subarea upgradient from Mount General fault)							
Quarterly	324	324	3.8	4.2	Nonparametric	93	336
Median	81	81	3.8	4.0	Normal	—	—

[1] Includes four samples of porewater extracted from core material at site MW-192, March 2018. Each porewater sample was treated as an independent median concentration for calculation of the UTL_{95}.

Although they have less geologic specificity, normal UTL_{95} values estimated from the larger PG&E regulatory dataset (table G.4) are statistically more robust than the values estimated for Mojave-type deposits. The median Cr(VI) concentration in water from well MW-137S3, which had unusual Cr(VI) concentrations given low dissolved-oxygen concentrations and had increasing Cr(VI) concentrations between April 2017 and March 2018, and the median Cr(VI) concentration in water from well MW-207S1 were included in the calculation of the normal Cr(VI) UTL_{95} values for the northern subarea downgradient from the Mount General fault. The median Cr(VI) concentrations in water from wells completed in weathered bedrock; from wells completed in partly consolidated Miocene deposits; and from wells MW-159S, MW-159D, and MW-163S downgradient from the western excavation site were not included in the calculation of the normal UTL_{95} value for the western subarea.



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 G.9. 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 appendix G.2 (table G.2.2).

G.3.4. Limitations and Use of Hexavalent Chromium Background Values

The SSA identified natural and anthropogenic Cr(VI) in water from wells in a wide range of geologic, geochemical, and hydrologic settings in Hinkley and Water Valleys for the period March 2015 through November 2017 (fig. G.2). The Cr(VI) background concentrations were estimated as the UTL_{95} on the basis of Cr(VI) concentrations collected from wells outside the summative-scale Cr(VI) plume between Q2 2017 and Q1 2018. On the basis of the SSA, water from these wells contains natural Cr(VI).

The 1-year period (four quarters) of data collection was incorporated into the study design 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, 2011). Estimation of Cr(VI) background over periods longer than 1 year also would have incorporated upward or downward Cr(VI) concentration trends into the data, complicating the interpretation of Cr(VI) background concentrations. By design, samples used for calculation of Cr(VI) background concentrations were not affected by the pumping of larger volumes of water required for the more complete chemical and isotopic analyses (including age-dating constituents) of samples collected as part of this study between March 2015 and November 2017.

The UTL_{95} values were calculated for wells outside the summative-scale Cr(VI) plume extent using two sets of data. The first dataset included wells completed (screened) within Mojave-type deposits that had been sampled for detailed chemical and isotopic data, including age-dating constituents, as part of this study. The second dataset included additional wells completed within undifferentiated, unconsolidated deposits sampled for regulatory purposes. The UTL_{95} values calculated from the larger regulatory dataset have less geologic specificity but have greater statistical power and greater spatial resolution than the smaller dataset that included only sampled wells completed in Mojave-type deposits. The larger regulatory dataset also addressed the reality of network design in which available monitoring wells were screened in multiple geologic units and do not solely represent water from Mojave-type deposits.

The normal Cr(VI) UTL_{95} values calculated from the median of quarterly data from wells completed within undifferentiated, unconsolidated deposits sampled in the eastern and western subareas and in the northern subarea upgradient from the Mount General fault were 2.8, 3.8, and 4.8 µg/L, respectively (table G.5). These values were selected as background Cr(VI) concentrations for the different subareas in this study. An overall normal UTL_{95} value of 3.8 µg/L was calculated for the eastern, western, and northern subareas upgradient from the Mount General fault. This value is the same as the overall normal UTL_{95} value of 3.8 µg/L calculated for Mojave-type deposits (tables G.3, G.4) and is similar to the maximum Cr(VI) concentration of older groundwater in contact with Mojave-type deposits of 3.6 µg/L (chapter F, table F.4). Additional UTL_{95} values were calculated for the northern subarea downgradient from the Mount General fault, Water Valley, mudflat/playa deposits and older groundwater in the eastern subarea near Mount General, and for the regulatory Cr(VI) plume extent after regulatory updates (table G.5).

Table G.5. Summary of upper 95-percent tolerance limits for hexavalent chromium, Cr(VI), Hinkley 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 appendix G.2 (tables G.2.1, G.2.2).

[Background Cr(VI) concentrations calculated as the upper 95-percent tolerance limit (UTL_{95}) using the computer program ProUCL (Singh and Maichle, 2015). Values calculated as the median of four quarterly samples from wells completed in undifferentiated unconsolidated deposits. Number of wells is the number of wells used in the calculation. **Abbreviation**: µg/L, microgram per liter]

Number of wells	UTL_{95}, in µg/L	Maximum Cr(VI), in µg/L	Model distribution
Eastern subarea[1]			
24	2.8	2.3	Normal
Western subarea			
27	3.8	3.8	Normal
Northern subarea (upgradient from Mount General fault)[2]			
30	4.8	4.0	Normal
Overall (eastern and western subareas, and the northern subarea upgradient from Mount General fault)			
81	3.8	4.0	Normal

[1] A separate UTL_{95} value of 5.8 µg/L was calculated for mudflat/playa deposits and older groundwater near Mount General. An additional UTL_{95} value of 2.3 µg/L was calculated for the regulatory Cr(VI) plume extent after regulatory updates.

[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, respectively.

Wells were selected for inclusion in the USGS Cr(VI) background study for a variety of reasons, most commonly high Cr(VI) concentrations or upward Cr(VI) concentration trends. As a consequence, Cr(VI) concentrations in water from sampled wells completed within Mojave-type deposits were biased positive (high) compared to the Cr(VI) concentrations in regulatory data from other wells. Although not biased by the well selection process used in this study, the data for wells completed within undifferentiated unconsolidated deposits also were positively biased to high values as a result of the 2015 cleanup and abatement order (Lahontan Regional Water Quality Control Board, 2015) that reduced or eliminated sample collection from wells having low Cr(VI) concentrations of less interest for regulatory purposes. Consequently, the UTL_{95} values (tables G.3, G.4, G.5) likely overestimate the actual Cr(VI) background concentrations in Hinkley and Water Valleys; however, positive bias within data used to calculate the UTL_{95} values ensured that wells with higher Cr(VI) concentrations that effectively control estimates of Cr(VI) background concentrations were included in the calculations. Additionally, the UTL_{95} values calculated by ProUCL may be positively biased because of the philosophical approach to statistical calculations within ProUCL and numerical methods used to control for type-II statistical errors (Daniel, 2015). The extent of these positive biases on UTL_{95} estimates of Cr(VI) background concentrations was not estimated as part of his study.

Between April 2011 and March 2019, the Cr(VI) plume extent was updated quarterly for regulatory purposes (Lahontan Regional Water Quality Control Board, 2019). The process evaluated regulatory data from sampled wells and involved PG&E and regulators with input from the local community and other stakeholders. Redefining the regulatory Cr(VI) plume was beyond the scope of this study; however, the UTL_{95} values are intended to inform that process. Although identified as anthropogenic, some Cr(VI) concentrations within the summative-scale Cr(VI) plume are low and may not require regulatory attention. Consequently, for Q1 2018, the latest data available for this study, an updated regulatory Cr(VI) plume would not likely include wells within the summative-scale Cr(VI) plume that have Cr(VI) concentrations less than the UTL_{95} values for their respective subareas. However, an updated Q1 2018 regulatory Cr(VI) plume would likely have included well MW-128S1 near the leading edge of the Q4 2015 regulatory Cr(VI) plume and well MW-97S in the northern subarea with Cr(VI) concentrations of 6.7 and 6.4 µg/L, respectively.

The UTL_{95} value is defined as the value below which 95 percent of the concentrations are expected to fall with 95-percent confidence (Singh and Singh, 2015). For samples collected each quarter from wells outside the summative-scale Cr(VI) plume extent, not more than 5 percent of the time would the 95th percentile of the sample distribution for a quarter exceed the UTL_{95} value. Between Q2 2017 and Q1 2018, samples from wells MW-173S1, MW-139S1, and MW-142S1 in the northern subarea upgradient from the Mount General fault and well MW-121D in the western subarea (fig. G.9) exceeded the overall Cr(VI) normal UTL_{95} value of 3.8 µg/L in at least one quarter, and Cr(VI) concentrations in water from well MW-139S1 were greater than 3.8 µg/L in all four quarters. Only 2 of 81 median Cr(VI) values from wells MW-139S1 and MW-173S1, outside the summative-scale Cr(VI) plume extent in the northern subarea upgradient from the Mount General fault (fig. G.9), exceeded the overall UTL_{95} value. These exceedances are less than the number of exceedances expected by chance alone, indicating that in most cases the overall UTL_{95} value may be an acceptable choice for a regulatory Cr(VI) background value.

Geologic, geochemical, and hydrologic conditions differ in aquifers in the subareas composing Hinkley and Water Valleys; consequently, different UTL_{95} values were estimated for the different subareas. The normal UTL_{95} values for the eastern, western, and northern subareas upgradient from the Mount General fault (table G.4) provide greater precision for updating the regulatory Cr(VI) plume extent and for plume management than the overall normal UTL_{95} value.

The normal Cr(VI) UTL_{95} value of 2.8 µg/L (table G.5) calculated for the eastern subarea reflects low chromium concentrations in younger (post-1952) groundwater in Mojave-type deposits in that area. Because most of the summative-scale Cr(VI) plume is within the eastern subarea, this value has implications for plume management. 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, 2018b; Lahontan Regional Water Quality Control Board, 2018), earlier than the overall UTL_{95} value of 3.8 µg/L. However, the normal UTL_{95} value for the eastern subarea does not account for high natural Cr(VI) concentrations associated with mudflat/playa deposits and older alkaline groundwater isolated from surface sources of recharge by mudflat/playa deposits near Mount General. A higher normal UTL_{95} value of 5.8 µg/L (table G.5) was calculated for wells completed in these materials. Although poorly estimated because of a lack of data, this value may be an appropriate background value for wells MW-110S, MW-192D, and MW-199S1 associated with mudflat/playa deposits in that part of the eastern subarea (fig. G.9). During Q1 2018, the latest quarter for which data were available as part of this study, Cr(VI) concentrations in water from these wells were 3.7, 2.9, and 2.9 µg/L, respectively, and did not exceed the overall UTL_{95} value or the normal UTL_{95} value for mudflat/playa deposits in the eastern subarea (well MW-192S was dry and not sampled during Q1 2018). During Q1 2018, Cr(VI) concentrations in older groundwater from well MW-115D were 3.8 µg/L.

A nonparametric UTL_{95} value of 2.3 µg/L (table G.5) was calculated for Mojave-type deposits downgradient from the Hinkley compressor station (fig. G.9). This lower value reflects thicker, coarse-textured, low-chromium Mojave-type deposits and neutral to slightly alkaline groundwater near recharge areas along the Mojave River with a high degree of geologic specificity and may be a suitable metric for Cr(VI) cleanup goals within the regulatory Cr(VI) plume in the eastern subarea after regulatory updates.

The normal Cr(VI) UTL_{95} value of 3.8 µg/L in the western subarea (table G.5) is the same as the overall normal UTL_{95} value of 3.8 µg/L. This value reflects (1) the greater abundance of older Mojave River deposits with chromium-containing actinolite in the western subarea, and (2) chromium abundance in iron- and manganese-oxide coatings on mineral grains formed near redox boundaries and weathered hornblende diorite that underlies much of the western subarea. In Q1 2018, Cr(VI) concentrations in two quarterly samples of water from well MW-121D of 3.9 µg/L exceeded the normal UTL_{95} value for the western subarea and the overall UTL_{95} value. Concentrations of Cr(VI) in water from well MW-121S within the summative-scale Cr(VI) plume increased monotonically and ranged from 2.3 to 3.7 µg/L between Q2 2017 and Q1 2018 but did not exceed the overall normal UTL_{95} value of 3.8 µg/L and likely would not be included in an updated regulatory Cr(VI) plume.

The normal Cr(VI) UTL_{95} value of 4.8 µg/L in the northern subarea upgradient from the Mount General fault (table G.5) is greater than the overall normal UTL_{95} value of 3.8 µg/L. The higher normal UTL_{95} value for the northern subarea upgradient from the Mount General fault results from water-level declines associated with agricultural pumping. As a result of these declines a thin veneer (commonly less than 10 ft thick) of saturated Mojave-type deposits in this area overlies lacustrine and mudflat/playa deposits at depth; consequently, many monitoring wells in this area are partly or entirely screened in the underlying deposits. The higher UTL_{95} value better accounts for potential natural Cr(VI) in water from wells completed in undifferentiated unconsolidated deposits in the northern subarea than the overall normal UTL_{95} value of 3.8 µg/L and provides for possible increases in Cr(VI) concentrations if water levels continue to decline. Concentrations of Cr(VI) in water from wells MW-139S1, MW-142S1, and MW-173S1 (fig. G.9), which exceed the overall normal UTL_{95} value, do not exceed the normal Cr(VI) UTL_{95} value of 4.8 µg/L for undifferentiated, unconsolidated deposits in the northern subarea upgradient from the Mount General fault. Although the provenance of core material penetrated by wells MW-139S1, MW-142S1, and MW-173S1 was not described as part of this study (Miller and others, 2020), drillers' logs indicate the wells penetrate clay-rich materials consistent with mudflat/playa deposits.

Farther downgradient from the Q4 2015 regulatory Cr(VI) plume and the summative-scale Cr(VI) plume, higher normal Cr(VI) UTL_{95} values of 9.0 and 6.4 µg/L were calculated for undifferentiated, unconsolidated deposits in the northern subarea downgradient from the Mount General fault and for Water Valley, respectively (table G.5). These values result from natural Cr(VI) concentrations associated with mudflat/playa deposits in the northern subarea downgradient from the Mount General fault and locally derived alluvium containing basalt in Water Valley; additionally, both areas contain weathered Miocene materials. Water from wells in these areas is strongly alkaline with pH values commonly greater than 8.2 that contribute to the desorption of Cr(VI) from aquifer materials. Although reflective of conditions between Q2 2017 and Q1 2018, UTL_{95} values for the northern subarea downgradient from the Mount General fault are less than some regulatory Cr(VI) values as high as 20 µg/L in water from well MW-154S1 collected before this study. Geologic, geochemical, and hydrologic conditions in the northern subarea downgradient from the Mount General fault and Water Valley differ from conditions near the Q4 2015 regulatory Cr(VI) plume and summative-scale Cr(VI) plume margins, and these UTL_{95} values do not represent appropriate background values for determining the extent of the regulatory Cr(VI) plume released from the Hinkley compressor station.

The summative-scale Cr(VI) plume estimates the extent of anthropogenic Cr(VI) for March 2015 to November 2017, and the UTL_{95} background values were calculated from data outside the summative-scale Cr(VI) plume extent for the 1-year period from April–June 2018 to January–March 2019. The SSA may partly explain why the mapped summative-scale Cr(VI) plume extent includes wells, such as MW-121S and other wells, having chromium concentrations less than UTL_{95} values for the various subareas in Hinkley Valley. For example, water from well MW-121S in the western subarea, sampled as part of this study in March 2015 and March 2017, had Cr(VI) concentrations of 2.0 µg/L. These values are less than the normal UTL_{95} value for the western subarea of 3.8 µg/L, but the well was included within the summative-scale Cr(VI) plume. Regulatory Cr(VI) concentrations in water from well MW-121S were as high as 11 µg/L shortly after the well was installed in August 2011 and water from well MW-121S may have contained anthropogenic Cr(VI) at that time. The SSA used to estimate the summative-scale plume extent includes trend data (question 4, table G.4) for the period of July 2012–June 2017. Additionally, Cr(VI) is a strong oxidant (Guertin and others, 2004); pH-dependent sorption and selected trace-element concentration data used within the summative scale (questions 5 and 6, table G.1) describe the physical and chemical alteration of surface sorption sites on aquifer materials and changes in aqueous geochemistry that have occurred within the Cr(VI) plume since the initial Cr(VI) releases occurred in 1952 (chapter C, figs. C.15, C.22; chapter E, figs. E.14*A, B, C*). Incorporation of longer-term trend data and pH-dependent sorption processes for Cr(VI) and other trace elements within the SSA may partly explain why the mapped summative-scale Cr(VI) plume extent includes wells, such as MW-121S and other wells, having chromium concentrations less than UTL_{95} values for the various subareas in Hinkley Valley.

Background Cr(VI) concentrations calculated as part of this study do not represent predevelopment Cr(VI) concentrations in Hinkley and Water Valleys. Predevelopment (pre-1930) water levels (Thompson, 1929) were higher, and low-chromium Mojave-type deposits above the water table at the time of this study (2015–18) were saturated. Water-chemistry data collected before development of Hinkley and Water Valleys for agricultural purposes (Thompson, 1929) do not include Cr(VI) measurements. However, data indicate low dissolved-solids concentrations (less than 420 mg/L) and calcium/bicarbonate-type waters typical of recent recharge from the Mojave River as far downgradient as Water Valley near the margins of Harper (dry) Lake. Although pH was not measured, it was likely less alkaline than conditions at the time of this study, and Cr(VI) would likely have been sorbed to aquifer solids, with low Cr(VI) concentrations in water from wells.

G.4. Comparison of Hexavalent Chromium Background Concentrations with Water from Domestic Wells

Between January 27 and 31, 2016, more than 70 domestic wells were sampled for Cr(VI) and other constituents (fig. G.1). Analyses of Cr(VI) onsite in a USGS mobile field laboratory enabled interested residents and well owners to follow a sample from their well from the time of collection to analysis (chapter E), providing transparency in data collection and analysis and increasing trust in the process.

Concentrations of Cr(VI) in sampled domestic wells analyzed in the mobile laboratory ranged from less than the SRL of 0.1 to 4.0 µg/L (chapter E, appendix E.1, table E.1.3) and had a median value of 1.2 µg/L. The highest Cr(VI) concentration was in water from well 21N-04, the northernmost well sampled in Water Valley and the well farthest downgradient from the Hinkley compressor station (fig. G.1). Although Cr(VI) concentrations in water from well 21N-04 exceeded the overall normal Cr(VI) UTL_{95} value of 3.8 µg/L, they did not exceed the normal UTL_{95} value for Water Valley of 6.4 µg/L (table G.4). Several domestic wells in the eastern subarea were within the summative-scale Cr(VI) plume extent; however, water from these wells did not exceed the normal UTL_{95} value of 2.8 µg/L for the eastern subarea. No water samples from domestic wells in the western and northern subareas had Cr(VI) concentrations that exceeded the normal UTL_{95} values for undifferentiated, unconsolidated deposits in those areas.

By 2016, PG&E purchased most land overlying and near the Q4 2015 regulatory Cr(VI) plume. After the land was purchased, unused domestic wells were routinely destroyed based on guidance from the Lahontan Regional Water Quality Control Board (2013b), and water from some domestic wells that had higher Cr(VI) concentrations was unavailable for sample collection.

G.5. Conclusions

Hexavalent chromium, Cr(VI), was released between 1952 and 1964 from the Pacific Gas and Electric Company (PG&E) Hinkley compressor station in the Mojave Desert about 80 miles northeast of Los Angeles, California. Maps of Hinkley and Water Valleys prepared for regulatory purposes seemed to show rapid expansion of the extent of Cr(VI) concentrations greater than the interim regulatory background concentration of 3.1 micrograms per liter (µg/L) in water from monitoring wells between 2008 and 2012. By 2015, the mapped extent of Cr(VI) concentrations greater than 3.1 µg/L included discontinuous areas in the eastern, western, and northern subareas of Hinkley Valley and extended into Water Valley more than 8 miles downgradient from the Hinkley compressor station. However, it was unclear whether Cr(VI) in newer monitoring wells was associated with Cr(VI) released from the Hinkley compressor station or Cr(VI) was naturally occurring and predated releases from the Hinkley compressor station.

The U.S. Geological Survey was requested by the Lahontan Regional Water Quality Control Board to complete an updated background study of Cr(VI) concentrations in Hinkley and Water Valleys. The purpose of this chapter is to (1) estimate the extent of anthropogenic Cr(VI) released from the Hinkley compressor station in the upper aquifer in Hinkley and Water Valleys and (2) calculate background Cr(VI) concentrations in the upper aquifer near and within the estimated Cr(VI) plume extent.

A summative scale was developed to answer the question, “Is Cr(VI) in water from sampled wells natural or anthropogenic?” The scale was used to define the extent of anthropogenic Cr(VI) associated with releases from the Hinkley compressor station and to identify natural Cr(VI). The scale consisted of eight items formulated as questions requiring binary (yes or no) answers addressing the geology of aquifer materials, aqueous geochemistry, and the hydrologic history of water from wells. 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 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 scored −1 for answers consistent with natural Cr(VI) and +1 for answers consistent with anthropogenic Cr(VI). The scores were summed to create a single value for each well. Data used to score wells included (1) physical and chemical data (handheld X-ray fluorescence data) on aquifer materials adjacent to the screened interval of sampled wells (chapter B), (2) time-series results based on more than 10,000 Cr(VI) analyses from more than 550 wells collected for regulatory purposes by PG&E between July 2012 and June 2017 (chapter D), and (3) chemical and isotopic data (including groundwater age-dating constituents) collected as part of this study from more than 100 wells (chapters E and F). When data from each well are scored using 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 were developed, and scoring metrics for those questions were refined, with input from a technical working group composed of Hinkley community members, the Independent Review Panel Manager (Project Navigator, Ltd.), the Lahontan Regional Water Quality Control Board, PG&E, and consultants for PG&E. A preliminary version of the scale was published by Izbicki and Groover (2018). Subsequently, the summative scale and scoring metrics were further refined with input from the technical working group for final use in this study.

The summative scale provides little discretion in the interpretation of data collected as part of this study. By design, when data collected from each well were 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. Differences in sorption of Cr(VI), and other trace elements, with pH addressed by the summative scale are well founded from a geochemical basis, and of all the questions within the scale, question 5 (“Is there an excess of Cr(VI) with respect to pH…?”) is potentially the most relevant for decision makers. Both Cr(VI) and pH are measured quarterly as part of regulatory data collection; in the future Cr(VI) and pH data can be used in the absence of the detailed geologic, geochemical, and hydrologic data collected as part of this study to provide information on the natural or anthropogenic source of Cr(VI) in water from wells. A different study design may have collected different data, formulated different summative-scale questions with different metrics to answer those questions, and may have produced a different summative-scale Cr(VI) plume extent.

The summative scale did not include a threshold Cr(VI) concentration or use water-level data as items in the scale. A numerical groundwater-flow model of Hinkley and Water Valleys was updated by consultants for PG&E with the intent of addressing physical and hydraulic constraints on groundwater flow and Cr(VI) movement downgradient from the Hinkley compressor station. Hydraulic data collected in support of model development are provided in chapter H within this professional paper, and the suitability of the updated model for use in this study is described in chapter H within this professional paper (appendix H.2).

The summative-scale Cr(VI) plume downgradient from the Hinkley compressor station was mapped as the lowest positive summative-scale score that produced a contiguously mappable plume. The areal extent of anthropogenic Cr(VI) within the mapped summative-scale Cr(VI) plume was 5.5 square miles (mi^2). This area encompasses the 2.2-mi^2 extent of the October–December 2015 (Q4 2015) Cr(VI) regulatory plume but is smaller than the 8.3-mi^2 maximum mapped extent of Cr(VI) greater than 3.1 µg/L. The summative-scale Cr(VI) plume included all shallow wells within the footprint of the Q4 2015 regulatory plume, but summative-scale scores indicate that anthropogenic Cr(VI) was not present in several wells screened within the deep zone of the upper aquifer. The summative-scale Cr(VI) plume is within the area covered by the PG&E monitoring well network and lies within “Mojave-type” deposits (Mojave River alluvium and lake-margin deposits) sourced from the Mojave River. The summative-scale Cr(VI) plume included 2.5 mi^2 of the eastern subarea and 0.7 mi^2 of the northern subarea not included within the Q4 2015 regulatory Cr(VI) plume. Identification of anthropogenic Cr(VI) within the lower aquifer in Hinkley Valley was outside the scope of this study.

Aquifer materials, including chromium-containing minerals and chromium sorbed to the surfaces of mineral grains, and groundwater in contact with those materials are a single system, and scores for questions within the summative scale are not strictly independent measures of natural or anthropogenic Cr(VI) occurrence in groundwater. However, the summative-scale analysis (SSA) identified Cr(VI) in water from wells in a wide range of geologic, geochemical, and hydrologic settings as natural or anthropogenic. Water from most wells was oxic (contained dissolved oxygen), and Cr(VI) was not generally present in water from wells that did not contain dissolved oxygen. Wells having high Cr(VI) concentrations attributable to chromium within visually abundant iron- and manganese-oxide coatings on the surfaces of mineral grains were identified as containing natural Cr(VI). Similarly, wells having high Cr(VI) concentrations attributable to mudflat/playa deposits, weathered mafic bedrock, or weathered minerals within Miocene deposits also were identified as containing natural Cr(VI). Additionally, Cr(VI) concentrations in older water from wells that are isolated from sources of groundwater recharge have alkaline pH, with a greater probability of containing natural Cr(VI) than younger water from wells having neutral to slightly alkaline water, also were identified as natural Cr(VI). Wells near the margins of the summative-scale Cr(VI) plume that had low levels of tritium consistent with post-1952 recharge were not identified as anthropogenic Cr(VI) within the SSA solely on the basis of the age (time since recharge) of water from those wells. Wells downgradient from the western excavation site with no obvious source of natural chromium were not consistently identified as anthropogenic within the SSA but were not used to calculate Cr(VI) background concentrations on the basis of other data collected as part of this study. Summative-scale results were generally consistent with other mineralogic and geochemical data collected as part of the study that were not included within the SSA.

Background concentrations of Cr(VI) were estimated as the upper 95-percent tolerance limit (UTL_{95}) using the computer program ProUCL 5.1. The UTL_{95} values were calculated using two sets of data from wells outside the summative-scale Cr(VI) plume collected between April 2017 and March 2018. On the basis of the SSA, water from these wells contained natural Cr(VI). The first dataset included only wells screened within Mojave-type deposits that had been sampled for detailed chemical and isotopic data, including age-dating constituents, as part of this study. The second dataset included additional wells screened within undifferentiated, unconsolidated deposits sampled for regulatory purposes. The UTL_{95} values calculated from the larger regulatory dataset have less geologic specificity but greater spatial resolution and more statistical power than the smaller dataset that included only sampled wells completed in Mojave-type deposits.

The normal Cr(VI) UTL_{95} values calculated from the median of quarterly data from sampled wells in undifferentiated, unconsolidated deposits within the eastern and western subareas and in the northern subarea upgradient from the Mount General fault were 2.8, 3.8, and 4.8 µg/L, respectively. These values were selected as background Cr(VI) concentrations for the subareas in this study. An overall normal UTL_{95} value of 3.8 µg/L was calculated for the eastern, western, and northern subareas upgradient from the Mount General fault. This value is similar to the overall UTL_{95} value of 3.9 µg/L that was calculated for the Mojave-type deposits and is similar to the maximum Cr(VI) concentration of 3.6 µg/L that was calculated for older groundwater in contact with Mojave-type deposits (chapter F, table F.4). The provenance of most PG&E monitoring wells is not precisely known and, in most cases, the overall normal UTL_{95} value of 3.8 µg/L calculated for undifferentiated, unconsolidated deposits may be an acceptable choice for a regulatory Cr(VI) background value.

The UTL_{95} value of 2.8 µg/L in the eastern subarea is important for plume management because most of the summative-scale Cr(VI) plume is within the eastern subarea; this UTL_{95} value of 2.8 µg/L would provide for earlier identification of plume expansion in the eastern subarea than the overall UTL_{95} value of 3.8 µg/L for undifferentiated, unconsolidated deposits. The UTL_{95} value of 4.8 µg/L in the northern subarea upgradient of the Mount General fault accounts for construction practices in which monitoring wells penetrate Mojave-type deposits and yield water from underlying deposits; this UTL_{95} value provides for possible increases in Cr(VI) concentrations if water levels continue to decline. A UTL_{95} value was calculated separately for (1) mudflat/playa deposits in the eastern subarea, (2) the northern subarea downgradient from the Mount General fault and for Water Valley, and (3) for the Cr(VI) plume extent once updated for regulatory purposes.

The normal UTL_{95} values estimated for the different subareas in Hinkley Valley provide greater precision for updating the regulatory Cr(VI) plume extent and for plume management than the overall UTL_{95} value. For example, the normal UTL_{95} value of 2.8 µg/L for the eastern subarea would have facilitated rapid identification of 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. This value does not include higher natural Cr(VI) concentrations associated with mudflat/playa deposits and older (pre-1952) groundwater near Mount General and a higher UTL_{95} value of 5.8 µg/L was calculated for wells in that part of the eastern subarea. A UTL_{95} value of 2.3 µg/L was computed for anthropogenic Cr(VI) within the aquifer downgradient from the Hinkley compressor station. This value estimated background Cr(VI) concentrations downgradient from the Hinkley compressor station if Cr(VI) had not been released into groundwater. The lower UTL_{95} value accounts for Cr(VI) concentrations in coarse-textured, low-chromium Mojave-type deposits containing younger (post-1952), neutral to slightly alkaline groundwater recharged from the Mojave River within that area and may be a suitable metric for Cr(VI) cleanup goals within the Cr(VI) plume after regulatory updates. The UTL_{95} value of 4.8 µg/L for undifferentiated unconsolidated deposits in the northern subarea upgradient from the Mount General fault accounts for subsurface geologic conditions that result in some monitoring wells penetrating Mojave-type deposits and deriving part of their water from underlying non-Mojave-type deposits. Farther downgradient from the Q4 2015 regulatory Cr(VI) plume and the summative-scale Cr(VI) plume, higher 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, respectively. These downgradient UTL_{95} values are suitable to identify unusual Cr(VI) concentrations in water from wells in these areas.

Between April 2011 and March 2019, the regulatory Cr(VI) plume was updated quarterly by PG&E and regulators, with input from the local community and other stakeholders. Updating the regulatory Cr(VI) plume was beyond the scope of this study; however, the UTL_{95} values are intended to inform that process by providing scientifically defensible estimates of background Cr(VI) concentrations that differ with local geologic, geochemical, and hydrologic conditions in Hinkley and Water Valleys. Although identified on the basis of the SSA as containing anthropogenic Cr(VI), Cr(VI) concentrations in some wells within the summative-scale Cr(VI) plume are low and may not require regulatory attention. Consequently, for January–March 2018, the latest data available for this study, an updated regulatory Cr(VI) plume would lie within the summative-scale Cr(VI) plume extent and would not likely include wells that have Cr(VI) concentrations less than the UTL_{95} values calculated for the eastern and western subareas and the northern subarea upgradient from the Mount General fault.

Positive bias within data used to calculate the UTL_{95} values resulting from the well selection process and previous regulatory decisions ensured that wells with higher Cr(VI) concentrations that effectively control estimates of Cr(VI) background concentrations were included in the calculations. The extent of positive bias on the UTL_{95} estimates of Cr(VI) background concentrations was not estimated as part of his study.

The study results, including the estimate of the summative-scale Cr(VI) plume extent and UTL_{95} background values, were developed for data representing specific periods. The summative-scale Cr(VI) plume estimates the extent of anthropogenic Cr(VI) for the period from March 2015 and November 2017; the UTL_{95} background values were calculated from data outside the summative-scale Cr(VI) plume extent for the 1-year period (four quarters) from April 2018 to March 2019. The 3-year period of data collection used to estimate the summative-scale Cr(VI) plume extent was incorporated into 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 1-year period of data collection used to estimate the UTL_{95} values was incorporated into the study design 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. However, study results incorporate some data collected over longer timeframes. For example, the summative-scale Cr(VI) plume extent was estimated from Cr(VI) concentration trend data within the summative scale that were calculated from regulatory data collected between July 2012 and June 2017. Additionally, the pH-dependent sorption and selected trace-element concentration data used within the summative scale reflect changes in aquifer materials and aqueous geochemistry that have occurred as a results of Cr(VI) releases from the Hinkley compressor station since the initial Cr(VI) releases occurred in 1952.

Concentrations of Cr(VI) in water from more than 70 domestic wells sampled and analyzed onsite in a U.S. Geological Survey mobile field laboratory between January 27 and 31, 2016, ranged from less than the study reporting level of 0.1 to 4 µg/L, and the median concentration was 1.2 µg/L. The highest Cr(VI) concentration was in water from well 21N-04, the northernmost well sampled in Water Valley and the well farthest downgradient from the Hinkley compressor station. Although the Cr(VI) concentration in water from well 21N-04 exceeded the overall Cr(VI) UTL_{95} value of 3.8 µg/L, the concentration did not exceed the normal UTL_{95} value for Water Valley of 6.4 µg/L. Several domestic wells in the eastern subarea were within the summative-scale Cr(VI) plume extent; however, water from these wells did not exceed the normal UTL_{95} value of 2.8 µg/L for the eastern subarea. No water samples from domestic wells in the western or northern subareas had Cr(VI) concentrations that exceeded the normal UTL_{95} values for undifferentiated, unconsolidated deposits in those areas. Unused domestic wells on property purchased by PG&E were routinely destroyed under guidance from the Lahontan Regional Water Quality Control Board; water from destroyed domestic wells that had high Cr(VI) concentrations greater than the UTL_{95} values for the western and northern subarea was unavailable for sample collection as part of this study.

Groundwater in much of Hinkley and Water Valleys has been affected by activities other than Cr(VI) releases from the Hinkley compressor station, including water-level declines and recharge of return water from agricultural and residential development. Background Cr(VI) concentrations calculated as part of this study do not represent predevelopment Cr(VI) concentrations in Hinkley and Water Valleys.

The UTL_{95} values calculated as part of this study are not background Cr(VI) concentrations for regulatory purposes. The authority to establish regulatory values resides solely with the Lahontan Regional Water Quality Control Board.

G.6. References Cited

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Appendix G.1. Water Chemistry, Isotope Data, and Summative-Scale Scores Used to Estimate the Summative-Scale Hexavalent Chromium Plume Extent

This appendix contains one table with selected well-construction data, chemical and isotopic data, and summative-scale scores for sampled wells in Hinkley and Water Valleys, California (table G.1.1, available for download at https://doi.org/10.3133/pp1885). Scores for each question within the summative scale and the alternative anthropogenic and natural summative scales described within this chapter are provided for each sampled well. The summed scores for the summative scale and the alternative summative scales also are provided. Chemical and isotopic data within this table are available through the U.S. Geological Survey National Water Information System database (U.S. Geological Survey, 2021).

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Appendix G.2. Data Used to Calculate Hexavalent Chromium Background Concentrations

This appendix contains two tables (tables G.2.1, G.2.2, available for download at https://doi.org/10.3133/pp1885). Well information and hexavalent chromium, Cr(VI), data used to calculate Cr(VI) background concentrations in "Mojave-type" deposits within Hinkley and Water Valleys, California, are provided in table G.2.1. Well information and hexavalent chromium, Cr(VI), data used to calculate Cr(VI) background concentrations in undifferentiated unconsolidated deposits within Hinkley and Water Valleys, Calif., are provided in table G.2.2. The subarea and the Pacific Gas and Electric Company well identification and aquifer designation are identified within each table. Chemical data within this table for wells having the prefix "BG" are available through the U.S. Geological Survey National Water Information System database (U.S. Geological Survey, 2021). Chemical data for wells collected for regulatory purposes are in annual reports from the Pacific Gas and Electric Company available through the online database GeoTracker (State Water Resources Control Board, 2020).

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