An Assessment of Oil and Gas Water Cycle Reporting in California

Evaluation of Data Collected Pursuant to California Senate Bill 1281, Phase II Report

FULL REPORT

A Commissioned Report prepared by the
California Council on Science and Technology

CCST
CALIFORNIA COUNCIL ON
SCIENCE & TECHNOLOGY

A nonpartisan, nonprofit organization established via the California State Legislature
— making California's policies stronger with science since 1988

An Assessment of Oil and Gas Water Cycle Reporting in California:

Evaluation of Data Collected Pursuant to California Senate Bill 1281

An Independent Review of Scientific and Technical Information

Phase II Report

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About CCST

The California Council on Science and Technology is a nonpartisan, nonprofit organization established via the California State Legislature in 1988. CCST responds to the Governor, the Legislature, and other State entities who request independent assessment of public policy issues affecting the State of California relating to science and technology. CCST engages leading experts in science and technology to advise state policymakers—ensuring that California policy is strengthened and informed by scientific knowledge, research, and innovation.

Note

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Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

2015 Q1 (Q2, etc.)	The first quarter of the year 2015, second quarter of 2015, and so on.
ACGIH	American Conference of Governmental Industrial Hygienists
ACToR	U.S. EPA, Aggregated Computational Toxicology Resource Database
AF	Acre-feet (or acre-foot)
AFQ	Acre-feet per quarter
AFY	Acre-feet per year
AGR	Agricultural beneficial use
amu	Atomic mass unit
ATSDR	U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry
B	Boron
bbd	Barrels per day
Bbbl	Billion barrels
bbl	Barrels (petroleum liquid)
BTEX	Benzene, toluene, ethylbenzene, and xylene
BOD	Biochemical oxygen demand
CARB	California Air Resources Board
CASRN	Chemical Abstracts Service registry numbers
CCL	Contaminant Candidate List
CCST	California Council on Science and Technology
CDWR	California Department of Water Resources

CFR	Code of Federal Regulations
COD	Chemical oxygen demand
CVRWQCB	Central Valley Regional Water Quality Control Board
CV-SALTS	Central Valley Salinity Alternatives for Long-Term Sustainability
DBP	Disinfection byproducts
DI	Disinfection
DO	Deoiling
DOC	Dissolved organic carbon
DOGGR	Division of Oil, Gas, and Geothermal Resources
DS	Desalinization
dS/m	deciSiemens per meter
EC	Electrical conductivity
DWR	Department of Water Resources
EC50	Effective concentration where 50% of population is immobilized
ECHA	European Chemicals Agency
ECOTOX	U.S. EPA, Ecotoxicology Database
ELAP	Environmental Laboratory Accreditation Program
EOR	Enhanced oil recovery
EPISuite	U.S. EPA Estimation Programs Interface Suite
EU	European Union
FO	Forward osmosis
Fresh/Brackish	Produced water identified in the SB 1281 dataset that has less than or equal to 10,000 mg/L TDS

GAMA	Groundwater Ambient Monitoring and Assessment
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
gpd	Gallons per day
HAP	Hazardous air pollutant
HBSL	U.S. Geological Survey, Health Based Screening Levels
HEAST	U.S. EPA, Health Effects Assessment Summary Tables
HHBP	U.S. EPA, Human Health Benchmarks for Pesticides
HSDB	Hazardous Substance Data Bank
IARC	International Agency for Research on Cancer
IND	Industrial beneficial use
IPCS	World Health Organization, International Programme on Chemical Safety
IRIS	U.S. EPA Integrated Risk Information System
IUCLID	European Chemicals Agency, International Uniform Chemical Information Database
KH	Henry's constant
Koc	Organic carbon-water partition coefficients
Kow	Octanol-water partition coefficients
LC50	Lethal concentration to 50% of a study population
LD50	Lethal dose to 50% of a study population
m	Meters
Mbbl	Thousand barrels
MMbbl	Million barrels

mg/L	Milligrams/Liter, a measurement of concentration
mmhos/cm	millimhos per centimeter
MRL	Minimal risk level
µS/cm	Micromhos per centimeter
MT	Membrane treatment
MUN	Municipal and domestic beneficial use
MWCO	Molecular weight cut-off
NIOSH	National Institute for Occupational Safety and Health
NIOSH REL	National Institute for Occupational Safety and Health recommended exposure level
NORM	Naturally occurring radioactive material
NPDES	National Pollution Discharge Elimination System
NWIS	National Water Well Information System
OECD	United Nations Organisation for Economic Co-operation and Development
OEHHA	California Office of Environmental Health and Hazard Assessment
OSHA	Occupational Safety and Health Administration
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
OT	Other treatments
PAHs	Polycyclic aromatic hydrocarbons
PBT/vPvB	Persistent, bioaccumulative, and toxic/very persistent and very bioaccumulative
PHG	Public health goals

PLONOR	Posing little or no risk
POM	Polycyclic organic matter
PPRTV	U.S. EPA, Provisional Peer Reviewed Toxicity Values
PRC	Public Resources Code
PRO	Industrial process beneficial use
QAC	Quaternary ammonium compounds
QSAR	Quantitative structure-activity relationship
RAHC	Reasonably anticipated to be a human carcinogen
REACH	Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals
REL	Reference exposure level
RfC	Reference concentration
RfD	Reference dose
RfV	Reference value
RO	Reverse osmosis
Saline	Produced water identified in the SB 1281 Production dataset that has more than 10,000 mg/L TDS
SAR	Sodium adsorption ratio
SB	Senate Bill
SC	Specific conductance
SCAQMD	South Coast Air Quality Management District
SVHC	Substances of Very High Concern
SWRCB	California Water Resources Control Board

TAC	Toxic Air Contaminants
TDS	Total dissolved solids
TEDX	The Endocrine Disruption Exchange
TOXNET	National Library of Medicine, Toxicology Data Network
UF	Ultrafiltration
UIC	Underground Injection Control
USGS	United States Geological Survey
UVCB	Substance of unknown or variable composition, complex reaction products, and biological materials
VOCs	Volatile organic compounds
WDR	Waste discharge requirements
WOR	Water-to-oil ratio

Introduction:

SB 1281 Water Data Study

Brie Lindsey, Senior Program Associate, Project Manager, California Council on Science and Technology

Introduction

California Senate Bill (SB) 1281 (Pavley, 2014) mandates the collection of data about the use, production, and disposition of water in the oil and gas (O&G) industry. The passage of SB 1281 epitomized the state legislature's need for increased understanding of the water cycle during a multi-year period of drought. Between 2011 and 2017, the state experienced an intense drought lasting more than seven years (U.S. Drought Monitor, 2019). Amid these hydrologic conditions, a heightened awareness of water management and limitations in the Golden State was apparent in legislative discussions and activities concerning the use, conservation, and protection of existing water resources. During this period, SB 4 (Pavley, 2013) was passed. It declared that "protecting the state's groundwater for beneficial use, particularly sources and potential sources of drinking water, is of paramount concern," and required increased transparency of O&G operations related to hydraulic fracturing via additional data collection and reporting. This piece of legislation was followed by other bills intended to conserve and protect water through improved management and increased transparency in reporting involving water source and quality. The year after SB 4 passed, Governor Brown signed into law a trio of bills that together make up the foundation of the Sustainable Groundwater Management Act (SGMA, 2014): Assembly Bill (AB) 1739, SB 1319, and SB 1168. These bills contain provisions that task local and regional jurisdictions to work with State agencies toward the goal of sustainable groundwater management in California by 2042. The framework relies in part on groundwater data that can be accessed through various agencies, including The Division of Oil, Gas, and Geothermal Resources ("the Division" or DOGGR) under the Department of Conservation.

During the drought, decision makers needed information to understand the impact of oil and gas development, production, and transport on the state's water resources. The result was an emphasis on transparency in these activities as evidenced by subsequent passage of legislation such as AB 1420 (Salas, 2015) and AB 1328 (Limón, 2017). Among other things, AB 1420 requires operators to submit to The Division maps of all natural gas pipelines that pass through designated waterways. AB 1328 authorizes Regional Water Quality Control Boards to require and make publicly available certain information about added chemicals (including trade secrets, with some protections of these) if oilfield-produced waters are discharged to surface or land.

Also passed during this period was SB 1281, a data collection mandate to enhance existing water reporting requirements. This legislation required operators to furnish to The Division more detailed information about the sources, destinations, volumes, quality, storage, and treatments of water involved in upstream O&G activities. While the Public Resources Code (PRC) already required monthly reporting of the volumes of oil, gas, and water produced *from* each well, the sources of water applied *to* wells to produce these quantities—and the destinations of water produced in the process—were not reported with great specificity. SB 1281 required greater specificity in reporting on these items, as well as the treatment of produced water, the use of recycled water both on and off the oilfield, the storage of water, and whether untreated water was "suitable for domestic or irrigation purposes." (For the full text of SB 1281 and a comparison of how it amended the PRC, please see Appendix Intro.1.) The new reporting added by SB 1281 required:

- An annual inventory of unlined O&G field sumps (lined or unlined pits) (PRC 3226.3).
- Greater detail on the source and volume of water used, and disposed of, on a per-well basis (PRC 3227(a)(5 and 7), f(1 and 2)).
- Treatment of water used, and the use of treated and recycled water (PRC 3227(a)(6), f(2)).
- Information on water stored on O&G fields (PRC 3227(a)(7)(B)).

Pursuant to SB 1281, The Division designed a new reporting form to compile data collected from operators, resulting in a supplemental dataset on the water cycle for the California O&G industry. The dataset, herein referred to as the "SB 1281 dataset," is updated quarterly, beginning in the first quarter of 2015. The greater amount of information provided on the source, treatment, reuse, and disposition of water by the O&G industry is collected with the intent to enable stakeholders to better address important, policy-relevant questions pertaining to water use for oil and gas production than were previously possible. SB 1281 was written to increase transparency and was also intended to build a bridge to other existing datasets so that more complex questions could also be addressed than what is possible with data originating from a single agency.

The Division provides quarterly summaries of the SB 1281 dataset in PDF format (DOGGR, 2019). These summaries provide standard reports of information, such as the volume of water produced and injected for two quality categories (> or ≤10,000 mg/L Total Dissolved Solids (TDS)), disposition methods for produced water, sources of injected water, and treatment methods applied to produced water. Additionally, the data can be downloaded via The Division website[1]; it was recently incorporated into The Division's updated data

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[1] ftp://ftp.consrv.ca.gov/pub/oil/SB1281/ NB: At the time of this writing, data available for download directly from the FTP site spanned 2015 through 2017.

platform, WellSTAR[2]. Though the main functionality of WellSTAR is currently directed at operators for reporting data as mandated, The Division states on its website it plans to make the data available to the public through WellSTAR in the future.

Now that The Division has collected and reported on the items mandated by SB 1281 since 2015, it has requested that the California Council on Science and Technology perform a preliminary assessment of the value of this dataset to answer important research and policy-relevant questions.

CCST's Role and Charge

The California Council on Science and Technology (CCST) is called upon to provide credible, relevant, and independent information and analysis to inform policy decisions related to science and technology issues. This report is the deliverable of the second phase of a study CCST has undertaken to evaluate the utility of the SB 1281 dataset under contract with The Division. The SB 1281 dataset was designed by The Division to collect data from operators about water use, production, storage, and disposition in the O&G industry in California. This document has been researched and written by principal researchers and select CCST staff under the guidance of a Steering Committee with an appropriate range of expertise, a balance of perspectives, and no conflicts of interest (see Appendices B and C).

CCST strives to produce reports through a transparent process that ensures the final product is responsive to the questions of the sponsor, while maintaining full scientific independence. Transparency is achieved by engaging the sponsor in dialogue about the nature of their needed information and informing the sponsoring agency of the study progress.

Report Objective

This report is the second document produced in a two-phase study. In Phase I, the primary goal was to provide a list of questions responsive to the intent of SB 1281 (to increase transparency about the impacts of O&G activities on water resources in California) that could guide the Phase II preliminary assessment of the SB 1281 dataset, available for 2015 through 2017. These questions function in complementary fashion:

1. The **primary study question** was concerned with the quality and utility of the dataset itself—answering some of the operational questions associated with the primary study question will require direct assessment of the database, as highlighted above.

2. The series of **secondary evaluation questions** were key questions that users of the SB 1281 dataset might wish to answer. Phase I outlined **operational questions**

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[2] WellSTAR can be accessed via: https://www.conservation.ca.gov/dog/for_operators/Pages/WellSTAR.aspx

> associated with these topics, which could guide a functional evaluation of the dataset, including whether there are sufficient data to arrive at satisfactory answers, whether the dataset lends itself well to connectivity with other relevant datasets, etc.

The resulting Phase I study and evaluation questions were:

> **Primary study question**: What is the utility of the current SB 1281 dataset to answer important questions on water resources, public health, and the environment, and are there opportunities for improvement?
>
> **Secondary Question 1**: What are the sources, volumes, and quality of water used for oil and gas development and production in California?
>
> **Secondary Question 2**: What are the characteristics and quality of produced water across the state, and how do these vary over time?
>
> **Secondary Question 3**: How does treatment impact produced water availability as a potential resource, both within and outside of oilfields?
>
> **Secondary Question 4**: What are the potential and actual hazards, risks, and impacts to environmental and human health from various dispositions of reused water discharges to land, water, and subsurface injection?
>
> **Secondary Question 5**: Are there unrealized opportunities to improve and expand direct and indirect reuse of produced water while limiting unintended consequences?

Each of these questions was considered in Phase I with a brief discussion of the data required to answer supporting operational questions. Though each question in Phase I is considered relevant to the intent of SB 1281, not all questions from Phase I were intended to be the subject of analysis in Phase II. A subset was chosen during Phase II based on considerations of their tractability, significance, relevance, and feasibility, as well as available resources.

Early in Phase II, while datasets were being prepared for research and analysis, the selected questions were further refined to allow for a more streamlined report to address the widest array of questions given resource limitations. Therefore, not all questions addressed in the Phase II report are phrased identically to those listed in Phase I. (See Appendix Intro.2 for the full list of evaluation questions and their associated operational questions, some of which are directly addressed in the chapters of this Phase II report.)

The overall purpose of Phase II was to assess the ability of the SB 1281 dataset to increase transparency in California's O&G industry with respect to water consumption, production, treatment, storage, transport, reuse, and disposal. Herein, that assessment is based on an evaluation of the structure of the database itself, and on how well the SB 1281 dataset improves the ability to address select questions like those identified in Phase I of this study—important, policy-relevant questions about water in the O&G industry in California. Finally, the goal of this report is to provide feedback to The Division on how to improve the SB 1281 dataset toward answering these important questions.

Direct initial assessment of the SB 1281 dataset compares relevant SB 1281 data with datasets long in use by The Division and operators to report oil production and oilfield produced water injection quantities. The initial assessment is followed by an evaluation of the dataset structure and function both as a standalone resource and as it functions in conjunction with other available relevant datasets. This evaluation is achieved through application of the SB 1281 dataset and other relevant datasets to a selection of questions of which an array of stakeholders might expect SB 1281 to improve answerability.

In broadest terms, a key policy-relevant question SB 1281 is meant to help address is: *What impact does the development of oil and gas in California have on water resources, public health, and the environment?* Of course, such a broad and complex topic must be broken into multiple focus areas, as discussed in Phase I of this study. Considering resources available, this report addresses the following general questions, each having multiple parts:

1. **What are the sources, volumes, and quality of water used for oil and gas development and production in California?** (Chapters 1 and 3)
    - How much fresh/brackish and saline water are produced and injected, and what are the sources and destinations of the water? (Ch 1)
    - How much water does the O&G industry use, and how much water do they reuse for their operations? (Ch 1)
    - Is the O&G industry a net consumer or generator of water? (Ch 1)
2. **What are the characteristics/quality of produced water across the state, and how do these vary over time?** (Chapters 1 and 3)
    - What is known about the quality of produced water in California? (Ch 3)
3. **How does treatment impact produced water availability as a potential resource, both within and outside of oilfields?** (Chapters 2 and 3)
    - What are the treatment approaches that have been used for produced water and how effective are they? (Ch 3)
4. **What are the potential and actual hazards, risks, and impacts to environmental and human health from various dispositions of reused water discharges to land, water, and subsurface injection?** (Chapters 3 and 4)

- What are the pathways through which human populations and the environment can be exposed to hazardous chemicals in produced water? (Ch 3)
- What is the volume of produced water sent to unlined produced water ponds and where are unlined produced water ponds in California? (Ch 4)
- Are groundwater resources, as measured in levels of total dissolved solids (TDS), in proximity to unlined produced water ponds? (Ch 4)
- Are there documented cases of unlined produced water ponds causing groundwater contamination? (Ch 4)

5. **Are there opportunities to expand reuse of produced water in some cases?** (Chapters 1 and 2)
    - Where is produced water reused for agriculture? (Ch 2)
    - How much water does the O&G industry withdraw and discharge compared to total human withdrawals in a region? (Ch 1)
    - What is the potential for expansion of produced water reuse for agricultural irrigation in California? (Ch 2)

Background: Water, Oil and Gas

Oil and Gas Production

United States

Petroleum production has been a major industry in the United States (U.S.) since the discovery of oil in Pennsylvania in the mid-1800s. Globally, the U.S. has ranked as an oil producer for some time, moving from third position behind Saudi Arabia and Russia in 2008 to leading the world in crude oil and natural gas production in 2018. During this span, U.S. petroleum and natural gas production has increased nearly 60% (U.S. Energy Information Administration (EIA), 2018c). The U.S. is currently recognized as the "oil and gas leader in the world over the next several decades," according to the U.S. Energy Information Administration (EIA, 2018d).

This trend is expected to continue, owing in large part to increased production since 2014 with the shale oil boom. This boom is supported by a combination of factors including advances in drilling and stimulation technologies, vast tight shale oil and gas reserves, and oil prices high enough to make it economically feasible for U.S. companies to explore and produce them profitably (Ratner and Tiemann, 2015).

California

Oil and gas have been commercially produced in California since the first producing well was drilled in the 1860s in the Petrolia oilfield. This was followed by longer-term commercially successful wells drilled in the 1870s in the Pico Canyon oilfield (Snell, 1963)—prolifically so after the Los Angeles City oilfield was discovered and commercialized in 1892 (Crowder, 1961). By 1903, California was the leading oil-producing state in the U.S., producing four million barrels a year (MMbbl/yr) (Department of Conservation, 2010). While California also produces natural gas—both as a byproduct of oil production and from gas production wells—the state's primary contribution to hydrocarbon production nationwide is via crude oil. While the state's gas production accounts for less than 0.75% of the U.S.'s total production annually, California contributed over 5% of the U.S.'s total oil production in 2017 (EIA, 2018a).

Today, California remains a major oil producing state. With annual production of over 174 MMbbl/yr in 2017, it was the fourth largest producer in the U.S. that year, behind Texas, North Dakota, and Alaska (Figure 1; EIA, 2018b). But while crude production has been increasing for the U.S. as a whole—a trend expected to continue for decades—California oil production has declined from a peak of nearly 400 MMbbl in 1985, to 44% of that figure, 174 MMbbl in 2017 (EIA, 2017a). This decline, which predates the shale boom, is due in part to the type of oil resources and geological reservoirs in the state—largely heavy (more viscous) crude that has migrated into relatively shallow formations—which requires enhanced oil recovery (EOR) techniques, especially as wells age and pressure in the formation naturally declines.

Box 1. Water Volume Units

The units used to measure and compare water volumes vary based on location, how much fluid is under discussion, and by industry. Generally speaking, the units of volume most commonly used to describe water in the United States are *gallons, barrels,* and *acre-feet*.

A **gallon (gal)** is the unit typically used when discussing relatively small volumes of water. This unit is reasonably intuitive for the average water consumer and is the preferred unit to use when speaking about water with the general public—in terms of the household, for instance. One U.S. gallon is defined as 231 cubic inches of fluid.

A **barrel (bbl)**—or more specifically, an "oil barrel"—is a unit of measurement used by the oil industry to describe volumes of oil and water alike. This unit of volume is unique to the oil industry, and should not be confused with the general volumetric unit of a fluid barrel in other contexts; in the U.S., most fluid barrels are 31.5 U.S. gallons, whereas a barrel of water reported by the O&G industry is equivalent to 42 U.S. gallons.

An **acre-foot (AF)** is the unit of volume commonly applied to large water resources, such as reservoirs, river flows, and irrigation water. In the water management industry, the acre-foot is the preferred unit, defined as 43,560 cubic feet, which is equivalent to 325,851 gallons.

Most volumes in this report are presented in acre-feet (with barrel and gallon conversions) because the questions often involve large volumes of water, summed across large regions of the state. When appropriate, gallons are used instead (with acre-feet conversions).

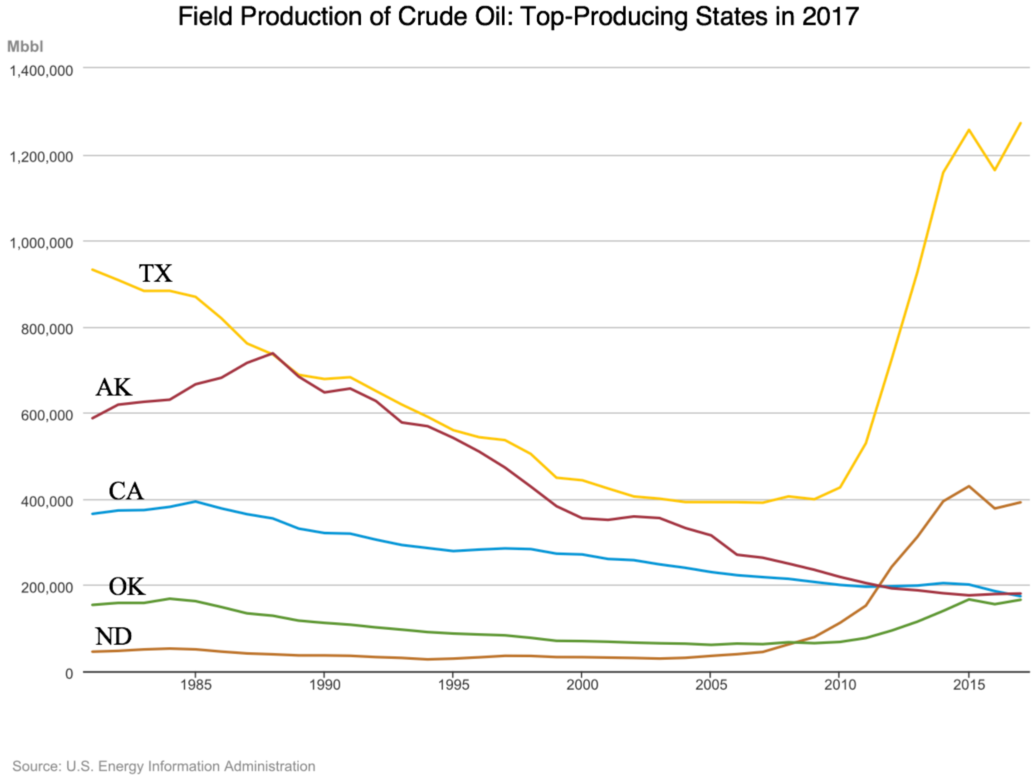

Figure 1. California (CA) annual crude oil production (blue line), with four other top-producing states: Texas (TX), North Dakota (ND), Oklahoma (OK), and Alaska (AK). Source: EIA data.

California's 516 fields and 135,000 active wells (as of 2017) are generally found along tectonic boundaries. Of the ten oil and gas producing basins, five sedimentary basins (San Joaquin, Los Angeles, Santa Barbara-Ventura, Santa Maria, and Salinas) account for the majority of the state's productivity. Within each basin, there may be several petroleum systems, or areas where hydrocarbons with common characteristics accumulate. Within petroleum systems, there may be multiple fields, each consisting of one or more pools—distinct reservoirs of oil under a single trap. Oilfields generally support many wells. By far, the most productive oil and gas region in the state is the southern portion of the San Joaquin basin in the southern half of the Central Valley, where some of the nation's largest oil fields are located (EIA, 2015). Production statistics by county show the state's productivity is largely driven by a few small regions within these basins, with Kern County accounting for nearly 75% of California's total oil production in 2017 (see Table 1; DOGGR, 2017a.).

Table 1. Top oil-producing counties in California in 2017. Of a total of 19 oil-producing counties, Kern County produces the most oil per year, nearly three-quarters of the state's total production. Source: DOGGR (2017a).

County	Oil Produced (bbl)	% of CA Total Oil Production	Water Produced (AF)	% of CA Total (Produced) Water Production
Kern	123,752,181	71%	233,893	57%
LA County	19,814,335	11%	112,473	28%
Monterey	7,476,885	4%	17,239	4%
Fresno	7,067,233	4%	10,908	3%
Ventura	6,988,161	4%	6,839	2%
Orange	3,942,372	2%	12,539	3%
Santa Barbara	3,469,843	2%	12,260	3%
Other Counties	1,550,812	<1%	2,141	<1%

Water in California's Oil and Gas Industry

Water Applied to Oil and Gas Activities

Oil and gas production requires water. From construction and commissioning (e.g. concrete batching, dust control, pipeline testing) and personnel supply to exploration and drilling (e.g. drilling fluids, well stimulation fluids and well flushing), to production (e.g. flooding) and operations (e.g. wash down, cooling water, etc.), water is an essential part of the industry (Figure 2). California's remaining oil reserves are mostly heavy crude—significantly heavier (more viscous) than what is found in other top oil-producing states; more than 90% of its oil has an American Petroleum Institute (API) gravity[3] of 30.0° or less (Figure 3; EIA, 2017b), and about half has an average API gravity of 18° or less (Sheridan, 2006). In fact, as of 2010, the state's extra-heavy oil production accounted for about 97% of the extra-heavy oil produced in the U.S. to date (Attansi and Meyer, 2010). To recover these challenging resources, California operators have relied upon improved and enhanced recovery techniques (Enhanced Oil Recovery, EOR)[4] for more than half a century; water flooding is widely used in California, and steam flooding has been used commercially since the 1960s (Alvarado and Manrique, 2010). This and other improved and enhanced recovery techniques frequently require large inputs of water to move the crude to production wells.

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3. The API (American Petroleum Institute) gravity of crude oil is an inverse measure of the density of a petroleum liquid relative to that of water, which has an API gravity of 10∞. Liquids with API gravity of less than 10 will sink in water; those with higher API gravities will float. For crude oil, an API of 18∞ or less qualifies it as "heavy," whereas crudes with API gravities greater than 18 and less than 36∞ are referred to as "intermediate." Any crude with API gravities of 36∞ or greater are termed "light."

4. The term "enhanced oil recovery" (EOR) encompasses recovery methods that require drivers (physical, thermal, or chemical) in excess of either natural pressure and artificial lift/pumps (primary production) or a water front to increase hydrocarbon production. Water flooding may be referred to as an "improved" recovery technique, whereas steam injection would be referred to as an "enhanced" recovery technique.

The volume of water required to recover crude varies considerably with formation and technology applied. (See Table 2 for examples of ratios of water applied per quantity of oil recovered.) Water use[5] in California's O&G industry is discussed in more detail in Chapter 1.

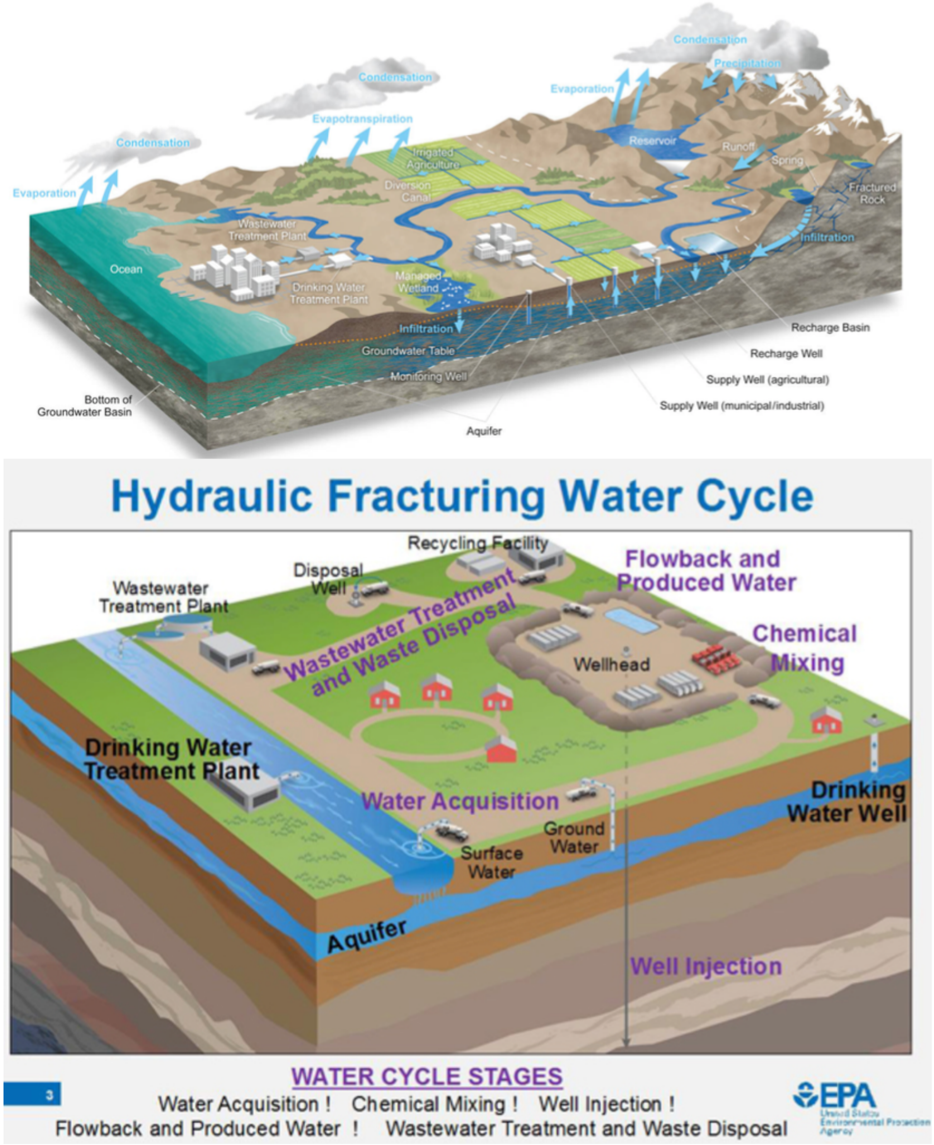

Figure 2. Top: Overview of the hydrological cycle. Source: California Department of Water Resources, Water Budget Best Management Practices, December 2016. Bottom: Hydraulic fracturing water cycle stages. Source: U.S. EPA.

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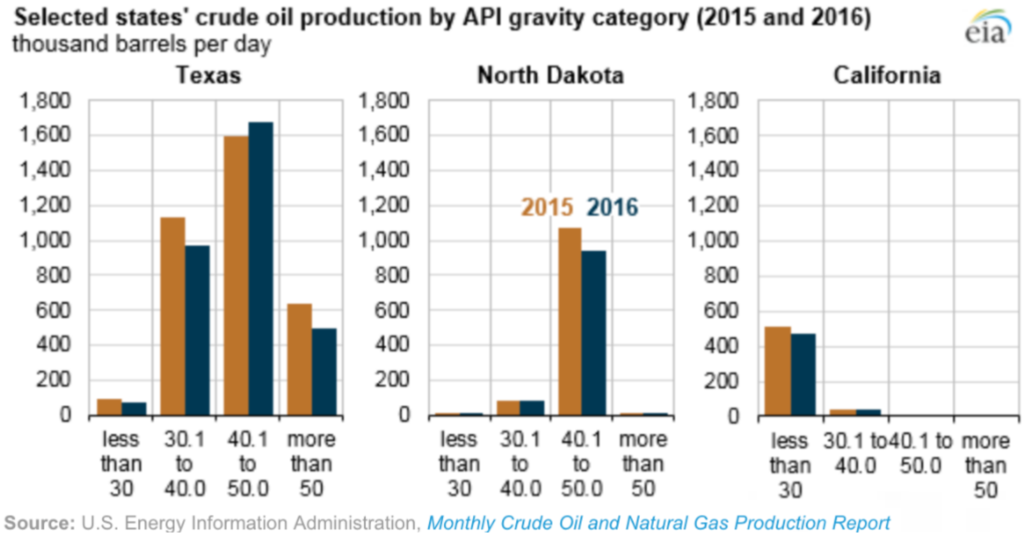
[5] The term water "use" is nuanced depending on the context; a discussion of the definition of water use is included in Chapter 1.

Each of these processes requires water of at least some minimal quality to prevent formation and equipment damage, depending on how it is being used. In some cases, fresh water is sourced from outside the oilfield for these activities. In many cases, water that is produced along with the hydrocarbons is treated enough to be reinjected for improved recovery purposes.



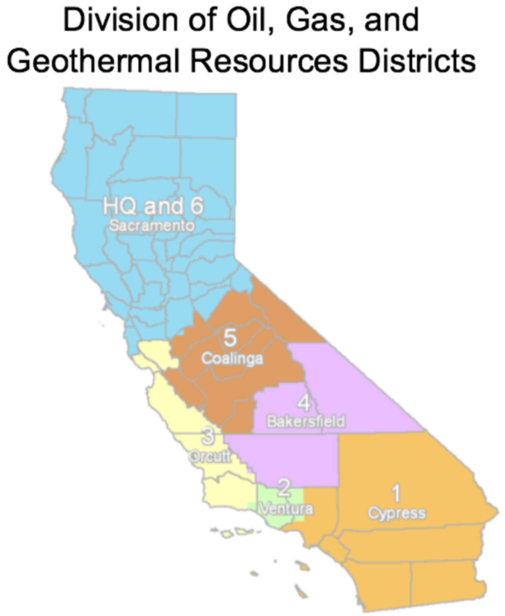
Source: U.S. Energy Information Administration, *Monthly Crude Oil and Natural Gas Production Report*

Figure 3. State-level data show the difference in crude oil API gravity in Texas, North Dakota, and California. Lower API gravity indicated more dense oil. Notice that in comparison with other major crude oil-producing states, California's oil is mostly heavy (more viscous), and more than 90% has an API gravity of less than 30°. Source: Reproduced from EIA (2017b).

Box 2. Enhanced Oil Recovery

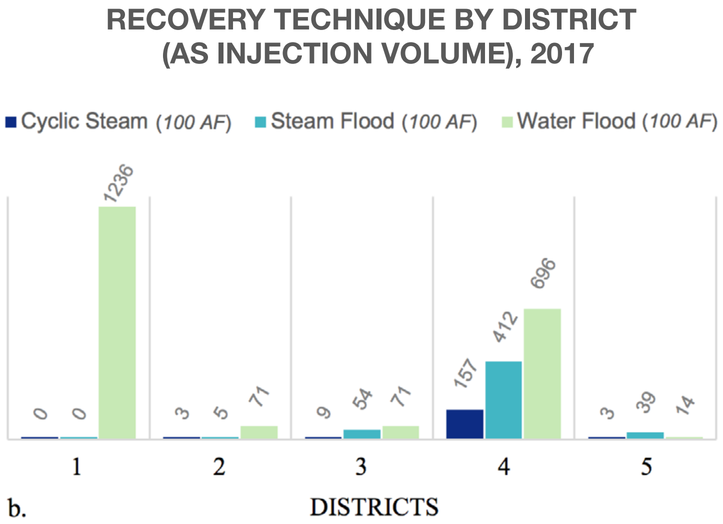
Enhanced oil recovery (EOR) uses heat and/or injected fluids to increase the flow of oil and gas to the surface. A well may pass through multiple stages of recovery over its lifetime. Primary oil recovery—the use of a well's natural pressure or pumping to bring oil, gas, and formation water to the surface—is the method of choice until the well matures enough that the natural pressure or pumping (without injection) is no longer sufficient to maintain production. Once a well's production begins to decline, operators will routinely employ water flooding, a secondary recovery technique that requires the injection of water into an injection well to maintain formation pressure and to drive an oil front toward the producing well. This water is most commonly sourced from the subsurface to reduce the potential for forming undesirable precipitates which can occur as a result of contact between surface or ocean waters and formation waters. Water flooding is used throughout California, most heavily in Southern California (District 1), with nearly 124,000 AF of water injected for water flooding in 2017; and in the southern Central Valley region (District 4), where more than half that amount was injected over the same period (Figure 4).

To improve production further, a thermal recovery technique such as steam flooding may be used. There are two primary ways steam can be used to enhance oil flow to the surface—cyclic and continuous—which operate on different spatial and temporal scales. The first, cyclic, is performed via a single well: steam is injected down the production well and is then shut in, allowing the formation to "soak" for about a one-week period to decrease the viscosity of the crude. Then the same well is produced for some period (also usually about a week) until production declines and the procedure is repeated. This process is sometimes called a "huff and puff" technique, as a well is used as an injection and then a production well in repeating cycles. In contrast, in continuous (or conventional) steam flooding, steam is injected through one or more injection wells and production occurs via separate production wells. Both cyclic and conventional steam flooding occur in California, though these practices are largely confined to District 4, which features "giant oilfields" containing heavy crude (Figure 4).



a.

Figure 4. (a) Division districts. Currently, District 1 is named the Southern District, 2 and 3 are named the Coastal District, 4 and 5 are named the Inland District, and 6 is named the Northern District.



b.

Figure 4. (b) Recovery technique used by district, reported as injection volume in 2017 in hundreds of acre-feet (100 AF). District 6 had no reported volumes used in any of the three recovery techniques displayed.

As the term “enhanced oil recovery” generally refers to subsurface methods that increase pressure and/or reduce viscosity of oil to help it flow to the surface, hydraulic fracturing and other forms of well stimulation are not commonly considered enhanced recovery techniques. Hydraulic fracturing (also called “fracking”) has been used in the U.S. since the 1940s, and in California since as early as the 1950s (CCST and LBNL, 2015), though it has gained much wider attention since the application of the technique to source rock (e.g., shale), yielding large volumes of oil, gas and condensate in other states. In hydraulic fracturing, fluid is injected into low permeability formations at pressures high enough to open small fractures in the target formation, making it more of a well completion technique. These fractures are then filled with proppant—sand or ceramic that is suspended in the fracturing fluids to hold the fractures open—allowing the hydrocarbons to flow to the well. Fracturing fluids are constituted primarily of water and sand or ceramic (the proppant), with chemicals added for different purposes, depending on the formation characteristics. For instance, chemicals may be added to increase fluid viscosity and keep the proppant in suspension, reduce friction, prevent microorganism growth to reduce biofouling of the fissures, anti-corrosion agents and acids for washing/anti-scaling of the wellbore area and associated subsurface infrastructure. (For a thorough discussion of hydraulic fracturing in California, see CCST and LBNL, 2015.)

Table 2. Injection water requirement estimates by crude recovery technology. Source: Wu, M. et al. (2009).

Recovery Technique	Injection Water Ratio (bbl water/bbl crude)	Reference
Primary Recovery	0.2	Gleick (1994)
Secondary Water Flooding	8.6	Bush and Helander (1968)
Tertiary Steam Flooding	5.4	Gleick (1994)

Water Produced in Oil and Gas Activities: Volume

Concern about the use of fresh water by the O&G industry was one driving force behind the drafting of SB 1281 in 2014, following several years of intense drought. Another primary concern was the large amount of water produced along with oil and gas. Produced water is water brought to the surface during oil and gas production. It may originate as natural water in the formation, or it may include water that was previously injected into the formation (for instance, during water- or steam-flooding the same formation).

The state's oil fields are mature—past peak production and in decline, with their more mobile hydrocarbons already recovered—especially compared with the shale plays only recently being profitably exploited elsewhere. As production of a formation continues, the volume of recovered oil tends to decrease while the volume of water produced typically increases; therefore, the water-to-oil ratio (WOR) of fluid recovered typically increases. With California's long production history, it follows that the average WOR throughout the state has increased substantially over several decades: from 6.7 bbl water/bbl oil in 1982 to 18.2 bbl water/bbl oil in 2017 (Figure 5). For comparison, the national average has been calculated as 7.6 bbl/bbl (Clark and Veil, 2009) to 9.2 bbl/bbl (Veil, 2015), though these estimates relied on incomplete data[6] lacking numbers from states with mature fields—Texas and Oklahoma—so the water-to-oil ratio for the U.S. is likely higher than these estimates indicate. Globally, WORs have been estimated to be 3 to 5 bbl/bbl (French Institute of Petroleum, 2011).

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[6] The 2009 report used data collected from 14 states, while the 2012 report used data from 31 states and federal agencies. Neither Texas nor Oklahoma provided estimates. Both estimates are for onshore production only.

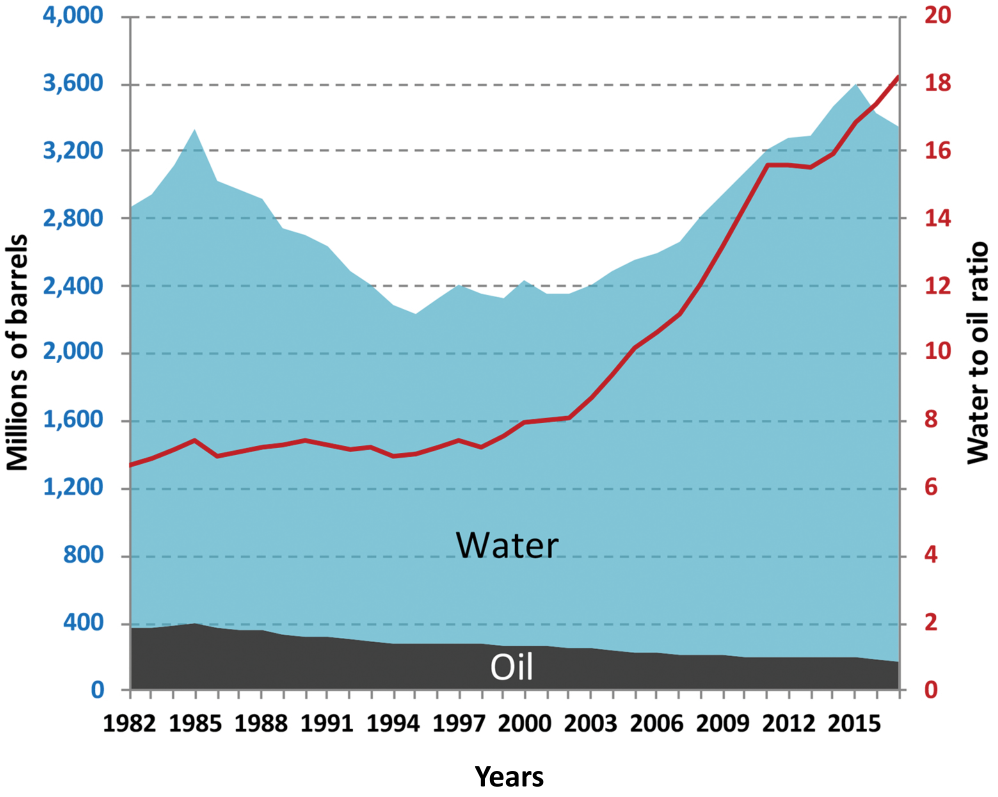

Figure 5. California average water-to-oil ratio from 1982 to 2017. Oil production has been declining since about 1985, while water production began increasing in the early-mid 1990s. The water-to-oil ratio has increased steadily. Note: Black indicates the volume of oil produced, blue the volume of water produced, and red the proportion of water to oil. Source: Reproduced from Jordan (2019); original data from DOGGR (2018a, 2018b).

Produced water is the largest waste stream in the O&G industry (Clark and Veil, 2009). In 2012, nearly 20.6 billion barrels (Bbbl) of produced water were brought to the surface in the U.S. (Veil, 2015). Behind only Texas in produced water generation in 2012, California saw nearly 3.1 Bbbl of water produced in its oil fields that year, or more than 408,000 acre-feet (AF).[7] This figure accounts for 15% of all produced water generated in the U.S. in 2012 (Veil, 2015). According to a survey of state agencies, 93% of water produced from onshore wells in the U.S. that year was reinjected: 46% was injected for EOR; 40% was injected into non-commercial injection wells; and 7% was injected into commercial disposal wells (Veil, 2015).

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[7] For context, California uses about 34 million AF annually to irrigate crops (Department of Water Resources, 2012).

Water Produced in Oil and Gas Activities: Quality

Not only are there large volumes of produced water to manage in the O&G industry, the chemical makeup may require special handling. Formation water, or water that is naturally found together with petroleum in reservoirs, varies widely, depending on many factors: it can range in pH, and can contain dispersed and dissolved oil components such as BTEX (benzene, toluene, ethylbenzene, and xylene), PAHs (polyaromatic hydrocarbons), and phenols. In addition, dissolved inorganic chemicals (salts, metals, and radioactive elements) are sometimes found in high concentrations. (For an illustration of the variability of parameters and constituents in oilfield produced waters sampled from around the world, see Table 3.)

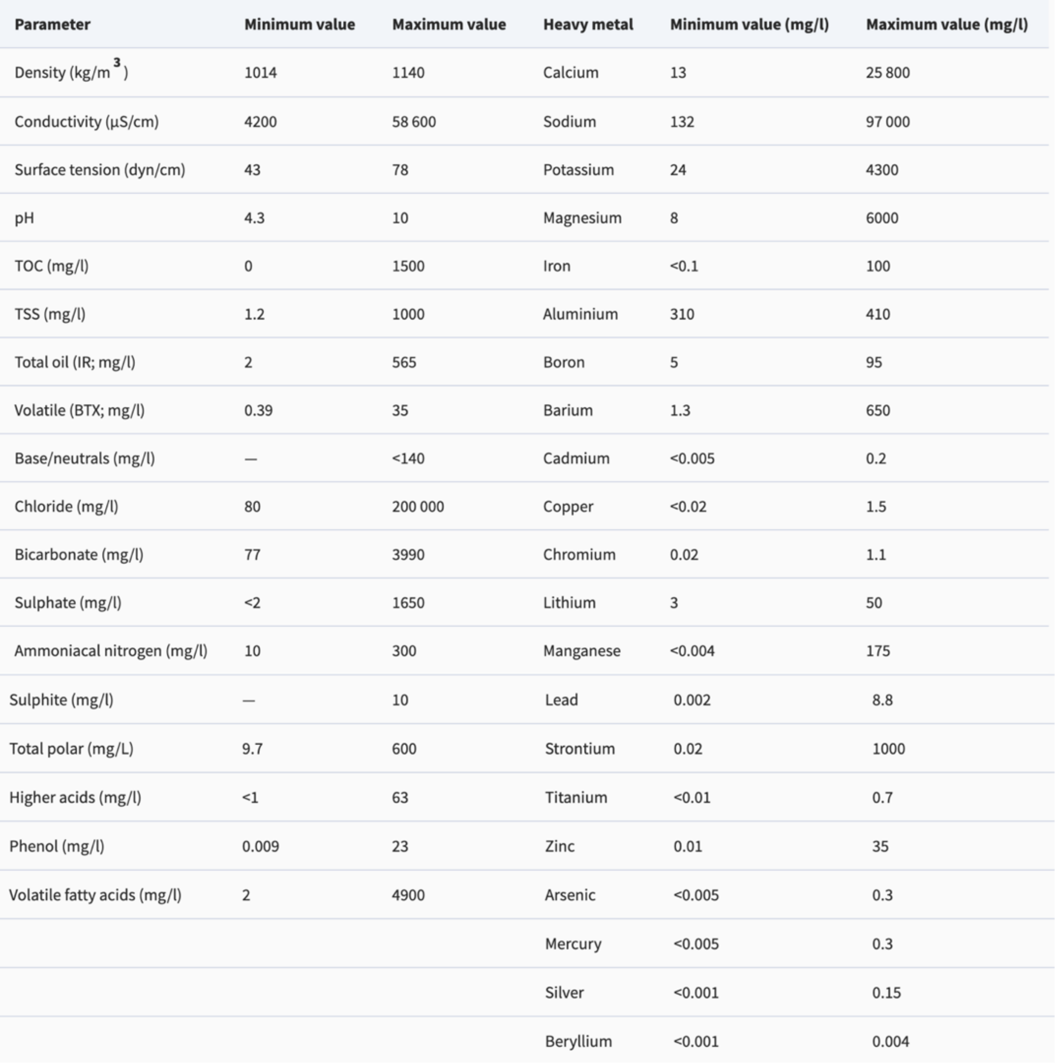
Produced water is a blend of formation water, injected water, hydrocarbons, and treating chemicals, resulting in a complex composition which varies substantially across geographic, geological, and operator space. The constituents of primary concern are those sourced from the petroleum reservoirs, those which are added during O&G activities, and transformed byproducts and degradation products that result from mixing of these classes of compounds:

- salts (often referred to as total dissolved solids, or TDS)
- petroleum hydrocarbons (oil, gas, and grease)
- inorganic and organic chemicals
- naturally-occurring radioactive materials (NORMs)

In addition to these compounds, produced water usually contains suspended solids. These can include clays or sands either from the formation or from previous well activities, microorganisms, silts, carbonates, and injected proppants.

The production of large volumes of water can be costly, as water is heavy and expensive to pump, process and transport. Thus, operators must make choices regarding the management of the large volumes of water produced during O&G operations. Broadly, they can: attempt to minimize production through physical or chemical means; treat the water to enable recycling or beneficial use in another application; or dispose of the water. In California, disposal is most often in the form of underground injection into the subsurface or discharge to evaporation and percolation ponds.

Table 3. Composition of selected samples of oilfield produced water from around the world. Source: Data originally from Tibbetts et al. (1992), as summarized in Fakhru'l-Razi et al. (2009) and presented in Igunnu and Chen (2014). Ranges of values are given for various water quality parameters. This table is given as an illustration of constituents found in produced water, and although ranges are given, they should not be taken to be fully inclusive of all produced water constituents or parameters. (For instance, the TDS for some California produced water can be at least as low as 1,000 mg/L, equivalent to an electrical conductivity of 500 µS/cm). Chapter 3 discusses in detail the constituents found in produced water sampled within California.



Parameter	Minimum value	Maximum value	Heavy metal	Minimum value (mg/l)	Maximum value (mg/l)
Density (kg/m ^{3})	1014	1140	Calcium	13	25 800
Conductivity (µS/cm)	4200	58 600	Sodium	132	97 000
Surface tension (dyn/cm)	43	78	Potassium	24	4300
pH	4.3	10	Magnesium	8	6000
TOC (mg/l)	0	1500	Iron	<0.1	100
TSS (mg/l)	1.2	1000	Aluminium	310	410
Total oil (IR; mg/l)	2	565	Boron	5	95
Volatile (BTX; mg/l)	0.39	35	Barium	1.3	650
Base/neutrals (mg/l)	—	<140	Cadmium	<0.005	0.2
Chloride (mg/l)	80	200 000	Copper	<0.02	1.5
Bicarbonate (mg/l)	77	3990	Chromium	0.02	1.1
Sulphate (mg/l)	<2	1650	Lithium	3	50
Ammoniacal nitrogen (mg/l)	10	300	Manganese	<0.004	175
Sulphite (mg/l)	—	10	Lead	0.002	8.8
Total polar (mg/L)	9.7	600	Strontium	0.02	1000
Higher acids (mg/l)	<1	63	Titanium	<0.01	0.7
Phenol (mg/l)	0.009	23	Zinc	0.01	35
Volatile fatty acids (mg/l)	2	4900	Arsenic	<0.005	0.3
			Mercury	<0.005	0.3
			Silver	<0.001	0.15
			Beryllium	<0.001	0.004

Produced water recycling and reuse represents potential opportunities to create a resource out of a waste stream. Many operators re-inject produced water back into formations to maintain formation pressure and/or for EOR to enable the production of more hydrocarbons. In some cases, produced water is treated to a level of quality that can be used for other industrial uses outside of the oilfield, for instance as cooling water or wash fluid, or for agricultural irrigation and livestock watering (Veil, 2015), although the hazards and risks of these practices remain relatively understudied (Kahrilas et al., 2016; Shonkoff et al., 2016; Stringfellow et al., 2017). Recent (2012) estimates of produced water management practices across the U.S. indicated that of the water produced, the largest portions were reinjected, either for enhanced recovery (45%) or for disposal (39%). Less than one percent was reported as reused for any beneficial purpose (Veil, 2015) (Figure 6). Reuse of produced water in California's agricultural sector—a key beneficial reuse application in the state—is discussed in more detail in Chapter 2. Produced water treatment and management are discussed more thoroughly in Chapters 3 and 4.

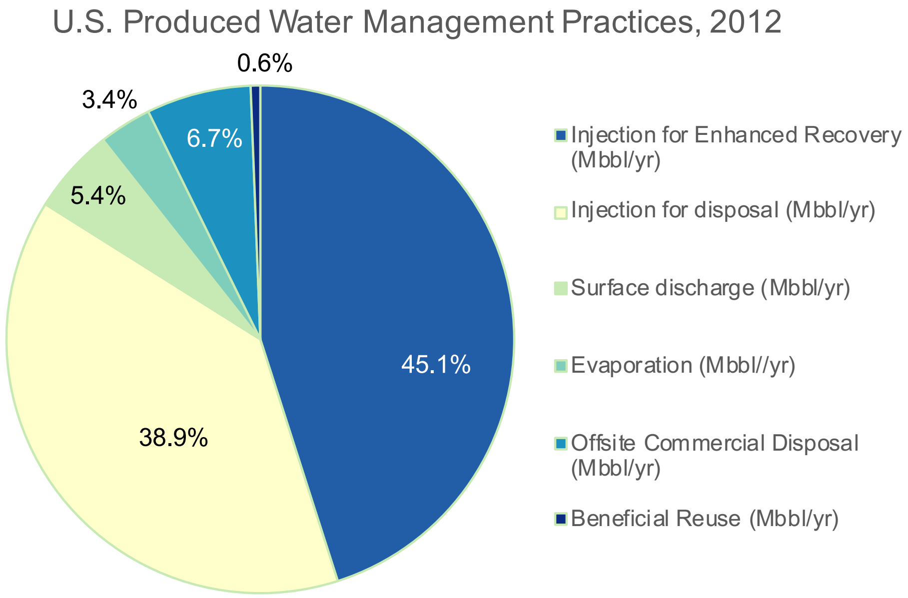
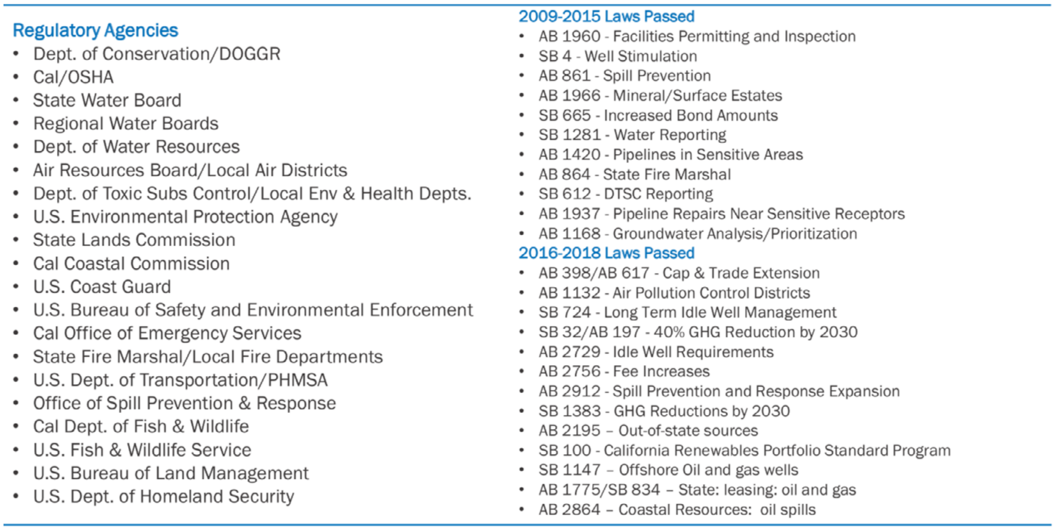


Figure 6. U.S. produced water management practices in 2012. Percentage of total volumes (20.7 Bbbl, or 2.67 million AF) managed throughout the U.S., according to surveys from 31 states and several federal agencies. These volumes are for onshore and offshore wells. Source: Veil (2015).

Data on Water in the Oil and Gas Industry

O&G operators working in California must follow regulations set forth by a multitude of state and federal agencies. In addition to oversight by The Division, which regulates the drilling, operation, maintenance, and abandonment of O&G wells in the state, operators must also report to the U.S. EPA, the State and Regional Water Quality Control Boards, the California Air Resources Board (CARB), and many others. (See Table 4 for an expanded list for one operator in California.)

Table 4. Regulatory bodies and select recent laws requiring reporting from oil and gas operators in California (M. Densmore, personal communication, January 2019).



Regulatory Agencies

- Dept. of Conservation/DOGGR
- Cal/OSHA
- State Water Board
- Regional Water Boards
- Dept. of Water Resources
- Air Resources Board/Local Air Districts
- Dept. of Toxic Subs Control/Local Env & Health Depts.
- U.S. Environmental Protection Agency
- State Lands Commission
- Cal Coastal Commission
- U.S. Coast Guard
- U.S. Bureau of Safety and Environmental Enforcement
- Cal Office of Emergency Services
- State Fire Marshal/Local Fire Departments
- U.S. Dept. of Transportation/PHMSA
- Office of Spill Prevention & Response
- Cal Dept. of Fish & Wildlife
- U.S. Fish & Wildlife Service
- U.S. Bureau of Land Management
- U.S. Dept. of Homeland Security

2009-2015 Laws Passed

- AB 1960 - Facilities Permitting and Inspection
- SB 4 - Well Stimulation
- AB 861 - Spill Prevention
- AB 1966 - Mineral/Surface Estates
- SB 665 - Increased Bond Amounts
- SB 1281 - Water Reporting
- AB 1420 - Pipelines in Sensitive Areas
- AB 864 - State Fire Marshal
- SB 612 - DTSC Reporting
- AB 1937 - Pipeline Repairs Near Sensitive Receptors
- AB 1168 - Groundwater Analysis/Prioritization

2016-2018 Laws Passed

- AB 398/AB 617 - Cap & Trade Extension
- AB 1132 - Air Pollution Control Districts
- SB 724 - Long Term Idle Well Management
- SB 32/AB 197 - 40% GHG Reduction by 2030
- AB 2729 - Idle Well Requirements
- AB 2756 - Fee Increases
- AB 2912 - Spill Prevention and Response Expansion
- SB 1383 - GHG Reductions by 2030
- AB 2195 – Out-of-state sources
- SB 100 - California Renewables Portfolio Standard Program
- SB 1147 – Offshore Oil and gas wells
- AB 1775/SB 834 – State: leasing: oil and gas
- AB 2864 – Coastal Resources: oil spills

Such oversight means O&G operators in California file reports on many aspects of their operations with different state and federal agencies—in conversations with O&G operators across the state, the study team learned some of these carried redundant information. In some cases, the data comprising these reports would likely be collected regardless of mandate, as they are essential for efficient operations. In other cases, the operator may only be collecting the data to satisfy regulation. At the same time, O&G producers may be collecting more data than they are required to report, so they can optimize the balance between production, waste management, and compliance. To capture the spirit of the combined regulations—that is, to understand the industry's resource use and waste management—while also recognizing that "just collect more data" is not always the most efficient path toward understanding, it is important to determine which are the correct variables to address critical concerns of Californians. In the following technical chapters, the SB 1281 dataset is examined for its ability to do so, while specific recommendations for data still needed to answer important questions are made where appropriate.

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Chapter 1

Direct Assessment of the SB 1281 dataset

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[†]These authors contributed equally to the chapter.

1.0. Abstract

The oil and gas (O&G) industry has been required to track water produced from and injected into oil and gas wells since at least 1977. The passage of Senate Bill (SB) 1281 (Pavley, 2014) expanded the industry reporting requirements to include all inputs, applications, and outputs of water in O&G operations, both on and off the oilfield. The SB 1281 dataset offers a more comprehensive view of water handled by the industry than previously available. In this chapter, we test and validate the SB 1281 dataset against an independent dataset, the Division of Oil, Gas, and Geothermal Resources ("the Division" or DOGGR) monthly O&G production and injection report (monthly dataset). We focused our analysis on three reports in the SB 1281 dataset: Production, Injection, and Other Allocation. Much of the new information in the SB 1281 dataset is found in the Other Allocation report, which is the sole source of state information on water that is neither produced nor injected. Our examination found the SB 1281 dataset appears to capture 95% of produced water in the state during 2015 Q4–2017 Q1. However, we discovered deficiencies in earlier and later quarters of reporting and in the minor basins. We also constructed a detailed water cycle for each of the five major oil and gas producing basins in California using the SB 1281 dataset. With a full water cycle for each major basin, we could calculate the net impact by industry to the surface water cycle and percent reuse in O&G operations. We found that the O&G industry is a net generator of saline water and a net consumer of fresh/brackish water in their hydrologic regions. For the five major basins, the industry consumes 1,300 net Acre-Feet per Quarter (AFQ) of fresh/brackish water, and discharges 9,400 net AFQ of saline water. The O&G industry's fresh/brackish water use from external sources accounts for less than 0.1% of the total water used for human purposes. The industry meets 68% of their saline water demand through reuse, but only 41% of their fresh water demand is satisfied by reuse. We conclude that the SB 1281 dataset offers unique insight into the industry's impacts to regional water balances and suggest improvements to help answer the questions of interest and to reduce redundancy with the pre-existing monthly dataset.

Questions Addressed in Chapter 1

1. Exploratory data analysis
    - **Question 1.1**. Can we validate the SB 1281 dataset with independent water use information for California's O&G industry?
    - **Question 1.2**. How much fresh/brackish and saline water are produced and injected, and what are the sources and destinations of the water?
    - **Question 1.3**. Does the SB 1281 dataset provide an accurate understanding of the quality of water used by the O&G industry?
2. Assessment of the oil and gas water cycle
    - **Question 2.1**. How much water does the O&G industry use, and how much water do they reuse for their operations?
    - **Question 2.2**. Is the O&G industry a net consumer or generator of water?
    - **Question 2.3**. How much fresh/brackish water does the O&G industry withdraw compared to total human withdrawals in a region?

Conversion Table

1 acre-foot (AF)	325,851 gallons (gal)
1 acre-foot (AF)	7,758 barrels (bbl)
1 mg/L[1]	1 part per million (ppm)
1 barrel (bbl)	42 gallons (gal)

Equations

The following equations characterize the water cycle for the O&G industry. All variables are expressed in volumetric units, except for percent reuse, which is unitless.

1. Inputs = All flows with origins of Produced Water and Flowback or External Source
2. Outputs = All flows with endpoints of Disposal or Discharge

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[1] Accurate for water; approximation for materials with specific gravity other than 1.

3. Reuse = $W_{\text{AOGO, AOGO}} + W_{\text{AOGO, EORS}} + W_{\text{PW, AOGO}} + W_{\text{PW, EORS}}$

   Where W indicates a flow of water defined by its origin and endpoint, indicted in the subscript as $_{\text{ORIGIN, ENDPOINT}}$ *and*

   AOGO = Ancillary O&G Operations, EORS = Enhanced Oil Recovery and Well Stimulation, PW = Produced Water

4. Demand = Inputs + Reuse

5. External Source = All flows with origins of External Source

6. Discharge = All flows with endpoint of Discharge

7. Net Impact to Surface Water Cycle = External Source - Discharge
   If >0, industry is a net external generator
   If <0, industry is a net external consumer

8. Percent Reuse = (Reuse/Demand)*100% (unitless)

1.1. Introduction

California is a water-limited state, and State policymakers have enacted increasingly rigorous statutes and regulations governing transparency in water use as a tool to better manage water resources. Urban water suppliers are required to report information on water use in their Urban Water Management Plans.[2] Similarly, agricultural water suppliers are required to submit Agricultural Water Management Plans and deliveries per customer.[3]

These public reporting requirements are part of larger efforts to better understand water availability and usage in the state. The California Department of Water Resources (CDWR) prepares a Water Plan every five years that provides a water balance for each of the State's ten hydrologic regions (CDWR, 2005, 2018, 2019).[4] In 2016, the State adopted the Open and Transparent Water Data Act, which gather and harmonize water datasets to provide a better understanding of water availability and allocation.[5]

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[2] Senate Bill (SB) X7-7 (Steinberg, 2009).

[3] Agricultural Water Management Plans required pursuant to SB X7-7; farm gate deliveries required pursuant to AB 1404, Statutes of 2007.

[4] California Water Plans are required under California Water Code Section 10005.

[5] Assembly Bill (AB) 1755 (Dodd, 2016).

The O&G industry in California has also been subject to more stringent reporting requirements on its intakes, discharges, and uses of water. Operators have reported the water produced from and injected into O&G wells in a digitized version since at least 1977. The data are reported in the monthly oil and gas production and injection dataset (DOGGR, 1977).[6] Reporting on water use by the industry was expanded in 2015 with the passage of SB 4 (Pavley, 2013), which required reporting of the volumes of water used in base fluids for hydraulic fracturing and other well stimulation activities.[7] The monthly oil and gas production and injection report and the SB 4 well stimulation dataset independently collect information on subsets of water use and disposition by the industry. Most recently, the State enacted a law to require all O&G operators in the state to file more detailed quarterly reports on the source, use, reuse, storage, treatment, and disposition of water (SB 1281, 2014). The SB 1281 dataset offers a previously unavailable overview of the entire water cycle for the O&G industry.

> ***Finding 1.1.1.*** *Prior attempts to collect data on water use by the O&G industry, such as the monthly and SB 4 datasets, captured only a subset of water handled by the industry.*

The SB 1281 dataset allows the construction of a detailed water cycle including water sources, outputs, allocations to various applications, and percentage of water reused on and off the oilfield. Consequently, it is now possible to understand the overall water demand (or water use) for the industry; the percentage of demand satisfied through reuse of industry wastewater; the volume of water diverted from external sources; the volume discharged to the surface; and the net impact of diversions and discharges to the surface water cycle.

> ***Finding 1.1.2****. The SB 1281 dataset provides unique value by encompassing all water handled by the O&G industry in its three reports, including previously unreported uses such as for dust suppression, equipment cleaning, drilling muds, and domestic water.*

There are ten oil and gas producing basins in California, encompassing 516 fields and 135,000 active wells in 2017 (Figure 1.1; DOGGR, 2018a). Five basins produce substantially more water than the others and are the main focus of this chapter: San Joaquin, Los Angeles, Santa Barbara-Ventura, Santa Maria, and Salinas. Each of the major basins produced at least 170 acre-feet of water per quarter during the reporting period, whereas each of the minor basins produced less than 60 AFQ.

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[6] Monthly reporting of water produced and injected by the O&G industry is required by California Public Resources Code Section 3227.

[7] Reporting of well stimulation base fluids required under Public Resources Code Section 3160.

Figure 1.1. Overview of oil and gas producing basins and hydrologic regions in California. Source: Basins from U.S. Geological Survey (2015); Hydrologic Regions from DWR (2018).

This chapter explores the SB 1281 dataset as a tool to understand the water cycle for California's O&G industry. The analysis is organized around two key objectives.

Objective 1. An exploratory data analysis to better understand the utility of the dataset and how it can be improved, answering three key questions:

- **Question 1.1**. Can we validate the SB 1281 dataset with independent water use information for California's O&G industry?
- **Question 1.2**. How much fresh/brackish and saline water are produced and injected, and what are the sources and destinations of the water?
- **Question 1.3**. Does the SB 1281 dataset provide an accurate understanding of the quality of water used by the O&G industry?

Objective 2. An assessment of the oil and gas water cycle using the SB 1281 dataset, answering three key questions:

- **Question 2.1**. How much water does the O&G industry use, and how much water do they reuse for their operations?
- **Question 2.2**. Is the O&G industry a net consumer or generator of water?
- **Question 2.3**. How much water does the O&G industry withdraw compared to total human withdrawals in a region?

In our results and discussion, we describe the outcome from our analysis, and use the results as a basis for recommendations to improve the SB 1281 dataset.

1.2. Data Sources and Exploratory Data Analysis

Here we present the methods employed in evaluating the SB 1281 dataset to understand its apparent quality and the core facts and figures it provides on water production, injection, sources, and destination. We used two major sources of information for this chapter.

1.2.1. Data Sources

Data Source 1: SB 1281

The primary dataset was the SB 1281 dataset, which includes information on volumes of water produced and injected for each quarter. Data was retrieved from the Division of Oil, Gas, and Geothermal Resources subsection of the California Department of Conservation's website. At the time of this analysis, three years of data had been released, from 2015 Q1 to 2017 Q4. The SB 1281 dataset is divided into four reports:

1. Form 110Q Water Production Report ("Production report"): Provides information on the water produced by each well, and the allocation of that water to single or multiple disposition methods. It also gives basic water quality information on total dissolved solids (TDS) (> or ≤10,000 mg/L), and treatment information.

2. Form 110BQ Water Injection Report ("Injection report"): Provides information on water injected into each underground injection control (UIC) well, and the source or sources of that water. It also gives basic water quality information on TDS (> or ≤10,000 mg/L), and treatment information.

3. Form 110FQ Other Water Allocation Report ("Other Allocation report"): Provides field-level information on water use within oil field operations that cannot be directly tied to a well's production or injection. This form is also used to report water in storage at the end of the reporting period. Water is reported along with its source, intended use, and basic water quality information on TDS (> or ≤10,000 mg/L).

4. Form 110EQ Well-to-Well Allocation Report ("Well-to-Well Allocation report"): Provides well-level information on which injection wells are receiving water from a production well, and what portion of that water production can be attributed to an injection well.

The analysis was focused on three reports: Production, Injection, and Other Allocation. The Well-to-Well Allocation report did not provide useful information for the analysis. The three reports of interest share many variable types. Table 1.1 describes the variables that appear in all three reports. Table 1.2 describes the variables that appear in only some of the reports.

> ***Finding 1.1.3.*** *Much of the new information gained from the SB 1281 dataset is found in the Other Allocation report, which is the sole source of state information on water used by the industry that is neither produced nor injected.*

Table 1.1. Key variables common to the Production, Injection, and Other Allocation reports.

Variable Name	**Description**
Quarterly Reporting Period	Name of reporting quarter (e.g., 2015 Q1).
Operator	Name of operator of well.
Field	Name of the oil field where the well is located.
Quality	Fresh/brackish (≤10,000 mg/L TDS) designated with 1, saline (>10,000 mg/L TDS) designated with 0.
Volume (bbl)	Volume of water in barrels.

Source: Data Dictionary for Water Report Form and SB 1281 Dataset (DOGGR 2018a, 2018b).

Table 1.2. Key variables not shared across the SB 1281 Production, Injection, and Other Allocation reports.

Variable Name	Reports Where Variable Appears	Description
API Number	Production, Injection	Division assigned American Petroleum Institute (API) number, consisting of 3-digit county number and 5-digit unique well number.
Destination	Production, Other Allocation	Destination of water; referred to as "Disposition Method" in the Production Report, and "Intended Use" in the Other Allocation Report. Chosen from 12 specified categories.
Source	Injection, Other Allocation	The source of the injected water or injected steam. Chosen from 11 specified categories.

Source: Data Dictionary for Water Report Form and SB 1281 Dataset (DOGGR 2018a, 2018b).

To better understand geographic patterns of water use in the O&G industry, we aggregated the information in the SB 1281 dataset by each unique field/operator combination. We also grouped fields by oil and gas producing basins. For simplicity, we refer to field/operator combinations as a "lease." This use of the term is informal, as there may in fact be more than one legal lease for a single operator in a field.

> ***Finding 1.2.1**. The SB 1281 dataset includes three reports: Injection, Production, and Other Allocation, which have non-parallel sets of columns.*

> ***Conclusion 1.2.1.** The Well-to-Well Allocation report seeks to itemize the movement of water from every production well to every injection well. In practice, however, water moves from production wells to centralized treatment facilities (e.g. oil-water separators) and back to injection wells, and these volumes cannot be accurately tracked in the way intended by this report.*

Data Source 2: Monthly Data on Injection/Production

In addition to reporting required by SB 1281, O&G operators also submit monthly production and injection reports ("monthly dataset") under California Public Resources Code (PRC) § 3227. Any operator of a well in California must file a statement each month that provides the prior month's production and injection data. The Division compiles the monthly information and releases the dataset to the public once each year. As of this analysis, 2017 is the most recent full calendar year of injection and production data available. Information is provided by API number for individual wells in the monthly dataset. Additional spatial data provided include township, range, section, and county; O&G leases, fields, areas, and pools; and Division districts. Latitude-longitude coordinates for each well were joined from the "All Wells" dataset. Oil and gas field boundary geography is also available from a separate Division shapefile named "Field Boundaries."

The monthly dataset is released in three reports: Injection, Production, and "California oil and gas wells" (full variable list in Appendix 1.2). The monthly Injection report parallels the SB 1281 Injection report, providing volumes of water injected during a given time period, and information regarding the source and quality of injected water. The monthly Production report also parallels the SB 1281 Production report, providing water production volumes (in addition to oil and gas volumes) during a time period, and some information on water allocations. The monthly California oil and gas wells report includes the supporting information on geography described above, as well as ownership, type, well status, operator status, and pool status. A comparison of the monthly and SB 1281 datasets can be seen in Table 1.3.

> ***Finding 1.2.2.*** *The monthly dataset includes three reports: Injection, Production, and California oil and gas wells. The Injection and Production reports give information on volumes of water (in addition to oil and gas where appropriate), and source/disposition and quality of water that are similar to information found in the SB 1281 dataset.*

Table 1.3. Comparison of variables in the SB 1281 and monthly datasets.

Category	SB 1281 dataset	Monthly Dataset
Well API Numbers	Y	Y
Field Names	Y	Y
Operator Names	Y	Y
Lease (Unique Operator x Field Combinations)	Y	Y
First Data Available	2015 Q1	1977 (digitized version)
Last Data Available as of September 2018	2017 Q4	February 2018
Update Period	Quarterly	Monthly
Water Sources	Y (11 categories, pick as many as applicable per well)	Y (Seven categories, pick one per well)
Water Destinations	Y (12 categories, pick as many as applicable per well)	Y (Six categories, pick one per well)
Water Quality Information	Y (Two categories, pick one per source and destination of water from a well)	Y (Four categories, pick one per well)

As indicated by Table 1.3, much of the information found in the SB 1281 dataset is also reported in the monthly dataset. The SB 1281 dataset provides greater resolution on sources and destinations, while the monthly dataset provides a longer historical record and greater frequency of reporting. The SB 1281 dataset also provides a greater number of reporting categories on source and destination than the monthly dataset, and the categories are more precisely defined. Regarding water quality information, the monthly dataset provides more categories than the SB 1281 dataset (four rather than two), but these categories are not clearly defined. The monthly dataset asks operators whether water is "saline, fresh, a chemical mixture, other, or not applicable" without providing precise definitions of the terms. The SB 1281 dataset water quality categories provide greater insight into water quality because they are distinguished by whether the water is either at and below or above 10,000 mg/L TDS. The SB 1281 dataset also includes information on water neither produced nor injected, and thus captures water uses not reflected in the monthly dataset.

> ***Conclusion 1.2.2.*** *Per-well reporting of produced and injected water in the SB 1281 dataset was largely redundant with existing reporting in the monthly dataset. At the same time, the Well-to-Well Allocation report was excessively complex and failed to accurately represent how water moves through an oil field.*

> ***Conclusion 1.2.3.*** *The SB 1281 dataset provides better information on source, destination, and quality of water than the monthly dataset.*

> ***Conclusion 1.2.4.*** *Redundancy between the SB 1281 dataset and the monthly dataset can be reduced by appropriately augmenting the monthly dataset to take over well-by-well reporting on production and injection from the SB 1281 dataset.*

> ***Conclusion 1.2.5.*** *The SB 1281 dataset can be used to gather information at the lease scale or larger.*

1.2.2. Exploratory Data Analysis

Question 1.1. Can we validate the SB 1281 dataset with independent sources of information on water accounting for California's O&G industry?

Our first step in analyzing the SB 1281 dataset was to validate its accuracy by comparing it to an existing dataset on water produced and injected by the O&G industry, the monthly dataset. The monthly dataset is not perfect, but it is the best point of comparison we have available. We evaluated the consistency between the two data sources (Table 1.4). For the state of California, 1.16 million AF of produced water was reported in the SB 1281 dataset from 2015 Q1–2017 Q4, as compared to 1.30 million AF from the monthly dataset (11.04% difference).

Table 1.4. Comparison of total volume of water produced and injected during the three years of existing data (2015 Q1–2017 Q4).

Statewide Total Volume, 2015–2017	SB 1281 dataset (AF)	Monthly Dataset (AF)	SB 1281 dataset/ Monthly Dataset
Water Produced	1,159,033	1,302,822	0.89
Water Injected	1,017,625	1,149,834	0.89

Source: 2015 Q1 - 2017 Q4 SB 1281 Dataset (DOGGR 2018); DOGGR Monthly Production and Injection Reports (DOGGR 2018)

We also compared the SB 1281 and monthly datasets on produced and injected water volumes by basin and quarter. Different patterns emerged for the five major basins (Figure 1.2) as compared to the minor basins (Figure 1.3). For the major basins, the SB 1281 and monthly datasets tracked fairly well during the six quarters from 2015 Q4–2017 Q1. However, for the first three and the last three quarters, 1281 volumes were markedly below the monthly volumes. The volumes reported in the monthly dataset remained relatively consistent over time, while the SB 1281 dataset showed sudden declines at the beginning of 2015 and the end of 2017.

For the minor basins, the monthly dataset was fairly consistent over time. However, the SB 1281 dataset varied erratically throughout the entire available period of reporting. The volumes of produced and injected water were also quite small in the minor basins. The largest minor basin, Cuyama, never exceeded 550 AFQ of produced or injected water, and the other basins had volumes in the range of 0-25 AFQ.

Given that oil production in California from 2015 to 2017 was relatively stable or very slightly declined (see Introduction, Figures 1 and 3), it is reasonable to assume the monthly dataset is correct. This comparison suggests there were systematic reporting errors (usually underreporting) in the SB 1281 dataset. The reporting errors were most pronounced in the first and last three quarters of reporting, and for the minor basins (Figure 1.2).

> ***Conclusion 1.2.6.*** *The monthly dataset appears to have more reliable information on volumes of produced and injected water than the SB 1281 dataset.*

> ***Recommendation 1.2.1.*** *Make the monthly dataset the repository for volumes of water produced and injected; focus the SB 1281 dataset instead on flows of water into and out of the O&G industry.*

> ***Recommendation 1.2.2.*** *The monthly dataset should adopt similar variables for source, destination, and quality as the SB 1281 dataset to eliminate the per-well reporting in the SB 1281 dataset; operators can be required to simply report on a per-lease basis to the SB 1281 dataset.*

> ***Recommendation 1.2.3.*** *Add a column to the monthly production and injection dataset for operators to report the water treatment facility to which each production and injection well connects.*

> ***Recommendation 1.2.4.*** *Instead of attempting to apportion flows of water between individual wells as is currently done in the Well-to-Well Allocation report, operators should simply include the water treatment facility or facilities connected to each production and injection well in the monthly dataset.*

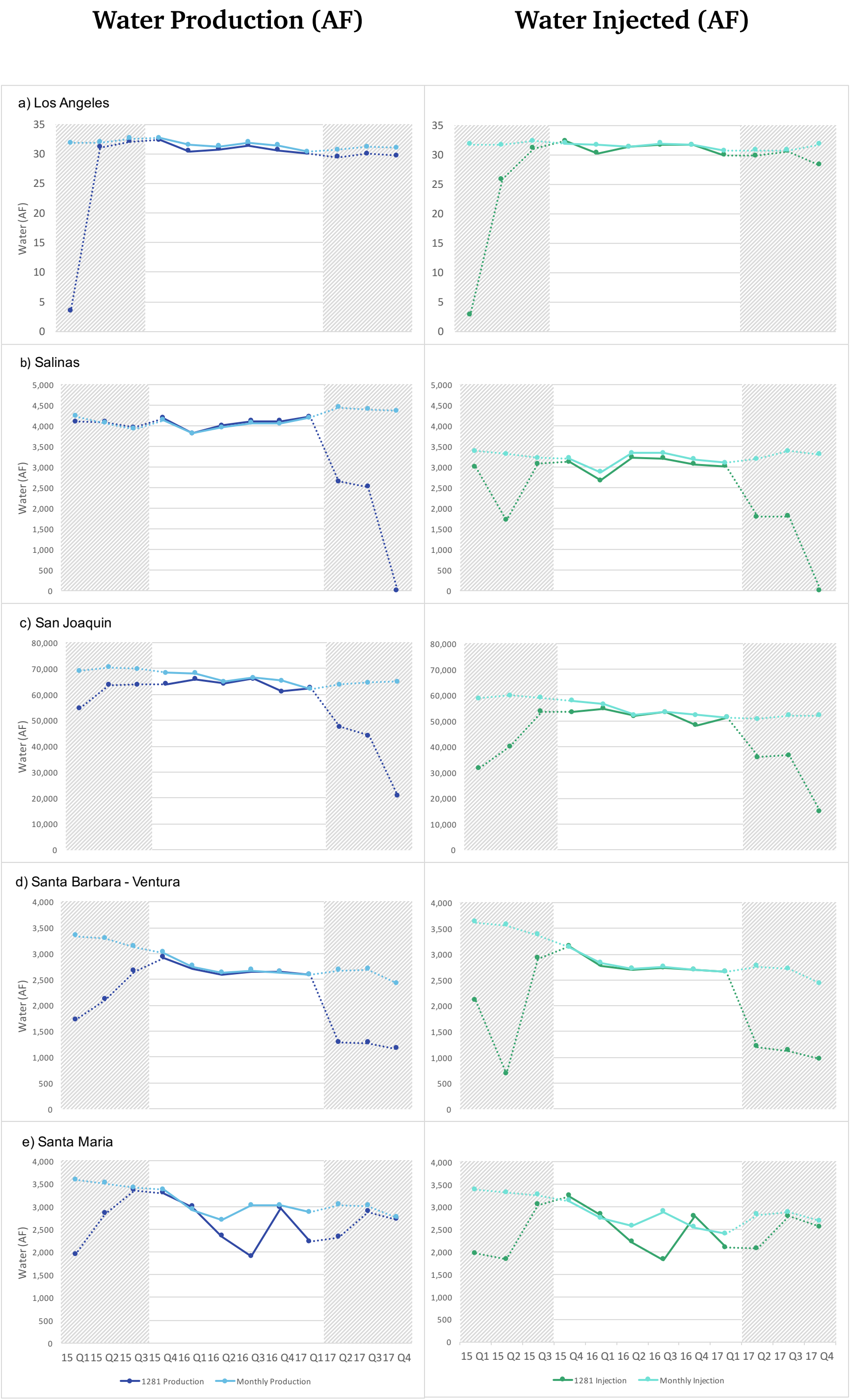

Figure 1.2. Comparison of the SB 1281 and monthly datasets for major basins. Grey hatching indicates periods of less reliable information in the SB 1281 dataset. Source: 2015 Q1 - 2017 Q4 SB 1281 Dataset (DOGGR 2018); DOGGR Monthly Production and Injection Reports (DOGGR 1977)

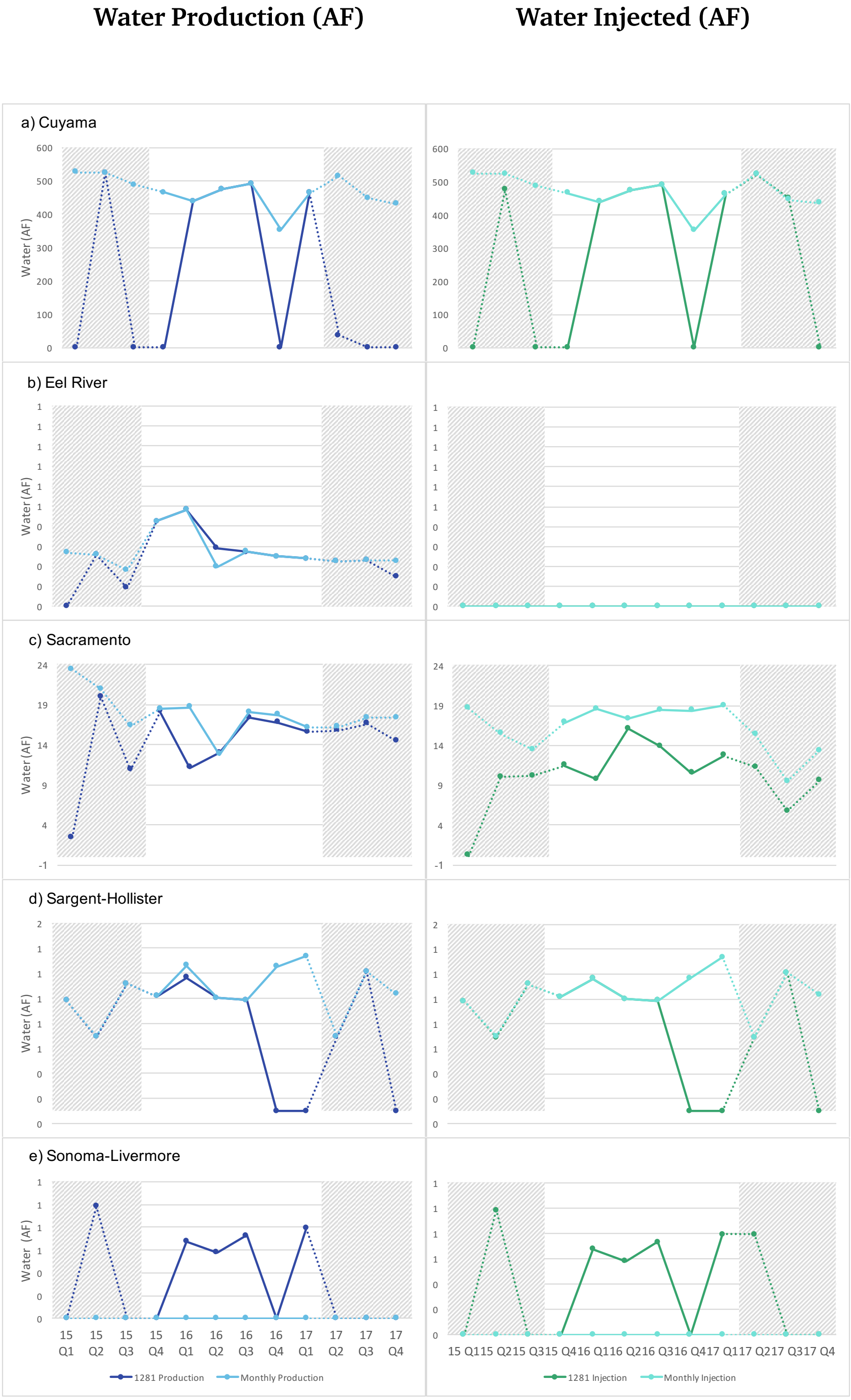

Figure 1.3. Comparison of SB 1281 and monthly datasets for minor basins. Grey hatching indicates periods of less reliable information in the SB 1281 dataset. Source: 2015 Q1 - 2017 Q4 SB 1281 Dataset (DOGGR 2018); DOGGR Monthly Production and Injection Reports (DOGGR 1977)

Because of the discrepancies between the SB 1281 and monthly datasets for the minor basins, we focused our subsequent analyses on the SB 1281 dataset for the five major basins. The vast majority of produced water is generated in the five major basins. There was 104,000 AFQ of water produced from 2015 Q4–2017 Q1 in the five major basins according to the SB 1281 dataset, compared to 108,000 AFQ of water produced during that same time period statewide according to the monthly dataset. Although our assessment of the SB 1281 dataset is limited in geographic scope to the major basins, our analysis indicates these basins account for an estimated 96% of produced water from the monthly dataset, statewide. Appendix 1.2 provides further detail on methods.

Additionally, within the Injection dataset in the SB 1281 dataset, there is a surprisingly large volume of injected saline water reported as sourced from Municipal Wastewater and Water Suppliers (not Operator Owned). In contrast, within the Production dataset, there is unexpectedly large volumes of produced saline water reported as being used for Agriculture and Recharge.

Question 1.2. How much fresh/brackish and saline water are produced and injected, and what are the sources and destinations of the water?

We evaluated volumes of fresh/brackish and saline water produced and injected, and the sources and destinations of that water. Figure 1.4 shows the sources of water injected in the O&G industry. A total of 87,946 AFQ of saline and 3,813 AFQ of fresh/brackish water is injected into UIC wells in the state of California,[8] for a a total of 91,760 AFQ. The SB 1281 dataset includes both EOR and disposal in the category of subsurface injection. For saline injected water, Figure 1.4 shows the largest source is production wells, i.e. produced water, which accounts for more than 90% of the saline water injected. The majority of this water is produced within the same field it is injected. Some water is transferred from other fields. However, fresh/brackish water that is injected comes from sources largely external to the industry. In the Los Angeles basin, municipal wastewater accounts for 94% of all fresh/brackish water acquired for injection purposes. In the San Joaquin basin, 24% of fresh/brackish water is purchased from water suppliers, and 18% is acquired from surface water bodies.

Figure 1.5 shows the destinations of water produced in the O&G industry. A total of 100,660 AFQ of saline and 3,001 AFQ of fresh/brackish water are produced in the state of California,[9] making up a produced water total of 103,661 AFQ. The major destination for produced water, irrespective of quality, is subsurface injection. It makes up over 80% of the total volume of produced water across all the analyzed basins. In the San Joaquin

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[8] As noted in the section on data validation, data for the state should be taken with some caution. We include all basins in the calculation of state total, but focus on validated data from the five major basins for this chapter.

[9] As noted in the section on data validation, data for the state should be taken with some caution. We include all basins in the calculation of state total, but focus on validated data from the five major basins for this chapter.

basin, 25% of fresh/brackish produced water is sent for agriculture and recharge. Produced water is used for well stimulation only in the San Joaquin basin, and accounts for only a small percentage (about 2%) of the statewide use of produced water. In terms of lined and unlined ponds, lined ponds not a major destination in any basin. Unlined ponds received about 2% of produced water in the San Joaquin basin. The majority of produced water is injected back underground. The portion of produced water that is reused or disposed of at the surface is of particular interest because it has direct impacts to the surface water cycle. Discharge to surface water, agriculture and recharge are examined in greater detail in Chapter 2, while Chapter 4 discusses discharges to unlined ponds.

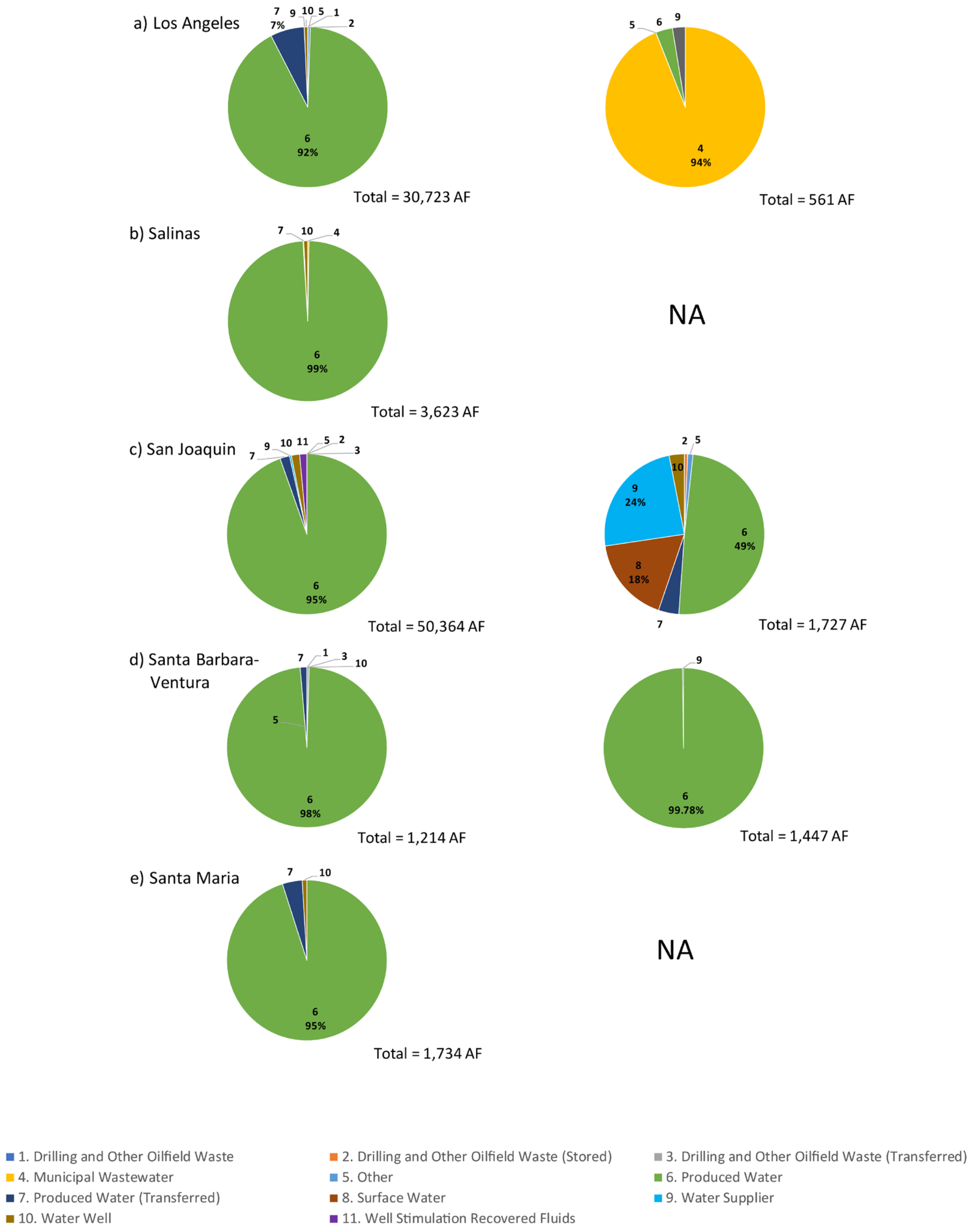

Figure 1.4. Sources of saline (left) and fresh/brackish (right) injected water in the O&G industry. Data are labeled only for larger values for greater visual clarity. Entire list of values can be found in Appendix 1.4. Source: 2015 Q4 - 2017 Q1 SB 1281 Dataset (DOGGR, 2018a).

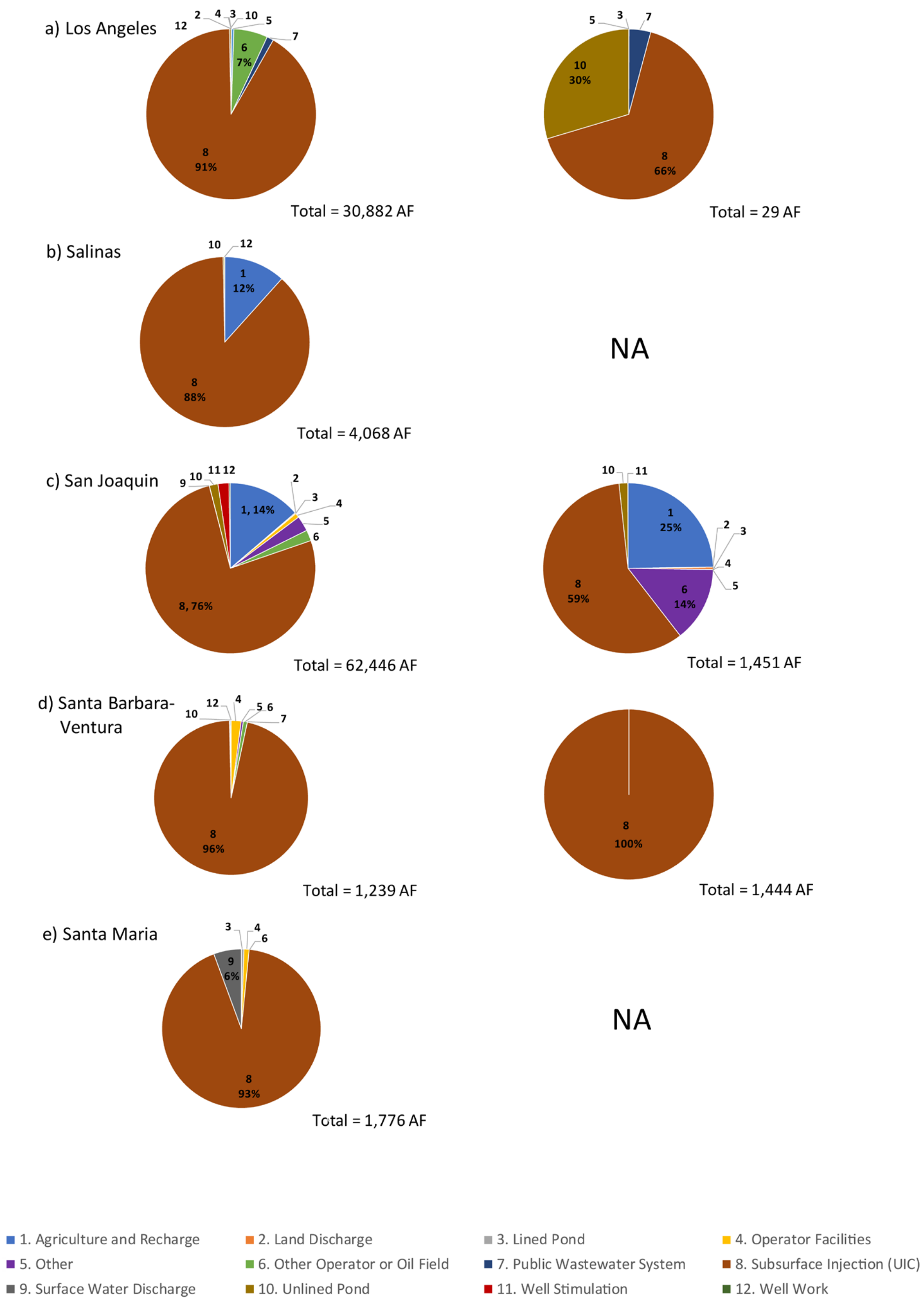

Figure 1.5. Destinations of saline (left) and fresh/brackish (right) produced water in the O&G industry. Data are labeled only for larger values for greater visual clarity. Entire list of values can be found in Appendix 1.4. Source: 2015 Q4 – 2017 Q1 SB 1281 Dataset (DOGGR, 2018a).

Question 1.3. Does the SB 1281 dataset provide an accurate understanding of the quality of water used by the O&G industry?

Our examination of sources and destinations of water in the SB 1281 dataset revealed some oddities that merited further exploration. Based on logical inferences on the likely quality of water from various sources, some of the water quality information on TDS appears suspect (Figure 1.6). In particular, some water from municipal wastewater suppliers, surface water, water suppliers, and water wells was reported to have salinities greater than 10,000 mg/L (Figure 1.4). It is possible that operators may source saline water from water wells or from the ocean (categorized as a type of surface water). The other categories, however, seem improbable. We are not aware of any water supplier or municipal wastewater stream that would have had such high TDS concentrations. Based on these results, we recommend regarding the water quality reporting in the SB 1281 dataset with some caution.

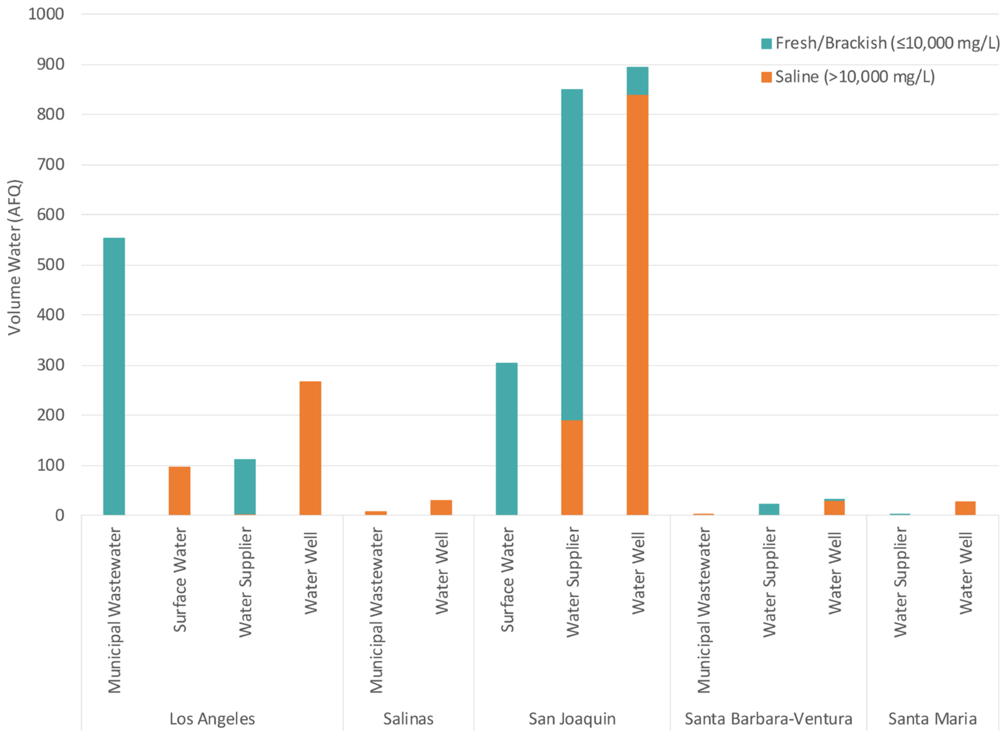

Figure 1.6. Water quality from external water supplies. Source: 2015 Q4 - 2017 Q1 SB 1281 Dataset (DOGGR, 2018a).

A second challenge in evaluating the SB 1281 dataset was understanding and integrating the Other Allocation report into our analysis. The Other Allocation report is formatted differently from the Production and Injection reports. For example, all water in the Production report came from one source (produced water), and all water in the Injection report had a single destination (UIC wells). But water in the Other Allocation report could have any of 11 sources and 12 destinations, for a total of 132 reporting categories. The water volumes reported in other allocation were also quite modest compared to those in Production and Injection. However, the Other Allocation report had a relatively large proportion of fresh/brackish water inputs (Figure 1.7). Statewide, including the water inputs from the Other Allocation report increased total inputs to the O&G industry by less than 1% above what was reported in the Injection report, but raised the inputs of fresh/brackish water by 13%. The fresh/brackish water inputs for the San Joaquin basin increased by 17%, while fresh/brackish water inputs in the Los Angeles basin were five times greater once the Other Allocation data was included (Figure 3.4). This is presumably because a number of oilfield activities require water with a lower salt concentration than can be obtained from produced water. Consequently, much of fresh/brackish water used for O&G operations is reported in the Other Allocation report.

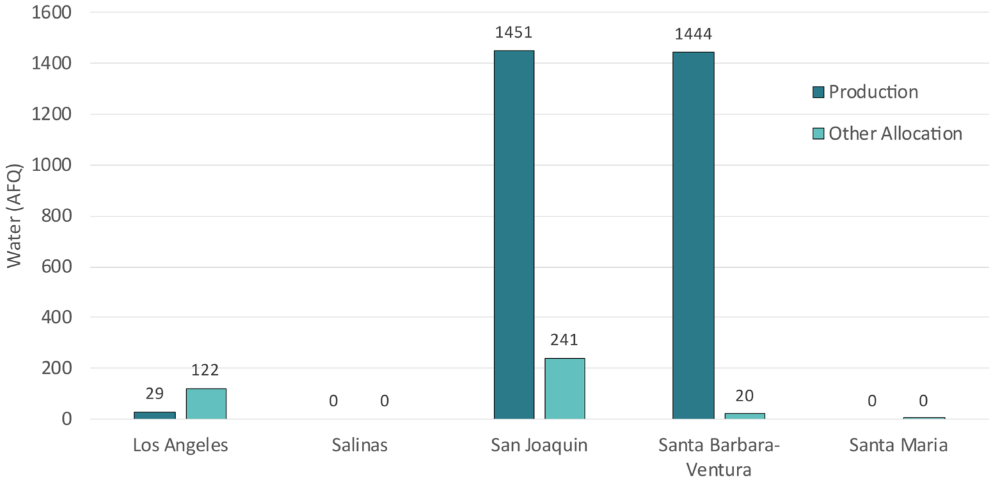

Figure 1.7. Inputs of fresh/brackish water from Production and Other Allocation reports. Source: 2015 Q4 – 2017 Q1 SB 1281 Dataset (DOGGR, 2018a).

1.3. Water Cycle Analysis

To fully understand the information in the SB 1281 dataset and the full volumes of water used by the O&G industry required integrating the Other Allocation, Production, and Injection into a master dataset.

In its unaltered form, the SB 1281 dataset did not enable us to calculate total water inputs, outputs, reuse or demand for the O&G industry in each basin because the Other Allocation report was formatted quite differently from the Production and Injection reports. Consequently, it was not possible to understand net impacts to water availability in a basin, nor the percentage of industry demand satisfied with reuse. Answering these questions required developing a conceptual diagram of the oil and gas water cycle, and restructuring the three reports to align with each other and with the framework of the water cycle.

1.3.1. Background on Water Cycle Frameworks

Water cycle or water accounting frameworks have been developed previously for resource extraction industries. The International Council on Mining and Minerals (ICMM), a voluntary organization of mining companies, developed a water accounting framework to standardize water reporting by its members (SMI & ICMM, 2014). Likewise, IPIECA, a membership agency of petroleum producers, developed a common spreadsheet interface for O&G operators to report water use for their operations (IPIECA, 2015).

The two frameworks share a number of common features. First, they define the boundaries of the geographic units and sectors being examined. For example, they may select a single mining area or a watershed as the geographic unit of analysis and examine categories of human and environmental use within that area. The clear definition of boundaries allows the accounting framework to classify volumes of water as inputs and outputs from the system (ICMM, 2017). The frameworks differentiate between inputs of water versus total use of (or demand for) water. Although inputs constitute extraction of water from outside the unit of interest, the amount of water used includes both reuse and inputs. Accounting frameworks also seek to differentiate between outputs of water that are available to downstream users and those that are not, i.e. consumptive and non-consumptive uses (ICMM, 2017; Gleick, 2013). The frameworks provide useful first-order estimates of how water moves through a system by simplifying the many flows of water into, within, and out of a sector—and the attendant changes in water quality (SMI & ICMM, 2014).

1.3.2. Water Cycle Analysis Methods

Once we cleaned and aggregated the data by basin, field, and operator, we reorganized the data to align with the water cycle in Figure 1.8. This was challenging because: (1) some information on specific flow patterns was located across three different spreadsheets; and (2) some of the spreadsheets did not include all relevant variables. This fragmented data structure prevents users from calculating estimated totals for metrics such as "All Flows" (Appendix 1.6).

> ***Finding 1.3.1.*** *Calculating water inputs, outputs, and applications by the O&G industry required extensive parsing, reorganizing, and compiling of data from three reports: Production, Injection, and Other Allocation.*

> ***Finding 1.3.2.*** *The three reports contained similar variables but had slightly different structures, making it challenging to sum quantities across reports. For example, produced water used for well stimulation was reported in the Production report, whereas water from external sources used for well stimulation was found in the Other Allocations report.*

> ***Finding 1.3.3.*** *The three reports also allowed for duplicate reporting of some flows of water. For example, produced water that was injected into a UIC well was reported in all three reports: once in the Production report with a destination of underground injection, once in the Injection report with a source of produced water, and once (erroneously) in the Other Allocations report with a source of produced water and destination of underground injection.*

The key to aligning the three reports was to treat every record as a flow defined by four characteristics: source, destination, quality, and stored. All water listed in the Production report had a source of produced water, one of 12 destinations, a binary quality designation, and a negative designation for stored. Water in the Injection report had one of 11 sources, a destination of subsurface injection (UIC), a binary quality designation, and a negative designation as stored. Records in the Other Allocation report were categorized according to the stored designation. Water that was reported as stored was kept separate from All Flows, as the source and intended destinations for stored water were reported multiple times—once for every quarter a volume of water was stored. Non-stored water from the Other Allocation report was integrated into All Flows, designated by source, destination, and quality.

The resulting All Flows dataset was more concise and useful than the three separate reports. However, it was still difficult to detect larger patterns and impacts to regional water resources because water flows could have any permutation of 11 sources and 12 destinations. To resolve this problem, we aggregated the sources and destinations into larger groupings, which we called water cycle origins and endpoints (Table 1.5).

Table 1.5 Classifications of SB 1281 dataset sources and destinations into a water cycle.

S#	Source	Water Cycle Origin
1	Produced Water	Produced Water and Flowback
2	Water Well	External Source
3	Water Supplier	External Source
4	Surface Water	External Source
5	Drilling and Other Oilfield Waste (Transferred)	Ancillary O&G Operations

1. Percentage allocated to disposal versus EOR and stimulation per basin was based on the monthly dataset because the SB 1281 dataset does not separate out the processes.

S#	Source	Water Cycle Origin
6	Municipal Wastewater	External Source
7	Other	Other
8	Produced Water (Transferred)	Ancillary O&G Operations
9	Well Stimulation Recovered Fluids	Produced Water and Flowback
10	Drilling and Other Oilfield Waste (Stored)	Ancillary O&G Operations
11	Drilling and Other Oilfield Waste	Ancillary O&G Operations
D#	**Destination**	**Water Cycle Endpoint**
1	Unlined Pond	Discharge
2	Lined Pond	Disposal
3	Surface Water Discharge	Discharge
4	Public Wastewater System	Discharge
5	Subsurface Injection (UIC)	Disposal EOR and Stimulation[1]
6	Other	Other
7	Other Operator or Oil Field	Ancillary O&G Operations
8	Land Discharge	Discharge
9	Operator Facilities	Ancillary O&G Operations
10	Well Stimulation	EOR and Stimulation
11	Agriculture and Recharge	Discharge
12	Well Work	Ancillary O&G Operations

1. Percentage allocated to disposal versus EOR and stimulation per basin was based on the monthly dataset because the SB 1281 dataset does not separate out the processes.

Using the new All Flows dataset and following the procedure described in the ICMM (2017) and SMI Petroleum (SMI, 2014) protocols on water accounting, we developed a flow diagram to describe the major inputs, applications, and outputs of water for the O&G industry (Figure 1.8). The inputs are from: (1) external sources such as water wells, municipal water suppliers, municipal wastewater, and surface diversions; and (2) produced water and flowback. Produced water and flowback are waste fluids from production wells. The fluids represent a mixture of formation water (ancient seawater that was deposited with the organic parent material of hydrocarbons); injectate from O&G activities; and (in some shallow producing zones) natural recharge from connected aquifers (McMahon et al., 2018). Thus, while we classify it as an input for purposes of simplicity, in reality produced water and flowback represents a mixture of water newly entering O&G operations and reuse of water previously injected for EOR and stimulation. The applications are activities that use water for O&G operations. These are split into two categories: (1) injection for enhanced oil recovery (EOR) and well stimulation; and (2) water used for ancillary O&G activities. The latter include transfers of water between lease operators, cleaning and operating equipment (i.e., facility operations), and mixing with drilling muds, cement, and other fluids for well work on the oil field.

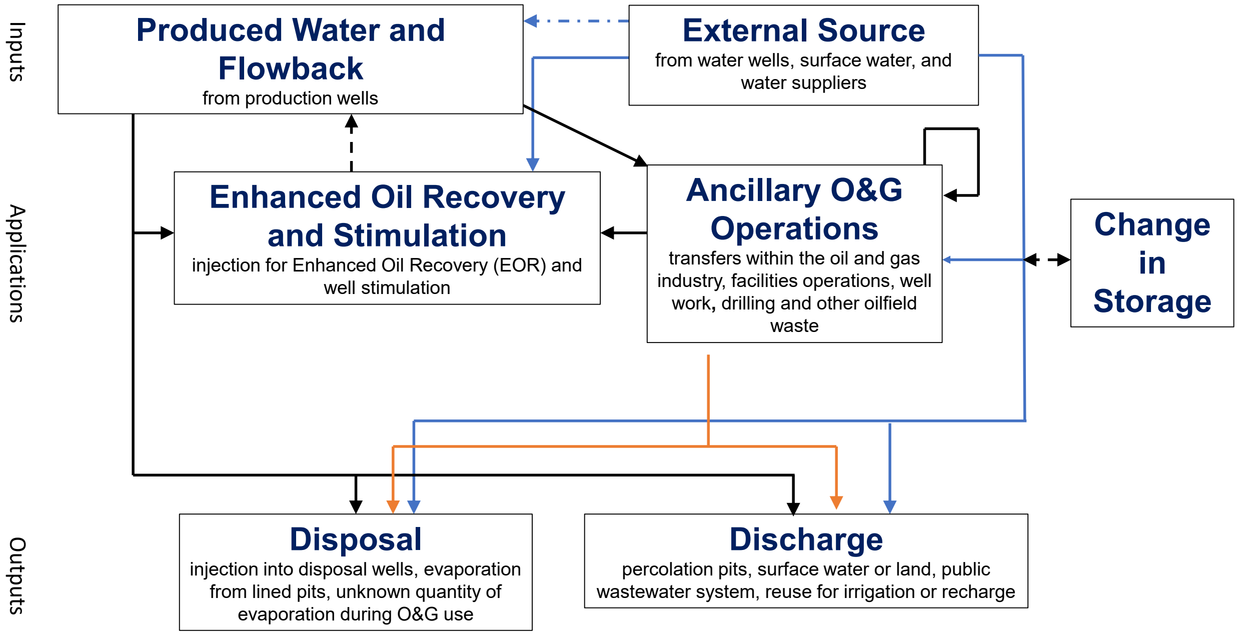

Figure 1.8. Water cycle diagram for California's O&G industry. Solid lines represent flows we were able to directly estimate using the SB 1281 dataset. Dashed lines represent flows that we cannot directly estimate. Different color arrows are used simply to differentiate non-intersecting flows Change in storage refers to the net change in storage for each quarter of reporting.

The outputs are from disposal and discharge. Disposal is defined as releases of water for which there are no evident downstream user, such as UIC Class II Disposal Wells and evaporation from lined ponds. Discharge refers to releases of water that are available for potential downstream users. This includes discharge to unlined evaporation and percolation ponds, surface water, land, public wastewater systems, reuse for irrigation or groundwater recharge, and an unknown quantity of water lost in produced water spills. Some water is likely lost in the process of injection for EOR as well, but the extent is not known.

Each arrow in the water cycle represents a flow of water, defined by its origin and endpoint. There are 12 flows of water depicted with solid arrows in the diagram; these are flows of water for which we had relevant information from the SB 1281 dataset to estimate volumes within two quality categories. We used dashed lines to indicate the two flows of water for which we lacked data to directly estimate the volumes. We were not able to calculate the flows into and out of storage. Instead, we calculated a net change in storage for each quarter of reporting. We also cannot directly calculate the volume of water moving from EOR and stimulation to produced water and flowback, because this flow occurs underground. We ignored flows coming from and to the category of other because it is not well-defined and because of this, it was not possible to place it in input, applications, or output categories.

Some of the flows reported in the SB 1281 dataset are perplexing. For example, there are flows reported as going from external sources directly for disposal, and saline water going towards reuse in agriculture. However, to maintain consistency and assess the SB 1281 dataset as reported, we have included all reported flows.

With the master All Flows spreadsheet, we could tabulate results for the water cycle. We calculated 12 flows of water, plus change in storage, as shown in Table 1.6. All units were expressed in mean AFQ and were calculated for fresh/brackish, saline, and total flows of water.

A basic challenge with the SB 1281 dataset was that subsurface injection combines injection for both EOR as well as for disposal. In terms of how we view the water cycle, these two processes lead to different endpoints for water. Water injected for disposal is no longer further available in the cycle, while water injected for EOR is an industry use to improve oil recovery. To estimate the volumes of water going to EOR versus disposal, we used the monthly dataset. The monthly dataset has well-type codes assigned as well as volumes of water injected. We calculated the proportion of water volumes going to disposal versus EOR wells for each basin, and applied this ratio to our volumes of water being injected for each basin. However, the well-type codes are not well-defined and there can be ambiguity in designation.

In addition to summing input, demand, reuse, and output, we calculated the following metrics:

1. Inputs = All flows with origins of Produced Water and Flowback or External Source

2. Outputs = All flows with endpoints of Disposal or Discharge

3. Reuse = $W_{\text{AOGO, AOGO}} + W_{\text{AOGO, EORS}} + W_{\text{PW, AOGO}} + W_{\text{PW, EORS}}$

   Where W indicates a flow of water defined by its origin and endpoint, indicted in the subscript as $_{\text{ORIGIN, ENDPOINT}}$ *and*

   AOGO = Ancillary O&G Operations, EORS = Enhanced Oil Recovery and Well Stimulation, PW = Produced Water

4. Demand = Inputs + Reuse

5. External Source = All flows with origins of External Source

6. Discharge = All flows with endpoint of Discharge

7. Percent Reuse = (Reuse/ Demand)*100% (unitless)

8. Net Impact to Surface Water Cycle = External Source - Discharge
   If >0, industry is a net external generator
   If <0, industry is a net external consumer

Table 1.6. Generic water cycle results table. Results for each flow (and change in storage) were calculated within two quality categories, fresh/brackish and saline.

Origin	**Endpoint**	**Abbreviation**	**Input**	**Demand**	**Reuse**	**Output**
Ancillary O&G Operations	Ancillary O&G Operations	$W_{AOGO,\ AOGO}$		X	X	
	Disposal	$W_{AOGO,\ D}$				X
	Discharge	$W_{AOGO,\ SD}$				X
	EOR and Stimulation	$W_{AOGO,\ EORS}$		X	X	
External Source	Ancillary O&G Operations	$W_{ES,\ AOGO}$	X	X		
	Disposal	$W_{ES,\ D}$	X	X		X
	Discharge	$W_{ES,\ SD}$	X	X		X
	EOR and Stimulation	$W_{ES,\ EORS}$	X	X		
Produced Water (and Flowback)	Ancillary O&G Operations	$W_{PW,\ AOGO}$	X	X	X	
	Disposal	$W_{PW,\ D}$	X	X		X
	Discharge	$W_{PW,\ SD}$	X	X		X
	EOR and Stimulation	$W_{PW,\ EORS}$	X	X	X	
Change in Storage	Change in Storage	W_S				

> ***Conclusion 1.3.*** *The SB 1281 dataset is not structured to facilitate straightforward calculations of water inputs, outputs, and applications by the O&G industry, key variables for understanding the impact of the O&G industry on regional water resources.*

> ***Recommendation 1.3.1.*** *Collapse the three SB 1281 datasets (Injection, Production, Other Allocation) into one master All Flows report, as described in Recommendations 1.4.2 and 1.4.3.*

> ***Recommendation 1.3.2.*** *Denote source and destination for every flow. Produced water should be a source, rather than a separate report. Likewise, water injected into a UIC well should be a destination, rather than a standalone report. Make Storage a source and a destination, rather than a separate variable.*

> ***Recommendation 1.3.3.*** *Eliminate duplicate reporting across the three reports. In theory, collapsing the three reports into one should reduce the likelihood of duplicate reporting. Definitions of sources and destinations should also be revised as necessary to prevent ambiguity. For example, Destination 9, "Operator's Facilities," should not include onsite storage if the stored water is reported elsewhere.*

> ***Recommendation 1.3.4.*** *The Division quarterly summary reports should give use, reuse, percentage reused, sources, and destinations per hydrologic region. This additional information would not replace sources and destinations, but would facilitate calculating larger, more integrative categories such as demand, reuse, total inputs from external sources, and total discharges to the surface.*

1.3.3. Water Cycle Analysis Results

Question 2.1. How much water does the O&G industry use, and how much water do they reuse for their operations?

We used tabulations of the water cycle to calculate water inputs, demand, reuse, and outputs for the five major basins, and calculated a sum of the five major basins. Table 1.7 shows the water cycle and Table 1.8 gives the water cycle metrics summed for the five major basins. Figures 1.9 and 1.10 show water demand, reuse, and percent reuse broken out for the five major basins in the state. Results tables can be found in Appendix 1.6.

Table 1.7. Water cycle results for the five major basins in California.

Water Cycle Origin	Water Cycle Endpoint	Volume of water (AFQ)		
		Saline	**Fresh/Brackish**	**Total**
Ancillary O&G Operations	Ancillary O&G Operations	250	0	250
	Disposal	401	29	430
	Other	0	0	0
	Discharge	0	0	0
	EOR and Stimulation	2,795	53	2,848
External Source	Ancillary O&G Operations	82	328	409
	Disposal	396	279	674
	Other	0	0	0
	Discharge	109	49	158
	EOR and Stimulation	909	1,045	1,953
Other	Ancillary O&G Operations	16	0	16
	Disposal	3	7	9
	Other	0	0	0
	Discharge	0	0	0
	EOR and Stimulation	148	12	160
Produced Water and Flowback	Ancillary O&G Operations	4,056	207	4,263
	Disposal	20,827	650	21,477
	Other	1,963	0	1,963
	Discharge	10,815	400	11,215
	EOR and Stimulation	63,482	1,667	65,149
Change in Storage	Change in Storage	-136	2	-134

Table 1.8. Water cycle metrics for the five major basins in California.

Metrics	**Volume of water (AFQ)**		
	Saline	**Fresh/Brackish**	**Total**
Inputs	100,674	4,625	105,299
Outputs	32,548	1,407	33,955
Demand	103,719	4,678	108,396
Reuse	70,582	1,927	72,509
External Source	1,494	1,701	3,195
Discharge	10,924	449	11,373

The five basins have a combined industry demand of about 110,000 AFQ of water and receive about 105,000 AFQ of water as inputs. The industry demand for fresh/brackish water is about 5,000 AFQ. About 2,000 AFQ comes from external sources. The vast majority of industry demand, about 103,000 AFQ, is satisfied with saline water. Out of this, about 67,000 AFQ goes towards EOR and well stimulation. About 11,500 AFQ is discharged to the surface, and 96% of this is saline. Further, 96% of the water handled by the industry is produced water, and 82% of all water handled is injected underground.

Across the five major basins, the O&G industry meets 68% of their saline water demand through reuse, but only 41% of their fresh water demand is satisfied by reuse (Figures 1.9 and 1.10). The ranges vary by basin; on the low end, 38% of saline water is reused in the Santa Maria basin, while the figure is as high as 97% in the Los Angeles basin. A smaller percentage of demand for fresh water is met through reuse, ranging from 3% for the Los Angeles basin to 75% for the Santa Barbara basin. In the San Joaquin basin, reuse represents about 55% of the saline water demand and 30% of the fresh/brackish water demand. In the Los Angeles basin, reuse represents nearly all of the saline water demand. Santa Barbara-Ventura has about 75% reuse for both water quality categories. Santa Maria and Salinas both have relatively small demands for saline water, reusing about 40% on the field, and both have zero demand for fresh water.

> ***Finding 1.4.*** *The O&G industry meets much of its demand for saline water by reusing produced water.*

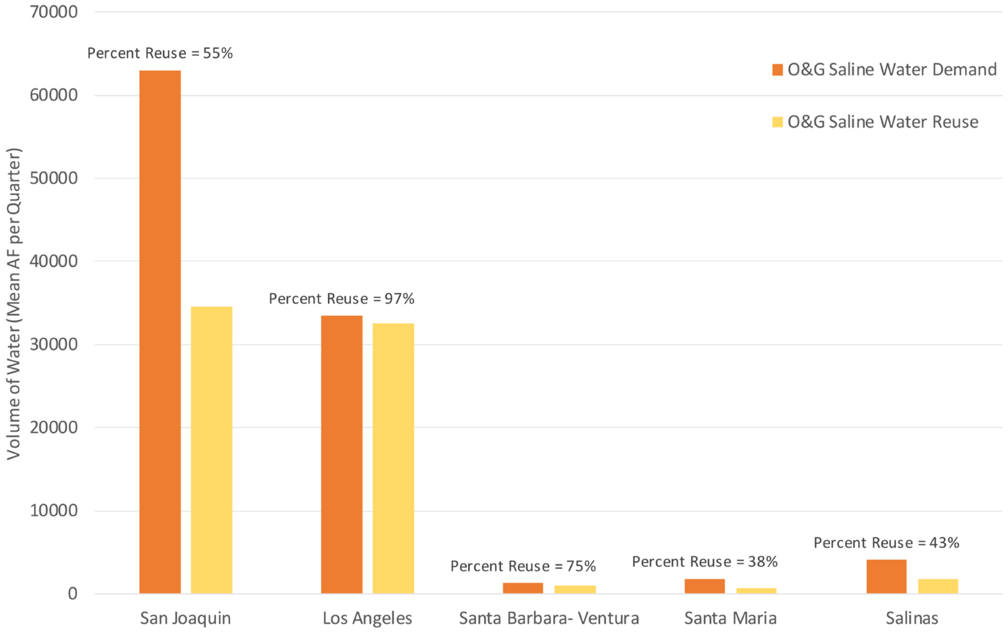

Figure 1.9. Saline water demand, reuse, and percent reuse for the O&G industry by basin. Percent Reuse = O&G Water Reuse/ O&G Water Demand. As noted under Question 1.3, reporting on TDS values should be viewed with caution. Source: 2015 Q4 - 2017 Q1 SB 1281 Dataset (DOGGR, 2018a).

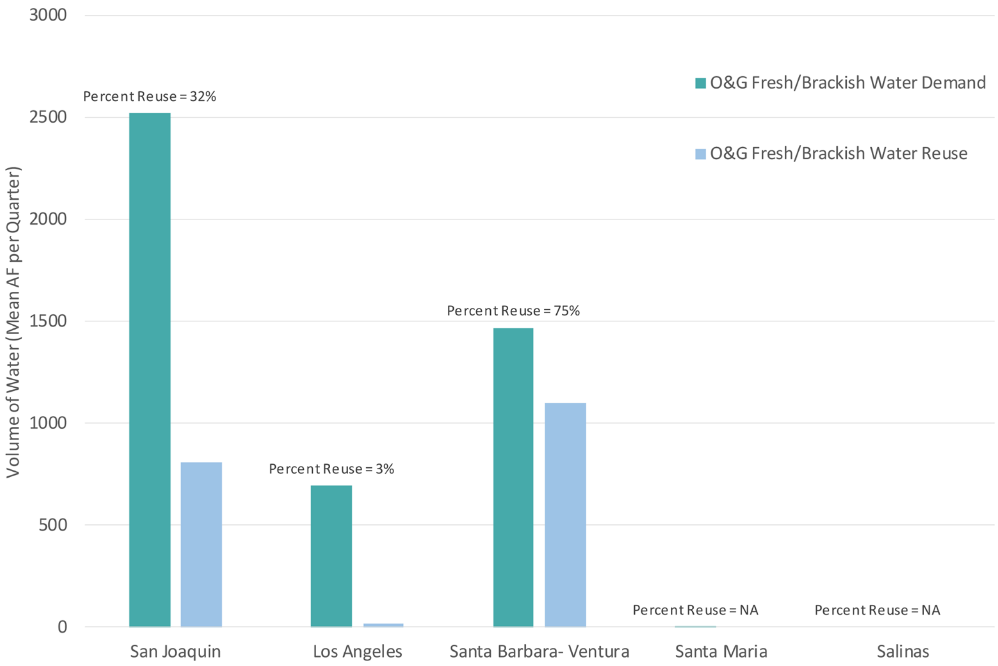

Figure 1.10. Fresh/brackish water demand, reuse, and percent reuse for the O&G industry by basin. Percent Reuse = O&G Water Reuse/ O&G Water Demand. As noted under Question 1.3, reporting on TDS values should be viewed with caution. Source: 2015 Q4 - 2017 Q1 SB 1281 Dataset (DOGGR, 2018a).

Question 2.2. Is the O&G industry a net consumer or generator of water?

In total, for the five major basins, 104,067 AFQ of water is produced water and flowback, and 70,110 AFQ is injected for the purpose of EOR and stimulation. The total amount of discharged water is 11,373 AFQ, 96% of which is saline water. This includes: discharge to surface water bodies, to lined pits, recharge of groundwater, and reuse for agriculture. The industry meets 68% of their saline water demand and 41% of their fresh water demand by reuse. For produced water and flowback, 63% is reinjected for oil recovery, and 21% is disposed of. In general, the O&G industry is a net generator of saline water, and a net consumer of fresh/brackish water (Figure 1.11). For example, in the San Joaquin basin, operators consumed a net 609 AFQ of fresh/brackish water from external sources. They discharged a net 8,700 AFQ of saline water. Net withdrawal of fresh/brackish water for the oil and gas industry is less than 0.1% of water applied for human uses in a hydrologic region. Minor basins show different patterns, but they have very small net flows. On the whole, the volumes of saline water generated by the O&G industry far exceed the fresh/ brackish water consumed.

> ***Conclusion 1.4.*** *Although the O&G industry reuses much of the saline water it produces, in certain basins, a substantial amount is either disposed of underground or discharged at the surface. A smaller proportion of industry fresh water demand is met by recycled water, because the majority of fresh/brackish water used by the O&G industry is water obtained from external sources rather than produced water.*

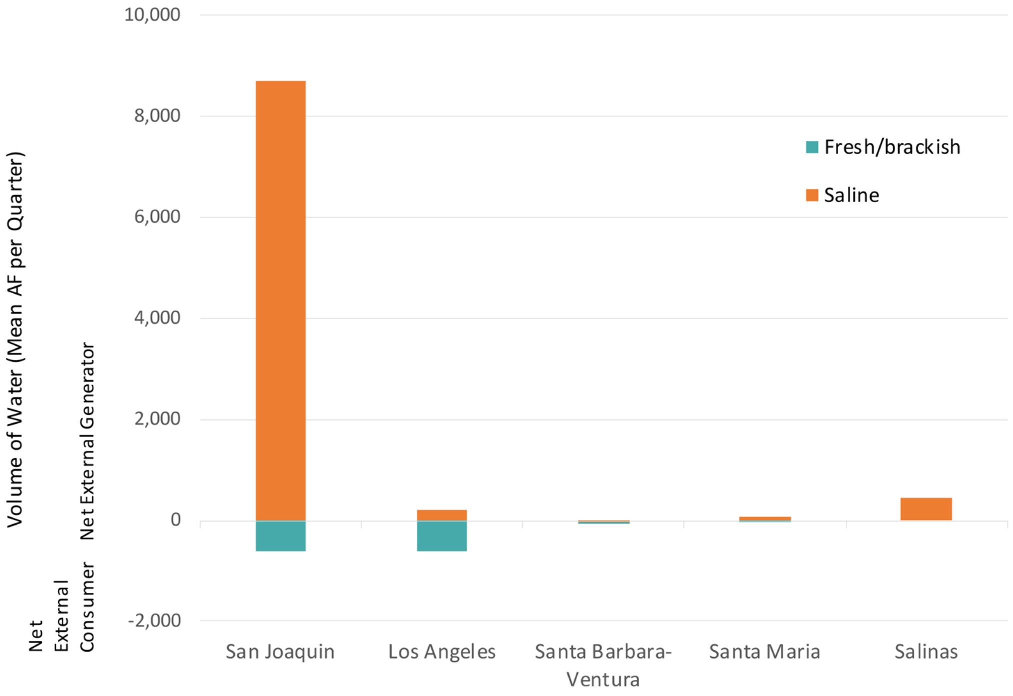

Figure 1.11. Net impact to surface water cycle. Calculated as Discharge - External Source for fresh/brackish and saline water, respectively. Volumes correspond to the difference in volumes between water flows to Discharge and water flows from external source. As noted under Question 1.3, reporting on TDS values should be viewed with caution. Source: 2015 Q4 - 2017 Q1 SB 1281 Dataset (DOGGR, 2018a).

Questions 2.2 & 2.3. Is the O&G industry a net consumer or generator of water? How much fresh/brackish water does the O&G industry withdraw compared to total human withdrawals in a region?

We correlated sedimentary basins to hydrologic regions in order to compare human withdrawals for a region with fresh/brackish inputs to the O&G industry from external sources. Even though boundary alignment was not perfect, we could make approximations to allow for a comparison of water use for three areas, as shown in Table 1.9. We focused on industry withdrawals of fresh/brackish water, as the vast majority of water applied for human use would fall under the threshold of 10,000 mg/L TDS. The O&G industry's fresh/brackish water use from external sources accounts for less than 0.1% of the total water used for human purposes. Overall the O&G industry has a small impact on the total amount of water used in California.

Table 1.9. Comparison of total water applied for human use to water inputs and outputs from the O&G industry. TAFY = Thousand Acre Feet Per Year. Water applied for human use includes urban and agricultural uses. Source: California Water Plan Update 2018 (DWR, 2018); 2015 Q4 - 2017 Q1 SB 1281 Dataset (DOGGR, 2018b).

Sedimentary Basin(s)	Hydrologic Region(s)	Water Applied for Human Use 2015 (TAFY)	O&G Industry Water from External Source (Fresh/Brackish)	Percent of Total Human Use
Santa Barbara - Ventura and Los Angeles	South Coast	4,130	2.75	0.07%
Salinas and Santa Maria	Central Coast	1,333	0.00	0.00%
San Joaquin	San Joaquin River Tulare Lake	19,480	4.05	0.02%

> ***Finding 1.5.1.*** *For saline water, volumes discharged at the surface exceeded water diverted from external sources. For fresh/brackish water, volumes diverted from external sources exceeded what was discharged at the surface.*

> ***Finding 1.5.2.*** *Net withdrawal of fresh/brackish water for the O&G industry is less than 0.1% of all water applied for human use in a hydrologic region.*

> ***Conclusion 1.5.*** *The O&G industry is a net generator of saline water and a net consumer of fresh/brackish water.*

> ***Finding 1.6.*** *Hydrologic region can serve as a reasonable framework for assessing water budgets, but hydrologic region is not reported as a variable in the SB 1281 dataset.*

> ***Conclusion 1.6.*** *Without hydrologic region reported, the SB 1281 dataset structure and data quality do not facilitate assessment of regional water availability and quality.*

> ***Recommendation 1.6.1.*** *The SB 1281 dataset should be expanded to denote hydrologic region of each lease.*

> ***Recommendation 1.6.2.*** *To enable the assessment of regional water availability, The Division quarterly summary reports should be expanded to provide use, reuse, sources, and destinations of water as a function of hydrologic region.*

> ***Conclusion 1.1.1.*** *The SB 1281 dataset, while imperfect, allows a fuller understanding of the O&G industry's role in regional water balances than was previously possible. By capturing all inputs, outputs, and applications of water, the dataset enables calculations of metrics such as demand, reuse, and net impact to the surface water cycle, which were previously impossible to calculate.*

> ***Conclusion 1.1.2.*** *Any revisions to the SB 1281 dataset should preserve and enhance its unique capacity to provide insight into the oil and gas water cycle and the impact of the industry to regional water balances.*

1.4. Discussion: Improving the SB 1281 Dataset

Through analyzing the SB 1281 dataset, we developed an understanding of many of its limitations and identified opportunities for improvement. An evident problem was the tendency toward underreporting in the SB 1281 dataset relative to the monthly dataset, particularly in the first and last three quarters of 2015 –2017 and in the minor basins. The errors during the first three quarters of reporting are likely due to operators learning how to use the system. More worrying is the dropoff in reported volumes beginning in 2017 Q2. This suggests that the dataset may not prove reliable in the future. A detailed exploration of which operators are underreporting relative to the monthly dataset, an examination of The Division's internal data stewardship to ensure that data loss is not occurring during their data manipulations, and possibly some beta testing with operators to understand problems during the reporting stage would help resolve the reason for the dropoff. Accuracy of the SB 1281 dataset as a whole may also benefit from some simplifications of the reporting requirements, which we discuss below.

Based on logical inferences on the likely quality of water from various sources, some of the water quality information appeared suspect. It seems unlikely that water suppliers, municipal wastewater, or surface water would supply water over 10,000 mg/L TDS. Flagging large volumes of water with improbable quality values, and asking operators for clarification, might improve the water quality data. Again, beta testing to better understand sources of error during the reporting process might improve usability of the reporting forms.

The SB 1281 Production and Injection reports provide information on a per-well basis. The SB 1281 Well-to-Well Allocation report attempts to trace water flows between individual wells. Information aggregated at a larger scale is more useful for understanding impacts to hydrologic water cycles. The well-by-well reporting also is largely redundant with information already available in the monthly dataset. The main added utility of the SB 1281 dataset is providing insight into the impact of each lease on regional water resources. Consequently, the SB 1281 dataset could be revised to require information on the volumes of water inputs, applications, and outputs on a per-lease basis. Adding a column indicating hydrologic region would locate a lease within its region. The operator would not need to report hydrologic region; this can be defined as a function of lease location. The monthly reporting could retain the per-well reporting of production and injection volumes. Adding a variable to the monthly dataset could allow linking each production and UIC well to a water handling point or points, such as a manifold or treatment facility. This would improve traceability of how water moves between wells (and the formations they produce from or inject into) better than the Well-to-Well Allocation report.

While the source and destination variables are useful and should be retained in the dataset, source and destination categories could be more clearly defined and delineated. While we recommend keeping or expanding the number of categories to describe sources and destinations of water off the field, some of the categories on Class II waste could be collapsed into fewer categories. We make detailed recommendations on how to update the source and destination categories in Appendix 1.1. Key points to consider in renaming sources and destinations are: a) "Domestic Use" should not be used to refer to reuse for agriculture or recharge; b) Oceans and surface water should be distinguished in sources and destinations, given the large quality differences; c) Constrain the definition of the "Other" category so it explicitly excludes reporting water that could be reported in another, better-defined category; d) Create separate categories for injection in disposal wells versus injection in EOR wells to enable calculation of percent reuse for the industry; e) Treat storage as a source and a destination, not a separate variable. We make additional recommendations on updating source and destination codes, and identifying relevant permits for select destination codes, in Chapter 2.

We also recommend classifying into larger water cycle groupings with the addition of "Water Cycle Origin" and "Water Cycle Endpoint" variables. These larger groupings facilitate the calculation of key metrics such as inputs, outputs, reuse, demand, withdrawals from external sources, discharges, percent reuse, and net impact to surface water cycle. These metrics, tallied separately for fresh/brackish and saline water, should be included in The Division quarterly summary reports (see DOGGR (2018c) for a sample summary report).

Finally, the overall utility of the SB 1281 dataset could be improved through aggregating the Production, Injection, and Other Allocation reports into a master dataset with a unified structure. We created such a dataset, named "All Flows," and include a downloadable copy in Appendix 1.5. The key to aligning the three reports is to define every flow of water by a source and destination. This facilitates summing all inputs, outputs, and applications for which water is used for the industry as a whole, rather than separating produced and injected water from other applications on the field.

Finding 1.7. *There are a large number of data quality problems in the SB 1281 dataset. Examples include.*

- *Much of the water quality reporting did not appear credible when considering the source or destination of the water, such as saline water from a municipal water supplier, or saline water discharged for agriculture and recharge.*
- *Blank fields could signify zeroes, not applicable, or failure to report.*
- *Multiple source and destination categories were vaguely defined or aggregated in groupings that are very different.*
- *Text fields with slight variants or misspellings (i.e. Smith Corp., smith corp., Smith corporation, and Smith corporation) created unintentional mismatches in the dataset.*
- *Invalid data entries, such as data of the wrong value type or outside the range of possible values, caused loss of information.*

Conclusion 1.7.1. *Data quality problems made accurate analysis challenging. In particular, water quality reporting that seems illogical undermines the ability to accurately assess impacts to water resources. Simple data validation fixes could make accurate analysis easier and faster.*

Recommendation 1.7.1. *Zero values should always be actively reported (not left blank) to enable accurate calculations of means.*

Recommendation 1.7.2. *Source and destination categories should be better defined to better elucidate the industry's impact on water resources.*

Conclusion 1.7.2. *The SB 1281 dataset could be improved with certain changes in data quality assurance to reduce the errors in the final dataset. Specific recommendations follow:*

Recommendation 1.7.3. *Update the terms and definitions for sources and destinations to better describe and distinguish the categories as described in Appendix 1.1. Key points to consider in renaming sources and destinations: a) "Domestic Use" should not be used to refer to reuse for agriculture or recharge; b) Oceans and surface water should be distinguished in sources and destinations, given the large quality differences; c) Constrain the definition of the "Other" category such that it explicitly excludes reporting water that could be reported in another, better-defined category; d) Create separate categories for injection in disposal wells versus injection in EOR wells; and e) Treat storage as a source and a destination, not a separate variable.*

> ***Recommendation 1.7.4.*** *Reducing the number of sources and destinations reported by field would simplify reporting without functional loss of important information. For instance, Source 10, “Other Class II Recycled fluid source,” along with Source 11, “Recycled Class II fluids from operator’s drilling,” and Source 5, “Industrial Waste – Class II fluid treated by 3rd party” could become one source defined simply as “Class II Fluids (other than produced water).”*

> ***Recommendation 1.7.5.*** *Add columns to the reports to allow more detailed reporting on the identity and location of the source and destination. For example, external sources (such as municipal suppliers and municipal wastewater) should provide names of public water systems and their associated Public Water System Identification Number (PWSID), the tracking identification number used by the State Water Board. Discharges should identify the relevant permit, if applicable. Discharges to municipal wastewater systems should include PWSID.*

> ***Recommendation 1.7.6.*** *Limit invalid data entry by requiring operators to choose from a drop-down list where appropriate and restrict the ability to leave fields blank. There should be pre-defined options for every field. Most text entry fields, such as operator and field names, should be selected from a drop-down menu to prevent alternative spellings.*

> ***Recommendation 1.7.7.*** *Enact mechanisms to distinguish between zero, not applicable, and failure to report. All fields should require the reporter to select an option before submitting the report. If an operator fails to report information, that should be noted as “failure to report” in the master dataset, rather than blanks.*

> ***Recommendation 1.7.8.*** *Beta test the form to observe how operators interpret the form. This would enable The Division to find opportunities to clarify the form.*

> ***Recommendation 1.7.9.*** *Perform selective ground-truthing on the information reported in the dataset. Reports of large volumes of saline water from a water well, municipal water supplier, or municipal wastewater, as well as substantial discharges of saline water, should be flagged for closer inspection to verify that the reporting is accurate. Independent datasets on groundwater quality, such as GeoTracker GAMA, could be used to validate the SB 1281 dataset.*

> ***Recommendation 1.7.10.*** *Perform further, in-depth data validation between information reported in the SB 1281 dataset and in the monthly dataset, and compare volumes reported for well stimulation with those reported in SB 4.*

1.5. Summary: Findings, Conclusions, and Recommendations

The SB 1281 dataset offers unique insight into the oil and gas water cycle and the industry's impacts to regional water balances. Working with the SB 1281 dataset, both alone and in conjunction with other available datasets as detailed in the chapter, we were able to construct the first-ever complete water cycle for the O&G Industry in California. In the process, we found a number of opportunities to improve the dataset to answer the main questions of interest, reduce redundancies with the monthly dataset, and reduced errors.

FCR 1.1. Value of the SB 1281 dataset *(Chapter 1, Sections 1.1, 1.2.1)*

Finding 1.1.1. Prior attempts to collect data on water use by the O&G industry, such as the monthly and SB 4 datasets, captured only a subset of water handled by the industry.

Finding 1.1.2. The SB 1281 dataset provides unique value by encompassing all water handled by the O&G industry in its three reports, including previously unreported uses such as for dust suppression, equipment cleaning, drilling muds, and domestic water.

Finding 1.1.3. Much of the new information gained from the SB 1281 dataset is found in the Other Allocation report, which is the sole source of state information on water used by the industry that is neither produced nor injected.

Conclusion 1.1.1. The SB 1281 dataset, while imperfect, allows a fuller understanding of the O&G industry's role in regional water balances than was previously possible. By capturing all inputs, outputs, and applications of water, the dataset enables calculations of metrics such as demand, reuse, and net impact to the surface water cycle, which were previously impossible to calculate.

Conclusion 1.1.2. Any revisions to the SB 1281 dataset should preserve and enhance its unique capacity to provide insight into the oil and gas water cycle and the impact of the industry to regional water balances.

FCR 1.2. Redundancy between the 1281 and monthly datasets *(Chapter 1, Sections 1.2.1, 1.2.2)*

Finding 1.2.1. The SB 1281 dataset includes three reports: Injection, Production, and Other Allocation, which have non-parallel sets of columns.

Finding 1.2.2. The monthly dataset includes three reports: Injection, Production, and California oil and gas wells. The Injection and Production reports give information on volumes of water (in addition to oil and gas where appropriate), and source/disposition and quality of water that are similar to information found in the SB 1281 dataset.

Conclusion 1.2.1. The Well-to-Well Allocation report seeks to itemize the movement of water from every production well to every injection well. In practice, however, water moves from production wells to centralized treatment facilities (e.g. oil-water separators) and back to injection wells, and these volumes cannot be accurately tracked in the way intended by this report.

Conclusion 1.2.2. Per-well reporting of produced and injected water in the SB 1281 dataset was largely redundant with existing reporting in the monthly dataset. At the same time, the Well-to-Well Allocation report was excessively complex and failed to accurately represent how water moves through an oil field.

Conclusion 1.2.3. The SB 1281 dataset provides better information on source, destination, and quality of water than the monthly dataset.

Conclusion 1.2.4. Redundancy between the SB 1281 dataset and the monthly dataset can be reduced by appropriately augmenting the monthly dataset to take over well-by-well reporting on production and injection from the SB 1281 dataset.

Conclusion 1.2.5. The SB 1281 dataset can be used to gather information at the lease scale or larger.

Conclusion 1.2.6. The monthly dataset appears to have more reliable information on volumes of produced and injected water than the SB 1281 dataset.

Recommendation 1.2.1. Make the monthly dataset the repository for volumes of water produced and injected; focus the SB 1281 dataset instead on flows of water into and out of the O&G industry.

Recommendation 1.2.2. The monthly dataset should adopt similar variables for source, destination, and quality as the SB 1281 dataset to eliminate the per-well reporting in the SB 1281 dataset; operators can be required to simply report on a per-lease basis to the SB 1281 dataset.

Recommendation 1.2.3. Add a column to the monthly production and injection dataset for operators to report the water treatment facility to which each production and injection well connects.

Recommendation 1.2.4. Instead of attempting to apportion flows of water between individual wells as is currently done in the Well-to-Well Allocation report, operators should simply include the water treatment facility or facilities connected to each production and injection well in the monthly dataset.

FCR 1.3. Using the SB 1281 dataset for insight into the water cycle *(Chapter 1, Section 1.3.2)*

Finding 1.3.1. Calculating water inputs, outputs, and applications by the O&G industry required extensive parsing, reorganizing, and compiling of data from three reports: Production, Injection, and Other Allocation.

Finding 1.3.2. The three reports contained similar variables but had slightly different structures, making it challenging to sum quantities across reports. For example, produced water used for well stimulation was reported in the Production report, whereas water from external sources used for well stimulation was found in the Other Allocations report.

Finding 1.3.3. The three reports also allowed for duplicate reporting of some flows of water. For example, produced water that was injected into a UIC well was reported in all three reports: once in the Production report with a destination of underground injection, once in the Injection report with a source of produced water, and once (erroneously) in the Other Allocations report with a source of produced water and destination of underground injection.

Conclusion 1.3. The SB 1281 dataset is not structured to facilitate straightforward calculations of water inputs, outputs, and applications by the O&G industry, key variables for understanding the impact of the O&G industry on regional water resources.

Recommendation 1.3.1. Collapse the three SB 1281 datasets (Injection, Production, Other Allocation) into one master All Flows report, as described in Recommendations 1.4.2 and 1.4.3.

Recommendation 1.3.2. Denote source and destination for every flow. Produced water should be a source, rather than a separate report. Likewise, water injected into a UIC well should be a destination, rather than a standalone report. Make Storage a source and a destination, rather than a separate variable.

Recommendation 1.3.3. Eliminate duplicate reporting across the three reports. In theory, collapsing the three reports into one should reduce the likelihood of duplicate reporting. Definitions of sources and destinations should also be revised as necessary to prevent ambiguity. For example, Destination 9, “Operator’s Facilities,” should not include onsite storage if the stored water is reported elsewhere.

Recommendation 1.3.4. The Division quarterly summary reports should give use, reuse, percentage reused, sources, and destinations per hydrologic region. This additional information would not replace sources and destinations, but would facilitate calculating larger, more integrative categories such as demand, reuse, total inputs from external sources, and total discharges to the surface.

FCR 1.4. Water reuse by the O&G industry *(Chapter 1, Section 1.3.3)*

Finding 1.4. The O&G industry meets much of its demand for saline water by reusing produced water.

Conclusion 1.4. Although the O&G industry reuses much of the saline water it produces, in certain basins, a substantial amount is either disposed of underground or discharged at the surface. A smaller proportion of industry fresh water demand is met by recycled water, because the majority of fresh/brackish water used by the O&G industry is water obtained from external sources rather than produced water.

FCR 1.5. Water use and discharges by the O&G industry *(Chapter 1, Section 1.3.3)*

Finding 1.5.1. For saline water, volumes discharged at the surface exceeded water diverted from external sources. For fresh/brackish water, volumes diverted from external sources exceeded what was discharged at the surface.

Finding 1.5.2. Net withdrawal of fresh/brackish water for the O&G industry is less than 0.1% of all water applied for human use in a hydrologic region.

Conclusion 1.5. The O&G industry is a net generator of saline water and a net consumer of fresh/brackish water.

FCR 1.6. Facilitating assessment of regional water impacts *(Chapter 1, Section 1.3.1)*

Finding 1.6. Hydrologic region can serve as a reasonable framework for assessing water budgets, but hydrologic region is not reported as a variable in the SB 1281 dataset.

Conclusion 1.6. Without hydrologic region reported, the SB 1281 dataset structure and data quality do not facilitate assessment of regional water availability and quality.

Recommendation 1.6.1. The SB 1281 dataset should be expanded to denote hydrologic region of each lease.

Recommendation 1.6.2. To enable the assessment of regional water availability, The Division quarterly summary reports should be expanded to provide use, reuse, sources, and destinations of water as a function of hydrologic region.

FCR 1.7. Data quality, organization, and reporting requirements in the SB 1281 dataset *(Chapter 1, Section 1.4)*

Finding 1.7. There were a large number of data quality problems in the SB 1281 dataset. Examples include:

- Much of the water quality reporting did not appear credible when considering the source or destination of the water, such as saline water from a municipal water supplier, or saline water discharged for agriculture and recharge.

- Blank fields could signify zeroes, not applicable, or failure to report.

- Multiple source and destination categories were vaguely defined or aggregated in groupings that are very different.

- Text fields with slight variants or misspellings (i.e. Smith Corp., smith corp., Smith corporation, and Smith corporation) created unintentional mismatches in the dataset.

- Invalid data entries, such as data of the wrong value type or outside the range of possible values, caused loss of information.

Conclusion 1.7.1. Data quality problems made accurate analysis challenging. In particular, water quality reporting that seems illogical undermines the ability to accurately assess impacts to water resources. Simple data validation fixes could make accurate analysis easier and faster.

Recommendation 1.7.1. Zero values should always be actively reported (not left blank) to enable accurate calculations of means.

Recommendation 1.7.2. Source and destination categories should be better defined to better elucidate the industry's impact on water resources.

Conclusion 1.7.2. The SB 1281 dataset could be improved with certain changes in data quality assurance to reduce the errors in the final dataset. Specific recommendations follow:

Recommendation 1.7.3. Update the terms and definitions for sources and destinations to better describe and distinguish the categories as described in Appendix 1.1. Key points to consider in renaming sources and destinations: a) "Domestic Use" should not be used to refer to reuse for agriculture or recharge; b) Oceans and surface water should be distinguished in sources and destinations, given the large quality differences; c) Constrain the definition of the "Other" category such that it explicitly excludes reporting water that could be reported in another, better-defined category; d) Create separate categories for injection in disposal wells versus injection in EOR wells; and e) Treat storage as a source and a destination, not a separate variable.

Recommendation 1.7.4. Reducing the number of sources and destinations reported by field would simplify reporting without functional loss of important information. For instance, Source 10, "Other Class II Recycled fluid source," along with Source 11, "Recycled Class II fluids from operator's drilling," and Source 5, "Industrial Waste – Class II fluid treated by 3rd party" could become one source defined simply as "Class II Fluids (other than produced water)."

Recommendation 1.7.5. Add columns to the reports to allow more detailed reporting on the identity and location of the source and destination. For example, external sources (such as municipal suppliers and municipal wastewater) should provide names of public water systems and their associated Public Water System Identification Number (PWSID), the tracking identification number used by the State Water Board. Discharges should identify the relevant permit, if applicable. Discharges to municipal wastewater systems should include PWSID.

Recommendation 1.7.6. Limit invalid data entry by requiring operators to choose from a drop-down list where appropriate and restrict the ability to leave fields blank. There should be pre-defined options for every field. Most text entry fields, such as operator and field names, should be selected from a drop-down menu to prevent alternative spellings.

Recommendation 1.7.7. Enact mechanisms to distinguish between zero, not applicable, and failure to report. All fields should require the reporter to select an option before submitting the report. If an operator fails to report information, that should be noted as "failure to report" in the master dataset, rather than blanks.

Recommendation 1.7.8. Beta test the form to observe how operators interpret the form. This would enable The Division to find opportunities to clarify the form.

Recommendation 1.7.9. Perform selective ground-truthing on the information reported in the dataset. Reports of large volumes of saline water from a water well, municipal water supplier, or municipal wastewater, as well as substantial discharges of saline water, should be flagged for closer inspection to verify that the reporting is accurate. Independent datasets on groundwater quality, such as GeoTracker GAMA, could be used to validate the SB 1281 dataset.

Recommendation 1.7.10. Perform further, in-depth data validation between information reported in the SB 1281 dataset and in the monthly dataset, and compare volumes reported for well stimulation with those reported in SB 4.

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Chapter 2

Reuse of Produced Water for Irrigation

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2.0. Abstract

In this chapter, we examine current reuse of produced water for agriculture outside of oil and gas industry operations and develop a high-end estimate of the quantity of produced water available for reuse. We utilize the Senate Bill (SB) 1281 dataset volumes of fresh/brackish produced water as well as eight additional water quality datasets based on waters needing minimal treatment (i.e. Total Dissolved Solid (TDS) up to 2,000 mg/L). The 2,000 mg/L TDS level was chosen based on irrigation water quality guidelines published by the United Nations Food and Agriculture Organization (Ayers & Westcot, 1985). In California, there are ten permits for reuse of water outside of the oilfield. Six are for direct reuse for agriculture; three are for indirect reuse via discharges to ground or surface water with designated agricultural beneficial uses, and one covers both activities. There are an additional 11 operators on 11 fields reporting discharges to agriculture, groundwater recharge, or surface water for which we could not find evidence of a permit. Most reuse outside of the oil and gas industry occurs in the southeastern San Joaquin basin. A total of 413,000 acre feet per year (AFY) of water is produced in the five major basins in California, which could conceivably be reused with treatment. Of this, the SB 1281 dataset indicates that a total average annual volume of 11,337 AFY has equal to or less than 10,000 mg/L TDS and is not reused by agriculture. However, because the threshold for TDS is not based on irrigation water quality guidelines, this may not be a useful value for assessing potential for reuse. Following a second approach based on eight additional produced water quality datasets we estimate that there could be approximately 64,000 AFY of produced water available for reuse needing minimal treatment. The potential for expansion of reuse of produced water off the field was concentrated in the southeast San Joaquin basin, the center of much of California's agricultural water use. The 64,000 AFY represents a very small quantity relative to total water used for irrigation in the region (less than 0.4%). Future research should assess the limitations on reuse of produced water imposed by other chemical constituents besides boron and TDS that have potential impacts to soil, crop, human and environmental health.

Questions Addressed in Chapter 2

- **Question 2.1**. Where is produced water reused for agriculture?
- **Question 2.2**. What is the potential for expansion of produced water reuse for agricultural irrigation in California?

2.1. Introduction

With the passage of SB 1281 by the California State legislature in 2014, more detailed information on the volume, source, quality, treatment, and destination of water used by oil and gas operators has become available. These new data make it possible for policy makers, government regulators, and other interested parties to better understand the impacts of the oil and gas industry on the water cycle across the state. One of the key questions the SB 1281 dataset can help answer is on the potential for increasing the reuse of produced water outside of oil and gas operations. To this end, SB 1281 mandates that: "the volume of untreated water suitable for domestic or irrigation purposes shall be reported" (PRC Sec. 3227(a)(5)).

The majority of produced water in the state comes from oil and gas producing basins in dryer regions where water supplies are scarce (see Chapter 1, Figure 1.2). Agriculture is also common in these same, water-scarce regions (Heberger & Donnelly, 2015). Water demand in these regions has been met primarily with imported water supplies and groundwater. However, when imported supplies have been less reliable such as during times of drought, excessive groundwater pumping has caused rapid depletion of water tables, declines in streamflows, land subsidence, and in coastal regions, salt-water intrusion (Zektser et al., 2004). During the 2012–2016 drought, many basins in the state experienced loss of stream and river flows, directly harming endangered fish and other aquatic species (Mount et al., 2017). Also, during drought, agricultural activities were curtailed due to lack of water availability, regulatory requirements protecting fish, and other factors, such as the price of water (Cooley et al., 2015; Medellin-Azuara et al., 2016).

Water scarcity is an ongoing challenge in California, amplified by a growing population, periodic drought, climate change, and contamination of surface and groundwater sources. Climate research indicates that variation in precipitation will increase over time, leading to more extreme periods of dry and wet years (Swain et al., 2018). Agricultural water suppliers and farmers are increasingly turning to alternative water sources that have traditionally been considered unusable due to concerns about water quality or impracticable due to cost (e.g., Thebo, 2018), such as produced water or treated municipal wastewater. Already in a small number of cases in California, produced water is sent to water districts that supply water to farmers (Heberger & Donnelly, 2015). Additionally, produced water discharged to streams and rivers is known to support some downstream irrigators (Stringfellow et al., 2015). For example, Cawelo Water District in Kern County has been selling water that is a blend of produced water and other water sources to its customers for more than three decades (Cawelo Water District, 2014).

The oil and gas industry is both a consumer and producer of water. While the industry diverts water from external sources such as water wells, municipal supplies, and surface water, it also co-produces large volumes of water along with oil and gas (see Chapter 1, this report). This water is separated from commercial hydrocarbons (oil and/or gas) and is typically re-injected for enhanced oil recovery (EOR), discarded as a waste product in Class II Underground Injection Control (UIC) wells, or discharged into unlined produced water ponds on the ground surface. While much of the water produced by the oil and gas industry is far too salty to reuse off the oil field without appropriate treatment, some fields are net producers of fresh to brackish water that could potentially be reused for irrigation, recharge of groundwater, or to augment streamflows. Produced water has been applied to such "beneficial uses," as they are commonly referred to in the water sector, for more than three decades in California (State Water Board, 2019). However, new attention to potential impacts to ecosystems and human health from reuse of produced water have brought greater scientific scrutiny and oversight, such as through the Central Valley Water Resources Control Board Food and Safety Expert panel (CVRWQCB, 2019b). In this chapter, we did not seek to assess the potential impacts of reuse of produced water for human or ecosystem health. Rather, we sought to formulate a first-order estimate of the volume of water that could be reused for irrigation based on key constituents of concern for soil and crop health alone. While there may be a potential for reuse of produced water by industry or for other activities, the scope of this paper was limited to agriculture.

In this chapter, we present the results of a spatial analysis of produced water quality and quantity. Pairing the SB 1281 dataset with several different sources provides greater insight into the availability and quality of produced water in active fields across the state. The motivating questions for the analysis are:

1. Where is produced water reused for agriculture?
2. What is the potential for expansion of produced water reuse for agricultural irrigation in California?

To understand where produced water is presently reused in California, we compiled information from the SB 1281 dataset as well as permits issued by regional water quality control boards. To assess potential for expansion, we used the SB 1281 dataset on produced water quality, yet due to the limited nature of the SB 1281 analytical data, we sought additional sources for our analysis. Based on eight produced water quality datasets and the SB 1281 water quality and volumetric data, we produced a range of the estimated additional volume of produced water of a suitable quality potentially available for reuse by the agricultural industry. We identify the oil and gas fields where this water may be available. Finally, we use the outcomes of our analysis and results as a basis for recommendations for SB 1281 data collection.

2.2. Literature Review: Produced Water Suitability for Agriculture

As a primary step in evaluating produced water availability for reuse by the agricultural industry, we reviewed literature on water quality guidelines for crop and soil health. From this body of literature, a relatively standard set of inorganic chemicals and associated parameters have been identified as important to the suitability of water for irrigation purposes. Here we review the water quality characteristics of major concern for irrigation: total dissolved solids (TDS) (also reported as electrical conductivity (EC)): calcium (Ca^{2+}), sodium (Na^{+}), chloride (Cl^{-}), boron (B), and the sodium adsorption ratio (SAR).

2.2.1. Total Dissolved Solids

Total dissolved solids (TDS) is a measurement of the amount of dissolved substances in a volume of water, including salts, minerals, metals and organic compounds.[1] For low organic content waters, TDS in milligrams per liter (mg/L) is directly proportional to the Electrical Conductivity in deciSiemens per meter at 25 degrees C (dS/m); for waters with high organic content, such as produced water, the actual TDS value can be larger than that predicted from EC by the mass of dissolved, non-volatile organic content. Due to the relatively simple instrumentation that allows for instantaneous field measurements of EC, this parameter is more commonly used within the agricultural sector (Grattan, 2002). Waters with high TDS are naturally occurring and may be caused by the dissolution of minerals from contact with soluble media (e.g., soils), especially when the contact lasts for long periods of time, such as in the case of groundwater. TDS must be managed in many agricultural areas, such as the Tulare Lake basin in the San Joaquin Valley, where high amounts of saline groundwater and poor drainage have contributed to ongoing and long-term soil salinization issues (Johnston et al., 2011). The Central Valley Regional Water Quality Control Board (CVRWQCB) has designed a program for managing high salinity and nitrate, called the Central Valley Salinity Alternatives for Long-term Salinity (CV-SALTS) (CVRWQCB, 2017). CV-SALTS is a multi-stakeholder collaborative effort that seeks to identify both the natural and human influences of high salinity in the region and to provide planning that addresses the identified issues.

High TDS is a concern for irrigators because it can reduce the water availability to crops, impact soil water infiltration, and accumulates in soils over time. Excess salts in the crop root zone reduces the ability of plants to extract water from the soil, reducing crop yield (Ayers and Westcot, 1985). Table 2.1 provides a classification for irrigation waters based on their TDS and EC values.

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1. Salinity is another term common in certain disciplines, such as soil science, for TDS and EC. Throughout this report, we use the terms TDS and EC rather than salinity, which we felt better capture the breadth of chemical constituents dissolved in produced water.

Table 2.1. Permissible TDS and EC limits for classes of irrigation water. Source: Adapted from Ayers and Westcot (1985).

Degree of Restriction on Use	TDS (mg/L)	EC (dS/m)
None	<450	<0.7
Slight to Moderate	450-2,000	0.7-3.0
Severe	>2,000	>3.0

TDS problems can be controlled to some extent with management approaches and/or water treatment technologies. Strategies include options such as irrigation timing. Another common approach to reducing the impact of high TDS water on soil and crop health is through leaching, which is the practice of applying extra water to allow removal of salts particularly in the root zone. This practice is commonly cited as an effective means of dealing with high TDS in soils, however there must be effective drainage of the soils and additional water for this purpose (Ayers and Westcot, 1985; Fipps, n.d.; Johnston et al., 2011; Letey et al., 2011). Some agricultural regions in California, such as the Tulare Lake region, do not have effective drainage and may be less able to manage ongoing salinity issues (CDM Smith, 2016). In addition, during times of water scarcity leaching may not be an appropriate use with limited water resources. Treatment technology exists to achieve necessary levels of TDS; however, more often limitations for this approach are based on initial water quality, which impacts cost (NRC, 2010).

Many produced waters have high TDS (e.g., Benko & Drewes, 2008; Pichtel, 2016; Echchelh et al., 2018). Analysis of the National Produced Waters Geochemical Database, curated by the U.S. Geological Survey, has shown a range of concentrations between 1,000 mg/L and 400,000 mg/L, with a median of 32,300 mg/L (Benko & Drews, 2008). For reference, drinking water typically has TDS values under 500 (U.S. EPA, n.d.), while seawater is typically in the range of 35,000 mg/L TDS (Haluszczak et al., 2013).

2.2.2. Sodium Adsorption Ratios

Waters with high TDS levels can have high sodium adsorption ratios (SAR). SAR is the ratio of sodium to calcium and magnesium dissolved in water. SAR is calculated following Equation 2.1. Using water with a high SAR (high sodium content) leads to a compaction of clayey soils. This can impact water infiltration rates, with high SAR causing lower infiltration rates. Adding calcium and magnesium can counteract the impacts of the sodium.

Equation 2.1

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Where *Na* is sodium, *Ca* is calcium, and *Mg* is magnesium. All constituents are measured in milliequivalents per liter (meq/L). An equivalent is the amount of a constituent that will react with one mole of another, oppositely charged constituent, such as hydrogen. A milliequivalent is 1/1,000 equivalents.

EC (and therefore TDS) and SAR have interactive effects on soil quality. A low SAR will likely cause soil infiltration problems only at very low TDS (here discussed as EC) levels. But as SAR increases, the range of EC values within which SAR causes soil infiltration problems grows. Table 2.2 provides guidance on the combined effect of EC and the SAR on water infiltration. The EC of the irrigation water source is indicated by EC_w to distinguish it from the EC of the soil water. SAR varies widely in produced water, with values reported between 1 and 3,759 (Echchelh et al., 2018). The upper end of the range for SAR in produced water is far above what is commonly used in irrigation water, with values over 26 typically considered unsuitable for use on cropland (Fipps, n.d.).

Table 2.2. Combined effect of electrical conductivity of irrigation water (ECw) and sodium adsorption ratio (SAR) on the likelihood of water infiltration problems. Source: Adapted from Grattan (2002) and Ayers and Westcot (1985).

	Water infiltration problem	
SAR of irrigation water or soil	**Unlikely when EC_w (dS/m) is more than**	**Likely when EC_w (dS/m) is less than**
0-3	0.6	0.3
3 to 6	1.0	0.4
6 to 12	2.0	0.5
12 to 20	3.0	1.0
20 to 40	5.0	2.0

2.2.3. Chloride, Sodium, and Boron

Water can be toxic to certain crops when it contains high levels of certain dissolved constituents, particularly chloride, sodium, and boron. Sodium in water can cause injury to crops when applied via sprinkler irrigation, through absorption by the leaves of the plants, with many crops showing injury at 69 mg/L and above (Ayers and Westcot, 1985). Sodium can also damage crops when in water applied by drip and furrow irrigation as a component of SAR, described above (Grattan, 2002).

Chloride, like sodium, is most likely to cause damage in sprinkler irrigation, with many crops showing leaf damage at chloride levels exceeding 105 mg/L (Ayers and Westcot, 1985). Crop tolerances for chloride in soil water vary widely, with sensitive crops tolerating only up to 120 mg/L, while plants such as grapes can tolerate up to 700 mg/L or more (Grattan, 2002).

Boron can be better tolerated in short-term use and under cool, moist climatic conditions. Furthermore, soil properties mediate the impact of boron, with finer soil textures delaying injury (Grattan, 2002). However, boron is known to accumulate in soils over time. There are no management strategies available for removing boron from the soil, but adjustments to crop types that tolerate it may be possible (Yau & Ryan, 2008). A general rule of thumb is that boron is unlikely to cause damage at less than 0.7 mg/L, while caution should be exercised at levels between 0.7 – 3.0 mg/L, and damage is likely at levels over 3.0 mg/L (Ayers and Westcot, 1985).

Concentrations of boron in produced water have been found to range from lower than the detection limit (typically around 0.05 mg/L) to as high as 564 mg/L (Echchelh et al., 2018). Sodium and chloride concentrations likewise vary widely in produced water, with values reported to range from 1 to 434,000 mg/L and less than 1 to 311,000 mg/L, respectively (Echchelh et al., 2018). At the lower end, the boron, sodium, and chloride concentrations found in produced water can be well-tolerated in most circumstances, while the higher-end values would render the water unusable for irrigation without significant treatment.

2.2.4. Miscellaneous Water Quality Characteristics of Concern

Certain crops will have other water quality constituents that must be avoided or monitored for optimal crop output. Crop appearance can be damaged by water with high bicarbonate (HCO_3-), especially when overhead sprinklers are used. Bicarbonate has been reported to range from less than one to 43,000 mg/L and pH from 3.1 to 11.8 in produced water (Echchelh et al., 2018). A pH outside of the typical range (6.5-8.4) can also damage crops. Nitrate nitrogen (NO_3-N) concentrations above 5 mg/L can be damaging to many crops; however, it is an unlikely constituent in produced water (Mitchell, 1989). A summary of 11 produced water chemistry sources by Echchelh et al. (2018) found that nitrate nitrogen was only reported in coalbed methane produced water at concentrations of less than 0.01 mg/L.

Further miscellaneous chemicals of concern for agricultural use may reside in produced water. Hydrocarbons and naturally occurring radioactive material from the geologic formation from which the water was produced may be dissolved in the water (USGS, 1999). Heavy metals can also be a concern due to their impact on human health and the environment (Echchelh et al., 2018). Heavy metals can be biotransformed to become biologically available to plants. Therefore, their presence in produced water is particularly concerning for crops where leaves are consumed. Furthermore, inorganic and organic toxins from chemical additives used in the drilling and production operations can leach into the water from the formation or other processes. It is likely that all of these types of constituents would need to be removed prior to using produced water for irrigation of agricultural crops. Removal of inorganic constituents of concern and heavy metals require additional processes, such as desalination, which can be energy intensive and costly. For example, Alspach (2014) presents life cycle costs for desalination of produced water that range from $1.90–$4.40 per 1,000 gallons. This translates to $619–$1,433 per AF. Relative to irrigation water rates that are often below $100 per AF in California, this cost is still quite high compared to other water supply options (e.g., Central California Irrigation District, 2019). However, treatment costs will vary depending on starting and desired end concentrations.

Hydrocarbons and other organic compounds are not considered a major concern for soil and crop health but are a focus of reuse in terms of human health. This topic is addressed in Chapter 3.

2.2.5. Summary of Water Quality Constituents of Concern

A summary of the major constituents of concern and the associated concentrations at which they may cause irrigation issues is summarized in Table 2.3.

Table 2.3. Guidelines for interpretations of water quality for irrigation. Source: Modified from Ayers and Westcot (1985).

Potential Irrigation Problem			**Units**	**Degree of Restriction on Use**		
				None	**Slight to Moderate**	**Severe**
EC and TDS[1]	ECw		dS/m	<0.7	0.7-3.0	>3.0
	TDS		mg/L	<450	450-2,000	>2,000
SAR[2]	0 - 3	and ECw	dS/m	>0.7	0.7-0.2	<0.2
	3 to 6			>1.2	1.2-0.3	<0.3
	6 to 12			>1.9	1.9-0.5	<0.5
	12 to 20			>2.9	2.9-1.3	<1.3
	20 to 40			>5.0	5.0-2.9	<2.9
Toxicity	Sodium (Na)[3]	surface irrigation	SAR	<3	3 to 9	>9
	Sodium (Na)	sprinkler irrigation	mg/L	<69	>69	
	Chloride (Cl)[4]	surface irrigation	mg/L	<140	140 to 350	>350
	Chloride (Cl)	sprinkler irrigation	mg/L	<105	>105	
	Boron (B)		mg/L	<0.7	0.7-3.0	>3.0
Miscellaneous Effects	Nitrogen (NO3-N)[5]		mg/L	<5	5 to 30	>30
	Bicarbonate (HCO3)	(overhead sprinkling only)	mg/L	<92	92 to 519	>519
	pH			Normal Range 6.5-8.4		

1. ECw – electrical conductivity, reported in deciSiemens per meter at 25 deg C (dS/m) or in units millimhos per centimeter (mmhos/cm). Both are equivalent.

2. SAR – sodium adsorption ratio. At a given SAR, infiltration rate increases as EC increases. Evaluate the potential infiltration problem by SAR as modified by EC_w.

3. For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use the values shown. Most annual crops are not sensitive; other TDS (or EC) tolerance tables should be used.

4. For chloride tolerance of selected fruit crops, see other sources. With overhead sprinkler irrigation and low humidity (<30%), sodium and chloride may be absorbed through the leaves of sensitive crops.

5. NO3-N – nitrate nitrogen reported in terms of elemental nitrogen.

2.3. Methods for Assessment of Current and Potential Reuse

2.3.1. Assessment of Where Current Reuse Occurs

We used two approaches to assess where reuse of produced water for agriculture currently occurs. The first approach involved assessment of the SB 1281 dataset, which contains volumes of water produced and injected for each quarter by field. Similar to Chapter 1, we perform our analyses on data from six quarters, from 2015 Q4 to 2017 Q1. Outside of this timeframe there are major discrepancies between the quarterly dataset and the monthly production and injection dataset (DOGGR, 1977). The SB 1281 dataset is divided into four reports (for a detailed description of each report, please refer to Chapter 1). For all analyses in this chapter, we used the Production report (DOGGR, 2018b), which provides information on the operator of each well, the oil and gas field where the well is located, the volume of water produced by each well, and the allocation of that water to single or multiple disposition methods/codes. It also gives basic water quality information on TDS (i.e., ≤ or > 10,000 milligrams per liter (mg/L)), and treatment information. To answer the question of where reuse of produced water currently occurs, we extracted quarterly volumes of produced water by operator and field for two disposition methods: "Agriculture and Recharge" and "Surface Water Discharge."[2] Agriculture and Recharge includes water "used for agriculture, irrigation, water replenishment, water banking, livestock, etc." (DOGGR, 2018d). Surface Water Discharge is water "discharged into a surface body of water such as an ocean, lake, pond, river, creek, aqueduct, canal, stream, or watercourse" (DOGGR, 2018d). We acknowledge that the definitions of both of these disposition codes are more broad than agricultural reuse. However, as will be reported in the results of this chapter, these are the two codes that were applied to produced water discharged by oil and gas operators with known permits for agricultural reuse. Based on the broad applications included within each disposition code, it is possible that our analysis incorrectly locates agricultural reuse, especially in those cases where we were not able to identify a state-issued permit to confirm the actual end use of the discharge. In addition, the broadness of these codes may have caused our analysis to over-estimate the volume of water currently reused for agriculture.

The second approach used to assess where reuse of produced water is currently occurring was by gathering relevant Waste Discharge Requirements (WDRs)/National Pollution Discharge Elimination System (NPDES) permits from regional water quality control board websites.[3] In addition, personal communication with staff from the Central Valley Regional

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[2] Disposition methods/codes were renamed for this report to enhance the readability and clarity of the chapter. Agriculture and Recharge is the pseudonym applied to disposition method 11, "Sale/Transfer – Domestic Use." Surface Water Discharge is the pseudonym applied to disposition method 3, "Surface water discharge – Ocean, lake, pond, etc." In addition, disposition method if referred to as destination, as explained in Chapter 1.

[3] WDRs/NPDES permits serve as the primary mechanism in California to regulate waste discharges, including produced water.

Water Quality Control Board (CVRWQCB) provided us with information on several permits and other documents relevant to produced water reuse for agriculture (Harvey, 2019). Permits contained detailed descriptions of the locations of produced water reuse. For the purposes of our analysis, we focused on reporting the name of the oil and gas operator, the field where the produced water originates, and the name of the destination of the discharge, typically a water district that sells water from a variety of sources to agricultural water users or a water body that serves as a supply to agricultural water users.

In addition to reporting the names of fields and destinations of reuse, we used spatial data from the Division of Oil, Gas, and Geothermal Resources ("The Division") to map the fields where reuse has been reported in the SB 1281 dataset (DOGGR, 2018d). We overlay this data with our own map of the locations of reuse with known permits. Finally, our map includes both the surface water bodies that are known to receive produced water and the water district boundaries of those districts receiving produced water. Water district boundaries were obtained via request from the California Special Districts Association (CSDA, 2018). This data has not been vetted by the water districts themselves and therefore, only provides a general representation of district boundaries.

2.3.2. Assessment of Potential for Expanded Reuse

We used two approaches to assess the potential for expanded reuse of produced water for irrigation. Our first approach used the SB 1281 dataset to answer this question. We extracted quarterly volumes of produced water that were reported to have less than or equal to 10,000 mg/L TDS (i.e. fresh/brackish) for each oil and gas producing basin for 2015 Q4 through 2017 Q1. The average annual volume of produced water potentially available for expanded reuse, in Acre-Foot per Year (AFY), is equal to the sum of the volumes over the six quarters, divided by six, then multiplied by four (Equation 2.2).

Equation 2.2

$$Average\ Annual\ Volume = 4 * \frac{\sum V_{2015\ Q4},\ V_{2016\ Q1},\ V_{2016\ Q2},\ V_{2016\ Q3},\ V_{2016\ Q4},\ V_{2017\ Q1}}{6}$$

Where V is the volume, in AF, reported by the operator for the quarter identified in the subscript. The final annual volumes by basin were summed to get a state-wide estimate. This value provides a rough estimation of the amount of produced water potentially available for reuse with some treatment.

Because this first approach was based only on a threshold of TDS (i.e. $\leq$ 10,000 mg/L) rather than a quantitative measurement, we sought additional water quality datasets to more accurately assess statewide potential for expanded reuse of produced water for irrigation. We obtained produced water quality datasets from federal and state agency websites, or through contact with authors of published data. Due to time and resource constraints, we limited our search to datasets that were available in electronic formats (i.e.

already in spreadsheets, rather than PDFs), available by December 31, 2018. Additionally, we focused on datasets with produced water samples from individual wells rather than samples of produced water from co-mingled facilities. The eight datasets included in the analysis in this chapter are presented in Table 2.4. There were seven additional produced water quality data sources that did not meet these limitations. However, if added, the seven additional sources may change the results of this analysis, likely by increasing the amount of produced water potentially available for reuse. These seven unused datasets are presented in Appendix 2.1.

Table 2.4. Sources of produced water analytical data.

Dataset name	**Data source**	**Date accessed**	**Reference**	**Chapters where data are used**
USGS Produced Waters Dataset	https://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data	12/4/2018	(U.S. Geological Survey, 2018)	2, 3
WST Disclosures	https://www.conservation.ca.gov/dog/Pages/WSTDisclosureSearchDisclaimer.aspx	11/11/2018	(DOGGR, 2018a)	2, 3
Davis et al., 2016	https://www.sciencebase.gov/catalog/item/57a50c48e4b0ebae89b6d87f	8/13/2018	(Davis, Kulongoski, & McMahon, 2016)	2, 3
Gannon et al., 2018	https://www.sciencebase.gov/catalog/item/5a569e73e4b01e7be2444dab	8/13/2018	(Gannon et al., 2018)	2, 3
Gans et al., 2018	https://www.sciencebase.gov/catalog/item/5a68d773e4b06e28e9c7224e	11/2018	(Gans, Metzger, Gillespie, & Qi, 2018)	2, 3
Gillespie et al., 2016	Received by email	12/3/2018	(Gillespie, Kong, & Anderson, 2016)	2
Metzger et al., 2018	https://www.sciencebase.gov/catalog/item/5ade1913e4b0e2c2dd2b80a3	12/6/2018	(Metzger, Davis, Peterson, Brilmyer, & Johnson, 2018)	2
WDR Irrigation Permits	CVRWQCB & CCRWQCB websites. See References Cited.	11/2018	Multiple. See References Cited.	2 (only a subset of 5 samples)

Data for the analysis were selected based on the variables available with a minimum requirement for inclusion of: an American Petroleum Institute (API) well number, information on sample type to ensure sample origin of produced water, and results for constituents of interest.[4] Sample date was not factored into the analysis as the authors did

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4. API well numbers are unique, permanent, numeric identifiers assigned to every oil and gas well in the United States. Each API number is composed of at least ten digits including the two-digit state code, three-digit county code, and five-digit unique well identifier. More recently, API numbers have included a two-digit directional sidetrack code and two-digit even sequence code to track well additions and the sequence of the additions.

not want to make an arbitrary cutoff date for samples that would reduce the total sample number even further. It is acknowledged that produced water quality can change as wells mature, and more analysis will be needed to fully evaluate water quality suitability where it is deemed potentially available for reuse.

Water quality guidelines for irrigation, as identified by our literature review were used to identify wells where produced water might be available for reuse, requiring minimal treatment. For the analysis, measured concentrations of TDS (mg/L) were used in addition to concentrations of boron (mg/L). When TDS was not available but EC was, we converted from EC to TDS following instruction from the University of California Division of Agriculture and Natural Resources (n.d.). The instruction included different conversion factors based on EC (640 for when EC was 0.1 to 5 dS/m and 800 for when EC was greater than 5 dS/m). TDS and boron are key indicators of irrigation water suitability, according to the United Nations Food and Agricultural Organizations (FAO) Water Quality for Agriculture irrigation guidelines (Ayers & Westcot, 1985). In addition, boron is often the major limiting factor in the suitability of water for agriculture due to the challenge of treatment and treatment cost (Kim et al., 2009). Boron also accumulates in the soil, and there are few management strategies to address this issue (Fipps, n.d.; Yau & Ryan, 2008). Other key indicators, such as chloride and sodium adsorption ratio (SAR), were not used in this analysis due to time constraints, however, data checks revealed that the application of these constituents to the analysis would not likely alter the results. Soluble and insoluble hydrocarbons, radioactive elements, chemicals from oil and gas industry processes, and other constituents that may be present in produced water were not assessed due to the data availability at the scale of this statewide analysis. Lack of data on these constituents makes our estimate an upper bound on water available.

The API well number was used to join the water quality data to location data from The Division's "All Wells" dataset (DOGGR, 2018c). We filtered the dataset for active and idle oil and gas wells (Type Code "OG"). We also reviewed reports on produced water quality in WDRs from the regional water quality control boards, and included five samples in the analysis (CVRWQCB, 1998; 2006; 2012a; 2012b; 2015). These five samples were not associated with single wells but came from the facilities used to treat produced water from several wells. The reports indicated that the samples were not treated for removal of inorganic constituents, such as TDS or boron, and therefore were considered acceptable for use in this analysis. Combining the produced water quality data with The Division's All Wells dataset yielded 1,954 unique samples for inclusion in the analysis (Appendix 1.2).

To assess produced water quality for new agricultural reuse, a rating system for oil and gas fields in the state was devised based on FAO guidelines for irrigation water quality. (Table 2.3; Ayers & Westcot, 1985.) A field score of "0" indicates the field has poor produced water quality for reuse, "1" indicates the field has insufficient data for assessing produced water quality, "2" indicates the field has acceptable produced water quality for reuse, and "3" indicates the field has operators that are permitted for reuse and additionally, water quality (where available) met the criteria of suitable for reuse (Table 2.5). The rule used to apply field scores was, if at least 30% of all wells with samples were of acceptable quality, then it received a field score of 2. If no samples were available for the field, then it was indicated with a field score of 1. A field score of 3 was applied to all fields where permitted reuse is already occurring. This method does not take into account the pool (i.e., geologic formation) from where the oil, gas, and water were produced because less than 15% of the samples contained information on pool. Within a single field, and even within a single well, oil, gas, and the subsequent water produced from it can be from multiple different pools, and pool is a key factor in produced water hydrochemistry. Therefore, our method may overestimate the volume of water of suitable quality for reuse from a field.

Table 2.5. Rating and criteria used for determining fields with produced water quality acceptable for agricultural reuse.

Rating	Criteria
0	**Poor Quality for Reuse:** produced water quality from more than 70% of all samples have TDS concentrations of >2000 mg/L and boron of >3 mg/L.
1	**Need More Samples:** no sample results for TDS and/or boron.
2	**Potential Quality for Reuse:** produced water quality from 30% or more of all samples have TDS concentrations of ≤ 2000 mg/L and boron of ≤ 3 mg/L.
3	**Permitted Reuse Occurring, Water Quality Acceptable for Reuse:** WDR permit found.

At fields where our water quality analysis revealed suitability (i.e. a field score of 2), we used the SB 1281 volumetric dataset to estimate the volume potentially available for reuse. The volume potentially available for reuse (in AFY) by field was calculated as the difference between the total amount of produced water for a field (in AFY) and the total produced water already used for agriculture for that field (in AFY). The total amount of produced water already used for agriculture is assumed to be produced water allocated to the destinations of Surface Water Discharge and Agriculture and Recharge. All volumes in AFY were calculated following Equation 2.2.

2.4. Current Reuse of Produced Water for Agriculture

Planned reuse of produced water for agriculture occurs through two routes: (1) direct reuse via conveyance from oil and gas operators to water districts that supply agricultural water users, or (2) indirect reuse that occurs after discharge of produced water into surface waters (i.e., streams), and/or groundwater, that are also sources of water for downstream agricultural operations.[5] Both of these routes require WDRs/NPDES permits authorized by the regional water quality control board. We were able to locate ten permits for oil and gas operators (and affiliated entities) to supply produced water for agriculture (Table 2.6). Six permits cover direct reuse, three permits cover indirect reuse, and one permit covers both direct and indirect reuse. For some operators we were unable to identify associated permits. Discharges for which we could not identify a permit

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[5] Direct reuse is the intentional use of water that is delivered to the user directly from a wastewater treatment facility. Indirect reuse the intentional use of water from a wastewater treatment facility that is first blended in the environment with other water(s) (e.g., river water).

do not necessarily indicate a current unpermitted discharge; they could reflect a reporting error in the 1281 dataset, a historical discharge that has ceased, or a failure on the part of the authors to identify all relevant permits.

Table 2.6. Details of current reuse of produced water for agriculture including all occurrences, both permitted and those with no identified permit, by oil and gas basin, field, operator(s), produced water destination specified in WDR permit, when available, produced water destination specified in SB 1281 reports, estimated annual volume reused (AFY), permit (where identified), and data source. Total Estimated Annual Vol. Reused for Agriculture is the sum of reuse for the state. NA=Not Applicable.

Basin	Field	Operator(s)	Destination Specified by Permit	Destination Specified in SB 1281 Reports	Estimated Annual Vol. Reused (AFY)	Permit	Data Source(s)
San Joaquin	Asphalto	Cather-Herley Oil Co.	NA	Surface Water Discharge	16	None Identified	14
	Deer Creek	Pentarch Petroleum[1]	NA	Agriculture and Recharge	12	None Identified	13, 14
	Dyer Creek	Daybreak Oil and Gas, Inc.[2]	NA	Agriculture and Recharge	31	None Identified	14
	Edison	Verjill Oil Co.	NA	Surface Water Discharge	16	None Identified	14
	Edison, Northeast	Hathaway LLC	NA	Agriculture and Recharge	<1	None Identified	14
	Jasmin	Hathaway LLC	Jasmin Ranchos Mutual Water Company and Kern-Tulare Water District	Agriculture and Recharge	1,321	WDRs Order No. 98-205	11,14
	Kern Front	California Resources Production Corporation	North Kern Water Storage District	Agriculture and Recharge	5,856	WDR R5-2015-0127	8,14
		California Resources Production Corporation (Vintage Production California LLC)	Cawelo Water District	Agriculture and Recharge	1,782	WDR R5-2012-0059	6,14
		Unknown	NA	Agriculture and Recharge	4,429	None Identified	14
	Kern River	Chevron U.S.A. Inc.	Cawelo Water District	Agriculture and Recharge	22,177	WDR R5-2012-0058	5,14
	Mount Poso	California Resources Production Corporation	Cawelo Water District, via Jones Reservoir	Agriculture and Recharge	7	WDRs Order No. R5-2006-0050	12, 14
		Daybreak Oil and Gas, Inc.[3]	NA	Agriculture and Recharge	79	None Identified	14

Basin	**Field**	**Operator(s)**	**Destination Specified by Permit**	**Destination Specified in SB 1281 Reports**	**Estimated Annual Vol. Reused (AFY)**	**Permit**	**Data Source(s)**
San Joaquin		Griffin Resources, LLC	Little Creek	Surface Water Discharge	38	WDR R5-2002-0108	14, 15
		Little Creek Properties, Inc.[3]	NA	Agriculture and Recharge	7	None Identified	14, 15
		California Resources Production Corporation (Vintage Production California LLC)	Cawelo Water District, via Vedder Reservoir	Agriculture and Recharge	65	WDR R5-2006-0051	14, 15
	Poso Creek	E&B Natural Resources Management Corporation et al.	Sherwood Hills LLC	NA[4]	NA	WDRs Order No. R5-2019-0024	10
	Round Mountain	Coffee Petroleum	NA	Agriculture and Recharge	2	None Identified	14
Santa Barbara-Ventura	Cascade	DCOR, LLC	NA	Surface Water Discharge	<1	None Identified	14
Santa Maria	Arroyo Grande	Freeport-McMoRan O&G LLC	Private land, Pismo Creek	Surface Water Discharge	607	Order R3-2013-0029, NPDES No. CA0050628	9, 14
Sacramento	Rio Vista Gas	Romara Energy, Inc.	NA	Agriculture and Recharge	<1	None Identified	14
Salinas	San Ardo	Chevron U.S.A., Inc.	Private land, groundwater	Agriculture and Recharge	1,900	WDRs Order No. R3-2005-0070	7, 14
				Total Estimated Annual Vol. Reused for Agriculture:	**38,345**		

1. This operator has changed to Modus, Inc. (Harvey, 2019).

2. CVRWQCB has issued a Cease and Abatement Order to this operator (CAO R5-2016-0709).

3. CVRWQCB has issued a Cease and Abatement Order to these two operators (CAO R5-2016-0790).

4. The WDRs/NPDES permit for E&B Natural Resources Management Corporation et al. that regulates the discharge of produced water from Poso Creek field for reuse was issued in April, 2019. Prior to this time no destination of Agriculture and Recharge or Surface Water Discharge had been reported in SB 1281 reports from this field.

Sources (Table 2.6):

1. Central Valley Regional Water Quality Control Board (CVRWQCB). (2012). Waste Discharge Requirements for Chevron USA, Inc., and Cawelo Water District, Produced Water Reclamation Project, Kern River Area Station 36, Kern River Oil Field, Kern County. http://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/kern/r5-2012-0058.pdf

2. CVRWQCB. (2012). Order R5-2012-0059, Waste Discharge Requirements for Valley Water Management Company and Cawelo Water District, Produced Water Reclamation Project, Kern Front No. 2 Treatment Field, Kern Front Oil Field, Kern County. https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/kern/r5-2012-0059.pdf

3. Central Coast Regional Water Quality Control Board (CCRWQCB). (2013). Order No. R3-2013-0029, NPDES No. CA0050628, December 13, 2013. http://www.waterboards.ca.gov/centralcoast/board_decisions/adopted_orders/2013/2013_0029_freeport_npdes_permit.pdf.

4. CVRQCB. (2015). Order No. R5-2015-0127, Waste Discharge Requirements, for California Resources Production Corporation and North Kern Water District, Oil Field Produced Water Reclamation Project, Kern County. https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/kern/r5-2015-0127.pdf.

5. CCRWQCB. (2005). Waste Discharge Requirements Order No. R3-2005-0070, For ChevronTexaco San Ardo Oilfield, Water Management Facility, Monterey County. https://www.waterboards.ca.gov/rwqcb3/board_info/agendas/2005/july/item20/item20_attach1_wdr.pdf.

6. CVRWQCB. (2019a). Order No. R5-2019-0024, Waste Discharge Requirements for Sherwood Hills, LLC; Jay LLC; Steir Berton Trust; Homewood Mountain Partners, LLC; Famoso Hills Ranch, LLC; Yurosek Farms, LLC; and E&B Natural Resources Management Corporation. Produced Wastewater Reclamation Project, McVan Area Treatment Facility, Poso Creek Oil field, Kern County.

7. CVRWQCB. (1998). Order No. 98-205, Waste Discharge Requirements for E&B Natural Resources and Jasmin Mutual Water District, Jasmin Oil Field, Quinn Oil Lease, Kern County. https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/kern/98-205.pdf.

8. CVRWQCB. (2006). Order No. R5-2006-0050, Waste Discharge Requirements for SOC Resources, Inc., Jones Lease, Mount Poso Oil Field, Kern County. https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/kern/r5-2006-0050.pdf.

9. Heberger, M., and Donnelly, K. (2015). Oil, Food, and Water: Challenges and Opportunities for California Agriculture. Pacific Institute. https://pacinst.org/wp-content/uploads/2015/12/PI_OilFoodAndWater_.pdf.

10. SB 1281 dataset (DOGGR, 2018b)

11. Harvey, D. (2019). Personal communication, Central Valley Regional Water Quality Control Board. Email response received April 22, 2019.

Eight of the ten permitted operations for agricultural reuse are in the Poso Creek, Jasmin, Mount Poso, Kern River, and Kern Front fields, all of which are located in the southeastern San Joaquin basin (Figure 2.1). WDRs/NPDES permits from these operations indicate that Hathaway LLC, California Resources Production Corporation, Chevron U.S.A., Inc., and Vintage Production California LLC each provide produced water for direct reuse to agriculture through water districts from this basin. E&B Natural Resources Management Corporation et al. received their WRDs/NPDES to permit sending produced water from the Poso Creek field for direct reuse in April 2019 (CVRWQCB, 2019a). Therefore, the period of analysis does not include any produced water under the destination of Agriculture and Recharge or Surface Water Discharge from this field. Permits indicate that water is treated to remove oil and grease prior to delivery to the water districts and that the water districts blend the produced water with other supplies before delivering it to agricultural users. Permits in this basin indicate that produced water is sent to either Cawelo Water District, Jasmin Ranchos Mutual Water Company, or North Kern Water Storage District. In the SB 1281 dataset all of these operators report volumes of produced water to the destination of Agriculture and Recharge.

The other two permitted operations for agricultural reuse are from the Santa Maria and Salinas oil and gas basins. Both permits allow for indirect reuse of produced water. In the Santa Maria basin, Freeport-McMoRan's operation is permitted to discharge treated produced water from the Arroyo Grande field into Pismo Creek (at approximately 607 AFY). Pismo Creek has a beneficial use designation for agricultural use and it is also known to recharge shallow groundwater which serves as supplies for agricultural wells downstream of the discharge (CCWQRCB, 2013). In the Salinas basin, Chevron is permitted to discharge treated produced water into shallow groundwater aquifers from its operation in the San Ardo field (and does at approximately 1,900 AFY). The groundwater is hydrologically connected to the Salinas River, which serves as a water source for agricultural, municipal, and industrial users downstream. Investigation of the SB 1281 dataset indicates that annually, these permitted operations discharge a combined average of 33,753 AFY for reuse. Nearly all of this discharge (31,246 AFY) originated from five fields in the San Joaquin basin; the remainder (a combined 2,508 AFY) comes from single fields within the Santa Maria (607 AFY) and Salinas (1,900 AFY) basins.

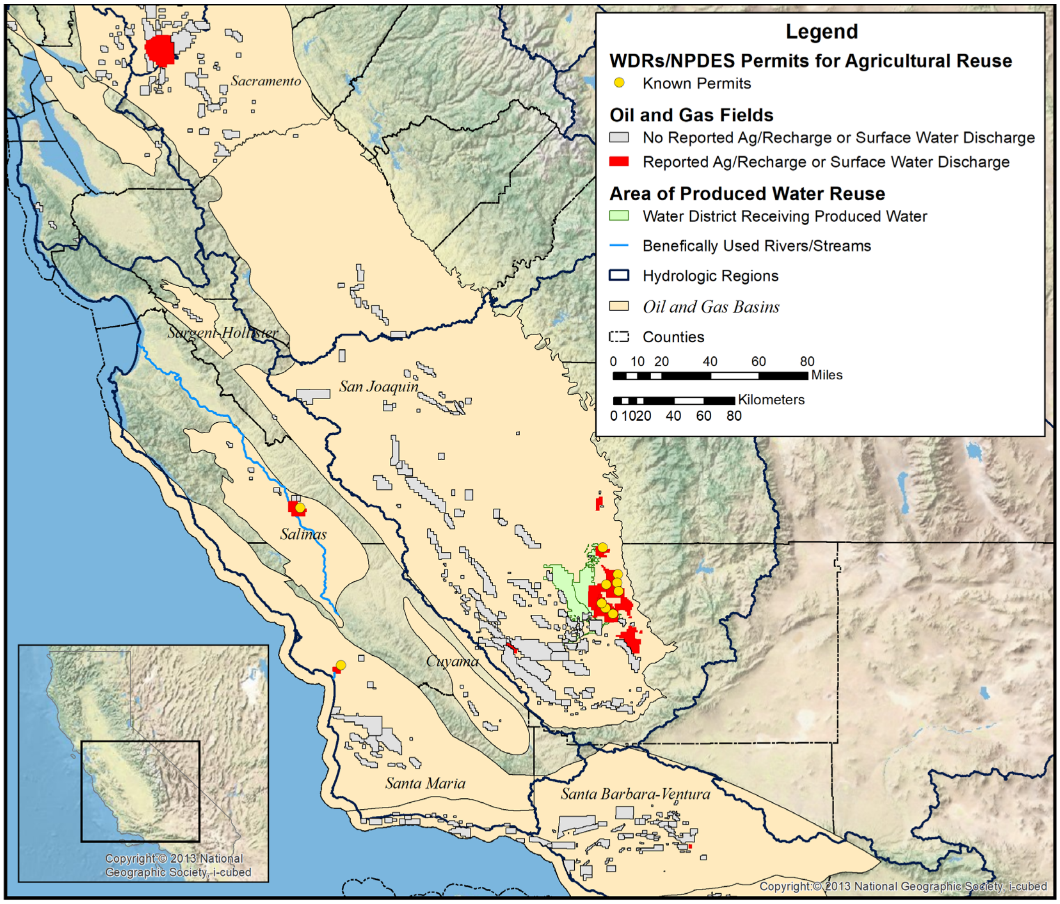

Figure 2.1. Map of fields where current produced water reuse for agriculture is occurring in California (red). Fields in grey do not currently report Agriculture and Recharge nor Surface Water Discharge. Areas receiving produced water for agriculture are shown in green. Other features identified include locations of facilities with a known WDRs/NPDES permit for produced water reuse (orange circles) and a river and a stream with the designated beneficial use of agriculture that receive produced water (Salinas River in Monterey County and Pismo Creek in San Luis Obispo County). Sources: Reported destination of Surface Water Discharge and Agriculture and Recharge from the SB 1281 dataset. WDR Permits from Central Valley and Central Coast Regional Water Boards. Water Districts shapefile from CSDA (2018).

In total, there were 11 operator-field combinations reporting Surface Water Discharge and/or Agriculture and Recharge in the SB 1281 dataset for which we could not locate a WDRs/NPDES permit (Table 2.6). Nine of these were in the San Joaquin basin. Of these, four operators in the Mount Poso field report discharge to Agriculture and Recharge totaling approximately 86 AFY. This volume does not include the discharged waters from the WDRs permit holders for the field: California Resources Production Corporation, Vintage

Production California LLC, and Griffin Resources LLC. Furthermore, one unknown operator in the Kern Front field reported more than 3,200 AF in 2016 Q3 and Q4 to Agriculture and Recharge. It is possible that this volume was discharged by Vintage Production California LLC or California Resources Production Corporation, which are the two permit holders in the field, but was misreported in these two quarters as an unclaimed discharge. In such case, the estimated annual volume reused from the Kern Front field, as well as the total for all fields, may be overestimated here. Six other fields in the San Joaquin basin report an annual average of <1 AF to 31 AF to either Surface Water Discharge or to Agriculture and Recharge. Based on these destination codes it is possible there is direct, indirect, and/or incidental reuse of produced water occurring in California.[6] Therefore, most produced water already sent off oilfields for reuse in the San Joaquin basin (31,246 AFY, or 87% of San Joaquin-originating discharge volumes) corresponds with an identified permit, and a smaller amount (only 4,592 AFY, or 13% of San Joaquin-originating discharge volumes) had no identifiable permit.

In the Sacramento basin a single operator, Romara Energy, Inc. (in the Rio Vista Gas field), reports an annual average of <1 AFY of discharge to Agriculture and Recharge. And in the Santa Barbara-Ventura basin, DCOR LLC reports <0.01 AFY of Surface Water Discharge. The authors could not identify a WDRs/NPDES permit for either of these discharges.

In total, the sum of the volumes from operations where we could not identify permits but that are reporting discharge of produced water that may be currently reused for agriculture was 4,592 AFY (12% of the total volume discharged annually). This sum is equivalent to approximately 13.6% of the volume reused for agriculture for which we were able to identify permits. Figure 2.2 illustrates the reported volumes with the destination of Agriculture and Recharge or Surface Water Discharge, both those that are permitted versus those with no known permit. Discharges to Agriculture and Recharge with a known permit accounted for 86%, or an average of 33,108 AFY, of the reported discharges in the SB 1281 dataset that are likely reused by the agricultural industry. Permits were not identified for 4,560 AFY of produced water discharged to Agriculture and Recharge. This represents 12% of the total that is likely reused by the agricultural industry. We identified permits corresponding to reported Surface Water Discharge of 645 AFY (2% of the total) and could not identify permits corresponding to 32 AFY (less than 1% of the total).

> ***Finding 2.1.1.*** *Based on operator-reported produced water volumes in the SB 1281 dataset, an estimated total annual volume of 38,345 AFY was discharged from oil and gas fields in California to the destinations of Agriculture and Recharge or Surface Water Discharge between 2015 Q4 and 2017 Q1. Of this amount, 35,838 AFY originated from 11 fields in the San Joaquin basin. Only 2,508 AFY was discharged from a single field in each of the following basins: Sacramento, Santa Barbara-Ventura, Salinas, and Santa Maria.*

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[6] Incidental reuse is unplanned reuse that occurs when a downstream water user draws raw water from a source that receives water from an upstream wastewater discharge.

> ***Conclusion 2.1.1.*** *Reuse of produced water for agriculture is predominantly occurring in the southeastern San Joaquin basin where the majority of agricultural production occurs in the state. The rest of the reuse is spread between four other basins across the state.*

Additional pathways of unpermitted incidental reuse of produced water are also possible in California, however the SB 1281 dataset does not suggest this is occurring on a large scale. Disposal into unlined pits that allow for percolation of produced water into groundwater aquifers may in some cases have impacted the quality of waters used for irrigation. Further discussion of the impact of percolation from unlined pits is in Chapter 4 of this report.

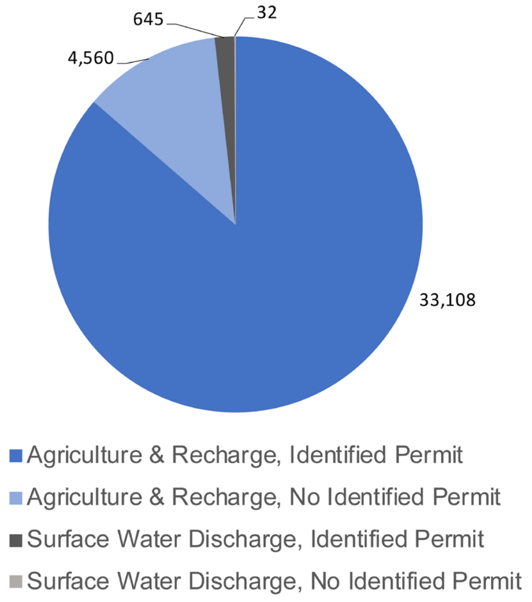

Figure 2.2. Annual volumes (AFY) of produced water reported in the SB 1281 dataset under the destinations of either Agriculture & Recharge or Surface Water Discharge, aggregated by whether a permit for the discharge was identified or not. Six quarters of data were averaged to estimate annual volumes. (Note the proportion of Surface Water Discharge without an identified permit is small enough not to show on the chart, but the volume is noted as 32 AFY.)

> ***Finding 2.1.2.*** *We were able to identify WDRs/NPDES permits associated with an estimated 33,753 AFY (88%) of the total volume reported as going to Agriculture and Recharge or Surface Water Discharge. We were not able to identify WDRs/NPDES permits for an estimated 4,592 AFY (12%) of the total volume reported as going to Agriculture and Recharge or Surface Water Discharge.*

> ***Conclusion 2.1.2.*** *WDRs/NPDES permits are the main source of information on how the water is used after leaving the oil and gas field. By examining these permits, we identified a mixture of direct reuse for agriculture and indirect reuse via discharge to ground and surface water.*

> ***Recommendation 2.1.2.*** *The SB 1281 dataset should require the operator to report the associated permit for discharges to Agriculture and Recharge and Surface Water Discharge.*

> ***Conclusion 2.1.3.*** *For the water reported as going to Agriculture and Recharge or Surface Water Discharge for which we could not identify permits, we were unable to conclude whether the water is reused directly, indirectly, or incidentally by agricultural or other water users.*

> ***Recommendation 2.1.3.1.*** *SB 1281 reporting requirements for operators should be updated to include information on the receiving entity, groundwater water system, or surface water body when reporting volumes of water under the Agriculture and Recharge or Surface Water Discharge destination codes.*

> ***Recommendation 2.1.3.2.*** *For cases where we were not able to identify permits associated with discharges labeled as Agriculture and Recharge or Surface Water Discharge the relevant regional board should review operator records.*

The destination codes—"Agriculture and Recharge" and "Surface Water Discharge."—used in this analysis were defined more broadly than agricultural reuse. Agriculture and Recharge includes water "used for agriculture, irrigation, water replenishment, water banking, livestock, etc." (DOGGR, 2018d). In addition to lacking specificity of direct versus indirect reuse, the broad range of discharges to which this code may apply makes the clear accounting of water volumes currently being reused for agriculture very difficult. The broad applications included within each disposition code make locating agricultural reuse very challenging, especially in those cases where we were not able to identify a state-issued permit to confirm the actual end use of the discharge.

Even in those cases where permits were located, it was clear that operators were using the same codes to cover a broad range of discharges. In most cases, the code "Agriculture and Recharge" referred to an operator passing water to a water supplier for direct reuse in agriculture, but not always. In one case, this code was used to refer to a discharge to shallow groundwater that feeds the Salinas River, which is designated for agricultural, municipal, and industrial beneficial uses. In another case, this code referred to discharge to North Kern Water Storage District, which uses the water both for direct reuse for irrigation and for groundwater banking.

> ***Finding 2.2.1.*** *The current destination code of Agriculture and Recharge does not distinguish between direct and indirect reuse for agriculture.*

> ***Finding 2.2.2.*** *From our inspection of WDRs/NPDES permits, we observed that this destination code was used for a wide variety of discharges. A few operators appear to be reporting what happens to the water one or more steps downstream, rather than simply reporting what happens to the water at the moment it leaves their custody.*

> ***Finding 2.2.3.*** *Direct reuse for irrigation provides a more direct pathway of exposure for soil, crops, and human health than indirect reuse.*

> ***Conclusion 2.2.1.*** *It is important to differentiate between direct and indirect reuse of produced water. Direct and indirect reuse are not mutually exclusive, making it difficult to distinguish them with a single reporting code.*

> ***Recommendation 2.2.1.*** *To distinguish between direct and indirect produced water reuse applications SB 1281 should eliminate the Agriculture and Recharge code and replace it with three codes: "Water Supplier," "Agriculture," and "Groundwater Recharge." If a discharge requires a permit, the operator should report such in a separate field associated with that discharge.*

> ***Recommendation 2.2.2.*** *Operators should be responsible only for reporting what happens to the water at the moment it leaves their custody. The eventual fate of produced water after it leaves the hands of the operator should be traced via the permit, not the SB 1281 dataset.*

2.5. Potential for Expansion of Produced Water Reuse in California

2.5.1. Potential for Expansion of Produced Water Reuse Based on 1281 Reports

One of the main goals of SB 1281 was to identify extra water from the oil and gas industry that could potentially be put to beneficial use outside of the industry, should it be economically feasible to do so. To this end, the The Division asked experts from the State Water Quality Resources Control Board (State Water Board, SWB) to identify a threshold for categorizing produced water that could potentially be reused without significant levels of treatment. The SWB recommendation (i.e., Bishop, 2015) resulted in the SB 1281 dataset category of either above 10,000 mg/L TDS or at or below 10,000 mg/L TDS. For this report we refer to these two categories as saline (>10,000 mg/L TDS) and fresh/brackish (≤10,000 mg/L TDS).

Based on this categorization we found that of the total annual average volume of fresh/brackish produced water not currently reused by agriculture from 2015 Q4 to 2017 Q1 in the five major basins was 11,337 AFY (Table 2.7). This volume represents 2.7% of the total annual average volume of produced water (413,340 AFY) from these basins. However, the actual volumes and percentages categorized as fresh/brackish varies substantially between the five major basins. In both the Salinas and Santa Maria basins, none of the produced water was categorized as fresh/brackish, and in the Los Angeles basin, 115 AFY, or less than 0.01%, was categorized as fresh/brackish. Combined, these three basins generate less than half of all of the produced water from the five major basins. In the San Joaquin basin, which generates approximately 256,000 AFY of produced water, 5,445 AFY, or 2.1% of the total volume from the basin, was categorized as fresh/brackish. And in the Santa-Barbara Ventura basin, where on average 10,732 AFY is reported, 5,776 AFY, or 53.8%, is reported as fresh/brackish. It is interesting to note that permitted reuse is occurring in the Salinas and Santa Maria basins, where water is not categorized by operators as fresh/brackish, but in the Santa Barbara-Ventura basin where no permitted reuse is known to occur, there is a proportionally high volume of water reported as fresh/brackish. Unfortunately, as detailed later in this section, the water quality data from the Santa Barbara-Ventura basin oil and gas fields was mostly insufficient for further characterization of the field where the majority of this fresh/brackish water originates. Therefore, beyond this simple categorization, no further analysis could be done to understand the potential for reuse in this area based on water quality. Because more factors than TDS have impacts on agriculture, information on other constituents of concern (as listed in Table 2.3) in produced water discharged for reuse in agriculture are needed to give a clear picture of reuse potential.

Table 2.7. Average annual volumes of total produced water and of fresh/brackish produced water (not currently reused by agriculture) from 2015 Q4 to 2017 Q1 in the five major sedimentary basins.

Basin	**Total Produced Water (AFY)**	**Fresh/Brackish Produced Water (AFY)**	**Percent Fresh/Brackish**
Los Angeles	123,643	115	< 0.01%
Salinas	16,271	0	0%
San Joaquin	255,590	5,445	2.1%
Santa Barbara-Ventura	10,732	5,776	53.8%
Santa Maria	7,104	0	0%
Total	413,340	11,337	2.7%

> ***Finding 2.3.1.*** *According to the SB 1281 dataset, 11,337 AFY of fresh/brackish water (≤ 10,000 mg/L TDS) not currently reused by agriculture was produced in the five major basins between 2015 Q4 and 2017 Q1.*

> ***Conclusion 2.3.1.*** *Based solely on the criterion of having a TDS of < 10,000 mg/L, there may be as much as 11,337 AFY of fresh/brackish water available for reuse outside of the O&G industry.*

> ***Conclusion 2.3.2.*** *The water quality information in the SB 1281 dataset is inadequate for a complete assessment of water suitability for agricultural reuse intended by the SB 1281 legislation. Additional water quality data are needed to better characterize the potential for expanded reuse of produced water for irrigation.*

> ***Recommendation 2.3.1.*** *The Division should carry out the intent of SB 1281 to track water "suitable for domestic or irrigation purposes" by more accurately capturing relevant water quality parameters; at a minimum, quantitative TDS concentrations should be reported. Boron and SAR concentrations are also important for determining irrigation suitability.*

2.5.2. Potential for Expansion of Produced Water Reuse Based on Additional Datasets

To more completely address the question of the potential for expansion of reuse of produced water in California, we gathered water quality data from eight datasets beyond the SB 1281 dataset (Table 2.4). These additional data sources provided 1,954 unique samples of produced water from wells in California. Our analysis focused on TDS and boron concentrations in produced water due to the relative availability of these two constituents across the datasets, and because our literature review revealed that TDS and boron are both limiting factors of water reuse for agriculture based on their impact to treatment costs (NRC, 2008; Kim et al., 2009). Of the samples used in the analysis, 1,941 (99.3%) include TDS (mg/L) and 1,247 (63.8%) include boron (mg/L); 1,241 (63.5%) samples include both constituents. The final dataset used for the analysis covers 62 oil and gas fields, mostly from the San Joaquin basin but also from the Santa Maria, Cuyama, Santa Barbara-Ventura, and Los Angeles basins. Samples are dated from 1930 through 2018 and 37 samples did not include a sample date. Care was taken to ensure that none of the samples were duplicates.

> ***Finding 2.3.2*** *Information to assess the potential for expansion of produced water for reuse was limited.*

FAO Guidelines for Irrigation Water Quality were used to assign a field score of 0, 1, 2, or 3 to every oil and gas field in the state to indicate the potential for reuse with minimal treatment of produced water based on concentrations of TDS and boron (Figure 2.3). The potential for reuse of produced water requiring high levels of treatment was not part of this assessment, although it is important to note that advanced treatment technology is already in use in California. For example, Chevron U.S.A., Inc.'s operation in the San Ardo field is currently treating produced water that requires significant treatment processes, such as reverse osmosis (RO; CCRWQCB, 2013). Furthermore, advancements in treatment technology, such as artificial intelligence that can improve treatment and energy efficiency (e.g., Atkinson, 2018; Cox, 2018), may soon make treatment of lower quality water more economically feasible. These examples suggest that it in certain circumstances, treating produced water with higher levels of TDS, boron, and other constituents for reuse may be or soon become feasible.

Of the 516 oil fields in the state, we were not able to obtain usable produced water sample data for the majority (475) of the fields. Therefore, we were not able to assess the water quality characteristics of produced water from most fields in the state. Based on guidelines for agricultural water quality, 31 fields were found to have poor quality for reuse. Eight fields, all in the San Joaquin basin, had produced water quality samples that indicate potential for expanded agricultural reuse (Table 2.8). Five of these eight fields already have at least one operator with a WDRs/NPDES permit for direct reuse as agricultural supply.

Total average annual volumes available for reuse were calculated for fields determined to have suitable water quality (Equation 2.2). The amount of produced water available for reuse was calculated as the marginal difference between the total average annual volume discharged (i.e., all water reported under all 12 destination codes) and the average annual volume reported with the Agriculture and Recharge and Surface Water Discharge destination codes. This method allowed for assessment of whether fields where reuse is already occurring may have additional volumes potentially available for reuse. However, these volumes still may be an upper-bound estimates for these fields due to the potential presence of other exclusionary factors, such as hydrocarbons or naturally-occurring radioactive elements, which were not included in this analysis.

This second approach for estimating volumes potentially available for reuse based on measured TDS and boron concentrations returned much higher volumes than compared to only using the SB 1281 dataset for fresh/brackish volumes. Of the eight fields found to have a potential for reuse (Table 2.8), Round Mountain had the highest volume, with an estimated 22,205 AFY potentially available for reuse. The Poso Creek field, where we estimated 17,728 AFY is potentially available for reuse, is the field where E&B Natural Resources Management Corporation et al. have recently obtained a permit for agricultural reuse from the Central Valley Regional Water Board (CVRWQCB, 2019a). We estimate that from the four fields where permitted reuse is already occurring, Jasmin operators may have 47 AFY additionally available, Mount Poso operators may have 3,450 AFY, Kern Front operators may have 7,920 AFY, and Kern River operators may have 11,723 AFY beyond their current supply sent to area water districts. The other two fields with produced water available for reuse include Edison, where operators may have 1,080 AFY additionally available, and Kern Bluff, where operators may have 120 AFY. In total, we estimate 64,272 AFY of produced water is potentially available in the San Joaquin basin for reuse by agriculture with minimal treatment. This volume is approximately 5.5 times the average yearly amount of fresh/brackish water reported (11,337 AFY) in the SB 1281 dataset. This discrepancy may be caused in part by O&G producers under-reporting or misreporting water quality in the SB 1281 dataset. It is also likely that 64,272 AFY is an overestimation of the volume of low-TDS water available from these eight fields as our methods lump all produced water from a single field so long as 30% of the samples from that field were of an acceptable level (Table 2.5). Furthermore, since a high proportion of produced water is reused on the field for EOR and other operations (see Chapter 1), it is not guaranteed that operators, even if their wells produce water of a higher quality, will opt to pursue opportunities to supply agricultural users.

Table 2.8. Fields where water quality is potentially suitable for reuse by agriculture without significant treatment, along with volumes of total annual water produced, total water reported for Surface Water Discharge and Agriculture and Recharge, and the difference of these two, the estimated additional volume for expanded reuse. All volumes in acre-foot per year (AFY). Source: SB 1281 dataset (DOGGR, 2018b).

Field	Total Produced (AFY)	Total Surface Water Discharge + Agriculture and Recharge (AFY)	Estimated Additional Volume For Expanded Reuse (AFY)
Edison	1,096	16	1,080
Jasmin	1,367	1,321	47
Kern Bluff	120	0	120
Kern Front	19,986	12,067	7,920
Kern River	33,900	22,177	11,723
Mount Poso	3,646	196	3,450
Poso Creek	17,728	0	17,728
Round Mountain	22,207	2	22,205
Total	100,051	35,779	64,273

Note: A WDRs/NPDES permit for E&B Natural Resources Management Corporation et al. to reuse produced water from the Poso Creek field for agriculture was issued in April 2019. The volume reported here does not take this new permit into account.

Figure 2.3 shows a map of areas with potential for reuse, based on water quality data. It also shows the volumes of water potentially available for reuse. In general, produced water from the southeastern portion of the San Joaquin basin are of suitable quality for reuse. This is unsurprising because many of the oil fields currently permitted for agricultural reuse are in the southeastern portion of the San Joaquin basin. Furthermore, because several operators in this portion of the state are already sending produced water to local water districts, infrastructure is already in place that may allow for expanding volumes of produced water of suitable quality to willing users. More work is needed in fields marked for potential for reuse to assess destinations of produced waters to further delineate between produced water that is already being reused for purposes other than oil and gas operations and water that may be available for agricultural reuse.

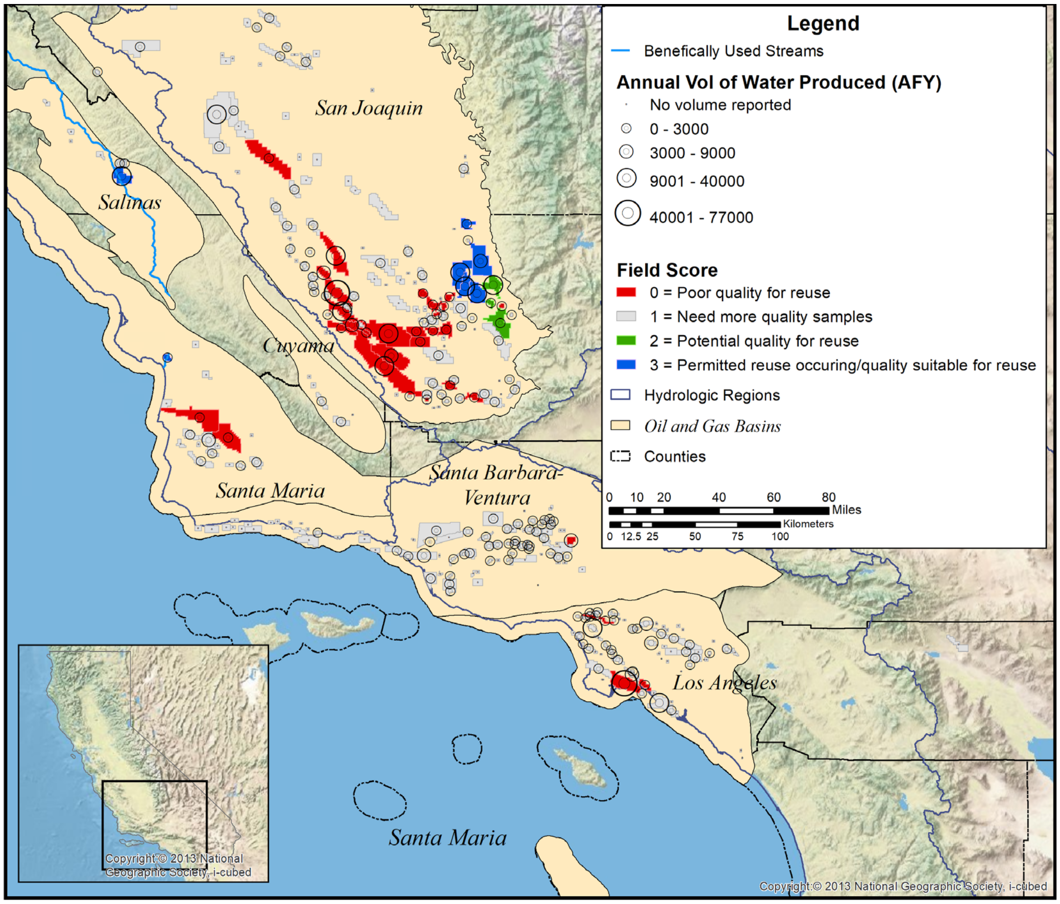

Figure 2.3. Map of oil and gas fields in California color-coded by field score to indicate potential for reuse of produced water for agriculture and average annual volume of water (AFY) produced. Red indicates water is of poor quality for reuse, grey indicates there is a need for more water quality samples before potential for reuse can be assessed, green indicates water quality is potentially suitable for reuse for agriculture, and blue indicates permitted reuse of water for agriculture is already occurring. Fields in the remaining portion of California did not have data on produced water quality.

> ***Finding 2.3.3.*** *Based on available water quality data beyond the SB 1281 dataset, we estimate that there is approximately 64,000 AFY of additional produced water available for expanded reuse with minimal treatment. This potential resource originates from eight fields, all within the San Joaquin basin.*

> ***Finding 2.3.4.*** *Where data were available, we found modest potential for expansion outside of the O&G industry for reuse by the agricultural industry. Of the eight fields where data supported a potential for reuse of produced water for agriculture, five currently have known permitted operations for agricultural reuse.*

The quality standards in our ranking system embody produced water that could be reused with minimal treatment to remove the bulk of hydrocarbons and other organic constituents, as is already the case for existing reuse operations in California (e.g., CVRWQCB, 1998, 2006). Additional factors required for consideration of whether expanded reuse of produced water is viable include: (1) reliability of sustained supply over time; (2) proximity of the location of produced water to potential end user(s) (to a greater degree than presented here); (3) availability of alternative options, such as storage and disposal sites; (4) legal and regulatory factors; (5) economics of all available alternatives; and (6) willingness of oil and gas operators to assume risk of liability associated with water management (NRC, 2010). Furthermore, oil and gas operators may need to use some or all excess produced water for their own production purpose (e.g., water flooding as the fields mature). We did not attempt to evaluate the volume of water that might be suitable with more extensive treatment, such as RO. However, it is challenging to estimate the economic likelihood that an oil and gas operator or irrigation district would be willing to fund the cost of building and operating an RO facility. The costs of constructing and operating an RO plant are highly variable and depend on numerous factors including the quality of the feedstock, building costs, energy costs, and requirements for brine disposal (National Research Council [NRC], 2008). A 2008 review by the NRC on the cost of desalination concluded that it was not possible to estimate generalized costs for brackish water desalination because of the large variation in costs between RO facilities and the lack of standardized financial data reporting. Future research could attempt to evaluate the economic viability of more extensive treatment of produced water for reuse.

Produced water currently reused for agriculture represents less than 1% of the total volumes of water used for irrigation in the San Joaquin River and Tulare Lake hydrologic regions (Table 2.9). In the Central Coast region, the current annual volume of reuse is 0.23% of the total water applied for irrigated agriculture in 2015 in the same region. And in the South Coast region, produced water represents less than 0.01% of the total applied water used for agriculture.

The estimated additional volume for expanded reuse represents a modest amount, at only 0.35% of applied water use for irrigated agriculture in the San Joaquin River and Tulare Lake basins. No potential for expanded reuse was identified in the South Coast and Central Coast regions. More data are needed in order to provide a complete picture of the potential for expanded reuse of produced water for agriculture in these regions and in other parts of the state.

Table 2.9. Comparison of applied water in 2015 and current and potential produced water reuse. TAFY=Thousands of Acre Feet per Year. Source: CDWR (2018), DOGGR (2018b, 2018c).

Applied Water in 2015 (TAFY)					**O&G Industry Reuse (TAFY)**			
Sedimentary Basin(s)	Hydrologic Region(s)	Total	Urban	Irrigated Agriculture	Reported Volumes of Agriculture & Recharge and Surface Water Discharge	Percent of Irrigated Agriculture	Potential Marginal Volume for Expanded Reuse	Percent of Irrigated Agriculture
Santa Barbara - Ventura and Los Angeles	South Coast	4,130	3,439	691	<0.1	<0.01%	0	<0.01%
Salinas and Santa Maria	Central Coast	1,333	245	1,088	3	0.23%	0	<0.01%
San Joaquin	San Joaquin River and Tulare Lake	19,480	982	18,498	36	0.19%	64	0.35%

Notes: Figures on Water Applied for Human Use are annual totals for 2015, a drought year, when volumes of water used were relatively low compared to the prior four years. Figures on O&G Industry Use are annual averages calculated from 2015 Q4–2017 Q1.

> ***Recommendation 2.3.2*** *Where there are indications of substantial volumes of produced water with TDS values feasible for reuse, from fields that are in proximity to agricultural regions, the Division should commission a study to conduct a detailed assessment of reuse potential. Such an assessment would evaluate the quality of water produced from each pool in a field for, at a minimum, boron and SAR concentrations; and potentially might consider other analytes of concern for soil and crop health identified in the United Nations Food and Agriculture Organization guidelines (Table 2.3).*

> ***Finding 2.3.5.*** *Produced water for reuse is typically obtained from centralized water-handling facilities.*

> ***Conclusion 2.3.3.*** *Sampling and reporting requirements for SB 1281 could be simplified by allowing operators to report water quality at centralized water handling facilities when commingled water shows little variation in parameters of interest.*

> ***Recommendation 2.3.3.*** *Water samples for assessing quality for agricultural reuse should be obtained from centralized water-handling facilities; in cases where there is significant variability in TDS (or EC), boron, and the SAR between wells, these samples should be taken from single wells.*

> ***Recommendation 2.3.4.*** *Research should be undertaken that provides a greater understanding of the technical and economic reuse potential for produced water in California. The study should assess the quality of produced water in alignment with accepted guidelines for irrigation water, as well as the economic cost-benefit analysis of treating and transporting produced water, taking into consideration local conditions.*

2.6. Summary: Findings, Conclusions, and Recommendations

Competition for water is intensifying, particularly in arid regions where the O&G industry commonly operates. This sector generates large amounts of produced water, some of which may be suitable for reuse. The agriculture industry, which is also commonly operating in arid regions, may have an interest in reuse of produced water. As pressures on surface water and groundwater resources intensify, water sources once considered less desirable due to water quality, cost, and public perception—including water produced during oil and gas extraction—may be reassessed for their resource potential. A full assessment of the factors involved in this reevaluation of costs and benefits was beyond the resources available for this effort; we have examined the additional potential of produced water for agricultural reuse in California given the data available, including the SB 1281 dataset. We have also suggested specific improvements to the dataset to help inform future, comprehensive assessments of O&G produced water as a potential resource to fill local needs. Our major findings, conclusions, and recommendations are:

FCR 2.1. Reuse of produced water that is presently occurring *(Chapter 2, Section 2.4)*

Finding 2.1.1. Based on operator-reported produced water volumes in the SB 1281 dataset, an estimated total annual volume of 38,345 AFY was discharged from oil and gas fields in California to the destinations of Agriculture and Recharge or Surface Water Discharge between 2015 Q4 and 2017 Q1. Of this amount, 35,838 AFY originated from 11 fields in the San Joaquin basin. Only 2,508 AFY was discharged from a single field in each of the following basins: Sacramento, Santa Barbara-Ventura, Salinas, and Santa Maria.

Conclusion 2.1.1. Reuse of produced water for agriculture is predominantly occurring in the southeastern San Joaquin basin where the majority of agricultural production occurs in the state. The rest of the reuse is spread between four other basins across the state.

Finding 2.1.2. We were able to identify WDRs/NPDES permits associated with an estimated 33,753 AFY (88%) of the total volume reported as going to Agriculture and Recharge or Surface Water Discharge. We were not able to identify WDRs/NPDES permits for an estimated 4,592 AFY (12%) of the total volume reported as going to Agriculture and Recharge or Surface Water Discharge.

Conclusion 2.1.2. WDRs/NPDES permits are the main source of information on how the water is used after leaving the oil and gas field. By examining these permits, we identified a mixture of direct reuse for agriculture and indirect reuse via discharge to ground and surface water.

Recommendation 2.1.2. The SB 1281 dataset should require the operator to report the associated permit for discharges to Agriculture and Recharge and Surface Water Discharge.

Conclusion 2.1.3. For the water reported as going to Agriculture and Recharge or Surface Water Discharge for which we could not identify permits, we were unable to conclude whether the water is reused directly, indirectly, or incidentally by agricultural or other water users.

Recommendation 2.1.3.1. SB 1281 reporting requirements for operators should be updated to include information on the receiving entity, groundwater water system, or surface water body when reporting volumes of water under the Agriculture and Recharge or Surface Water Discharge destination codes.

Recommendation 2.1.3.2. For cases where we were not able to identify permits associated with discharges labeled as Agriculture and Recharge or Surface Water Discharge the relevant regional board should review operator records.

FCR 2.2. SB 1281 Destination Codes *(Chapter 2, Section 2.4)*

Finding 2.2.1. The current destination code of Agriculture and Recharge does not distinguish between direct and indirect reuse for agriculture.

Finding 2.2.2. From our inspection of WDRs/NPDES permits, we observed that this destination code was used for a wide variety of discharges. A few operators appear to be reporting what happens to the water one or more steps downstream, rather than simply reporting what happens to the water at the moment it leaves their custody.

Finding 2.2.3. Direct reuse for irrigation provides a more direct pathway of exposure for soil, crops, and human health than indirect reuse.

Conclusion 2.2.1. It is important to differentiate between direct and indirect reuse of produced water. Direct and indirect reuse are not mutually exclusive, making it difficult to distinguish them with a single reporting code.

Recommendation 2.2.1. To distinguish between direct and indirect produced water reuse applications SB 1281 should eliminate the Agriculture and Recharge code and replace it with three codes: “Water Supplier,” “Agriculture,” and “Groundwater Recharge.” If a discharge requires a permit, the operator should report such in a separate field associated with that discharge.

Recommendation 2.2.2. Operators should be responsible only for reporting what happens to the water at the moment it leaves their custody. The eventual fate of produced water after it leaves the hands of the operator should be traced via the permit, not the SB 1281 dataset.

FCR 2.3. Potential for expanded reuse of produced water for irrigation *(Chapter 2, Sections 2.5.1, 2.5.2)*

Finding 2.3.1. According to the SB 1281 dataset, 11,337 AFY of fresh/brackish water (≤ 10,000 mg/L TDS) not currently reused by agriculture was produced in the five major basins between 2015 Q4 and 2017 Q1.

Conclusion 2.3.1. Based solely on the criterion of having a TDS of < 10,000 mg/L, there may be as much as 11,337 AFY of fresh/brackish water available for reuse outside of the O&G industry.

Conclusion 2.3.2. The water quality information in the SB 1281 dataset is inadequate for a complete assessment of water suitability for agricultural reuse intended by the SB 1281 legislation. Additional water quality data are needed to better characterize the potential for expanded reuse of produced water for irrigation.

Recommendation 2.3.1. The Division should carry out the intent of SB 1281 to track water "suitable for domestic or irrigation purposes" by more accurately capturing relevant water quality parameters; at a minimum, quantitative TDS concentrations should be reported. Boron and SAR concentrations are also important for determining irrigation suitability.

Finding 2.3.2. Information to assess the potential for expansion of produced water for reuse was limited.

Finding 2.3.3. Based on available water quality data beyond the SB 1281 dataset, we estimate that there is approximately 64,000 AFY of additional produced water available for expanded reuse with minimal treatment. This potential resource originates from eight fields, all within the San Joaquin basin.

Finding 2.3.4. Where data were available, we found modest potential for expansion outside of the O&G industry for reuse by the agricultural industry. Of the eight fields where data supported a potential for reuse of produced water for agriculture, five currently have known permitted operations for agricultural reuse.

Recommendation 2.3.2. Where there are indications of substantial volumes of produced water with TDS values feasible for reuse, from fields that are in proximity to agricultural regions, the Division should commission a study to conduct a detailed assessment of reuse potential. Such an assessment would evaluate the quality of water produced from each pool in a field for, at a minimum, boron and SAR concentrations; and potentially might consider other analytes of concern for soil and crop health identified in the United Nations Food and Agriculture Organization guidelines (Table 2.3).

Finding 2.3.5. Produced water for reuse is typically obtained from centralized water-handling facilities.

Conclusion 2.3.3. Sampling and reporting requirements for SB 1281 could be simplified by allowing operators to report water quality at centralized water handling facilities when commingled water shows little variation in parameters of interest.

Recommendation 2.3.3. Water samples for assessing quality for agricultural reuse should be obtained from centralized water-handling facilities; in cases where there is significant variability in TDS (or EC), boron, and the SAR between wells, these samples should be taken from single wells.

Recommendation 2.3.4. Research should be undertaken that provides a greater understanding of the technical and economic reuse potential for produced water in California. The study should assess the quality of produced water in alignment with accepted guidelines for irrigation water, as well as the economic cost-benefit analysis of treating and transporting produced water, taking into consideration local conditions.

Acknowledgements

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Chapter 3

California Produced Water Quality: Implications for Human Health and the Environment

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3.0. Abstract

Senate Bill 1281 (SB 1281) was passed to improve regulator, researcher, and general public understanding of water resources used in and produced from California oil and gas development. In this chapter we analyze, review, and synthesize the state of scientific knowledge on produced water quality in California within the context of environmental and human health using the SB 1281 dataset and other publicly available datasets. This chapter includes four primary components: (1) a discussion of produced water quality data provided in the SB 1281 dataset and how improved data collection and integration can inform risk management; (2) an analysis of California's publicly available statewide produced water quality datasets; (3) a toxicological assessment of publicly available chemical use data in California upstream oil and gas (O&G) operations; and (4) an assessment of the current and potential technologies used to treat produced water, as reported by operators.

The SB 1281 dataset evaluated in Chapter 1 indicates that the majority of produced water generated in California is re-injected into the subsurface. Approximately 10% of all produced water (fresh and saline) is discharged to the surface in lined and unlined produced water ponds; to land; to surface waters; to public water treatment systems; or for agricultural irrigation. However, produced water reuse, disposal, and management practices vary statewide. The San Joaquin basin, for example, accounts for approximately 60% of produced water volumes generated and 90% of produced water volumes discharged to the surface and reused outside the oilfield statewide. The SB 1281 dataset provides additional information about water sources, water dispositions (destinations), and water treatment methods. However, water quality information is lacking. In the SB 1281 dataset, quality is reported only as total dissolved solids (TDS) concentrations above or below 10,000 mg/L as a proxy for salinity.

While a critical measure of water quality, TDS is only one of many factors to consider when assessing the management and reuse options for a water source. Produced water may contain additional chemical constituents not reported in the SB 1281 dataset, including chemical additives used in oil and gas development; compounds from hydrocarbon reservoirs; and degradation byproducts of chemical transformations. This renders the SB 1281 dataset—on its own—insufficient to evaluate the quality of produced water in California and to assess potential hazards, risks, and impacts to human health and the environment, in particular for produced water that is discharged to the surface and reused outside the oilfield. Furthermore, while various water destinations are categorized in SB 1281 dataset, it does not require spatial tracking of produced water (e.g., from the point of production to geographically explicit point of disposal or reuse). The lack of spatial tracking of produced water in the SB 1281 dataset makes it difficult to assess human and ecological health risks at relevant spatial scales.

Our primary conclusion is that the SB 1281 dataset lacks much of the information required to adequately assess produced water quality in California in the context of human and environmental health where exposure pathways are likely to exist. This is important for produced water that is discharged to the surface and reused outside of the oilfield (e.g., discharge to unlined produced water ponds and for irrigation of food crops). While site-specific surface discharge of produced water is evaluated through permitting, integrated water quality and spatial information is needed to inform current and future produced water management at the state level, particularly for produced water that is discharged to the surface and reused outside of the oilfield. In addition, aspects of our analyses suggest that many of the technologies currently used to treat produced water may not effectively remove chemical additives used in oil and gas development in California. However, more advanced treatment technologies are available that are capable of meeting specific water quality objectives for many reuse options.

We also find that questions of produced water quality and associated public health and ecological risks are aided, but not answered, by chemical disclosure. While pollutant-by-pollutant chemical disclosure and monitoring is important, produced water reuse outside of the oilfield—with human and ecological exposure potential—could benefit from more holistic approaches to water quality testing (e.g., non-targeted chemistry, cell line assays) that are not directly focused on understanding all of the chemicals in the mixture. Existing water reuse frameworks that address evolving chemical landscapes (e.g., municipal wastewater) may also inform produced water treatment, monitoring, and management.

Questions Addressed in Chapter 3

- **Question 3.1.** What are the pathways through which human populations and the environment can be exposed to hazardous chemicals in produced water?

- **Question 3.2.** What is known about the quality of produced water in California?

- **Question 3.3.** What are the chemical additives used in California oil and gas operations that could be in produced water?

- **Question 3.4.** What are the treatment approaches that have been used for produced water and how effective are they?

3.1. Introduction

SB 1281 requires O&G operators to report on various aspects of their operations that involve the water life cycle. In addition to the disclosure of information on the source of water used for injections, well stimulation, and other activities, operators are also responsible for reporting specified measures of the quality, treatment, and management of their produced water.

Produced water contains various chemical constituents including: (1) chemical additives used in oil and gas wells for well stimulation (e.g., hydraulic fracturing) and routine activities including; drilling, maintenance, well re-works, wellbore cleanouts, and other activities; (2) compounds that are from the oil and gas reservoir, including total petroleum hydrocarbons, naturally occurring radioactive materials, boron, and heavy metals; and (3) daughter products and degradation byproducts of chemical transformations.

Methods for estimating produced water quantities (volumes) using the SB 1281 dataset are described in Chapter 1. Briefly, approximately 100,000 acre-feet (AF) of produced water is generated in California each quarter, the majority of which is injected for disposal or to enhance hydrocarbon production (82%; Table 3.1). Approximately one-tenth of produced water generated statewide is discharged to the surface for agricultural irrigation (9%); to lined and unlined produced water ponds (1%); to public wastewater systems (0.4%); to land (0.1%); and to surface water (0.1%). Meanwhile, approximately 4% of produced water generated statewide is used for ancillary O&G operations (Table 3.1).

Table 3.1. Estimated produced water volumes (acre-feet per quarter, AFQ) generated in California[1] by water destination across six quarters, 2015 Q4–2017 Q1.

Water Destination[2]	AFQ[3]	Percent of total
Subsurface Injection (UIC)[4]	84,591	82%
Agriculture and Recharge	9,417	9%
Other Operator or Oil Field	3,496	3%
Other	1,963	2%
Well Stimulation	1,294	1%
Unlined Pond	1,163	1%
Operator Facilities	586	0.6%
Public Wastewater System	393	0.4%
Well Work	180	0.2%
Land Discharge	125	0.1%
Surface Water Discharge	118	0.1%
Lined Pond	9	0.01%
Total	103,335	100%

1. Volumes shown are for five key sedimentary basins in California: Los Angeles, Salinas, San Joaquin, Santa Barbara-Ventura, and Santa Maria. See Chapter 1 and All Flows dataset for more information.

2. Water destinations designated in SB 1281 are detailed in Chapter 1, Appendix 1.1.

3. Quarterly averages are calculated across six quarters of SB 1281 reporting, 2015 Q4 – 2017 Q1. See Chapter 1 for more information.

4. Subsurface injection includes both injection for disposal and injection to enhance hydrocarbon production (e.g., enhanced oil recovery).

In Chapters 1 and 2 of this report, the authors discuss how water quantities (volumes) and concentrations of total dissolved solids (TDS), sodium, chloride, and boron are important variables in decision-making with respect to produced water management and reuse of produced water for agricultural irrigation. While these variables are critical from water treatment, techno-economic, and soil and plant health perspectives, a much more detailed understanding of produced water quality is required to appropriately assess environmental and human health hazards and risks associated with management and reuse of produced water. In this chapter, we address the following key questions:

- **Question 3.1.** What are the pathways through which human populations and the environment can be exposed to hazardous chemicals in produced water?
- **Question 3.2.** What is known about the quality of produced water in California?
- **Question 3.3.** What are the chemical additives used in California O&G operations that could be in produced water?

- **Question 3.4.** What are the treatment approaches that have been used for produced water and how effective are they?

In this chapter, we first discuss produced water quality as reported in the SB 1281 dataset, including significant limitations that prevent further risk analysis. We then summarize available produced water quality data from additional data collection efforts in California beyond the SB 1281 dataset. Next, we evaluate all publicly available California O&G chemical additive disclosure datasets in the context of human and environmental health. We then summarize produced water treatment information from the SB 1281 dataset and evaluate the potential treatment approaches to remove chemical additives from produced water. Finally, we highlight existing data gaps and emphasize the need for further data collection regarding produced water quality, especially where human and ecological exposure pathways may be likely, such as in the context of discharge of produced water to the surface (e.g., to unlined ponds) including for reuse outside of the oilfield (e.g., for agricultural irrigation). Building on this analysis of what is known regarding the chemical composition of produced water in California, we discuss opportunities, challenges, and research and policy recommendations with respect to the management and reuse of produced water across sectors in the context of human health and the environment.

3.2. Produced Water Quality Reporting in the SB 1281 Dataset

Under SB 1281, O&G operators are required to report produced water quality as a single water quality variable: concentrations of TDS. In the SB 1281 dataset, TDS concentrations are reported by operators in a binary, categorical fashion (either <10,000 milligrams per liter [mg/L] TDS or >10,000 mg/L TDS). TDS concentrations less than 10,000 mg/L are—according to SB 1281—considered suitable for domestic or irrigation use, and TDS concentrations greater than 10,000 mg/L are considered unsuitable for domestic or irrigation use. While TDS of 10,000 mg/L is not actually suitable for irrigation or domestic consumption (see Chapter 2), this salinity is tied to a number of federal and state regulations.

> ***Finding 3.1.1.*** *Salinity is reported in SB 1281 as above or below 10,000 mg/L TDS. With the exception of salinity, produced water quality parameters are not reported to SB 1281.*

Although salinity is a critical measure of water quality, salinity is only one of many factors to consider in the management and reuse of a water source. As noted above, produced water may contain additional chemical components that are not reported in the SB 1281 dataset, including chemical additives used in O&G development, chemical constituents from hydrocarbon reservoirs, and daughter products or degradation byproducts of chemical transformations. As such, the SB 1281 dataset alone is insufficient to evaluate the quality of produced water in California and to assess potential hazards, risks, and impacts to human health and the environment, in particular where human and ecological exposures may be likely, such as in the context of discharge to the surface and reuse outside of the oil field. Therefore, we examine additional datasets throughout this chapter to further evaluate produced water quality and constituents that may comprise produced water. Furthermore, while various produced water destinations are categorized in the SB 1281 dataset (Table 3.1), SB 1281 does not require spatial tracking of produced water. For example, it may be reported that produced water from a given well in a particular oilfield and production zone was sent to an unlined produced water pond facility, but it is not clear which pond facility. This lack of spatially-explicit information in the SB 1281 dataset makes it difficult to assess risk at spatial scales relevant to human and environmental exposures.

> ***Finding 3.1.2.*** *Chemical constituents that are or may be in produced water (e.g., residual petroleum hydrocarbons, chemical additives, geogenic compounds, daughter products, and degradation byproducts of chemical transformations) are not required to be reported to SB 1281.*

> ***Conclusion 3.1.*** *SB 1281 is inadequate in reporting water quality parameters. An understanding of produced water quality is essential to assess the potential for environmental and human health hazards, risks and impacts associated with produced water, to inform produced water management, and to identify opportunities for reuse outside of the oilfield.*

> ***Recommendation 3.1.1.*** *Require the SB 1281 dataset to include reporting of actual TDS measurements for all produced water at the level of the oil-water separator or similar point of aggregation.*

> ***Recommendation 3.1.2.*** *Priority water quality parameters and other approaches to water quality monitoring should be identified by a convened group of human and environmental health scientists with expertise in produced water quality and human and environmental health.*

> ***Recommendation 3.1.3.*** *SB 1281 should require reporting of all priority health- and environmentally-relevant water quality parameters for produced water discharged to the surface (e.g., to agricultural irrigation and unlined produced water ponds).*

> ***Finding 3.2.*** *The SB 1281 dataset includes water disposition categories that are informative, but produced water disposition reporting lacks adequate spatial resolution. For instance, it may be reported that produced water from a given well in a particular oilfield and production zone was sent to an unlined produced water pond facility, but which pond facility is not clear.*

> ***Conclusion 3.2.*** *The lack of spatially-explicit tracking of produced water in the SB 1281 dataset makes it difficult to assess and manage potential environmental, ecological, and human health hazards risks and impacts, at spatial scales relevant to human and environmental exposures.*

> ***Recommendation 3.2.*** *Update the SB 1281 dataset requirements to enable regulators to trace the geographic and geological source and fate of produced water to support assessments of environmental and exposure pathways, particularly for produced water discharged to the surface. For example, the use of unique spatial identifiers should be considered: these could include latitude and longitude coordinates for specific produced water pond facilities or water recipient facility locations where water is intended for reuse (e.g. agricultural irrigation).*

3.2.1. Discussing Produced Water Using a Risk Analysis Framework

Evidence-based policy and risk management approaches to produced water management require information on the hazards, risks, and impacts posed by produced water. The terms hazard, risk, and impact are often used interchangeably in everyday conversation. However, in technical contexts they represent distinctly different concepts with regard to the formal practice of risk assessment and risk management. A hazard is defined as any biological, chemical, mechanical, environmental, or physical stressor that is reasonably likely to cause harm or damage to humans, other organisms, the environment, and/or engineered systems in the absence of control (Sperber, 2001). Risk is the probability that a given hazard plays out in a scenario that causes a particular harm, loss, or damage (NRC, 2009). Impact is the particular harm, loss, or damage that is experienced if the risk-based scenario occurs. In the context of impacts related to exposure to radiation, food, water, or air, hazard can be considered an intrinsic property of a stressor that can be assessed through some biological or chemical assay. Hazard can also refer to the potential for physical harm, as when a person is exposed to fire or a collapsing building. However, defining the probability of harm requires a receptor (e.g., human population or high-value resource) to be exposed to the hazard, and often depends on the vulnerability of the population (or receptor based on age, gender, and other factors). As a result, risk is extrinsic and requires detailed knowledge (scenarios) about how a stressor agent (hazard) is handled, released, and transported to the receptor populations. In this chapter, hazard is discussed in detail, as data limitations and broader focus render us unable to assess risk and impact.

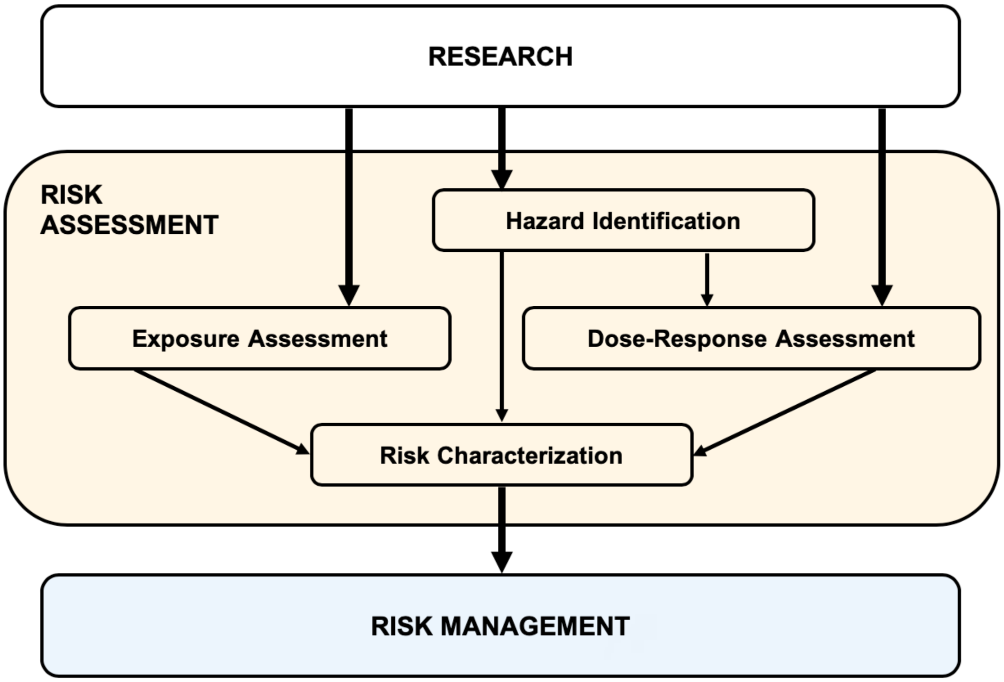

Figure 3.1. Risk Analysis Framework. National Research Council (1983).

In its widely cited 1983 report, the National Research Council (NRC) first laid out the now-standard risk-analysis framework consisting of research, risk assessment, and risk management as illustrated in Figure 3.1 (NRC, 1983). The NRC proposed this framework to organize and evaluate existing scientific information for the purpose of decision-making. In 2009, the NRC issued an updated version of its risk assessment guidance titled “Science and Decisions: Advancing Risk Assessment” (NRC, 2009). This report reiterated the value of the framework illustrated in Figure 3.1, but expanded it to include a solutions-based format that integrates planning and decision-making with the risk-characterization process. The NRC risk framework illustrates the parallel activities that take place during risk assessment and the reliance of all activities on existing research. These activities combine through the risk characterization process to support risk management.

Following the framework in Figure 3.1, the first task in the risk analysis process is to identify features, events, and processes associated with an activity that could cause harm (hazard identification). Any given hazard may or may not be a problem. It depends on the answers to two additional questions: First, is the hazardous condition likely to result in a population being exposed to the hazard? Second, what will be the impact if the hazardous exposure does occur (dose-response)? If we know the magnitude of a specific hazard exposure and the relationship between the magnitude of exposure and response or harm, then we can estimate the risk associated with that hazard. In cases where the hazardous condition is unlikely or where, even if it did occur, the harm is insignificant, then the risk is low. Risk is only high when the hazardous condition is both likely to occur and would cause significant harm if it did occur. Of course, there are many combinations of likelihood and harm possible. Formal risk analysis presents difficulties, because we often lack:

- Data on all the possible hazards.
- Comprehensive understanding and definition of all of the failure scenarios.
- Information on the likelihood and magnitude of exposure.
- Data to support an understanding of the relationship between exposure (dose) and harm (response).

If a hazard has not been identified, then it is difficult to develop steps to mitigate potential harm in a risk management plan. In this case, a useful approach is to avoid the problem where possible, for example by choosing chemical additives that are better understood, less toxic, or more controllable rather than choosing ones for which there is little toxicity information or poor understanding of the relationship between the hazard and risk to the environment and/or to public health. Although one can attempt to identify all hazards associated with produced water, it is important to note that this does not mean that all hazards that are identified present risks. A formal risk assessment is required to estimate risk associated with any given hazard. A formal risk assessment is a significant site-specific undertaking that is beyond what was possible in this report. Among the goals of this chapter are to identify hazards and highlight those where additional study or data collection may be warranted in the context of developing and informing produced water and risk management strategies.

3.2.2. Environmental Exposure Pathways Relevant to Produced Water

As we discuss throughout, this chapter primarily focuses on hazard identification given that the information required to quantify risk is largely unavailable. While exposure assessment is a site-specific task and beyond the scope of this report, there are known pathways through which produced water and its associated chemical load may enter the environment. Produced water may be reused (e.g., for agricultural irrigation, see Chapter 2) or disposed of via surface discharge (e.g., to unlined ponds, see Chapter 4), disposed of via subsurface injection (into Class II disposal wells), or reused within the oilfield for enhanced oil recovery (injected into Class II enhanced recovery wells). These disposal and reuse practices may pose health hazards if humans come into contact with toxic chemical constituents from produced water that enter the air, water, soil, or food.

Potential pathways between O&G activities and protected groundwater are illustrated in Figure 3.2. The majority of produced water generated in California is reinjected into the subsurface in Class II disposal or enhanced recovery wells. Produced water may reach groundwater after injection into subsurface via Class II disposal wells, which are permitted in exempt aquifers that are not sources of drinking water nor likely to be in the future due to high concentrations of TDS, boron, arsenic, or petroleum hydrocarbons (U.S. EPA, 2017). In California, there are, however, documented cases of Class II wells injecting into zones with groundwater with TDS concentrations less than 3,000 mg/L as a result of poor regulatory oversight (CalEPA, 2015). Produced water disposed in unlined ponds percolates through the soil and also may reach underlying aquifers that are currently or could be in the future used for domestic or agricultural consumption. Evidence of produced water from unlined ponds migrating to groundwater resources that may be used now or in the future for human consumption is discussed in further detail in Chapter 4.

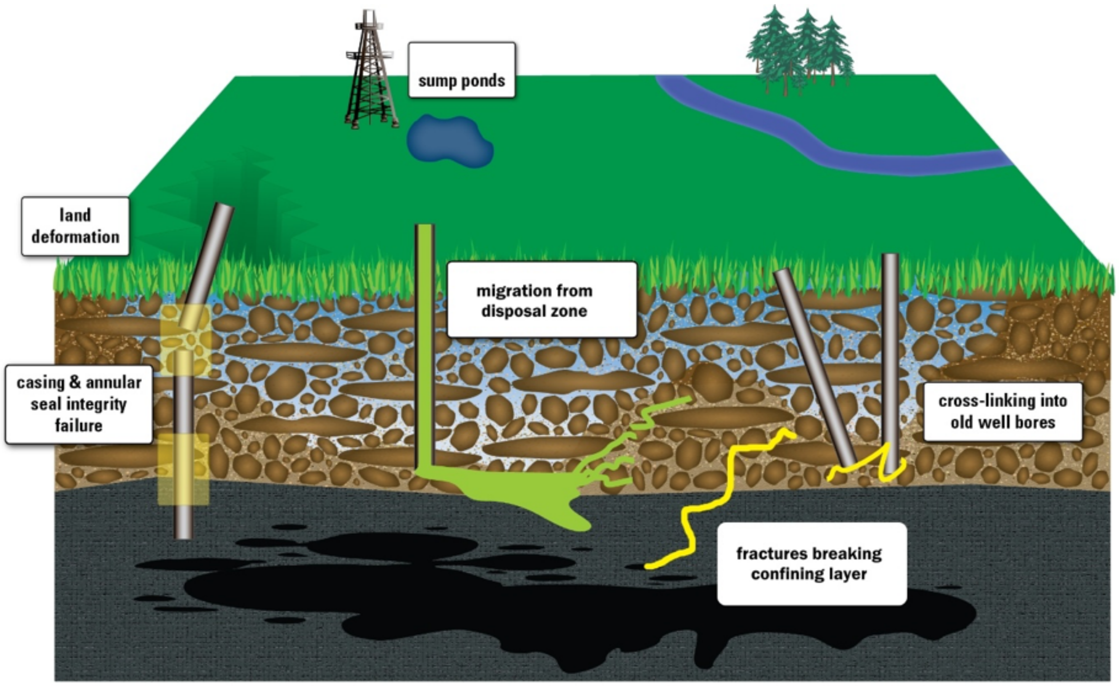

Figure 3.2. Examples of potential pathways between O&G activities and protected groundwater. Source: USGS (2019).

Exposure to produced water is perhaps most likely when produced water is discharged to the surface and in occupational settings. Employees and contractors responsible for produced water handling may come in direct contact with produced water during O&G production or during waste handling for disposal or reuse. Produced water may also introduce toxicological risks when used to irrigate food crops for human consumption, both via uptake of chemical constituents into food crops and if workers are exposed to the chemical constituents in produced water, which may be blended with additional water sources and used for crop irrigation. Crop irrigation or livestock watering using produced water may allow for produced water constituents to be taken up by agricultural crops or livestock, constituting a potential oral route exposure pathway (Shonkoff et al., 2016). This topic is currently being evaluated by the Food Safety Expert Panel[1] convened by the Central Valley Water Resources Control Board (CVRWQCB, 2019).

From an air pathway, volatile constituents of produced water may evaporate from lined or unlined produced water ponds (Lyman et al., 2018; SAGE Environmental Consulting, 2016; Tran et al., 2018), during storage or treatment phases, or during irrigation, leading to degradation of air quality and potentially opening exposure pathways via air for human populations. The California Air Resources Board (CARB) is currently evaluating emissions of volatile organic compounds from produced water ponds in the Central Valley (CARB, 2017).

Produced water may also be unintentionally discharged at the surface via leaks or spills. However, spilled water volumes are not included in the SB 1281 dataset. Of note, while operators may report produced water spills to the California Office of Emergency Services (CalOES), these spills are not characterized beyond water-type (as “produced water”). An estimated 272,000 barrels (35 AF) of produced water were reported as spilled in 2017 in California (CalOES, 2019).

It is important to note that chemical constituents and chemical additives in produced water may undergo transformation or degradation along environmental exposure pathways (via air, water, soil) in ways that could alter the toxicological properties in parent compounds or generate degradation products that may warrant further evaluation. This is discussed further in Section 3.6.

3.3. California Produced Water Quality Beyond the SB 1281 Dataset

Given that SB 1281 provides limited data on water quality, in this section, we summarize what is known about California produced water quality through the collation and broad analysis of other publicly available data sources. To build a collated produced water quality dataset, we compiled publicly available digital data sources on produced water quality measurements. It should be noted that produced water quality has substantial variability across time and geological, geographical, and operator space (Kim et al., 2016; Kondash et al., 2017; Rosenblum et al., 2017; Stringfellow & Camarillo, 2019). A number of factors may influence produced water quality including, but not limited to: hydrocarbon field

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[1] The Food Safety Expert Panel was convened by the CVRWQCB in California to provide scientific guidance on the use of O&G produced water for use in irrigation of food crops in the San Joaquin Valley of California. More information on this panel can be found at: https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/.

setting and petroleum geology; geologic history; flushing of meteoric water; confining geologic layers; history of O&G activities and water injection; current and historical downhole chemical use; and field temperature and pressure (Clark & Veil, 2009; Kahrilas et al., 2015; DiGiulio & Shonkoff, 2017; McMahon et al., 2018).

As such and due to limited data availability in inconsistent formats, we discuss produced water composition in broad terms at the statewide level using available data. Produced water quality is a broad topic and many questions, especially site-specific or use-case characterizations, were beyond the scope of this chapter.

> ***Finding 3.3.1.*** *Analysis of existing produced water quality information in the State of California currently requires collation from multiple data sources and data formats.*

3.3.1. Methods: Integrated Produced Water Quality Dataset

We compiled publicly available digitized federal and state databases of water quality in California for produced water assumed to be either untreated or which had undergone deoiling (Table 3.2). While Chapter 2 focuses exclusively on TDS, sodium, chloride, and boron concentrations, which are the primary limiting factors for agricultural irrigation from a yield and soil health perspective, the assessment in this chapter focuses on a more comprehensive list of chemical constituents, including major and minor ions, trace elements, low molecular weight organic acids, organic compounds, and naturally occurring radioactive materials.

Datasets included in this assessment were available as of December 31, 2018, in digitized, electronic format (e.g., Microsoft Excel). Datasets were included if they focused on untreated produced water (or produced water after deoiling alone), as opposed to treated produced water effluent discharged to the surface for specific use cases. Data sources were excluded if they were partially or entirely in paper or PDF format, given time restraints for this project (e.g., monitoring reports from waste discharge requirements, WDRs). Of note, numerous produced water quality data sources were published or became available in 2019, and additional site-specific or use-case specific evaluations of produced water quality data are being conducted by the Food Safety Expert Panel. Additional data sources of California produced water quality not included in this assessment are shown in Appendix 2.1.

For the included datasets (Table 3.2), we removed water chemistry results reported as presence/absence or as a range (e.g., <0.01 mg/L) to allow for water quality data consolidation across available datasets. We also removed results that had blank or empty values or non-detections for two reasons: (1) it was often unclear whether a blank value implied an absence of a compound or whether the compound was not tested for; and (2) to interpret results of “non-detection” it is imperative to understand what detection limit was used and this information was not available across all datasets. Measurements for dissolved gases and stable isotopes were also excluded from further analysis. We then calculated summary statistics, including percentiles, to show the distribution of concentrations for various water quality parameters included in the compiled dataset. Detailed descriptions of the sources of produced water quality information that we included in our assessment are included in Appendix 3.1.

Table 3.2. Overview of California produced water quality datasets included in this assessment.

Dataset	Source	Timeframe	Region	Description
USGS Federal Database	USGS National Produced Waters Chemical Database	February 1937–November 1996	Los Angeles, Sacramento, San Joaquin, Santa Barbara-Ventura, Santa Maria basins	Produced water quality data including major and major ions, trace elements, isotopes, dissolved gases, and naturally occurring radioactive materials.
Division monitoring	Division Well Stimulation Disclosures	July 2015–September 2018	California	Composition of recovered fluids within 60 days following the cessation of a well stimulation treatment.
Davis et al., 2016	Davis et al., 2016	November 2014	North Belridge, South Belridge, Lost Hills oilfields	Produced water from four petroleum wells analyzed for dissolved hydrocarbon gases and their isotopic composition, salinity, major ions, nutrients, dissolved organic carbon, and stable isotopes of water and strontium dissolved in water.
Gannon et al., 2018	Gannon et al., 2018	July 2016–October 2017	Fruitvale, Lost Hills, and North and South Belridge oilfields	Produced water data including dissolved noble and hydrocarbon gases and their isotopic composition, salinity, major ions, and nutrients, dissolved organic constituents and carbon, and stable isotopes of water and solutes dissolved in water.
Gans et al., 2018	Gans et al., 2018	January 1933–December 2013	Fruitvale oilfield	Historical produced water quality data including major ions, some minor ions, TDS, pH, specific gravity, resistivity, electrical conductivity, and charge balance.

3.3.2. Results: Integrated Produced Water Quality Dataset

Our integrated produced water quality dataset included 1,707 produced water samples analyzed for a total of 127 water chemistry parameters. The produced water samples contained in our dataset were collected between February 1937 and September 2018 (see Table 3.3). The USGS Federal Database included the largest number of overall produced water samples while the Gannon et al. (2018) dataset analyzed for the greatest number of water chemistry parameters. The DOGGR dataset provided the most recently collected produced water samples.

Table 3.3. California produced water quality samples summarized from available digital datasets and included in analyses.

Dataset	Number of water chemistry parameters	Number of samples	Sample date range
USGS Federal Database	45	856	February 1937 – November 1996
DOGGR monitoring	63	621	July 2015 – September 2018
Davis et al., 2016	38	4	November 2014
Gannon et al., 2018	75	23	July 2016 – October 2017
Gans et al., 2018	40	203	May 1958 – Decemeber 2013
Total	127	1,707	February 1937 – September 2018

Produced water chemistry data across digital datasets are summarized in Appendix 3.1. Water chemistry analytical data were available for low molecular weight organic acids, naturally occurring radioactive materials, major and minor ions, other trace elements, and general water quality indicators. In Appendix 3.1, we also list number of detections and concentration ranges (minimum and maximum), as well as distribution of concentrations represented by percentile (5th – 95th). Concentrations presented in Appendix 3.1 should be interpreted with careful consideration of the limited data availability and removed values (presence/absence values, non-detections, ranges and blanks) discussed previously and also below in Section 3.3.3.

Chloride, calcium, and TDS were the most commonly detected constituents (3,427; 2,238; and 2,230, respectively) (Appendix 3.1). Meanwhile, six compounds had only a single detected measurement (butanoic acid, lactic acid, chromate, phosphorus, p-Bromofluorobenzene, dibromofluoromethane). While many water quality parameters were reported across all datasets, monitoring data for organics often co-produced with oil and gas and with health relevance, such as benzene, toluene, ethylbenzene and xylene (BTEX), were only available in The DOGGR monitoring dataset. The DOGGR monitoring dataset also provided the majority of samples for radioactivity indicators.

It is important to note that the fifth percentile for TDS is 2,207 mg/L. As mentioned in Chapter 2 of this report, a commonly applied rule of thumb is that irrigation water should have TDS <450 mg/L, with TDS up to 2,000 mg/L acceptable in limited circumstances. Water with TDS of 450 mg/L and above would typically require treatment or dilution before reuse in irrigation. The vast majority of samples included in this compiled dataset had TDS concentrations far above the maximum considered acceptable for crop and soil health from an agricultural irrigation perspective.

The sodium adsorption ratio (SAR) is another indicator of the suitability of water for use in agricultural irrigation, derived using measured concentrations of sodium, calcium, and magnesium ions. Generally, the higher the SAR the less suitable the water is for irrigation. Using our compiled dataset, we calculate SARs ranging from 143 to 663 (using 5th and 50th percentiles, respectively). As discussed further in Chapter 2, this SAR range falls within observed ranges for produced water (1 to 375; Echchelh et al., 2018) and also exceeds the threshold to be considered for agricultural irrigation (SAR = 26; Fipps, n.d.). Also noted in Chapter 2, the portion of total produced water in the state that is suitable for agricultural irrigation (based solely on salinity) after minimal desalination is small.

3.3.3. Limitations and Summary: Integrated California Produced Water Quality Dataset

There are a number of limitations of this integrated California produced water quality dataset:

- The historical datasets (USGS, 2017; Gans et al., 2018) do not always indicate sampling protocols, standard analytical methods employed or associated limits of detection.
- Many historical datasets include sources that cannot be independently verified (USGS, 2017). Concentration ranges and distributions presented in Appendix 3.1 do not include presence/absence variables, non-detections, concentration ranges, or blank values because these variables were difficult to interpret and as such were difficult to integrate.
- While these data may provide indication of tendencies in produced water composition in California, they are not necessarily reflective of current produced water compositions or a reliable examination of trends at finer geographic and geological scales.
- Additional constituents of produced water, including chemical additives used in O&G development by operators and daughter products and degradation byproducts, were not found in the publicly available digitized datasets included in this assessment and as such are not included in this integrated dataset. They are discussed further in Sections 3.4 and 3.6 of this chapter.
- Across the majority of the produced water datasets included in this consolidated dataset, information regarding the disposition of the produced water was unavailable. Produced water source information (well identifier [API], field, or latitude/longitude) was also only available for some of the compiled, publicly and electronically available datasets. In order to characterize human health and environmental risk associated with produced water handling and reuse, particularly for cases where potential human and ecological exposure pathways may be likely (e.g., discharge to the surface or reuse outside the oilfield), clear information that enables geospatial tracing from production to disposal or reuse approach is required.

The SB 1281 dataset alone lacks adequate produced water quality data to inform produced water management. Upon our review of additional water quality datasets, we found various disparate data sources (see above and Appendix 2.1) and identified the need for a comprehensive and integrated produced water quality database for the State of California. Information in an integrated and digitized database is critical to assess potential environmental and public health hazards and risks, and to properly manage produced water. This is particularly important for approximately 10% of produced water statewide that is discharged to the surface (e.g., unlined produced water ponds) or reused outside of the oilfield (e.g., agricultural irrigation). Such a database should include unique chemical identifiers, concentrations, limits of detection, and geospatial information to enable assessment of exposure potential and associated potential environmental and human health risks.

> ***Finding 3.3.2.*** *The existing data may not sufficiently characterize produced waters to allow evaluation with respect to impacts on human and ecological health.*

> ***Conclusion 3.3.*** *To assess and manage potential risks and opportunities for produced water discharged to the surface and reused outside of the oilfield, there is a need for a comprehensive and current produced water quality database in the State of California.*

> ***Recommendation 3.3.*** *Agencies with jurisdiction should require comprehensive produced water quality monitoring information be disclosed and consolidated into an integrated, digitized, and publicly available database, especially for produced water that is discharged to the surface or reused outside of the oilfield. The SB 1281 dataset, in conjunction with Geotracker, may be a relevant repository for this information.*

3.4. Assessment of Chemical Additives used in California Oil and Gas Development Operations

Chemical additives are used throughout O&G operations for a variety of purposes, including to control scaling, corrosion, and bacteria growth, adjust pH, reduce friction, modify viscosity, dissolve formation matrix, and as cement and drilling additives (Stringfellow et al., 2014, 2015, 2017a, 2017b; U.S. EPA, 2016). Chemical additives used in O&G operations are expected to return to the surface as chemical constituents of produced water (Ferrer & Thurman, 2015a; Lester et al., 2015; Stringfellow et al., 2015; U.S. EPA, 2016). However, because data regarding the presence and concentrations of chemical additives in California produced water is limited, it is unclear what fraction of chemical additives returns to the surface with produced water, and it cannot be determined if the concentration of these additives pose a risk to human health. Because chemical additives are expected constituents of produced water, it would be prudent to analyze what is known regarding chemical additives used in O&G operations in California.

Recent studies have primarily focused on the potential environmental and human health impacts of chemical additives used in hydraulic fracturing and well stimulation in California (CCST et al., 2014; Shonkoff et al., 2015; Stringfellow et al., 2014; Stringfellow et al., 2015; Stringfellow et al., 2017;U.S. EPA, 2016). However, the potential risks and impacts from chemical use in conventional O&G activities, and the potential reuse of produced water, remain under-studied in California.

In this section, we describe and analyze chemical additive use for all O&G activities (including hydraulic fracturing) in California. Although SB 4 (Pavley, 2013) regulations prohibit the discharge of produced water from hydraulic fracturing operations to pits or sumps, and produced water reused for agricultural purposes is sourced from non-hydraulically fractured operations, there are other pathways, such as unintentional releases of produced water, that can result in exposure to chemical additives used in hydraulic fracturing operations. In this section we will address the following questions:

- Which chemical additives are used in California O&G development activities that could be in produced water?
- What are the chemical, physical, and toxicological properties of these chemical additives?

In this section, we undertake the following tasks:

1. Characterize existing chemical additive disclosure datasets;
2. Summarize acute and chronic toxicity, biodegradability, carcinogenicity of disclosed chemical additives; and
3. Identify air pollutants, potential endocrine disruptors, and priority compounds used in O&G operations in California.

Finally, we discuss our findings in the context of produced water that is reused for agricultural irrigation. Summarizing known and unknown information about chemical additive disclosure, toxicity, and environmental profiles, we discuss environmental, ecological, and human health hazards (see Section 3.2.1) and remaining data gaps to inform risk management decisions regarding produced water.

3.4.1. Methods: Assessment of Chemical Additives Used in California Oil and Gas Development Operations

Databases of chemical additives used in O&G operations in California were obtained from the Central Valley Regional Water Quality Control Board (CVRWQCB), the South Coast Air Quality Management District (SCAQMD), The Division, and from the California portions of the national hydraulic fracturing chemical disclosure database, FracFocus. These databases are detailed in Appendix 3.2 and summarized in Table 3.4.

The databases we obtained were in a variety of formats, including PDF, Access databases, and comma separated values (CSV) spreadsheets. Data from PDFs and Access databases were extracted and compiled into an Excel spreadsheet when relevant. This report follows data quality control and validation methods used in multiple studies of O&G chemical additive datasets by the California Council on Science and Technology (CCST et al., 2014); Stringfellow et al. (2015, 2017a, 2017b); Camarillo et al. (2016); and Shonkoff et al. (2016).

We identified chemical additives according to Chemical Abstracts Service registration number (CASRN) whenever possible. CASRN is a unique numeric identifier assigned to chemical substances, including organic and inorganic compounds, minerals, polymers, and substances of unknown or variable compositions, complex reaction products, and biological materials (UVCB substances). CASRN consists of three groups of numbers, separated by two dashes (e.g. 7732-18-5), where the last digit is a verification digit used to determine if a CASRN is valid or not. We formatted and validated CASRNs and standardized the chemical names. Utilizing CASRNs for chemical additive identification minimizes duplicate chemical entries between the various datasets.

We then evaluated and, when possible, identified chemical additives listed with invalid CASRNs. Chemical additives could be identified with a high degree of certainty if the CASRN was listed with leading zeros, one missing or added digit, one or two wrong digits, or swapped digits, and if the provided chemical named matched another chemical additive with a similar (but correct) CASRN. We provide examples of chemical additives with invalid CASRNs that we could identify in Appendix 3.2. Chemicals listed with an invalid CASRN and a generic name that was not similar to any other existing chemical names in the database could not be identified and no further analysis could be conducted on these additives. A complete list of chemical additives reported with invalid CASRNs and their corrected CASRNs is available in Appendix 3.2.

Chemical additives listed as proprietary information or trade secret that did not have a valid CASRN could not be definitively identified. Changes to the names of these proprietary and trade secret chemical additives were limited to fixing capitalization, punctuation, and obvious spelling errors (e.g. aicd to acid) to maintain consistency. Proprietary and trade secret chemical additive names that were plural (e.g. salt vs. salts, amine vs. amines), indicating a mixture of multiple compounds, were maintained as separate entries. Additives of the same name, but originating from different datasets, were maintained as separate entries because it cannot be determined if “ionic surfactants” from one dataset is the same “ionic surfactants” reported in another dataset. No further analyses could be done on these proprietary and trade secret chemical additives.

3.4.1.1. Characterization of Chemical Properties

Physical, chemical, biological, and toxicological data for all chemical additives used in O&G operations in California that could be uniquely identified by CASRN were obtained from various online databases, including national and international sources. These databases are listed in Table 3.5.

Table 3.4. Overview of chemical usage datasets.

Dataset	Source	Legislation/Rules	Timeframe	Region	Description
Irrigation 13267	Central Valley Regional Water Quality Control Board	California Water Code Section 13267	January 2014–May/June 2016	Kern Front Oil Field, Kern River Oil Field, Mount Poso Oil Field, Jasmin Oil Field, Deer Creek Oil Field	All chemical additives used in petroleum production (including enhanced oil recovery), treatment, and transportation processes that generate produced water for irrigation. Only includes data from operators.
AB 1328	Central Valley Regional Water Quality Control Board	California Assembly Bill No. 1328 (AB 1328) (California Water Code Section 13267 and 13267.5)	Two years prior to receiving orders (December 2017–May 2018)	Kern Front Oil Field, Kern River Oil Field, Mount Poso Oil Field, Jasmin Oil Field, Deer Creek Oil Field	All chemical additives used in petroleum production, treatment, and transportation processes that generate produced water for irrigation. Includes data from operators and their chemical suppliers.
SCAQMD	South Coast Air Quality Management District	SCAQMD Rule 1148.2	June 4, 2013–August 31, 2018	Orange County, and urban portions of Los Angeles, Riverside, and San Bernardino Counties	Routine O&G activities (well drilling, well completion, and well reworks) and well stimulation (hydraulic fracturing and matrix acidizing). Does not include enhanced oil recovery, refining, transmission, or storage activities.
DOGGR chemical	California Division of Oil, Gas, and Geothermal Resources	California Senate Bill No. 4, Public Resources Code section 3160, subdivisions (b) and (g), and California Code of Regulations (CCR), title 14, section 1788.	January 1, 2014–August 30, 2018	California	Composition of well stimulation fluids, including, but not limited to, hydraulic fracturing fluids, matrix acidizing fluids, acid fracturing fluids, and recovered fluids within 60 days following the cessation of a well stimulation treatment. Includes disclosures under bothiInterim and final SB 4 regulations.
FracFocus	Ground Water Protection Council, Interstate Oil and Gas Compact Commission	California Senate Bill No. 4, Public Resources Code section 3160, subdivisions (b) and (g), and California Code of Regulations (CCR), title 14,section 1788.	January 2011–September 2018	Nationwide (Analysis limited to California)	Composition of hydraulic fracturing fluids. Combines FracFocus 1.0, 2.0, and 3.0 data for completeness.

Table 3.5. Databases and other sources used to gather physical, chemical, and toxicological properties of chemical additives. An "X" indicates that this category of chemical information was found in the database.

Database Name	Physical/Chemical Properties	Acute Toxicity	Chronic Toxicity	Biodegradation
American Chemical Society SciFinder Database	X			
World Health Organization, International Programme on Chemical Safety (IPCS) Database	X	X		X
National Library of Medicine, Toxicology Data Network (TOXNET) Hazardous Substance Data Bank (HSDB) and ChemIDplus	X	X		X
Syracuse Research Corporation (SRC), Physical Properties Database (PHYSPROP)	X			
European Chemicals Agency, International Uniform Chemical Information Database (IUCLID)	X	X		X
National Institute of Technology and Evaluation, Chemical Risk Information Platform, Japan.	X			X
U.S. EPA, Aggregated Computational Toxicology Resource Database (ACToR)	X	X		X
European Chemicals Agency – Information on Chemicals Website	X	X		X
U.S. EPA, Ecotoxicology Database (ECOTOX)		X		
U.S. EPA, Integrated Risk Information System (IRIS)			X	
U.S. EPA, Human Health Benchmarks for Pesticides (HHBP)			X	
U.S. EPA, Provisional Peer Reviewed Toxicity Values (PPRTV)			X	
U.S. EPA, Health Effects Assessment Summary Tables (HEAST)			X	
U.S. EPA, Drinking Water Standards and Health Advisory Tables			X	
U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry (ATSDR) Priority List of Hazardous Substances			X	
U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health (NIOSH), Pocket Guide to Chemical Hazards			X	
California Office of Environmental Health and Hazard Assessment (OEHHA)			X	
USGS, Health Based Screening Levels for Evaluating Water-Quality Data (HBSLs)			X	

3.4.2. Results: Chemical Additives Used in California Oil and Gas Development Operations

3.4.2.1. Chemical Additives Identified in Each Dataset

Overall, we identified 1,119 chemical additives reported as either proprietary information/trade secrets or by unique CASRN across the five datasets, with the SCAQMD dataset contributing the greatest number of chemical additives (see Table 3.6). This is likely due to the long timeframe and the variety of O&G activities covered by the SCAQMD dataset, as the other datasets are narrower in scope or timeframe. Of the 1,119 chemical additives, 630 (or 54%) were identified by unique CASRN and were carried forward for further analysis. All analyses from this point forward pertain only to chemical additives identified by unique CASRN, unless explicitly stated otherwise.

The FracFocus and SCAQMD datasets cover operations as far back as 2011 and 2013, respectively. As a result, they may include older chemical additives that are no longer used or that have been replaced in newer formulations. The actual number of chemical additives used in O&G operations in California in recent years is likely to be smaller than the 1,119 chemical additives identified over the entire timeframe of the datasets examined in this report.

Table 3.6. Number of proprietary or trade secret chemical additives and chemical additives with valid CASRN by dataset.

Dataset	**Proprietary or Trade Secret**	**Invalid CASRN but Identifiable**	**Unique Chemicals with Valid CASRN**
Irrigation 13267	62	4	108
AB 1328	18[1]	3	284
SCAQMD	327[2]	51	324
DOGGR chemical	0	9	272
FracFocus	82	9	315
Total	489	75	630[3]

1. One chemical additive with CASRN (magma fibers CASRN: 6806-10-0000) could not be identified and was labeled proprietary.

2. Three chemical additives with CASRN (alkylaryl sulfonate CASRN: 68484-27-0; d-limonene CASRN: 254504-00-1; xanthan gum CASRN: 59370-00-0) could not be identified and were labeled proprietary.

3. Unique CASRN across all datasets.

3.4.2.2. Comparison of Chemical Additive Use Between Datasets

Of the five datasets analyzed, AB 1328, Irrigation 13267, and SCAQMD covered O&G operations in specific regions in California. The AB 1328 and Irrigation 13267 datasets focus on operations in the southern San Joaquin Valley that provide produced water for agricultural uses. The SCAQMD dataset covers operations in Los Angeles and Orange Counties. Comparison of these three regional datasets can provide insight into the commonality of chemical additive usage between varying regions of the state. Chemical additive usage for O&G operations is dependent on numerous factors including geology, geochemistry, well depth, reservoir age, type of operation, and operator preference.

Both the AB 1328 and Irrigation 13267 datasets cover O&G operations in the southern San Joaquin Valley that use produced water for agricultural uses, and as a result, the datasets are very similar (Figure 3.3). The requirements of AB 1328 served to build upon and expand the data gathered under California Water Code section 13267, meaning the Irrigation 13267 dataset was essentially a precursor to the AB 1328 dataset. The AB 1328 dataset contains all of the chemical additives with CASRN from the Irrigation 13267 dataset, with the exception of chloric acid, lithium salt (CASRN: 36355-96-1). It is unknown why chloric acid, lithium salt was not included in the AB 1328 dataset. Further comparison of the AB 1328 dataset with the SCAQMD dataset reveals that although the majority of chemical additives were unique to their respective datasets, 132 chemical additives with CASRN were reported as used in both datasets. The large number of chemical additives unique to the

SCAQMD dataset is likely due to the variety of O&G events covered by SCAQMD, including gravel packing, well drilling, matrix acidizing, maintenance acidizing, and hydraulic fracturing. However, because the AB 1328 dataset does not provide information regarding the specific type of O&G activities occurring, this cannot be verified.

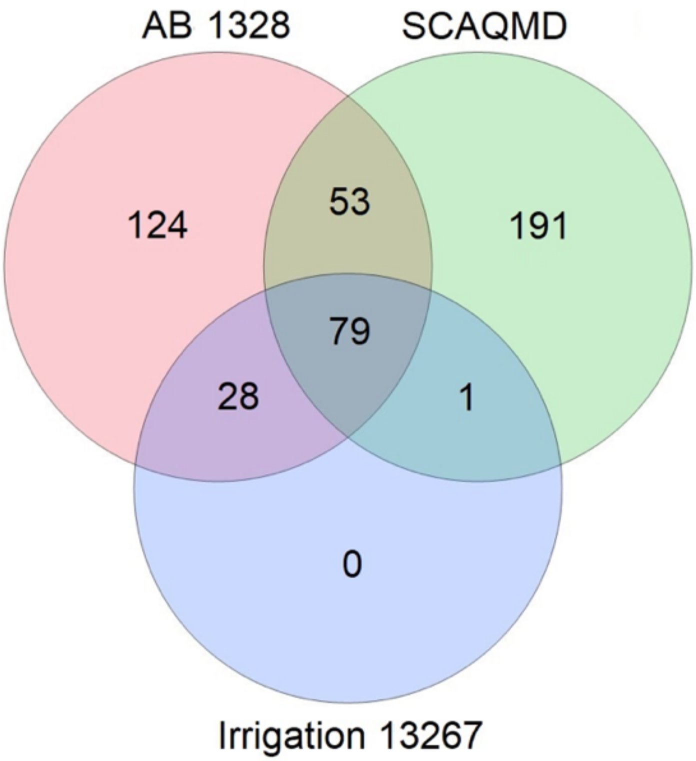

Figure 3.3. Venn diagram showing overlap in reported chemical additive usage between SCAQMD, AB 1328, and Irrigation 13267 datasets. Only chemical additives with CASRN are included in this analysis.

Comparison of chemical additive usage in the AB 1328, DOGGR chemical, SCAQMD, and FracFocus datasets is shown in Figure 3.4. The Irrigation 13267 dataset was left out of this analysis due to its full overlap with the AB 1328 and SCAQMD datasets. Overall, 314 chemical additives (51%) reported with CASRN were unique to a single dataset; 138 chemical additives were reported in two datasets; 107 chemical additives were reported in three datasets; and 71 chemical additives were reported in all four datasets. Both the AB 1328 and SCAQMD datasets contained more than 100 unique chemical additives (with CASRN) that were not reported in other datasets. Significant differences in chemical additive usage between the four datasets may in part be due to the variety of activities covered in each dataset, and the geographic regions covered. FracFocus only includes hydraulic fracturing, DOGGR chemical includes well stimulations (including hydraulic fracturing), SCAQMD includes routine O&G activities (well drilling, well completion, and well reworks) and well stimulation (hydraulic fracturing and matrix acidizing), and AB 1328 includes petroleum production (including EOR), treatment, and transportation processes.

The majority of chemical additives reported in the DOGGR chemical and FracFocus datasets were used in both datasets. This similarity is expected due to both datasets covering hydraulic fracturing operations statewide. A portion of the chemical additives unique to the FracFocus dataset are likely due to the longer timeframe covered by the FracFocus dataset (2011-2018), compared to the DOGGR chemical dataset (2014-2018).

Due to the number of chemical additives unique to each dataset, future studies of individual datasets may be prudent to determine specific hazards associated with regional O&G development.

Data regarding frequency of use and the mass of chemical additive used is incomplete. The DOGGR chemical, FracFocus, and SCAQMD datasets have available mass and frequency of use data; however, both the AB 1328 and Irrigation 13267 datasets do not have any associated mass or frequency of use data. Despite the limitations of these two datasets (AB 1328 and Irrigation 13267), it is unclear how representative an analysis of mass and frequency of chemical additive use based solely on three datasets (DOGGR chemical, FracFocus, and SCAQMD) would be, given the significant overlap in reported chemical usage between all five datasets.

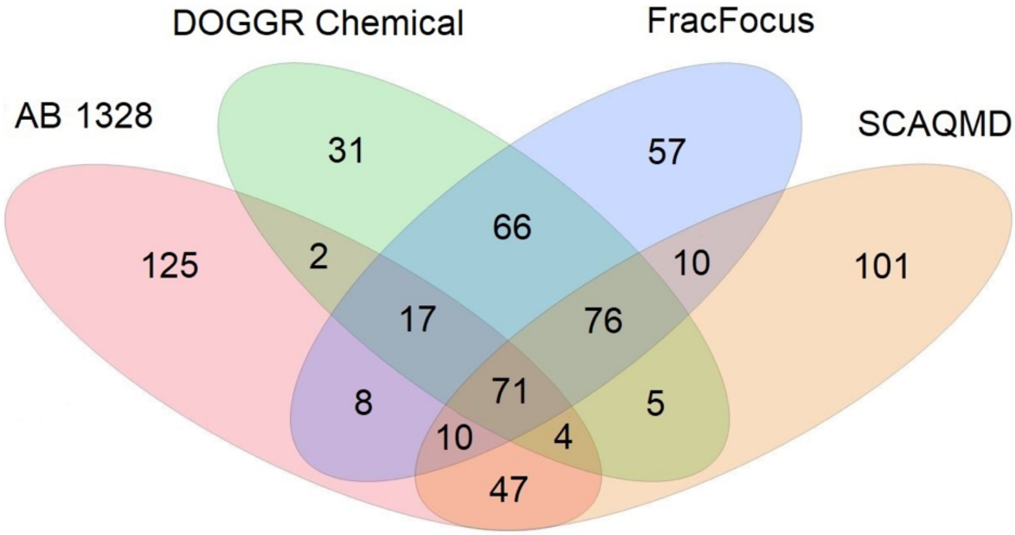

Figure 3.4. Venn diagram showing overlap in reported chemical additive usage between SCAQMD, AB 1328, DOGGR chemical, and FracFocus datasets. The Irrigation 13267 dataset was not included due to its similarity to the AB 1328 dataset. Only chemical additives with CASRN are included in this analysis.

3.4.2.3. Characterization of Acute Toxicity

Acute toxicity tests represent short-term cases of extreme chemical exposure, where the outcome is measured by the death of the test animal. Acute toxicity data are generally considered less useful than chronic toxicity data for assessing health outcomes from non-occupational settings. However, acute toxicity data are still useful for comparing chemicals to one another and identifying chemicals that are clearly hazardous (Shonkoff et al., 2015a).

Toxicity values are typically reported for pure compounds. In practice, most chemical additives are mixed on site or pre-mixed chemical formulations are provided by suppliers for use in O&G operations. Through normal O&G operations, these chemical mixtures can react with other chemicals in the subsurface in conditions characterized by high temperature and pressure. If exposure does occur, whether via ingestion or inhalation, it is unlikely that it will be limited to a single chemical compound. Additionally, standard toxicity tests do not account for chemical interactions, the generation of daughter and degradation byproducts, or the synergistic effects of complex mixtures of chemical additives used in O&G operations and chemicals endemic to hydrocarbon reservoirs. An assessment of the toxicity of chemical mixtures is beyond the scope of this report. However, such an assessment is a critical area of inquiry to determine potential chemical hazards and risks in O&G development in general and to inform the management, disposal, and reuse of produced water more specifically.

Overall, 450 chemical additives (71%) with valid CASRN had at least one toxicity value between all characterized categories of acute toxicity (oral, inhalation, and aquatic) (Figure 3.5). 142 chemical additives were classified as within the Globally Harmonized System of Classification and Labelling of Chemicals (GHS; United Nations, 2011) category 1, the most toxic category, and another 82 chemical additives were classified as GHS category 2. Of chemical additives with CASRN, 29% could not be classified according to acute toxicity. Acute toxicity for standard aquatic test species (*Daphnia magna*, fathead minnow, rainbow trout, green algae) was the most commonly available, followed by oral, and then inhalation toxicity. Complete lists of chemical additives classified as GHS categories 1 and 2 for acute toxicity can be found in Appendix 3.2.

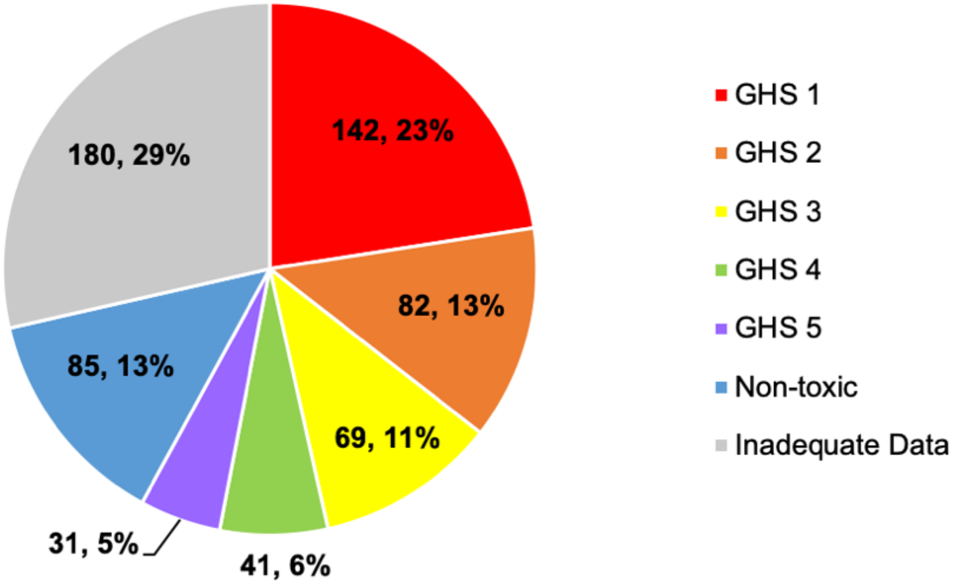

Figure 3.5. Combined acute oral, inhalation, and aquatic toxicity data for chemical additives with CASRN from all datasets. The lowest (most conservative) GHS value between all test species was selected. The first number represents the number of chemical additives with CASRN in each category.

Acute Oral Toxicity

Acute oral toxicity was classified for standard mammalian test species (rat, mouse, and rabbit). Overall, 312 (49%) chemical additives with valid CASRN had at least one oral toxicity value between all characterized mammalian test species (Figure 3.6). Twelve chemical additives were categorized as GHS category 2, and no chemical additives were identified as GHS category 1, the most toxic category. Data availability was highest for rats; if any acute oral toxicity testing was done, tests were likely done on rats (Appendix 3.2). An additional 90 chemical additives (14%) exceeded the maximum range for GHS Category 5 and are considered non-toxic. Just over 50% of all chemical additives with CASRN did not have adequate data to characterize acute oral toxicity.

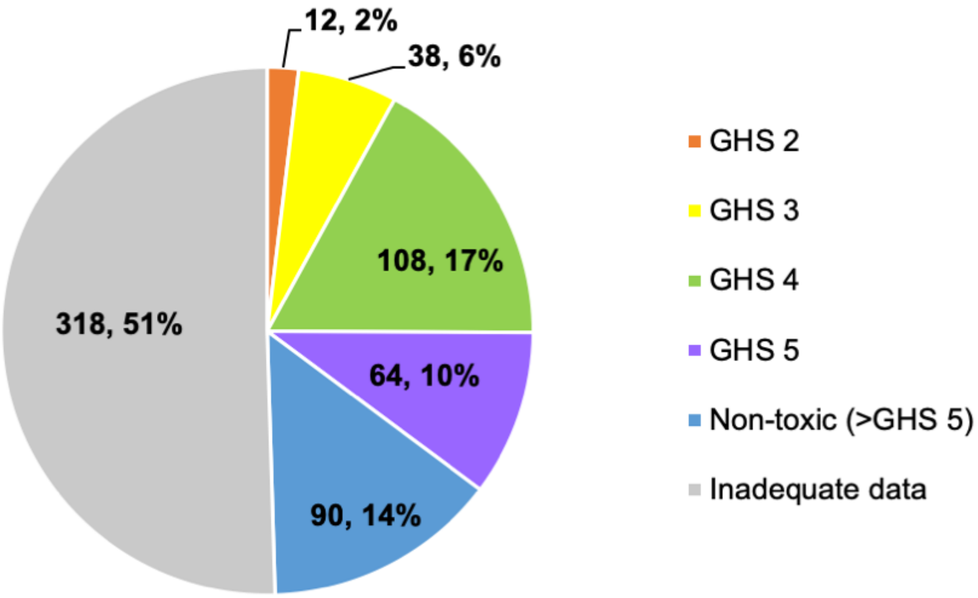

Figure 3.6. Availability of acute oral mammalian toxicity data according to GHS category for all datasets. The first number represents the number of chemical additives with CASRN in each category.

Acute Inhalation Toxicity

Acute mammalian inhalation toxicity data were classified for rats and mice. Only 85 chemical additives (13%) reported with valid CASRNs had available acute inhalation toxicity data (Figure 3.7). Twenty-one of these chemical additives (4%) are classified as GHS category 1 or 2. Due to the general lack of acute inhalation data, an attempt was made to categorize all available acute inhalation data that did not strictly adhere to GHS category guidelines using a floor level estimate. An additional 28 chemical additives were classified according to these estimated floor level GHS values (Figure 3.8). When floor level GHS values were taken into consideration, a total of 113 chemical additives (18%) with CASRN were characterized for acute inhalation toxicity (Figure 3.9), with a total of 28 chemicals classified as GHS category 1 or 2. Despite efforts to categorize all available data, significant data gaps remain because 82% of all chemical additives with CASRN could not be categorized according to acute inhalation toxicity. Similar to acute oral toxicity, acute inhalation data availability was highest for rats (Appendix 3.2).

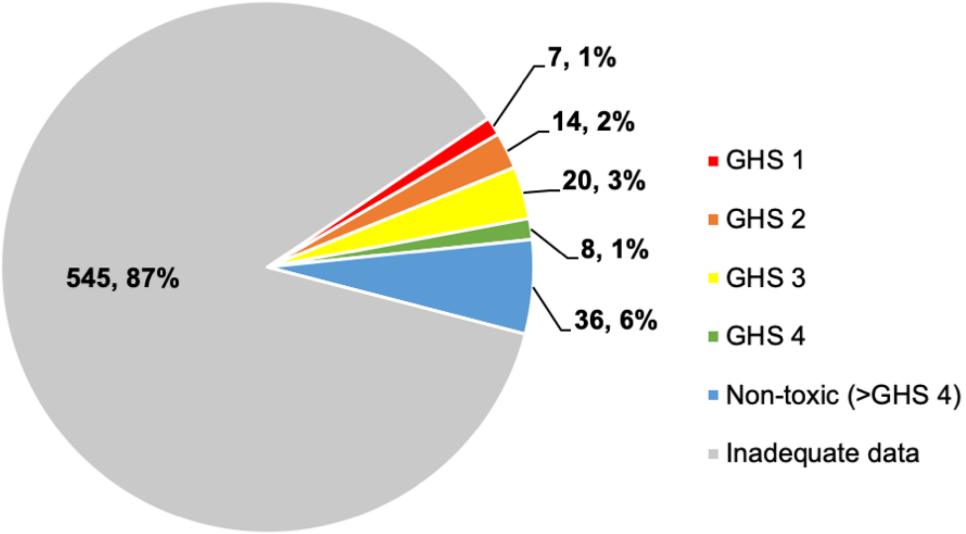

Figure 3.7. Availability of acute inhalation mammalian toxicity data according to GHS category for all datasets. The first number represents the number of chemical additives with CASRN in each category.

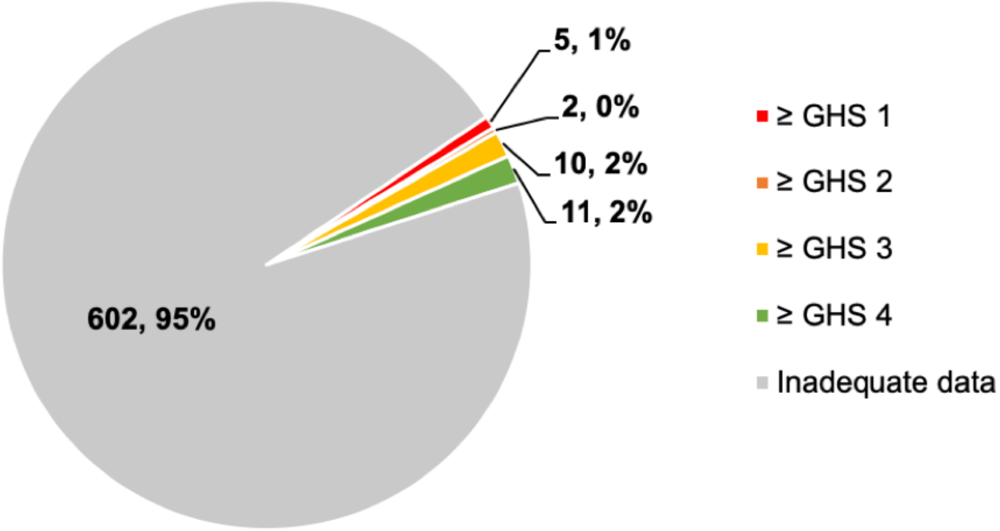

Figure 3.8. Acute mammalian inhalation toxicity data estimated from toxicity ranges according to GHS category for all datasets. This is based on the floor level analysis using toxicity values listed as a range, and provides a very conservative estimate of inhalation GHS. The first number represents the number of chemical additives with CASRN in each category.

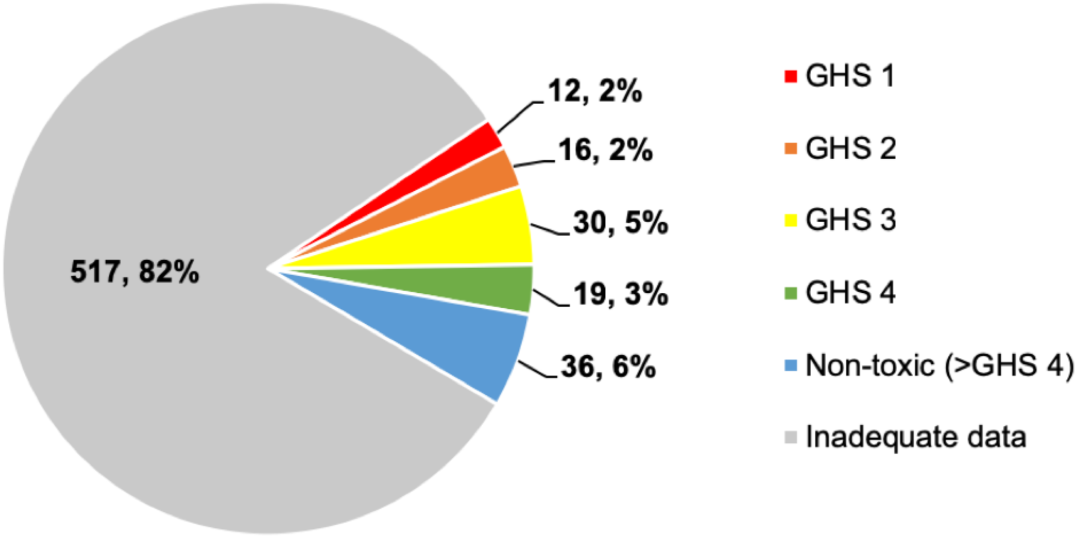

Figure 3.9. Combined acute mammalian inhalation toxicity data and estimated "floor level" analysis from toxicity ranges according to GHS category for all datasets. The first number represents the number of chemical additives with CASRN in each category.

Environmental Toxicity

Environmental toxicity is assessed by exposing test species to varying concentrations of a chemical over a specific time period and observing the effects. Standard aquatic test species for environmental toxicity typically include crustaceans, fish, and aquatic plants. Although aquatic toxicity tests are standardized, the toxicity results for a given chemical can vary greatly between species (Stringfellow et al., 2015).

Acute aquatic toxicity was classified for standard aquatic species (*Daphnia magna*, fathead minnow, trout, and green algae). Overall, 414 chemical additives (66%) with valid CASRN had at least one toxicity value between all characterized test species. 134 chemical additives (21%) were categorized as GHS category 1, and 69 chemical additives were categorized as GHS category 2 (Figure 3.10). This represents the highest number of toxic chemical additives between the three types of acute toxicity. Aquatic toxicity needs to be interpreted carefully, as standard test species may not be an accurate representation of aquatic species native to a study area. A comparison of acute aquatic toxicity values for alkyl dimethylbenzyl ammonium chloride (CASRN: 68424-85-1), a commonly used biocide in hydraulic fracturing operations, using a variety of standard test species and species native to California, revealed that toxicity values can vary by up to two orders of magnitude depending on the species of fish (Stringfellow et al., 2015).

As evident in the breakdown of aquatic toxicity data by species (Appendix 3.2), data availability was highest for green algae and contributed significantly to the overall GHS counts; however, this was due to the fact that all green algae toxicity data were calculated using U.S. EPA EPISuite^{TM} ECOSAR^{TM} v1.11 module. Experimental toxicity data for green algae was not assessed but is expected to be significantly less available compared to all other test species. Only 34% of all chemical additives with CASRN did not have adequate data to characterize acute aquatic toxicity.

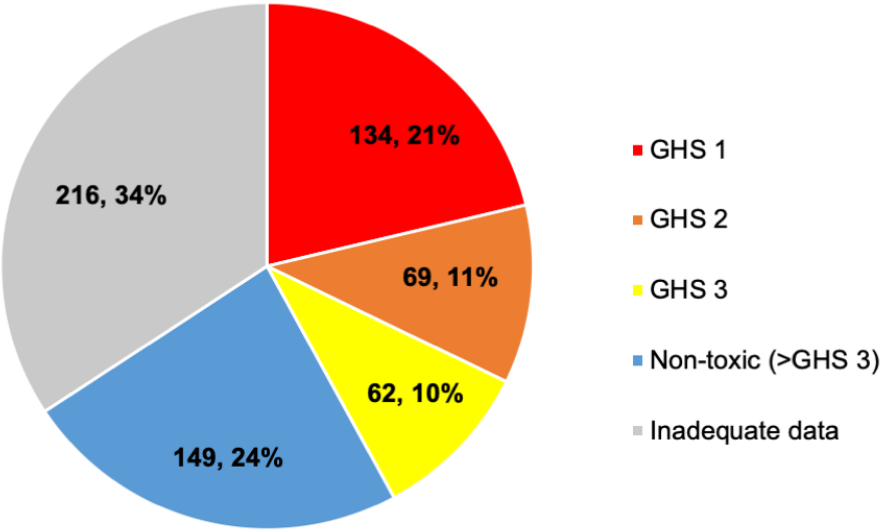

Figure 3.10. Availability of acute aquatic toxicity data according to GHS category for all datasets. The first number represents the number of chemical additives with CASRN in each category.

3.4.2.4. Characterization of Chronic Toxicity Data

Chronic toxicity data, while generally less available than acute toxicity data, are important to determine risks associated with repeated exposure. Common endpoints for chronic toxicity studies include increased frequency of cancer and tumors, decreased lifespan, and adverse reproductive, developmental, neurological, and respiratory impacts. Most chronic toxicity data are collected using animal studies; however, a few chemicals have human-based chronic data, often as a result of accidents, occupational exposure, or unregulated release of chemicals.

Similar to evaluations of acute toxicity, chronic toxicity values are typically reported for pure compounds. In practice, most chemical additives are mixed on site or pre-mixed chemical formulations are provided by suppliers for use in O&G operations. Standard toxicity tests do not account for chemical interactions in complex mixtures used in O&G operations. Assessing chemical mixtures is beyond the scope of this chapter.

Chronic toxicity data were available for 111 chemical additives (18%) reported with valid CASRNs (Figure 3.11). Non-cancer chronic oral toxicity and inhalation toxicity data were available for 91 chemicals and 54 chemical additives, respectively. Cancer-based chronic toxicity values were less available than non-cancer values. Oral slope factors and inhalation unit risk factors (both estimates of increased cancer risk from oral or inhalation exposure, respectively) were only available for 17 chemical additives. An additional 43 chemical additives without chronic toxicity data were characterized using occupational exposure limits from OSHA, NIOSH, and the Association Advancing Occupational and Environmental Health (ACGIH). Major data gaps remain as 75% of all chemical additives with CASRN have no available chronic toxicity data. Complete lists of chronic reference values (RfVs), slope factors, unit risk factors, and occupational exposure values can be found in Appendix 3.2.

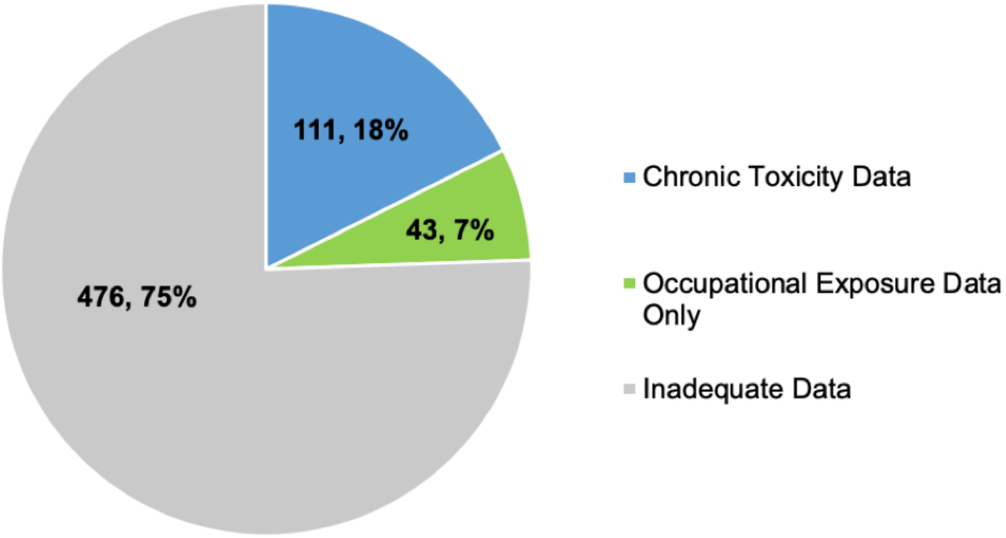

Figure 3.11. Availability of chronic toxicity data for all datasets. The first number represents the number of chemical additives with CASRN in each category.

3.4.2.5. Biodegradability

A key factor in evaluating the risk of chemical exposure is how persistent a chemical is in the environment. Biodegradation is a major mechanism for environmental attenuation. Chemicals that are readily biodegradable typically do not persist for long periods of time in the environment. Chemical additives that are resistant to biodegradation are more likely to accumulate in the environment and are more likely to be subject to exposure pathway transport mechanisms. Biodegradable chemicals are expected to have reduced risk of chemical exposure for pathways that occur over the course of days or months. However, the impact of biodegradation is expected to be negligible for exposure pathways that take place over the course of seconds to minutes.

Similar to acute and chronic toxicity, biodegradability is typically reported for pure compounds. In practice, most chemical additives are mixed on site or pre-mixed chemical formulations are provided by suppliers for use in O&G operations. Although standard testing accounts for simple mixtures of similar compounds that are inseparable, such as hydrocarbon distillates, it does not account for chemical interactions (e.g. bacterial inhibition) in complex mixtures used in O&G operations. Commonly used chemical additives include biocides, such as isothiazolones (e.g. 2-Methyl-3(2H)-isothiazolone) and quaternary ammonium compounds (QACs), which are added to prevent bacterial growth and, among other things, subsequent biodegradation of chemical additives. Thus, biocides are generally expected to be resistant to biodegradation, and mixtures that contain biocides may prevent the degradation of otherwise highly biodegradable chemicals in the environment. As discussed previously, assessing chemical mixtures and interactions with respect to biodegradability is beyond the scope of this report.

Experimental biodegradation data were found for 34% of chemical additives identified by CASRN, with an additional 21% of chemical additives characterized using computational estimates from U.S. EPA EPISuite™ BIOWIN™ module (U.S. EPA, 2012). Inorganic compounds were not evaluated for biodegradability.

Overall, 35% of chemical additives with CASRN are readily or inherently biodegradable, and as a result, are not expected to persistent in the environment. An additional 20% of additives were classified as not readily biodegradable, and 21% of additives had no available experimental or computational data to categorize them according to the Organisation for Economic Co-operation and Development (OECD) biodegradability standards (Figure 3.12). A complete list of chemical additives classified as not readily biodegradable (according to OECD standards) can be found in Appendix 3.2. Due to the large fraction of chemical additives that cannot be classified according to biodegradability, and the lack of data concerning biodegradability of chemical mixtures, there is inadequate data to predict the environmental persistence of chemical mixtures used in O&G operations.

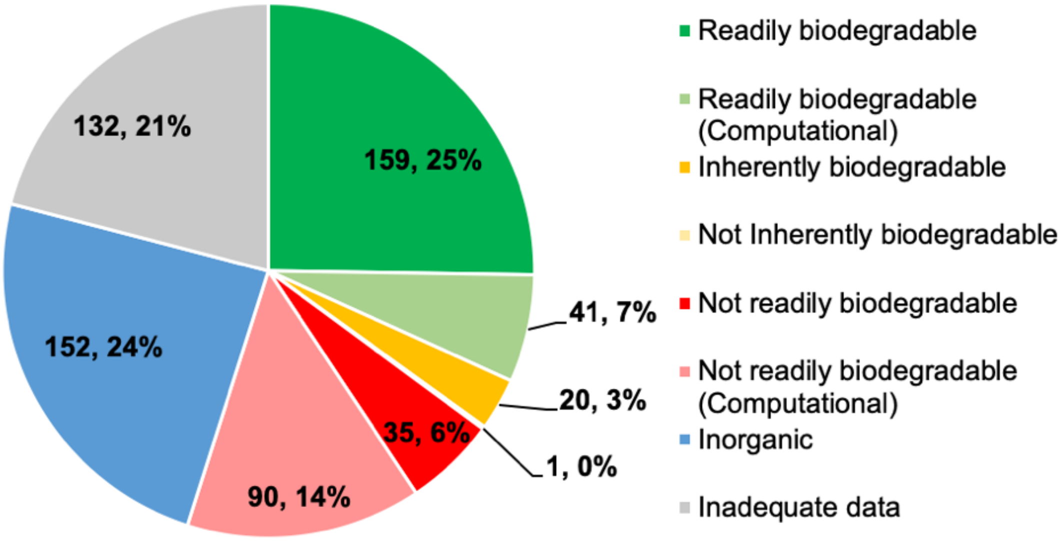

Figure 3.12. Available biodegradability data according to OECD standards for all datasets. The first number represents the number of chemical additives with CASRN in each category.

3.4.2.6. Carcinogenicity

Various environmental factors can contribute to increased risks of cancer in humans, including exposure to carcinogenic chemicals through ingestion, inhalation, or contact with the skin. For most carcinogens, there are no established safe exposure levels (Whittaker et al., 2017).

Chemical additives were screened for carcinogenicity using the International Agency for Research on Cancer (IARC) Monographs on the Evaluation of Carcinogenic Risks to Humans, the U.S. Department of Health and Human Services National Toxicity Program 14th Report on Carcinogens, and California's Proposition 65 (Prop 65) list of chemicals known to the state of California to cause cancer or reproductive toxicity (CalEPA, 2018; IARC, 2018; U.S. DHHS, 2016).

Chemical substances in the National Toxicity Program 14th Report on Carcinogens are identified as either known human carcinogens, where sufficient evidence for carcinogenicity in human studies is available, or reasonably anticipated to be a human carcinogen (RAHC), where there is limited evidence in human studies, sufficient evidence in animal studies, or the substance is in the same structurally related class as other identified carcinogens. Chemical substances identified by California's Prop 65 are listed as either causing cancer or developmental toxicity. The IARC classifies chemicals into 5 groups:

Group 1: Carcinogenic to humans.

Group 2A: Probably carcinogenic to humans.

Group 2B: Possibly carcinogenic to humans.

Group 3: Not classifiable as to its carcinogenicity to humans.

Group 4: Probably not carcinogenic to humans.

For the purposes of this report, only Groups 1, 2A, and 2B were considered carcinogens. Chemicals that were classified in Group 3 and 4 were not considered unless they were also identified on another cancer screening list.

Chemicals identified as carcinogens or probable carcinogens indicate potential hazard; actual cancer risk depends on many factors including levels of exposure, potency of the carcinogen, and individual susceptibility (U.S. DHHS, 2016). Chemicals identified as carcinogens were not ranked according to potency by any of the referenced agencies.

Overall, 47 chemical additives (7%) with CASRN were identified on cancer screening lists. A total of 36 chemical additives were identified by IARC as carcinogenic or probably/possibly carcinogenic (IARC Groups 1, 2A, and 2B). An additional 35 chemical additives were classified as IARC Group 3. Of the 40 chemical additives on California's Prop 65 list, 33 were listed for carcinogenicity and seven were listed for developmental toxicity. A list of all chemical additives identified as confirmed or probable human carcinogens or causing developmental toxicity can be found in Appendix 3.2.

In addition to these chemical additives, the three major forms of crystalline silica (cristobalite, quartz, and tridymite [CASRN: 14464-46-1, 14808-60-7, 15468-32-3]) are classified as known carcinogens by the National Toxicity Program and Prop 65; however, only cristobalite and quartz are classified as known carcinogens by the IARC. The IARC monographs specifically classify only the cristobalite and quartz forms of silica dust. Although toxicity data relevant to tridymite is mentioned in relevant IARC monographs, tridymite is not given a final IARC group classification (IARC, 2012).

3.4.2.7. Air Pollutants

The federal code of regulations identifies hazardous air pollutants (HAPs) as chemicals "known to be, or those that may reasonably be anticipated to be carcinogenic, mutagenic, teratogenic, neurotoxic, which cause reproductive dysfunction, or which are acutely or chronically toxic or [cause] adverse environmental effects whether through ambient concentrations, bioaccumulation, deposition, or otherwise" (U.S. Code, 1990). Air pollutants can pose health risks to O&G industry workers as well as to residents living nearby active O&G development and ancillary infrastructure (Adgate et al., 2014; Garcia-Gonzales et al., 2019; Shonkoff et al., 2015a, 2015b). Of the range of chemical additives used throughout industry, this section focuses on chemical additives used in O&G operations. Criteria air pollutants such as ozone, particulate matter, nitrogen dioxide (NO_2), and sulphur dioxide (SO_2) are often emitted from routine activities surrounding O&G production, and although important, are not necessarily specific to chemical additives and thus were not evaluated.

Chemical additives used in O&G operations in California were screened for air pollutants using the Clean Air Act List of Hazardous Air Pollutants, CARB Hot Spots Program, and CARB Toxic Air Contaminants (TAC) lists (U.S. Code, 1990; CARB, 2010).

The Clean Air Act (CAA) identifies 187 hazard air pollutants. Of these, 17 consist of broad chemical categories including cyanide compounds, fine mineral fibers, glycol ethers, coke oven emissions, polycyclic organic matter, and various metal compounds. Polycyclic organic matter (POM) is defined in the Code of Federal Regulations (CFR) as organic compounds that contain more than one benzene ring and have boiling points greater than 100°C (U.S. Code, 1990). POM has been further defined in U.S. EPA documents as having two or more fused aromatic rings, with the exception of some polyhalogenated compounds. POM includes the following groups of compounds: polycyclic aromatic hydrocarbons (PAHs), aza arenes, imino arenes, carbonyl and dicarbonyl arenes, oxa arenes and thia arenes, hydroxy carbonyl arenes, and polyhalo compounds (U.S. EPA, 1975; U.S. EPA, 1998). It is unclear if the U.S. EPA definition of POM is definitive, as other regulatory agencies, such as the California Air Resources Board (CARB), identify compounds that that fit the CFR definition, but not the U.S. EPA definition as POM (CARB, 2007).

Glycol ethers are defined as mono- and di-ethers of ethylene glycol, diethylene glycol, and triethylene glycol with the general formula $R\text{-}(OCH_2CH_2)_n\text{-}OR'$, where (U.S. EPA, 2000):

n = 1, 2, or 3

R = alkyl C7 or less; or phenyl or alkyl substituted phenyl;

R’ = H or alkyl C7 or less; or OR’ consisting of carboxylic acid ester, sulfate, phosphate, nitrate, or sulfonate

Additional guidance on identifying glycol ethers is provided by the U.S. EPA (2000).

CARB defines toxic air contaminants (TACs) as any “air pollutant which may cause or contribute to an increase in mortality or in serious illness, or which may pose a present or potential hazard to human health” and includes all hazardous air pollutants (CARB, 2010). TACs are divided into categories including:

Category 2a:	Substances identified as TACs, known to be emitted in California, with one or more health values under development.
Category 2b:	Substances not identified as TACs, known to be emitted in California, with one or more health values under development.
Category 3:	Substances known to be emitted in California and are nominated for development of health values or additional health values.
Category 4a:	Substance identified as TACs, known to be emitted in California and are to be evaluated for entry into Category 3.
Category 4b:	Substance not identified as TACs, known to be emitted in California and are to be evaluated for entry into Category 3.
Category 5:	Substance identified as TACs, and not known to be emitted from stationary source facilities in California based on information from the AB 2588 Air Toxic "Hot Spots" Program and the California Toxic Release Inventory.

The CARB "Hot Spots" Program maintains a list of "substances for which emissions must be quantified". Chemicals on this list may pose a threat to public health when present in the air and emissions of such substances must be reported (CARB, 2007).

Overall, 75 (12%) of the chemical additives with valid CASRN were identified on air pollution screening lists. A total of 51 chemical additives were identified as CAA hazardous air pollutants. Nine chemical additives were classifiable as POM using both CFR and U.S. EPA definitions. Two chemical additives were classifiable as POM using only the CFR definition. Three additional chemical additives may possibly be considered POM due to their chemical structures; however, boiling point data were unavailable for further classification. These chemicals are naphthalenesulfonate-formaldehyde condensate, sodium salt (CASRN: 9008-63-3); sodium polynaphthalenesulfonate (CASRN: 9084-06-4); and C.I. pigment red 5 (CASRN: 6410-41-9). Seventy chemical additives were identified on the California toxic air contaminants list; however, 17 fell under categories 2b or 4b and, while not classified as toxic air contaminants, are under review or have health values under development. A complete list of chemical additives identified on air pollution screening lists is provided in Appendix 3.2.

3.4.2.8. Endocrine Disrupting Compounds

The endocrine system is vital for hormone production, reproduction, and normal healthy development in both humans and wildlife. An endocrine disrupting compound (EDC) is any substance that disrupts or alters the endocrine system and causes negative health effects to an organism or its offspring. EDCs can disrupt endocrine systems even when present in very low environmental concentrations (NTP, 2011).

The European Commission maintains a priority list of possible EDCs for evaluation. Chemical substances on this list are classified into four categories based on evidence of endocrine disrupting activity in humans and wildlife (DHI Water & Environment, 2007):

Category 1:	Evidence of endocrine disrupting activity using intact animals.
Category 2:	Some in vitro evidence of biological activity relating to endocrine disruption.
Category 3a:	No evidence of endocrine disrupting activity.
Category 3b:	Insufficient or no data available.

Three chemical additives with valid CASRN were identified on the European Commission list of EDCs. Although only two were rated as category 1 for human health, all three received a combined rating of Category 1 (see Table 3.7). In addition to the three additives rated by the European Commission, 75 chemical additives with CASRN were identified as potential EDCs by The Endocrine Disruption Exchange (TEDX). TEDX maintains a list of chemicals that demonstrate effects on endocrine signaling in at least one scientific study (TEDX, 2018). Criteria for adding chemical substances to the TEDX list of potential endocrine disruptors is less stringent than most government agencies and research organizations. As a result, chemical additives identified on the TEDX list are provided in Appendix 3.2 solely as a reference, and inclusion on the TEDX list does not mean a chemical is recognized as an EDC by government or regulatory agencies.

Table 3.7. Chemical additives identified as endocrine disrupting compounds by the European Commission.

Chemical Name	CASRN	Human Health Category	Wildlife Category	Combined Category
Boric acid	10043-35-3	1	2	1
Poly(oxy-1,2-ethandiyl), a-(nonylphenyl)-w-hydroxy-	9016-45-9	2	1	1
Octamethylcyclotetrasiloxane	556-67-2	1	3b	1

3.4.2.9 Other Priority Screening Lists

We screened the list of chemical additives for more potential hazards using other priority lists including: the European Union (EU) Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Substances of Very High Concern (SVHC) Candidate List, Authorization List, and Restricted Substances List; the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) Priority Action Chemical List, Substances of Possible Concern List, Posing Little or No Risk (PLONOR) List; the Norway and U.K. National Lists of Candidates for Substitution; and the EPA Contaminant Candidate List (CCL) 4.

Results are shown in Table 3.8. Overall, 21 chemical additives (3%) with valid CASRNs were identified on the OSPAR Substance of Possible Concern List, the EU REACH SVHC Candidate List, or the EPA CCL4. Eight chemical additives are identified as candidates for the SVHC list. Chemicals are typically placed on the SVHC list if they are classified as persistent, bioaccumulative, and toxic, or very persistent and very bioaccumulative (PBT/vPvB), or if they are identified as a carcinogen, reproductive mutagen, or endocrine disruptor (European Chemicals Agency, 2015). Chemicals are selected for OSPARs Substances of Possible Concern list for reasons similar to those of the EU SVHC list. Eleven chemical additives are identified on the EPA CCL4. Chemical substances on the EPA CCL4 are chemicals which do not have any primary drinking water regulations but are known or anticipated to occur in public drinking water systems (U.S EPA, 2015b). Chemical substances on the CCL4 have been screened for public health concern and occurrence in water systems and are under consideration for regulation (U.S. EPA, 2015b). This list includes pathogens, pharmaceuticals, toxins, pesticides, industrial chemicals, and pesticides.

None of the chemical additives identified by CASRN appeared on the EU REACH SVHC Authorization List, Restricted Substances List, or the OSPAR Priority Action Chemical List or the Norway and U.K. National Lists of Candidates for Substitution.

Another 77 chemical additives identified by CASRN were identified on the OSPAR list as Posing Little or No Risk (PLONOR) to the environment. It should be noted that OSPAR is focused on preventing negative impacts to the marine environment, and as a result, many of the chemical additives on the PLONOR list are minerals, common salts, carbonates, or chemicals classified as readily biodegradable (OSPAR Commission, 2013). Although these chemical additives may not pose any risk to marine environments, they can still be hazardous to human health and terrestrial and aquatic ecosystems. For example, naturally-occurring minerals such as crystalline silica are known carcinogens and can be dangerous if inhaled, but pose little risk to marine environments. As such, inclusion in the PLONOR list does not prevent a chemical additive from being a potential chemical of concern. A complete list of these 77 chemical additives can be found in Appendix 3.2.

Table 3.8. Chemical additives identified on national and international priority lists for all datasets.

Chemical Name	CASRN	OSPAR Substance of Possible Concern	EU Candidate List of Substances of Very High Concern Candidate List	EPA CCL4
Bis(isopropyl)naphthalene	38640-62-9	X		
D-limonene	5989-27-5	X		
Poly(oxy-1,2-ethandiyl), a-(nonylphenyl)-w-hydroxy-	9016-45-9	X		
Acrylamide	79-06-1		X	
Boric acid	10043-35-3		X	
Boron oxide	1303-86-2		X	
Boron sodium oxide	1330-43-4		X	
Cadmium	7440-43-9		X	
Cobaltous acetate	71-48-7		X	
Formamide	75-12-7		X	
Sodium tetraborate decahydrate	1303-96-4		X	
1,4-Dioxane	123-91-1			X
Acetaldehyde	75-07-0			X
Acrolein	107-02-8			X
Benzyl chloride	100-44-7			X
Ethylene glycol	107-21-1			X
Ethylene oxide	75-21-8			X
Formaldehyde	50-00-0			X
Methanol	67-56-1			X
Methyl chloride (chloromethane)	74-87-3			X
n-Butyl alcohol	71-36-3			X
Quinoline	91-22-5			X

3.4.3. Chemical Properties for Datasets Pertinent to Agricultural Reuse of Produced Water

In California's San Joaquin Valley, O&G production occurs in close proximity to large agricultural operations. In some water districts, such as the Cawelo Water District and the North Kern Water Storage District, oilfield-produced water is reused for agricultural irrigation (Cawelo Water District, 2014; CVRWQCB, 2012; CVRWQCB, 2016). Although this practice has been occurring since the 1990s, the effects of continued use of produced water on food crops is understudied (Shonkoff et al., 2016). The CVRWQCB has developed the AB 1328 (Limón, 2017) and Irrigation 13267 datasets in part to investigate concerns surrounding the reuse of produced water for irrigation of food crops and its potential for other uses such as livestock watering and groundwater recharge. This section will analyze the AB 1328 and Irrigation 13267 datasets using the same methodology as the previous sections.

In total, 365 chemical additives were identified in the AB 1328 and Irrigation 13267 datasets. Eighty chemical additives (22%) were reported as proprietary information or trade secrets without CASRN and could not be further analyzed. Only 285 chemical additives (78%) were identified by unique CASRN. All further analyses in this section will pertain only to chemical additives identified by CASRN, unless explicitly stated otherwise. It was previously shown in this chapter that, with one exception, all chemical additives with CASRNs used in Irrigation 13276 are also used in AB 1328 (Figure 3.4). When compared to the SCAQMD, FracFocus, and Division datasets, 124 chemical additives (44%) with CASRN used in AB 1328 are unique to the dataset (Figure 3.5).

3.4.3.1. Acute Toxicity Data

Overall, 221 chemical additives (78%) with valid CASRN had at least one toxicity value between all characterized categories of acute toxicity (oral, inhalation, and aquatic) (Figure 3.13).

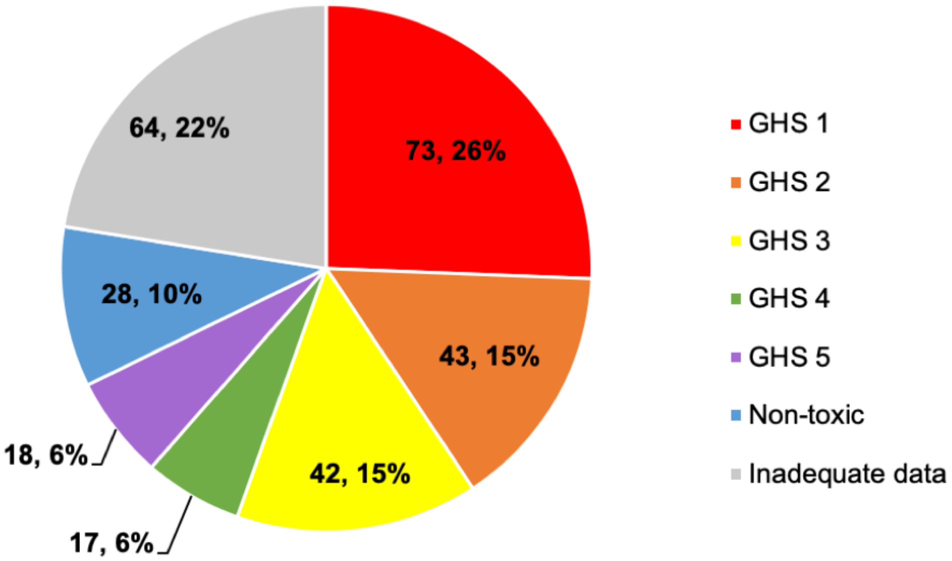

Figure 3.13. Combined acute oral, inhalation, and aquatic toxicity data for chemical additives with CASRN used in oil fields that send produced water for irrigation of food crops. The lowest (most conservative) GHS value between all test species was selected for the overall count. The first number represents the number of chemical additives with CASRN in each category.

A total of 167 chemical additives (58%) with valid CASRN had at least one acute oral toxicity value between all characterized test species (Figure 3.14). Eight chemical additives were categorized as GHS 2, and no chemicals were identified as GHS 1. There were 43 chemical additives (15%) that exceeded the maximum range for GHS category 5 and are considered non-toxic. Data availability was slightly better for the agricultural datasets at 58%, compared to 49% for all California datasets.

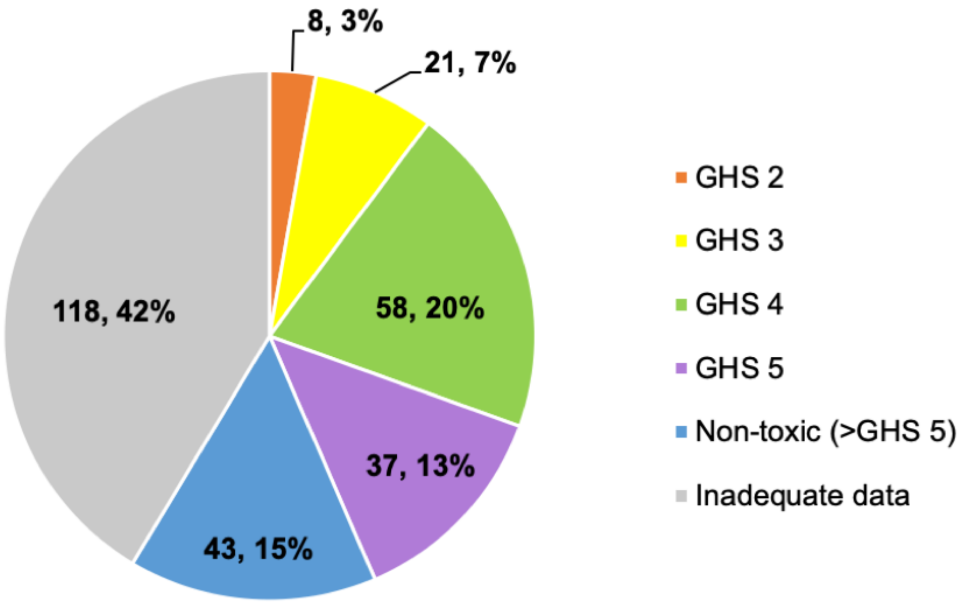

Figure 3.14. Availability of acute oral mammalian toxicity data according to GHS category for chemical additives with CASRN used in oil fields that send produced water for irrigation of food crops. The first number represents the number of chemical additives with CASRN in each category.

After floor level estimates (defined in Appendix 3.2) were taken into account, only 75 chemical additives (26%) with valid CASRNs could be classified according to GHS using acute inhalation toxicity data (Figure 3.15). Eighteen of these chemical additives are classified as GHS category 1 or 2. Despite efforts to categorize all available data, significant data gaps remain because 74% of all chemical additives with CASRN could not be categorized according to acute inhalation toxicity.

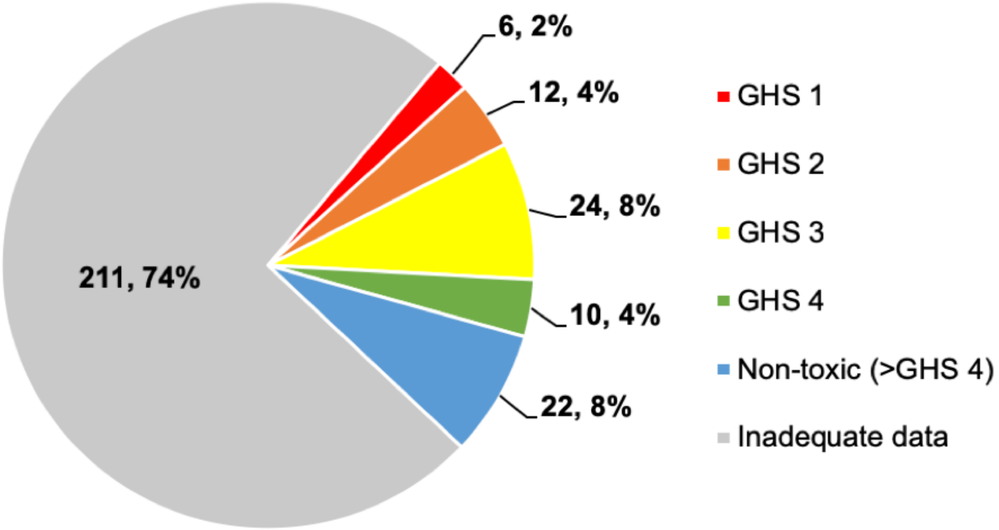

Figure 3.15. Combined acute mammalian inhalation toxicity data and estimated "floor level" analysis from toxicity ranges according to GHS category for chemical additives with CASRN used in oil fields that send produced water for irrigation of food crops. The first number represents the number of chemical additives with CASRN in each category.

A total of 207 chemical additives (73%) with CASRN were categorized for acute aquatic toxicity (Figure 3.16). Seventy chemical additives (25%) were categorized as GHS 1, and an additional 33 chemical additives were categorized as GHS 2. This represents the highest number of toxic chemical additives between the three types of acute toxicity. Only 27% of chemical additives with CASRN could not be classified according to acute aquatic toxicity.

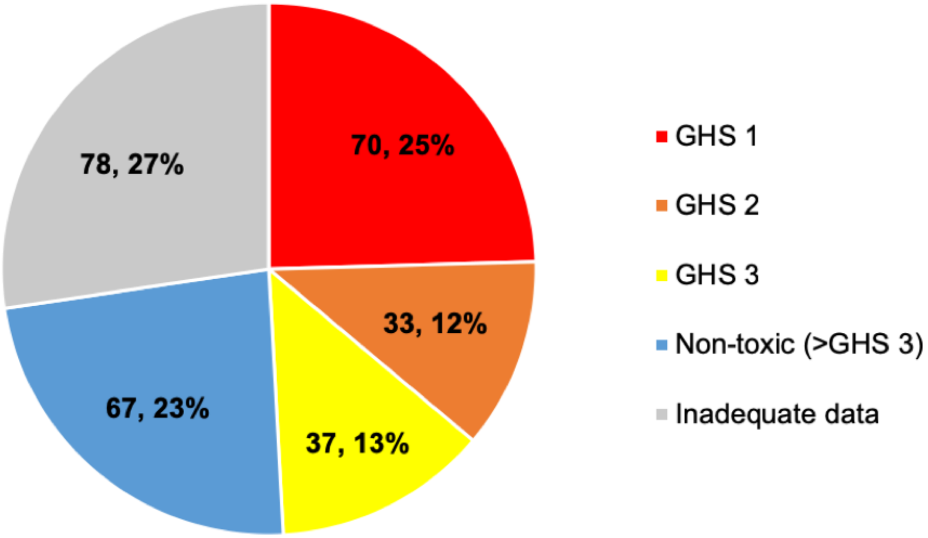

Figure 3.16. Available acute aquatic toxicity GHS values for chemical additives with CASRN used in oil fields that send produced water for irrigation of food crops. The first number represents the number of chemical additives with CASRN in each category.

General trends regarding acute toxicity remained the same for both the analysis of the agricultural datasets and all California datasets. Acute oral and inhalation data were most commonly available for rats, and aquatic toxicity data were most available for green algae. Large data gaps remain for acute inhalation toxicity; however, as a whole, acute toxicity data were slightly more available for agricultural datasets compared to the other California datasets (Appendix 3.2).

3.4.3.2. Chronic Toxicity Data

A total of 66 chemical additives (23%) with CASRN in the agricultural datasets had available chronic toxicity data. Non-cancer chronic oral toxicity and inhalation toxicity data were available for 56 and 41 chemical additives, respectively. Cancer-based chronic toxicity values were less available than non-cancer values. Oral slope factors and inhalation unit risk factors were only available for ten and 12 chemical additives, respectively. An additional 23 chemical additives without chronic toxicity data were characterized using occupational exposure limits from OSHA, NIOSH, and ACGIH. Chronic toxicity is slightly more available for agricultural datasets compared to all California datasets; however, there remains a significant data gap because 69% of all agricultural chemical additives with CASRN lack chronic toxicity data (Figure 3.17).

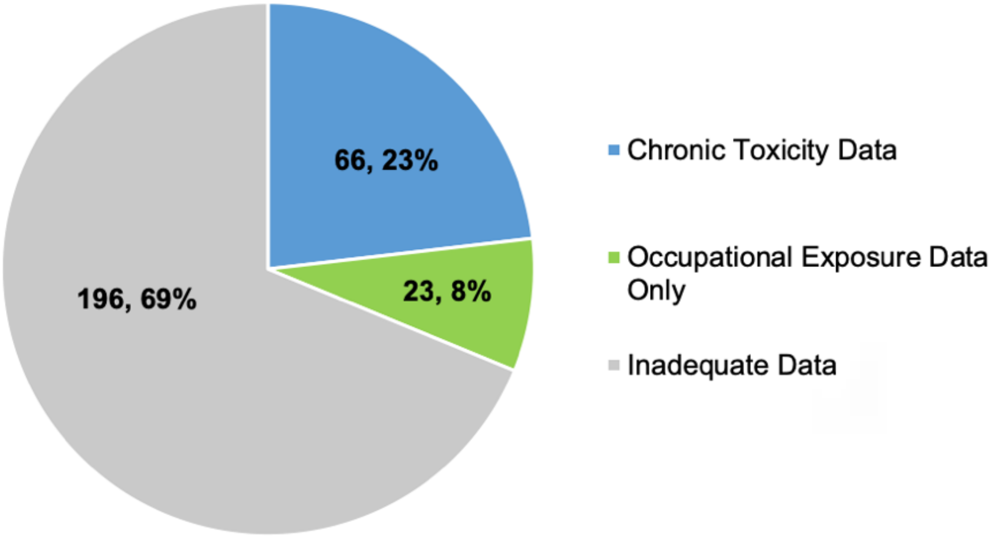

Figure 3.17. Availability of chronic toxicity data for chemical additives with CASRN used in oil fields that send produced water for irrigation of food crops. The first number represents the number of chemical additives with CASRN in each category.

3.4.3.3. Biodegradability

Experimental biodegradation data were found for 39% of chemical additives identified by CASRN, with an additional 17% of additives being characterized using computational estimates from U.S. EPA EPISuite™ BIOWIN™ module (U.S. EPA, 2012). Biodegradation does not apply to inorganic compounds so they were not evaluated for biodegradability.

Overall, 40% of chemical additives with CASRN are readily or inherently biodegradable, and as a result, are not expected to persist in the environment. An additional 16% of chemical additives were classified as not readily biodegradable, and 19% of chemical additives had no available experimental or computational data (Figure 3.18). Due to the large fraction of additives that cannot be classified according to biodegradability, and the lack of data concerning biodegradability of chemical mixtures, there is inadequate data to predict the environmental persistence of chemical mixtures used in O&G operations. A complete list of chemical additives classified as not readily biodegradable for agricultural datasets is provided in Appendix 3.2.

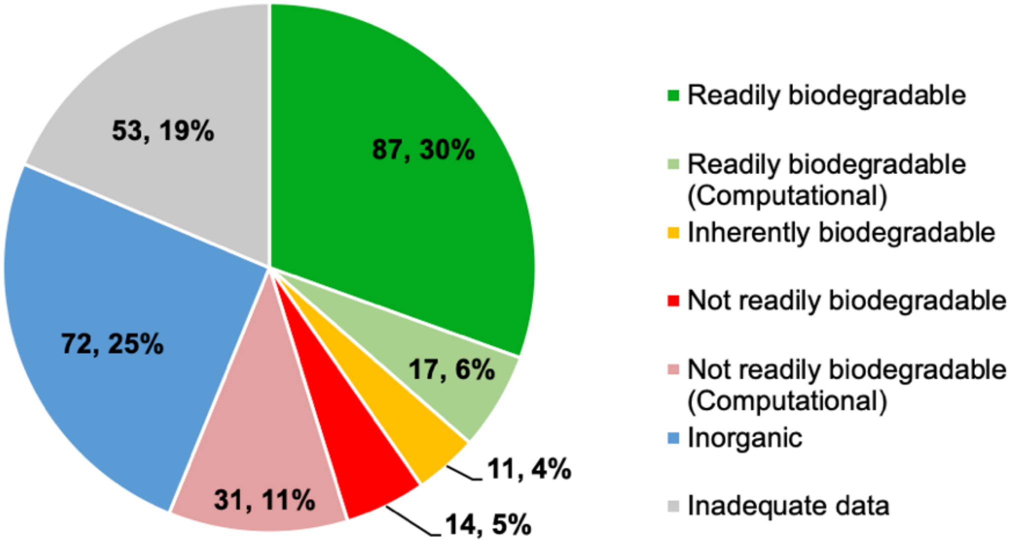

Figure 3.18. Available biodegradability data according to OECD standards for chemical additives with CASRN used in oil fields that send produced water for irrigation of food crops. The first number represents the number of chemical additives with CASRN in each category.

3.4.4.4. Carcinogenicity

Overall, 36 chemical additives (13%) with CASRN were identified on cancer screening lists. A total of 26 chemical additives were identified by IARC as carcinogenic or probably/possibly carcinogenic. An additional 24 additives were classified as IARC Group 3.

Of the 35 chemical additives on California’s Prop 65 list, seven were reported for developmental toxicity. Crystalline silica (tridymite) (CASRN: 15468-32-3) is classified as a known carcinogen by the National Toxicity Program and Prop 65 but is not classified by the IARC. A complete list of all chemical additives identified as known or probable human carcinogens or causing developmental toxicity and used in oil fields that send produced water for irrigation of food crops is provided in Appendix 3.2.

3.4.3.5. Air Pollutants

Overall, 48 chemical additives (17%) with CASRN were identified on air pollution screening lists. A total of 31 chemical additives were identified as CAA hazardous air pollutants. No chemicals were classifiable as POM.

There were 45 chemical additives identified on the California toxic air contaminants list; however, 12 fell under categories 2b or 4b and, while not classified as toxic air contaminants, are under review or have health values under development. All chemical additives identified by the CARB “Hot Spots” Program were on the “substances for which emissions must be quantified” list. A complete list of all chemicals identified as toxic air contaminants by the CAA and CARB that are used in oil fields that send produced water for irrigation of food crops is provided in Appendix 3.2.

3.4.3.6. Endocrine Disrupting Compounds

Only one chemical additive with valid CASRN (poly[oxy-1,2-ethandiyl], a-[nonylphenyl]-w-hydroxy-; CASRN: 9016-45-9) was identified on the European Commission list of EDCs and it was classified as Category 2 for human health.

3.4.4. Considerations for Agricultural Reuse of Produced Water

In total, 285 chemical additives with CASRN were identified in the Irrigation 13267 and AB 1328 datasets, where produced water is reused for agricultural irrigation. Major considerations regarding the reuse of produced water from regions covered by these datasets include:

- 116 chemical additives with CASRN are classified as GHS Categories 1 or 2 for acute toxicity; 22% chemical additives with CASRN had inadequate acute toxicity data.
- 69% of chemical additives with CASRN had inadequate chronic toxicity data.
- 45 chemical additives with CASRN were classified as not readily biodegradable; 53 chemical additives with CASRN had inadequate biodegradation data.
- 36 chemical additives with CASRN are known or probable carcinogens or developmental toxins.
- 31 chemical additives with CASRN are considered hazardous air pollutants; 47 chemical additives with CASRN require reporting under California Air Resources Board “Hot Spots” Program
- One chemical additive with CASRN is classified as an endocrine disrupting compound.
- 80 chemical additives were reported as proprietary/trade secrets without CASRN.

The use of produced water for agricultural irrigation introduces downstream exposure pathways that are not present in typical O&G operations; specifically, exposure of agricultural workers to produced water and the chemical constituents contained therein, and ingestion of food crops irrigated with produced water. The risk associated with these exposure pathways is dependent on multiple factors, including chemical toxicity; mass and frequency of chemical use; underground chemical transformations and reactions; produced water treatment and blending; irrigation methods; biodegradation and bioaccumulation potential of chemicals; and rate of ingestion of food crops irrigated with produced water.

Characterizing chemical additives for toxicity and biodegradability is a vital first step; however, more information is required to evaluate chemicals for potential hazard and subsequent human or environmental risk. Major data gaps remain, including the 79 chemical additives without CASRN and large percentages of chemical additives without acute toxicity, chronic toxicity, or biodegradability data. The data that is available suggest significant aquatic, air pollution, and carcinogenic hazards. Further studies should be conducted to characterize and determine the environmental fate of chemical additives, including above ground transformations, UV degradation, partitioning into air, soil, and water, plant uptake, and bioaccumulation. The Food Safety Expert Panel convened by the CVRWQCB in 2016 has begun to study chemical additives used in oil fields that provide produced water for agricultural reuse and samples various food crops irrigated in part with produced water; however studies are still ongoing (Stringfellow et al., 2018a, 2018b, 2018c, 2018d, 2018e; Shonkoff et al., 2016).

Furthermore, the AB 1328 and Irrigation 13267 datasets only contain data regarding the identities of chemical additives used in O&G operations. Without corresponding frequency of use and chemical mass data, or concentrations of chemical additives in produced water, it is difficult to prioritize chemical additives for further evaluation and assessment.

3.4.5. Data Gaps and Limitations

Some of the data gaps identified in previous studies of chemical use in well stimulation operations in California have been addressed (CCST et al., 2014; Stringfellow et al., 2015). All five chemical disclosure datasets are easily accessible to the public and available for download in electronic database formats, greatly facilitating research and analysis efforts. Since the implementation of SB 4 regulations, the SCAQMD has worked with The Division to standardize their classification of well stimulation categories and chemical reporting. SB 4 regulations have also reduced the instances of chemical additives being reported as trade secret for information disclosed to the FracFocus dataset. Despite this progress, many major data gaps remain unresolved.

All five datasets contain numerous errors and inconsistencies, including the misspelling of chemical additive names, incorrect CASRNs, and inconsistencies with punctuations and spacing. Datasets had to be extensively organized and corrected to prevent errors in analysis and interpretation. Basic spell checking, confirmation of CASRNs, and editing comma placement or the number of spaces between words would help reduce redundancies and instances of duplicate chemicals. Other datasets were poorly organized. For example, the SCAQMD dataset is maintained as event data and chemical usage data, which are further divided into the periods before and after September 2015, when reporting requirements changed. These four datasets had to be organized and reconciled before analysis could be done. Maintaining a single dataset where event and chemical usage data from the two time periods are reconciled would facilitate analysis in the future.

Many chemical additives lack sufficient physical, chemical, and toxicological data required for an environmental risk analysis and prediction of treatment potential. Chemical information essential for developing an environmental profile includes log octanol-water partition coefficients (log K_{ow}), log organic carbon-water partition coefficients (log K_{oc}), water solubility, Henry's constant (K_H), biodegradability, bioaccumulation, and acute and chronic toxicity (Stringfellow et al., 2015). Chronic toxicity is lacking for 75% of chemical additives, and essential properties such as K_{oc} and K_{ow} are missing for roughly 45% of all chemical additives. Furthermore, the primary methodology of matching chemical additive CASRNs to databases of chemical properties and screening lists limited the potential physical and chemical properties examined. As a result, other important properties, such as chemical speciation, transformation potential, and degradation pathways, were not considered in this analysis.

Major data gaps remain regarding the mass of chemical additives used and concentrations of chemical additives in produced water. Chemical additives used in O&G operations are expected to return to the surface with produced water (Ferrer & Thurman, 2015a; Lester et al., 2015; Stringfellow et al., 2015; U.S. EPA, 2016). However, due to the general lack of monitoring for specific chemical additives in produced water, it is unclear what fraction of chemical additives returns to the surface, conserved in their original physiochemical form in produced water, and if the concentration of these additives pose a risk to human health. Further investigation regarding environmental fate is required to thoroughly understand potential environmental and human health risks posed by chemical additives used in O&G operations. Additionally, a significant number of proprietary and trade secret chemical additives are reported in the SCAQMD, AB 1328, and Irrigation 13267 datasets. These chemical additives could not be identified or further characterized for potential hazards.

3.4.6. Summary of Chemical Additive Use in California Oil and Gas Operations

There were 630 unique chemical additives identified as being used in O&G operations in California from 2011–2018. A total of 489 disclosed chemical additives could not be definitively identified due to lack of CASRNs and thus could not be analyzed. While there is significant overlap in chemical additive usage between the five datasets analyzed, approximately half of all chemical additives identified by CASRN are unique to one dataset. This indicates that chemical risks associated with chemical use in O&G operations may vary by region, hydrocarbon development technique, petroleum geology, etc.

Acute toxicity data are generally available (450 of 630 chemical additives have available acute toxicity data); however, chronic toxicity data are extremely limited (154 of 630 chemical additives have available chronic toxicity data). A total of 38 chemical additives were categorized as GHS Category 1 or 2 for acute oral and inhalation toxicity. There were 203 chemical additives categorized as GHS Category 1 or 2 for acute aquatic toxicity, indicating potential for adverse environmental impacts if released into surface water. An additional 51 chemical additives were identified as hazardous air pollutants; 74 chemical additives were on the CARB "Hot Spots" Program List, which requires emissions of chemicals to be quantified and reported. Forty chemical additives were classified as known or possible/probable carcinogens; seven chemical additives were identified on the California Prop 65 List as causing reproductive toxicity. There were 125 chemical additives classified as not readily biodegradable according to OECD standards. These chemical additives are likely to persist in the environment, increasing the risk of exposure to humans and wildlife.

A thorough analysis of available physical, chemical, and toxicological properties for disclosed chemical additives used in O&G operations in California shows that many are poorly characterized and are lacking key data used to predict health hazards, potential treatability, and environmental fate and behavior. Chemical additives that are not disclosed using CASRN cannot be definitively identified and cannot be evaluated in terms of their potential human health hazards and environmental impacts. There are numerous data gaps concerning chemical additive use in O&G operations that provide produced water for agricultural reuse. The data that is available suggest significant aquatic, air pollution, and carcinogenic hazards; however, additional data regarding mass of chemical additives used and concentrations of chemical additives in produced water is needed for further risk assessment. Prior to utilizing produced water for new uses with potential for human health or environmental impacts, it would be prudent to do detailed sampling to determine the presence and concentration of chemical additives in produced water on a case-by-case basis, particularly for water discharged to the surface or reused outside the oilfield (approximately 10% of produced water generated statewide). Further studies should be done to characterize and determine environmental fate of chemical additives, including plant uptake and bioaccumulation.

> ***Finding 3.4.1.*** *The SB 1281 dataset lacks the water quality information necessary to conduct quantitative risk assessments. However, other publicly available datasets can be used in concert with the SB 1281 dataset to assess produced water quality, including chemical additives disclosed as used in O&G operations.*

> ***Finding 3.4.2.*** *Chemical additives reported to be used in O&G operations cannot always be identified, and when they can be, they may not be well-described. In datasets supplemental to the SB 1281 dataset, 630 unique chemical additives were identified as used in oil and gas wells and associated operations in California from 2011 – 2018. Nearly half of the disclosed chemical additives could not be definitively identified due to lack of a unique Chemical Abstract Service Registry Numbers (CASRNs). An analysis of available physical, chemical, and toxicological properties of identified chemicals used in O&G operations in California shows that many are poorly characterized and lack important data required to assess health hazards, treatment potential, and environmental fate and behavior.*

> ***Conclusion 3.4.1.*** *Available chemical data suggest there are aquatic, air pollution, and carcinogenic chemical hazards associated with produced water in California.*

> ***Conclusion 3.4.2.*** *Chemical additives that are not disclosed using CASRN cannot be definitively identified and cannot be evaluated in terms of their potential human health and environmental hazards, risks, and impacts. Available chemical data suggest that there are potential human and ecological health risks associated with produced water where exposure pathways exist.*

> ***Recommendation 3.4.*** *All chemical additives used in any type of O&G operation—not just for well stimulation—in California should be required to be disclosed to a publicly available, digitized database. Agencies with jurisdiction could consider phasing out the use of chemicals or chemical mixtures whose identities cannot be verified or disclosed. Submitted data including chemical names, CASRN, and usage data (frequency, mass, or concentration) should be validated and verified. Environmental and toxicological profiles should be developed for chemical additives and, to the extent possible, chemical additive mixtures used in O&G operations that lack any publicly available information.*

3.5. Produced Water Treatment Methods and Technologies

Various physical, chemical, biological, and combination treatment methods have been explored to treat actual and synthetic produced water from O&G operations. However, treatment efficacy is largely dependent on produced water composition and chemical-specific parameters. This section includes: (1) an assessment of produced water treatment in California using the SB 1281 dataset and (2) an assessment of potential treatment for chemical additives used in O&G operations in California.

3.5.1. Produced Water Treatment Reporting in the SB 1281 Dataset

The SB 1281 dataset provides the first consolidated reporting of produced water treatment in California. Treatment methods reported in the SB 1281 dataset are shown in Table 3.9. Operators report a binary variable (yes or no) if water volumes are intended to be or have been treated. Operators also indicate if treated water undergoes one or multiple treatment methods indicated in Table 3.9 using binary variables (yes or no) for each treatment method.

Table 3.9. SB 1281 water treatment categories, descriptions, and examples (DOGGR, 2018).

Treatment method	Description	Examples
Deoiling (DO)	Separation of hydrocarbons from water by use of gravity, physical, chemical, filtering, and/or absorption processes.	Gravity/corrugated plate, centrifuge, hydroclone, gas flotation, chemical extraction, oxidizer introduction, absorption, media filtration
Disinfection (DI)	Treatment of water for microbial contamination; often used for domestic use or disposal.	Chlorination, ultraviolet (UV) light or ozone exposure
Desalinization (DS)	Treatment (softening) of water to reduce TDS, such as salts and heavy metals; used for steam EOR.	Lime softening, ion exchange, electrodialysis, electrodeionization, capacitive deionization, electrochemical activation, rapid spray evaporation, freeze thaw evaporation
Membrane treatment (MT)	Treatment of water by microfiltration or RO to purify water through the removal of trace amounts of hydrocarbons, microbials, organics, and solids.	Microfiltration, ultrafiltration, nanofiltration, reverse osmosis
Other treatment (OT)	Other treatment or processes not covered by the methods listed, such as treatment of naturally-occurring radioactive materials (NORM) and unconventional processes.	Trickling filter, constructed wetland treatment – flora and fauna decomposition, sodium adsorption ratio adjustment, unspecified

3.5.1.1. Methods: Produced Water Treatment Reporting in the SB 1281 Dataset

In Chapter 1, reported water volumes in the SB 1281 dataset and The Division monthly dataset were compared, revealing significant differences in water volumes reported during the first three quarters (2015 Q1–Q3) and the last three quarters (2017 Q2–Q4) of the SB 1281 dataset. These discrepancies are discussed in detail in Chapter 1. While various water source and water disposition (destination) categories overlap between the SB 1281 and DOGGR monthly datasets, treatment method information is only available in the SB 1281 dataset. The SB 1281 dataset was restricted to 2015 Q4–2017 Q1 to evaluate the most reliable data provided by the SB 1281 dataset and to maintain consistency across chapters. This timeframe is referred to as the study period from this point forward.

Treatment method information is provided in three of the four SB 1281 reports: Form 110Q Water Production Report (Production report); Form 110BQ Water Injection Report (Injection report); and Form 110FQ Other Allocation Report (Other Allocation report). Water destination for produced water is provided in the Production report and the Other Allocation report, with noted overlapping water volumes between these reports (see Chapter 1). Treatment method information was aggregated by treatment combination from the Production Report, which accounts for the significant majority of produced water in the SB 1281 dataset and is the focus of our analyses. Similar to Chapter 1, results are presented statewide and by the five sedimentary basins with the largest water volumes: San Joaquin, Los Angeles, Santa Barbara-Ventura, Santa Maria, and Salinas.

Well-level water volumes from the Production report were summed by quarter, basin, field, operator, and treatment combination. Mean quarterly produced water volumes were calculated by basin, by treatment combination, and by destination using quarters included in the study period. Water volumes with indication of treatment but no treatment method specified were considered treated with treatment method indicated as “No method.”

3.5.1.2. Results: Produced Water Treatment Reporting in the SB 1281 Dataset

Statewide quarterly treated and untreated produced water volumes are shown in Figure 3.19. Each quarter, treated produced water volumes are significantly greater than untreated water volumes statewide. During the study period, untreated produced water accounts for approximately 5% of all produced water statewide (Figure 3.19).

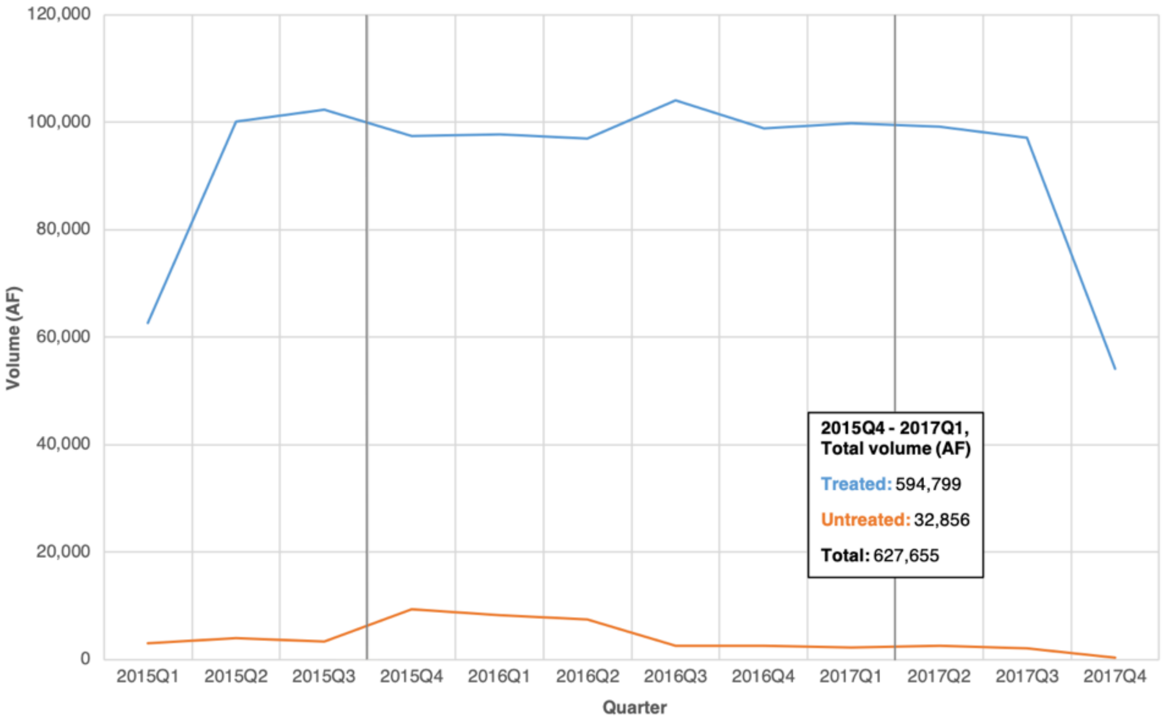

Figure 3.19. Statewide quarterly treated and untreated produced water volumes in acre-feet (AF) reported in the SB 1281 Production Report between 2015–2017. The study period, data reported between 2015 Q4 and 2017 Q1 and included in further analyses, is shown in black vertical lines. (Note: The treated category includes standard deoiling as a method.)

Produced water volumes presented in the remaining results reflect mean quarterly volumes. Mean quarterly produced water volumes by treatment method were calculated by averaging quarterly water volumes reported in the study period. Mean quarterly produced water volumes statewide and by sedimentary basin are presented in Figure 3.20. Deoiling (DO) alone accounts for the largest proportion of treated produced water statewide and across all basins. More than half (55%) of produced water from the Santa Barbara-Ventura basin goes untreated. DO in combination with other treatment (OT) accounts for significant proportions of produced water in the San Joaquin basin (17,408 AF, or 27%) and the Salinas basin (1,916 AF, or 47%,). Meanwhile, DO in combination with membrane treatment (MT) was reported for 17% (5,293 AF) of produced water in the Los Angeles basin and MT alone was reported for 13% (333 AF) of produced water in the Santa Maria basin. Notably, treatment combinations including MT only account for approximately 6% of produced water statewide and <0.001% of produced water in the San Joaquin basin, where a larger proportion of water is discharged to the surface (see Chapter 1, Question 5). Treated produced water using treatment combinations not shown individually in Figure 3.20 are grouped as Other. These treatment combinations account for less than 2% of produced water volumes statewide and by basin.

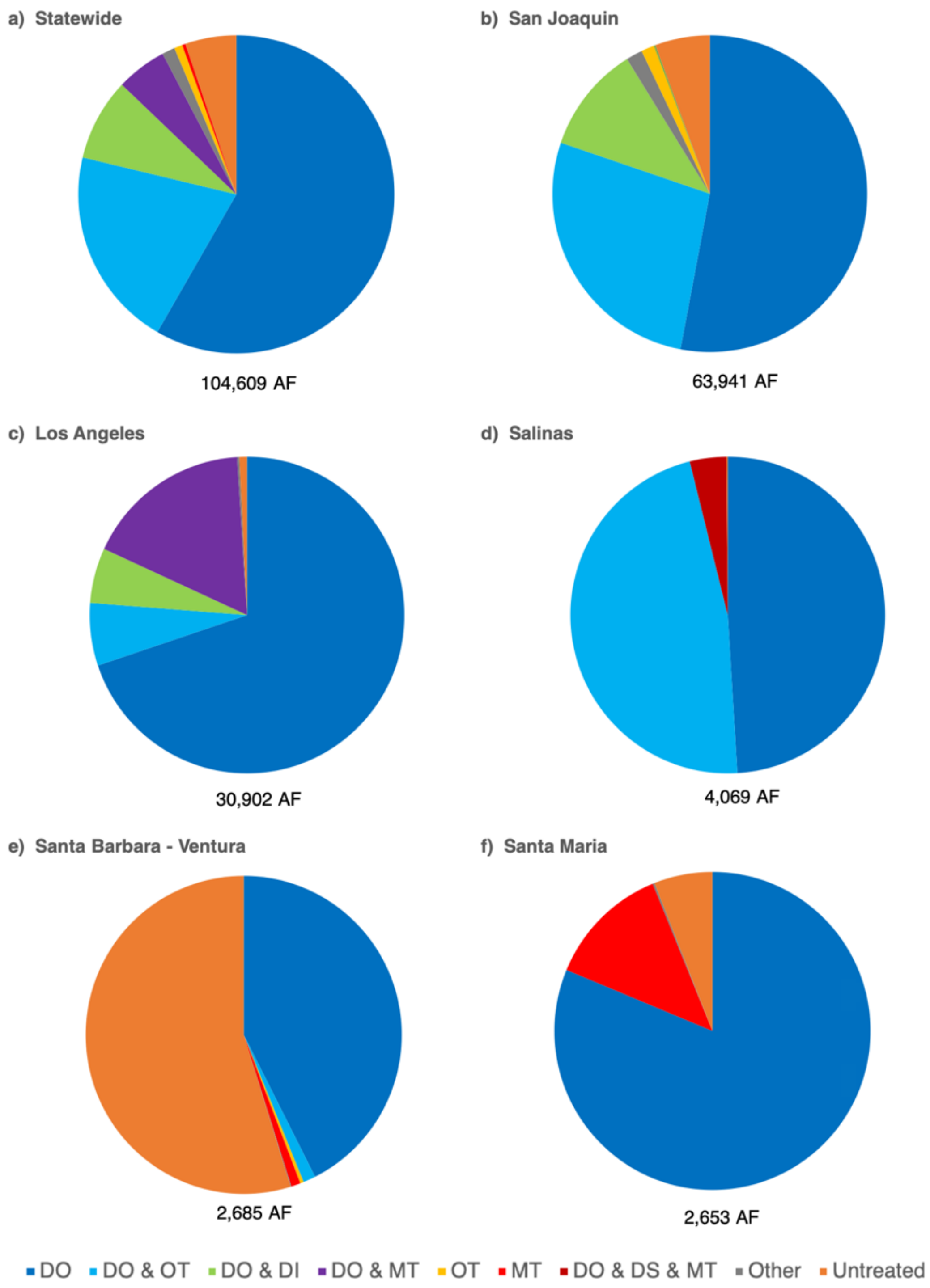

Figure 3.20. Mean quarterly produced water volumes by treatment method and sedimentary basin. Overall mean quarterly produced water volumes statewide and for each sedimentary basin are shown beneath each pie chart (DO – deoiling; DI – disinfection; DS – desalinization; MT – membrane treatment; OT – other treatment).

Produced Water Treatment By Disposition (Destination)

Operators report the intended disposition of produced water in the SB 1281 Production report. Produced water disposition categories included in the SB 1281 Production report were classified into destination groupings to simplify data visualization and interpretation. Destination groupings are shown in Table 3.10.

Table 3.10. Destination groupings and associated disposition categories in the SB 1281 Production report.

Destination Grouping	SB 1281 Disposition Category
Surface Discharge	Unlined pond
	Lined pond
	Surface water discharge
	Domestic sewer system
	Surface discharge – land
	Sale/Transfer – Domestic Use
O&G Reuse	Sale/Transfer – To other operator or oil field
	Operator's facilities within oil field
	Drilling, well work, and well abandonments
	Well Stimulation Treatment
Subsurface Injection – UIC[1]	Subsurface injection – in oil field by operator
Other	Other

1. Subsurface injection category includes both injection for disposal and injection for enhanced oil recovery as reported in the SB 1281 Production report.

Produced water treatment by destination is shown in Figure 3.21. DO accounts for the largest proportion of treated produced water for each destination, except for surface discharge. DO and OT accounts for 54% (6,059 AF) of produced water discharged to the surface. The largest proportion of untreated produced water by destination is O&G reuse (6%, or 334 AF); however, the largest untreated mean quarterly volume is injected into the subsurface (4,733 AF, or 5.5%). DO in combination with disinfection accounts for 10% (8,234 AF) of subsurface injection and 4% (225 AF) of O&G reuse, likely because water is reused for EOR (DOGGR, 2018). Treated produced water using combinations not shown individually in Figure 3.21 grouped as Other. These treatment combinations account for less than 0.02% of produced water volumes for each destination grouping.

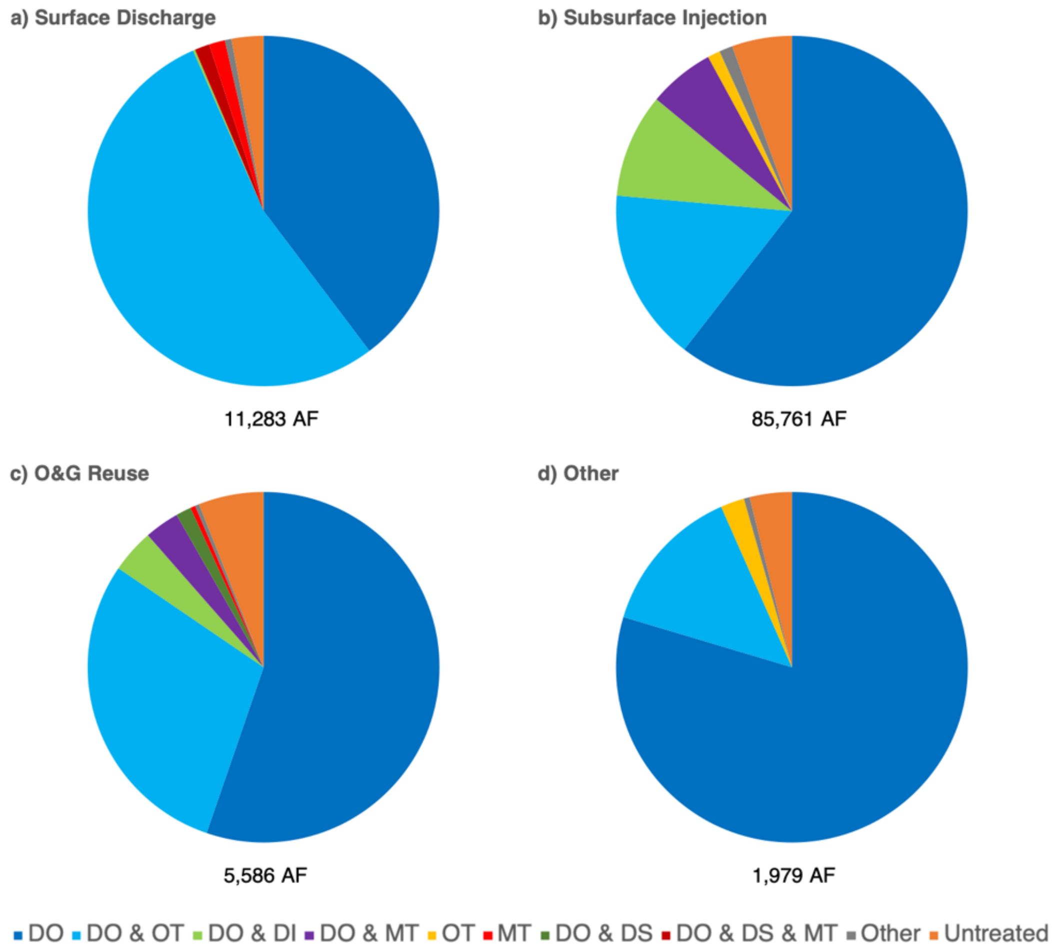

Figure 3.21. Statewide mean quarterly produced water volumes by treatment method and destination grouping. Overall mean quarterly produced water volumes by disposition are shown beneath each pie chart (DO – deoiling; DI – disinfection; DS – desalinization; MT – membrane treatment.)

Produced Water Treatment For Surface Discharge In The San Joaquin Basin

The San Joaquin basin accounts for 90% (10,130 AF) of produced water volumes discharged to the surface statewide (11,283 AF). Produced water volumes by treatment method and SB 1281 dataset categories that discharge to the surface are shown in Figure 3.22. Produced water discharged to the surface primarily undergoes DO or DO in combination with OT. These produced water volumes are used for domestic use (e.g., agricultural irrigation) or discharged to produced water ponds. Nearly all produced water discharged to produced water ponds in the San Joaquin Valley are discharged to unlined ponds (99.7%). Smaller water volumes are discharged to surface water and treated by DO alone (18 AF), and discharged to land and treated by DO & OT (117 AF). Operators are able to indicate that water has been treated without indicating any treatment method category in the SB 1281 dataset. This ability accounts for 31 AF discharged to produced water ponds as treated water with 'No method' indicated. Untreated produced water in the San Joaquin basin is discharged for domestic use (e.g., agricultural irrigation) (90%); to produced water ponds (9%); and to land (<1%). Even small volumes of produced water undergo additional methods, such as desalinization (DS) in combination with other treatment (OT), or membrane treatment (MT) alone.

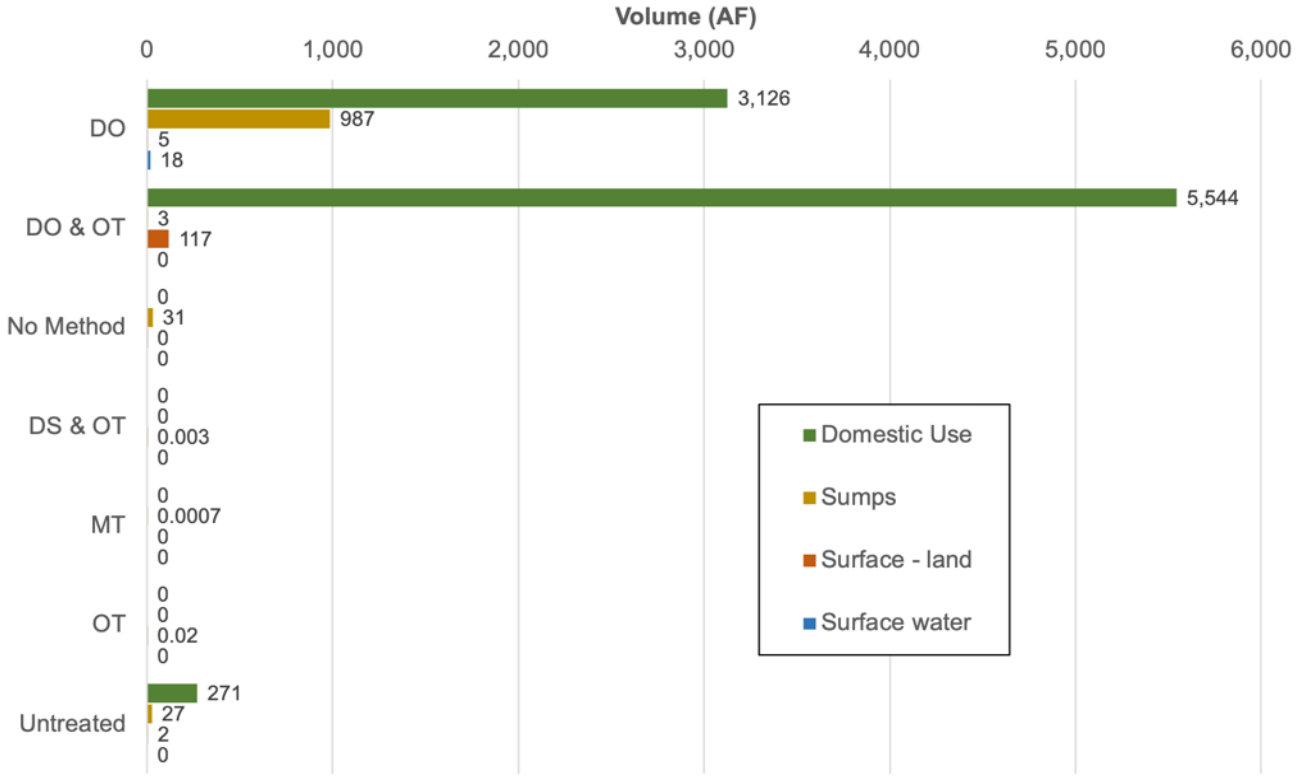

Figure 3.22. Mean quarterly produced water volumes by surface discharge disposition categories and treatment method in the San Joaquin basin. Notes: (1) Produced water volumes to produced water ponds are primarily to unlined ponds; lined ponds account for only 0.3 AF of untreated volume shown; (2) "Domestic use" predominantly refers to reuse for agricultural irrigation.

3.5.1.3. Discussion: Produced Water Treatment Reporting in the SB 1281 Dataset

The SB 1281 dataset allows for quantification of treated and untreated water volumes associated with O&G operations in California. However, the treatment categories included in the SB 1281 dataset lack specificity to determine which actual treatment technologies are employed for given water volumes. For example, the OT category likely serves as a catch-all treatment category for operators to select. Therefore, the OT category alone, and as a portion of a treatment train (e.g., DO & OT), tells us very little about how water is being treated.

More information about water treatment technologies deployed, and the sequence of water treatment technologies in treatment trains, would be desirable. This is of particular importance for water discharged to the surface that is reused outside of the oilfield with potential environmental and human exposure pathways. For example, additional information on treatment technologies should be prioritized for produced water that is reused for agricultural irrigation of food crops, and for produced water discharged to unlined produced water ponds with potential hydrological connectivity to aquifers with current or future potential for municipal, agricultural, and domestic use.

Disaggregation of the five existing treatment method categories in the SB 1281 dataset into a greater number of variables (similar to water disposition/destination) would enable operators to provide more specificity about treatment technologies used and prevent misclassification of treatment methods. For example, the existing membrane treatment category could be replaced with separate, more specific categories for RO and nanofiltration. An additional companion or linked variable to treatment method could be added to the SB 1281 dataset to indicate sequence of treatment.

> ***Finding 3.5.1.*** *The treatment categories used in the SB 1281 dataset are not sufficiently specific; they do not provide the detail necessary to determine which treatment process is being applied. Thus, treatment level cannot be accurately assessed in the context of responsible produced water beneficial reuse potential.*

> ***Conclusion 3.5.1.*** *More detailed and specific reporting regarding treatment technologies and treatment trains is required for risk management of produced water, in particular produced water that is discharged to the surface and reused outside of the oilfield.*

> ***Recommendation 3.5.1.*** *The SB 1281 dataset on treatment should be modified to require detailed information on the specific treatment process or processes used. The current categories are overly broad and should be abandoned and replaced by detailed descriptions of the actual treatment technology applied (e.g., three-phase separator, WEMCO, ion exchange, walnut-shell filters). The sequence of technologies used to treat produced water should be identified, especially for produced water that is discharged to the surface or reused outside of the oilfield.*

3.5.2. Potential Water Treatment Approaches for the Removal of Chemicals Used in Oil and Gas Operations in California

Produced water treatment is highly dependent on techno-economic factors and is often focused on the recovery of petroleum hydrocarbons and secondarily on meeting standard water quality parameters. These parameters include TDS, major ions, and total petroleum hydrocarbons based on the intended reuse or disposal method (Arthur et al., 2005; Fakhru'l-Razi et al., 2009). The conventional treatment of produced water for these constituents has been widely studied (Arthur et al., 2005; Camarillo & Stringfellow, 2018; Chang et al., 2019; Cho et al., 2016; Clark & Veil, 2009; Colorado School of Mines, 2009; Fakhru'l-Razi et al., 2009; Igunnu & Chen, 2012; Jiménez et al., 2018; Shaffer et al., 2013; Silva et al., 2017; U.S. EPA, 2016; Woo et al., 2017; Zhang, 2015; Zhong et al., 2016).

3.5.2.1. Background: Produced Water Treatment

Often, after initial oil-water separation (deoiling), a large proportion of the chemical load that remains in produced water is still petroleum hydrocarbons, TDS, major ions, and other constituents sourced from the hydrocarbon reservoir. Petroleum hydrocarbons have notable toxicological profiles (ATSDR, 1999; Tormoehlen et al., 2014) and the removal of petroleum hydrocarbons is important to reduce human and environmental health risks, especially for produced water discharged to the surface and reused outside of the oilfield. The analyses we undertake below focus on the suitability of water treatment technologies to remove chemical additives known to be used in the state of California. We take on this focus given that less is known about the efficacy of chemical additive removal by the water treatment technologies and treatment trains operators report using to treat produced water.

Chemical additives used in O&G operations are expected to return to the surface with produced water (Ferrer & Thurman, 2015a; Lester et al., 2015; Stringfellow et al., 2015). However, due to the general lack of monitoring for specific chemical additives in produced water (with the exception of some common organic acids and hydrocarbons), it is unclear what fraction of chemical additives remain in underground formations, what fraction react in the subsurface and are transformed, and what fraction returns to the surface, conserved in their original physiochemical form in produced water. Although produced water treatment systems are not specifically designed to remove chemical additives, some removal is likely (Camarillo et al., 2016; Faksness et al., 2004; Stringfellow et al., 2015).

Previous studies by Stringfellow et al. (2015), Camarillo et al. (2016) , and U.S. EPA (2016) have investigated the potential treatment of chemical additives used in well stimulation operations in California and nationwide. A generalized approach to determine the efficacy of select wastewater treatment technologies at removing various classes of well stimulation chemical additives was developed by Stringfellow et al. (2015) and U.S. EPA (2016), and was further refined to screen individual chemical additives by Camarillo et al. (2016). However, these studies were limited to evaluation of technological abilities to remove only well stimulation chemicals from produced water.

Because chemical additives are used in O&G operations where produced water is discharged to the surface (e.g., to unlined produced water ponds) with hydrological connectivity to usable groundwater, or reused outside of the oilfield (e.g., for agricultural irrigation) in some regions of the state, and because of the lack of data regarding the concentrations of chemical additives in these produced waters, it is important to understand the effectiveness of individual and sequenced water treatment technologies at removing these chemical additives. In this section, we use fundamental chemical and physical properties of chemical additives used in all O&G operations in California to predict the applicability of a selection of treatment technologies reported as used for produced water.

3.5.2.2. Methods: Potential Treatment of Chemical Additives Used in California Oil and Gas Operations

With the exception of water, all chemical additives used in O&G development operations in California and identified by CASRN were screened for suitability of treatment by select technologies using the methodology adapted from Camarillo et al. (2016). Four major classes of water treatment technologies were considered: membrane filtration (RO and nanofiltration); adsorptive media (organic and inorganic media); air stripping; and biological treatment. Treatment method categories provided in SB 1281 data were not used for this screening because each category is broad and includes a wide variety of treatment technologies. Physical and chemical properties were used to determine the potential applicability of the selected treatment technologies (i.e. if chemical additives are fundamentally compatible with the mechanisms of selected treatment technologies). When experimental values were unavailable, computational values estimated from U.S. EPA EPISuite™ modules were used. Chemical additives were considered candidates for removal by membrane filtration based on molecular weight cut-off (MWCO) values of 100 atomic mass units (amu) for RO and and 200-400 amu for nanofiltration. Chemical additive speciation and charge were not taken into account when determining suitability of RO as a treatment technology. Chemical additives were considered candidates for treatment by adsorptive media, such as activated carbon, and for removal via the oil fraction during oil-water separation if $\log K_{ow} > 2$. Chemical additives were considered candidates for treatment by organic adsorptive media if $\log K_{oc} > 3$. Chemical additives were considered candidates for air stripping if they had Henry's Law constants (K_H) of 0.001 atm-m^3 mol^{-1} or greater. Chemical additives were considered candidates for biological treatment if they were organic and were shown to be "readily biodegradable" or "inherently biodegradable" according to standardized OECD testing. It is important to note that treatment-specific removal efficiencies of individual chemical additives used for water treatment technologies in O&G operations in California were not calculated in this analysis; however, generalized removal efficiencies of broad classes of chemical additives are available and summarized by the U.S. EPA (2016), and to a lesser extent by Stringfellow et al. (2015). The concentration of possible chemical additives in produced water was not taken into account for this analysis due to the lack of data.

3.5.2.3. Results: Potential Removal of Chemical Additives Used in Oil and Gas Operations

Using our methodology, 477 (76%) chemical additives are considered candidates for removal from produced water by at least one of the treatment technologies we included in our analysis (Table 3.11). Eleven percent of chemical additives lacked any physical or chemical property data relevant to the screened technologies. Thirteen percent of chemical additives with at least one available physical or chemical property used to predict the applicability of treatment technologies are not expected to be removed from produced water using the screened technologies. It is important to note that the lack of physical and chemical property data to screen treatment technologies does not preclude them from being removed by these technologies; it only means that there is not enough information to determine whether or not this would be the case without laboratory testing. A detailed summary of chemical additives categorized according to chemical function and applicable treatment technologies is available in Appendix 3.3.

Of the analyzed treatment technologies, RO and biological treatment have the greatest potential for chemical additive removal from produced water. Dissolved solids, salts, and other unclassified chemical additives are prime candidates for removal using RO. Polymers and biocides are also candidates for removal by RO. However, in practical applications, they would be removed prior to RO due to the extensive pre-treatment of produced water streams required to remove minerals, organics, and other particulate matter that will foul membranes. Biological treatment is expected to be effective at removing amines/amides, surfactants, and some solvents. Although the efficacy of biological treatment of produced water generally decreases with increasing TDS, treatment of produced water with TDS up to 100,000 mg/L has been demonstrated under specific conditions well above the median TDS of 26,000 mg/L observed from California produced water quality datasets (see Section 3.3. and Appendix 3.1) (Camarillo & Stringfellow, 2018; U.S. EPA, 2016; Pendashteh et al., 2012). Some biocides, including quaternary ammonium compounds, or other inhibitive compounds are biodegradable in low concentrations under specific conditions, but can significantly inhibit the biodegradation of otherwise readily biodegradable compounds if present in high concentrations (Camarillo et al., 2016)

Air stripping and organic adsorption media have the lowest potential for chemical removal out of the treatment technologies analyzed using our methodology. However, this is likely due to the fact that almost half of all chemical additives with CASRN have no physical/chemical data with which to predict suitability of these treatment technologies.

Deoiling is by far the most commonly employed treatment method in California. The SB 1281 dataset deoiling treatment category includes a variety of technologies, such as fluid separation by gravity/corrugated plate separators, centrifuge, hydroclone, gas flotation, chemical extraction, oxidizer introduction, absorption, adsorption, and media filtration. Of the six screened treatment technologies, three (adsorption/oil-water separation, organic adsorption media, and air stripping) are relevant to deoiling. There are 210 (33%) chemical additive candidates for treatment by deoiling methods. An additional 171 (27%) chemical additives are unlikely to be removed during deoiling, and 248 (39%) chemical additives had no physical or chemical data relevant to deoiling treatments to predict treatment efficacy. These are very conservative estimates for deoiling, as the three screened technologies only cover a small portion of possible deoiling treatment technologies and more than 40% of analyzed chemicals lacked available chemical/physical data to predict efficacy of these three treatment technologies. Deoiling treatment processes such as centrifuges, hydroclones, gravity separation, and media filtration are expected to be effective at removing insoluble particulates, including proppants and other minerals, while chemical oxidation is expected to remove biocides, gelling agents, friction reducers, and other organic compounds (Stringfellow et al., 2015). Deoiling treatment processes are an important pre-treatment step to recover residual hydrocarbons and reduce produced water chemical load for subsequent treatment technologies.

Table 3.11. Summary of suitability of select treatment technologies for removal chemical additives used in O&G operations in California.

Treatment Technology	**Potentially Treatable**	**Not Treatable**	**No Data**
RO	313 (50%)	115 (18%)	201 (32%)
Nanofiltration	166 (26%)	262 (42%)	201 (32%)
Adsorption/Oil-water separation	174 (28%)	200 (32%)	255 (41%)
Organic adsorption mmedia	153 (24%)	195 (31%)	281 (45%)
Air stripping	76 (12%)	272 (43%)	281 (45%)
Biological treatment	221 (35%)	274 (44%)	134 (21%)
Overall	477 (76%)	80 (13%)[1]	72 (11%)[2]

1. Chemical additives with at least one available physical/chemical property relevant to treatment that were not expected to be treatable using any of the screened treatment technologies.

2. Chemical additives with no available physical/chemical properties relevant to screened treatment technologies.

Only a small fraction of treated produced water undergoes a form of membrane treatment. However, membrane treatment has the potential to remove the greatest number of chemical additives of all treatment methods analyzed. The SB 1281 dataset membrane treatment category includes microfiltration, ultrafiltration, nanofiltration, and RO. An estimated 50% and 26% of identified chemical additives are candidates for removal using RO and nanofiltration, respectively. This represents a conservative estimate: although 32% of chemical additives had no definitive chemical formula and exact molecular mass could not be determined, the majority of them could be identified as long chain thoxylates, polymers, and other high molecular mass compounds which are likely to be removed using membrane treatment. Furthermore, a properly designed membrane treatment system will involve multiple pre-treatment steps that are expected to remove a portion of the chemical load prior to membrane treatment. Although pre-treatment steps add to the already high cost and energy requirements of membrane treatment, it is necessary to minimize and control fouling. As a result, potential membrane fouling was not taken into account for this analysis.

We identified 35% of chemical additives as candidates for removal using “other treatments” (OT), specifically those geared toward biological treatment such as trickling filters, constructed wetland treatments, and biological decomposition. However, OT is a broad category that also includes treatment of naturally-occurring radioactive materials (NORM), sodium adsorption ratio adjustment, and other unspecified treatment technologies which were not considered in this study.

3.5.2.4. Discussion: Potential Removal of Chemical Additives Used in Oil and Gas Operations

Prediction of suitable treatment technologies using our methodology is limited by several factors: (1) the availability of chemical and physical property data; (2) the lack of complete chemical additive mass data and concentrations of chemical additives in produced water; (3) the examined treatment technologies; and (4) the lack of understanding in how chemical interactions may affect potential treatment options. The treatment categories used in the SB 1281 dataset (deoiling, disinfection, desalinization, membrane treatment, and other treatment) cover a wide breadth of treatment technologies, the majority of which were not evaluated in this analysis. Additionally, water treatment technologies are usually never used in isolation; treatment trains involving multiple complimentary treatment technologies are typically employed. These treatment trains can be relatively simple, such as Chevron’s Station 36 Facility in the Kern River Oil Field, which treats produced water for agricultural reuse with mechanical separation, sedimentation, air flotation, and walnut hull filtration (CVRWQCB, 2012). Treatment trains can also be highly complex, utilizing two-pass RO systems with pre-treatment consisting of gas flotation, walnut shell filtrations, coagulation and flocculation, media filtration, softening, and cartridge filtration, such as the San Ardo Oil Field Water Management Facility (Veolia Water, 2012). A properly designed treatment train utilizing treatment technologies included in the SB 1281 dataset (beyond the six technologies analyzed in this study) is expected to exceed the estimated removal of 76% of chemical additives.

Other methods, such as quantitative structure-activity relationship (QSAR) models, can be used to predict chemical removal by wastewater treatment technologies (Blum et al., 1994; de Ridder et al., 2010; Magnuson & Speth, 2005; Sudhakaran & Amy, 2013; Wols & Vries, 2012). Although QSAR models were used in this analysis to predict the physical and chemical properties of chemical additives without experimental data (through the use of EPA EPISuite™ estimation modules for biodegradation, K_{ow}, K_{oc}, and Henry’s Law constants), a more detailed analysis of QSARs for the 629 chemical additives used in O&G operations in California (with respect to specific water treatment technologies) is beyond the scope of this report. Due to the various limitations of this analysis, the estimated number of chemical additives that are candidates for removal from produced water using the selected wastewater treatment technologies is very conservative. In actuality, almost any chemical can be removed from wastewater using a combination of multiple treatment technologies if cost is not a consideration. Ultimately, chemical additive removal efficiency should be demonstrated using bench scale, pilot, or existing treatment trains prior to the beneficial reuse or environmental release of produced water.

> ***Finding 3.5.2.*** *No one treatment technology can be expected to adequately remove all potential chemicals of concern that can exist in produced water, but treatment trains can be developed for functionally complete treatment. Of the screened technologies, reverse osmosis and biological treatment have the greatest potential to treat chemical additives of concern that may be found in produced water intended for reuse outside of the oilfield.*

> ***Conclusion 3.5.2.1.*** *Certain chemical constituents are well-proven to be removed by state-of-the-art physical, chemical, and biological treatment approaches. However, some chemical additives reported as used in O&G development operations in California are not expected to be effectively removed by commonly-used physical, chemical, and biological treatment technologies.*

> ***Conclusion 3.5.2.2.*** *Further research and applied investigations are warranted to assess the efficacy of removal of chemical additives and other chemical constituents, particularly for applications of produced water discharged and reused at the surface.*

3.6. Discussion: Data Collection Required to Further Inform Produced Water Management and Reuse

There are multiple regulatory resources for O&G chemical disclosure in California (see Section 3.4). While chemical additive disclosure in O&G development operations is helpful to identify potential environmental and health hazards, chemical additive use and produced water composition varies greatly across time and geographic, geological, and operator space. Furthermore, chemical disclosure does not capture chemical transformations that may occur through environmental processes or during treatment. For example, glutaraldehyde, a biocide influenced by temperature and pH conditions, is known to return to the surface in produced water with associated transformation byproducts (Kahrilas et al., 2016). Although many relatively toxic biocides are degradable through abiotic and biotic processes, some may transform into more toxic or more environmentally persistent compounds (Kahrilas et al., 2015). A few of these biocides have been identified as used in O&G operations in California (CASRN: 10222-01-2, 55566-30-8, 533-74-4; see Appendix 3.2).

Chemical transformations may also occur as a result of subsequent treatment and disposal. Water disinfection byproduct (DBP) precursors have been identified in untreated O&G produced water (Harkness et al., 2015; Parker et al., 2014; Liberatore et al., 2017). When produced water is released into surface waters, DBPs have been detected downstream from points of discharge (Hladik et al., 2014). Toxicity of various regulated and unregulated DBPs has been noted in the literature (Liberatore et al., 2017). As such, conducting produced water monitoring for disclosed chemicals is appropriate, but may not provide conclusive results with respect to the toxicological profile of any given source of produced water. The deployment of monitoring approaches that can provide information on DBPs and other transformation byproducts, or non-targeted water monitoring methods that assess the toxicity and mutagenicity of water without identifying specific chemical mechanisms (e.g., bioassays), may help to close these data gaps. These monitoring approaches are most important for discharge of produced water to the surface and for produced water reuse outside of the oilfield.

Regulatory monitoring of produced water in California includes monitoring and characterization of recovered fluids and produced water after well stimulation and produced water discharged to the surface. Monitoring occurs via Waste Discharge Requirements (WDRs) under waste discharge permits issued by Regional Water Boards in the State of California. Federal and state produced water monitoring includes targeted evaluations of known compounds using U.S. EPA Environmental Laboratory Accreditation Program (ELAP) approved analytical methods, also called standard methods. For example, as of 2016, the CVRWQCB required additional monitoring of produced water used for agricultural irrigation in the San Joaquin Valley, in which operators are required to monitor quarterly for suites of constituents typically found in oilfield reservoirs and for “oil production and process chemicals and additives.” If no ELAP-approved analytical methods are available for a given compound, the discharger is required to submit a technical report describing how this issue is addressed, and analytical methods must be approved by the Executive Officer (e.g., CVRWQCB , 2016).

3.6.1. Non-targeted Approaches to Monitor Produced Water

3.6.1.1. High-resolution Mass Spectrometry (HRMS) with Liquid Chromatography Approaches to Produced Water Quality Monitoring

Beyond targeted standard methods, the peer-reviewed literature includes studies that employ emerging and sometimes experimental non-targeted monitoring approaches to characterize produced water composition and evaluate potential environmental and health hazards. One key non-targeted analytical method to identify unknown compounds in produced water is high-resolution mass spectrometry (HRMS) with liquid chromatography (Santos et al., 2019). This analytical technique features high resolution and increased mass accuracy, can provide compound identification by mass, and has been used to characterize previously unidentified ethoxylated compounds and halogenated organic compounds in hydraulic fracturing fluids and produced water (Ferrer & Thurman, 2015a; Luek et al., 2017; Thurman et al., 2014; Thurman et al., 2017). While these experimental techniques are under development, in the future, HRMS is anticipated to have a significant impact in the identification of unknown chemical transformation products, which is currently a significant data gap (Santos et al., 2019).

3.6.1.2. Bioanalytical and Non-targeted Approaches to Produced Water Quality Monitoring

Numerous studies have used more holistic and bioanalytical approaches to water quality testing (e.g., non-targeted chemistry and cell line assays) to assess the toxicity of flowback and produced water (He et al., 2017; Liberatore et al., 2017; Tasker et al., 2018; Yao et al., 2015) and synthetic mixtures of constituents detected in flowback and produced water (Kassotis et al., 2015, 2016, 2018a; Robert et al., 2018). Bioassays include in vitro (outside a living organism, e.g., cell line) and in vivo (within a living organism, e.g., animal model) toxicity studies used to evaluate toxicity specific to various physiological systems. Results observed in these approaches include changes in metabolic and hormone signaling pathways. Experimental findings in the literature demonstrate adverse effects to the endocrine, metabolic, and reproductive systems associated with known and unknown substances that comprise produced water (He et al., 2017; Kassotis et al., 2015, 2016, 2018b; Tasker et al., 2018). Despite insufficient information to identify and quantify specific constituents in produced water, results of bioassays indicate exposure to produced water may have health relevance. These types of non-targeted, bioanalytical approaches to produced water monitoring may be most important to consider under situations where produced water is discharged to the surface and reused outside of the oilfield.

In 2018, a Science Advisory Panel convened by the SWRCB published recommendations regarding constituents of emerging concern in municipal wastewater (recycled water) for potable and non-potable reuse, with the exception of irrigation water for food crops (Drewes et al., 2018). While there are differences in categories of pollutants of concern for municipal recycled wastewater compared with produced water, extensive research has established frameworks to begin to address constituents of emerging concern, which may have relevance to the case of produced water management. Both recycled wastewater and produced water include dynamic chemical inputs and many unknowns regarding chemical composition and transformations.

The following is an example of the similar challenges in water quality monitoring to ensure that consumers are not exposed to hazardous concentrations of chemicals of concern. In the case of municipal recycled water, millions of people put pharmaceuticals, cleaners, personal care products, pesticides, and other complex chemical compounds and chemical mixtures down their drains, which may have human health implications should there be an exposure pathway. Some of these compounds and their associated transformation byproducts and DBPs are well understood, but many are not. In oilfields, operators inject a wide variety of chemical constituents into petroleum reservoirs, adding to the connate suite of chemical constituents. Similar to municipal recycled water, many of the constituents that compose the chemical and suspended loads in produced water are not well understood both in their human health and environmental profiles, as well as in the best approaches to monitoring.

To address these dynamic issues in approaches to monitoring the quality of municipal recycled water, a Science Advisory Panel convened by the SWRCB recommended that bioanalytical methods be implemented and non-targeted analyses considered for recycled water for domestic consumption (e.g., drinking water). In particular, two in vitro bioassays, Estrogen Receptor alpha (ER-α) and the Aryl hydrocarbon Receptor (AhR), were selected because they may be standardized for screening recycled water quality at potable reuse projects (Drewes et al., 2018).

In California, reuse of produced water in drinking water systems has not been officially proposed. However, current regulation allows the reuse of produced water outside of the oilfield for agricultural irrigation of food crops, livestock watering, and aquifer recharge, all of which have potential environmental pathways of exposure. Additionally, produced water recharges aquifers indirectly via discharge to unlined produced water ponds in the San Joaquin Valley. The framework outlined to assess the presence, concentrations, and public health implications of chemicals of emerging concern in municipal recycled water reuse may be useful to address unknowns regarding produced water composition, chemical transformations, and potential hazards and risks to human health and the environment.

> ***Finding 3.6.1.*** *Produced water quality is highly heterogeneous across geographic and geological space and operators use a wide variety of chemical additives in their operations. While disclosure of chemicals is expected to result in significantly more information about chemical use, questions remain as to how these chemicals may transform under high temperature and pressure and in the presence of other chemical constituents in oilfield reservoirs and associated processes.*

> ***Finding 3.6.2.*** *Produced water can meet traditional water quality standards and still pose toxicological, mutagenic, and carcinogenic risks when there is a human or ecological exposure pathway. These mechanisms are difficult to ascertain without non-targeted or bioanalytical testing.*

> ***Conclusion 3.6.*** *Answering questions of produced water quality and associated public health and ecological risks is aided, but not satisfied by, chemical disclosure. While pollutant-by-pollutant chemical disclosure and monitoring is important, produced water reuse outside of the oilfield with human and ecological exposure potential could benefit from more holistic approaches to water quality testing (e.g., non-targeted chemistry and cell line assays) that are not directly focused on understanding all of the chemicals in the mixture. Existing water reuse frameworks that address evolving chemical landscapes (e.g., municipal wastewater) may inform produced water treatment, monitoring, and management.*

> ***Recommendation 3.6.1.*** *Agencies with jurisdiction should ensure that the best available research informs their regulations. To this end, they should convene water quality and public health experts to conduct non-targeted water quality research on produced water that is currently or is being considered to be reused outside of oilfields with potential human and ecological exposure pathways (e.g., agricultural irrigation).*

> ***Recommendation 3.6.2.*** *More holistic approaches to water quality testing (e.g., non-targeted chemistry and cell line assays) could be integrated into produced water discharge permit requirements as is being considered for municipal wastewater recycling for potable reuse.*

3.7. Summary: Findings, Conclusions, and Recommendations

Our primary conclusion is that the SB 1281 dataset—on its own—lacks much of the information required to adequately assess produced water quality in California in the context of human health and environmental risk management where likely exposure pathways exist. This is primarily an issue for produced water that is discharged to the surface and reused outside of the oilfield (e.g., discharge to unlined produced water ponds or for irrigation of food crops). While there is an emerging body of data reported pursuant to the waste discharge requirements for agricultural irrigation and unlined produced water ponds, the data are disparate, often not digitized, and not electronically integrated with the SB 1281 dataset. More specific produced water quality and spatial information is needed, especially for produced water that is discharged to the surface and reused outside of the oilfield. However, even if more comprehensive produced water quality information was available, aspects of our analyses suggest that many of the treatment technologies currently in use may lack the efficacy to remove chemicals of concern that have been disclosed as used in oil and gas development in the State of California. However, more advanced treatment technologies are available that are capable of meeting specific water quality objectives for many reuse options.

There are a number of ways that the SB 1281 dataset could be modified to help address these data gaps in combination with other data sources. Below, we provide detailed findings and conclusions that emerged from the analyses undertaken in this chapter and detail our policy and research recommendations. The associated recommendations will help to inform improvements in the human health and environmental risk management of produced water handling in California, in particular for produced water that is discharged to the surface and reused outside the oilfield.

FCR 3.1. Produced water quality in California *(Chapter 3, Section 3.2)*

Finding 3.1.1. Salinity is reported in SB 1281 as above or below 10,000 mg/L TDS. With the exception of salinity, produced water quality parameters are not reported to SB 1281.

Finding 3.1.2. Chemical constituents that are or may be in produced water (e.g., residual petroleum hydrocarbons, chemical additives, geogenic compounds, daughter products, and degradation byproducts of chemical transformations) are not required to be reported to SB 1281.

Conclusion 3.1. SB 1281 is inadequate in reporting water quality parameters. An understanding of produced water quality is essential to assess the potential for environmental and human health hazards, risks and impacts associated with produced water, to inform produced water management, and to identify opportunities for reuse outside of the oilfield.

Recommendation 3.1.1. Require the SB 1281 dataset to include reporting of actual TDS measurements for all produced water at the level of the oil-water separator or similar point of aggregation.

Recommendation 3.1.2. Priority water quality parameters and other approaches to water quality monitoring should be identified by a convened group of human and environmental health scientists with expertise in produced water quality and human and environmental health.

Recommendation 3.1.3. SB 1281 should require reporting of all priority health- and environmentally-relevant water quality parameters for produced water discharged to the surface (e.g., to agricultural irrigation and unlined produced water ponds).

FCR 3.2. Spatial tracking of produced water from production to disposal and reuse *(Chapter 3, Section 3.2)*

Finding 3.2. The SB 1281 dataset includes water disposition categories that are informative, but produced water disposition reporting lacks adequate spatial resolution. For instance, it may be reported that produced water from a given well in a particular oilfield and production zone was sent to an unlined produced water pond facility, but which pond facility is not clear.

Conclusion 3.2. The lack of spatially-explicit tracking of produced water in the SB 1281 dataset makes it difficult to assess and manage potential environmental, ecological, and human health hazards risks and impacts, at spatial scales relevant to human and environmental exposures.

Recommendation 3.2. Update the SB 1281 dataset requirements to enable regulators to trace the geographic and geological source and fate of produced water to support assessments of environmental and exposure pathways, particularly for produced water discharged to the surface. For example, the use of unique spatial identifiers should be considered: these could include latitude and longitude coordinates for specific produced water pond facilities or water recipient facility locations where water is intended for reuse (e.g. agricultural irrigation).

FCR 3.3. Other produced water quality datasets *(Chapter 3, Section 3.3)*

Finding 3.3.1. Analysis of existing produced water quality information in the State of California currently requires collation from multiple data sources and data formats.

Finding 3.3.2. The existing data may not sufficiently characterize produced waters to allow evaluation with respect to impacts on human and ecological health.

Conclusion 3.3. To assess and manage potential risks and opportunities for produced water discharged to the surface and reused outside of the oilfield, there is a need for a comprehensive and current produced water quality database in the State of California.

Recommendation 3.3. Agencies with jurisdiction should require comprehensive produced water quality monitoring information be disclosed and consolidated into an integrated, digitized, and publicly available database, especially for produced water that is discharged to the surface or reused outside of the oilfield. The SB 1281 dataset, in conjunction with Geotracker, may be a relevant repository for this information.

FCR 3.4. Chemical use in oil and gas operations *(Chapter 3, Section 3.4)*

Finding 3.4.1. The SB 1281 dataset lacks the water quality information necessary to conduct quantitative risk assessments. However, other publicly available datasets can be used in concert with the SB 1281 dataset to assess produced water quality, including chemical additives disclosed as used in O&G operations.

Finding 3.4.2. Chemical additives reported to be used in O&G operations cannot always be identified, and when they can be, they may not be well-described. In datasets supplemental to the SB 1281 dataset, 630 unique chemical additives were identified as used in oil and gas wells and associated operations in California from 2011 – 2018. Nearly half of the disclosed chemical additives could not be definitively identified due to lack of a unique Chemical Abstract Service Registry Numbers (CASRNs). An analysis of available physical, chemical, and toxicological properties of identified chemicals used in O&G operations in California shows that many are poorly characterized and lack important data required to assess health hazards, treatment potential, and environmental fate and behavior.

Conclusion 3.4.1. Available chemical data suggest there are aquatic, air pollution, and carcinogenic chemical hazards associated with produced water in California.

Conclusion 3.4.2. Chemical additives that are not disclosed using CASRN cannot be definitively identified and cannot be evaluated in terms of their potential human health and environmental hazards, risks, and impacts. Available chemical data suggest that there are potential human and ecological health risks associated with produced water where exposure pathways exist.

Recommendation 3.4. All chemical additives used in any type of O&G operation—not just for well stimulation—in California should be required to be disclosed to a publicly available, digitized database. Agencies with jurisdiction could consider phasing out the use of chemicals or chemical mixtures whose identities cannot be verified or disclosed. Submitted data including chemical names, CASRN, and usage data (frequency, mass, or concentration) should be validated and verified. Environmental and toxicological profiles should be developed for chemical additives and, to the extent possible, chemical additive mixtures used in O&G operations that lack any publicly available information.

FCR 3.5. The SB 1281 dataset on produced water treatment categories *(Chapter 3, Section 3.5)*

Finding 3.5.1. The treatment categories used in the SB 1281 dataset are not sufficiently specific; they do not provide the detail necessary to determine which treatment process is being applied. Thus, treatment level cannot be accurately assessed in the context of responsible produced water beneficial reuse potential.

Conclusion 3.5.1. More detailed and specific reporting regarding treatment technologies and treatment trains is required for risk management of produced water, in particular produced water that is discharged to the surface and reused outside of the oilfield.

Recommendation 3.5.1. The SB 1281 dataset on treatment should be modified to require detailed information on the specific treatment process or processes used. The current categories are overly broad and should be abandoned and replaced by detailed descriptions of the actual treatment technology applied (e.g., three-phase separator, WEMCO, ion exchange, walnut-shell filters). The sequence of technologies used to treat produced water should be identified, especially for produced water that is discharged to the surface or reused outside of the oilfield.

Finding 3.5.2. No one treatment technology can be expected to adequately remove all potential chemicals of concern that can exist in produced water, but treatment trains can be developed for functionally complete treatment. Of the screened technologies, reverse osmosis and biological treatment have the greatest potential to treat chemical additives of concern that may be found in produced water intended for reuse outside of the oilfield.

Conclusion 3.5.2.1. Certain chemical constituents are well-proven to be removed by state-of-the-art physical, chemical, and biological treatment approaches. However, some chemical additives reported as used in O&G development operations in California are not expected to be effectively removed by commonly-used physical, chemical, and biological treatment technologies.

Conclusion 3.5.2.2. Further research and applied investigations are warranted to assess the efficacy of removal of chemical additives and other chemical constituents, particularly for applications of produced water discharged and reused at the surface.

FCR 3.6. Evolving chemical landscapes and produced water reuse *(Chapter 3, Section 3.6)*

Finding 3.6.1. Produced water quality is highly heterogeneous across geographic and geological space and operators use a wide variety of chemical additives in their operations. While disclosure of chemicals is expected to result in significantly more information about chemical use, questions remain as to how these chemicals may transform under high temperature and pressure and in the presence of other chemical constituents in oilfield reservoirs and associated processes.

Finding 3.6.2. Produced water can meet traditional water quality standards and still pose toxicological, mutagenic, and carcinogenic risks when there is a human or ecological exposure pathway. These mechanisms are difficult to ascertain without non-targeted or bioanalytical testing.

Conclusion 3.6. Answering questions of produced water quality and associated public health and ecological risks is aided, but not satisfied by, chemical disclosure. While pollutant-by-pollutant chemical disclosure and monitoring is important, produced water reuse outside of the oilfield with human and ecological exposure potential could benefit from more holistic approaches to water quality testing (e.g., non-targeted chemistry and cell line assays) that are not directly focused on understanding all of the chemicals in the mixture. Existing water reuse frameworks that address evolving chemical landscapes (e.g., municipal wastewater) may inform produced water treatment, monitoring, and management.

Recommendation 3.6.1. Agencies with jurisdiction should ensure that the best available research informs their regulations. To this end, they should convene water quality and public health experts to conduct non-targeted water quality research on produced water that is currently or is being considered to be reused outside of oilfields with potential human and ecological exposure pathways (e.g., agricultural irrigation).

Recommendation 3.6.2. More holistic approaches to water quality testing (e.g., non-targeted chemistry and cell line assays) could be integrated into produced water discharge permit requirements as is being considered for municipal wastewater recycling for potable reuse.

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Chapter 4

Potential Impact to Groundwater Resources from Disposal of Produced Water into Unlined Produced Water Ponds in the San Joaquin Valley

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4.0. Abstract

Senate Bill (SB) 1281 was crafted to improve the transparency in the treatment, reuse, and disposal of produced water. The data provided on the source, treatment, reuse, and disposition of water by the oil and gas (O&G) industry generates information that can be used by the public, researchers, decision makers, and other stakeholders to inform improved stewardship of crucial State water resources.

In this chapter, we assess the usefulness of the SB 1281 dataset to assess the risks posed to groundwater resources by the disposal of produced water into unlined produced water ponds in California. We combined information reported in the SB 1281 dataset with information from other datasets to answer the following questions: (1) Where in California are unlined produced water ponds located and what is the volume of produced water sent to these ponds? (2) Are there groundwater resources, as measured in levels of total dissolved solids (TDS), present in areas of unlined produced water ponds? (3) Are there documented cases of unlined produced water ponds causing groundwater contamination?

According to the SB 1281 dataset, there are 541 active and 509 inactive unlined produced water ponds in California—nearly all of which lie in the southern San Joaquin Valley. Between 2015 Q1–2017 Q4, more than 10,800 acre-feet (AF) of produced water was disposed onto land and into unlined produced water ponds in the San Joaquin Valley. While this volume is large, it accounts for a relatively small percent (~1.5%) of the 708,720 AF of produced water disposed and reused in the San Joaquin Valley and reported in the SB 1281 dataset.

Because the SB 1281 dataset tracks the disposition (e.g., reuse, disposal) but not the destination of produced water, the SB 1281 dataset cannot be used to determine the origin of produced water discharged into specific produced water ponds, nor to estimate cumulative volumes of disposal at individual produced water ponds over time. Potential impact to groundwater resources is in part a function of cumulative discharge volumes.

There appears to be deep (>900 m below surface) groundwater resources having levels of TDS < 3,000 milligrams per liter (mg/L) in the southeastern portion of the San Joaquin Valley near the Sierra Nevada Mountains. There is a transition to surficial (<300 m below surface) groundwater resources in the southcentral portion of the San Joaquin Valley, with levels of TDS < 3,000 mg/L. Moving further west, groundwater transitions to surficial, brackish resources (levels of TDS between 3,000 and 10,000 mg/L). These findings indicate that in the southeastern and southcentral portion of the San Joaquin Valley, groundwater resources with levels of TDS < 3,000 mg/L are vulnerable to degradation from disposal of saline produced water (>10,000 mg/L TDS) into unlined produced water ponds. The southcentral portion of the San Joaquin Valley is particularly vulnerable because groundwater resources in this area are limited to surficial deposits.

To better understand site-specific disposal conditions (e.g., cumulative disposal volume) and hydrogeologic conditions (e.g., thickness of the vadose zone, physical heterogeneity), we examined a produced water pond facility—the McKittrick 1 & 1-3 Facility. These conditions determine the impact to groundwater resources from disposal of saline produced water into unlined produced water ponds, and allow us to document impact to groundwater resources from this practice. The McKittrick 1 & 1-3 Facility is one of the largest facilities in California where saline produced water is currently discharged to unlined produced water ponds. Cumulative discharge over a 60-year period is estimated at more than 189,120 AF. Monitoring wells show trends of increasing concentrations of TDS, chloride, and boron; and enrichment in water isotopes $\delta^{18}O$ and deuterium, to values indicative of produced water near the McKittrick 1 & 1-3 Facility; these trends indicate contamination of the regional aquifer (Central Valley Regional Water Quality Control Board (CVRWQCB), 2019).

Questions Addressed in Chapter 4

To better understand the potential for impact to groundwater resources attributable to the disposal of produced water in unlined produced water ponds, we investigate three questions:

- **Question 4.1.** Where in California are unlined produced water ponds located and what is the volume of produced water sent to these ponds?
- **Question 4.2.** Are there groundwater resources, as measured in levels of TDS, in areas of unlined produced water ponds?
- **Question 4.3.** Are there documented cases of unlined produced water ponds causing groundwater contamination?

4.1. Introduction

Oil and gas production occurs throughout California but is concentrated in the southern portion of the state, principally the San Joaquin Valley (Lindsey et al., 2018). The San Joaquin Valley is one of the most productive oil and gas producing basins in the U.S., with more than 100,000 oil and gas wells (Hosford Scheirer, 2007). In the San Joaquin Valley, on average, approximately 16 barrels of water are produced with each barrel of oil (CVRWQCB, 2017a). This production has resulted in the generation of large volumes of water associated with oil and gas development. A portion of this produced water is discharged to the surface in lined and unlined produced water ponds. Produced water is water brought to the surface during oil and gas production. It may originate in the formation being produced, or it may include water that was previously injected into the formation.

The State Water Resources Control Board (State Water Board, SWB) defines a produced water pond as “an earthen structure, lined or unlined, that is used to store, dispose, treat and/or separate liquids; and of which produced water comprises a significant amount of liquid” (SWB, 2019). An active produced water pond is defined as a pond that is currently receiving produced water (SWB, 2019). An inactive produced water pond is a pond with a physical connection to a produced water source, but not currently receiving produced water (SWB, 2019). Inactive produced water ponds also include “historical ponds,” defined as having no physical connection to a produced water source and that appear to have been out of service for an extended period of time (SWB, 2019).

According to the SB 1281 dataset, there are 541 active and 509 inactive unlined produced water ponds in California. A majority lie within the Central Valley Regional Water Quality Control Board (CVRWQCB) jurisdiction in the southern portion of the San Joaquin Valley within the Tulare Lake Hydrologic Region (SWB, 2019).

In California, facilities containing unlined produced water ponds vary from single ponds to large complexes consisting of multiple ponds. In the large complexes, produced water enters smaller ponds that provide for floatation and skimming of remaining undissolved oil. Water from these ponds then flows to larger ponds for evaporation and percolation (Jordan et al., 2015). The fraction of water typically lost to evaporation is unclear. Evaporation would serve to concentrate dissolved salts in solution. In practice, the year-round flow of water to these ponds indicates that most water percolates to subsurface media because evaporation rates are low in the winter (Jordan et al., 2015). Since the purpose of unlined produced water ponds is to percolate produced water into subsurface media, this wastewater disposal provides a direct pathway of contaminants to groundwater resources of current or potential future use. However, impact to groundwater resources would be dependent on site-specific disposal conditions (e.g., cumulative disposal volume) and hydrogeologic conditions (e.g., thickness of the vadose zone, or the unsaturated zone above the water table; physical heterogeneity).

The potential for impact to groundwater resources from the disposal of produced water into unlined produced water ponds is well documented. In 1987, in a report to Congress, the U.S. EPA stated that, “The use of evaporation and percolation pits has the potential to degrade usable ground water through seepage of produced water constituents into unconfined, freshwater aquifers underlying such pits” (U.S. EPA, 1987).

In 2015, in an independent scientific assessment of well stimulation in California, the California Council on Science and Technology (CCST) and the Lawrence Berkeley National Laboratory (LBNL) concluded that the disposal of produced water in unlined produced water ponds poses a risk to groundwater resources in California and that produced water discharged to these ponds should contain non-hazardous concentrations of chemicals or their use should be phased out in the future (Jordan et al., 2015; Stringfellow et al., 2015). They stated further that groundwater investigations should be conducted to determine if past disposal activities have impacted groundwater resources in the vicinity of these unlined produced water ponds (Jordan et al., 2015). Groundwater investigations are ongoing at a number of facilities containing unlined produced water ponds, including the McKittrick 1 & 1-3 Facility (CVRWQCB, 2019).

Groundwater resources are especially important in arid regions of the country experiencing rapid population growth, including the San Joaquin Valley. In these regions, surface water rights for irrigation are often fully appropriated, and drought, population growth, and climate change are expected to further exacerbate water demand (Roy et al., 2012). An intense drought from 2012–2016 resulted in substantial groundwater depletion in the San Joaquin Valley and the Central Valley—a world-class agricultural production region that supplies over one-third of the country’s vegetables and two-thirds of the country’s fruits and nuts (Xiao et al., 2015; California Department of Food and Agriculture, 2018).

Produced water reuse represents potential opportunities to create a resource out of a waste stream. However, beneficial use of produced water (e.g. irrigation for agriculture) requires the identification and quantification of chemical compounds present, sufficient information on physiochemical and biological properties of compounds present, and adequate information on toxicity to estimate safe aqueous concentrations. This fundamental information is lacking for many constituents in oil and gas wastewater (DiGiulio & Shonkoff, 2017).

To address deficiencies in the evaluation and permitting of unlined produced water ponds in its jurisdiction, the CVRWQCB developed a work plan in 2014 and issued notices of violation (NOVs) to facility operators not having Waste Discharge Requirements (WDRs). The following year, the CVRWQCB issued a directive to 77 facility operators to provide information on daily discharge rates to produced water ponds and to analyze for constituents of concern in effluent discharged to unlined produced water ponds (CVRWQCB, 2015a, 2015b). Chemical characterization included analysis for TDS, chloride, boron, other trace elements (e.g., arsenic, strontium, thallium, lithium), metals, petroleum hydrocarbons, polynuclear aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) including benzene, toluene, ethylbenzene, xylenes (BTEX components), and radionuclides (CVRWQCB, 2015c).

More recently, the CVRWQCB proposed the development of three general orders to facilitate permitting the operation of produced water ponds. The permits would be based on the ability of a facility operator to meet the discharge requirements in the Water Quality Control Plan for the Tulare Lake basin, and beneficial use of groundwater in the vicinity of produced water ponds (CVRWQCB, 2017a, 2017b, 2017c).

The CVRWQCB set maximum salinity effluent limits for wastewaters in unlined produced water ponds overlying groundwater with existing or probable beneficial uses at 1,000 μS/cm electrical conductivity, 200 mg/L chloride, and 1 mg/L boron. If a facility operator cannot meet the Tulare Lake basin effluent requirements, the operator may submit an application for an exception and must participate in the Central Valley Salinity Alternatives for Long-Term Sustainability (CV-SALTS) program (CVRWQCB, 2017a, 2017b, 2017c). The CV-SALTs program is a stakeholder effort to develop comprehensive salt and nitrate management plans in the Central Valley (CVRWQCB, 2018a). However, it was the intent of the CVRWQCB that facilities having outdated WDRs would also apply for coverage under one of the general orders (CVRWQCB, 2017a, 2017b, 2017c).

The SB 1281 dataset offers a more comprehensive view of water handled by the industry than previously available. In this chapter we assess the usefulness of the SB 1281 dataset to assess the risks to posed to groundwater resources by the disposal of produced water into unlined produced water ponds in the San Joaquin Valley, and supplement this discussion with other data sources.

To better understand the potential impact to groundwater resources from disposal of produced water in unlined produced water ponds, we pose three questions:

1. Where in California are unlined produced water ponds located and what is the volume of produced water sent to these ponds?

2. Are there groundwater resources, as measured in levels of total dissolved solids (TDS), in areas of unlined produced water ponds?

3. Are there documented cases of unlined produced water ponds causing groundwater contamination?

4.2. Locations of produced water ponds in California and volume of produced water sent to unlined produced water ponds

4.2.1. Number and Locations of Produced Water Ponds in California

Based on the latest SWB Produced Water Pond Status report, there are 1,229 lined and unlined produced water ponds in California (Table 4.1) (SWB, 2019). All produced water pond facilities are located in the Central Coast, Santa Ana, Los Angeles, and the Central Valley regional water board jurisdictions, as illustrated in Figure 4.1. Most (1,093 out of

1,229, or 89%) produced water ponds lie within the CVRWQCB jurisdiction (Table 4.1; Figure 4.2). There are only two produced water ponds in the Santa Ana Region, both of which are unlined (Table 4.1). Most produced water ponds under the Central Coast and Los Angeles Water Quality Control Board jurisdictions are lined, 47 of 56 (84%) and 76 of 78 (97%) of produced water ponds, respectively (Table 4.1).

Table 4.1. Summary of active, inactive, lined, and unlined produced water ponds in Regional Water Board jurisdictions in California.

Regional Water Board	**Active Ponds**		**Inactive Ponds**		**Total Ponds**	
	Lined	Unlined	Lined	Unlined	Lined	Unlined
Central Coast	32	9	15	0	47	9
Los Angeles	76	0	0	2	76	2
Central Valley	31	530	25	507	56	1,037
Santa Ana	0	2	0	0	0	2

There are 1,050 unlined produced water ponds in California, nearly all of which (1,037) are located within the CVRWQCB region (Table 4.1). For this reason, our analysis focuses on unlined produced water ponds in the CVRWQCB region. Approximately half (530 of 1,037, or 51%) of unlined produced water ponds in the CVRWQCB region are active (Table 4.1, Figure 4.3).

The SWB graphically illustrates the locations of 660 produced water pond facilities (facilities often have multiple ponds) on its Geotracker website (Figure 4.3) (SWB, 2018). Not all produced water pond facilities are illustrated on the SWB Geotracker site (Figure 4.1). For instance, the SE Taft (New) produced water pond facility near Taft (southwest of Bakersfield), consisting of six unlined oil-water separation ponds and 23 unlined produced water ponds, is listed in the SWB water pond status report but not on the Geotracker site.

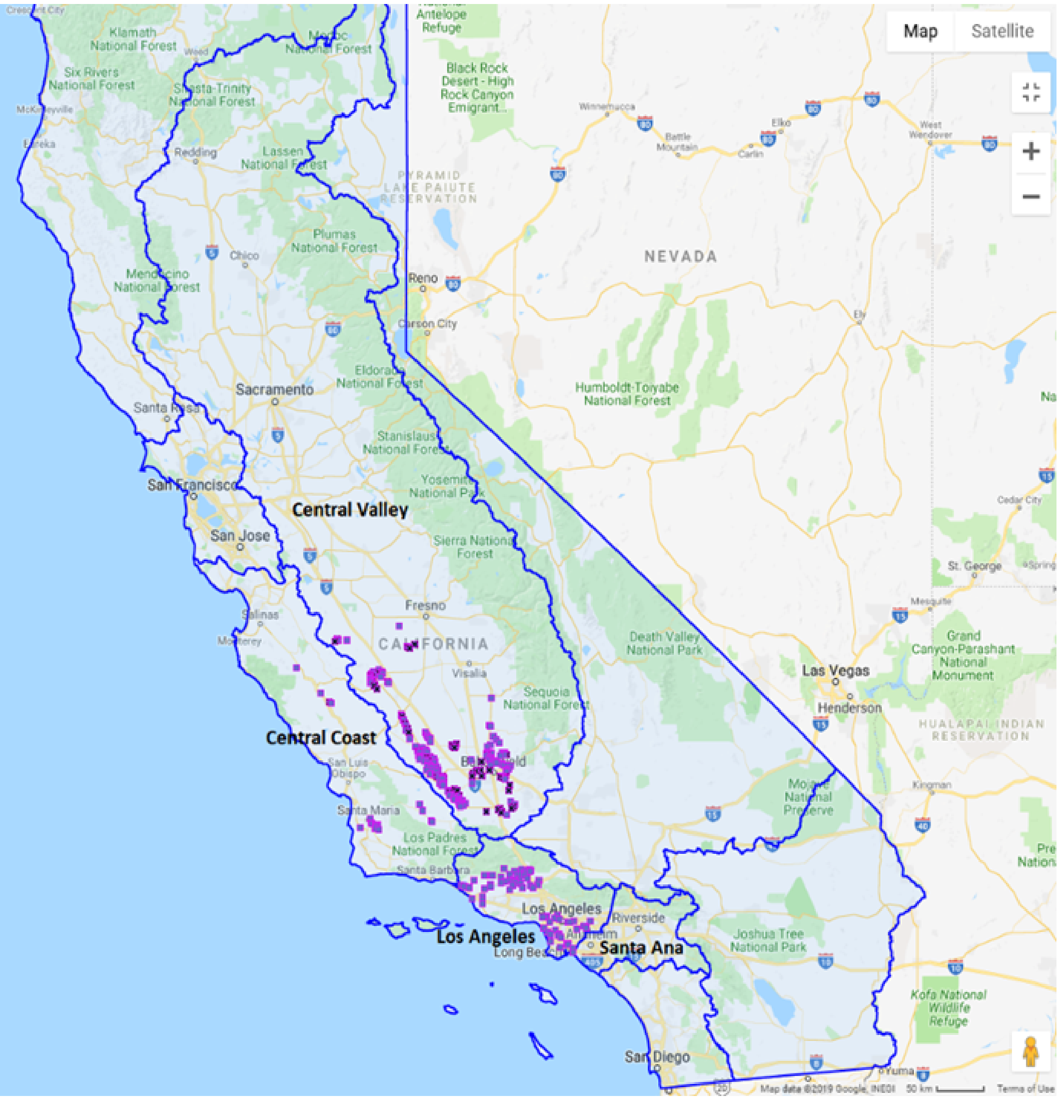


Figure 4.1. Geographic location of the 660 produced water pond facilities (in magenta dots) in State Water Board jurisdictions. Source: SWB Geotracker website (SWB, 2018).

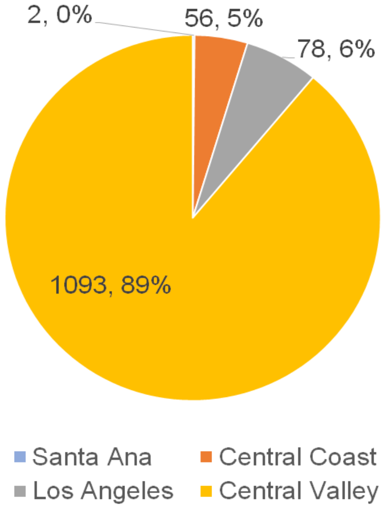


Figure 4.2. The Regional Water Quality Control Board reporting of the 1,229 produced water ponds. Source: SWB produced water pond status report (SWB, 2019). (Note: there are only 2 produced water ponds located in Santa Ana (blue), or <0.002% of the total found in the state.)

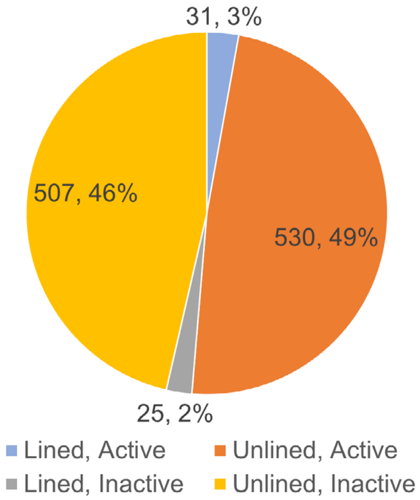


Figure 4.3. The proportion of lined, unlined, active, and inactive produced water ponds in the Central Valley Regional Water Quality Control Board Region. Source: SWB Produced Water Pond Status Report (SWB, 2019).

Geographically, nearly all unlined produced water ponds in California are located in the Tulare Lake Hydrologic Region in the southern half of the San Joaquin Valley. The San

Joaquin Valley occupies the southern two-thirds of the Central Valley. The Tulare Lake Hydrologic Region consists of seven groundwater subbasins with varying hydrogeologic conditions between and within subbasins. Most unlined produced water ponds lie within the Kern County subbasin, with lesser numbers of unlined produced water ponds in the Pleasant Valley subbasin and the southwestern Kettleman Plain area (Figure 4.4).

4.2.2. Volume of Produced Water Discharged to Unlined Produced Water Ponds in the San Joaquin Valley

Between 2015 Q1 and 2017 Q4, 708,220 acre-feet (AF) of produced water was generated in the San Joaquin Valley, resulting in an average yearly generation of 236,240 AF of produced water (Table 4.2) (DOGGR, 2019). Unlike in Chapter 1, various quarters of reporting were not weighted to potentially increase reliability.

Table 4.2. Methods of disposal of produced water in the San Joaquin Valley reported between 2015 Q1 and 2017 Q4 in the SB 1281 dataset (1 acre-foot=325,851 gallons).

Disposal Method	**Volume (acre-feet)**	**Volume (billions of gallons)**	**Percent**
Sump (unlined)	9,546.08	3.11	1.35
Surface discharge - land	1,256.94	0.41	0.18
Sump (lined)	1.92	<0.01	<0.01
Subsurface injection - in oil field by operator	525,436.14	171.21	74.14
Sale/Transfer - to other operator or oil field	32,431.97	10.57	4.58
Operator's facilities within oil field	4,549.66	1.48	0.64
Well stimulation treatment	13,080.38	4.26	1.85
Drilling, well work, and well abandonments	1,808.98	0.59	0.26
Sale/Transfer - domestic use	100,545.77	32.76	14.19
Surface water discharge	199.89	0.07	0.03
Domestic sewer system	<0.01	<0.01	<0.01
Other	19,861.89	6.47	2.80
Total	708,720	230.94	100.00

The categories of produced water disposal summarized in Table 4.2 are described in the Water Use Dictionary provided by the Division of Oil, Gas, and Geothermal Resources (The Division, DOGGR, 2019). Underground injection was the most common method of produced water disposal (74.14%), followed by sale/transfer - domestic use (14.19%) (DOGGR, 2019).

Approximately 92% of produced water disposed on land, and 96% of produced water disposed in unlined produced water ponds, was saline (>10,000 mg/L TDS), according to the SB 1281 dataset. Disposal in lined produced water ponds was insignificant, accounting for less than 0.0003% of total discharge during this period (DOGGR, 2019). As discussed in Chapter 1 (Abraham et al., 2019), under the reporting requirements for SB 1281, underground injection for disposal in Underground Injection Control (UIC) wells is not distinguished from underground injection for enhanced oil recovery (EOR).

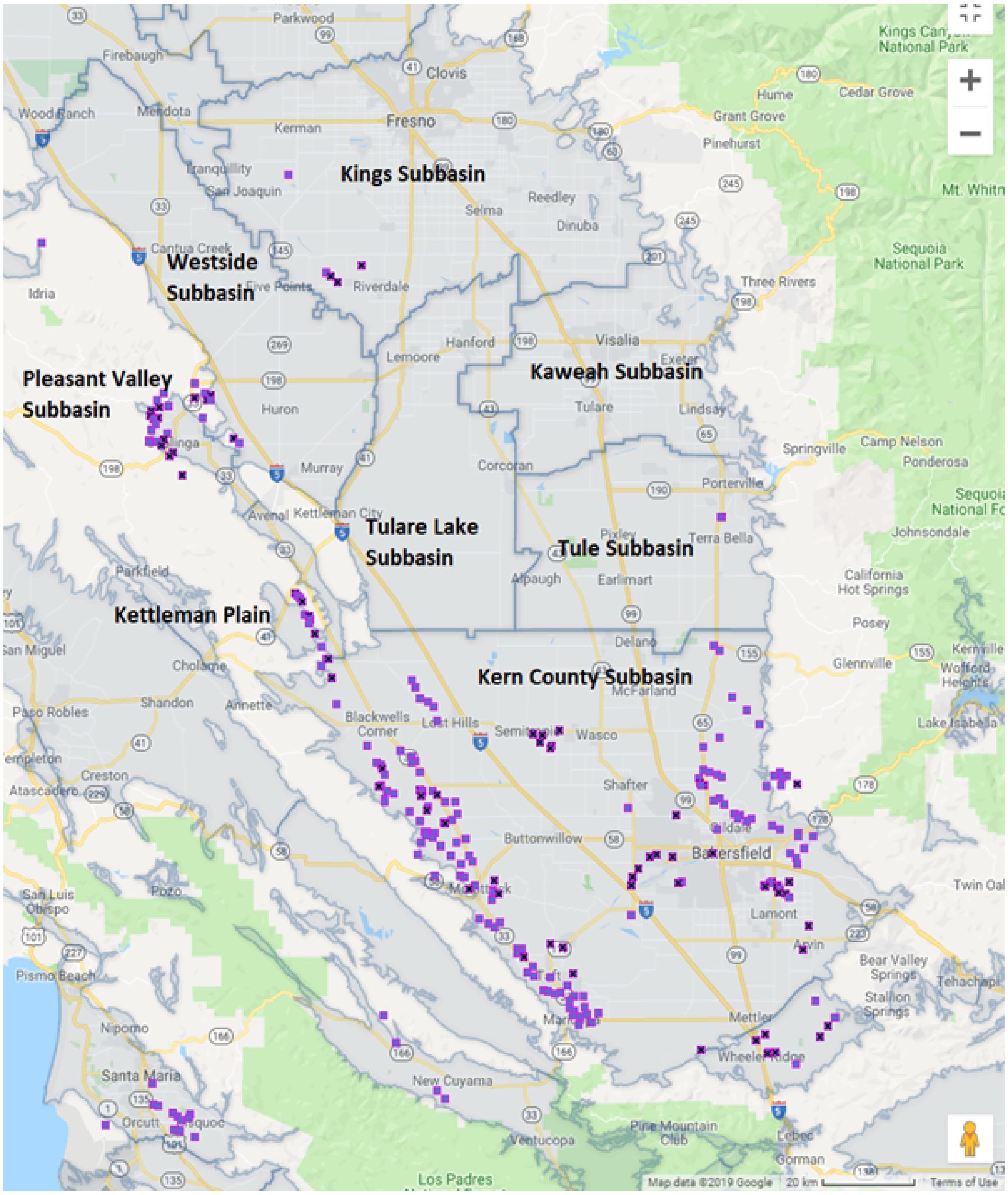


Figure 4.4. Location of produced water pond facilities and groundwater subbasins in the Tulare Lake Hydrologic Basin. Source: SWB Geotracker website (SWB, 2018).

Although the proportion of produced water disposed to land is small compared to underground injection, the absolute volume of disposal is nevertheless large. Between 2015 Q1–2017 Q4, 10,803 AF (equivalent to about 3,601 AFY) of produced water was disposed to land and into unlined produced water ponds. Of this volume, 12% was disposed to the soil surface while 88% was disposed into unlined produced water ponds.

> ***Finding 4.1.1.*** *Reporting pursuant to SB 1281 indicates that 3,182 AFY of produced water is currently disposed into unlined produced water ponds in the San Joaquin Valley.*

However, the annual volume of produced water disposed to unlined produced water ponds is in question. According to facility discharge records, the annual disposal volume of produced water to unlined produced water ponds at one facility—the McKittrick 1 & 1-3 Facility—is on average 3,152 AFY (CVRWCB, 2018c). This amount nearly equals the total disposal volume of produced water reported to be disposed in unlined produced water ponds in the entire San Joaquin Valley (about 3,182 AFY). While the McKittrick 1 & 1-3 Facility is one of the largest unlined produced water pond facilities in the San Joaquin Valley, it is unlikely that this facility accounts for nearly the entire disposal volume in the San Joaquin Valley, which has a number of other large unlined disposal facilities. Also, facility discharge records indicate that the nearby McKittrick 1-1 Facility discharges approximately 1,059 AFY into unlined produced water ponds. The combined discharge amount for the two McKittrick facilities equals 4,211 AFY—greater than the disposal volumes for the entire San Joaquin Valley as reported in the SB 1281 dataset. A review of all facility files is necessary to compare annual discharge volumes in the SB 1281 dataset with discharge volumes reported by facility operators. This review would better evaluate apparent underreporting of discharge of produced water to unlined produced water ponds in the SB 1281 dataset.

> ***Finding 4.1.2.*** *A review of discharge records at the McKittrick 1 & 1-3 Facility (a single facility) indicates that on average 3,152 AFY is disposed into unlined produced water ponds at this facility.*

> ***Conclusion 4.1.*** *Considering the numerous active facilities of comparable size to the McKittrick 1 & 1-3 Facility in the San Joaquin Valley—including the McKittrick 1-1 Facility where 1,059 AFY of produced water is currently disposed into unlined produced water ponds—the accuracy of volumes reported pursuant to SB 1281 is in question.*

> ***Recommendation 4.1.*** *All facility records should be reviewed to verify that reporting under SB 1281 accurately reflects volumes of disposal of produced water into unlined produced water ponds in the San Joaquin Valley.*

What appears to be an underreporting of produced water discharge to unlined produced water ponds may also be the result of unclear or poorly-resolved disposition categories in the SB 1281 dataset. The volumes discussed in this analysis as disposed to unlined produced water ponds all come from entries tagged with the “01” disposal method code, or “Sump (unlined),” as shown in Table 4.2. However, there is another disposal method, “06,” which refers simply to “Other” disposal methods than those listed in Table 4.2. According to the Data Dictionary for Water Report Form (DOGGR, 2019), the “Other” category encompasses water that is “disposed of by another method, such as commercial disposal, industrial use, non-class II wells, etc…" If an O&G field operator transfers produced water to a commercial water disposal facility which subsequently discharges it into unlined produced water ponds, these volumes would not necessarily be reported as disposed into unlined produced water ponds. Given that the volume of produced water reported under this category in the SB 1281 dataset (19,862 AF, or about 6,621 AFY) is more than double the volume reported as disposed to unlined produced water ponds, this unclear classification could account for some of the apparent underreporting of disposal to unlined produced water ponds. The ambiguity of this category is therefore problematic when attempting to clearly answer the straightforward question of, "How many AF are disposed to unlined produced water ponds?"

> ***Finding 4.2.1.*** *The volume of produced water reported disposed by "other" methods is more than twice the volume of produced water reported disposed into unlined produced water ponds.*

> ***Finding 4.2.2.*** *The SB 1281 dataset includes a disposal method category "06 – Other," which may include, but not be limited to, disposal to unlined produced water ponds, if those produced water ponds are managed by a commercial entity. It is unclear what portion, if any, of this produced water has been disposed of in unlined produced water ponds operated by commercial entities.*

> ***Conclusion 4.2.*** *Categories such as "Other" may make parsing out relevant information challenging or impossible, rendering even some straightforward questions unanswerable.*

> ***Recommendation 4.2.*** *At a minimum, the SB 1281 dataset should be modified to include "Transfer to Commercial Disposal" to the disposition codes. A more useful code in this case would include the specific method of disposal (e.g. "Commercial Disposal to Unlined Sump").*

Since wastewater reporting under SB 1281 did not commence until 2015, the proportion of wastewater disposed in produced water ponds in previous years is unknown. However, given that nearly half of unlined produced water ponds are now inactive or closed (SWB, 2019), it is likely that the proportion and volumes of wastewater disposed using unlined produced water ponds was higher in previous years.

For instance, in 2001, in a facsimile transmittal from the Valley Water Disposal Company (VWDC) to the CVRWQCB, the VWDC reported disposal of 70,000 barrels per day (bbd) at the McKittrick 1, 1-1, and 1-3 Facilities; 100,000 bbd at the McKittrick 6, 6A, and 6B Facilities; and 15,000 bbd at the McKittrick 7 Old and New Facilities (VWDC, 2001). This reporting results in a cumulative disposal volume of 185,000 barrels per day, or over 8,700 AFY at the McKittrick facilities alone—2.4 times the amount reported for the entire San Joaquin Valley in the SB 1281 dataset. Also, Bean and Logan (1983) estimate that 570,000 AF of produced water containing 15 million tons of salt was disposed of in sumps or shallow injection wells between 1900 and 1980 in southwestern Kern County alone.

There are five reporting treatment categories for produced water in the SB 1281 dataset—deoiling, disinfection, desalination, membrane treatment, and other treatment (DOGGR, 2019). Between 2015 Q1–2017 Q4, treatment of produced water prior to discharge into unlined produced water ponds was primarily through deoiling (94.86%). Deoiling consists of separation of hydrocarbons from water by use of gravity, physical, chemical filtering, and/or absorption processes (Shonkoff et al., 2019). There were no reported cases of desalination to reduce TDS prior to discharge into unlined produced water ponds in the San Joaquin Valley.

Because reporting under SB 1281 tracks the disposition (e.g., reuse, disposal) but not destination of produced water, the SB 1281 dataset cannot be used to determine the origin (e.g., field, depth, formation) of produced water discharged into specific produced water ponds. The SB 1281 dataset also cannot be used to track annual or cumulative discharge volumes to individual produced water pond facilities. Potential impact to groundwater resources from disposal of produced water into unlined produced water ponds is in part a function of cumulative discharge volume.

> ***Finding 4.3.1.*** *The overall volume and categorical disposition (e.g., reuse, disposal) of produced water is currently reported under SB 1281, but not the spatially-explicit destination.*

> ***Conclusion 4.3.1.*** *Without spatially-explicit destination information, it is not possible to trace produced water from a particular oil field or formation to a particular produced water pond, and volumes of produced water discharged to a particular unlined produced water pond cannot be ascertained.*

> ***Recommendation 4.3.1.*** *Data reported under SB 1281 should include spatially-explicit destination information (e.g., facility name and latitude/longitude) in addition to disposition of produced water to improve the ability to assess the risk posed to groundwater resources from disposal of produced water into unlined produced water ponds.*

> ***Finding 4.3.2.*** *Potential impact to groundwater resources from disposal of produced water into unlined produced water ponds is, in part, a function of annual and cumulative discharge volumes and the quality of discharged produced water.*

> ***Conclusion 4.3.2.*** *Though this information is necessary to assess potential impacts of discharging to unlined ponds, data reported to SB 1281 is currently not useful to determine annual or cumulative discharge volumes to individual produced water pond facilities.*

> ***Recommendation 4.3.2.*** *Annual and cumulative discharge volumes should be assessed at active produced water pond facilities.*

4.3. Groundwater resources in areas of unlined produced water ponds

In this section, we evaluate the risk posed to groundwater resources by unlined produced water ponds by examining the presence of unlined produced water ponds in areas having groundwater resources.

4.3.1. Background on Hydrogeology of the Tulare Lake Hydrologic Basin

There are significant groundwater resources in the Tulare Lake Hydrologic Basin. Page (1973) defined fresh groundwater resources in the San Joaquin Valley as water having a maximum specific conductance of 3,000 micromhos per centimeter (μS/cm), about 2,000 mg/L TDS. Kang and Jackson (2016) estimate that 1,010 cubic kilometers (km^3) of fresh (<3,000 mg/L TDS) and 1,282 km^3 of brackish (3,000 – 10,000 mg/L TDS) groundwater exists to a depth of 3 km in the Tulare Lake basin. Previous estimates of groundwater reserves in the basin were limited to a depth of 305 m and 456 km^3 (Bertoldi et al., 1991).

Understanding where groundwater resources are present in areas of unlined produced water ponds in the Tulare Lake basin requires understanding the geology and hydrogeology of the area within and surrounding the basin. The salinity of groundwater in the southern portion of San Joaquin Valley and the Tulare Lake basin is affected by many factors, including: the origin of sediments (marine versus continental); sources and quality of stream and irrigation water percolating through unconsolidated deposits to recharge groundwater; evaporation and transpiration; geochemical processes such as ion exchange, mineral dissolution, and precipitation; and biological reactions that affect the oxidation/reduction state of groundwater (Fujii & Swan, 1995).

Groundwater in sediments of marine origin are generally higher in TDS than groundwater in sediments deposited in freshwater environments. Also, salinity generally increases with depth due to groundwater having more time to interact with rock and being less likely to be flushed by meteoric recharge (Stephens et al., 2018). Faulting can influence salinity by providing preferential pathways for groundwater flow or by inhibiting groundwater flow by causing low permeability strata to lie adjacent to permeable strata (Stephens et al., 2018). Stratigraphy can also affect salinity by influencing the movement of fresh meteoric water (Stephens et al., 2018).

There are places in the San Joaquin Valley where marine sediments have been sufficiently flushed by meteoric water to provide groundwater with TDS levels of less than 3,000 mg/L (Bertoldi et al., 1991). These areas are in the eastern portion of the Kern groundwater subbasin, where these formations are uplifted and recharged near the surface.

The two primary formations containing groundwater resources in the southern San Joaquin Valley are the Kern River and Tulare Formations, both of nonmarine origin (Hosford Scheirer & Magoon, 2007). The Kern River Formation is an important source of municipal and domestic drinking water in the eastern portion of the Kern County subbasin (CGWB, 2006). The Kern River Formation is derived from sediment from the Sierra Nevada Mountains, is moderately to highly permeable, and yields moderate to large quantities of water to wells (Hilton et al., 1963). The Tulare Formation is primarily derived from sediment from the Coastal Range, is moderately permeable, and is a major source of municipal and domestic water in the southcentral to southwestern portion of the San Joaquin Valley (CGWB, 2006; Hosford Scheirer, 2007).

The Corcoran Clay Member is a unit of the Tulare Formation, and is present throughout the central portion of the San Joaquin Valley (Hosford Scheirer & Magoon, 2007). Where present, this clay layer generally divides the groundwater flow system into an upper, semi-confined zone and a lower, confined zone (Williamson et al., 1989; Belitz & Heimes, 1990). However, thousands of long, large-diameter irrigation wells have perforated the Corcoran Clay and increased the hydraulic connection of aquifer systems above and below the Corcoran Clay (Williamson et al., 1989; Bertoldi et al., 1991). Hence, in locations where the Corcoran Clay underlies unlined produced water ponds, it is unlikely that it would form an effective barrier to the downward migration of contaminants.

Groundwater in the eastern portion of the Kern subbasin is primarily calcium bicarbonate waters in the shallow zones, increasing in sodium with depth (CGWB, 2006). Bicarbonate is replaced by sulfate and to a lesser degree by chloride in an east to west trend across the subbasin (CGWB, 2006). In general, concentrations of TDS in groundwater increase from east to west across the basin.

The Tulare and Kern River Formations also contain substantial reservoirs of petroleum. A review of U.S. Geological Survey (USGS) petroleum assessment units provide insight into locations where the Tulare and Kern River Formations have both groundwater associated with oil development and groundwater resources for potential municipal and domestic use. A more detailed discussion of formations of significance to groundwater resources and USGS petroleum assessment units is provided in Appendix 4.1.

4.3.2. Evaluation of Salinity in Surficial Groundwater in Proximity to Unlined Produced Water Ponds

Surficial groundwater resources having TDS levels < 3,000 mg/L exist in the vicinity of produced water ponds in the central, northwestern, and eastern portion of the Tulare basin. Given the proximity of produced water ponds to groundwater resources, produced water ponds present a risk to groundwater resources in these areas. Brackish groundwater resources having potential use exist in the western portion of the Kern County subbasin of the Tulare basin.

4.3.2.1. Methods

Most municipal and domestic water wells in the San Joaquin Valley are within 300 m of the surface. To evaluate TDS concentrations in surficial (defined here as less than 300 m below ground surface) groundwater at locations of unlined produced water ponds, we plotted the locations of produced water ponds and TDS concentrations of municipal and domestic water wells within the area of 34.9 to 36.3 latitude and -120.5 to -118.7 longitude of the NAD83 coordinate system. This area includes all unlined produced water ponds within the Tulare basin.

To determine the TDS concentrations of groundwater in domestic and public water supply wells within this area, we accessed: (1) the USGS national study on brackish groundwater (Stanton et al., 2017) and downloaded the associated dataset (Qi & Harris, 2017); (2) the USGS report on groundwater salinity mapping near selected oil fields in Central and Southern California (Metzger & Landon, 2018a, 2019b) and downloaded associated data (Metzger et al., 2018); and (3) data from the California State Water Board Groundwater Ambient Monitoring and Assessment (GAMA) GeoTracker Groundwater Information System (SWB, 2018).

Metzger & Landon (2018a, 2018b) and Metzger et al. (2018) obtained data on TDS levels of aqueous samples from 3,546 domestic and public water wells, of which 2,322 water wells had information on the bottom of the perforated interval. Most domestic and public water wells were within 330 m of land surface. Domestic and municipal water wells were within 3.2 km of the administrative boundaries of oil and gas fields. Data sources included the California Department of Water Resources (CDWR) Water Data Library, the California State Water Board Division of Drinking Water, the USGS National Water Information System (NWIS), the Water Replenishment District of Southern California, and the SWB GeoTracker database. When information on salinity was limited to specific conductance (SC), Metzger & Landon (2018a, 2018b) and Metzger et al. (2018) used the equation $TDS=0.718SC$, where TDS is in mg/L and SC is in microsiemens per centimeter (μS/cm). This equation had an R-squared value in excess of 0.98 and hence was reliable.

The CVRWQCB provides the centroid coordinates for 992 produced water ponds in its Produced Water Ponds Report (CVRWQCB, 2018a). Because nearly 96% of produced water ponds under the jurisdiction of the CVRWQCB are unlined and the CVRWQCB did not distinguish lined versus unlined produced water ponds in its locations, it was assumed for plotting purposes that all produced water ponds in the Tulare Lake basin were unlined.

To provide a perspective on the locations of produced water ponds in proximity to oil and gas fields, we determined the location of active, plugged, and abandoned oil and gas production wells (as of April 27, 2018) within the area of produced water ponds in the CVRWQCB region. We accessed metadata files from The Division dataset (DOGGR, 2019b). In The Division dataset, there are 35 code identifiers which include well status: new (N), active (A), idle (I), plugged and abandoned (P), and buried (B) and hydraulic fracturing: yes (Y), no (N). Buried wells are older wells not abandoned to current standards with approximate location.

In the State's Sources of Drinking Water Policy (SWB Resolution No. 88-63), all groundwater in the State is considered suitable, or potentially suitable, for municipal or domestic (MUN) beneficial use if the following conditions are met (SWB, 2006).

1. Groundwater has a level of TDS less than 3,000 mg/L or a specific conductance less than 5,000 μS/cm and can be reasonably expected to supply a public water system.

2. Groundwater is not contaminated by either natural processes or by human activity unrelated to the specific pollution incident and can be reasonably be treated for domestic use using either best management practices or best economically achievable treatment practices.

3. Groundwater can provide sufficient water to supply a single well capable of producing an average, sustained yield of 200 gallons per day.

4. An aquifer has not been exempted pursuant to 40 CFR § 146.4 for the purpose of underground injection of fluids associated with the production of hydrocarbons or geothermal energy.

To be consistent with the State's sources of drinking water policy conditions, conditions 2, 3, and 4 must be met for agricultural supply beneficial use and conditions 2 and 3 must be met for industrial service supply and industrial process supply beneficial use (CVRWQCB, 2017c). In this chapter we use TDS levels as a proxy for groundwater quality and beneficial use. Groundwater having a TDS level <3,000 mg/L is considered a groundwater resource. Groundwater having a TDS level between 3,000 and 10,000 mg/L is considered a potential groundwater resource.

4.3.2.2. Discussion

Throughout the eastern portion of the Tulare basin in Kern and Tulare Counties, relatively uniform minimum concentrations of TDS in water wells indicate that active and inactive produced water ponds are located in areas with surficial groundwater resources having TDS levels < 500 mg/L (Figure 4.5). An analysis of the distance between unlined produced water ponds and domestic, municipal, and agricultural water wells was not conducted here. However, Petela et al. (2018) indicate that less than 1,000 water wells are within 2 km of unlined produced water ponds; more than 4,000 water wells are within 5 km of unlined produced water ponds, and more than 14,000 water wells are within 10 km of unlined produced water ponds.

In the southcentral portion of the Tulare basin in Kern and Kings Counties, minimum TDS levels vary from <500 to 3,000 mg/L. There appear to be few unlined produced water ponds in this area. However, groundwater resources are present where unlined produced water ponds do exist. The Corcoran Clay member is present throughout this area, but as previously discussed, likely does not prevent the vertical subsurface migration of soluble contaminants associated with produced water.

In the Pleasant Valley groundwater subbasin, in the northwest corner of the Tulare basin in Kings and Fresno Counties, minimum levels of TDS in surficial groundwater range from 1,000 to 3,000 mg/L (Figure 4.5). While information on TDS levels is sparse in this area, TDS levels are uniformly below 3,000 mg/L in this area, indicating that groundwater resources exist in the area of unlined produced water ponds.

In the western Kern County groundwater subbasin, in Kern County along the Coast Ranges, minimum levels of TDS in surficial groundwater are highly variable but generally range from 3,000 to over 10,000 mg/L (Figure 4.5). Brackish to saline surficial groundwater is present in this area. Western Kern County contains a large number of produced water ponds (Figure 4.5). Given the sparseness of data in this area, site-specific evaluations of groundwater salinity in areas of unlined produced water ponds would be ne601eded to evaluate potential groundwater resources.

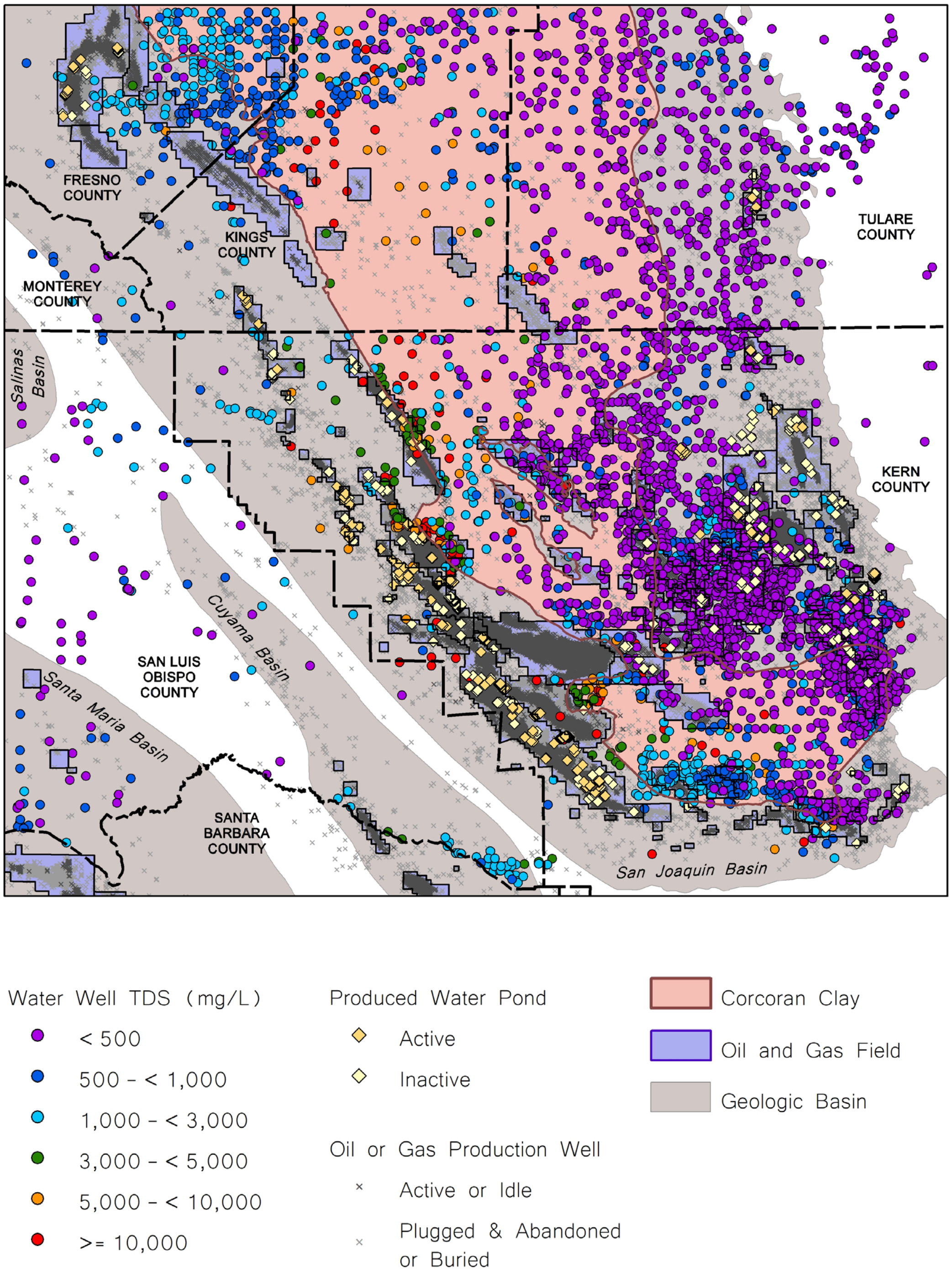


Figure 4.5. The location of active produced water ponds, inactive produced water ponds, active and idle oil and gas wells, plugged and abandoned or buried oil and gas wells, and water wells having data on TDS levels.

4.3.3. Evaluation of Salinity with Depth in USGS Study Areas

4.3.3.1. Methods

In this study, we considered datasets having only domestic water depths and datasets where domestic water wells and production wells were combined. This is because we wanted to evaluate the statistical distribution of TDS levels in surficial groundwater resources—the groundwater resources most susceptible to contamination from unlined produced water ponds. We also wanted to know where groundwater resources were limited to surficial (e.g., <300 m in depth) deposits. In areas having only surficial groundwater resources, potential users cannot install deeper water wells to access water having municipal or domestic use without treatment. Hence, in these areas, groundwater resources are particularly vulnerable.

To better understand the vertical extent of groundwater resources in locations of unlined produced water ponds, we used data compiled by Metzger et al. (2018) for a recent USGS study by Metzger & Landon (2018a, 2018b) and plotted TDS concentrations as a function of depth for water and production wells. This dataset was used because of the availability of TDS concentrations in both production wells and water wells, and because the 27 oilfields studied represent a range of geographic and hydrogeologic settings across the Kern County subbasin.

While produced water ponds are present in or in proximity to most of these 27 oilfields, these fields do not necessarily contain the greatest number or density of produced water ponds. For instance, the Midway-Sunset Field in the western end of the Kern County subbasin contains 218 active and 68 inactive produced water ponds and is not considered in this discussion (SWB, 2019).

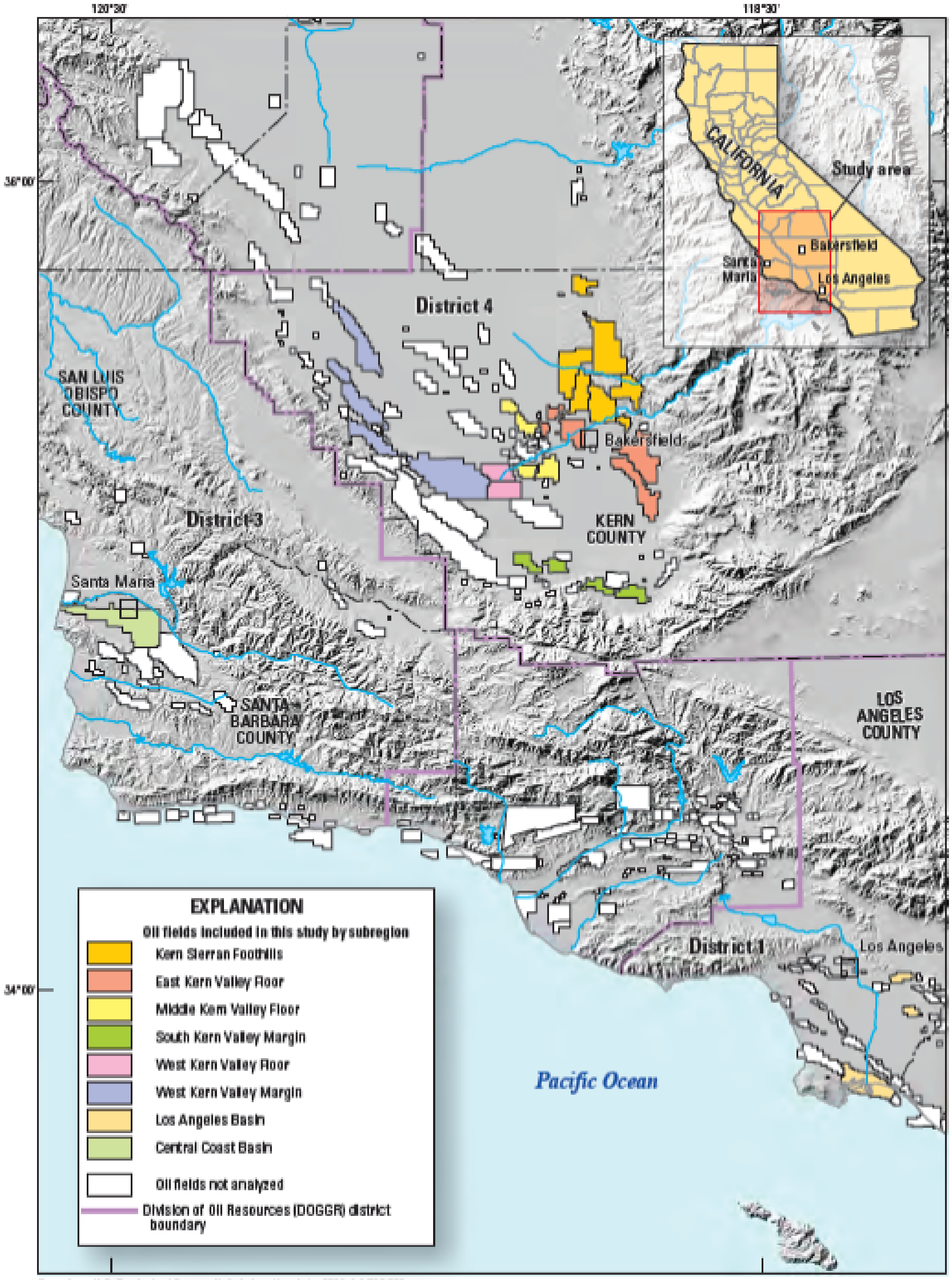
Metzger & Landon (2018a, 2018b) separated these 27 fields into six subregional areas in Kern County as illustrated in Figure 4.6 and summarized in Table 4.3. When evaluating salinity with depth in these study areas, Metzger & Landon (2018a, 2018b) combined water well and produced water samples. The objective of their study was to determine the minimum depth to groundwater resources having a TDS level of 10,000 mg/L consistent with the definition of protected groundwater during well stimulation under California Water Code section 10783, subdivisions (g)(2) and (j) (SWB, 2015).

Table 4.3. ***Description of subregional areas, geographic areas, and oil fields considered by Metzger and Landon (2018a, 2018b) in a USGS salinity study of Southern California.***

USGS Subregional Area	**Geographic Area**	**Oilfields**
Kern Sierran Foothills	Eastern and northeastern section of the Kern County subbasin adjacent to the Sierra Nevada Mountains	Jasmin, Mount Poso, Poso Creek, Kern Front, Kern River, Round Mountain, Kern Bluff
East Kern Valley Floor	Eastern section of the Kern County subbasin	Rosedale Ranch, Rosedale, Fruitvale, Edison, Mountain View
Middle Kern Valley Floor	Central part of the Kern County subbasin	Rio Bravo, Greeley, Ten Section, Canfield Ranch
South Kern Valley Margin	Southeastern section of the Kern County subbasin	Yowlumne, San Emidio Nose, Wheeler Ridge, Tejon
West Kern Valley Floor	Central-western part of the Kern County subbasin	North Coles Levee, South Coles Levee
West Kern Valley Margin	Western portion of the Kern County subbasin adjacent to the Coast Ranges	Lost Hills, North Belridge, South Belridge, Cymric, Elk Hills

Metzger et al. (2018) obtained information on TDS concentrations from produced water samples of 1,151 oil and gas wells, of which 1,126 production wells had information on the depth of the top of perforation intervals. Information sources included: Underground Injection Control (UIC) program database from The Division's California Well Information Management System; The Division's Oil and Gas Online Data website; SWB Geotracker database; and the USGS National Produced Waters Geochemical Database. Production wells included in the data analysis by Metzger and Landon (2018a, 2018b) included production wells considered by Gillespie et al. (2017) in a previous analysis of trends of TDS as a function of depth in produced water samples from oil and gas wells. Metzger and Landon (2018a) stated that water samples from the UIC database were from formation water in the injection zone prior to any injection. Injectate analyses were not used in the UIC database because that water can be a mixture of produced waters, wastewater, or water mixed with chemicals that is unrepresentative of the formation into which it is injected.

When information was lacking for the top of a perforation interval for oil and gas wells, Metzger and Landon (2018a, 2018b) assumed the median depth of top of perforation intervals for an oil and gas field. In this investigation, production wells lacking information on the top of perforation interval were excluded from analysis.



Base from U.S. Geological Survey digital elevation data, 2016, 1:1,500,000
Albers Equal-Area Conic projection, standard parallels are 29°30' North and 45°30' North
North American Datum of 1983

Data sources: DOGGR, 2014a (district boundaries); DOGGR, 2014b (oil field boundaries)

Figure 4.6. Locations of oil fields six subregions in Kern County examined by Metzger and Landon (2018).

4.3.3.2. Discussion

Surficial groundwater resources with TDS levels < 3000 mg/L exist in the vicinity of produced water ponds in the central, northwestern, and eastern portion of the Tulare Lake basin. Given their proximity to groundwater resources, unlined produced water ponds present a risk to groundwater resources in these areas. Brackish groundwater resources having potential use exists in the western portion of the Kern County subbasin of the Tulare Lake basin.

An evaluation of TDS levels with depth in six USGS study areas (detailed below) indicates that groundwater with TDS levels < 3000 mg/L extends to significant depths in the eastern portion of the Tulare Lake basin. Primarily surficial groundwater resources having TDS levels < 3000 mg/L appear to be present in the central portion of Tulare Lake basin. There was insufficient information to examine the depth of groundwater resources having TDS levels < 3000 mg/L in the northwestern portion of the Tulare Lake basin.

Based on reporting from SB 1281, TDS levels of produced water disposed in unlined produced water ponds appear to be significantly higher than the TDS levels in underlying groundwater. Hence, the disposal of produced water into unlined produced water ponds presents a risk to groundwater resources in these areas.

Kern Sierran Foothills subregion

Associations of produced water ponds with oil fields are based on the SWB produced water ponds report for this and other subregions. There are 46 active and 115 inactive (eight historical) produced water ponds associated with oil fields in the Kern Sierran Foothills subregion (SWB, 2019). There are eight active and ten inactive produced water ponds associated with the Jasmin Field area; eight active and 18 inactive produced water ponds associated with the Mount Poso Field area; 15 active and 30 inactive (five historical) produced water ponds associated with the Poso Creek Field area; 15 active and 38 inactive produced water ponds associated with the Kern Front Field area; 16 inactive (three historical) produced water ponds associated with the Kern River Field area; and three inactive produced water ponds associated with the Kern Bluff Field area (SWB, 2019a).

The median, upper quartile, and 90% concentrations of TDS levels in water wells in proximity to oil fields and produced water ponds in the Kern Sierran Foothills subregion was 330, 523, and 984 mg/L, respectively (Figure 4.7a). Aqueous samples from water wells indicate that groundwater having TDS levels < 3,000 mg/L in this area extends to at least 700 m in depth (Figure 4.7b).

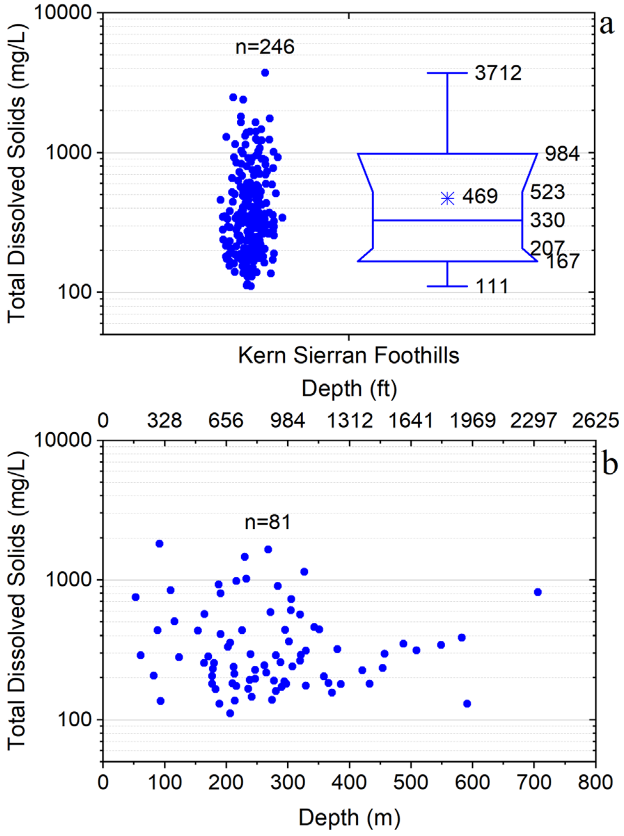


Figure 4.7. Concentrations of total dissolved solids in water wells within 3.2 km of oil production wells in the Kern Sierran Foothills subregion. (a) Box plot illustrating distribution of values: the asterisk denotes the mean concentration. Values outside the box plot in ascending value denote minimum, 10%, 25%, 50% (median), 75%, 90%, and maximum values. (b) Total dissolved solids concentration as a function of the lower perforation depth of water wells. Source: Metzger et al. (2018).

Levels of TDS in produced water samples from oil fields in the Kern Sierran Foothills subregion also indicates the presence of groundwater having TDS levels < 3,000 mg/L at depths of 700 to 1,000 m in this area. Groundwater having TDS levels < 10,000 mg/L may extend to depths of more than 1,700 m (Figure 4.8). In the Kern River, Poso Creek, and Mount Poso Fields, levels of TDS < 10,000 mg/L may extend to crystalline bedrock (Gillespie et al., 2017). In some locations, salinity rises gradually with depth, but in other locations, such as Poso Creek, salinity rises exponentially (linear on logarithmic scale) with depth before leveling off. A rapid rise in salinity with depth in areas of the San Joaquin Valley may be due to a transition to an underlying formation of marine origin (Gillespie et al., 2017). In these areas, groundwater resources may be limited to surficial deposits.

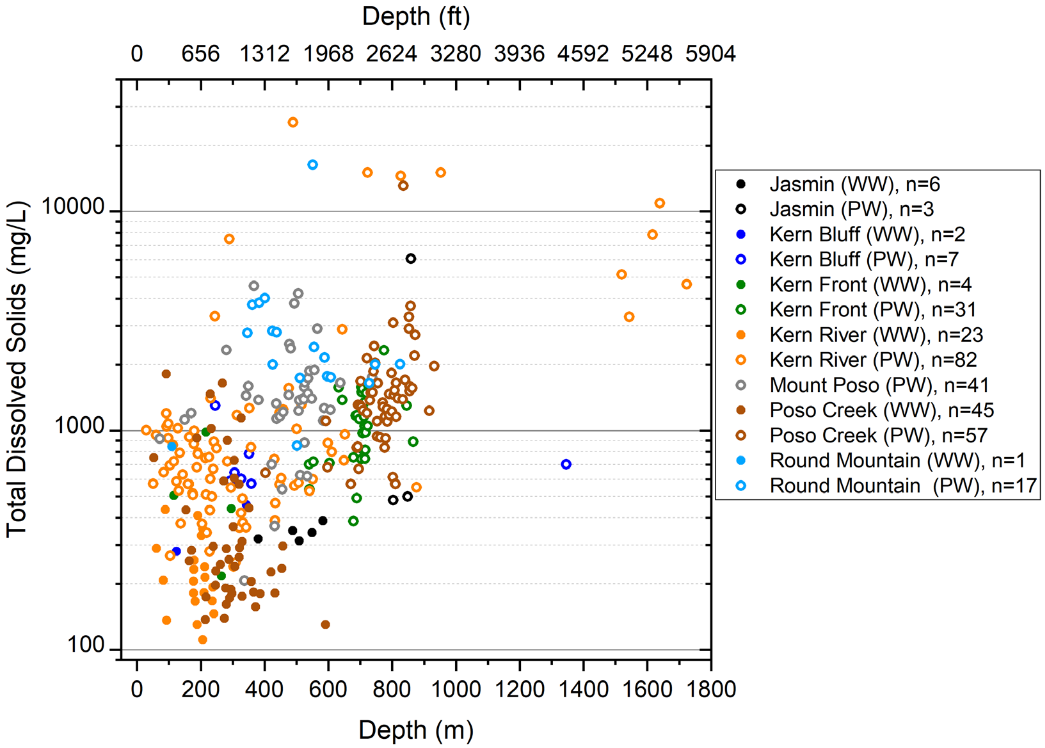


Figure 4.8. Total dissolved solids concentrations of aqueous samples from water wells (WW) (solid circles) and production wells (PW) (hollow circles) in oil fields in the Kern Sierran Foothills as a function of the lower perforation and upper perforation depths of water and production wells, respectively. Source: Data from Metzger et al. (2018).

In the Kern River Field, there is little separation between depths of water well use and depths of oil and gas development. This does not mean that oil is mixed with water in water wells near the Kern River Field. Water wells are located in the vicinity of the Kern River Field where oil has not migrated to depths of well water use. Water wells within 3.2 km of the Kern River Field have lower TDS levels than produced water samples at the same depth. While there are a number of possible causes for this observation, such as less contact with meteoric recharge water, the reason or reasons are unknown.

East Kern Valley Floor subregion

There are 36 active and 38 inactive (one historical) produced water ponds associated with oil fields in the East Kern Valley subregion (SWB, 2019a). There are 36 active and 18 inactive (one historical) produced water ponds associated with the Edison Field, 14 inactive produced water ponds associated with the Mountain View Field, five inactive produced water ponds associated with the Fruitvale Field, one inactive produced water pond associated with the Rosedale Ranch Field, and no produced water ponds associated with the Rosedale Field (SWB, 2019a).

The median, upper quartile, and 90% concentrations of TDS levels in water wells in proximity to oil fields in the East Kern Valley Floor subregion was 434, 613, and 903 mg/L, respectively (Figure 4.9a) This indicates the presence of groundwater having TDS levels < 3000 mg/L in this area to at least 700 m in depth (Figure 4.9b).

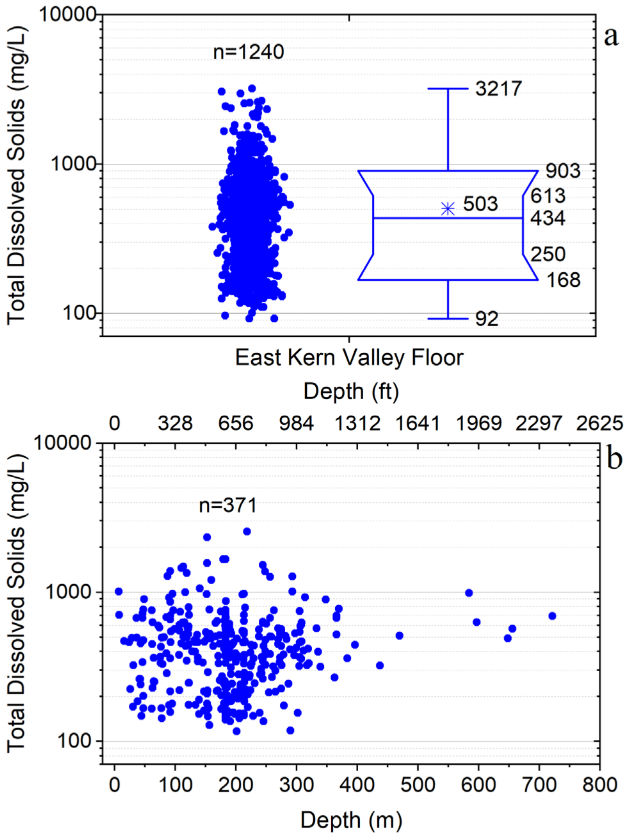


Figure 4.9. Concentrations of TDS in water wells with 3.2 km of oil production wells in the East Kern Valley Floor subregion. (a) Box plot illustrating distribution of values: the asterisk denotes the mean concentration. Values outside the box plot in ascending value denote minimum, 10%, 25%, 50% (median), 75%, 90%, and maximum values. (b) Total dissolved solids concentration as a function of the lower perforation depth of water wells. Source: Metzger et al. (2018).

Levels of TDS in produced water samples from oil fields in the East Kern Valley Floor subregion indicate the presence of groundwater having TDS levels < 3,000 mg/L to at least 800 m in depth in this area (Figure 4.10). However, above a TDS concentration of 1,000 mg/L there is an approximate linear (logarithmic scale) gradient in increasing TDS concentration with depth at the Edison, Fruitvale, Mountain View and Rosedale Ranch oilfields (Figure 4.10), indicating an exponential or rapid rise in salinity with depth. There is insufficient data to draw a similar conclusion at the Rosedale field.

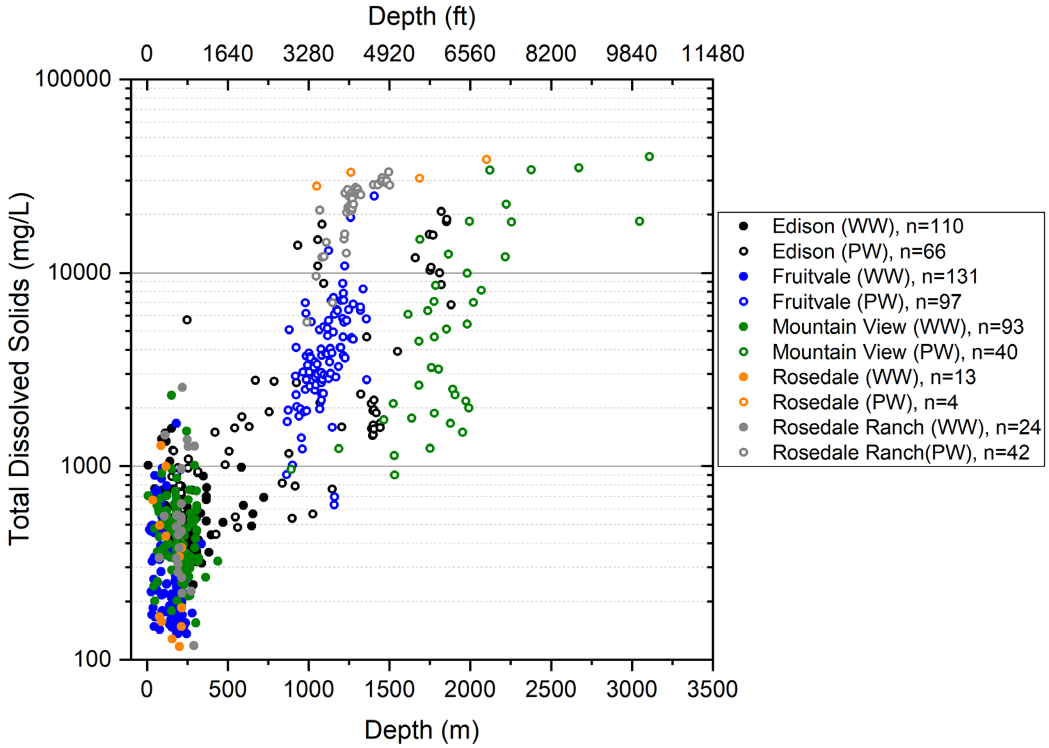


Figure 4.10. Total dissolved solids concentrations of aqueous samples from water wells (WW) (solid circles) and production wells (PW) (hollow circles) in oil fields in the East Kern Valley Floor subregion as a function of the lower perforation and upper perforation depths of water and production wells, respectively. Source: Metzger et al. (2018).

Middle Kern Valley Floor subregion

There are five inactive produced water ponds associated with the Middle Kern Valley Floor subregion (SWB, 2019a). There are three inactive produced water ponds associated with the Rio Bravo Field, one inactive produced water pond associated with the Ten Section Field, and one inactive produced water pond associated with the Canfield Ranch Field (SWB, 2019a). There are no active or inactive produced water ponds in the Greeley Field.

The median, upper quartile, and 90% concentrations of TDS levels in water wells in proximity to oil fields in the Middle Kern Valley Floor subregion was 216, 355, and 560 mg/L, respectively (Figure 4.11a), indicating the presence of groundwater having TDS levels < 3000 mg/L in this area to at least 250 m in depth (Figure 4.11b). Levels of TDS in produced water samples in this subregion indicates the presence of groundwater having TDS levels <3,000 mg/L to at least 500 m in depth (Figure 4.12).

The median TDS levels of produced water samples in the Canfield Ranch, Greeley, Rio Bravo, and Ten Section Fields were 28,403, 19,815, 25,035, and 21,324 mg/L, respectively (Metzger & Landon, 2018). Again, there is a transition to saline water over a relatively short vertical distance (Figure 4.12) indicating only surficial groundwater resources in this area.

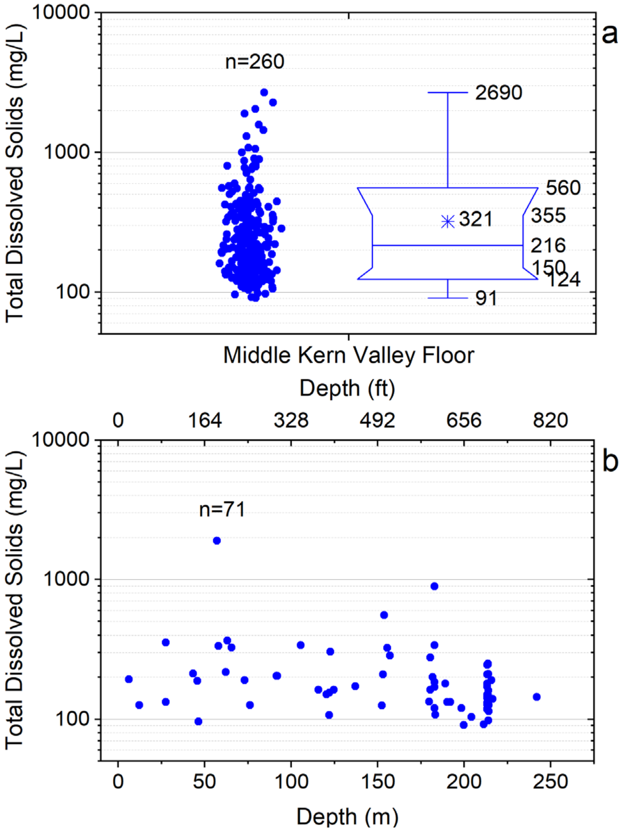


Figure 4.11. Concentrations of total dissolved solids in water wells within 3.2 km of oil production wells in the Middle Kern Valley Floor subregion. (a) Box plot illustrating distribution of values: the asterisk denotes the mean concentration. Values outside the box plot in ascending value denote minimum, 10%, 25%, 50% (median), 75%, 90%, and maximum values. (b) Total dissolved solids concentration as a function of the lower perforation depth of water wells. Source: Metzger et al. (2018).

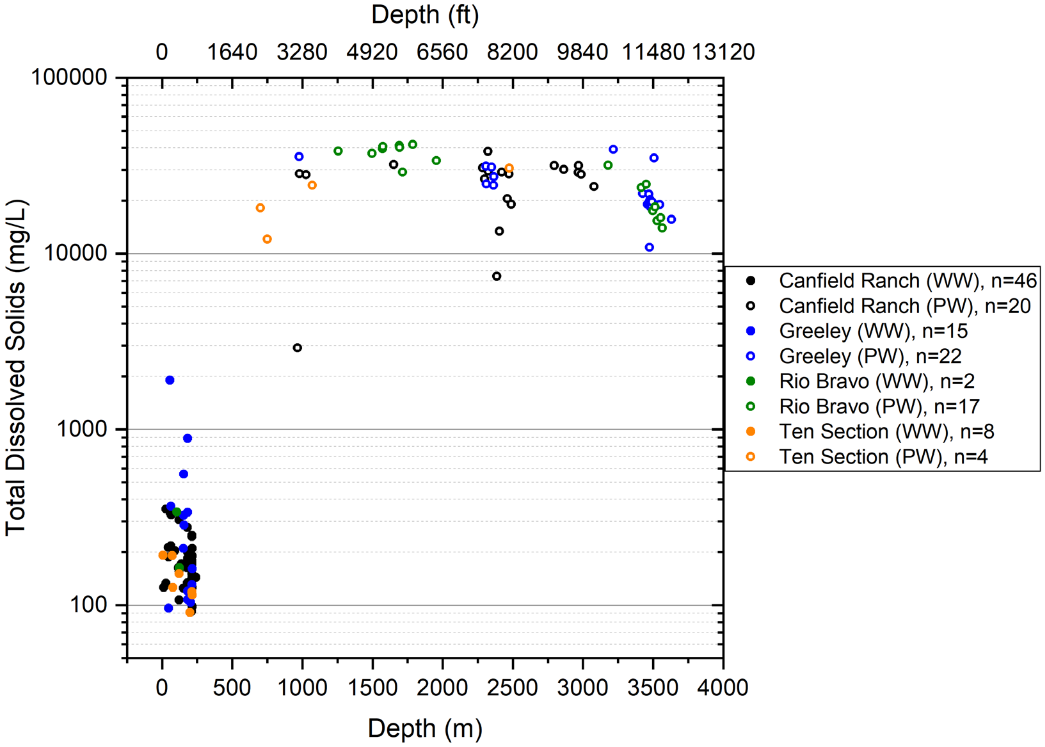


Figure 4.12. Total dissolved solids concentrations of aqueous samples from water wells (WW) (solid circles) and production wells (PW) (hollow circles) in oil fields in the Middle Kern Valley Floor subregion as a function of the lower perforation and upper perforation depths of water and production wells, respectively. Source: Metzger et al. (2018).

South Kern Valley Margin

There are 17 inactive produced water ponds in the South Kern Valley Margin subregion, all of which are in the Tejon Field (SWB, 2019). The median, upper quartile, and 90% concentrations of TDS levels in water wells in proximity to oil fields in the South Kern Valley Margin subregion were 1,005, 1,329, and 1,917 mg/L, respectively (Figure 4.13a) indicating the presence of groundwater having TDS levels < 3000 mg/L to at least 650 m in depth (Figure 4.13b). Levels of TDS in produced water samples in this area indicate the presence of brackish and saline water beyond 700 m in depth and a transition from fresh to saline water over a relatively short vertical distance (Figure 4.14).

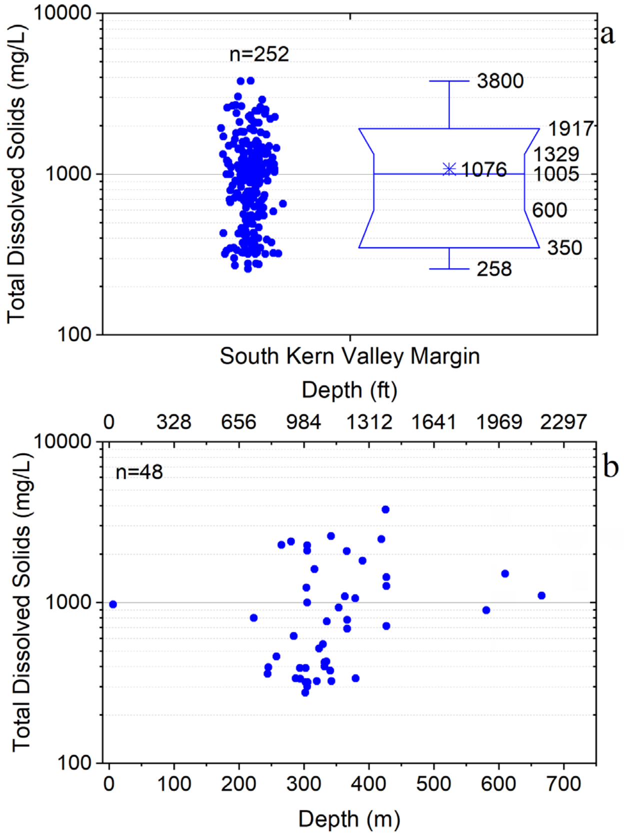


Figure 4.13. Concentrations of total dissolved solids in water wells within 3.2 km of oil production wells in the South Kern Valley Margin subregion. (a) Box plot illustrating distribution of values: the asterisk denotes the mean concentration. Values outside the box plot in ascending value denote minimum, 10%, 25%, 50% (median), 75%, 90%, and maximum values. (b) Total dissolved solids concentration as a function of the lower perforation depth of water wells. Source: Metzger et al. (2018).

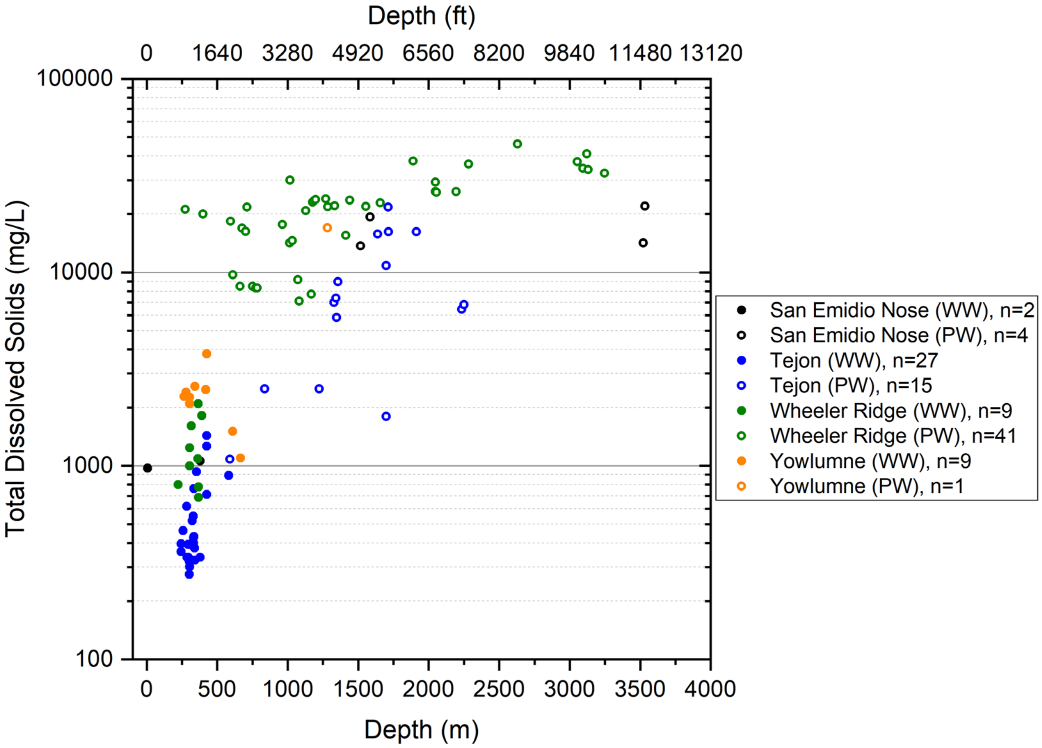


Figure 4.14. Total dissolved solids concentrations of aqueous samples from water wells (WW) (solid circles) and production wells (PW) (hollow circles) in oil fields in the South Kern Valley Margin subregion as a function of the lower perforation and upper perforation depths of water and production wells, respectively. Source: Data from Metzger et al. (2018).

West Kern Valley Floor Subregion

There are 11 inactive produced water ponds in the West Kern Valley Floor subregion, all of which are in the Coles Levee South Field (SWB, 2019). The median, upper quartile, and 90% concentrations of TDS levels in water wells in proximity to oil fields in the West Kern Valley Floor subregion are 332, 863, and 1,416 mg/L, respectively (Figure 4.15a). Data from water wells indicates the presence of groundwater having TDS levels < 3000 mg/L to a depth of at least 350 m (Figure 4.15b). However, produced water samples again indicate an abrupt transition to saline groundwater conditions at approximately 500 m in depth (Figure 4.16).

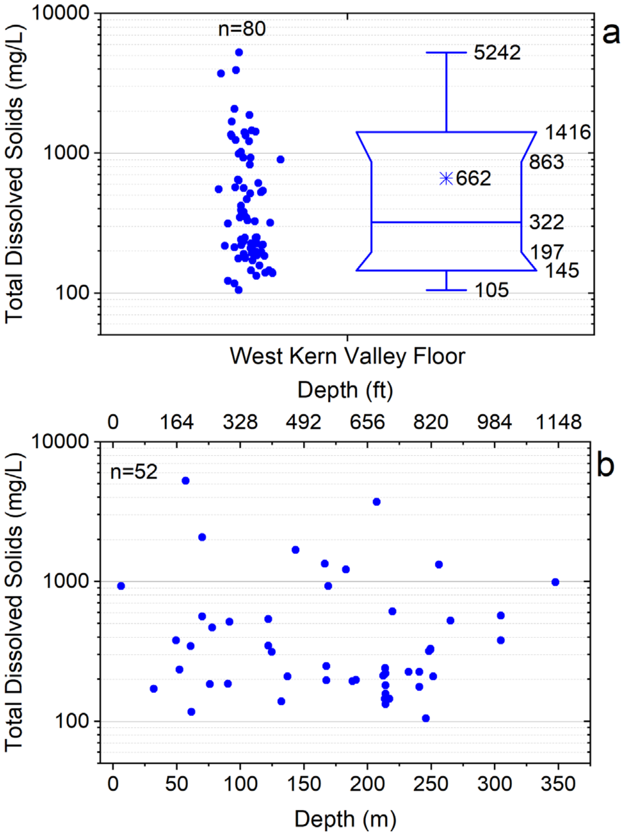


Figure 4.15. Concentrations of total dissolved solids in water wells within 3.2 km of oil production wells in the West Kern Valley Floor subregion. (a) Box plot illustrating distribution of values: the asterisk denotes the mean concentration. Values outside the box plot in ascending value denote minimum, 10%, 25%, 50% (median), 75%, 90%, and maximum values. (b) Total dissolved solids concentration as a function of the lower perforation depth of water wells. Source: Metzger et al. (2018).

West Kern Valley Margin Subregion

There are 81 active and 161 inactive (six historical) produced water ponds associated with oil fields in the West Kern Valley Margin subregion. There are 59 active and 112 inactive produced water ponds associated with the Cymric Field (includes disposal combined with the Belgian Anticline Field), 17 active and 11 inactive produced water ponds associated with the Belridge South Field, 14 inactive (five historical) produced water ponds associated with the Belridge North Field, and one active and 30 inactive produced water ponds associated with the Elk Hills Field (SWB, 2019).

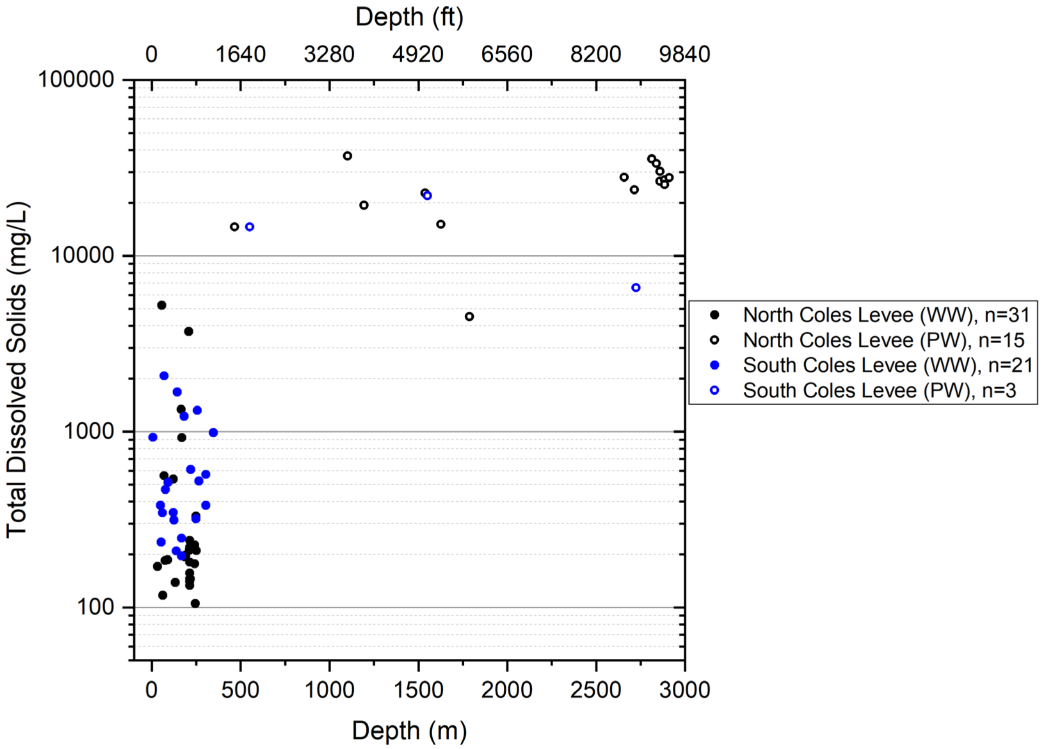


Figure 4.16. Total dissolved solids concentrations of aqueous samples from water wells (WW) (solid circles) and production wells (PW) (hollow circles) in oil fields in the West Kern Valley Floor subregion as a function of the lower perforation and upper perforation depths of water and production wells, respectively. Source: Data from Metzger et al. (2018).

The median, upper quartile, and 90% concentrations of TDS levels in water wells in proximity to oil fields in the West Kern Valley Margin subregion was 4,745, 12,200, and 21,300 mg/L, respectively (Figure 4.17a). The median concentrations of TDS in water wells in proximity to the Belridge North, Belridge South, Elk Hills, and Lost Hills Fields were 3,657, 11,000, 2,176, and 4,100 mg/L, respectively. There were only two water well measurements near the Cymric Field, 901 and 2,018 mg/L TDS. This indicates that groundwater having TDS levels < 3000 mg/L is largely absent throughout most of this area.

There were five water wells having high to very high levels of TDS (54,400, 87,500, 82,200, 158,772, 231,000 mg/L) within 3.2 km of the southeastern administrative boundary of the Elk Hill Field. Only one had information on depth (158,772 mg/L at 2.9 m). Metzger and Landon (2018) state that high levels of TDS in shallow wells (< 21 m) may be associated with perched aquifers influenced by agricultural activities or infiltration from surface impoundments associated with O&G activities. Examination of the geographic location of these water wells and produced water ponds indicates that they are not in the vicinity (>

3 km) of each other. Hence, these high levels of TDS are likely highly evaporated shallow groundwater previously used for irrigation.

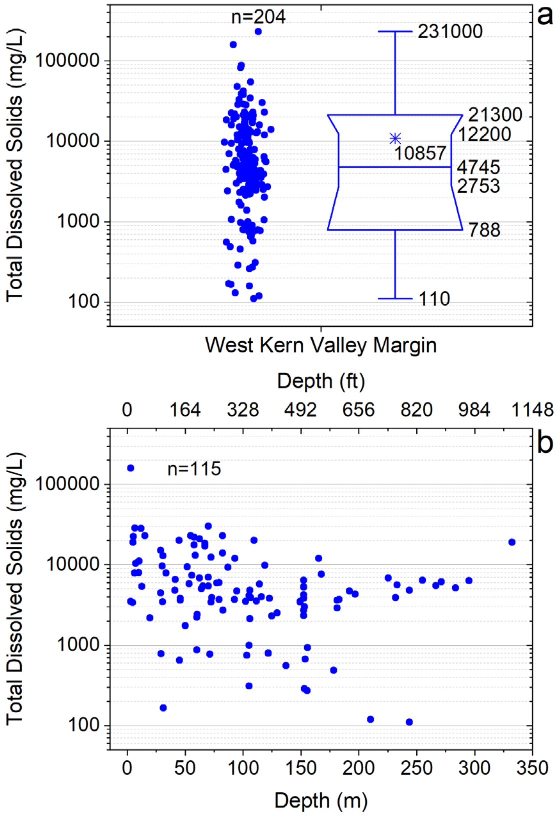


Figure 4.17. Concentrations of total dissolved solids in water wells within 3.2 km of oil production wells in the West Kern Valley Margin subregion. (a) Box plot illustrating distribution of values: the asterisk denotes the mean concentration. Values outside the box plot in ascending value denote minimum, 10%, 25%, 50% (median), 75%, 90%, and maximum values. (b) Total dissolved solids concentration as a function of the lower perforation depth of water wells. Source: Data from Metzger et al. (2018).

There appears to be a wide mixture of fresh, brackish, and saline groundwater within 300 m of the surface throughout the West Kern Valley Margin subregion (Figure 4.17b). However, the median value of 4,745 mg/L for water well samples indicates that groundwater within 300 m of the surface is best characterized as brackish in this area.

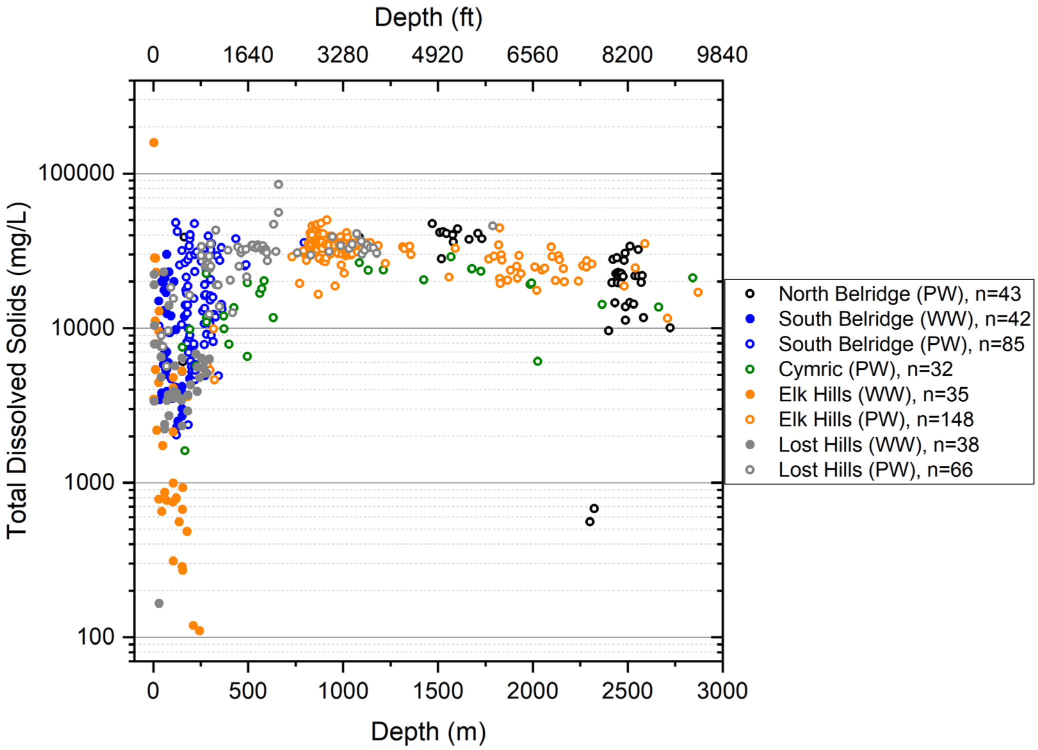


Figure 4.18. Total dissolved solids concentrations of aqueous samples from water wells (WW) (solid circles) and production wells (PW) (hollow circles) in oil fields in the West Kern Valley Margin subregion as a function of the lower perforation and upper perforation depths of water and production wells, respectively. Source: Data from Metzger et al. (2018).

Produced water samples in this area indicate a rapid transition to saline conditions within 300 m of the surface (Figure 4.18). The median concentrations of TDS from produced water samples from the North Belridge, South Belridge, Cymric, Elk Hills, and Lost Hills Field are 22,546, 14,685, 16,767, 32,636, and 31,336 mg/L, respectively.

Approximately 85% of hydraulic fracturing in California occurs in the Elk Hills, South Belridge, North Belridge, and Lost Hills Fields (Jordan et al., 2015). Disposal of produced water into unlined produced water ponds from stimulated wells appears limited to areas within and around these fields (Stringfellow et al., 2015). Hydraulically-fractured formations in the North and South Belridge Fields and the Lost Hills Field contain intervals of biogenic Opal A, a type of siliceous rock formed from the skeletons of single-celled marine organisms. The formation also contains intervals of Opal A diatomite recrystallized to Opal CT (cristobalite and tridymite) and quartz due to increased temperature and pressure from deep burial (Jordan et al., 2015).

Hydraulically-fractured formations in the Elk Hills Field consist of sands (Jordan et al., 2015). In 2013, nearly all produced water associated with hydraulic fracturing in the North Beldridge, South Belridge, and Elk Hills Fields was discharged to unlined produced water ponds, the specific location of which are unknown. Depending on the formation hydraulically fractured, 22% to 59% of produced water from wells at the Lost Hills Field was discharged into unlined produced water ponds (Jordan et al., 2015).

Produced water from hydraulically fractured production wells was commingled with produced water from non-hydraulically fractured production wells during disposal into produced water ponds. Jordan et al. (2015) estimated dilution factors of 82, 140, 230, and 200 for the North Belridge, South Belridge, Elk Hills, and Lost Hills Fields, respectively, during commingling.

> ***Finding 4.4.1.*** *Reporting pursuant to SB 1281 provides information on the locations of produced water ponds and the volumes of produced water disposed in unlined produced water ponds in general.*

> ***Finding 4.4.2.*** *Groundwater resources that are or could be used for agricultural, municipal, or domestic use exist in areas of unlined produced water ponds in the central, northwestern, and eastern portion of the Tulare basin. Groundwater resources that could be treated for these uses exist in the western portion of the Kern County subbasin of the Tulare basin. With the exception of the eastern portion of the Tulare basin, where deep groundwater resources are present, groundwater resources having beneficial use appear to be limited to surficial (less than 300 m in depth) deposits.*

> ***Conclusion 4.4.1.*** *Due to their shallow depth, many groundwater resources in the Tulare basin with potential for beneficial use may be particularly vulnerable to contamination from unlined produced water ponds.*

> ***Conclusion 4.4.2.*** *Discharge of produced water into unlined produced water ponds poses risks to groundwater resources that are currently used or could be used in the future for beneficial purposes.*

> ***Recommendation 4.4.1.*** *Agencies with jurisdiction should continue to investigate the use of produced water ponds and require appropriate testing and treatment of any water discharged into produced water ponds.*

> ***Recommendation 4.4.2.*** *These agencies should develop a risk prioritization system to designate which unlined produced water ponds require in-depth, site investigations to determine the nature and extent of historical, current, and future impacts from the discharge of produced water. Such a risk prioritization should start with produced water ponds having the greatest present or past cumulative discharge volumes and should also include criteria such as the presence of groundwater resources having agricultural, municipal or domestic uses or potential for use with treatment.*

> ***Recommendation 4.4.3.*** *For high-priority produced water ponds, a facility-by-facility assessment should be undertaken to determine where impacts to groundwater resources have already occurred or are likely to occur if the practice continues.*

> ***Recommendation 4.4.4.*** *Agencies with jurisdiction should promptly ensure through appropriate testing and treatment that any water discharged into produced water ponds does not contain concentrations of chemicals related to oil and gas development that could impact groundwater resources. Given the potential for impact to groundwater resources, it may be advantageous for these volumes to decrease over time and the agencies with jurisdiction should thoroughly consider alternatives to this practice in the future.*

4.4. Evidence of water contamination from unlined produced water ponds

In this section we provide a case study of the McKittrick 1 & 1-3 Facility to better understand the site-specific hydrogeologic conditions which determine the impact to groundwater resources from disposal of produced water into unlined produced water ponds, and to document impact to groundwater resources from this practice.

Saline produced water has been discharged into unlined produced water ponds at the McKittrick 1 & 1-3 Facility for more than 60 years, with a cumulative discharge volume estimated at 60 billion gallons. Increasing concentrations of TDS, chloride, and boron, and enrichment in $\delta^{18}O$ and δD with time in monitoring wells indicates groundwater contamination of the regional aquifer. Groundwater monitoring data at the McKittrick 1 & 1-3 Facility indicates that disposal of produced water into unlined produced water ponds can impact groundwater resources given a large cumulative volume of discharge and pathways for contaminant migration.

The McKittrick 1 & 1-3 Facility was selected as a case study to explore groundwater contamination from the disposal of produced water into unlined produced water ponds for the following reasons:

- The public record of disposal practices and groundwater monitoring is extensive and easily accessible through the SWB Geotracker database (SWB, 2018).
- The first Waste Discharge Requirement (WDR) permit for the McKittrick 1 & 1-3 Facility was issued in 1961 (CVRWQCB, 1961) and as such this facility is an example of the long-term and continued practice of disposal of saline (> 10,000 mg/L TDS) produced water into unlined produced water ponds.
- Reported discharge rates between 2015 through 2018 have varied from 105,000 barrels per day (bbd) to 38,000 bbd, with an average of approximately 67,000 bbd (CVRWQCB, 2019). Based on the average discharge rate, cumulative disposal volume over a 60-year operating period is estimated to be more than 189,125 AF.

- Complex hydrogeological and geochemical conditions that underlie and are in proximity to the facility are likely typical of numerous produced water ponds throughout the Tulare basin.

- Land utilized for agriculture with irrigation water supplied by water wells is located 457 m north of the McKittrick 1 & 1-3 Facility.

4.4.1. Background on the McKittrick 1 & 1-3 Facility

The Valley Water Management Company (VWMC) (formerly the Valley Waste Disposal Company) operates four large oil and gas wastewater unlined disposal pond facilities northwest of the town of McKittrick in western Kern County (CVRWQCB, 2009). These produced water ponds are the McKittrick 1 & 1-3 Facility, the McKittrick 1-1 Facility, the McKittrick 6, 6A, 6B Facility, and the McKittrick 7 Old and New Facility. The facilities receive or have received saline produced water from numerous oil wells in the Belgian Anticline, South Belridge, Cymric, and McKittrick oilfields (CVRWQCB, 2009, 2018c). Oil produced from these fields is largely associated with marine diatomite (CVRWQCB, 2018c).

The McKittrick 1-1 Facility is currently active and as of 2015 was receiving on average about 22,500 bbd of produced water. The McKittrick 6, 6A, 6B Facility and McKittrick 7 Old and New Facility have been inactive since 2014 (CVRWQCB, 2018c).

Investigation of produced water ponds in the McKittrick area by the CVRWQCB is focused on the McKittrick 1 & 1-3 Facility. The McKittrick 1 & 1-3 Facility covers approximately 60.3 hectares (1 hectare = 10,000 m^2) and consists of two side-by-side interconnected pond areas that are used for disposal of oil field produced water via evaporation and percolation (Figure 4.19).

The McKittrick 1 ponds occupy the west side of the facility and consist of six unlined rectangular oil-water separation ponds, eight unlined pass-through ponds, and 14 unlined evaporation/percolation ponds (CVRWQCB, 2018c). The oil-water separation ponds are up to 44.8 x 21.3 m (length by width) in dimension (CVRWQCB, 2018c). The evaporation/percolation ponds are up to 514.8 x 20.0 m in dimension. Depths of produced water ponds are not provided in CVRWQCB reports.

Figure 4.19. A screenshot of the McKittrick 1-1 (to the west) and the McKittrick 1 & 1-3 (to the east) Facilities. Source: SWB Geotracker website.

The McKittrick 1-3 ponds occupy the east side of the facility and consist of three netted, unlined rectangular oil-water separation ponds, 23 unlined pass-through ponds, and 29 unlined evaporation/percolation ponds. The oil-water separation ponds are up to 30.1 x 23.2 m in dimension. The evaporation/percolation ponds are up to 571.5 x 27.1 m in dimension (CVRWQCB, 2018c).

The elevation of the McKittrick 1 ponds is slightly higher than the elevation of the McKittrick 1-3 ponds, allowing the two pond systems to be partially connected by gravity flow. The average discharge rate into unlined produced water ponds at the McKittrick 1 & 1-3 Facility is 67,000 bbd (3,152 AFY), but the facility has accepted up to 115,000 bbd at times (CVRWQCB, 2018c). Based on average flow, the volume of produced water discharged to the ponds during 1960 to 2018 is 1.4 billion barrels (CVRWQCB, 2018c).

There are ten Class II UIC disposal wells within 3.2 km of the McKittrick 1 & 1-3 Facility. Also, a hazardous waste disposal facility (Clean Harbors Facility) is located ~3.2 km northeast of the McKittrick 1 & 1-3 Facility. Early operations at the Clean Harbors Facility included the use of unlined ponds for liquid waste storage and disposal. By the mid-1990s, all unlined ponds were closed, and lined units were utilized for storage of liquid waste (CVRWQCB, 2016). Land utilized for agriculture is located 457 m north of the McKittrick 1 & 1-3 Facility (CVRWQCB, 2018c). Agricultural wells downgradient of the facility have TDS concentrations ranging from 1,300 to 6,800 mg/L (CVRWQCB, 2018c). The year of construction or the age of agricultural wells was not provided by the CVRWQCB. The existence of these wells indicates that groundwater having a beneficial use for agriculture exists near the McKittrick 1 & 1-3 Facility (CVRWQCB, 2018c).

The disposal of oil and gas wastewater from the Cymric, McKittrick, and Belgian Oil Fields into produced water ponds at McKittrick 1 & 1-3 Facility dates back to at least the late-1950s (Baldwin, 1959). Measurements of electrical conductivity, TDS, chloride, and boron in wastewater discharged to produced water ponds have been as high as 42,000 μS/cm, 24,000 mg/L, 16,000 mg/L, and 130 mg/L, respectively (CVRWQCB 1997, 2001). These values far exceed the discharge limits of 1,000 μS/cm, 200 mg/L, and 1.0 mg/L, respectively in the Tulare Lake basin plan (CVRWQCB 2018b). Benzene, toluene, ethylbenzene, and xylenes were detected at concentrations in produced water ponds at up to 190, 220, 26, and 110 μg/L, respectively (CVRWQCB 2001).

4.4.2. Hydrogeology and a Conceptual Model of Contaminant Transport

The installation of monitoring wells has resulted in the development of various and sometimes conflicting hydrogeological conceptual models by the VWMC and the CVRWQCB. The following discussion represents what we believe is a common understanding of hydrogeology in the area of the facility, illustrated by transects of monitoring wells hydraulically downgradient of the facility and cross-sectional schematics associated with the transects (Figures 4.20 and 4.21).

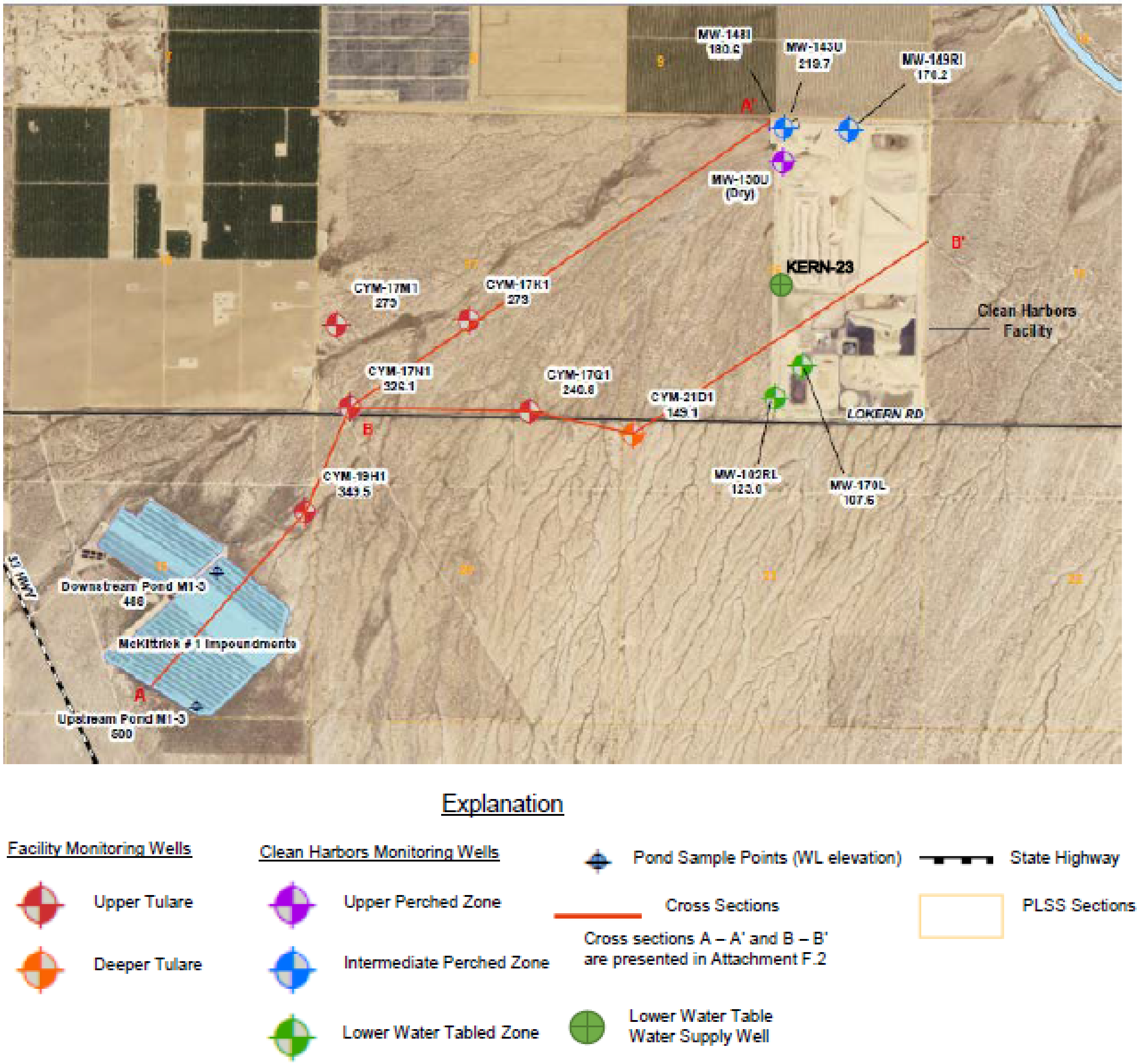


Figure 4.20. Locations of monitoring wells installed as of August 2018 at the McKittrick 1 & 1-3 Facility. Groundwater flow is to the northeast. CYM-19H1, CYM-17N1, and CYM-21D1 were installed in November 2002. CYM-17K1, CYM-17Q1, and CYM-17M1 were installed in August 2006. Source: CVRWQCB (2019).

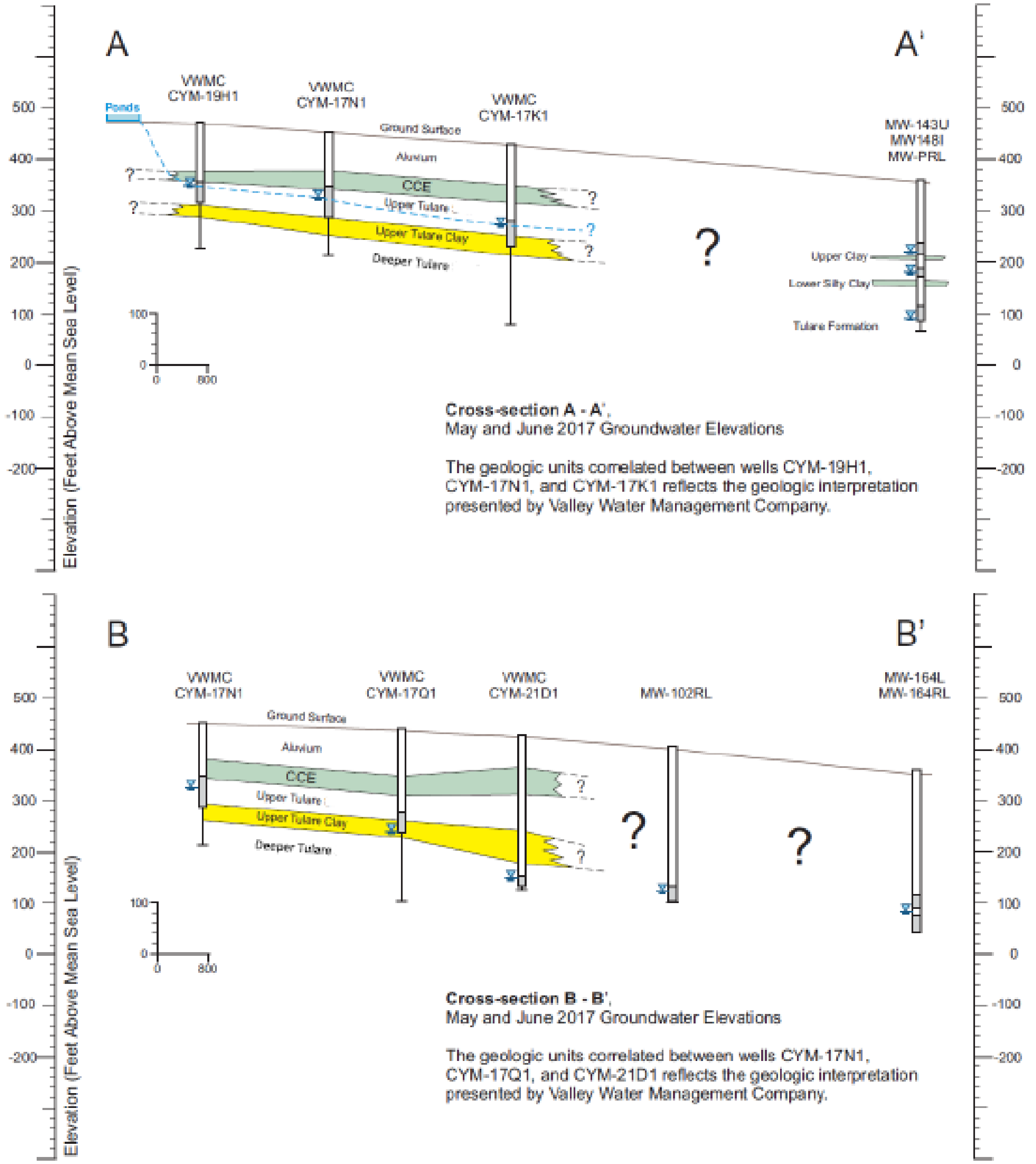


Figure 4.21. Cross-sectional schematic A–A' from Figure 4.20 illustrating stratigraphy and the possible extent of migration of produced water in the Upper Tulare Sand above the Upper Tulare Clay. Source: CVRWQCB (2019).

The McKittrick 1 & 1-3 Facility produced water ponds overlie Holocene-age alluvial fan deposits (Figure 4.21) from the Temblor Hills and Elk Hills area of the Coast Range. These deposits were transported eastward toward the axis of the San Joaquin Valley (Geomega, 2007). Alluvial fan deposits formed where high-gradient streams carried sediment from the Coast Range west of the Cymric area to the relatively flat floor of the San Joaquin Valley (Geomega, 2003).

In the Cymric area, alluvial fan deposits consist of interbedded layers of poorly sorted, relatively coarse-grained, subangular to angular sands with silts and clays of initial marine origin. Angular to subangular gravelly sands occasionally occur in the interbedded sequence (CVRWQCB, 2018c). At the McKittrick 1 & 1-3 Facility, alluvial deposits are saturated below produced water ponds due to the continuous disposal of water in these ponds (Figure 4.21) (Geomega, 2003). However, outside the McKittrick 1 & 1-3 Facility area, these alluvial deposits are unsaturated (Figure 4.21).

A regional bed of silt and clay, referred to as the Corcoran Clay Equivalent (CCE), underlies alluvial deposits (Geomega, 2003). This silty clay to clay bed was deposited in an alluvial plain to lacustrine transition and separates the Holocene alluvium from the Pleistocene Tulare stratigraphic units (Geomega, 2003; CVRWQCB, 2018c).

In the area of the McKittrick 1 & 1-3 Facility, the CCE is thinner than is typically observed in the western San Joaquin Valley, and appears to have gone through a facies change from an organic-rich clay to a more permeable silty clay unit (Geomega, 2007). The Corcoran Clay is generally very fined-grained. However, along the boundary of its regional extent, the Corcoran Clay thins and transitions from a clay to a silty layer with greater permeability (Page, 1986). The CCE unit in the area of the McKittrick 1 & 1-3 Facility does not act as an aquitard or a significant barrier to the downward migration of produced wastewater discharged from the McKittrick 1 & 1-3 Facility ponds (Geomega, 2007; CVRWQCB, 2018c).

The Pleistocene age Upper Tulare Sand lies below the CCE (Figure 4.21). The depositional environment of the Upper Tulare Sand varies significantly across the McKittrick 1 & 1-3 Facility area from lacustrine delta to meandering stream and point bar deposits (Geomega, 2007; CVRWQCB, 2018b). The Upper Tulare Sand deposits are comprised of fine-grained sands with interbedded silt and clay layers and gravel lenses (Geomega, 2007). The Upper Tulare Sand thickens eastward from the McKittrick 1 & 1-3 Facility area (Geomega, 2007). In the vicinity of the McKittrick 1 & 1-3 Facility, perched water is present in the Upper Tulare Sand due to disposal of produced water in unlined produced water ponds.

The Upper Tulare Sand is separated from what is called the Lower or Deeper Tulare Sand by a dense, stiff clay bed referred to as the Upper Tulare Clay (Figure 4.21). The Upper Tulare Clay is approximately 21 m thick. The Upper Tulare clay does not completely restrict downward movement of produced water in the area of the McKittrick 1 & 1-3 Facility. The Upper Tulare Clay unit may contain more permeable channel deposits that compromise the integrity of the clay layer (CVRWQCB, 2018c).

The Lower Tulare Sand is composed primarily of fine-grained to medium-grained well-sorted sands. The Lower Tulare Sand is the regional aquifer for the area in the vicinity of the McKittrick 1 & 1-3 Facility (CVRWQCB, 2018c). Monitoring well CYM-21D1 was installed in the Lower Tulare Sand 2.01 km northeast of the McKittrick 1 & 1-3 Facility (Figure 4.21). Groundwater monitoring commenced at CYM-21D1 in June 2002. Since this time, there has been a substantial increase in TDS levels, chloride, and boron (Figure 4.22). Sample results also indicate continued enrichment of water isotopes $\delta^{18}O$ and deuterium (δD) in aqueous samples from CYM-21D1 toward values indicative of aqueous samples collected from produced water ponds (Figure 4.23).

Hence, as stated by the CVRWQCB (2019), increasing concentrations trends in TDS, chloride, and boron, and enrichment in $\delta^{18}O$ and δD with time, in monitoring well CYM-21D1 indicates groundwater contamination of the regional aquifer. The continued enrichment of $\delta^{18}O$ and δD over time along a linear trend characteristic of $\delta^{18}O$ and δD values of produced water ponds is compelling. Given the hydraulic gradient to the northeast, it is unlikely that enrichment of $\delta^{18}O$ and δD values at CYM-21D1 is from operations at the Clean Harbors facility. Scatter of enriched values of $\delta^{18}O$ and δD for produced water ponds may be due to evaporation or variation in source water for produced water ponds. Data from CYM-21D1 provides evidence that the practice of disposal of produced water into unlined produced water ponds can impact groundwater resources.

The annual disposal volume at the McKittrick 1 & 1-3 Facility is nearly equivalent to the total disposal volume in unlined produced water ponds in the San Joaquin Valley as estimated from the SB 1281 dataset. Given the large number of other unlined produced water pond disposal facilities in the San Joaquin Valley, it is unlikely that the McKittrick 1 & 1-3 Facility accounts for the entire disposal volume.

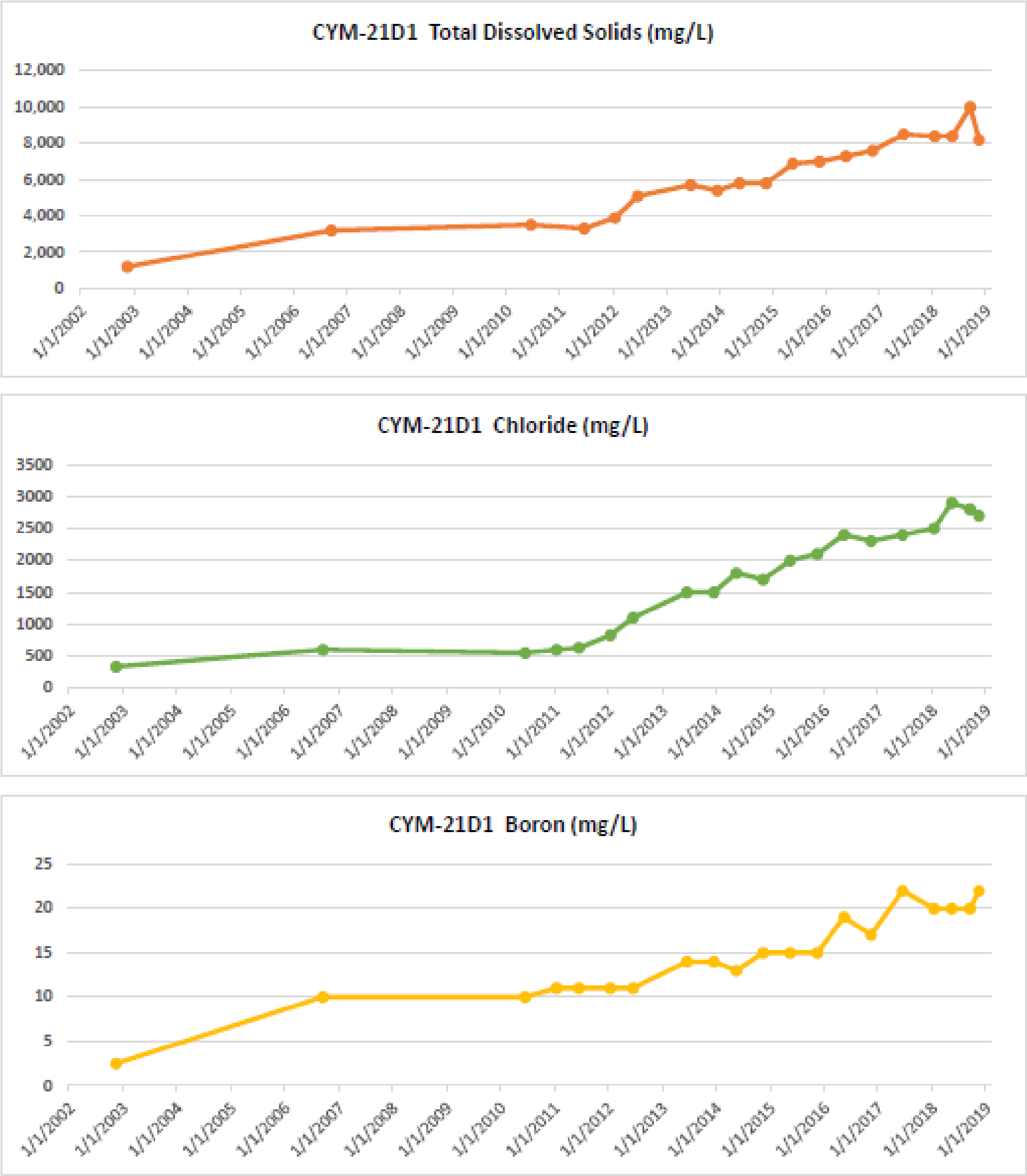


Figure 4.22. Concentration of total dissolved solids, chloride, and boron in deep monitoring well CYM-21D1 over time. Source: CVRWQCB (2019).

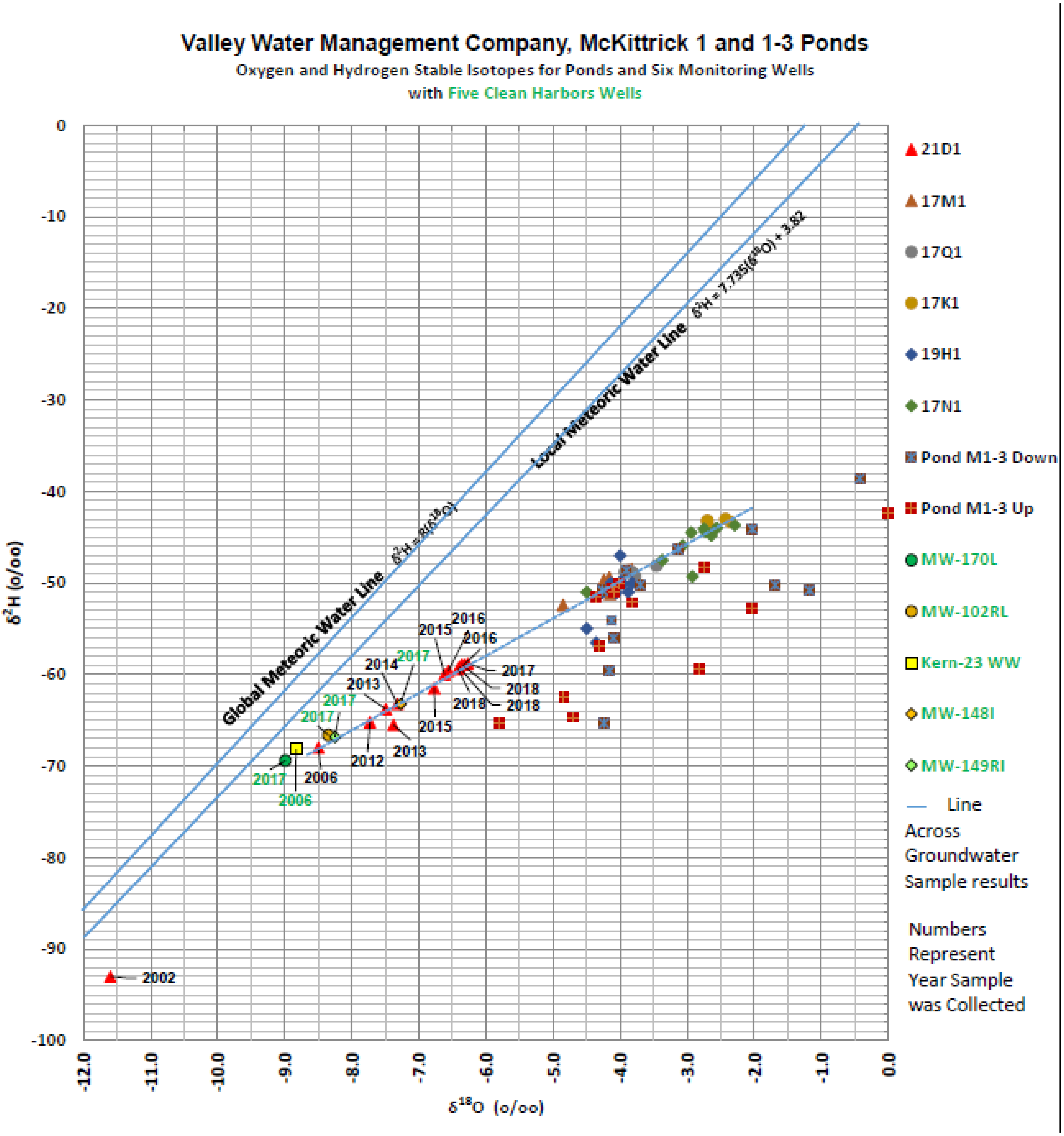


Figure 4.23. Water isotope figure of produced wastewater and groundwater wells. Source: CVRWQCB (2019).

4.5. Summary: Findings, Conclusions, and Recommendations

This chapter outlines a number of recommendations to improve the SB 1281 dataset's ability to help address important questions about produced water disposal in California. To determine whether the SB 1281 dataset accurately reflects the volume of produced water disposal to unlined produced water ponds, a comprehensive review of disposal practices at all unlined produced water facilities is necessary. This activity was beyond the scope of work for this effort but should be considered in order to better understand disposal patterns of produced water in the San Joaquin Valley. While flow measurements at both production wells and at facilities may not be precise, volumes reported pursuant to SB 1281 and volumes reported by facility operators should be reasonably close. Additionally, modifications to the dataset's disposition codes, as described in this chapter, would better allow for straightforward calculations of volumes of various produced water dispositions.

Since most produced water ponds have been in existence for an extended period of time (e.g., McKittrick 1 & 1-3 for 60 years), and nearly half of produced water ponds are now inactive, the proportion of produced water disposed in unlined produced water ponds has likely decreased in recent years. Beyond improvements to the SB 1281 dataset, future work should involve examination of both past and present discharge rates and cumulative discharge volumes to allow a more complete assessment of impact to groundwater resources, which is in part a function of cumulative discharge volume.

FCR 4.1. Reporting of disposal volumes into unlined produced water ponds pursuant to SB 1281 *(Chapter 4, Section 4.2)*

Finding 4.1.1. Reporting pursuant to SB 1281 indicates that 3,182 AFY of produced water is currently disposed into unlined produced water ponds in the San Joaquin Valley.

Finding 4.1.2. A review of discharge records at the McKittrick 1 & 1-3 Facility (a single facility) indicates that on average 3,152 AFY is disposed into unlined produced water ponds at this facility.

Conclusion 4.1. Because there are numerous active facilities of comparable size to the McKittrick 1 & 1-3 Facility in the San Joaquin Valley, including the McKittrick 1-1 Facility where 1,059 AFY of produced water is currently disposed into unlined produced water ponds, the accuracy of reported volumes pursuant to SB 1281 is in question.

Recommendation 4.1. All facility records should be reviewed to verify that reporting under SB 1281 accurately reflects volumes of disposal of produced water into unlined produced water ponds in the San Joaquin Valley.

FCR 4.2. Produced Water Disposal Method Codes in the SB 1281 dataset *(Chapter 4, Section 4.2)*

Finding 4.2.1. The volume of produced water reported disposed by "other" methods is more than twice the volume of produced water reported disposed into unlined produced water ponds.

Finding 4.2.2. The SB 1281 dataset includes a disposal method category "06 – Other," which may include, but not be limited to, disposal to unlined produced water ponds, if those produced water ponds are managed by a commercial entity. It is unclear what portion, if any, of this produced water has been disposed of in unlined produced water ponds operated by commercial entities.

Conclusion 4.2. Categories such as "Other" may make parsing out relevant information challenging or impossible, rendering even some straightforward questions unanswerable.

Recommendation 4.2. At a minimum, the SB 1281 dataset should be modified to include "Transfer to Commercial Disposal" to the disposition codes. A more useful code in this case would include the specific method of disposal (e.g. "Commercial Disposal to Unlined Sump").

FCR 4.3. Spatially-explicit information for produced water ponds: risk assessments

(Chapter 4, Section 4.2)

Finding 4.3.1. The overall volume and categorical disposition (e.g., reuse, disposal) of produced water is currently reported under SB 1281, but not the spatially-explicit destination.

Conclusion 4.3.1. Without spatially-explicit destination information, it is not possible to trace produced water from a particular oil field or formation to a particular produced water pond, and volumes of produced water discharged to a particular unlined produced water pond cannot be ascertained.

Recommendation 4.3.1. Data reported under SB 1281 should include spatially-explicit destination information (e.g., facility name and latitude/longitude) in addition to disposition of produced water to improve the ability to assess the risk posed to groundwater resources from disposal of produced water into unlined produced water ponds.

Finding 4.3.2. Potential impact to groundwater resources from disposal of produced water into unlined produced water ponds is, in part, a function of annual and cumulative discharge volumes and the quality of discharged produced water.

Conclusion 4.3.2. Though this information is necessary to assess potential impacts of discharging to unlined ponds, data reported to SB 1281 is currently not useful to determine annual or cumulative discharge volumes to individual produced water pond facilities.

Recommendation 4.3.2. Annual and cumulative discharge volumes should be assessed at active produced water pond facilities.

FCR 4.4. Produced water ponds are in areas that have groundwater that is or could be fit for agricultural, municipal, or domestic use *(Chapter 4, Section 4.3)*

Finding 4.4.1. Reporting pursuant to SB 1281 provides information on the locations of produced water ponds and the volumes of produced water disposed in unlined produced water ponds in general.

Finding 4.4.2. Groundwater resources that are or could be used for agricultural, municipal, or domestic use exist in areas of unlined produced water ponds in the central, northwestern, and eastern portion of the Tulare basin. Groundwater resources that could be treated for these uses exist in the western portion of the Kern County subbasin of the Tulare basin. With the exception of the eastern portion of the Tulare basin, where deep groundwater resources are present, groundwater resources having beneficial use appear to be limited to surficial (less than 300 m in depth) deposits.

Conclusion 4.4.1. Due to their shallow depth, many groundwater resources in the Tulare basin with potential for beneficial use may be particularly vulnerable to contamination from unlined produced water ponds.

Conclusion 4.4.2. Discharge of produced water into unlined produced water ponds poses risks to groundwater resources that are currently used or could be used in the future for beneficial purposes.

Recommendation 4.4.1. Agencies with jurisdiction should continue to investigate the use of produced water ponds and require appropriate testing and treatment of any water discharged into produced water ponds.

Recommendation 4.4.2. These agencies should develop a risk prioritization system to designate which unlined produced water ponds require in-depth, site investigations to determine the nature and extent of historical, current, and future impacts from the discharge of produced water. Such a risk prioritization should start with produced water ponds having the greatest present or past cumulative discharge volumes and should also include criteria such as the presence of groundwater resources having agricultural, municipal or domestic uses or potential for use with treatment.

Recommendation 4.4.3. For high-priority produced water ponds, a facility-by-facility assessment should be undertaken to determine where impacts to groundwater resources have already occurred or are likely to occur if the practice continues.

Recommendation 4.4.4. Agencies with jurisdiction should promptly ensure through appropriate testing and treatment that any water discharged into produced water ponds does not contain concentrations of chemicals related to oil and gas development that could impact groundwater resources. Given the potential for impact to groundwater resources, it may be advantageous for these volumes to decrease over time and the agencies with jurisdiction should thoroughly consider alternatives to this practice in the future.

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Appendix to Introduction

Table 1. Senate Bill 1281 and a comparison with Public Resources Code as of 2013.

Public Resources Code Pre-SB 1281	**Public Resources Code as amended by SB 1281**	**Notes on changes enacted by SB 1281**
Through 2013 Source: Justia U.S. Law, California Code through 2013 Legislative Session	Filed with Secretary of State Sep 25, 2014 Source: California Legislative Information	
	3226.3. The Division shall annually provide to the State Water Resources Control Board and the California regional water quality control boards an inventory of all unlined oil and gas field sumps.	SB 1281 newly required an annual inventory of unlined pits
3227. The owner of any well shall file with the supervisor, on or before the last day of each month, for the last preceding calendar month, a statement, in the form designated by the supervisor, showing all of the following:	3227. (a) The owner of any well shall file with the supervisor, on or before the last day of each month, for the last preceding calendar month, a statement, in the form designated by the supervisor, showing all of the following:	No change. Requires monthly reporting of subdivision (a) paragraphs 1,2,3 and 4.
a) The amount of oil and gas produced from each well during the period indicated, together with the gravity of the oil, the amount of water produced from each well, estimated in accordance with methods approved by the supervisor, and the number of days during which fluid was produced from each well.	(1) The amount of oil and gas produced from each well during the period indicated, together with the gravity of the oil, the amount of water produced from each well, estimated in accordance with methods approved by the supervisor, and the number of days during which fluid was produced from each well.	No change
(b) The number of wells drilling, producing, injecting, or idle, that are owned or operated by the person.	(2) The number of wells drilling, producing, injecting, or idle, that are owned or operated by the person.	No change
(c) What disposition was made of the gas produced from each field, including the names of persons, if any, to whom the gas was delivered, and any other information regarding the gas and its disposition that the supervisor may require.	(3) What disposition was made of the gas produced from each field, including the names of persons, if any, to whom the gas was delivered, and any other information regarding the gas and its disposition that the supervisor may require.	No change

Public Resources Code Pre-SB 1281	Public Resources Code as amended by SB 1281	Notes on changes enacted by SB 1281
(d) What disposition was made of the water produced from each field, and the amount of fluid or gas injected into each well used for enhanced recovery, underground storage of hydrocarbons, or waste water disposal and any other information regarding those wells that the supervisor may require. `	(4) What disposition was made of water produced from each field and the amount of fluid or gas injected into each well used for enhanced recovery, underground storage of hydrocarbons, or wastewater disposal, and any other information regarding those wells that the supervisor may require.	No change
	(5) The source of water, and volume of any water, reported in paragraph (4), including the water used to generate or make up the composition of any injected fluid or gas. Water volumes shall be reported by water source if more than one water source is used. The volume of untreated water suitable for domestic or irrigation purposes shall be reported. Commingled water shall be proportionally assigned to individual wells, as appropriate.	SB 1281 required more information on source of water used by oil and gas industry. Required information on whether that water was "suitable for domestic or irrigation purposes." Required reporting commingled water sources on a per-well basis.
	(6) The treatment of water and the use of treated or recycled water in oil and gas field activities, including, but not limited to, exploration, development, and production.	SB 1281 required reporting on treatment of water. Required information on use of treated or recycled water.
	(7) (A) The specific disposition of all water used in or generated by oil and gas field activities, including water produced from each well reported pursuant to paragraph (1). Water volumes shall be reported by disposition method if more than one disposition method is used. Commingled water shall be proportionally assigned to individual wells, as appropriate.	SB 1281 required information on "specific disposition of water" (PRC already asked for general information on disposition in subdivision(a), paragraph 4). Required separating disposition methods if more than one was used for a given stream of water. Required reporting commingled water dispositions on a per-well basis.
	(B) This information shall also include the temporary onsite storage of water, as or if appropriate, and the ultimate specific use, disposal method or method of recycling, or reuse of this water.	SB 1281 required reporting stored water.

Public Resources Code Pre-SB 1281	**Public Resources Code as amended by SB 1281**	**Notes on changes enacted by SB 1281**
Any operator that produces oil by the application of mining or other unconventional techniques shall file a report with the supervisor, on or before March 1 of each year, showing the amount of oil produced by those techniques in the preceding calendar year.	(b) Any operator that produces oil by the application of mining or other unconventional techniques shall file a report with the supervisor, on or before March 1 of each year, showing the amount of oil produced by those techniques in the preceding calendar year.	No change
Upon request and making a satisfactory showing therefor, a longer filing period may be established by the supervisor for any particular owner or operator.	(c) (1) Upon request and making a satisfactory showing therefor, a longer filing period may be established by the supervisor for any particular owner or operator.	No change
	(2) Notwithstanding subdivision (a), the owner of any well shall file with the supervisor, on a quarterly basis, a statement containing the information required to be reported pursuant to paragraphs (5), (6), and (7) of subdivision (a) in the form designated by the supervisor.	Notwithstanding the above requirement in subdivision (a), SB 1281 required quarterly reporting of all information described in subdivision (a) paragraphs (5), (6), and (7) on source, treatment, use of treated and recycled water, specific dispositions of water, and storage of water.
	(d) The Division shall use a standardized form or format to facilitate reporting required pursuant to this section.	SB 1281 required a standardized form for reporting (Note: unclear why this merited specification in statute. Were operators not previously using a standard form?)
	(e) The Division shall use noncustom software, as feasible, to implement online reporting by the operator of the information required pursuant to paragraphs (5), (6), and (7) of subdivision (a). This information may be reported separately from other information required to be reported pursuant to this section.	SB 1281 required that The Division use noncustomer software for the new reporting requirements. SB 1281 allowed, but did not mandate, that the quarterly information could be reported separately from the pre-existing monthly requirements.
	(f) For purposes of this section, the following terms have the following meanings:	

Public Resources Code Pre-SB 1281	**Public Resources Code as amended by SB 1281**	**Notes on changes enacted by SB 1281**
	(1) “Source of water” or “water source” means any of the following: (A) The well or wells, if commingled, from which the water was produced or extracted. (B) The water supplier, if purchased or obtained from a supplier. (C) The point of diversion of surface water.	SB 1281 specified what was meant by source of water.
	(2) “Specific disposition of all water” means the identification of the ultimate specific use, disposal method or method of recycling, or reuse of the water. This includes, but is not limited to, the identification of any treatment or recycling method used, injection of the water into specific injection or disposal well or wells, if commingled, discharge of the water to surface water or sumps, and sale or transfer of the water to a named entity.	SB 1281 specified what was meant by disposition of water.
	SEC. 3. No reimbursement is required by this act pursuant to Section 6 of Article XIII B of the California Constitution because the only costs that may be incurred by a local agency or school district will be incurred because this act creates a new crime or infraction, eliminates a crime or infraction, or changes the penalty for a crime or infraction, within the meaning of Section 17556 of the Government Code, or changes the definition of a crime within the meaning of Section 6 of Article XIII B of the California Constitution.	SB 1281 stated that no reimbursement would be made by state to local entities in carrying out the statute.

Appendix 1

Appendix 1.1. Recommended Revisions to SB 1281 Terms

Table A1.1. Destinations for water in Production and Other Allocation reports.

Destinations (SB 1281 Dataset Term)	Destinations (Authors' Term)	Recommended Revised Definition	Water Cycle Category
01 – Sump (unlined) – Evaporation and Percolation (infiltration): Water is placed into an unlined sump, allowed to percolate into the ground and/or evaporate into the atmosphere.	Unlined Pond		Discharge
02 – Sump (lined) – Evaporation: Water is placed into a lined sump, open tank, or similar container for evaporation into the atmosphere.	Lined Pond		Disposal
03 – Surface Water Discharge: Water is discharged into a surface body of water such as an ocean, lake, pond, river, creek, aqueduct, canal, stream, or watercourse.	Surface Water Discharge		Discharge
04 – Domestic Sewer System: Water is placed into a sewage disposal or treatment system, which is generally operated by a municipality or consortium for domestic waste.	Public Wastewater System		Discharge
05 – Subsurface Injection: Water is injected into the subsurface of the same oil field and operator from which it was produced. (Note: the volume attributed for each well for this disposition type on Form 110Q should match the sum for each well on the Well-to-Well Allocation List form.)	Subsurface Injection (UIC)	Subsurface Injection should be separated into two categories to distinguish between Disposal Wells and injection for Enhanced Oil Recovery (EOR).	Mix of EOR and Stimulation and Disposal

Destinations (SB 1281 Dataset Term)	**Destinations (Authors' Term)**	**Recommended Revised Definition**	**Water Cycle Category**
06 – Other: Water is disposed of by another method, such as commercial disposal, industrial use, non-class II wells, etc.	Other	The activities covered under Other should be clarified and any potential overlap with other Disposition categories should be reduced. In particular, the terms "Commercial Disposal" and "Industrial Use" could arguably cover activities covered in other destinations.	Other
07 – Sale/Transfer – To other operator or oil field: Water is sold or transferred to another operator or oil field.	Other Operator or Oilfield		Ancillary O&G Operations
08 – Discharge: Water is used on oil field land or surface for dust control, landscaping, pasture augmentation, infiltration, evaporation, etc.	Discharge to Land		Discharge
09 – Operator's facilities within oil field: Water is used for operator's facilities within the oil field (e.g., tankage, equipment operation, onsite storage, equipment/facilities cleaning and testing, etc.)	Operator Facilities	Onsite storage should be removed from the definition. Stored water should be its own source and destination.	Ancillary O&G Operations
10 – Well Stimulation Treatment: Water is used in a well stimulation treatment operation (e.g., hydraulic fracturing, acid matrix, acid fracturing, etc.)	Well Stimulation		Ancillary O&G Operations

Destinations (SB 1281 Dataset Term)	**Destinations (Authors' Term)**	**Recommended Revised Definition**	**Water Cycle Category**
11 – Sale/Transfer – Domestic Use: Water is used for agriculture, irrigation, water replenishment, water banking, livestock, etc.	Reuse for Agriculture or Recharge	"Sale/Transfer – Domestic Use" is a misleading term for a category that is meant to denote reuse in agriculture or groundwater recharge. Domestic Use implies use for household purposes, i.e. "domestic purposes such as drinking, cleaning, washing, or sanitation" (California Water Code, Section 112).	Discharge
12 – Drilling, well work, and well abandonments: Water is used to support well drilling, rework, and abandonment operations, with uses such as well control fluid, drilling mud, cementing, etc.	Well Work		Ancillary O&G Operations

Table A1.2. Sources for water in Injection and Other Allocation reports.

Sources (SB 1281 Dataset Term)	**Sources (Authors' Term)**	**Recommended Revised Definition**	**Water Cycle Category**
01 – Oil or gas well produced – In oil field by operator: Produced from an oil or gas well, and used within the same field by the same operator from which it was produced.	Produced Water		Produced Water and Flowback
02 – Water source well – In oil field by operator: Produced from a water source well and used within the same field by the same operator from which it was produced.	Water Well (Operator-Owned)		External Source
03 – Domestic Water System – Fresh water: Obtained from domestic fresh water system (water district, municipality, public or private entity) where the water is primarily intended for residential or commercial use.	Water Supplier (not Operator Owned)		External Source
04 – Surface Water – Ocean, Lake, Pond, River, Creek, etc.: Extracted from a surface water body such as an ocean, lake, pond, river, creek, aqueduct, canal, stream, or watercourse.	Surface Water		External Source
05 – Industrial Waste – Class II fluid treated by 3rd party: Class II fluid obtained for disposal in a commercial class II well.	Drilling and Other Oilfield Waste (Transferred Between Operators)	Waste produced on the oil field other than produced water. Legally allowed to be injected into a Class II well; referred to in regulator shorthand as "Class II waste."	Ancillary O&G Operations
06 – Domestic Waste Water Treatment Facility – Recycled water: Obtained as recycled water from a domestic wastewater treatment facility.	Municipal Wastewater		External Source

Sources (SB 1281 Dataset Term)	**Sources (Authors' Term)**	**Recommended Revised Definition**	**Water Cycle Category**
07 – Other – Specify source: This category is used for tracking all non-class II fluid used in EPA wells and monitored by The Division. This category is also used for all other class II fluid not covered by the defined water source categories. The source of the fluid must be specified (e.g., XYZ refinery waste, John's Automotive Service waste pit reclamation).	Other		Other
08 – Oil or gas well produced – Transferred or purchased from other operator or oil field: Obtained as a purchase/transfer from a produced oil or gas well from another operator or oil field. This is not to be used for commercial class II wells.	Produced Water (Transferred)		Ancillary O&G Operations
09 – Well Stimulation Treatment – Recycled fluid: Produced as flowback fluids after the completion of a well stimulation treatment operation (e.g., hydraulic fracturing, acid matrix, acid fracturing, etc.).	Well Stimulation Recovered Fluids	Well Stimulation encompasses hydraulic fracturing (fracking), matrix acidizing, and acid fracturing.	Ancillary O&G Operations
10 – Other Class II Recycled fluid source – In oil field by operator: In oil field by Operator (e.g., tankage, onsite storage, sumps, cellars, spillage-cleanup).	Drilling and Other Oilfield Waste (Stored)		Ancillary O&G Operations
11 – Recycled class II fluids from operator's drilling: Class II fluid recycled from operator's drilling, rework, and abandonment operations, including recovered well control fluid, well cleanup and displacement fluids, etc.	Drilling and Other Oilfield Waste	Drilling and Other Oilfield Waste, neither stored nor transferred between operators.	Ancillary O&G Operations

Appendix 1.2. Detailed Methods

A. SB 1281

The SB 1281 dataset has three main reports—Production, Injection, and Other Allocation—submitted quarterly to The Division. The various data fields reported in the original dataset are in Table 2.A.1, Table 2, and Table 3. Additional information can be found in the Data Dictionary for the SB 1281 dataset (DOGGR, 2018). To conduct our analysis, we needed to reorganize and aggregate the production and injection dataset to a more easily readable format. We carried out this reorganization out using R (R Core Team, 2013). The final formatted dataset can found in Appendix 1.5. The main steps of this reorganization are as follows:

- Combining the multiple quarterly datasets into one master dataset
- Reorganizing so that consecutive columns referring to sources/destinations were reformatted to consecutive rows
- Error checking
- Joining field names to sedimentary basins
- Aggregating to unique combinations of field/operator while retaining information on water quality, source/destination, volume of water
- Export to .csv format

While aggregating to the field/operator level, we considered a sum of the data field titled ‘Total Water Produced or Injected’ to get a total volume for that field/operator.

The error-checking process led to multiple errors found in reporting. The main error found was wrong type of input for the given column, such as data entry values outside the range of possible values for that field.

The Other Allocation dataset describes 528 possible flows, from 11 sources to 12 destinations, by two storage categories (stored/not stored) and two quality categories. It is reported at the field level. This dataset is meant to account for volumes of water not connected to production or injection. However, the dataset does include these volumes. For our water accounting calculations, we disregarded water in the Other Allocation report with a source of production or destination of injection, assuming that it represented double reporting of flows in other reports.

The Other Allocation dataset also accounts for water stored on a field. However, water is reported as absolute volumes each quarter, leading to double-counting flows of water that have already been reported as stored in previous quarters. In addition, destination for stored water was denoted as "intended destination." However, volumes of water stored were, by definition, not used in that given quarter and had no destination yet. Therefore, when calculating the volume of water stored, we calculated the change in storage each quarter and disregarded the designated source and volume.

Table A1.3. Data fields available in the SB 1281 Production dataset.

Data Field
Operator Name
Operator Code
Quarterly Reporting Period
Date Report Prepared
Report Prepared By
Field
Lease
Well Number
API Number
Pool
Pool Code
Pool Well Type
Total Water, Total Water Produced/Steam Injected (bbl)
Calculated Total Water, Total Water Produced/Steam Injected (bbl)
Produced Water Disposal Method
Water Produced (bl)
Disposition of Water (Code #)
If Untreated, is Water Suitable for Domestic or Irrigation Use?
Is Water to be (Has Water been) Treated by Operator?
Water Treatment Method(s)
Name of Water Source/Disposal Recipient
Type of Water Source/Disposal Recipient

Table A1.4. Data fields available in the SB 1281 Injection dataset.

Data Field
Operator Name
Operator Code
Quarterly Reporting Period
Date Report Prepared
Report Prepared By
Field
Lease
Well Number
API Number
Pool
Pool Code
Pool Well Type
Total Water, Total Water Produced/Steam Injected (bbl)
Calculated Total Water, Total Water Produced/Steam Injected (bbl)
Produced Water Disposal Method
Water Produced (bbl)
Disposition of Water (Code #)
If Untreated, is Water Suitable for Domestic or Irrigation Use?
Is Water to be (Has Water been) Treated by Operator?
Water Treatment Method(s)
Name of Water Source/Disposal Recipient
Type of Water Source/Disposal Recipient
Water Source
Water or Steam Injected (bbl)
Source of Water

Table A1.5. Data fields available in the SB 1281 Other Allocation dataset.

Data Field
Operator Name
Operator Code
Quarterly Reporting Period
Date Report Prepared
Report Prepared By
Field
Lease
Well Number
API Number
Pool
Pool Code
Pool Well Type
Total Water, Total Water Produced/Steam Injected (bbl)
Calculated Total Water, Total Water Produced/Steam Injected (bbl)
Produced Water Disposal Method
Water Produced (bbl)
Disposition of Water (Code #)
If Untreated, is Water Suitable for Domestic or Irrigation Use?
Is Water to be (Has Water been) Treated by Operator?
Water Treatment Method(s)
Name of Water Source/Disposal Recipient
Type of Water Source/Disposal Recipient
Water Source
Water or Steam Injected (bbl)
Source of Water
Field
Water (bbl)
At the Time of this Report, is Water in Storage Onsite?

B. Division All Wells and Injection/Production

Data Sources

The secondary set of well production and injection data, which we call the monthly dataset, is submitted by operators monthly and is provided by The Division (DOGGR, 2018c). Production data include oil, gas, and condensate production volumes, as well as wastewater production volumes and the type of wastewater disposal used, referred to as water disposition. Injection data include water injection volumes; where the injected water was sourced from; and the content of the injected water (fresh, saline, chemical mixture), known as water kind. A full list of variables is provided in Table 2.B.1. Accompanying the production and injection data is a third file for each year, which provides well-level status and geographic information. We downloaded these data for the period from 2015 to 2017.

Table A1.6. Full list of variables included in The Division monthly production reporting.

Variable Name	**Description**
ProductionDate	First day of each production reporting period
ProductionStatus	Production status for each month 0 – Well on production 1 – Standing (incapable of production in its present condition) 4 – Uncompleted 5 – Abandoned or converted to another well type (Division approved) 6 – Shut-In, capable of production in its present condition 8 – Other (e.g., observation well) 9 – Operator Change (well transferred)
CasingPressure	Casing pressure at the well head in pounds per square inch (psi)
TubingPressure	Tubing pressure value at the wellhead in pounds per square inch (psi). Static pressure if the well is not on production, flowing pressure if the well is flowing
BTUofGasProduced	British Thermal Unit (Btu) of Gas Produced per cubic foot for each well
MethodOfOperation	
APIGravityOfOil	API Gravity of Oil for each well, with API Gravity indicating how heavy or light the oil is as compared to water
WaterDisposition	Water Disposition: the water disposal method used to dispose of produced water from a production well 0 – Not Applicable 1 – Evaporation-Percolation: water is allowed to percolate into the ground and evaporate into the atmosphere, such as in an unlined sump 2 – Evaporation-lined sump: water is placed in a lined sump, open tank, or similar container for evaporation into the atmosphere 3 – Surface water body: water is dumped into any surface body of water such as a lake, ocean, pond, stream, river, canal, or irrigation ditch 4 – Sewer system: water is placed in a sewage disposal or treatment system 5 – Subsurface injection: water is injected into the subsurface 6 – Other: water is disposed of by another method, such as being turned over to a water disposal contractor

Variable Name	**Description**
OilorCondensateProduced	Oil or condensate produced from each well during the month, in barrels
DaysProducing	Number of days a well produced fluids in a month, values are between zero and the total number of calendar days in the month
GasProduced(MCF)	Gas produced from each well during the month, in thousand cubic feet (MCF)
WaterProduced(BBL)	Water produced from each well during the month, in barrels
MissingDataCode	Missing production data code
PWT__ID	Pool Well Type ID code, with one value per well; one-to-one match with API number

Table A1.7. Full list of variables included in The Division monthly injection reporting.

Variable Name	**Description**
InjectionDate	First day of each injection reporting period
InjectionStatus	Injection status, reason well not injecting 0 – Well injecting 1 – Standing (incapable of injection in its present condition) 4 – Uncompleted 5 – Abandoned or converted to another well type (Division approved) 6 – Shut-Down (capable of injection in its present condition) 8 – Other (e.g., well was used for observation) 9 – Operator Change (well transferred)
Gas/AirInjected(MCF)	Gas or air injected for each well during the month, in thousand cubic feet (MCF)
Steam/WaterInjected(BBL)	Water or steam (as water equivalent) injected for each well during the month, in barrels
DaysInjecting	Number of days a well injected in a month, values are between zero and the total number of calendar days in the quarter
SurfaceInjPressure	Injection pressure at the well head, in psig
WaterSource	Code which indicates the source of injected water Blank – Not applicable (not injecting) 0 – Not applicable 1 – Oil or Gas well 2 – Water source well 3 – Domestic water system 4 – Ocean 5 – Industrial waste 6 – Domestic waste 7 – Other
WaterKind	Code which indicates the kind/quality of water being injected Blank – Not applicable (not injecting) 0 – Not applicable 1 – Saline 2 – Fresh 3 – Chemical mixture 4 – Other
MissingDataCode	Missing injection data code
PWT__ID	Pool Well Type ID code, with one value per well; one-to-one match with API number

Table A1.8. Full list of variables included in The Division well-level status and geographic information reporting, which accompanies monthly production and injection reporting.

Variable Name	Description
DistrictNumber	Division district number, ranging from 1 to 6
FieldCode	Numeric code assigned to each field
AreaCode	Numeric code assigned to each area
APINumber	Unique, permanent number assigned to each well as standardized by the American Petroleum Institute; API format is ########, with the first three digits representing the county code and the last five digits representing the well ID
WellStatus	Code identifying well status at time of production/injection reporting (2015 – 2017)
Section	Public Land Survey System Section number
Subsection	Public Land Survey System Subsection number
Township	Public Land Survey System Township
Range	Public Land Survey System Range
BaseMeridian	Base Meridian: principle meridians required for all California surveys; defines PLSS base H – Humboldt MD – Mount Diablo SB – San Bernardino
OperatorCode	Operator code: five-character division-assigned code
LeaseName	Name of oil & gas lease
WellNumber	Operator-assigned alpha numeric designation for well
FieldName	Name of the oil & gas field
AreaName	Name of area
OperatorName	Operator name
OperatorStatus	Operator status at time of production/injection reporting (2015 – 2017)
OperatorReportingMethod	Hard copy or computerized
CountyName	U.S. county that each well is located within
PoolCode	Two-digit pool code number, assigned by The Division
WellTypeCode	Well-type code, indicates the production or injection usage of the pool completion
SystemEntryDate	Date entered into system
PoolName	Pool name
PWT__ID	Pool Well Type ID code, with one value per well; one-to-one match with API number

Table A1.9. Number of monthly well entries with injection and production reported data, 2015–2017.

	Production	Injection
2015	1,010,375	278,277
2016	999,661	254,094
2017	981,868	244,457
Sum	2,991,904	776,828

We also downloaded a 2018 layer of well-level data, named All Wells, which provided xy coordinates for each well; coordinates are missing from all other data sources (DOGGR, 2018a). Although this file duplicated many data fields available in the basic well information dataset, it updates certain fields with 2018 information, such as well status. It also provides xy coordinates for total well depth, and fields indicating well age and whether a well was has been hydraulically fractured. All these fields are not available from any prior dataset.

We also obtained a spatial layer of oil and gas field boundaries from The Division (DOGGR, 2018b). It includes data for 516 oil and gas fields within California and provides attributes for field name and identifying field code, area, date ranges of use, and The Division district that each field is located within.

We included sedimentary and groundwater basins in this analysis to provide information on regional hydrocarbon and groundwater trends. We used the same sedimentary basin spatial data that was used in the CCST SB 4 2015 report (Long et al., 2015). We downloaded groundwater basin and subbasin spatial data from the California Department of Water Resources (CDWR, 2016).

For use in calculating and error-checking geographic information for oil and gas wells and fields, we downloaded a U.S. county shapefile from the U.S. Census Bureau (2017), and a shapefile of California townships from the Public Land Survey System (PLSS) as released by the U.S. Bureau of Land Management (2018).

Well-Level Dataset

We assigned each monthly data entry to a quarter of the year starting with the first quarter (representing January, February, and March). We used these quarters to aggregate the monthly injection and production data at the quarterly level to temporally match the granularity of the SB 1281 data. In the process of converting data presented by month to data presented by quarter, we had to summarize the data fields. Fields such as Oil or condensate produced, and Gas produced, we summed over all months in a quarter. For other fields, such as surface injection pressure and API gravity of oil, sums didn’t make sense with the type of data, so instead we calculated mean, minimum, and maximum. With text fields, any aggregation option would have resulted in losing data, so we kept all unique data values for each field, grouping all other variables by these fields (“Group By”).

Table A1.10. Type of aggregation used to convert monthly data to quarterly data.

Group By	**Summed**	**Calculated mean, minimum, and maximum**	**Only included a single value over all months in a quarter**
PWT ID	Oil or condensate produced	Casing pressure	Missing data code, production
Year	Gas produced (MCF)	Tubing pressure	Missing data code, injection
Quarter	Water produced (Bbl)	BTU of gas produced	County
Water disposition	Days producing	API gravity of oil	Division District
Injection status	Days injecting	Surface injection pressure	Field
Water source	Gas/Air injected (MCF)		Area
Water kind	Steam/Water injected (Bbl)		Section
			Subsection
			Township
			Range
			Base Meridian
			Operator
			Lease
			Well number
			Operator status
			Well status
			County
			Pool

Note: A few fields had other methods of summarization. For the field production status, we calculated the status for the third month of the quarter to denote the most recent status value. We also calculated yes/no binary fields for hydrocarbon production and water production, derived from the production status, Oil or Condensate Produced, and Water produced data fields.

Multiple fields, including production status, injection status, water disposition, water source, and water kind, were populated with integer data codes. We created secondary fields for each of these data variables and populated them with the text definitions for each code we obtained from Division documentation (DOGGR, 2014). We joined the three Division tables (injection, production, and basic well information) into a single dataset with one row for each quarter of data for each well covering 2015 – 2017. There are 6,374 rows of data that have both injection and production data reported with a quarter. We included all of these data in a single row, combining rows included in both injection and production databases, and resulting in a total of 1,368,351 rows of data. This includes data for 104,032 individual wells.

Using ArcGIS 10.3, we spatially joined each basin layer to The Division All Wells point layer which provided the sedimentary basin, groundwater basin, and groundwater subbasin that each well is located within. Spatial match is very strong for sedimentary basins; 224,690 out of 226,730 wells (99.1%) were located within the boundaries of a sedimentary basin. The overlay relationship between oil and gas wells and groundwater basins is less strong; 195,691 wells (86.3%) were located within a groundwater basin. We joined this resulting well layer with the injection and production data using API number. A total of 45.9% of the wells in the All Wells dataset also have reported data in The Division injection and production data.

There were 1,452 wells in the SB 1281 Production and/or Injection datasets that did not have data in The Division production and/or injection datasets, but did have a matching API with the All Wells dataset. We added these data into the combined injection/production dataset, with one row per well, year, and quarter, resulting in an additional 17,424 rows in the dataset. We populated these records with data available from the All Wells dataset, including xy coordinates, which are required for all mapping and spatial analysis of the SB 1281 dataset.

Field-Level Dataset

One of the SB 1281 datasets, Other Water Allocation, is released at the oil- and gas-field level. Therefore, we created a second version of the injection and production data aggregated at the oil- and gas-field level to allow for parallel joining and comparison. To aggregate well-level data to field-level data, we followed a similar approach to aggregating monthly data to quarterly data. Variables that had been summed for the well-level dataset were summed again in this step. Variables for which mean, minimum, and maximum had been calculated for the well-level dataset again had the same metrics calculated over all wells to come up with field summary statistics. The major difference in aggregation methods between the well-level dataset and the field-level dataset is the method we used to aggregate text fields. In the well-level dataset, we used text fields as “Group by” fields for aggregation, and all values were kept and parsed into multiple rows of data. To keep file sizes down in the field-level dataset, each oil and gas field had a single row of data for each quarter for which there was reported data, thus 12 rows in total (three years, four quarters a year). Where a field had multiple values in a text field, these were split out into different column fields. For example, if an oil and gas field was located within the boundaries of more than one county, there would be values in County field A and County field B.

The vast majority of wells have an assigned field (99.8%). Only 212 wells were assigned a field name of “Any field” indicating wildcat wells that were drilled outside of a field. These 212 wells did not have data represented in the field-level dataset.

Using ArcGIS, we spatially joined The Division oil and gas fields to U.S. counties, PLSS townships, sedimentary basins, groundwater basins, and groundwater subbasins to assign these geographic identifiers to each oil and gas field. With sedimentary and groundwater basins, it is common for an oil and gas field to be located only partially within the boundaries of a basin. To determine oil and gas fields in which this occurs, we intersected oil and gas fields with sedimentary and groundwater basins and subbasins, and calculated the percentage of the area of each type of basin that resided within the boundaries of each oil and gas field.

The naming convention of field names in The Division Field Boundaries shapefile is different than the naming convention used for field names in the injection and production datasets. In the injection and production data, abandoned oil and gas fields are denoted by adding the characters “(ABD)” after the name of the field. For example, the Boyle Heights oil and gas field is listed as “Boyle Heights (ABD).” However, in the Field boundaries shapefile, there are no such abandoned qualifiers after field names. This discrepancy would have prevented correct data joining, so we created a modified oil and gas field name column in the injection and production dataset, which we populated with field names excluding the (ABD) qualifiers. We then joined the oil and gas field spatial analysis output to the injection and production field-level dataset.

Appendix 1.3. Detailed Cross-Validation of SB 1281 and Monthly Datasets

A. State-Wide Trends

We compared the SB 1281 dataset to the monthly dataset to evaluate the consistency between the two data sources. For the state of California, 1.16 million acre-feet (AF) of water were reported as produced from the SB 1281 dataset from 2015 – 2017, as compared to 1.30 million AF from the monthly dataset (11.04% change). Injected water volumes are slightly lower, with 987,000 AF reported from the SB 1281 dataset and 1.15 million AF from the monthly dataset (14.2% change). The median quarterly volume of water produced is reported as 103,000 AF and 108,000 AF from the SB 1281 and monthly datasets, respectively.

While the state summary numbers are similar between SB 1281 and monthly reporting, there are some substantial differences in data trends between the two datasets. First, there are considerable differences in production and injection volumes between quarters, particularly in the SB 1281 dataset. In the monthly dataset, the minimum and maximum production and injection volumes are within 12,000 AF from each other. The range in the SB 1281 dataset is > 50,000 AF (55,000 – 107,000 AF produced; 42,000 – 95,000 AF injected). At the state level, these discrepancies primarily lie in the first quarter (2015 Q1) and the last quarter (2017 Q4).

B. Trends in Produced Water Disposition

Produced water volumes are lower in the SB 1281 dataset for every water disposition category except Other/Unknown (see Table 3.B.1). Decreases from monthly to SB 1281 dataset volumes range from 13.1% volume decrease (subsurface injection) to 91.9% volume decrease (surface water body). In contrast, water volumes in the other/unknown category increased by 28.3% from monthly to the SB 1281 dataset. Thus, not only is there less reported data in the SB 1281 dataset, but the quality of the reporting is also worse, with more data not given a known water disposition. This is in spite of a greater number of disposition categories in the SB 1281 dataset (see Table 3.B.1).

Table A1.11. Produced water volumes by disposition for SB 1281 and monthly reporting.

	SB 1281 Reporting		**Monthly Reporting**	
Water Disposition	Volume (acre-ft)	%	Volume (acre-ft)	%
Subsurface Injection	938,000	80.9%	1,080,000	82.8%
Other/Unknown	204,000	17.6%	159,000	12.2%
Evaporation-Percolation (unlined)	11,200	1.0%	34,200	2.6%
Surface Water Body	1,870	0.2%	23,200	1.8%
Sewer System	4,040	0.3%	6,970	0.5%
Evaporation (lined)	160	0.0%	710	0.1%

Table A1.12. Produced water disposition category comparison between monthly and SB 1281 datasets.

Monthly dataset	**SB 1281 dataset**
Evaporation-Percolation	Sump (unlined) – Evaporation and Percolation (infiltration)
Evaporation-Lined Sump	Sump (lined) – Evaporation
Surface water body	Surface water discharge, further broken out by ocean, lake, pond, river, creek, aqueduct, canal, and watercourse
Sewer System	Domestic sewer system
Subsurface injection	Subsurface injection – In oil field by operator
Other	Sale/transfer; land discharge; operator's facilities within oil field; well stimulation treatment; drilling, well work, and well abandonments; or other

C. Trends in Water Source Category Comparison Between Monthly and SB 1281 Datasets

Trends for the source of injected water are more nuanced than the water disposition trends reported directly above. Although the monthly reporting has higher reported volumes overall, volumes reported in each category are not always higher in the monthly reporting, and in fact there are some substantial shifts in category choice (see Table 3.C.1). In the SB 1281 dataset, lower waste volumes are reported to domestic water systems, industrial waste, and other/unknown, with percent decreases ranging from 42.5% – 94.3%. Conversely, higher volumes in the SB 1281 dataset are reported to oil or gas well, water source well, and domestic waste, with 20.3% to > 4,000% increase (domestic waste increased by 4,092.3%). There is also a dramatic drop in the amount of waste categorized as other/unknown, which drops from 329,000 AF in the monthly reporting to 18,600 AF in the SB 1281 dataset. Some of these shifts in water volumes are likely due to differing category definition and an increased number of water source categories in the SB 1281 dataset (see Table 3.C.2).

Table A1.13. Injected water volumes by source for SB 1281 and monthly reporting.

	SB 1281 Reporting		**Monthly Reporting**	
Water Source	Volume (acre-ft)	%	Volume (acre-ft)	%
Oil or gas well	942,000	95.5%	783,000	68.1%
Other/Unknown	18,600	1.9%	329,000	28.6%
Domestic water system	7,640	0.8%	30,700	2.7%
Water source well	12,700	1.3%	6,440	0.6%
Industrial waste	191	0.0%	332	0.0%
Domestic waste	5,450	0.6%	130	0.0%

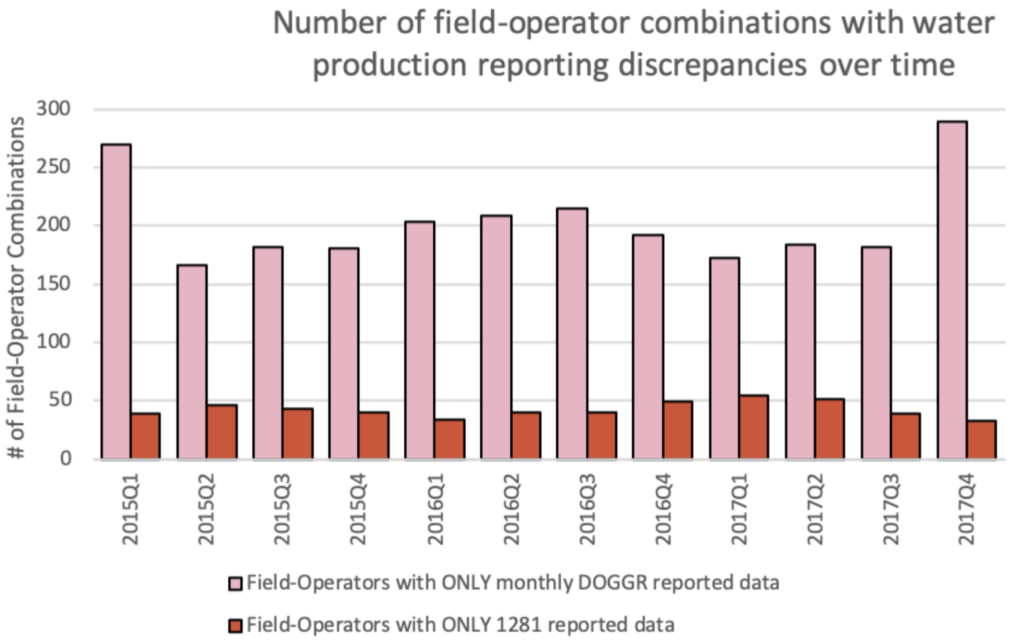
Table A1.14. Injected water source category comparison between monthly and SB 1281 datasets.

Monthly dataset	SB 1281 dataset
Oil or gas well	Oil or gas well produced, further broken out by produced in oil field by operator; or transferred or purchased from other operator or oil field
Water source well	Water source well – in oil field by operator
Domestic water system	Domestic water system – Fresh water
Ocean	Surface water, further broken out into ocean, lake, pond, river, creek, aqueduct, canal, and watercourse
Industrial waste	Industrial waste – Class II fluid treated by third party
Domestic waste	Domestic water treatment facility – Recycled
Other	Well stimulation treatment; Recycled class II fluids from operator's drilling; other Class II recycled fluid source; or Other

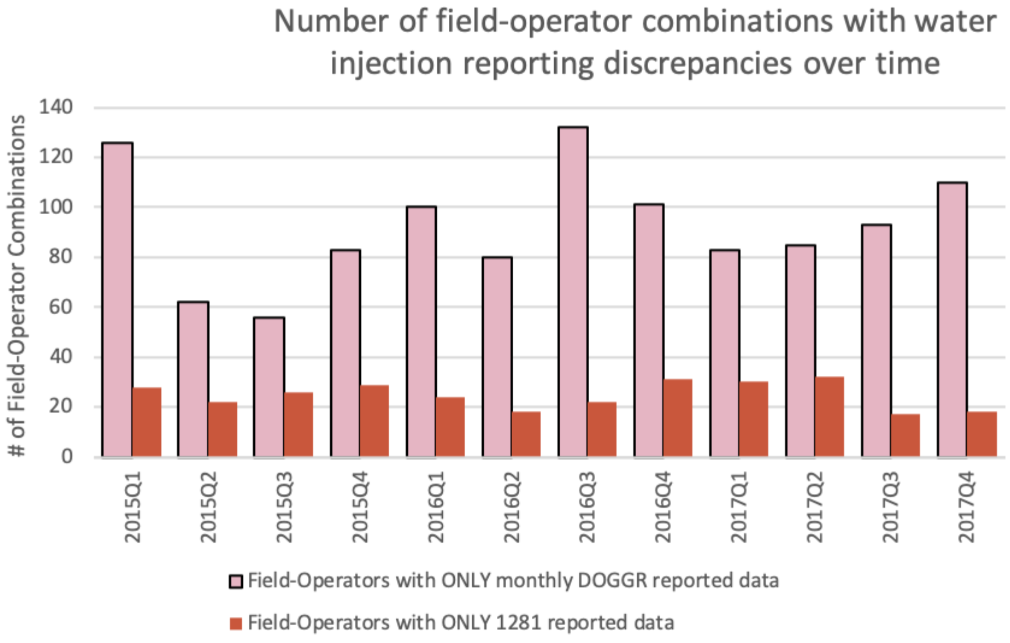
D. Trends Within Sedimentary Basins

There are also notable discrepancies between the SB 1281 and monthly datasets at the sedimentary basin level. In general, the monthly dataset has consistent data between quarters within basins, with the exception of basins with very small produced and injected water quantities (< 3,000 AF; five of the ten basins). For the monthly data, all basins with ≥ 3,000 AF have water production and injection volumes within one standard deviation of the mean (+/- 34.1%). But in the SB 1281 data, only one basin (Santa Maria) has data within one standard deviation of the mean. The discrepancies mostly lie below the mean. This means the discrepancies for the most part are from underreporting rather than overreporting in the SB 1281 dataset. In most cases the issue is not higher or lower quantities reported between the two sources, but rather data are more commonly reported to one source (usually monthly) and not reported at all to the other source (usually SB 1281). In fact, for many quarters there are no data for injection and production volumes for entire basins. For example, the Cuyama basin has reported production volumes of between 400 and 600 AF, but in 2015 Q1, 2015 Q3, 2015 Q4, 2016 Q4, 2017 Q3, and 2017 Q4, there were no reported produced water volumes.

Figure 3.D.1 shows the discrepancies between monthly and SB 1281 datasets by field-operator combinations, which are unique combinations of a single operator that is producing on a single oil and gas field. Discrepancies in this figure are shown by production and injection reporting to one source (SB 1281 or monthly), but not the other. When discrepancies in reporting exist, the underreporting occurs much more frequently within the SB 1281 dataset, both for production and injection. The first and last reporting quarters (2015 Q1 and 2017 Q4) stand out as particularly flawed, especially with water production, as having substantially more reporting to the monthly data than SB 1281.



Number of field-operator combinations with water production reporting discrepancies over time



Number of field-operator combinations with water injection reporting discrepancies over time

Figure A1.1. Number of field-operator combinations with water production (top) and injection (bottom) reporting discrepancies over time.

Appendix 1.4. Injected Water Sources And Destinations By Main Basin

Table A1.15. Breakdown of sources for water injected.

	Volume of Water (acre-feet per quarter)									
	Los Angeles		**Salinas**		**San Joaquin**		**Santa Barbara-Ventura**		**Santa Maria**	
Source name	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**
Drilling and Other Oilfield Waste	0.22						0.00			
Drilling and Other Oilfield Waste (Stored)	17.71				0.06	11.07				
Drilling and Other Oilfield Waste (Transferred Between Operators)					6.37		5.31			
Municipal Wastewater		527.18	8.52							
Other	143.28	0.11			6.77	18.51	0.07			
Produced Water	28,090.68	21.52	3,223.00		48,397.84	139.95	2,753.76		2,405.54	
Produced Water (Transferred)	2,102.48		5.55		974.70	71.00	16.29		69.25	
Surface Water						300.63				
Water Supplier (not Operator Owned)	3.06	14.48			189.71	419.36		3.24		
Water Well (Operator-Owned)	218.99		29.29		838.11	53.03	0.03		16.39	
Well Stimulation Recovered Fluids					732.07					
TOTAL	30,576.41	563.30	3,266.37	0.00	51,145.63	1,013.56	2,775.46	3.24	2,491.18	0.00

Table A1.16. Breakdown of destinations for water produced.

	Volume of Water (acre-feet per quarter)									
	Los Angeles		**Salinas**		**San Joaquin**		**Santa Barbara-Ventura**		**Santa Maria**	
Destination Name	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**	**Saline**	**Fresh/ Brackish**
Discharge to Land	0.49				117.40	6.87				
Lined Pond	0.04	0.01			0.02				9.07	
Operator Facilities	18.80				522.63	0.00	25.79		18.78	
Other	141.44	0.01			1816.45		5.58			
Other Operator or Oil Field	1,991.99				1,286.77	206.94	10.32		0.02	
Public Wastewater System	392.13	1.19					0.18			
Reuse for Agriculture or Recharge			475.07		8,582.36	359.42				
Subsurface Injection (UIC)	28,237.73	19.09	3,579.43		47,616.54	853.13	1,192.71	1,444.09	1,648.17	
Surface Water Discharge					17.60				100.04	
Unlined Pond	95.20	8.54	10.74		1,022.14	23.95	2.03			
Well Stimulation					1,293.21	0.82				
Well Work	4.20		2.57		171.32		2.39			
TOTAL	30,882.03	28.84	4,067.81	0.00	62,446.45	1,451.12	1,239.00	1,444.09	1,776.08	0.00

Appendix 1.5. Additional Data Organization

SB 1281 All Flows Dataset, Aggregated by Field and Operator

Provided as a separate Excel spreadsheet download.

Appendix 1.6. Water Cycle Details

Table A1.17. Water Cycle Results for the Five Major Basins

San Joaquin

		Volume of water (Mean AFQ)		
Water Cycle Origin	**Water Cycle Endpoint**	**Saline**	**Fresh/ brackish**	**Total**
Ancillary O&G Operations	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	349.57	29.24	378.81
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation Operations	631.56	52.83	684.39
External Source	Ancillary O&G Operations	3.71	221.08	224.79
	Disposal	366.23	281.05	647.28
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation Operations	661.62	497.60	1,159.21
Other	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	2.41	6.59	9.01
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation Operations	4.36	11.91	16.28
Produced Water and Flowback	Ancillary O&G Operations	1,980.72	206.94	2,187.67
	Disposal	16,965.48	307.91	17,273.39
	Other	1,816.45	0.00	1,816.45
	Discharge	9,739.50	390.23	10,129.73
	EOR and Stimulation Operations	31,944.29	557.11	32,501.40
Change in Storage	Change in Storage	-135.54	1.98	-133.56
Metrics				
Inputs		61,661.55	2,461.92	64,123.47
Outputs		27,420.78	1,008.44	28,429.21
Demand		62,293.11	2,514.76	64,807.86
Reuse		34,556.57	816.88	35,373.46
External Source		1,031.56	999.73	2,031.28
Discharge		9,739.50	390.23	10,129.73
Discharge – External Source		8,707.94	-609.49	8,098.45
Efficiency		55%	32%	55%

Los Angeles

		Volume of water (AFQ)		
Water Cycle Origin	**Water Cycle Endpoint**	**Saline**	**Fresh/ Brackish**	**Total**
Ancillary O&G Operations	Ancillary O&G Operations	249.58	0.00	249.58
	Disposal	1.89	0.00	1.89
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	2,118.50	0.00	2,118.50
External Source	Ancillary O&G Operations	47.29	86.35	133.64
	Disposal	0.20	0.48	0.68
	Other	0.00	0.00	0.00
	Discharge	96.38	35.40	131.78
	EOR and Stimulation	221.85	541.18	763.03
Other	Ancillary O&G Operations	15.66	0.00	15.66
	Disposal	0.13	0.00	0.13
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	143.15	0.11	143.26
Produced Water and Flowback	Ancillary O&G Operations	2,014.99	0.00	2,014.99
	Disposal	25.28	0.02	25.30
	Other	141.44	0.01	141.45
	Discharge	487.82	9.73	497.55
	EOR and Stimulation	28,212.50	19.08	28,231.58
Change in Storage	Change in Storage	-0.91	0.30	-0.61
Metrics				
Inputs		31,106.31	692.24	31,798.55
Outputs		611.56		
Demand		33,474.39	692.24	34,166.64
Reuse		32,595.58	19.08	32,614.66
External Source		365.72	663.41	1,029.13
Discharge		584.19	45.13	629.33
Discharge – External Source		218.48	-618.28	-399.80
Efficiency		97%	3%	95%

Santa Barbara-Ventura

		Volume of water (AFQ)		
Water Cycle Origin	**Water Cycle Endpoint**	**Saline**	**Fresh/ Brackish**	**Total**
Ancillary O&G Operations	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	5.17	0.00	5.17
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	16.43	0.00	16.43
External Source	Ancillary O&G Operations	30.48	20.11	50.60
	Disposal	0.01	0.78	0.78
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	Ancillary O&G Operations	0.02	2.46	2.49
Other	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	0.02	0.00	0.02
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	0.06	0.00	0.06
Produced Water and Flowback	Ancillary O&G Operations	38.50	0.00	38.50
	Disposal	285.42	345.57	630.99
	Other	5.58	0.00	5.58
	Discharge	2.21	0.00	2.21
	EOR and Stimulation	907.29	1,098.51	2,005.81
Change in Storage	Change in Storage	0.00	0.00	0.00
Metrics				
Inputs		1,263.93	1,467.44	2,731.37
Outputs		292.80		
Demand		1,280.37	1,467.44	2,747.80
Reuse		962.23	1,098.51	2,060.74
External Source		30.51	23.35	53.87
Discharge		2.21	0.00	2.21
Discharge – External Source		-28.30	-23.35	-51.66
Efficiency		75%	75%	75%

Santa Maria

		Volume of water (AFQ)		
Water Cycle Origin	**Water Cycle Endpoint**	**Saline**	**Fresh/ Brackish**	**Total**
Ancillary O&G Operations	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	41.70	0.00	41.70
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	27.55	0.00	27.55
External Source	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	9.87	0.00	9.87
	Other	0.00	0.00	0.00
	Discharge	11.64	0.00	11.64
	EOR and Stimulation	6.52	0.00	6.52
Other	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	0.00	0.00	0.00
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	0.00	0.00	0.00
Produced Water and Flowback	Ancillary O&G Operations	18.80	0.00	18.80
	Disposal	1,001.43	0.00	1,001.43
	Other	0.00	0.00	0.00
	Discharge	100.04	0.00	100.04
	EOR and Stimulation	655.81	0.00	655.81
Change in Storage	Change in Storage	0.00	0.00	0.00
Metrics				
Inputs		1,804.11	0.00	1,804.11
Outputs		1,164.67		
Demand		1,831.67	0.00	1,831.67
Reuse		702.17	0.00	702.17
External Source		28.04	0.00	28.04
Discharge		111.68	0.00	111.68
Discharge - External Source		83.65	0.00	83.65
Efficiency		38%	NA	38%

Salinas

		Volume of water (AFQ)		
Water Cycle Origin	**Water Cycle Endpoint**	**Saline**	**Fresh/ Brackish**	**Total**
Ancillary O&G Operations	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	2.84	0.00	2.84
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	2.72	0.00	2.72
External Source	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	19.31	0.00	19.31
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	18.50	0.00	18.50
Other	Ancillary O&G Operations	0.00	0.00	0.00
	Disposal	0.00	0.00	0.00
	Other	0.00	0.00	0.00
	Discharge	0.00	0.00	0.00
	EOR and Stimulation	0.00	0.00	0.00
Produced Water and Flowback	Ancillary O&G Operations	2.57	0.00	2.57
	Disposal	1,827.90	0.00	1,827.90
	Other	0.00	0.00	0.00
	Discharge	485.81	0.00	485.81
	EOR and Stimulation	1,751.53	0.00	1,751.53
Change in Storage	Change in Storage	0.00	0.00	0.00
Metrics				
Inputs		4,105.63	0.00	4,105.63
Outputs		2,335.85	0.00	2335.85
Demand		4,108.34	0.00	4,108.34
Reuse		1,756.82	0.00	1,756.82
External Source		37.81	0.00	37.81
Discharge		485.81	0.00	485.81
Discharge - External Source		448.00	0.00	448.00
Efficiency		43%	NA	43%

Appendix 2

Appendix 2.1. Produced Water Quality Datasets Not Included in Chapter 2 or Chapter 3 of This Report.

Table A2.1. Destinations for water in Production and Other Allocation reports.

Source	**Reference**	**Reason for exclusion**
CVRWQCB (2018)	Central Valley Regional Water Quality Control Board (CVRWQCB). (2018). Compiled Analytical Results for Irrigation With Petroleum Production Wastewater, April 2018 version. Available Data, Oil Fields - Food & Safety, California Water Boards, Central Valley - R5. https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/#data	Dataset includes irrigation and effluent water samples presumed to be treated or blended. Untreated produced water samples were difficult to discern.
DOGGR (2012)	California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (DOGGR). (2012). California Oil and Gas Fields, Volumes 1, 2, 3, Central, Southern, and Northern California, Contour Maps, Cross Sections, and Data Sheets. http://repository.stategeothermaldata.org/repository/resource/98ddf901b9782a25982e01af3b0eaede/	Most data only available in a non-digitized format (e.g., PDF)
DOGGR (2019)	California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (DOGGR). (2019). "Aquifer Exemptions Status." California Department of Conservation. https://www.conservation.ca.gov/dog/Pages/Aquifer-Exemptions-Status.aspx	Most data only available in a non-digitized format (e.g., PDF)
Everett et al. (2019)	Everett, R.E., Fenton, N.C., Hill, J.M., Stephens, M.J., Martinez Francisco, D., Metzger, L.F., Gans, K.D., and Qi, S.L. (2019). Geochemical and geophysical data for selected wells in and surrounding the South Cuyama oil and gas field: U.S. Geological Survey data release. https://doi.org/10.5066/P9KTYCNC.	Published after December 31, 2018.
Gans et al. (2019)	Gans, K.D., Metzger, L.F., Gillespie, J.M., and Qi, S.L. (2019). Historical produced water chemistry data compiled for the lost hills and North and South Belridge Oilfields, Kern County, California: U.S. Geological Survey data release. https://doi.org/10.5066/F7F18Z12.	Published after December 31, 2018.
GeoTracker Electronic Data Files	Personal communication. SWRCB. January 25, 2019. Electronic data for oil and gas-related operations (e.g. produced water ponds) extracted from: https://geotracker.waterboards.ca.gov/	Received from SWRCB after December 31, 2018. Additional produced water quality data are also reported pursuant to waste discharge requirements, General Orders, and 13267 Orders. Also largely available in non-digitized format (e.g., PDF)
Gillespie et al. (2019)	Gillespie, J.M., Davis, T.A., Ball, L.B., Herrera, P.J., Wolpe, Z., Medrano, V., Bobbitt, M., and Stephens, M.J. (2019). Geological, geochemical, and geophysical data from the Lost Hills and Belridge oil fields: U.S. Geological Survey data release. https://doi.org/10.5066/P90QH6CI.	Published after December 31, 2018.

Appendix 3

Appendix 3.1. California Produced Water Quality Datasets.

3.1.1. Description of produced water quality datasets in California.

USGS Federal Database

The United States Geological Survey (USGS) National Produced Waters Geochemical Database contains geochemical information from produced water samples across the United States. The database is a compilation of 40 individual data sources and includes major element data as well as trace elements, dissolved gases, and isotopes. This dataset does not include analytical methods or associated limits of detection. We extracted the California-specific samples for inclusion in our assessment. We converted water quality parameters reported in parts per million (ppm) to mg/L using specific gravity, as recommended by USGS (2017). For the rest of this report we refer to this database as the "USGS Federal Database."

DOGGR Monitoring Dataset

The Division of Oil, Gas, and Geothermal Resources ("The Division," also DOGGR) under the California Department of Conservation regulates the subsurface activities of oil and gas development in the State of California. Pursuant to Senate Bill 4 (SB 4) (Pavley, 2013) and the California Code of Regulations, title 14 section 1788 (CCR, 2015), The Division requires that operators that conduct well stimulation treatments (acid matrix, acid fracturing, hydraulic fracturing) in California must disclose well location, volume and sources of water used, chemicals used in operations, and chemical composition of recovered fluids within 60 days of ending well stimulation treatments. The Division has made chemical disclosures and information regarding oil and gas well operations publicly available on their website (DOGGR, 2018).

We downloaded well stimulation disclosures on November 11, 2018 and subsequently extracted produced water quality monitoring data for recovered fluids. Recovered fluids include produced water during the first three well-volumes of flow and after 30 days of production. Although it is arguable that recovered fluids may differ in certain ways than produced water more generally, we included this database in our assessment of produced water given that recovered fluids are handled in the same way as produced water in the State of California. This dataset will be referred to as the "DOGGR monitoring dataset." Chemical additive disclosures from The Division dataset are examined in further detail in Chapter 3, Section 3.4.

Recent California Produced Water Sampling Efforts

Between 2014 and 2017, the USGS independently and in the cooperation with the California State Water Resources Control Board (SWRCB) sampled produced water quality and consolidated historical produced water quality datasets at select oil fields in California. These research efforts resulted in digitized produced water quality monitoring datasets and we describe each of these datasets below.

Davis et al., 2016

USGS in cooperation with the SWRCB collected produced water samples from four petroleum wells in the southern San Joaquin Valley on November 5, 2014. This dataset contains the site information, analytical methods, and water chemistry and quality control results for these samples. Water chemistry results in this investigation included dissolved hydrocarbon gases and their isotopic composition, salinity, major ions, nutrients, dissolved organic carbon, and stable isotopes of water and strontium dissolved in water.

Gannon et al., 2018

As part of the SWRCB Regional Groundwater Monitoring Program of Water Quality in Areas of Oil and Gas Production, USGS in cooperation with SWRCB collected produced water samples from petroleum wells, produced water ponds, and injectate stored for underground injection in Fruitvale, Lost Hills, and North and South Belridge oil fields in 2016 and 2017. This dataset contains site information, analytical methods, water and gas chemistry, and quality control results for these samples. We included the water samples and excluded the casing gas samples from our analysis. Water chemistry results include dissolved noble and hydrocarbon gases and their isotopic composition; salinity (TDS); major ions and nutrients; dissolved organic constituents and carbon; and stable isotopes of water and solutes dissolved in water.

Gans et al., 2018

This dataset contains historical geochemical and other information for produced water samples from the Fruitvale oilfield, compiled from preexisting datasets and scanned images. The geochemical analyses include major ions, some minor ions, TDS, pH, specific gravity, resistivity, electrical conductivity, and charge balance.

Table A3.1. Characterization of California produced water quality including monitoring data for major and minor ions, low molecular weight organic acids, radioactivity indicators, trace elements, nutrients, organics, and other general water quality parameters.

Constituent(s)	**No. of detections**	**Min**	**Med**	**Max**	**Percentile**					**Unit**
					5th	**25th**	**50th**	**75th**	**95th**	
MAJOR AND MINOR IONS / TRACE ELEMENTS										
Acetate	54	0.8	34	4,865	3	12	34	414	1,727	mg/L
Aluminum	32	0.01	0.5	17	0.02	0.07	0.5	1.3	5	mg/L
Ammonium	195	3	140	502	9	64	140	201	367	mg/L
Antimony	48	0.0009	0.3	0.9	0.03	0.2	0.3	0.3	0.7	mg/L
Arsenic	56	0.008	0.3	5	0.08	0.2	0.3	0.5	1.4	mg/L
Barium	528	0.1	10	285	0.5	3	10	42	97	mg/L
Beryllium	31	0.001	0.01	0.1	0.002	0.01	0.01	0.02	0.08	mg/L
Borate	210	7	160	715	43	106	160	223	326	mg/L
Bromide	1,392	0.2	110	9,020	21	83	110	130	170	mg/L
Cadmium	3	0.0004	0.01	0.03	0.0014	0.005	0.01	0.02	0.03	mg/L
Calcium	2,238	1.2	220	160,000	24	141	220	440	3,408	mg/L
Cesium	42	0.02	0.2	0.9	0.02	0.06	0.2	0.4	0.6	mg/L
Chloride	3,427	0.05	8,700	350,000	4.2	9	8,700	16,000	21,300	mg/L
Chromate	1	22	22	22	22	22	22	22	22	mg/L
Chromium	274	0.004	0.05	1.2	0.02	0.03	0.05	0.07	0.2	mg/L
Chromium, hexavalent	70	0.0004	0.006	0.6	0.001	0.004	0.006	0.01	0.09	mg/L
Cobalt	38	0.002	0.04	0.1	0.007	0.02	0.04	0.05	0.08	mg/L
Copper	376	0.003	0.04	33	0.02	0.03	0.04	0.07	0.5	mg/L
Fluoride	240	0.03	1.2	53	0.2	0.5	1.2	3	23	mg/L
Hydrogen sulfide	256	0.01	0.33	1,111	0.06	0.1	0.3	3	34	mg/L
Hydroxide	3	37	99	243	43	68	99	171	229	mg/L
Iodine	431	0.1	35	294	2.1	15	35	63	138	mg/L
Iron	1,128	0.01	15	660	1.2	5	15	35	126	mg/L
Iron, 2+	38	0.05	4	3,800	0.1	1.2	4	25	867	mg/L
Iron, 3+	10	0.1	1.1	3,800	0.1	0.7	1.1	3	3,800	mg/L
Iron, total	377	0.03	3	1,600	0.1	0.8	2.7	9	72	mg/L
Lead	61	0.0001	0.08	1	0.003	0.02	0.08	0.1	0.5	mg/L
Lithium	1,382	0.004	6	460	0.8	4	6	8	14	mg/L
Magnesium	2,225	0.19	124	8,100	9	68	124	170	470	mg/L
Manganese	1,199	0.01	0.5	39	0.1	0.3	0.5	0.9	3	mg/L
Mercury	600	0.00003	0.00008	0.008	0.00004	0.00006	0.00008	0.0001	0.0003	mg/L
Molybdenum	111	0.002	0.04	0.3	0.006	0.03	0.04	0.07	0.2	mg/L
Nickel	158	0.008	0.07	2	0.01	0.05	0.07	0.2	0.4	mg/L
Phosphorus	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	mg/L
Potassium	1,528	1.4	180	20,000	25	130	180	280	856	mg/L

Constituent(s)	No. of detections	Min	Med	Max	Percentile					Unit
					5th	25th	50th	75th	95th	
Selenium	140	0.03	0.4	15	0.07	0.2	0.4	0.7	2.1	mg/L
Sodium	2,171	4.5	8,700	110,000	581	5,600	8,700	10,334	13,000	mg/L
Silica	478	0.2	59	2,200	14	34	59	82	160	mg/L
Sulfate	1,621	0.1	34	15,251	2.1	21	34	73	387	mg/L
Sulfide	80	0.03	4	850	0.3	2	4	7	70	mg/L
Rubidium	160	0.02	0.3	2	0.05	0.2	0.3	0.4	0.6	mg/L
Thallium	8	0.02	0.04	6	0.02	0.03	0.04	0.7	5	mg/L
Vanadium	31	0.01	0.07	0.9	0.01	0.06	0.07	0.1	0.2	mg/L
Zinc	454	0.006	0.1	149	0.06	0.08	0.1	0.2	1	mg/L
LOW MOLECULAR WEIGHT ORGANIC ACIDS										
Acetic acid	9	2.2	37	910	2.28	2.7	37	340	850	mg/L
Butanoic acid	1	39	39	39	39	39	39	39	39	mg/L
Lactic Acid	1	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	mg/L
RADIOACTIVITY INDICATORS										
Gross alpha	1,172	-830	54.4	2,248	-49	14	54	95	187	pCi/L
Gross beta	1,177	-209	134	15,930	18	82	134	208	1,284	pCi/L
Radium-224	21	2.3	12	130	4	8	12	25	48	pCi/L
Radium-226	1,195	-4	25	915	5	16	25	32	62	pCi/L
Radium-228	68	-0.1	13	99	0.97	5	13	27	49	pCi/L
Radon	181	-198	83	704	-67	24	83	166	326	pCi/L
Radon-222	987	-36,570	51	250,690	-103	-12	51	143	680	pCi/L
Sr-87/Sr-86 ratio	27	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	Ratio
Strontium	1,448	0.07	12	3,100	4	7	12	17	124	mg/L
Uranium	4	0.0003	0.001	0.002	0.0003	0.0006	0.001	0.002	0.002	mg/L
NUTRIENTS										
Ammonia	156	1.3	28	164	7	17	28	41	74	mg/L
Nitrate	142	0.1	10	310	0.5	1.3	10	19	84	mg/L
Nitrite	372	0.04	0.09	5	0.04	0.1	0.09	0.2	0.9	mg/L
Phosphate	6	0.2	1.2	20	0.2	0.2	1.2	2	16	mg/L
OTHER ORGANICS										
1,2,4-Trimethylbenzene	2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	mg/L
Benzene	1,175	0.0003	0.8	25	0.1	0.4	0.8	1.5	3	mg/L
Dibromofluoromethane	1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	mg/L
Ethylbenzene	1,172	0.0006	0.3	5.3	0.06	0.2	0.3	0.4	0.7	mg/L
Guar gum	38	30	125	3,500	31	56	125	325	2,450	mg/L
m-Xylene	29	0.2	0.8	2.1	0.4	0.7	0.8	1.3	1.8	mg/L
o-Xylene	1,163	0.001	0.4	6	0.07	0.3	0.4	0.7	1.2	mg/L
p-Bromofluorobenzene	1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	mg/L
Phenols	3	0.05	0.2	0.2	0.06	0.1	0.2	0.2	0.2	mg/L

Constituent(s)	**No. of detections**	**Min**	**Med**	**Max**	**Percentile**					**Unit**
					5th	**25th**	**50th**	**75th**	**95th**	
Toluene	1,179	0.004	2	61	0.3	1.1	2	3.1	5.1	mg/L
Xylenes	1,178	0.004	1.3	19	0.2	0.7	1.3	2.1	3.8	mg/L
Xylenes, Isomers m & p	1,136	0.002	0.8	13	0.1	0.5	0.8	1.4	2.7	mg/L
WATER QUALITY CHARACTERISTICS										
Alkalinity	182	73	2,700	4,700	803	2,100	2,700	3,100	4,000	mg/L
Bicarbonate	969	2	1,060	12,809	147	535	1,060	1,974	4,299	mg/L
Carbonate	138	1	69	2040	2	13	69	184	501	mg/L
TDS	2,230	52	26,000	890,000	2,207	18,000	26,000	31,000	42,000	mg/L
Boron	1,628	0.05	92	602	1.3	54	92	104	150	mg/L
Dissolved inorganic carbon	26	42	80	174	49	68	80	109	144	mg/L
Dissolved organic carbon	68	6	130	2,900	10	41	130	190	1,614	mg/L
Electrical conductivity	72	1	2,800	22,470	3	1,630	2,800	5,540	9,865	milliMhos/cm
pH	2,100	1	8	12	6.7	7.3	7.6	7.8	8.2	pH unit
Resistivity	400	0.08	0.3	8	0.2	0.2	0.3	0.7	4	ohm-m
Total carbohydrates	1,129	1.2	120	4,400	1.2	1.2	1.2	1.2	1.2	mg/L
Total organic carbon	22	18	225	2,054	26	110	225	798	1,167	mg/L

Appendix 3.2. Chemical Additive Use in California Oil and Gas Operations

3.2.1. Description of chemical additive datasets in California

Databases of chemical additives used in oil and gas operations in California were obtained from the Central Valley Regional Water Quality Control Board (CVRWQCB), the South Coast Air Quality Management District (SCAQMD), The Division of Oil, Gas, and Geothermal Resources ("The Division"), and from the national database FracFocus.

Irrigation 13267 Dataset

The CVRWQCB used California Water Code section 13267 (an information order) to obtain data from oil and gas field operators regarding chemical additives used in oil and gas field operations, treatment, and transportation of produced water used for irrigation. In May 2016, the CVRWQCB ordered at least six oil and gas operators that provide produced water for irrigation and Valley Water Management Company (which receives and treats produced water) to disclose all chemical additives that they had used in their operations for the prior two years. These producers operate in Kern Front Oil Field, Kern River Oil Field, Mount Poso Oil Field, Jasmin Oil Field, and Deer Creek Oil Field, and provide produced water to the Cawelo Water District, the North Kern Water Storage District, the Jasmin Ranchos Mutual Water District, and the Kern-Tulare Water District. These individual orders covered the following:

> "[A]ll chemicals and additives used in any stage of the production or transportation of produced fluids including, but not limited to, substances injected into production and enhanced oil recovery wells and distribution and collection lines, substances added or applied to produced fluids either prior to or after treatment, and substances applied to transportation infrastructure such as corrosion inhibitors" from January 1, 2014, to May 2016, when the orders were sent to production companies (CVRWQCB, 2016).

Responses were received between May 2016 and June 2016 and are publicly available on the Water Board Food Safety website (CVRWQCB, 2019). Individual responses were compiled into a dataset (the "Irrigation 13267 dataset"). The Irrigation 13267 dataset only includes chemical names and Chemical Abstracts Service registry numbers (CASRN). Mass, volume, event, location, frequency of use, or temporal data were not included in the dataset.

AB 1328 Dataset

Pursuant to California Assembly Bill 1328 (AB 1328) (Limón, 2017), California Water Code Section 13267 was amended and Section 13267.5 was added to allow the SWRCB and Regional Water Quality Control Boards to collect information regarding all chemicals in discharges of oil and gas field wastewater, including provisions for trade secret formulations directly from suppliers and manufacturers if suppliers will not provide the information to oil and gas field operators. From December 2017 to May 2018, CVRWQCB sent information orders to multiple oil and gas field operators and chemical suppliers for chemical information. Chemical suppliers were required to provide information for chemicals supplied to oil and gas operators for a period of two years prior to receiving notice.

The most recent responses to these requests were compiled by the CVRWQCB into a dataset (the "AB 1328 dataset") and released June 2018. The dataset is publicly available on the Water Board Food Safety website (CVRWQCB, 2019). The AB 1328 dataset only includes chemical names and CASRN. Mass, volume, event, location, frequency of use and temporal data were not included in the dataset.

SCAQMD Dataset

The South Coast Air Quality Management District (SCAQMD) regulates air pollution for Orange County and urban portions of Riverside, Los Angeles, and San Bernardino counties (SCAQMD, 2018a). Pursuant to Rule 1148.2, all onshore oil and gas well operators, along with their chemical suppliers, were required to submit data on chemical usage regarding routine oil and gas activities (well drilling, well completion, and well rework) and well stimulation operations within the SCAQMD (SCAQMD, 2015a)2,14]]}}}],"schema":" https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} . Operators must notify SCAQMD of drilling, well completion, or well rework operations anywhere from two to ten days prior to starting (SCAQMD, 2015a)2,14]]}}}],"schema":" https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} . Rule 1148.2 went into effect on June 4, 2013. On September 4, 2015, Rule 1148.2 was amended and new, more detailed, oil and gas chemical reporting forms were required (SCAQMD, 2015b). These data are publicly available online on the SCAQMD oil and gas well electronic notification and reporting portal (SCAQMD, 2018b).

Chemical and event data from the SCAQMD from June 4, 2013, to August 31, 2018, were downloaded on August 31, 2018. Chemical reporting data and event notification data were downloaded and merged together using event IDs to combine use chemical data with operation start dates, well latitude, and well longitude. This combined dataset will be referred to as the "SCAQMD dataset."

DOGGR Chemical Dataset

The Division of Oil, Gas, and Geothermal Resources ("The Division," also DOGGR) is the primary regulator of drilling, operations, maintenance, stimulation, and abandonment of oil and gas wells in California. Pursuant to SB 4 (Pavley, 2013) and California Code of Regulations, title 14, section 1788 (CCR, 2015)3,15]]}}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} , any operators conducting well stimulation treatments (acid matrix, acid fracturing, hydraulic fracturing) in California must disclose well location, volume, and sources of water used; chemicals used in operations; and chemical composition of recovered fluids to The Division within 60 days of ending well stimulation treatments. The Division has made these chemical disclosures and information regarding oil and gas well operations publicly available on their website (DOGGR, 2018).

Well stimulation disclosures from January 1, 2014, to June 30, 2015, were submitted under the Interim SB 4 regulations. Well stimulation disclosures after July 1, 2015, were submitted under the Final SB 4 regulations and represent a more complete dataset. The Division has made their online disclosure database searchable according to chemical constituent name and CASRN, as well as trade name products (i.e. trade secret and proprietary chemicals). Well stimulation chemical disclosures from both Interim and Final SB 4 regulations were downloaded on August 30, 2018, and merged together. It is worth noting that operators are first required to submit chemical names that they plan to use in a well stimulation treatment, and then, after they conduct the well stimulation treatment, submit a list of chemicals that they actually used. The dataset that we included in our analysis is only the latter—the chemicals that were reported as actually used during well stimulation treatments. This dataset will be referred to as the "DOGGR chemical dataset."

FracFocus Dataset

FracFocus is a national database of hydraulic fracturing operations managed by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission. Pursuant to California Code of Regulations, title 14, section 1788 (CCR, 2015)3,15]]}}}],"sch ema":"https://github.com/citation-style-language/schema/raw/master/csl-citation. json"} , California requires any operators conducting hydraulic fracturing well stimulation treatments in California to disclose well location, volume, and sources of water used; chemicals used in operations; and chemical composition of recovered fluids to both the state ("The Division") and a national "chemical disclosure registry," defined in regulations as the FracFocus database. These disclosures must occur within 60 days of ending well stimulation treatments. FracFocus has made the submitted chemical disclosures publicly available on their website (Ground Water Protection Council & Interstate Oil and Gas Compact Commission, 2018).

From January 2011 to May 31, 2013, FracFocus utilized a submission format referred to as FracFocus 1.0. From November 2012 to June 2016, FracFocus utilized a newer, more user-friendly database format referred to as FracFocus 2.0, with some overlap during the transition. The current version of FracFocus, known as FracFocus 3.0, went live on June 23, 2016, and served to improve data reliability and data accessibility. FracFocus 3.0 data were downloaded from the FracFocus website on October 8, 2018, and covered a period of activity from January 2011 to September 2018. Previous studies of the FracFocus 1.0 and 2.0 datasets have shown that chemicals contained in FracFocus 1.0 dataset were not always present in the FracFocus 2.0 dataset, though the reason for this is unclear. To ensure that this dataset captured as much information as possible, FracFocus 3.0 data were combined with previously downloaded versions of FracFocus 1.0 and FracFocus 2.0. Due to the scope of this study, this combined FracFocus dataset was filtered to include only results from hydraulic fracturing in California. This combined FracFocus 1.0, 2.0, and 3.0 datasets will be referred to as the "FracFocus dataset."

3.2.2. Methods: Assessment of chemical additives used in California oil and gas development operations

Data Quality Assurance/Quality Control

The databases that we obtained from the various governmental and organizational sources were in a variety of formats, including PDF, Access databases, and Comma Separated Values (.csv) spreadsheets. Data from PDFs and Access databases were extracted and compiled into an Excel spreadsheet. This report follows data quality control and validation methods used in multiple studies of oil and gas chemical datasets by the California Council on Science and Technology (CCST et al., 2014), Stringfellow et al. (2015, 2017a, 2017b), Camarillo et al. (2016), and Shonkoff et al. (2016).

Table A3.2. Examples of chemical additives with invalid CASRNs that could be identified.

Standardized Name	Correct CASRN	Original Reported Name	Original Invalid CASRNs
Alcohols, C12-15 ethoxylated	68131-39-5	Ethoxylated alcohol C12-15	683131-39-5
Corundum	1302-74-5	Corundum	1302-74-56 1302-44-56
Isotridecanol, ethoxylated	9043-30-5	Isotridecanol, ethoxylated	9403-30-5
Sodium polynaphthalenesulfonate	9084-06-4	Naphthalenesulfonate-formaldehyde condensate, sodium salt	908-46-4
Phosphoric acid salt	7632-05-5	Phosphoric acid salt	5-5-7632
Guar gum	9000-30-0	Guar gum	009000-30-0

Physical and Chemical Properties

Understanding the physical and chemical properties of chemicals used in oil and gas operations is vital to determine the chemical fate and behavior with respect to hazard and risk analyses of produced water treatment, management and reuse. The physical and chemical properties that we used to characterize the list of constituents include: chemical formula, molecular weight, density, acid dissociation constants (pK_a), melting and boiling point, log octanol-water partition coefficients ($\log K_{ow}$), log organic carbon-water partition coefficients ($\log K_{oc}$), water solubility, vapor pressure, and Henry's constant (K_H). Where possible, we used experimental data. In cases where experimental model data were unavailable, we used computational estimates from the U.S. EPA Estimation Programs Interface Suite (EPISuite™) KOWWIN™, MPBPWIN™, HENRYWIN™, KOCWIN™, and KOAWIN™ estimation modules (U.S. EPA, 2012). EPISuite™ is a screening-level tool used to estimate physical/chemical properties and environmental fate and was only used if reliable experimental results were unavailable (U.S. EPA, 2012).

Biological and Toxicological Data

Biological and toxicological data that we gathered included: acute oral mammalian toxicity, acute inhalation mammalian toxicity, acute aquatic toxicity, chronic and sub-chronic oral toxicity, oral and inhalation slope factors, oral and inhalation reference doses and concentrations, and biodegradability.

Acute Toxicity

Acute toxicity data were collected for common mammalian and aquatic test species including: rats, mice, rabbits, *Daphnia magna*, *Pimephales promelas* (fathead minnow), *Oncorhynchus mykiss* (rainbow trout), and green algae. We rated acute chemical toxicity results according to United Nations Globally Harmonized System of Classification and Labelling of Chemicals (GHS) (United Nations, 2017). GHS categories range from 1-5, 1-4, and 1-3 for acute oral toxicity, acute inhalation toxicity, and acute aquatic toxicity, respectively. In GHS classifications, lower numbered categories indicate higher toxicity, with GHS 1 being the most toxic. GHS categorization utilizes LD_{50} values (lethal dose to 50% of a study population) for acute oral mammalian toxicity; four-hour LC_{50} values (lethal concentration to 50% of a study population) for acute inhalation mammalian toxicity; 48-hour EC_{50} values (effective concentration where 50% of population is immobilized) for *Daphnia magna*; and 96-hour LC_{50} (lethal concentration for 50% of a study population) for fish species. A summary of GHS categories is provided in Table A3.

To align with standard risk assessment protocols, when multiple values for acute toxicity were available, we used the most conservative (i.e. most toxic) value to determine GHS category. Chemicals that exceeded the maximum GHS category limits (e.g. >GHS 5 for acute oral, >GHS 4 for acute inhalation, and >GHS 3 for acute aquatic toxicity) were labeled as “non-toxic” for the purposes of this assessment. Computational estimates from U.S. EPA EPISuite™ BIOWIN v4.11 module were used as the sole source for acute aquatic toxicity for green algae. Experimental acute aquatic toxicity data for green algae was not assessed due to a lack of availability.

Due to the general lack of acute inhalation data, we made an attempt to categorize available acute inhalation data that did not meet standardized time frames for GHS categorization. For example, an acute inhalation LC_{50} value of 0.25 mg/L/30min for vapor does not meet the standard four-hour test time frame; however, it could be safely assumed to fall into GHS Category 1 due to being inherently more toxic than a GHS Category 1 LC50 value of 0.25 mg/L/4hr value due to its shorter time frame. In some instances, inhalation toxicity was listed as a range (e.g. >4 mg/L/4hr). We categorized these instances based on the “floor level” values that provide a very conservative estimate of inhalation GHS. For example, an inhalation toxicity range of >4 mg/L/4hr for a vapor would be assigned a GHS value of 3 based on the floor value of 4 mg/L/4hr. “Floor level” estimates need to be interpreted with caution, as they do not take into account possible physical limitations on chemical concentrations in the air.

When acute oral, inhalation, and aquatic toxicity data were available but were not reported as a dose descriptor categorized by GHS (e.g. NOEL, NOAEL), or when the time-period of the test was not compatible with GHS categorization standards (e.g. 12-hour EC_{50} tests for *Daphnia magna*), we labeled these chemicals as “inadequate data.”

Table A3.3. GHS categories for acute oral, inhalation, and aquatic toxicity (United Nations, 2017).

	Acute Oral Toxicity	**Acute Inhalation Toxicity**			**Acute Aquatic Toxicity**		
GHS Category	LD$_{50}$ (mg/kg)	LC$_{50}$ Gasses (ppm/4hr)	LC50 Vapors (mg/L/4hr)	LC$_{50}$ Dusts and mists (mg/L/4hr)	EC$_{50}$ Crustacea (mg/L/48hr)	LC$_{50}$ Fish (mg/L/96hr)	ErC$_{50}$ Algae (mg/L/96hr or 72hr)
1	≤5	≤100	≤0.5	≤0.05	≤1	≤1	≤1
2	5< x ≤50	100< x ≤500	0.5< x ≤2	0.05< x ≤0.5	1< x ≤10	1< x ≤10	1< x ≤10
3	50< x ≤300	500< x ≤2,500	2< x ≤10	0.5< x ≤1.0	10< x ≤100	10< x ≤100	10< x ≤100
4	300< x ≤2,000	2,500< x ≤20,000	10< x ≤20	1.0< x ≤5	--	--	--
5	2,000< x ≤5,000	--	--	--	--	--	--

Chronic Toxicity

We categorized chronic chemical toxicity values with input from multiple databases. Chronic toxicity databases were divided into 3 tiers. When multiple chronic toxicity values were reported, data from higher tiered sources were given priority. If multiple values were reported from databases within the same tier, the most conservative (i.e. most toxic) value was chosen.

- Tier 1: California Office of Environmental Health Hazard Assessment (OEHHA)

- Tier 2: U.S. EPA Integrated Risk Information System (IRIS), U.S. EPA Provisional Peer-Reviewed Toxicity Values (PPRTV), U.S. Department of Health Agency for Toxic Substances and Disease Registry (ATSDR), U.S. EPA Health Effects Assessment Summary Tables (HEAST), etc.

- Tier 3: Occupational exposure limits (National Institute for Occupational Safety and Health [NIOSH], the Occupational Safety and Health Administration [OSHA], and the American Conference of Governmental Industrial Hygienists [ACGIH])

Chronic toxicity information analyzed in this study was limited to chronic reference doses (RfD), reference concentrations (RfC), minimal risk levels (MRLs), health-based screening levels (HSBL), reference exposure levels (RELs), public health goals (PHGs), oral and inhalation slope factors, and unit risk (UR) factors. Sub-chronic toxicity information was not assesses. A brief description of the various chronic toxicity screening values is provided below. Many of the chronic toxicity screening values are similar in definition, but vary on how they are calculated.

- Reference dose (RfD): estimate of lifetime daily oral exposure where there is unlikely to be appreciable risk of adverse health effects (mg/kg/day). RfDs are developed by the U.S. EPA.

- Health-based screening levels (HBSL): non-enforceable water quality benchmarks below which adverse health effects are not expected over a lifetime (μg/L). HBSLs are developed by the U.S. Geological Survey.

- Public health goals (PHG): concentration of a chemical in drinking water that does not pose a significant risk to human health over a lifetime (mg/L). PHGs are developed by OEHHA and are not regulatory standards.

- Minimal risk level (MRL): estimate of daily exposure in humans where there is unlikely to be appreciable risk of adverse non-cancer health effects (mg/kg/day for oral, mg/m^3 for inhalation). MRLs are developed by ATSDR.

- Reference exposure levels (REL): estimated inhalation exposure for which adverse non-cancer health effects are not anticipated over a specified exposure period (μg/m^3). RELs are developed by OEHHA.

- Reference concentration (RfC): estimate of lifetime daily inhalation exposure where there is unlikely to be appreciable risk of adverse health effects (mg/m^3). RfCs are developed by the U.S. EPA.

- Slope factor: 95% confidence limit for increased cancer risk due to a lifetime of exposure to a chemical (mg/kg/day)$^{-1}$.

- Unit risk (UR) factor: estimate of increased cancer risk from inhalation exposure over a lifetime (μg/m^3)$^{-1}$.

To compare chronic oral toxicity values across multiple databases and various screening values, a chronic reference value (RfV) with units of mg/kg/day was used for oral toxicity, and mg/m^3 was used for inhalation toxicity. The chronic oral RfV includes reference doses (RfDs), minimal risk levels (MRLs), public health goals (PHGs), and health-based screening levels (HBSLs). The chronic inhalation RfV includes reference exposure levels (RELs), reference concentrations (RfCs), and minimal risk levels (MRLs). An average human body weight of 80 kg and daily water intake of 2.5 L were used to convert HBSL values to mg/kg/day; all other conversions used a standard adult human body weight of 70 kg, water intake of 2 L/day, and inhalation rate of 20 m^3/day. The chronic RfV is only used to compare chemicals to one another; the original chronic toxicity values should be used for any additional analyses or risk assessment.

We evaluated cancer risks using slope factors and unit risk factors for oral and inhalation exposure pathways, respectively. Cancer risk screening values were assessed separately from non-cancer screening values.

For chemicals where chronic toxicity data were unavailable, we used occupational exposure limits from the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), and the American Conference of

Governmental Industrial Hygienists (ACGIH). These occupational limits include permissible exposure limits (PEL), threshold limit values (TLV), and recommended exposure limits (NIOSH REL) (NIOSH, 2007, 2016). These limits are defined as:

- NIOSH recommended exposure limits (NIOSH REL): recommended guideline for upper exposure limits to hazardous substances, set by NIOSH, that would be protective of employee health over a working lifetime (mg/m^3 or ppm, time weighted average).

- OSHA permissible exposure limits (PEL): legal limit for worker exposure to a substance set by OSHA (mg/m^3 or ppm, time weighted average).

- ACGIH threshold limit values (TLV): limit to which a worker can be exposed daily without adverse effects, or "workday concentration," set by ACGIH (mg/m^3 or ppm, time weighted average).

If multiple values were reported from occupational exposure databases, the most conservative (i.e. lowest) value was chosen. It should be noted that occupational exposure limits are developed for healthy working adults over an eight-hour workday and are inappropriate for protection of the health of the general population.

Biodegradability

Biodegradability data were categorized according to United Nations Organisation for Economic Co-operation and Development (OECD) criteria for biodegradability (OECD, 1981, 1992b, 1992a, 2009) The OECD specifies two major tests for biodegradability: Test No. 301: Ready Biodegradability and Test No. 302: Inherent Biodegradability (OECD, 1981, 1992b, 1992a, 2009). A chemical is classified as readily biodegradable if it has demonstrated: (1) a biodegradation greater than 60% theoretical oxygen demand (ThOD) removal; 60% theoretical carbon dioxide ($ThCO_2$) removal, or 70% dissolved organic carbon (DOC) removal, under aerobic conditions, in 28 days, and (2) the 60%/70% level is reached within 10 days of reaching the 10% mark ("10-day window" criterion) using unacclimated bacteria. For structurally similar compounds that are provided by chemical suppliers as mixtures and cannot be reasonably separated, such as hydrocarbons mixtures or surfactants, the 10-day window criterion is not applied to account for sequential biodegradation of individual compounds.

A chemical classified as inherently biodegradable had demonstrated biodegradation above 20% of theoretical as measured by biological oxygen demand (BOD), DOC removal, or chemical oxygen demand (COD). Inherent biodegradability is generally a separate test from ready biodegradability; however, when readily biodegradability tests are slightly below the 60%/70% mark, or when they fail the 10-day window criterion, they can generally be considered inherently biodegradable.

There is no OECD test for non-biodegradability; chemicals that failed readily biodegradability tests were categorized as "not readily biodegradable." Computational estimates from the U.S. EPA EPISuite™ BIOWIN™ module were used when no experimental biodegradability data were available (U.S. EPA, 2012).

Carcinogenicity, Air Pollutants, and Other Hazards

We also screened chemicals with valid CASRNs using lists of known carcinogens, endocrine disruptors, hazardous air pollutants, and others priority action lists for potential hazards (Table A3.).

Table A3.4. Screening lists and databases used to identify potentially hazardous chemicals by screening type.

Screening Type	Screening List
Carcinogenicity	California EPA Safe Drinking Water and Toxic Enforcement Act of 1986 (Prop 65)
	National Toxicity Program Report on Carcinogens 14th ed.
	International Agency for Research on Cancer Monographs
	U.S. EPA National Primary Drinking Water Standards and Health Advisories
Air Pollution	U.S. EPA Clean Air Act Hazardous Air Pollutants
	California Air Resources Board Air Toxics "Hot Spots" Program – Substances for Which Emissions Must Be Quantified/Substances for Which Production, Use, or Other Presence Must be Reported
	California EPA Toxic Air Contaminant (TAC) Identification List
General Hazard	EU REACH Substances of Very High Concern (SVHC) Authorization List
	EU REACH Substances of Very High Concern (SVHC) Candidate List
	EU REACH Restricted List
	OSPAR List of Substances/Preparations Used and Discharged Offshore which are Considered to Pose Little or No Risk to the Environment (PLONOR)
	OSPAR List of Substances of Possible Concern
	U.S. EPA Contaminant Candidate List 4 (CCL4)
Endocrine disrupting compounds	The Endocrine Disruptors Exchange (TEDX) List of Potential Endocrine Disrupting Compounds
	EU Priority List of substances for further evaluation for their role in endocrine disruption
	U.S. EPA Tier 1 Endocrine Disrupting Compound Evaluations

3.2.3. Results: Assessment of chemical additives used in California oil and gas development operations

A total of 170 chemicals were reported in the Irrigation 13267 dataset. Of these chemicals, 62 were considered trade secrets with no reported CASRN. Three chemicals were reported with invalid CASRNs but were able to be identified, resulting in a total of 108 chemicals with valid CASRN. A report conducted by two members of the Food Safety Expert Panel convened by the CVRWQCB listed 107 chemicals with valid CASRN for the Irrigation 13267 dataset (Shonkoff et al., 2016). This was due to the chemical "polyacrylate" (CASRN: 9003-79-8) which had an invalid CASRN and could not be identified at the time of the report. However, with the release of AB 1328 dataset, it became clear that the correct CASRN for this chemical was "9033-79-8" and it could be subsequently identified.

The FracFocus dataset contained 315 unique chemicals with valid CASRN. When combining the FracFocus 1.0, 2.0, and 3.0 datasets, 29 chemicals with CASRN were present in the FracFocus 1.0 and 2.0 datasets that were not present in the FracFocus 3.0 dataset. It is unclear why these chemicals were missing in FracFocus 3.0, but it is possible they represented data from old events that were removed when the event was edited and updated. Because the exact reason for this discrepancy is unknown, the 29 chemicals were retained in the FracFocus dataset for completeness.

Four chemicals—magma fibers (CASRN: 6806-10-0000), alkylaryl sulfonate (CASRN: 68484-27-0), xanthan gum (CASRN: 59370-00-0), and D-limonene (CASRN: 254504-00-1)—did not have valid CASRNs and could not be identified with confidence. Magma fibers was reported once in the AB 1328 dataset and the provided CASRN was not similar to any other known chemical. Alkylaryl sulfonate was reported 24 times throughout the SCAQMD dataset and was not similar in name or CASRN to any other known chemicals. Xanthan gum (CASRN: 59370-00-0), and d-limonene (CASRN: 254504-00-1) were both reported once in the SCAQMD dataset, and although other entries for d-limonene and xanthan gum appear in the SCAQMD dataset with the correct CASRNs, the incorrect CASRNs provided were completely different from the correct CASRN. These chemicals were labeled as proprietary chemicals and were excluded from all analyses. Seventy-five additional chemicals were reported with invalid CASRNs but were identified with high confidence based on chemical name and CASRN similarities.

A total of 489 chemicals were identified as trade secret exempted or proprietary chemicals and no further analysis could be conducted on these chemicals. It is important to note that virtually all trade secret/proprietary chemicals from the FracFocus dataset were reported prior to 2016. When the final SB 4 regulations regarding chemical disclosure for well stimulation activities in California went into effect in 2015, disclosure was required for all chemical components of mixtures, including trade secrets. However, individual chemical components were no longer linked to their corresponding chemical mixtures. Chemical mixtures and their respective chemical components were listed separately to allow for chemical disclosure while protecting proprietary industry information (SCAQMD, 2015b).

SCAQMD disclosures also adopted a similar format in 2015 (SCAQMD, 2015a). Although roughly 900 disclosed chemical mixtures were reported without CASRNs and their exact chemical compositions remain unknown, because the sum of their individual components are disclosed on a per event basis, they are not included in the 489 chemicals identified as trade secrets for this study.

Table A3.5. Available acute oral mammalian data according to GHS values for standard test species.

GHS Category	Rat	Mouse	Rabbit	Overall[1]
GHS 1	0	0	0	0
GHS 2	8	6	2	12
GHS 3	29	19	11	38
GHS 4	94	60	14	108
GHS 5	70	38	10	64
Non-toxic (> GHS 5)	95	45	20	90
Inadequate data	334	462	573	318

1. *The lowest (most conservative) GHS value between all test species was selected for the overall count*

Table A3.6. Available acute inhalation mammalian data according to GHS values for standard test species.

GHS Category	Rat	Rat (floor level estimate)[1]	Mouse	Mouse (floor level estimate)[1]	Overall[2]
GHS 1	7	5	1	0	12
GHS 2	14	2	3	1	16
GHS 3	19	10	5	0	30
GHS 4	8	11	0	0	19
Non-toxic (> GHS 4)	36	0	2	0	36
Inadequate data	545	602	619	626	517

1. *Floor level estimates were only calculated if there was no standard value available*
2. *The lowest (most conservative) GHS value between all test species was selected for the overall count*

Table A3.7. Available acute aquatic toxicity data for examined species according to GHS values

GHS Category	Daphnia magna	Fathead minnow	Rainbow trout	Green algae[1]	Overall[2]
GHS 1	41	21	27	96	134
GHS 2	34	15	20	52	69
GHS 3	36	24	24	44	62
Non-toxic (> GHS 3)	70	47	39	162	149
Inadequate data	449	523	520	276	216

1. *Only includes computational estimates from EPISuite™. Does not contain experimental data.*
2. *The lowest (most conservative) GHS value between all test species was selected for the overall count.*

Table A3.8. Summary of available acute oral, inhalation, and aquatic toxicity GHS values for chemicals with CASRN used in oil fields that send produced water for irrigation of food crops.

	Acute Oral GHS			**Acute Inhalation GHS**				**Acute Aquatic GHS**			
GHS Category	**Rat**	**Mouse**	**Rabbit**	**Rat**	**Rat "Floor value"[1]**	**Mouse**	**Mouse "Floor value"[1]**	**Daphnia magna**	**Fathead minnow**	**Rainbow trout**	**Green algae**
GHS 1	0	0	0	4	2	1	0	26	14	18	46
GHS 2	6	4	2	10	2	3	1	20	11	17	24
GHS 3	14	9	4	15	8	4	0	22	15	18	27
GHS 4	53	32	12	6	5	0	0	-	-	-	-
GHS 5	41	22	4	-	-	-	-	-	-	-	-
Non-toxic	46	24	13	22	-	2	-	38	28	28	79
Insufficient data	125	194	250	228	268	275	281	179	217	204	109

1. Floor values were only used if no standard value was available for a chemical

Table A3.9. Complete list of chemical additives reported with invalid CASRNs that could and could not be identified.

Standardized Name	**Correct CASRN**	**Original Reported Name**	**Original Invalid CASRN**
1,2-Ethanediaminium, N1, N2-bis[2-[bis(2-hydroxyethyl) methylammonio]ethyl]-N1, N2-bis(2-hydroxyethyl)-N1,N2-dimethyl-, chloride (1:4)	138879-94-4	OXYAKYLATED AMINE QUAT	13887-99-4
1,2,3-Trimethylbenzene	526-73-8	1,2,3-Trimethylbenzene	536-73-8
1,2-Ethanediamine, N1-(2-aminoethyl)-N2-(2-((2-aminoethyl)amino)ethyl)-, polymer with 2-methyloxirane and oxirane	68815-65-6	POLYAMINE POLYETHERS	68815-65-1 68815-69-6
1-Eicosene	3452-07-1	1-Eicosene	567-04-0
2-Butoxyethanol	111-76-2	2-BUTOXY ETHANOL	111-76-1
2-propenoic acid, polymer with sodium 2-propenoate	9033-79-8	2-PROPENOIC ACID, POLYMER WITH SODIUM 2-PROPENOATE (1:1)	9003-79-8
Acetic acid	64-19-7	ACETIC ACID	6-41-9
Acrylonitrile	107-13-1	Acrylonitrile	107-31-1
Alcohols, C12-15 ethoxylated	68131-39-5	ETHOXYLATED ALCOHOL	683131-39-5
Aluminum distearate	300-92-5	ALUMINUM DISTEARATE	300-32-5
Ammonium chloride	12125-02-9	AMMONIUM CHLORIDE ((NH4)CL)	12125-20-9 121215-45-9 1212-50-2
Ammonium fluoride	12125-01-8	Ammonium fluoride	12125-0108
Bentonite	1302-78-9	BENTONITE	1308-78-9 1305-78-9

Standardized Name	**Correct CASRN**	**Original Reported Name**	**Original Invalid CASRN**
Benzenesulfonic acid, C10-16-alkyl derivs., compds. With cyclohexylamine	255043-08-4	BENZENESULFONIC ACID, C10-16-ALKYL DERIVS., COMPDS. WITH CYCLOHEXYLAMINE	25504-30-8
C13-16 Isoparaffin	68551-20-2	C13-C16 ISOALKANES	6855-10-2
Calcium carbonate	471-34-1	CARBONIC ACID CALCIUM SALT (1:1)	741-34-1
Calcium chloride	10043-52-4	CALCIUM CHLORIDE (CACL2)	1004-35-2
Cellophane	9005-81-6	CELLOPHANE	9005-18-6
Citric acid	77-92-9	CITRIC ACID	779-29-9 77-92-1 72-92-9
Citrus terpenes	94266-47-4	CITRUS TERPENES	4266-47-4
Coco-amido-propylamine oxide	68155-09-9	AMPHOTERIC SURFACTANT	6815-50-9
Corundum	1302-74-5	Corundum	1302-74-56 1302-44-56
Crystalline silica (quartz)	14808-60-7	CRYSTALLINE SILICA, QUARTZ	14808-43-7
Ethyl octynol	5877-42-9	1-OCTYN-3-OL, 4-ETHYL-	5477-42-9
Ethylbenzene	100-41-4	ETHYLBENZENE	10-04-1
Extract of yeast	8013-01-2	Extract of yeast	08013-01-2
Glutaraldehyde	111-30-8	GLUTARAL	11-30-8
Glycerol	56-81-5	1,2,3-PROPANETRIOL	5-68-1
Guar gum	9000-30-0	Guar gum	009000-30-0
Heavy aromatic naphtha	64742-94-5	SOLVENT NAPHTHA (PETROLEUM), HEAVY AROM.	6004742-94-5
Hexamethylenetetramine	100-97-0	Hexamethylenetetramine	1009-7-0
Hydrochloric acid	7647-01-0	HYDROGEN CHLORIDE	6747-01-0
Isotridecanol, ethoxylated	9043-30-5	ISOTRIDECANOL, ETHOXYLATED	9403-30-5
Kyanite	1302-76-7	Kyanite	1304-76-7
Laurl hydrosultaine	13197-76-7	Lauryl hydroxysultaine	131970-76-7
Limestone	1317-65-3	CALCIUM DERIVATIVE (CALCIUM CARBONATE)	131-76-5
Limonene	138-86-3	P-MENTHA-1,8-DIENE or D-LIMONENE (Classified as proprietary)	254504-00-1 (Classified as proprietary)
Methanol	67-56-1	METHANOL	67-57-1 67-51-1
Nitrilotris (methylene phosphonic acid)	6419-19-8	Aminotrimethylene phosphonic acid	6419—19-8
Octamethylcyclotetrasiloxane	556-67-2	Octamethylcyclotetrasiloxane	556.67-2
Phenolic resin	9003-35-4	Phenol, polymer with formaldehyde	900303-35-4
Phosphoric acid salt	7632-05-5	Phosphoric acid salt	5-5-7632
Pine oil	8002-09-3	PINE OIL or TERPENE HYDROCARBON	8002-09-0 80020-90-3

Standardized Name	**Correct CASRN**	**Original Reported Name**	**Original Invalid CASRN**
Poly(oxy-1,2-ethanediyl), .alpha.-isodecyl-.omega.-hydroxy-, phosphate, potassium salt	68071-17-0	POLY(OXY-1,2-ETHANEDIYL), .ALPHA.-ISODECYL-.OMEGA.-HYDROXY-, PHOSPHATE, POTASSIUM SALT	680711-70-0
Poly(oxy-1,2-ethanediyl), a-tridecyl-w-hydroxy-branched	69011-36-5	Alkoxylated alcohol	69011-369-5
Polyacrylic acid	9003-01-4	Polyacrylate	9003-79-8
Potassium chloride	7447-40-7	POTASSIUM CHLORIDE	7477-40-7
Propargyl alcohol	107-19-7	2-PROPYN-1-OL	107-19-1
Sodium carboxymethylcellulose	9004-32-4	CARBOXYMETHYLCELLULOSE SODIUM SALT	900-43-4
Sodium chloride	7647-14-5	SODIUM CHLORIDE	7647-15-5 4647-14-5
Sodium polyacrylate	9003-04-7	ANIONIC ACRYLAMIDE COPOLYMER	90030-40-7 900-30-4 90-30-4
Sodium polynaphthalenesulfonate	9084-06-4	NAPHTHALENESULFONIC ACID, POLYMER WITH FORMALDEHYDE, SODIUM	908-46-4
Solvent naphtha, petroleum, light arom.	64742-95-6	LIGHT AROMATIC NAPHTHA	64742-95-5
Toluene	108-88-3	Toluene	1080-88-3
Triethanolamine zirconate	101033-44-7	Triethanolamine zirconate	10133-44-7
Unknown	Unknown	ALKYLARYL SULFONATE (Classified as proprietary)	68484-27-0 (Classified as proprietary)
Unknown	Unknown	MAGMA FIBERS (Classified as proprietary)	6806-10-0000 (Classified as proprietary)
Water	7732-18-5	WATER	7732-15-5 732-18-5 773-21-8
Xanthan gum	11138-66-2	XANTHAN GUM (Classified as proprietary)	59370-00-0 (Classified as proprietary)
Xylenes	1330-20-7	XYLENE	133-02-0
Zinc chloride	7646-85-7	Zinc chloride	7647-85-7
Zinc sulfate	7733-02-0	SULFURIC ACID, ZINC SALT (1:1)	7732-02-0
Zirconium dichloride oxide	7699-43-6	ZIRCONIUM DICHLORIDE OXIDE	7699-54-0

Table A3.10. List of chemical additives with valid CASRNs after corrections were made.

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
1,2-Ethanediaminium, N1, N2-bis[2-[bis(2-hydroxyethyl) methylammonio]ethyl]-N1, N2-bis(2-hydroxyethyl)-N1,N2-dimethyl-, chloride (1:4)	138879-94-4	Gelatin	9000-70-8
1,2,3-Trimethylbenzene	526-73-8	Gilsonite	12002-43-6
1,2,4,5-Tetrabromobenzene	636-28-2	Glassy calcium magnesium phosphate	65997-17-3
1,2,4-Trimethylbenzene	95-63-6	Glutaraldehyde	111-30-8
1,2-benzisothiazolin-3-one	2634-33-5	Glycerides, tall oil mono-, di, and tri	97722-02-6
1,2-Diiodobenzene	615-42-9	Glycerol	56-81-5
1,2-Ethanediamine, N1-(2-aminoethyl)-N2-(2-((2-aminoethyl)amino)ethyl)-, polymer with 2-methyloxirane and oxirane	68815-65-6	Glycine, N-(carboxymethyl)-N-(2-((carboxymethyl)amino)ethyl)-, sodium salt (1:3)	19019-43-3
1,2-Ethanediamine, N1,N2-bis(2-aminoethyl)-, polymer with 2-methyloxirane and oxirane	67939-72-4	Glycolic acid	79-14-1
1,2-Ethanediamine, polymer with 2-(chloromethyl)oxirane and N-methylmethanamine	42751-79-1	Glyoxal	107-22-2
1,3,5-Tribromobenzene	626-39-1	Graphite	7782-42-5
1,3,5-Trimethylbenzene	108-67-8	Guar gum	9000-30-0
1,3-Propanediaminium, 2-hydroxy-N,N,N,N′,N′-pentamethyl-N′-(3-((2-methyl-1-oxo-2-propenyl) amino)propyl)-, dichloride, homopolymer	86706-87-8	Heavy aromatic naphtha	64742-94-5
1,4-Dibromobenzene	106-37-6	Hematite	1317-60-8
1,4-Dioxane	123-91-1	Hemicellulase enzyme	9012-54-8
1,4-Dioxane-2,5-dione, 3,6-dimethyl-, (3R,6R)-,polymer with rel-(3R,6S)-3,6-dimethyl-1,4-dioxane-2,5-dione and (3S,6S)-3,6-dimethyl-1,4-dioxane-2,5-dione	9051-89-2	Hemicellulase enzyme concentrate	9025-56-3
1-bromo-3,5-dichlorobenzene	19752-55-7	Hexamethylenetetramine	100-97-0
1-Bromo-4-iodobenzene	589-87-7	Hexanedinitrile, hydrogenated, high-boiling fraction, polymer with epichlorohydrin, acetate (salt)	68955-69-1
1-Butoxy-2-propanol	5131-66-8	Hexylene glycol	107-41-5
1-Chloro-4-iodobenzene	637-87-6	Humic acids	1415-93-6
1-Eicosene	3452-07-1	Hydrocarbons, terpene processing by-products	68956-56-9

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
1-Hexadecene	629-73-2	Hydrochloric acid	7647-01-0
1-Iodonaphthalene	90-14-2	Hydrofluoric acid	7664-39-3
1-Methoxy-2-propanol	107-98-2	Hydrogen peroxide	7722-84-1
1-Octadecene	112-88-9	Hydroquinone	123-31-9
1-octanesulfonic acid sodium salt	5324-84-5	Hydrotreated Light Petroleum Distillate	64742-47-8
1-propanaminium, n-(carboxymethyl)-n,n-dimethyl-3-(((13z)-1-oxo-13-docosenyl) amino)-, inner salt	149879-98-1	Hydroxyethyl cellulose	9004-62-0
1-propanesulfonic acid, 2-methyl-2-[(1-oxo-2-propenyl) amino]-, monoammonium salt, polymer with 2-propenamide	110897-64-8	Hydroxylamine hydrochloride	5470-11-1
1-Tetradecene	1120-36-1	Iodine	7553-56-2
2-Propenoic acid, ammonium salt (1:1)	10604-69-0	Iron	7439-89-6
2-Propenoic acid, ammonium salt (1:1), polymer with 2-propenamide	26100-47-0	Iron oxide	1309-37-1
2,2 Dibromo-3-nitrilopropionamide	10222-01-2	Isobutylmethylcarbinol	108-11-2
2,2″-oxydiethanol (impurity)	111-46-6	Isopropanol	67-63-0
2,4,5-Tribromotoluene	3278-88-4	Isoquinoline	119-65-3
2,4,6-Tribromotoluene	6320-40-7	Isotridecanol, ethoxylated	9043-30-5
2,4-Dibromomesitylene	6942-99-0	Kerosene	8008-20-6
2,5-Dibromothiophene	3141-27-3	Krypton	7439-90-9
2-Acrylamido-2-methylpropane sulfonate	38193-60-1	Krypton 85	13983-27-2
2-Amino-2-methylpropanol	124-68-5	Kyanite	1302-76-7
2-Bromonaphthalene	580-13-2	Lactose	63-42-3
2-Butenedioic acid (2E)-, polymer with 2-methyloxirane, oxirane and 1,2,3-propanetriol	68400-71-5	Lactose	5989-81-1
2-butenedioic acid (e)-, polymer with 1,2-ethanediol and .alpha.,.alpha.?-[(1-methylethylidene)di-4,1-phenylene]bis[.omega.-hydroxypoly[oxy(methyl-1,2-ethanediyl)]]	39382-21-3	Laurl hydrosultaine	13197-76-7
2-Butoxyethanol	111-76-2	Lead	7439-92-1
2-Butoxypropan-1-ol	15821-83-7	Lecithins	8002-43-5
2-Ethylhexan-1-ol	104-76-7	L-Glutamic acid, N,N-diacetic acid	58976-65-1
2-Hexyl-1-decene	13043-55-5	L-Glutamic acid, N,N-diacetic acid, tetrasodium salt	51981-21-6

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
2-Iodobiphenyl	2113-51-1	Lignin	9005-53-2
2-Mercaptoethyl alcohol	60-24-2	Lignite	129521-66-0
2-Methoxy-1-propanol	1589-47-5	Lignocellulose	11132-73-3
2-Methyl-3(2H)-isothiazolone	2682-20-4	Lignosulfonic acid, ethoxylated, sodium salts	68611-14-3
2-Methyl-3-butyn-2-ol	115-19-5	Limestone	1317-65-3
2-Methylamino-2-methyl-1-propanol	27646-80-6	Linear/branched alcohol ethoxylate (11eo)	127036-24-2
2-Methylbutyrate	600-07-7	Lithium carbonate	554-13-2
2-Propen-1-aminium, N,N-dimethyl-N-2-propenyl-, chloride, polymer with 2-hydroxypropyl 2-	67990-40-3	Lithium chlorate	36355-96-1
2-Propenoic acid, 2-ethylhexyl ester, polymer with 2-hydroxyethyl 2-propenoate	36089-45-9	Lithium chlorate	13453-71-9
2-propenoic acid, 2-methyl-, polymer with 2-propenoic acid	25751-21-7	Lithium chloride	7447-41-8
2-Propenoic acid, 2-methyl-, polymer with methyl 2-methyl-2-propenoate, octadecyl 2-methyl 2 propenoate and 2propenoic acid, sodium salt	145417-45-4	Lithium hydroxide	1310-65-2
2-Propenoic acid, butyl ester, polymer with ethenylbenzene and 2-propenamide	25037-33-6	Lithium hypochlorite	13840-33-0
2-propenoic acid, polymer with 2-propenamide	9003-06-9	Maghemite	1309-38-2
2-Propenoic acid, polymer with 4-(1,1-dimethylethyl)phenol, formaldehyde, 2,5-furandione, 2-methyloxirane, 4-nonylphenol and oxirane	129828-31-5	Magnesium	7439-95-4
2-propenoic acid, polymer with sodium 2-propenoate	9033-79-8	Magnesium chloride	7786-30-3
2-Propenoic acid, polymer with sodium phosphinate	129898-01-7	Magnesium iron silicate	1317-71-1
2-Propenoic acid, polymer with sodium phosphinate (1:1), sodium salt	71050-62-9	Magnesium nitrate	10377-60-3
2-Propenoic acid, telomer with 2-methyl-2-(1-oxo-2-propenyl)-1-propanesulfonic acid, sodium salt	130800-24-7	Magnesium oxide	1309-48-4
2-Propenoic acid, telomer with sodium sulfite (1:1), sodium salt	68479-09-4	Magnesium silicate	1343-88-0
3,5-Dibromotoluene	1611-92-3	Magnesium silicate hydrate (talc)	14807-96-6
3-aminopropyl (sileanetriol)	58160-99-9	Maltodextrin	9050-36-6

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
4,4`-Diaminodiphenyl sulfone	80-08-0	MBNPA (2-bromo-3-nitrilopropionamide)	1113-55-9
4,7-methano-1h-indene, 3a,4,7,7a-tetrahydro-, polymer with 1,3-cyclopentadiene, cyclopentene, 1-hexene, 2-methyl-2-butene and 1,3-pentadiene	68003-51-0	Mercury	7439-97-6
4-Chlorobenzophenone	134-85-0	Methanol	67-56-1
4-Iodo-o-xylene	31599-61-8	Methyl borate	121-43-7
4-Iodotoluene	624-31-7	Methyl Chloride	74-87-3
5-Chloro-2-methyl-3(2H)-isothiazolone	26172-55-4	Methyl isobutyl ketone	108-10-1
5-Iodo-m-xylene	22445-41-6	Methyl salicylate	119-36-8
9-Bromophenanthrene	573-17-1	Mica	12001-26-2
Acetaldehyde	75-07-0	Mineral oil	8042-47-5
Acetaldol	107-89-1	Mineral Oil	8012-95-1
Acetic acid	64-19-7	Monoethanolamine	141-43-5
Acetic acid ethenyl ester, polymer with choroethene and ethene	25085-46-5	Monoethanolamine borate	26038-87-9
Acetic acid ethenyl ester, polymer with ethenol	25213-24-5	Morpholine	110-91-8
Acetic acid etheynl ester, polymer with ethene	24937-78-8	Mullite	1327-36-2
Acetic anhydride	108-24-7	Mullite	1302-93-8
Acetone	67-64-1	N,N-Dimethyldecylamine oxide	2605-79-0
Acetophenone	98-86-2	Naphtha (petroleum), heavy catalytic reformed	64741-68-0
Acetyltriethyl citrate	77-89-4	Naphtha, hydrotreated heavy	64742-48-9
Acrolein	107-02-8	Naphthalene	91-20-3
Acrolein dimer	100-73-2	Naphthalenesulfonate-formaldehyde condensate, sodium salt	9008-63-3
Acrylamide	79-06-1	Naphthalenesulfonic acid, bis(1-methylethyl)-, compd. with cyclohexanamine (1:1)	68425-61-6
Acrylic Acid	79-10-7	n-Beta-(aminoethyl)-gamma-aminopropyl trimethoxysilane	1760-24-3
Acrylic polymer	203008-81-5	n-Butyl alcohol	71-36-3
Acrylonitrile	107-13-1	Nickel	7440-02-0
Adipic acid, dimethyl ester	627-93-0	Nickel sulfate	7786-81-4
Alcohols, C10-16, ethoxylated	68002-97-1	Nitrilotriacetic acid	139-13-9
Alcohols, C10-14, ethoxylated	66455-15-0	Nitrilotris (methylene phosphonic acid)	6419-19-8
Alcohols, C10-16, ethoxylated propoxylated	69227-22-1	Nitrogen	7727-37-9

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Alcohols, C11 linear, ethoxylated	34398-01-1	Non-crystalline silica (impurity)	7631-86-9
Alcohols, C11-14-iso-, C13-rich	68526-86-3	Nonoxynols	26027-38-3
Alcohols, C12-13, ethoxylated	66455-14-9	Nonylphenol polyethylene glycol ether	127087-87-0
Alcohols, C12-14, ethoxylated	68439-50-9	n-Propanol	71-23-8
Alcohols, C12-14, ethoxylated Propoxylated	68439-51-0	n-Tetradecane	629-59-4
Alcohols, C12-15 ethoxylated	68131-39-5	n-Tridecane	629-50-5
Alcohols, C12-16, ethoxylated	68551-12-2	Octamethylcyclotetrasiloxane	556-67-2
Alcohols, C14-C15, ethoxylated	68951-67-7	Olefin/maleic ester	68188-50-1
Alcohols, C6-12, ethoxylated propoxylated	68937-66-6	Oleic acid	112-80-1
Alcohols, C9-11-iso-, C10-rich, ethoxylated	78330-20-8	Orange terpenes	68647-72-3
Alcohols, C9-C11, ethoxylated	68439-46-3	Oxirane, 2-methyl-, polymer with oxirane, ether with 1,2,3-propanetriol (3:1), ether with 2-(chloromethyl)oxirane polymer with 4,4'-(1-methylethylidene)bis(phenol)	68036-92-0
Alkanes, C11-15-iso	90622-58-5	Oxirane, 2-methyl-, polymer with oxirane, ether with 2-(chloromethyl)oxirane polymer with 4,4'-(1-methylethylidene)bis(phenol)	68036-95-3
Alkanes, C14-16	90622-46-1	Paraffinic petroleum distillate, hydrotreated light	64742-55-8
Alkenes, C>10 a-	64743-02-8	PEG-15 Cocoate	61791-29-5
Alkyl dimethylbenzyl ammonium chloride	68424-85-1	Pegoterate	25038-59-9
Aluminum	7429-90-5	Pentadecane, 3-methylene	56919-55-2
Aluminum chloride	7446-70-0	Pentadecane, 5-methylene	115146-98-0
Aluminum chloride	7784-13-6	Pentasodium diethylenetriamine pentaacetate	140-01-2
Aluminum chlorohydrate	12042-91-0	Pentasodium tripolyphosphate	7758-29-4
Aluminum distearate	300-92-5	Peracetic acid	79-21-0
Aluminum oxide	1344-28-1	Petroleum distillate-mineral oil grade	8002-05-9
Aluminum oxide silicate	12141-46-7	Petroleum distillates	68990-35-2
Amaranth	915-67-3	Petroleum distillates	64741-44-2
Amide, tallow, N-(3-(dimethylamino)propyl)-N-oxides	68647-77-8	Petroleum distillates	64742-46-7
Amides, C8-18 and C18-unsatd., N,N-bis(hydroxyethyl)	68155-07-7	Petroleum resins	64742-16-1
Amides, coco, N-(3-(dimethylamino)propyl)-	68140-01-2	Phenol, 4,4'-(1-methylethylidene) bis-, polymer with 2-(chloromethyl)oxirane, 2-methyloxirane and oxirane	68123-18-2

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Amines, C12-16-alkyldimethyl	68439-70-3	Phenol, 4,4’-(1-methylethylidene)bis-, polymer with 2-(chloromethyl)oxirane and 2-methyloxirane	36484-54-5
Amines, dicoco alkylmethyl	61788-62-3	Phenolic resin	9003-35-4
Amines, dimethyl soya alkyl	61788-91-8	Phosphogypsum	13397-24-5
Amines, hydrogenated tallow alkyl, acetates	61790-59-8	Phosphonic acid	13598-36-2
Aminoethyl sulfate	926-39-6	Phosphonic acid, P,P’,P”,P’”-(((phosphonomethyl)imino)bis(2,1-ethanediylnitrilobis(methylene))) tetrakis-, ammonium salt (1:?)	70714-66-8
Ammonium acetate	631-61-8	Phosphonomethylated polyamine	68132-59-2
Ammonium benzoate	1863-63-4	Phosphoric acid	7664-38-2
Ammonium bifluoride	1341-49-7	Phosphoric acid salt	7632-05-5
Ammonium bisulfate	10192-30-0	Pine oil	8002-09-3
Ammonium chloride	12125-02-9	Plaster of paris	26499-65-0
Ammonium fluoride	12125-01-8	Poly ethylene glycol tridecyl ether phosphate	9046-01-9
Ammonium hydroxide	1336-21-6	Poly(dimethylaminoethylmethylacrylate) dimethyl sulphate quat.	27103-90-8
Ammonium persulfate	7727-54-0	Poly(oxy-1,2-ethanediyl), α[(9Z)-1-oxo-9-octadecen-1-yl]-αhydroxy-	9004-96-0
Ammonium sulfate	7783-20-2	Poly(oxy-1,2-ethandiyl), a-(nonylphenyl)-w-hydroxy-	9016-45-9
Ammonium thiosulfate	7783-18-8	Poly(oxy-1,2-ethanediyl), .alpha.-[bis(1-methylpropyl)phenyl]-.omega.-hydroxy-	53964-94-6
Ampicillin	69-53-4	Poly(oxy-1,2-ethanediyl), .alpha.-2,4,6-tris(1-phenylethyl)phenyl-.omega.-hydroxy-	70559-25-0
Antimony trioxide	1309-64-4	Poly(oxy-1,2-ethanediyl), .alpha.-isodecyl-.omega.-hydroxy-, phosphate, potassium salt	68071-17-0
Arsenic	7440-38-2	Poly(oxy-1,2-ethanediyl), .alpha.-sulfo-.omega.-hydroxy-, c6-10-alkyl ethers, ammonium salts	68037-05-8
Ashes (residues), coal	68131-74-8	Poly(oxy-1,2-ethanediyl), -[2,4,6-tris(1-phenylethyl)phenyl]- -hydroxy-	70559-25-0
Attapulgite, activated	12174-11-7	Poly(oxy-1,2-ethanediyl), alpha-(nonylphenyl)-omega-hydroxy-, branched	68412-54-4
Aziridine, homopolymer, ethoxylated	68130-99-4	Poly(oxy-1,2-ethanediyl), alpha-(nonylphenyl)-omegahydroxy-,branched, phosphates	68412-53-3
Aziridine, polymer with methyloxirane and oxirane	52501-07-2	Poly(oxy-1,2-ethanediyl), alpha-hydro-omega-hydroxy-, ether with D-glucitol (2:1), tetra-(9Z)-9-octadecenoate	61723-83-9

Chemical Name	CASRN	Chemical Name	CASRN
Barite	7727-43-7	Poly(oxy-1,2-ethanediyl), alpha-tridecyl-omega-hydroxy	24938-91-8
Barite	13462-86-7	Poly(oxy-1,2-ethanediyl), a-tridecyl-w-hydroxy-branched	69011-36-5
Barium	7440-39-3	Poly(sodium styrenesulfonate)	25704-18-1
Bauxite	1318-16-7	Polyacrylamide	9003-05-8
Bentonite	1302-78-9	Polyacrylic acid	9003-01-4
Benzalkonium chloride	8001-54-5	Polydimethyl diallyl ammonium chloride	26062-79-3
Benzene	71-43-2	Polyepichlorohydrin, trimethyl amine quaternized	51838-31-4
Benzene, c10-c16 alkyl derivatives	68648-87-3	Polyethylene glycol monohexyl ether	31726-34-8
Benzene, diethenyl-, polymer with ethenylbenzene and ethenylethylbenzene	9052-95-3	Polyethylene glycol monostearate	9004-99-3
Benzene, tetrapropylene-	25265-78-5	Polyethylene glycol soya amine	61791-24-0
Benzenesulfonic acid, 4-methyl-, potassium salt	16106-44-8	Polyethylene glycol tallow amine	61791-26-2
Benzenesulfonic acid, C10-16-alkyl derivs	68584-22-5	Polyethylene glycol trimethyl nonyl ether	84133-50-6
Benzenesulfonic acid, c10-16-alkyl derivs., compds. with 2-propanamine	68584-24-7	Polyethylene oxide	25322-68-3
Benzenesulfonic acid, C10-16-alkyl derivs., compds. with cyclohexylamine	255043-08-4	Polyethylene, polypropylene ether glycol copolymer	9003-11-6
Benzenesulfonic acid, c10-16-alkyl derivs., compds. with triethanolamine	68584-25-8	Polyglycol ether	9038-95-3
Benzenesulfonic acid, C10-16-alkyl derivs., potassium salts	68584-27-0	Polyoxyethylene dinonylphenol	9014-93-1
Benzenesulfonic acid, dodecyl-, branched	68411-32-5	Polyoxyethylene isodecyl ether	61827-42-7
Benzenesulfonic acid, dodecyl-, branched, compds. with 2-propanamine	90218-35-2	Polyoxyl 15 hydroxystearate	70142-34-6
Benzenesulfonic acid, mono-C10-16-alkyl derivs., ammonium salts	68910-31-6	Polypropylene	9003-07-0
Benzenesulfonic acid, mono-C10-16-alkyl derivs., compds. with ethanolamine	68910-32-7	Polypropylene glycol	25322-69-4
Benzenesulfonic acid, mono-C10-16-alkyl derivs., sodium salts	68081-81-2	Polyquaternium 15	35429-19-7
Benzododecinium chloride	139-07-1	Polyquaternium 5	26006-22-4
Benzoic acid	65-85-0	Polyquaternium-33	69418-26-4

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Benzyl chloride	100-44-7	Polysorbate 20	9005-64-5
Benzyldimethylammonium chloride	122-18-9	Polysorbate 40	9005-66-7
Beryllium	7440-41-7	Polysorbate 85	9005-70-3
Beta mannanases	37288-54-3	Polytetrafluoroethylene	9002-84-0
Bis(isopropyl)naphthalene	38640-62-9	Polyurethane resin	57029-46-6
Bis(isopropylammonium) sulphate	64346-44-7	Polyvinyl alcohol	9002-89-5
Boric acid	10043-35-3	Pontacyl carmine 2B	6625-46-3
Boric acid (HBO2), sodium salt, tetrahydrate	10555-76-7	Portland cement	65997-15-1
Boron oxide	1303-86-2	Potassium acetate	127-08-2
Boron sodium oxide	1330-43-4	Potassium bicarbonate	298-14-6
Bromic acid, sodium salt (1:1)	7789-38-0	Potassium bisulfate	7646-93-7
Butanedioic acid, sulfo-, 1,4-ditridecyl ester, sodium salt	2673-22-5	Potassium borate	1332-77-0
Butyl glycidyl ether	2426-08-6	Potassium carbonate	584-08-7
Butyl lactate	138-22-7	Potassium chloride	7447-40-7
C.I. Pigment Red 5	6410-41-9	Potassium formate	590-29-4
C12-14 Isoparaffin	68551-19-9	Potassium hydroxide	1310-58-3
C13-16 Isoparaffin	68551-20-2	Potassium Iodide	7681-11-0
Cadmium	7440-43-9	Potassium metaborate	13709-94-9
Calcite	13397-26-7	Potassium oleate	143-18-0
Calcium bromide	7789-41-5	Potassium oxide	12136-45-7
Calcium carbonate	471-34-1	Prolonium chloride	55636-09-4
Calcium chloride	10043-52-4	Propargyl alcohol	107-19-7
Calcium hydroxide	1305-62-0	Propionaldehyde	123-38-6
Calcium lignosulfonate	8061-52-7	Propylene carbonate	108-32-7
Calcium magnesium oxide	37247-91-9	Propylene glycol	57-55-6
Calcium magnesium sodium phosphate frit	65997-18-4	Pumice	1332-09-8
Calcium oxide	1305-78-8	Quaternary ammonium chloride, benzylcoco alkyldimethyl, chlorides	61789-71-7
Calcium sulfate	7778-18-9	Quaternary ammonium compound	100765-57-9
Calcium sulfate hemihydrate	10034-76-1	Quaternary ammonium compounds, benzyl(hydrogenated tallow alkyl) dimethyl, stearates, salts with bentonite	121888-68-4
Canola oil	120962-03-0	Quaternary ammonium compounds, benzyl-C10-16alkyldimethyl, chlorides	68989-00-4
Caprylamidopropyl betaine	73772-46-0	Quaternary ammonium compounds, bis(hydrogenated tallow alkyl)dimethyl, salts with bentonite	68953-58-2
Carbon	7440-44-0	Quaternary ammonium compounds, trimethylsoya alkyl, chlorides	61790-41-8

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Carbon dioxide	124-38-9	Quinaldine	91-63-4
Castor oil, ethoxylated	61791-12-6	Quinoline	91-22-5
Cellophane	9005-81-6	Residual oils (petroleum), solvent-dewaxed	64742-62-7
Cellulose, microcrystalline	9004-34-6	Saponite	1319-41-1
Ceramic materials and wares	66402-68-4	Sepiolite	63800-37-3
Cetethyl morpholinium	78-21-7	Silanetrio; (3-aminopropyl, homopolymer	68400-07-7
Chlorinated paraffins	8029-39-8	Silica gel	112926-00-8
Chlorous acid, sodium salt	7758-19-2	Silicon dioxide crystalline	60676-86-0
Choline chloride	67-48-1	Siloxanes and Silicones, di-Me, 3-hydroxypropyl Me, ethoxylated propoxylated	68937-55-3
Chromium	7440-47-3	Siloxanes and silicones, di-Me, polymers with Me silsesquioxanes	68037-74-1
Cinnamaldehyde	104-55-2	Siloxanes and silicones, dimethyl,	63148-52-7
Citric acid	77-92-9	Siloxanes and silicones, dimethyl, reaction products with silica	67762-90-7
Citrus terpenes	94266-47-4	Smectite	1318-93-0
Coal, ground	50815-10-6	Sodium acetate	127-09-3
Cobaltous acetate	71-48-7	Sodium aluminate	1302-42-7
Cocamidopropyl betaine	61789-40-0	Sodium aminotris(methylenephosphonate)	20592-85-2
Coco-amido-propylamine oxide	68155-09-9	Sodium Benzoate	532-32-1
Coconut diethanolamide	68603-42-9	Sodium bicarbonate	144-55-8
Coke (petroleum), calcined	64743-05-1	Sodium bisulfite	7631-90-5
Copolymer of acrylamide and sodium acrylate	25987-30-8	Sodium borosilicate	50815-87-7
Copper	7440-50-8	Sodium C14-16 olefin sulfonate	68439-57-6
Copper dichloride	7447-39-4	Sodium carbonate	497-19-8
Copper sulfate pentahydrate	7758-99-8	Sodium carboxymethylcellulose	9004-32-4
Corundum	1302-74-5	Sodium chlorate	7775-09-9
Cottonseed, flour	68308-87-2	Sodium chloride	7647-14-5
Crystalline silica (cristobalite)	14464-46-1	Sodium chloroacetate	3926-62-3
Crystalline silica (quartz)	14808-60-7	Sodium citrate	68-04-2
Crystalline silica (tridymite)	15468-32-3	Sodium dichloroisocyanurate	2893-78-9
Cumene	98-82-8	Sodium dodecylpoly(oxyethylene) sulfate	9004-82-4
Cyclohexamine sulfate	19834-02-7	Sodium erythorbate	6381-77-7
Cyclohexanol	108-93-0	Sodium formate	141-53-7
Cyclohexasiloxane, 2,2,4,4,6,6,8,8,10,10,12,12-dodecamethyl-	540-97-6	Sodium gluconate	527-07-1
Cyclohexylamine	108-91-8	Sodium glycolate	2836-32-0

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Cyclopentasiloxane, 2,2,4,4,6,6, 8,8,10,10-decamethyl-	541-02-6	Sodium hydroxide	1310-73-2
Cymene	25155-15-1	Sodium hypochlorite	7681-52-9
Decyldimethylamine	1120-24-7	Sodium iodide	7681-82-5
D-glucitol	50-70-4	Sodium lignosulfonate	8061-51-6
D-Glucopyranuronic acid, polymer with 6-deoxy-L-mannose, D-glucose and D-mannose, calcium potassium sodium salt	72121-88-1	Sodium nitrite	7632-00-0
Diatomaceous earth, calcined	91053-39-3	Sodium oxide	12401-86-4
Diatomaceous earth, natural (kieselguhr)	61790-53-2	Sodium perborate tetrahydrate	10486-00-7
Dicoco dimethyl quaternary ammonium chloride	61789-77-3	Sodium persulfate	7775-27-1
Diethanolamine	111-42-2	Sodium polyacrylate	9003-04-7
Diethylene glycol mono-n-butyl ether	112-34-5	Sodium polynaphthalenesulfonate	9084-06-4
Diethylenetriamine, propoxylated, ethoxylated	68910-19-0	Sodium silicate	1344-09-8
Diethylenetriaminepenta(methylenephosphonic) acid	15827-60-8	Sodium starch glycolate	9063-38-1
Diisopropylnaphthalenesulfonic acid	28757-00-8	Sodium sulfate	7757-82-6
Dimethyl glutarate	1119-40-0	Sodium sulfite	7757-83-7
Dimethyl siloxanes and silicones	63148-62-9	Sodium tetraborate decahydrate	1303-96-4
Dioctyl sulfosuccinate sodium salt	577-11-7	Sodium thiosulfate	7772-98-7
Dipropylene glycol monomethyl ether	34590-94-8	Sodium Thiosulfate Pentahydrate	10102-17-7
Disodium ethylene diamine tetra acetate (impurity)	139-33-3	Sodium trimetaphosphate	7785-84-4
Disodium ethylenediaminediacetate	38011-25-5	Solvent naphtha, petroleum, light aliph.	64742-89-8
Disodium metasilicate	6834-92-0	Solvent naphtha, petroleum, light arom.	64742-95-6
Disodium octaborate tetrahydrate	12008-41-2	Sorbic acid	110-44-1
Disodium pyrophosphate	7758-16-9	Sorbitan monooleate, ethoxylated	9005-65-6
Distillates (petroleum), hydrotreated heavy paraffinic	64742-54-7	Sorbitan stearate	1338-41-6
Distillates (petroleum), solvent-dewaxed heavy paraffinic	64742-65-0	Sorbitan trioleate	26266-58-0
Distillates, hydrotreated light naphthenic	64742-53-6	Sorbitan, mono-(9Z)-9-octadecenoate	1338-43-8
Diutan	125005-87-0	Soybean oil, Me ester	67784-80-9
D-limonene	5989-27-5	Starch	9005-25-8

Chemical Name	CASRN	Chemical Name	CASRN
D-Limonene	138-86-3	Stearic acid	57-11-4
Dodecane	112-40-3	Steel mill slag	65996-69-2
Dodecanoic acid	143-07-7	Stoddard solvents	8052-41-3
Dodecylbenzene	123-01-3	Strontium chloride	10476-85-4
Dodecylbenzene sulfonic acid	27176-87-0	Succinic acid, dimethyl ester	106-65-0
Erythorbic acid	89-65-6	Sulferized polyolefin	68037-13-8
Esters of rosin oligomers with pentaerythritol	65997-12-8	Sulfonic acids, alkane, sodium salts	68608-15-1
Ethanaminium, N,N,N-trimethyl-2-((1-oxo-2-propen-1-yl)oxy)-, chloride (1:1)	44992-01-0	Sulfur dioxide	7446-09-5
Ethanaminium, N,N,N-trimethyl-2-((1-oxo-2-propenyl)oxy)-, chloride, homopolymer	54076-97-0	Sulfuric acid	7664-93-9
Ethanesulfonic acid, 2-[methyl[(9z)-1-oxo-9-octadecen-1-yl]amino]-, sodium salt (1:1)	137-20-2	Sulfurous acid, sodium salt (1:1), polymer with formaldehyde and 1,3,5-triazine-2,4,6-triamine	64787-97-9
Ethanol	64-17-5	Sweet almond extract	90320-37-9
Ethanol, 2,2′,2″-nitrilotris-, homopolymer, hydrochloride	67924-33-8	Tall oil	8002-26-4
Ethanol, 2-amino-, 1-acetate (1:1)	54300-24-2	Tall oil acid diethanolamide	68155-20-4
Ethanol, 2-amino-, phosphate	29868-05-1	Tallow alkylamines	61790-33-8
Ethanol,2,2′-oxybis-,reactionproductswithammonia,morpholine derivs.residues	68909-77-3	Tar bases, quinoline derivs.	68513-87-1
Ethanolamine thioglycolate	126-97-6	Tar bases, quinoline derivs., benzyl chloride quaternized	72480-70-7
Ethene, 1,1-dichloro-, homopolymer	9002-85-1	tert-Butyl hydroperoxide	75-91-2
Ethoxylated alcohol C11-14	78330-21-9	Tetradecylbenzyldimethylammonium chloride	139-08-2
Ethoxylated alcohol C6	104780-82-7	Tetrahydro-3,5-dimethyl-1,3,5-thiadiazine-2-thione	533-74-4
Ethoxylated alcohol C6-12	68439-45-2	Tetrakis hydroxymethyl phosphonium sulfate	55566-30-8
Ethoxylated alcohol C7-9-iso, C8	78330-19-5	Tetramethyl ammonium chloride	75-57-0
Ethoxylated alcohol C8-10	68603-25-8	Tetrasodium ethylenediaminetetraacetate	64-02-8
Ethyl acetate	141-78-6	Tetrasodium pyrophosphate	7722-88-5
Ethyl acrylate	140-88-5	Thiocyanic acid, sodium salt (1:1)	540-72-7
Ethyl lactate	97-64-3	Thioglycolic acid	68-11-1
Ethyl octynol	5877-42-9	Thiourea, polymer with formaldehyde and 1-phenylethanone	68527-49-1
Ethylbenzene	100-41-4	Titanium oxide	13463-67-7

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Ethylene glycol	107-21-1	Toluene	108-88-3
Ethylene oxide	75-21-8	Triazinetriethanol	4719-04-4
Ethylenediamine	107-15-3	Tributyl phosphate	126-73-8
Etidronic acid	2809-21-4	Tricalcium phosphate	7758-87-4
Extract of walnut	84012-43-1	Tridecylalcohol, ethoxylated, phosphated, monoethanolamine salt	68425-75-2
Extract of yeast	8013-01-2	Triethanolamine	102-71-6
Fatty acids, C16-18 and C18-unsatd., Me esters	67762-38-3	Triethanolamine condensate polymer, methyl chloride alkylate	68609-18-7
Fatty acids, C18-unsatd., dimers	61788-89-4	Triethanolamine homopolymer	64114-46-1
Fatty acids, C18-unsatd., dimers, ethoxylated propoxylated	68308-89-4	Triethanolamine zirconate	101033-44-7
Fatty acids, tall-oil	61790-12-3	Triethylene glycol	112-27-6
Fatty acids, tall-oil, ethoxylated	61791-00-2	Triisobutylene (mixed isomers)	7756-94-7
Fatty acids, tall-oil, monoesters with sorbitan, ethoxylated	61790-86-1	Trimethylamine, N-oxide	1184-78-7
Fatty acids, tall-oil, reaction products with diethylenetriamine, acetates	68153-60-6	Trimethylbenzenes	25551-13-7
Fatty acids, tall-oil, reaction products with triethanolamine	67784-78-5	Trisodium ethylenediaminetetraacetate	150-38-9
Fatty acids, tall-oil, sodium salts	61790-45-2	Trisodium nitrilotriacetate	5064-31-3
Ferric chloride	7705-08-0	Tryptones	73049-73-7
Ferrous sulfate, monohydrate	17375-41-6	Ulexite	1319-33-1
Food red 10	3734-67-6	Undecane	1120-21-4
Formaldehyde	50-00-0	Undecanol, branched and linear	128973-77-3
Formaldehyde polymer with 4,1,1-dimethylethyl phenolmethyl oxirane	29316-47-0	Urea	57-13-6
Formaldehyde, polymer with 2-methyloxirane, 4-nonylphenol and oxirane	63428-92-2	Vinylidene chloride/methylacrylate copolymer	25038-72-6
Formaldehyde, polymer with 4-(1,1-dimethylethyl)phenol, 2-methyloxirane and oxirane	30704-64-4	Water	7732-18-5
Formaldehyde, polymer with 4-(1,1-dimethylethyl)phenol, 4-nonylphenol and oxirane	68171-44-8	Xanthan gum	11138-66-2
Formaldehyde, polymer with 4-(1,1-dimethylpropyl)phenol, 2-methyloxirane and oxirane	63428-91-1	Xenon	7440-63-3
Formaldehyde, polymer with 4-nonylphenol and oxirane	30846-35-6	Xenon 133, radionuclide	14932-42-4
Formamide	75-12-7	Xylenes	1330-20-7
Formic acid	64-18-6	Xylenesulfonic acid	25321-41-9
Fuller's earth	8031-18-3	Zinc	7440-66-6

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Fulvic acid	479-66-3	Zinc chloride	7646-85-7
Fumes, silica	69012-64-2	Zinc sulfate	7733-02-0
Furfuryl alcohol	98-00-0	Zirconium dichloride oxide	7699-43-6

Table A3.11. List of chemical additives reported as trade secret or proprietary. These entries are exactly as the operators entered them into various chemical disclosure datasets, and illustrate the range of detail supplied by operators when reporting use of trade secret or proprietary chemical additives.

Chemical Name	**Chemical Name**	**Chemical Name**
? SAYS PROPRIETARY MATERIALS	3rd Party Proprietary	ACID MODIFIED PETROLEUM RES.
ACID MODIFIED PETROLEUM RESIDUUM	Acrylamide acrylate polymer	ACRYLIC CO-POLYMER
ALCOHOL	Alcohols, Ethoxylated	ALDEHYDE
ALIPHATIC ALCOHOL	ALIPHATIC ALCOHOL (1)	ALIPHATIC ALCOHOL (2)
ALIPHATIC ALCOHOL (3)	ALIPHATIC PROPYLENE GLYCOL ETHERS	ALIPHATIC SULFONATE
Alkane	ALKENES	Alkoxylated alcohol
Alkyl amine	ALKYL ARYL AMINE SULFONATE	ALKYL BENZENESULFONIC ACID
ALKYL DIAMIDE	Alkyl Diamide	Alkyl dimethyl benzyl ammonium chloride
ALKYL ETHER OF CORN SUGAR	ALKYLARYL SULFONATE	ALKYLARYL SULFONATE (68484-27-0)
ALKYLARYL SULFONATES	ALKYLARYL SULFONATES_2	Alkylarysulfonate amine salt
ALKYLBENZENESULFONIC ACID	Alkylene Oxide Block Polymer	ALKYLENEN OXIDE BLOCK POLYMER
ALKYNE ALCOHOL	AMBER DEFOAMER 7	AMID SURFACTANT
AMID SURFACTANT, ESTER ACID SALT	AMID SURFACTANT, PHOSPHATE ACID SALT	AMID SURFACTANT, PHOSPHATE ESTER SALT
Amide surfactant	AMIDE SURFACTANT	Amide surfactant acid salt
Amide surfactant acid salt	Amide surfactant ester salt	AMIDE SURFACTANT, PHOSPHATE
AMIDE SURFACTANT, PHOSPHATE ACID SALT	AMIDE SURFACTANT, PHOSPHATE ESTER SALT	AMIDE SURFACTANT, PHOSPHORIC ACID SALT
AMIDE SURFACTANT, SALT OF ORGANIC ACID	AMIDE SURFACTANTS	Amine derivative
Amine salt	Amine salt	AMINE SALTS
Amine salts	Amino Alkyl Phosphonic Acid	Ammonium alkylaryl sulfonates
AMMONIUM SALT	Ammonium salt	AMPHOTERIC SURFACTANT
Anionic acrylamide copolymer	ANIONIC ACRYLAMIDE COPOLYMER	ANIONIC COPOLYMER
ANIONIC POLYACRYLAMIDE	ANIONIC POLYMER	Anionic Polymer
Anitfoam	ANTI-FOAMER	Antistatic Additive
AROMATIC ALDEHYDE	Aromatic Aldehyde	AROMATIC AMINE, TOFA SALT
Aromatic amines	AROMATIC AMINES	Aromatic amines
AROMATIC AMINES, TOFA SALT	AROMATIC AMINES, TOFA SALTS	AROMATIC COMPOUND

Chemical Name	**Chemical Name**	**Chemical Name**
AROMATIC COMPOUND (1)	AROMATIC COMPOUND (2)	AROMATIC COMPOUND (3)
AROMATIC COMPOUND (4)	AROMATIC COMPOUND (5)	AROMATIC COMPOUND (6)
AROMATIC HYDROCARBON	AROMATIC HYDROCARBON (1)	AROMATIC HYDROCARBON (1) BENZENESULFONIC ACID, C10-16-ALKYL DERIVS., COMPDS. WITH CYCLOHEXYLAMINE
AROMATIC HYDROCARBON (2)	AROMATIC HYDROCARBON (3)	AROMATIC HYDROCARBON (3A)
AROMATIC HYDROCARBON (3B)	AROMATIC HYDROCARBON (3C)	AROMATIC HYDROCARBON (4)
AROMATIC HYDROCARBON (5)	AROMATIC HYDROCARBON (7)	AROMATIC HYDROCARBON (7A)
AROMATIC HYDROCARBON (7B)	AROMATIC HYDROCARBON A (7A)	AROMATIC HYDROCARBON A (7B)
AROMATIC HYDROCARBON A (7C)	AROMATIC HYDROCARBONS (7)	Aromatic solvent mixture
ASPHASOL SUPREME	BA	BA-10A
BC-3, 260 gl tote	BENZENESULFONIC ACID, C10-16-ALKYL DERIVS., COMPDS. WITH CYCLOHEXYLAMINE	BIOPOLYMER
Bis-quaternary methacrylamide monomer	BLEND	Blend of bisulfates and K Salts
Blend of cellulose fibers	BLEND OF VEGETABLE AND POLYMER FIBERS	BORATE
Borate salts	C-INHIB	CAL-ACID 50
CALCARB	CALCIUM CARBONATE	CALCIUM SALTS
CALCIUM SULFATE	CAP	CARBOHYDRATE
Carbohydrate	CARBOHYDRATES	Carbohydrates
CARBON	Carboxylic Acid Salt	CELLULOSE
CELLULOSE DERIVATIVE	CEMENT RETARDER	CF DESCO II
CINNAMIC IN	CINNAMIC INHIBITOR	CITRUS EXTRACT
CLAY	COAL, <5% SIO2	Complex alkylamine
Complex Ester	COMPLEX STEARATES	Condensed alkanolamine
CONQOR 404	CONTAINS NON-HAZARDOUS INGREDIENTS WHICH ARE LISTED IN THE NON-MSDS SECTION OF THE REPORT	COPOLYMER
Copolymer	CORROSION CONTROL	CORROSION INHIBITOR
Cotton	CROSSLINKED POLYOL ESTER	CURED ACRYLIC RESIN
Cured acrylic resin	Cured Resin	CYCLIC ALKANES
Cyclic Alkanes	D-AIR 5000	D-LIMONENE (254504-00-1)
D-MULSE	DDBSA SALT	DDBSA salt
DDBSA salt	DEFLOCCULANT	DEFOAM-X
DEFOAMER	DEFOAMER 7	DEFOAMING AGENT
DETERGENT	DIETHANOLAMINE	Dimethyl siloxane
DIOL COMPOUND	DISPERSANT	DISTILLATES (PETROLEUM), HYDRITREATED LIGHT; KEROSINE - UNSPECIFIED
DRILLING DETERGENT	DRILLING MUD ADDITIVE	Drilling paper

Chemical Name	**Chemical Name**	**Chemical Name**
EDTA/COPPER CHELATE	EDTA/Copper chelate	EMULSIFIER
EMULSION OF COMPLEX STEARATES	ENVIRO C-INHB	ENVIRO C-INHIB
ENVIRO D-MULSE	ENVIRO M-SOLV	ENVIRO MUD
ENVIRO OG	Enzyme	Enzyme G-I
ESTER	ETHOXYLATE	ETHOXYLATED ALCOHOL
Ethoxylated alcohol	ETHOXYLATED ALCOHOLS	ETHOXYLATED ALCOHOLS C12-16
ETHOXYLATED ALKYL AMINES	Ethoxylated amine	ETHOXYLATED CYCLIC AMINES
ETHOXYLATED NONYLPHENOL	Ethoxylated nonylphenol	ETHOXYLATED NONYLPHENOL ALCOHOL
Ethoxylated octylphenol	Ethoxylated octylphenol	ETHOXYLATED SURFACTANT
ETHYLENE OXIDE-NONYLPHENOL POLYMER	Ethylene-Vinyl Acetate Copolymer	Exualkylated Alkylphenol (1)
Exyalkylated Amine	FATTY ACID	FATTY ACID ESTER
FATTY ACID ESTERS	FATTY ACID OXYALKYLATE	Fatty acid tall oil amide
Fatty acids	Fatty Acids	FATTY ACIDS
FATTY ACIDS ESTER	Fatty acids, tall oil	FATTY ACIDS, TALL OIL
FDP-S1047-12	FORMATE SALT	GBW-30 BREAKER
GLYCOL	HALAD-322	HALAD-344
HALIDES, INORGANIC SALT	Haloalkyl heteropolycycle salt	HR-5
HYDROXIDE	Impurities	IngredientName
INORGANIC COMPOUND	Inorganic mineral	INORGANIC NITRATE SALT
INORGANIC POTASSIUM	INORGANIC POTASSIUM COMPOUND	INORGANIC POTASSIUM COMPOUND/A
INORGANIC POTASSIUM COMPOUND/ALKALI HYDROXIDE	INORGANIC SALT	INORGANIC SALT OF AN ACID
INORGANIC SOLVENT	INORGANIC SOLVENTS	IONIC COMPOUND
IONIC SURFACTANT	Ionic surfactants	Ionic surfactants
IONIC SURFACTANTS	IONIC SURFACTANTS SS-27	IONIC SURFACTANTS SW-211
KETONE	Krypton	LIGNOSULFONATE
LINEAR ALKYLBENZENE	LITHIUM CHLORATE	LUBRICANT
LUBRICANT (COMPLEX STEARATES)	M-SOLV	METHYL EST OF SULFONATE TANNIN
Methyl ester of sulfonated tannin	METHYL ESTER OF SULFONATED TANNIN	Methyl oxirane polymer
MINERAL	MINERAL FIBER	Mineral fiber
MIXTURE	MIXTURE OF SURFACTANTS	Mixture of Surfactants
MODIFIED ACRYLAMIDE CO-POLYMER	MODIFIED ALKANOLAMIDE	Modified bentonite
MODIFIED LIGNIN	MODIFIED LIGNOSULFONATE	MODIFIED STARCH
MODIFIED SULFONATE	MODIFIED THIOUREA POLYMER	MUD FLUSH III
MUTUAL SOLVENT	NAP-FORMALDEHYDE CONDENSATE, SODIUM SALT	NAPHTHALENESULFONATE-FORMALDEHYDE

Chemical Name	**Chemical Name**	**Chemical Name**
NAPHTHALENESULFONATE-FORMALDEHYDE CONDENSATE	NAPHTHALENESULFONATE-FORMALDEHYDE CONDENSATE, SODIUM SALT	NAPHTHALENESULFONIC ACID, BIS(1-METHYLETHYL)-, COMPD. WITH CYCLOHEXANAMINE (1:1)
NATURAL PEAT	Neutralized Polycarboxylic Acid	NON-HAZARDOUS
Non-Hazardous Ingredient	NON-HAZARDOUS INGREDIENTS	Non-hazardous Ingredients
NON-HAZARDOUS ORGANIC COMPOUND	NON-IONIC DEFOAMING AGENT	NON-IONIC SURFACTANT
NON-IONIC SURFACTANTS	NONYLPHENOL	Nonylphenol ethoxylate
NONYLPHENOL ETHOXYLATE	Nutshell	Olefin
OLEFIN	Olefin	OLEFINS
Olefins	Organic acid	Organic acid
ORGANIC ACID	ORGANIC ACID SALT	ORGANIC ACID SALT 2
ORGANIC PHOSPHONATE	Organic phosphonate	Organic sulfonic acid
ORGANIC SULFONIC ACID AMINE SALT	Organic Sulfur Compound	Organic surfactant
ORGANO SULFUR COMPOUNDS	ORGANOPHILIC CLAY	ORGANOPHOSPHONIC ACID SALT
ORGANOSULFUR COMPOUND (1)	ORGANOSULFUR COMPOUND (2)	OXIDE SUPPORT
Oxyakylated Amine Quat	Oxyalkalted alkylphenol	OXYALKYLATE
Oxyalkylated alcohol	Oxyalkylated alkylphenol	OXYALKYLATED ALKYLPHENOL
Oxyalkylated Alkylphenol (1)	Oxyalkylated Alkylphenol (2)	OXYALKYLATED ALKYLPHENOLIC RESIN
OXYALKYLATED AMINE	Oxyalkylated Amine	OXYALKYLATED AMINE QUAT
OXYALKYLATED FATTY ACID	Oxyalkylated Fatty Acid	Oxyalkylated phenolic resin
OXYALKYLATED POLYAMINE	Oxylalkylated alkylphenol	OXYLATED ALCOHOL
Oxylated alcohol	Oxylated phenolic resin	Paraffinic solvent
Petroleum Distillate Blend	PETROLEUM RESINS	PHOSPHATE ACID SALT
PHOSPHATE ESTER	PHOSPHATE ESTER SALT	Phosphate ester salt
PHOSPHONATE SALT	Phosphonate salt	PHOSPHONIC ACID SALT
Phosphonic Acid Salt	Phosphoric acid ester salt	Phosphoric acid ester salt
POL-E-FLAKES	POLYACRULAMIDE BLEND	Polyacrylamide copolymer
POLYACRYLATE	Polyacrylate/ phosphate scale inhibitor	POLYACRYLATE/POLYACRYLAMIDE POLYMER BLEND
polyalkylammonium choride	Polyanionic cellulose	POLYANIONIC CELLULOSIC POLYMER
POLYANIONIC POLYMER	POLYCYCLIC AROMATIC HYDROCARBON	POLYCYCLIC COMPOUND
POLYDIMETHYISILOXANE COMPOUND	Polydimethylsiloxane emulsion	POLYESTER
POLYETHER	Polyglycol ester	POLYGLYCOL ESTER
Polylactide resin	POLYMER	Polymer
POLYMER AND WATER	POLYNUCLEAR AROMATIC HYDROCARBON	POLYNUCLEAR AROMATIC HYDROCARBONS
POLYOLPHOSPATE ESTER	Polyoxyalklene	POLYOXYALKYLENE
Polyoxyalkylene	Polyoxyalkylene	POLYOXYALKYLENES

Chemical Name	Chemical Name	Chemical Name
Polyoxyalkylenes	Polyoxyalkylenes	POLYPHOSPHATE ESTER
Polyquaternary amine salt	POLYSACCHARIDE	Polysaccharide
Polysaccharide	Polysaccharide polyacrylamide blend	POLYTEK
Potassium salt solution	POWERVIS	Propene polymer
PROPRIETARY	Proprietary	PROPRIETARY BLEND
PROPRIETARY BLEND OF COMPLEX STEARATES	PROPRIETARY MATERIALS	Quaternary amine
QUATERNARY AMINE	Quaternary ammonium compound	QUATERNARY AMMONIUM COMPOUND
Quaternary ammonium compound	QUATERNARY AMMONIUM COMPOUND (1)	QUATERNARY AMMONIUM COMPOUND (2)
QUATERNARY AMMONIUM COMPOUND (3)	QUATERNARY AMMONIUM COMPOUND-1	QUATERNARY AMMONIUM COMPOUND-2
QUATERNARY AMMONIUM COMPOUND-3	Quaternary phosphorus compund	Raffinates (petroleum), sorption process
RCI 07289 CORROSION INHIBITOR	SA-1015	SALT COMPOUND
SALT OF AMINE/CARBONYL CONDENSATE	Salt of an organic sulfer compound	Salt of an organic sulfur compound
Salt of fatty acid polyamine	SALT OF FATTY ACID POLYAMINE	SALT OF INORGANIC ACID
SALT OF ORGANIC ACID	Salt of organic sulfur compound	SATURATED ALCOHOLS
SATURATED MONOCARBOXYLIC ACID, CALCIUM SALT	SAWDUST	SILICA FUME
SILICA SAND GRAVEL	SILICA SUPPORT	SILICA, CRYSTALLINE, QUARTZ
Silicon emulsion blend	SILICONE	SILICONE FLUID
Sodium hydroxide	Sodium iodine iodine	SODIUM POLYACRYLATE/ POLYCRYLAMIDE
SODIUM POLYNAPHTHALENE SULPHONATE	SODIUM SALT	Sorbitan ester
SS 26 IN XYLENE	SSP-40 IN XYLENE	Substituted alcohol
SUBSTITUTED FATTY AMIDE	SUFONATE	SUGAR
SULFATE	SULFONATE	Sulfonate
SULFONATE SALT	SULFONATED POLYMER	SULFONIC ACID SALT
Sulfur compound	SULFUR COMPOUND	SULFURIC ACID, BARIUM SALT (1:1)
SURFACTANT	Surfactant	SURFACTANT BLEND
SURFACTANT MIXTURE	Surfactant mixture	SURFACTANT, PHOSPHATE ACID SALT
Surfactants	Surfactants	SYNTHETIC ACID
TANNIN, SODIUM SALT POLYMER WITH ACRYLIC MONOMERS	Terpene	THRUTROL
Trade secret	TUNED SPACER III	UCS
UNSATURATED ALCOHOL	Unsulphonated Matter	VEGETABLE AND POLYMER FIBERS
Vegetable and polymer fibres	Vinyl Copolymer	VINYL COPOLYMER

Chemical Name	**Chemical Name**	**Chemical Name**
VISCOSIFIER	Walnut hulls	WALNUT SHELLS
Water (Including Mix Water Supplied by Client)	WATER (INCLUDING MIX WATER SUPPLIED BY CLIENT)	water soluable polymer
WOOD	WOOD CHEMICALS	Wood dust
Wood dust	WOOD DUST	WOOD DUST, SOFT WOOD
WOOD FIBER	XANTHAN GUM (59370-00-0)	Xenon

Table A3.12. Chemical additives categorized as GHS 1 or 2 for acute toxicity for all datasets.

Chemical Name	**CASRN**	**Oral GHS**	**Inhalation GHS**	**Aquatic GHS**
Acrolein	107-02-8	2	2	1
Acrylic Acid	79-10-7	2	3[1]	3
Acrylonitrile	107-13-1	2	NT[2]	2
Cyclohexylamine	108-91-8	2		2
Ethyl acetate	141-78-6	2	3	3
Ferric chloride	7705-08-0	2		2
Formaldehyde	50-00-0	2	2	3
Propargyl alcohol	107-19-7	2	3	2
Stoddard solvents	8052-41-3	2	3[1]	1
Tetramethyl ammonium chloride	75-57-0	2		NT
Tetrasodium ethylenediaminetetraacetate	64-02-8	2		3
Zinc sulfate	7733-02-0	2		1
2,2 Dibromo-3-nitrilopropionamide	10222-01-2	3	1	1
Boric acid	10043-35-3	5	1[1]	3
Cadmium	7440-43-9	3	1	1
Glutaraldehyde	111-30-8	3	1	1
Glycolic acid	79-14-1	4	1	NT
Hexylene glycol	107-41-5	5	1[1]	NT
Naphthalene	91-20-3	4	1[1]	1
Peracetic acid	79-21-0	3	1	2
Phosphoric acid	7664-38-2	4	1[1]	NT
Polyethylene, polypropylene ether glycol copolymer	9003-11-6	4	1	NT
Sodium tetraborate decahydrate	1303-96-4	4	1[1]	NT
Thioglycolic acid	68-11-1	3	1	3
2-Ethylhexan-1-ol	104-76-7	4	2[1]	3
5-Chloro-2-methyl-3(2H)-isothiazolone	26172-55-4	4	2	1
Benzyl chloride	100-44-7	4	2	1
Chlorous acid,sodium salt	7758-19-2	3	2	1
Ethylene oxide	75-21-8	3	2	3

1. Calculated using "floor level" estimates

2. NT – Non-toxic

Chemical Name	**CASRN**	**Oral GHS**	**Inhalation GHS**	**Aquatic GHS**
Furfuryl alcohol	98-00-0	3	2	NT
Hydrofluoric acid	7664-39-3		2	NT
Hydrogen peroxide	7722-84-1	4	2	2
Lithium hydroxide	1310-65-2	3	2	3
Pentasodium tripolyphosphate	7758-29-4	5	2[1]	NT
Petroleum distillates	64741-44-2		2	1
Polyglycol ether	9038-95-3	4	2	NT
Sulfuric acid	7664-93-9	5	2	NT
tert-Butyl hydroperoxide	75-91-2	4	2	3
1,2,4,5-Tetrabromobenzene	636-28-2			1
1,2-benzisothiazolin-3-one	2634-33-5	4		1
1,4-Dibromobenzene	106-37-6	5		1
2-Propenoic acid, ammonium salt (1:1), polymer with 2-propenamide	26100-47-0			1
2,4,6-Tribromotoluene	6320-40-7			1
2,4-Dibromomesitylene	6942-99-0			1
2-Iodobiphenyl	2113-51-1			1
2-Methyl-3(2H)-isothiazolone	2682-20-4			1
9-Bromophenanthrene	573-17-1			1
Acrylamide	79-06-1	3	4[1]	1
Alcohols, C10-16, ethoxylated	68002-97-1	5		1
Alcohols, C10-14, ethoxylated	66455-15-0			1
Alcohols, C10-16, ethoxylated propoxylated	69227-22-1			1
Alcohols, C11-14-iso-, C13-rich	68526-86-3	5		1
Alcohols, C12-13, ethoxylated	66455-14-9	NT		1
Alcohols, C12-14, ethoxylated	68439-50-9			1
Alcohols, C12-14, Ethoxylated Propoxylated	68439-51-0			1
Alcohols, C12-15 ethoxylated	68131-39-5	4		1
Alcohols, C12-16, ethoxylated	68551-12-2	4		1
Alcohols, C14-C15, ethoxylated	68951-67-7	4		1
Alcohols, C9-11-iso-, C10-rich, ethoxylated	78330-20-8			1
Alkanes, C14-16	90622-46-1			1
Alkenes, C>10 a-	64743-02-8			1
Alkyl dimethylbenzyl ammonium chloride	68424-85-1	4		1
Aluminum	7429-90-5	5	NT	1
Amides, coco, N-(3-(dimethylamino)propyl)-	68140-01-2			1
Amines, C12-16-alkyldimethyl	68439-70-3			1
Amines, dicoco alkylmethyl	61788-62-3			1

1. Calculated using "floor level" estimates

2. NT – Non-toxic

Chemical Name	**CASRN**	**Oral GHS**	**Inhalation GHS**	**Aquatic GHS**
Amines, dimethyl soya alkyl	61788-91-8			1
Benzalkonium chloride	8001-54-5	3		1
Benzene	71-43-2	4	NT	1
Benzene, c10-c16 alkyl derivatives	68648-87-3	NT		1
Benzene, tetrapropylene-	25265-78-5			1
Benzenesulfonic acid, C10-16-alkyl derivs., compds. With cyclohexylamine	255043-08-4			1
Benzenesulfonic acid, mono-C10-16-alkyl derivs., compds. With ethanolamine	68910-32-7			1
Benzyldimethylammonium chloride	122-18-9			1
Beryllium	7440-41-7			1
Bis(isopropyl)naphthalene	38640-62-9	5		1
Butanedioic acid, sulfo-, 1,4-ditridecyl ester, sodium salt	2673-22-5			1
C.I. Pigment Red 5	6410-41-9			1
C12-14 Isoparaffin	68551-19-9	NT		1
C13-16 Isoparaffin	68551-20-2	NT		1
Canola oil	120962-03-0			1
Cetethyl morpholinium	78-21-7			1
Chromium	7440-47-3			1
Coconut diethanolamide	68603-42-9	NT		1
Copper	7440-50-8			1
Copper dichloride	7447-39-4	3		1
Copper sulfate pentahydrate	7758-99-8	3		1
Cyclohexasiloxane, 2,2,4,4,6,6,8,8,10,10,12,12-dodecamethyl-	540-97-6	NT		1
Cyclopentasiloxane, 2,2,4,4,6,6,8,8,10,10-decamethyl-	541-02-6	NT	NT	1
Decyldimethylamine	1120-24-7	4		1
Dicoco dimethyl quaternary ammonium chloride	61789-77-3	4		1
Dimethyl siloxanes and silicones	63148-62-9	NT		1
Dioctyl sulfosuccinate sodium salt	577-11-7	4	NT	1
Distillates (petroleum), solvent-dewaxed heavy paraffinic	64742-65-0	NT		1
D-limonene	5989-27-5	5		1
Dodecane	112-40-3		NT	1
Dodecylbenzene	123-01-3	NT		1
Ethoxylated alcohol C11-14	78330-21-9			1
Ethyl acrylate	140-88-5	3	3	1

1. Calculated using "floor level" estimates

2. NT – Non-toxic

Chemical Name	**CASRN**	**Oral GHS**	**Inhalation GHS**	**Aquatic GHS**
Fatty acids, C16-18 and C18-unsatd., Me esters	67762-38-3			1
Fatty acids, C18-unsatd., dimers, ethoxylated propoxylated	68308-89-4			1
Fatty acids, tall-oil	61790-12-3	5		1
Fatty acids, tall-oil, ethoxylated	61791-00-2	NT		1
Fatty acids, tall-oil, monoesters with sorbitan, ethoxylated	61790-86-1			1
Fatty acids, tall-oil, reaction products with diethylenetriamine, acetates	68153-60-6			1
Fatty acids, tall-oil, sodium salts	61790-45-2			1
Heavy aromatic naphtha	64742-94-5	NT	NT	1
Hydrochloric acid	7647-01-0	3	3	1
Hydroquinone	123-31-9	3		1
Hydrotreated Light Petroleum Distillate	64742-47-8	NT	3[1]	1
Iodine	7553-56-2	NT	3[1]	1
Kerosene	8008-20-6	5		1
Lead	7439-92-1			1
Lecithins	8002-43-5			1
Lithium hypochlorite	13840-33-0			1
Mercury	7439-97-6			1
Mineral Oil	8012-95-1	NT	3	1
N,N-Dimethyldecylamine oxide	2605-79-0			1
Naphtha, hydrotreated heavy	64742-48-9	NT	4[1]	1
Naphthalenesulfonic acid, bis(1-methylethyl)-, compd. With cyclohexanamine (1:1)	68425-61-6			1
Nickel	7440-02-0	NT		1
n-Tetradecane	629-59-4	NT		1
n-Tridecane	629-50-5	NT	3[1]	1
Octamethylcyclotetrasiloxane	556-67-2	4	NT	1
Oleic acid	112-80-1	NT		1
Orange terpenes	68647-72-3			1
Petroleum distillate-mineral oil grade	8002-05-9	5		1
Petroleum distillates	64742-46-7			1
Poly(oxy-1,2-ethanediyl), α[(9Z)-1-oxo-9-octadecen-1-yl]-αhydroxy-	9004-96-0	NT		1
Polyethylene glycol monostearate	9004-99-3	NT		1
Polyethylene glycol soya amine	61791-24-0	4		1
Polyethylene glycol tallow amine	61791-26-2	4		1
Polyoxyethylene dinonylphenol	9014-93-1			1

1. Calculated using "floor level" estimates

2. NT – Non-toxic

Chemical Name	**CASRN**	**Oral GHS**	**Inhalation GHS**	**Aquatic GHS**
Polypropylene	9003-07-0			1
Polysorbate 85	9005-70-3			1
Potassium oleate	143-18-0	NT		1
Quaternary ammonium chloride, benzylcoco alkyldimethyl, chlorides	61789-71-7	3		1
Quinoline	91-22-5	4		1
Siloxanes and Silicones, di-Me, 3-hydroxypropyl Me, ethoxylated propoxylated	68937-55-3			1
Siloxanes and silicones, dimethyl,	63148-52-7			1
Sodium chloroacetate	3926-62-3	3		1
Sodium dichloroisocyanurate	2893-78-9	4		1
Sodium hypochlorite	7681-52-9	NT		1
Sodium iodide	7681-82-5	4		1
Sodium nitrite	7632-00-0	3	NT	1
Sodium silicate	1344-09-8	4		1
Sorbitan stearate	1338-41-6	NT		1
Sorbitan trioleate	26266-58-0	NT		1
Sorbitan, mono-(9Z)-9-octadecenoate	1338-43-8	NT		1
Soybean oil, Me ester	67784-80-9	5		1
Stearic acid	57-11-4	5		1
Sulferized polyolefin	68037-13-8			1
Tall oil	8002-26-4			1
Tall oil acid diethanolamide	68155-20-4			1
Tallow alkylamines	61790-33-8	4		1
Tetrahydro-3,5-dimethyl-1,3,5-thiadiazine-2-thione	533-74-4	3	3	1
Tributyl phosphate	126-73-8	4	NT	1
Triisobutylene (mixed isomers)	7756-94-7			1
Undecane	1120-21-4	5	NT	1
Zinc	7440-66-6	4		1
Zinc chloride	7646-85-7	4		1
1,2,3-Trimethylbenzene	526-73-8			2
1,2,4-Trimethylbenzene	95-63-6	5	4	2
1,2-Diiodobenzene	615-42-9			2
1,3,5-Tribromobenzene	626-39-1			2
1,3,5-Trimethylbenzene	108-67-8	5	NT	2
1-bromo-3,5-dichlorobenzene	19752-55-7			2
1-Bromo-4-iodobenzene	589-87-7			2
1-Chloro-4-iodobenzene	637-87-6			2

1. Calculated using "floor level" estimates

2. NT – Non-toxic

Chemical Name	**CASRN**	**Oral GHS**	**Inhalation GHS**	**Aquatic GHS**
1-Iodonaphthalene	90-14-2			2
2,5-Dibromothiophene	3141-27-3			2
2-Bromonaphthalene	580-13-2			2
2-Mercaptoethyl alcohol	60-24-2	3		2
3,5-Dibromotoluene	1611-92-3			2
4,4`-Diaminodiphenyl sulfone	80-08-0	3		2
4-Chlorobenzophenone	134-85-0			2
4-Iodotoluene	624-31-7			2
Acetaldehyde	75-07-0	4	NT	2
Alcohols, C11 linear, ethoxylated	34398-01-1			2
Alcohols, C9-C11, ethoxylated	68439-46-3	4		2
Aluminum chloride	7446-70-0	4		2
Ammonium chloride	12125-02-9	4		2
Arsenic	7440-38-2	3		2
Benzenesulfonic acid, C10-16-alkyl derivs	68584-22-5			2
Benzenesulfonic acid, mono-C10-16-alkyl derivs., ammonium salts	68910-31-6			2
Butyl glycidyl ether	2426-08-6	4	3[1]	2
Cinnamaldehyde	104-55-2	3		2
Cocamidopropyl betaine	61789-40-0	5		2
Cumene	98-82-8	4	4	2
Cymene	25155-15-1			2
Dodecanoic acid	143-07-7	NT		2
Dodecylbenzene sulfonic acid	27176-87-0	4		2
Ethanesulfonic acid, 2-[methyl[(9z)-1-oxo-9-octadecen-1-yl]amino]-, sodium salt (1:1)	137-20-2	4		2
Ethoxylated alcohol C6-12	68439-45-2	5		2
Ethoxylated alcohol C8-10	68603-25-8	4		2
Ethyl octynol	5877-42-9			2
Ethylbenzene	100-41-4	5	4	2
Ethylenediamine	107-15-3	4	NT	2
Fatty acids, C18-unsatd., dimers	61788-89-4	NT		2
Fatty acids, tall-oil, reaction products with triethanolamine	67784-78-5			2
Glyoxal	107-22-2	3	3	2
Isotridecanol, ethoxylated	9043-30-5			2
Methyl salicylate	119-36-8	4		2
Mineral oil	8042-47-5	NT		2
Naphtha (petroleum), heavy catalytic reformed	64741-68-0	5		2

1. Calculated using "floor level" estimates

2. NT – Non-toxic

Chemical Name	**CASRN**	**Oral GHS**	**Inhalation GHS**	**Aquatic GHS**
Nickel sulfate	7786-81-4			2
Nonoxynols	26027-38-3	4		2
Nonylphenol polyethylene glycol ether	127087-87-0	NT		2
PEG-15 Cocoate	61791-29-5			2
Polyethylene glycol tridecyl ether phosphate	9046-01-9			2
Poly(oxy-1,2-ethandiyl), a-(nonylphenyl)-w-hydroxy-	9016-45-9	4		2
Poly(oxy-1,2-ethanediyl), alpha-(nonylphenyl)-omega-hydroxy-, branched	68412-54-4			2
Poly(oxy-1,2-ethanediyl), alpha-tridecyl-omega-hydroxy	24938-91-8			2
Polyoxyethylene isodecyl ether	61827-42-7			2
Polysorbate 20	9005-64-5	NT		2
Quaternary ammonium compounds, trimethylsoya alkyl, chlorides	61790-41-8			2
Sodium C14-16 olefin sulfonate	68439-57-6			2
Sodium dodecylpoly(oxyethylene) sulfate	9004-82-4	4		2
Sodium perborate tetrahydrate	10486-00-7	4		2
Solvent naphtha, petroleum, light aliph.	64742-89-8			2
Solvent naphtha, petroleum, light arom.	64742-95-6	5	4[1]	2
Tetradecylbenzyldimethylammonium chloride	139-08-2	3		2
Trimethylbenzenes	25551-13-7	NT		2
Xylenes	1330-20-7	4	4	2

1. Calculated using "floor level" estimates

2. NT – Non-toxic

Table A3.13. Chemical additives with available chronic oral toxicity data for all datasets.

Chemical Name	**CASRN**	**Chronic Oral Ref Value (RfV) (mg/kg/day)**	**Source**
Cadmium	7440-43-9	1.14E-06	OEHHA PHG
Benzene	71-43-2	4.29E-06	OEHHA PHG
Lead	7439-92-1	5.71E-06	OEHHA PHG
Beryllium	7440-41-7	2.86E-05	OEHHA PHG
Mercury	7439-97-6	3.43E-05	OEHHA PHG
Zirconium dichloride oxide	7699-43-6	0.00008[1]	PPRTV RfD
Arsenic	7440-38-2	0.0003	IRIS RfD
Nickel	7440-02-0	0.00034	OEHHA PHG
Nickel sulfate	7786-81-4	0.00034[2]	OEHHA PHG
Acrolein	107-02-8	0.0005	IRIS RfD
Acrylamide	79-06-1	0.002	IRIS RfD
Benzyl chloride	100-44-7	0.002	PPRTV RfD
Propargyl alcohol	107-19-7	0.002	IRIS RfD
Chromium	7440-47-3	0.003	US EPA Drinking Water RfD
Diethanolamine	111-42-2	0.003	PPRTV RfD
Bromic acid, sodium salt (1:1)	7789-38-0	0.004	U.S. EPA Drinking Water RfD
Toluene	108-88-3	0.0042	OEHHA PHG
Ethyl acrylate	140-88-5	0.005	PPRTV RfD
Copper	7440-50-8	0.0085	OEHHA PHG
Ethylbenzene	100-41-4	0.0085	OEHHA PHG
1,2,3-Trimethylbenzene	526-73-8	0.01	IRIS RfD
1,2,4-Trimethylbenzene	95-63-6	0.01	IRIS RfD
1,3,5-Trimethylbenzene	108-67-8	0.01	IRIS RfD
1,4-Dibromobenzene	106-37-6	0.01	IRIS RfD
Iodine	7553-56-2	0.01	ATSDR MRL
Tributyl phosphate	126-73-8	0.01	PPRTV RfD
Aluminum	7429-90-5	0.017[3]	OEHHA PHG
Aluminum chloride	7446-70-0	0.017[3]	OEHHA PHG
Aluminum chloride	7784-13-6	0.017[3]	OEHHA PHG
Aluminum chlorohydrate	12042-91-0	0.017[3]	OEHHA PHG

1. Reference compound: Zirconium (CASRN: 7440-67-7)

2. Reference compound: Nickel and nickel compounds (CASRN: 7440-02-0)

3. Reference compound: Aluminum (CASRN: 7429-90-5)

4. Reference compound: Fluoride (CASRN: 16984-48-8)

5. Reference compound: Barium and compounds (CASRN: 7440-39-3)

6. Reference compound: Boron and compounds (CASRN: 7440-42-8)

7. Reference compound: Nitrates/nitrites as nitrogen (CASRN: 14797-65-0; 14797-55-8)

8. Reference compound: Zinc and compounds (CASRN: 7440-66-6)

9. Reference compound: Phosphoric acid (CASRN: 7664-38-2)

Chemical Name	**CASRN**	**Chronic Oral Ref Value (RfV) (mg/kg/day)**	**Source**
Aluminum oxide	1344-28-1	0.017[3]	OEHHA PHG
Aluminum oxide silicate	12141-46-7	0.017[3]	OEHHA PHG
Naphthalene	91-20-3	0.02	IRIS RfD
Ammonium bifluoride	1341-49-7	0.028[4]	OEHHA PHG
Ammonium fluoride	12125-01-8	0.028[4]	OEHHA PHG
Hydrofluoric acid	7664-39-3	0.028[4]	OEHHA PHG
1,4-Dioxane	123-91-1	0.03	IRIS RfD
Chlorous acid,sodium salt	7758-19-2	0.03	IRIS RfD
Diethylene glycol mono-n-butyl ether	112-34-5	0.03	PPRTV RfD
Solvent naphtha, petroleum, light arom.	64742-95-6	0.03	PPRTV RfD
Acrylonitrile	107-13-1	0.04	ATSDR MRL
Hydroquinone	123-31-9	0.04	PPRTV RfD
Xylenes	1330-20-7	0.051	OEHHA PHG
Barium	7440-39-3	0.057	OEHHA PHG
Barium sulfate	7727-43-7	0.057[5]	OEHHA PHG
Ethylenediamine	107-15-3	0.09	PPRTV RfD
2-Butoxyethanol	111-76-2	0.1	IRIS RfD
Acetophenone	98-86-2	0.1	IRIS RfD
Cumene	98-82-8	0.1	IRIS RfD
Glutaraldehyde	111-30-8	0.1	ATSDR MRL
n-Butyl alcohol	71-36-3	0.1	IRIS RfD
2-Ethylhexan-1-ol	104-76-7	0.125	USGS HBSL
Boric acid	10043-35-3	0.2[6]	IRIS RfD
Boron oxide	1303-86-2	0.2[6]	IRIS RfD
Boron sodium oxide	1330-43-4	0.2[6]	IRIS RfD
Cyclohexylamine	108-91-8	0.2	IRIS RfD
Disodium octaborate tetrahydrate	12008-41-2	0.2[6]	IRIS RfD
Formaldehyde	50-00-0	0.2	IRIS RfD
Methyl borate	121-43-7	0.2[6]	IRIS RfD
Monoethanolamine borate	26038-87-9	0.2[6]	IRIS RfD
Potassium borate	1332-77-0	0.2[6]	IRIS RfD

1. Reference compound: Zirconium (CASRN: 7440-67-7)

2. Reference compound: Nickel and nickel compounds (CASRN: 7440-02-0)

3. Reference compound: Aluminum (CASRN: 7429-90-5)

4. Reference compound: Fluoride (CASRN: 16984-48-8)

5. Reference compound: Barium and compounds (CASRN: 7440-39-3)

6. Reference compound: Boron and compounds (CASRN: 7440-42-8)

7. Reference compound: Nitrates/nitrites as nitrogen (CASRN: 14797-65-0; 14797-55-8)

8. Reference compound: Zinc and compounds (CASRN: 7440-66-6)

9. Reference compound: Phosphoric acid (CASRN: 7664-38-2)

Chemical Name	**CASRN**	**Chronic Oral Ref Value (RfV) (mg/kg/day)**	**Source**
Potassium metaborate	13709-94-9	0.2[6]	IRIS RfD
Sodium perborate tetrahydrate	10486-00-7	0.2[6]	IRIS RfD
Sodium tetraborate decahydrate	1303-96-4	0.2[6]	IRIS RfD
Magnesium nitrate	10377-60-3	0.28[7]	OEHHA PHG
Sodium nitrite	7632-00-0	0.28[7]	OEHHA PHG
Zinc	7440-66-6	0.3	IRIS RfD
Zinc chloride	7646-85-7	0.3[8]	IRIS RfD
Zinc sulfate	7733-02-0	0.3[8]	IRIS RfD
2-Propenoic acid, ammonium salt (1:1)	10604-69-0	0.5	IRIS RfD
Acrylic Acid	79-10-7	0.5	IRIS RfD
Benzenesulfonic acid, C10-16-alkyl derivs	68584-22-5	0.5	HHBP RfD
Dodecylbenzene sulfonic acid	27176-87-0	0.5	HHBP RfD
1-Methoxy-2-propanol	107-98-2	0.7	HEAST RfD
Iron	7439-89-6	0.7	PPRTV RfD
Acetone	67-64-1	0.9	IRIS RfD
Ethyl acetate	141-78-6	0.9	IRIS RfD
Formic acid	64-18-6	0.9	PPRTV RfD
Ethylene glycol	107-21-1	2	IRIS RfD
Isopropanol	67-63-0	2	PPRTV RfD
Methanol	67-56-1	2	IRIS RfD
Triethylene glycol	112-27-6	2	PPRTV RfD
Mineral Oil	8012-95-1	3	PPRTV RfD
Benzoic acid	65-85-0	4	IRIS RfD
Propylene glycol	57-55-6	20	PPRTV RfD
Phosphoric acid	7664-38-2	48.6	PPRTV RfD
Phosphoric acid salt	7632-05-5	48.6[9]	PPRTV RfD
Disodium pyrophosphate	7758-16-9	49	PPRTV RfD
Pentasodium tripolyphosphate	7758-29-4	49	PPRTV RfD
Sodium trimetaphosphate	7785-84-4	49	PPRTV RfD
Tetrasodium pyrophosphate	7722-88-5	49	PPRTV RfD

1. Reference compound: Zirconium (CASRN: 7440-67-7)

2. Reference compound: Nickel and nickel compounds (CASRN: 7440-02-0)

3. Reference compound: Aluminum (CASRN: 7429-90-5)

4. Reference compound: Fluoride (CASRN: 16984-48-8)

5. Reference compound: Barium and compounds (CASRN: 7440-39-3)

6. Reference compound: Boron and compounds (CASRN: 7440-42-8)

7. Reference compound: Nitrates/nitrites as nitrogen (CASRN: 14797-65-0; 14797-55-8)

8. Reference compound: Zinc and compounds (CASRN: 7440-66-6)

9. Reference compound: Phosphoric acid (CASRN: 7664-38-2)

Table A3.14. Chemical additives with available oral slope factors for all datasets.

Chemical Name	**CASRN**	**Oral Slope Factor (mg/kg/day)$^{-1}$**	**Source**
Acrylamide	79-06-1	4.5	OEHHA Slope Factor
Quinoline	91-22-5	3	IRIS Slope Factor
Arsenic	7440-38-2	1.5	OEHHA Slope Factor
Acrylonitrile	107-13-1	1	OEHHA Slope Factor
Bromic acid, sodium salt (1:1)	7789-38-0	0.49[1]	OEHHA Slope Factor
Ethylene oxide	75-21-8	0.31	OEHHA Slope Factor
Benzyl chloride	100-44-7	0.17	OEHHA Slope Factor
Furfuryl alcohol	98-00-0	0.131	HHBP Slope Factor
Naphthalene	91-20-3	0.12	OEHHA Slope Factor
Benzene	71-43-2	0.1	OEHHA Slope Factor
Hydroquinone	123-31-9	0.06	PPRTV Slope Factor
1,4-Dioxane	123-91-1	0.027	OEHHA Slope Factor
Formaldehyde	50-00-0	0.021	OEHHA Slope Factor
Ethylbenzene	100-41-4	0.011	OEHHA Slope Factor
Tributyl phosphate	126-73-8	0.009	PPRTV Slope Factor
Lead	7439-92-1	0.0085	OEHHA Slope Factor
Nitrilotriacetic acid	139-13-9	0.0053	OEHHA Slope Factor

1. Reference compound: Potassium bromate (CASRN: 7758-01-2)

Table A3.15. Chemical additives with available chronic inhalation toxicity data for all datasets.

Chemical Name	**CASRN**	**Chronic Inhalation Ref Value (RfV) (mg/m^3)**	**Source**
Beryllium	7440-41-7	0.000007	OEHHA REL
Nickel	7440-02-0	0.000014	OEHHA REL
Arsenic	7440-38-2	0.000015	OEHHA REL
Cadmium	7440-43-9	0.00002	OEHHA REL
Mercury	7439-97-6	0.00003	OEHHA REL
Glutaraldehyde	111-30-8	0.00008	OEHHA REL
Diethylene glycol mono-n-butyl ether	112-34-5	0.0001	PPRTV RfC
Antimony trioxide	1309-64-4	0.0002	IRIS RfC
Formic acid	64-18-6	0.0003	PPRTV Provisional RfC
Acrolein	107-02-8	0.00035	OEHHA REL
Sulfuric acid	7664-93-9	0.001	OEHHA REL
Benzyl chloride	100-44-7	0.001	PPRTV RfC
Acrylic Acid	79-10-7	0.001	IRIS RfC
Crystalline silica (cristobalite)	14464-46-1	0.003[1]	OEHHA REL
Crystalline silica (quartz)	14808-60-7	0.003	OEHHA REL
Diethanolamine	111-42-2	0.003	OEHHA REL

1. Reference compound: Crystalline silica (quartz) CASRN: 14808-60-7

Chemical Name	**CASRN**	**Chronic Inhalation Ref Value (RfV) (mg/m³)**	**Source**
Magnesium silicate hydrate (talc)	14807-96-6	0.003[1]	OEHHA REL
Mullite	1302-93-8	0.003[1]	OEHHA REL
Sepiolite	63800-37-3	0.003[1]	OEHHA REL
Bauxite	1318-16-7	0.003[1]	OEHHA REL
Kyanite	1302-76-7	0.003[1]	OEHHA REL
Benzene	71-43-2	0.003	OEHHA REL
Crystalline silica (tridymite)	15468-32-3	0.003[1]	OEHHA REL
Aluminum	7429-90-5	0.005	PPRTV RfC
Acrylonitrile	107-13-1	0.005	OEHHA REL
Acrylamide	79-06-1	0.006	IRIS RfC
Phosphoric acid	7664-38-2	0.007	OEHHA REL
Propionaldehyde	123-38-6	0.008	IRIS RfC
Ethyl acrylate	140-88-5	0.008	PPRTV RfC
Hydrochloric acid	7647-01-0	0.009	OEHHA REL
Naphthalene	91-20-3	0.009	OEHHA REL
Formaldehyde	50-00-0	0.009	OEHHA REL
Hydrofluoric acid	7664-39-3	0.014	OEHHA REL
Ethylene oxide	75-21-8	0.03	OEHHA REL
1,2,4-Trimethylbenzene	95-63-6	0.06	IRIS RfC
1,3,5-Trimethylbenzene	108-67-8	0.06	IRIS RfC
1,2,3-Trimethylbenzene	526-73-8	0.06	IRIS RfC
Ethyl acetate	141-78-6	0.07	PPRTV RfC
2-Butoxyethanol	111-76-2	0.082	OEHHA REL
Methyl Chloride	74-87-3	0.09	IRIS RfC
Solvent naphtha, petroleum, light arom.	64742-95-6	0.1	PPRTV RfC
Acetaldehyde	75-07-0	0.14	OEHHA REL
Toluene	108-88-3	0.3	OEHHA REL
Ethylene glycol	107-21-1	0.4	OEHHA REL
Cumene	98-82-8	0.4	IRIS RfC

1. Reference compound: Crystalline silica (quartz) CASRN: 14808-60-7

Table A3.16. Chemical additives with available inhalation unit risks for all datasets.

Chemical Name	**CASRN**	**Inhalation Unit Risk (μg/m³)⁻¹**	**Source**
Cadmium	7440-43-9	4.2 E-3	OEHHA Unit Risk
Arsenic	7440-38-2	3.3 E-3	OEHHA Unit Risk
Beryllium	7440-41-7	2.4 E-3	OEHHA Unit Risk
Acrylamide	79-06-1	1.3 E-3	OEHHA Unit Risk
Acrylonitrile	107-13-1	2.9 E-4	OEHHA Unit Risk

1. Reference compound: Potassium bromate CASRN: 7758-01-2

Chemical Name	**CASRN**	**Inhalation Unit Risk $(\mu g/m^3)^{-1}$**	**Source**
Nickel	7440-02-0	2.6 E-4	OEHHA Unit Risk
Bromic acid, sodium salt (1:1)	7789-38-0	1.4E-4[1]	OEHHA Unit Risk
Ethylene oxide	75-21-8	8.8 E-5	OEHHA Unit Risk
Benzyl chloride	100-44-7	4.9 E-5	OEHHA Unit Risk
Naphthalene	91-20-3	3.4 E-5	OEHHA Unit Risk
Benzene	71-43-2	2.9 E-5	OEHHA Unit Risk
Lead	7439-92-1	1.2 E-5	OEHHA Unit Risk
1,4-Dioxane	123-91-1	7.7 E-6	OEHHA Unit Risk
Formaldehyde	50-00-0	6.0 E-6	OEHHA Unit Risk
Acetaldehyde	75-07-0	2.7 E-6	OEHHA Unit Risk
Ethylbenzene	100-41-4	2.5 E-6	OEHHA Unit Risk
Nitrilotriacetic acid	139-13-9	1.5 E-6	OEHHA Unit Risk

1. Reference compound: Potassium bromate CASRN: 7758-01-2

Table A3.17. Chemical additives with available occupational exposure data for all datasets.

Chemical Name	**CASRN**	**Occupational Exposure Value (mg/m^3)**	**Source**
Beryllium	7440-41-7	0.0005	NIOSH REL
Arsenic	7440-38-2	0.002	NIOSH REL
Cadmium	7440-43-9	0.005	OSHA PEL
Nickel	7440-02-0	0.015	NIOSH REL
Nickel sulfate	7786-81-4	0.015[1]	NIOSH REL
Formaldehyde	50-00-0	0.019	NIOSH REL
Acrylamide	79-06-1	0.03	NIOSH REL
Crystalline silica (quartz)	14808-60-7	0.05	NIOSH REL
Mercury	7439-97-6	0.05	NIOSH REL
Lead	7439-92-1	0.1	NIOSH REL
Ethylene oxide	75-21-8	<0.18	NIOSH REL
Acrolein	107-02-8	0.25	NIOSH REL
Benzene	71-43-2	0.32	NIOSH REL
Barium	7440-39-3	0.5	NIOSH REL
Chromium	7440-47-3	0.5	NIOSH REL
Glutaraldehyde	111-30-8	0.8	NIOSH REL
Boron sodium oxide	1330-43-4	1	NIOSH REL
Copper	7440-50-8	1	NIOSH REL

1. Nickel compounds as Ni

2. Copper compounds as Cu

3. Reference compound: Phosphoric acid (CASRN:7664-38-2)

4. As respirable dust

5. Zirconium compounds as Zr

Chemical Name	**CASRN**	**Occupational Exposure Value (mg/m^3)**	**Source**
Copper dichloride	7447-39-4	1[2]	NIOSH REL
Copper sulfate pentahydrate	7758-99-8	1[2]	NIOSH REL
Iodine	7553-56-2	1	NIOSH REL
Phosphoric acid	7664-38-2	1	NIOSH REL
Phosphoric acid salt	7632-05-5	1[3]	NIOSH REL
Sulfuric acid	7664-93-9	1	NIOSH REL
Zinc chloride	7646-85-7	1	NIOSH REL
Hydrogen peroxide	7722-84-1	1.4	NIOSH REL
Calcium oxide	1305-78-8	2	NIOSH REL
Graphite	7782-42-5	2	ACGIH TLV
Hydroquinone	123-31-9	2	NIOSH REL
Magnesium silicate hydrate (talc)	14807-96-6	2	NIOSH REL
Potassium hydroxide	1310-58-3	2	NIOSH REL
Propargyl alcohol	107-19-7	2	NIOSH REL
Sodium hydroxide	1310-73-2	2	NIOSH REL
Acrylonitrile	107-13-1	2.17	NIOSH REL
Tributyl phosphate	126-73-8	2.2	ACGIH TLV
Hydrofluoric acid	7664-39-3	2.5	NIOSH REL
Mica	12001-26-2	3	NIOSH REL
1,4-Dioxane	123-91-1	3.6	NIOSH REL
Thioglycolic acid	68-11-1	4	NIOSH REL
Aluminum	7429-90-5	5[4]	NIOSH REL
Aluminum oxide	1344-28-1	5[4]	OSHA PEL
Barium sulfate	7727-43-7	5[4]	NIOSH REL
Benzyl chloride	100-44-7	5	NIOSH REL
Calcium hydroxide	1305-62-0	5[4]	OSHA PEL
Calcium sulfate	7778-18-9	5[4]	NIOSH REL
Cellulose, microcrystalline	9004-34-6	5[4]	NIOSH REL
Glycerol	56-81-5	5	NIOSH REL
Iron oxide	1309-37-1	5[4]	NIOSH REL
Limestone	1317-65-3	5[4]	NIOSH REL
Mineral Oil	8012-95-1	5	NIOSH REL
Phosphogypsum	13397-24-5	5[4]	NIOSH REL
Plaster of paris	26499-65-0	5[4]	NIOSH REL
Portland cement	65997-15-1	5[4]	NIOSH REL

1. Nickel compounds as Ni

2. Copper compounds as Cu

3. Reference compound: Phosphoric acid (CASRN:7664-38-2)

4. As respirable dust

5. Zirconium compounds as Zr

Chemical Name	**CASRN**	**Occupational Exposure Value (mg/m^3)**	**Source**
Sodium bisulfite	7631-90-5	5	NIOSH REL
Sodium tetraborate decahydrate	1303-96-4	5	NIOSH REL
Starch	9005-25-8	5[4]	NIOSH REL
Sulfur dioxide	7446-09-5	5	NIOSH REL
Tetrasodium pyrophosphate	7722-88-5	5	NIOSH REL
Triethanolamine	102-71-6	5	ACGIH TLV
Triethanolamine zirconate	101033-44-7	5[5]	NIOSH REL
Zirconium dichloride oxide	7699-43-6	5[5]	NIOSH REL
Acrylic Acid	79-10-7	6	NIOSH REL
Monoethanolamine	141-43-5	6	OSHA PEL
Non-crystalline silica (impurity)	7631-86-9	6	NIOSH REL
Hydrochloric acid	7647-01-0	7	NIOSH REL
Formic acid	64-18-6	9	NIOSH REL
Ammonium chloride	12125-02-9	10	NIOSH REL
Boron oxide	1303-86-2	10	NIOSH REL
Magnesium oxide	1309-48-4	10	ACGIH TLV
Titanium oxide	13463-67-7	10	ACGIH TLV
Diethanolamine	111-42-2	15	NIOSH REL
Formamide	75-12-7	15	NIOSH REL
Acetic anhydride	108-24-7	20	NIOSH REL
Ethyl acrylate	140-88-5	20	ACGIH TLV
2-Butoxyethanol	111-76-2	24	NIOSH REL
1,3,5-Trimethylbenzene	108-67-8	25	NIOSH REL
Acetic acid	64-19-7	25	NIOSH REL
Butyl lactate	138-22-7	25	NIOSH REL
Ethylenediamine	107-15-3	25	NIOSH REL
Butyl glycidyl ether	2426-08-6	30	NIOSH REL
Cyclohexylamine	108-91-8	40	NIOSH REL
Furfuryl alcohol	98-00-0	40	NIOSH REL
Acetaldehyde	75-07-0	45	ACGIH TLV
Naphthalene	91-20-3	50	NIOSH REL
Morpholine	110-91-8	70	NIOSH REL
Isobutylmethylcarbinol	108-11-2	100	NIOSH REL
Kerosene	8008-20-6	100	NIOSH REL
Methyl Chloride	74-87-3	105	ACGIH TLV

1. Nickel compounds as Ni

2. Copper compounds as Cu

3. Reference compound: Phosphoric acid (CASRN:7664-38-2)

4. As respirable dust

5. Zirconium compounds as Zr

Chemical Name	**CASRN**	**Occupational Exposure Value (mg/m³)**	**Source**
1,2,3-Trimethylbenzene	526-73-8	125	NIOSH REL
1,2,4-Trimethylbenzene	95-63-6	125	NIOSH REL
Hexylene glycol	107-41-5	125	NIOSH REL
Ethylene glycol	107-21-1	127	NIOSH REL
n-Butyl alcohol	71-36-3	150	NIOSH REL
Toluene	108-88-3	188	ACGIH TLV
Cyclohexanol	108-93-0	200	NIOSH REL
Methyl isobutyl ketone	108-10-1	205	NIOSH REL
Cumene	98-82-8	245	NIOSH REL
Methanol	67-56-1	260	NIOSH REL
Stoddard solvents	8052-41-3	350	NIOSH REL
1-Methoxy-2-propanol	107-98-2	360	NIOSH REL
Ethylbenzene	100-41-4	435	NIOSH REL
n-Propanol	71-23-8	500	NIOSH REL
Acetone	67-64-1	590	NIOSH REL
Dipropylene glycol monomethyl ether	34590-94-8	600	NIOSH REL
Isopropanol	67-63-0	980	NIOSH REL
Ethyl acetate	141-78-6	1,400	NIOSH REL
Petroleum distillate-mineral oil grade	8002-05-9	1,400	NIOSH REL
Ethanol	64-17-5	1,900	NIOSH REL
Carbon dioxide	124-38-9	9,000	NIOSH REL

1. Nickel compounds as Ni

2. Copper compounds as Cu

3. Reference compound: Phosphoric acid (CASRN:7664-38-2)

4. As respirable dust

5. Zirconium compounds as Zr

Table A3.18. Chemical additives classified as not readily biodegradable for all datasets.

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
1,2,3-Trimethylbenzene	526-73-8	Distillates (petroleum), solvent-dewaxed heavy paraffinic	64742-65-0
1,2,4,5-Tetrabromobenzene	636-28-2	Ethanesulfonic acid, 2-[methyl[(9z)-1-oxo-9-octadecen-1-yl]amino]-, sodium salt (1:1)	137-20-2
1,2-benzisothiazolin-3-one	2634-33-5	Ethanol, 2-amino-, phosphate	29868-05-1
1,2-Diiodobenzene	615-42-9	Ethanol,2,2'-oxybis-,reactionproductswithammonia,morpholinederivs. residues	68909-77-3
1,3,5-Tribromobenzene	626-39-1	Ethoxylated alcohol C11-14	78330-21-9
1,4-Dibromobenzene	106-37-6	Ethoxylated alcohol C7-9-iso, C8	78330-19-5

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
1,4-Dioxane	123-91-1	Etidronic acid	2809-21-4
1-bromo-3,5-dichlorobenzene	19752-55-7	Fatty acids, C18-unsatd., dimers	61788-89-4
1-Bromo-4-iodobenzene	589-87-7	Fatty acids, C18-unsatd., dimers, ethoxylated propoxylated	68308-89-4
1-Chloro-4-iodobenzene	637-87-6	Fatty acids, tall-oil, monoesters with sorbitan, ethoxylated	61790-86-1
1-Iodonaphthalene	90-14-2	Fatty acids, tall-oil, reaction products with diethylenetriamine, acetates	68153-60-6
2-Propenoic acid, ammonium salt (1:1)	10604-69-0	Fulvic acid	479-66-3
2,2 Dibromo-3-nitrilopropionamide	10222-01-2	Heavy aromatic naphtha	64742-94-5
2,4,6-Tribromotoluene	6320-40-7	Hydrotreated Light Petroleum Distillate	64742-47-8
2,4-Dibromomesitylene	6942-99-0	Isoquinoline	119-65-3
2,5-Dibromothiophene	3141-27-3	Lecithins	8002-43-5
2-Bromonaphthalene	580-13-2	Naphtha (petroleum), heavy catalytic reformed	64741-68-0
2-Iodobiphenyl	2113-51-1	Naphthalenesulfonic acid, bis(1-methylethyl)-, compd. with cyclohexanamine (1:1)	68425-61-6
2-Methyl-3(2H)-isothiazolone	2682-20-4	n-Beta-(aminoethyl)-gamma-aminopropyl trimethoxysilane	1760-24-3
2-Methyl-3-butyn-2-ol	115-19-5	Nitrilotris (methylene phosphonic acid)	6419-19-8
3,5-Dibromotoluene	1611-92-3	Nonoxynols	26027-38-3
3-aminopropyl (sileanetriol)	58160-99-9	Nonylphenol polyethylene glycol ether	127087-87-0
4,4`-Diaminodiphenyl sulfone	80-08-0	Octamethylcyclotetrasiloxane	556-67-2
4-Iodotoluene	624-31-7	Pentasodium diethylenetriamine pentaacetate	140-01-2
9-Bromophenanthrene	573-17-1	Petroleum distillates	68990-35-2
Alcohols, C6-12, ethoxylated propoxylated	68937-66-6	Phosphonic acid	13598-36-2
Alcohols, C9-11-iso-, C10-rich, ethoxylated	78330-20-8	Phosphonic acid, P,P',P'',P'''-(((phosphonomethyl)imino)bis(2,1-ethanediylnitrilobis(methylene))) tetrakis-, ammonium salt (1:?)	70714-66-8
Amaranth	915-67-3	Pine oil	8002-09-3
Amides, coco, N-(3-(dimethylamino) propyl)-	68140-01-2	Poly ethylene glycol tridecyl ether phosphate	9046-01-9
Amines, dicoco alkylmethyl	61788-62-3	Poly(oxy-1,2-ethanediyl), α[(9Z)-1-oxo-9-octadecen-1-yl]-αhydroxy-	9004-96-0
Amines, dimethyl soya alkyl	61788-91-8	Poly(oxy-1,2-ethanediyl), alpha-tridecyl-omega-hydroxy	24938-91-8
Aminoethyl sulfate	926-39-6	Polydimethyl diallyl ammonium chloride	26062-79-3

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Ammonium benzoate	1863-63-4	Polyethylene glycol monostearate	9004-99-3
Ampicillin	69-53-4	Polyethylene glycol soya amine	61791-24-0
Benzalkonium chloride	8001-54-5	Polyethylene glycol tallow amine	61791-26-2
Benzene, c10-c16 alkyl derivatives	68648-87-3	Polyglycol ether	9038-95-3
Benzene, tetrapropylene-	25265-78-5	Polyoxyethylene dinonylphenol	9014-93-1
Benzenesulfonic acid, 4-methyl-, potassium salt	16106-44-8	Polyoxyethylene isodecyl ether	61827-42-7
Benzenesulfonic acid, C10-16-alkyl derivs	68584-22-5	Polypropylene	9003-07-0
Benzenesulfonic acid, c10-16-alkyl derivs., compds. with 2-propanamine	68584-24-7	Polypropylene glycol	25322-69-4
Benzenesulfonic acid, C10-16-alkyl derivs., compds. with cyclohexylamine	255043-08-4	Polysorbate 40	9005-66-7
Benzenesulfonic acid, c10-16-alkyl derivs., compds. with triethanolamine	68584-25-8	Polysorbate 85	9005-70-3
Benzenesulfonic acid, C10-16-alkyl derivs., potassium salts	68584-27-0	Pontacyl carmine 2B	6625-46-3
Benzenesulfonic acid, dodecyl-, branched	68411-32-5	Prolonium chloride	55636-09-4
Benzenesulfonic acid, dodecyl-, branched, compds. with 2-propanamine	90218-35-2	Quaternary ammonium chloride, benzylcoco alkyldimethyl, chlorides	61789-71-7
Benzenesulfonic acid, mono-C10-16-alkyl derivs., ammonium salts	68910-31-6	Quaternary ammonium compound	100765-57-9
Benzododecinium chloride	139-07-1	Quinaldine	91-63-4
Bis(isopropyl)naphthalene	38640-62-9	Quinoline	91-22-5
Butyl glycidyl ether	2426-08-6	Siloxanes and Silicones, di-Me, 3-hydroxypropyl Me, ethoxylated propoxylated	68937-55-3
C13-16 Isoparaffin	68551-20-2	Siloxanes and silicones, dimethyl,	63148-52-7
Calcite	13397-26-7	Siloxanes and silicones, dimethyl, reaction products with silica	67762-90-7
Calcium lignosulfonate	8061-52-7	Sodium aminotris(methylenephosphonate)	20592-85-2
Cetethyl morpholinium	78-21-7	Sodium dichloroisocyanurate	2893-78-9
Cobaltous acetate	71-48-7	Sodium dodecylpoly(oxyethylene) sulfate	9004-82-4
Cyclohexamine sulfate	19834-02-7	Sodium erythorbate	6381-77-7
Cyclohexasiloxane, 2,2,4,4,6,6,8,8,10,10,12,12-dodecamethyl-	540-97-6	Sodium lignosulfonate	8061-51-6
Cyclopentasiloxane, 2,2,4,4,6,6,8,8,10,10-decamethyl-	541-02-6	Sulferized polyolefin	68037-13-8
Cymene	25155-15-1	Sulfonic acids, alkane, sodium salts	68608-15-1

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Diethylenetriamine, propoxylated, ethoxylated	68910-19-0	tert-Butyl hydroperoxide	75-91-2
Diethylenetriaminepenta(methylene phosphonic) acid	15827-60-8	Tetrahydro-3,5-dimethyl-1,3,5-thiadiazine-2-thione	533-74-4
Diisopropylnaphthalenesulfonic acid	28757-00-8	Triethanolamine zirconate	101033-44-7
Dimethyl siloxanes and silicones	63148-62-9	Trimethylbenzenes	25551-13-7
Disodium ethylene diamine tetra acetate (impurity)	139-33-3	Xylenesulfonic acid	25321-41-9

Table A3.19. Chemical additives recognized as carcinogenic or possibly carcinogenic by IARC, CA Prop 65, and National Toxicity Program for all datasets.

Chemical Name	**CASRN**	**IARC Group**	**National Toxicity Program**	**Prop 65 List**
Arsenic	7440-38-2	1	Known carcinogen	X
Benzene	71-43-2	1	Known carcinogen	X
Beryllium	7440-41-7	1	Known carcinogen	X
Cadmium	7440-43-9	1	Known carcinogen	X
Crystalline silica (cristobalite)	14464-46-1	1	Known carcinogen[1]	X[1]
Crystalline silica (quartz)	14808-60-7	1	Known carcinogen[1]	X[1]
Ethanol	64-17-5	1[2]	Known carcinogen	X
Ethylene oxide	75-21-8	1	Known carcinogen	X
Formaldehyde	50-00-0	1	Known carcinogen	X
Hydrochloric acid	7647-01-0	1[3]	NL[4]	NL
Nickel sulfate	7786-81-4	1[5]	Known carcinogen[5]	X[5]
Sulfuric acid	7664-93-9	1[3]	Known carcinogen[6]	X[6]
Xenon 133, radionuclide	14932-42-4	1[7]	Known carcinogen[7]	X[7]
Acrylamide	79-06-1	2A	RAHC[8]	X
Benzyl chloride	100-44-7	2A	NL	X
Magnesium nitrate	10377-60-3	2A[9]	NL	NL
Sodium nitrite	7632-00-0	2A[9]	NL	NL
1,4-Dioxane	123-91-1	2B	RAHC	X

1. Listed as silica, crystalline (airborne particles of respirable size)

2. Listed as alcoholic beverages

3. Listed as acid mists, strong inorganic

4. NL – Not listed

5. Listed as nickel compounds (nickel compounds are Class 1, metallic nickel is Class 2B)

6. Listed as strong inorganic acid mists containing sulfuric acid

7. Listed as radionuclides

8. RAHC - Reasonably anticipated to be a human carcinogen

9. Listed as nitrate or nitrite under conditions that result in endogenous nitrosation

10. Listed as cobalt sulfate and other soluble cobalt (II) salts

11. Listed for developmental toxicity

Chemical Name	**CASRN**	**IARC Group**	**National Toxicity Program**	**Prop 65 List**
Acetaldehyde	75-07-0	2B	RAHC	X
Acrylonitrile	107-13-1	2B	RAHC	X
Antimony trioxide	1309-64-4	2B	NL	X
Attapulgite, activated	12174-11-7	2B	RAHC	X
Bis(isopropyl)naphthalene	38640-62-9	2B	NL	NL
Cobaltous acetate	71-48-7	2B[10]	NL	NL
Coconut diethanolamide	68603-42-9	2B	RAHC	X
Cumene	98-82-8	2B	RAHC	X
Diethanolamine	111-42-2	2B	NL	X
Ethyl acrylate	140-88-5	2B	NL	X
Ethylbenzene	100-41-4	2B	NL	X
Furfuryl alcohol	98-00-0	2B	NL	X
Gilsonite	12002-43-6	2B	NL	NL
Lead	7439-92-1	2B	RAHC	X
Methyl isobutyl ketone	108-10-1	2B	NL	X
Naphthalene	91-20-3	2B	RAHC	X
Nickel	7440-02-0	2B	RAHC	X
Nitrilotriacetic acid	139-13-9	2B	RAHC	X
Chromium	7440-47-3	3	NL	X
Methyl chloride (chloromethane)	74-87-3	3	NL	X[11]
Mercury	7439-97-6	3	NL	X[11]
Sulfur dioxide	7446-09-5	3	NL	X[11]
Toluene	108-88-3	3	NL	X[11]
Crystalline silica (tridymite)	15468-32-3	NL	Known carcinogen[1]	X[1]
Ethylene glycol	107-21-1	NL	NL	X[11]
Lithium carbonate	554-13-2	NL	NL	X[11]
Methanol	67-56-1	NL	NL	X[11]
Nitrilotriacetic acid	139-13-9	NL	RAHC	X

1. Listed as silica, crystalline (airborne particles of respirable size)

2. Listed as alcoholic beverages

3. Listed as acid mists, strong inorganic

4. NL – Not listed

5. Listed as nickel compounds (nickel compounds are Class 1, metallic nickel is Class 2B)

6. Listed as strong inorganic acid mists containing sulfuric acid

7. Listed as radionuclides

8. RAHC - Reasonably anticipated to be a human carcinogen

9. Listed as nitrate or nitrite under conditions that result in endogenous nitrosation

10. Listed as cobalt sulfate and other soluble cobalt (II) salts

11. Listed for developmental toxicity

Table A3.20. Chemical additives identified as toxic air contaminants by the Clean Air Act and CARB for all datasets.

Chemical Name	CASRN	Clean Air Act Hazardous Air Pollutant	CARB Hot Spots Program	California Air Resources Board TAC Category
1,4-Dioxane	123-91-1	X	X	2a
1-Iodonaphthalene	90-14-2	X[1]	X[1]	2a[1]
2,2''-oxydiethanol (impurity)	111-46-6	X[2]	X[2]	2a[2]
2-Bromonaphthalene	580-13-2	X[1]	X[1]	2a[1]
2-Butoxyethanol	111-76-2	[3]	X	2a
2-iodobiphenyl	2113-51-1	X[4]	X[1]	2a[1]
4-chlorobenzophenone	134-85-0	X[4]	X[1]	2a[1]
9-Bromophenanthrene	573-17-1	X[1]	X[1]	2a[1]
Acetaldehyde	75-07-0	X	X	2a
Acrolein	107-02-8	X	X	2a
Acrylamide	79-06-1	X	X	2a
Acrylic Acid	79-10-7	X	X	2a
Acrylonitrile	107-13-1	X	X	2a
Amaranth	915-67-3	X[5]	X[5]	2a[5]
Antimony trioxide	1309-64-4	X[6]	X[6]	2a[6]
Arsenic	7440-38-2	X	X	2a
Benzene	71-43-2	X	X	2a
Benzyl chloride	100-44-7	X	X	2a
Beryllium	7440-41-7	X	X	2a
Bis(isopropyl)naphthalene	38640-62-9	X[1]	X[1]	2a[1]
Cadmium	7440-43-9	X	X	2a
Chromium	7440-47-3	X	X	2a
Cobaltous acetate	71-48-7	X[7]	X[7]	2a[7]
Diethanolamine	111-42-2	X	X	2a
Diethylene glycol mono-n-butyl ether	112-34-5	X[2]	X[2]	2a[2]
Diisopropylnaphthalenesulfonic acid	28757-00-8	X[5]	X[5]	2a[5]

1. Listed as polycyclic organic matter (POM)

2. Listed as glycol ethers

3. 2-butoxyethanol was removed from the list of hazardous air pollutants in November, 2004

4. Meets CFR definition of POM, but not U.S. EPA definition of POM

5. Listed as polycyclic organic matter (POM), boiling point estimated using U.S. EPA EPISuite™ MPBPWIN™ module

6. Listed as antimony compounds

7. Listed as cobalt compounds

8. Listed as nickel compounds

9. Listed as copper compounds

Chemical Name	**CASRN**	**Clean Air Act Hazardous Air Pollutant**	**CARB Hot Spots Program**	**California Air Resources Board TAC Category**
Ethylbenzene	100-41-4	X	X	2a
Ethylene glycol	107-21-1	X	X	2a
Ethylene oxide	75-21-8	X	X	2a
Food red 10	3734-67-6	X[5]	X[5]	2a[5]
Formaldehyde	50-00-0	X	X	2a
Hydrochloric acid	7647-01-0	X	X	2a
Hydrofluoric acid	7664-39-3	X	X	2a
Lead	7439-92-1	X	X	2a
Mercury	7439-97-6	X	X	2a
Methanol	67-56-1	X	X	2a
Naphthalene	91-20-3	X	X	2a
Naphthalenesulfonic acid, bis(1-methylethyl)-, compd. With cyclohexanamine (1:1)	68425-61-6	X[5]	X[5]	2a[5]
Nickel	7440-02-0	X	X	2a
Nickel sulfate	7786-81-4	X[8]	X[8]	2a[8]
Pontacyl carmine 2B	6625-46-3	X[5]	X[5]	2a[5]
Toluene	108-88-3	X	X	2a
Xylenes	1330-20-7	X	X	2a
Copper	7440-50-8		X	2b
Copper dichloride	7447-39-4		X[9]	2b[9]
Copper sulfate pentahydrate	7758-99-8		X[9]	2b[9]
Glutaraldehyde	111-30-8		X	2b
Isopropanol	67-63-0		X	2b
Phosphoric acid	7664-38-2		X	2b
Sodium hydroxide	1310-73-2		X	2b
Sulfuric acid	7664-93-9		X	2b
Zinc	7440-66-6		X	2b
Non-crystalline silica (impurity)	7631-86-9			3
Acetophenone	98-86-2	X	X	4a
Cumene	98-82-8	X	X	4a

1. Listed as polycyclic organic matter (POM)

2. Listed as glycol ethers

3. 2-butoxyethanol was removed from the list of hazardous air pollutants in November, 2004

4. Meets CFR definition of POM, but not U.S. EPA definition of POM

5. Listed as polycyclic organic matter (POM), boiling point estimated using U.S. EPA EPISuite™ MPBPWIN™ module

6. Listed as antimony compounds

7. Listed as cobalt compounds

8. Listed as nickel compounds

9. Listed as copper compounds

Chemical Name	**CASRN**	**Clean Air Act Hazardous Air Pollutant**	**CARB Hot Spots Program**	**California Air Resources Board TAC Category**
Ethyl acrylate	140-88-5	X	X	4a
Hydroquinone	123-31-9	X	X	4a
Methyl chloride (chloromethane)	74-87-3	X	X	4a
Methyl isobutyl ketone	108-10-1	X	X	4a
Propionaldehyde	123-38-6	X	X	4a
Xenon 133, radionuclide	14932-42-4	X	X	4a
1,2,4-Trimethylbenzene	95-63-6		X	4b
Aluminum	7429-90-5		X	4b
Aluminum oxide	1344-28-1		X	4b
Ammonium sulfate	7783-20-2		X	4b
Barium	7440-39-3		X	4b
n-Butyl alcohol	71-36-3		X	4b
Nitrilotriacetic acid	139-13-9		X	4b
Peracetic acid	79-21-0		X	4b
Quinoline	91-22-5	X	X	5
1-Methoxy-2-propanol	107-98-2		X	
Cyclohexanol	108-93-0		X	
Dipropylene glycol monomethyl ether	34590-94-8		X	
Tributyl phosphate	126-73-8		X	
Trimethylbenzenes	25551-13-7		X	

1. Listed as polycyclic organic matter (POM)

2. Listed as glycol ethers

3. 2-butoxyethanol was removed from the list of hazardous air pollutants in November, 2004

4. Meets CFR definition of POM, but not U.S. EPA definition of POM

5. Listed as polycyclic organic matter (POM), boiling point estimated using U.S. EPA EPISuite™ MPBPWIN™ module

6. Listed as antimony compounds

7. Listed as cobalt compounds

8. Listed as nickel compounds

9. Listed as copper compounds

Table A3.21. Chemical additives on OSPARs Pose Little or No Risk (PLONOR) to the Environment List for all datasets.

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Acetic acid	64-19-7	Lignin	9005-53-2
Aluminum oxide silicate	12141-46-7	Limestone	1317-65-3
Ammonium bisulfate	10192-30-0	Magnesium chloride	7786-30-3
Ammonium chloride	12125-02-9	Magnesium oxide	1309-48-4
Ammonium hydroxide	1336-21-6	Methanol	67-56-1
Attapulgite, activated	12174-11-7	Mica	12001-26-2
Barite	7727-43-7	n-Butyl alcohol	71-36-3
Barite	13462-86-7	Non-crystalline silica (impurity)	7631-86-9
Bentonite	1302-78-9	n-Propanol	71-23-8
Calcium bromide	7789-41-5	Pentasodium tripolyphosphate	7758-29-4
Calcium carbonate	471-34-1	Phosphoric acid salt	7632-05-5
Calcium chloride	10043-52-4	Portland cement	65997-15-1
Calcium hydroxide	1305-62-0	Potassium bicarbonate	298-14-6
Calcium lignosulfonate	8061-52-7	Potassium carbonate	584-08-7
Calcium oxide	1305-78-8	Potassium chloride	7447-40-7
Calcium sulfate	7778-18-9	Potassium formate	590-29-4
Carbon	7440-44-0	Potassium iodide	7681-11-0
Cellulose, microcrystalline	9004-34-6	Smectite	1318-93-0
Citric acid	77-92-9	Sodium acetate	127-09-3
Crystalline silica (quartz)	14808-60-7	Sodium benzoate	532-32-1
D-glucitol	50-70-4	Sodium bicarbonate	144-55-8
Diatomaceous earth, calcined	91053-39-3	Sodium bisulfite	7631-90-5
Diatomaceous earth, natural (kieselguhr)	61790-53-2	Sodium carbonate	497-19-8
Disodium metasilicate	6834-92-0	Sodium carboxymethylcellulose	9004-32-4
Disodium pyrophosphate	7758-16-9	Sodium chloride	7647-14-5
Erythorbic acid	89-65-6	Sodium formate	141-53-7
Ethanol	64-17-5	Sodium lignosulfonate	8061-51-6
Ethylene glycol	107-21-1	Sodium nitrite	7632-00-0
Formic acid	64-18-6	Sodium silicate	1344-09-8
Glycerol	56-81-5	Sodium sulfate	7757-82-6
Graphite	7782-42-5	Sodium sulfite	7757-83-7
Guar gum	9000-30-0	Sodium thiosulfate	7772-98-7
Hematite	1317-60-8	Sodium trimetaphosphate	7785-84-4
Hemicellulase enzyme	9012-54-8	Starch	9005-25-8
Hydroxyethyl cellulose	9004-62-0	Tetrasodium pyrophosphate	7722-88-5
Iron oxide	1309-37-1	Tricalcium phosphate	7758-87-4
Isopropanol	67-63-0	Urea	57-13-6
Lactose	63-42-3	Xanthan gum	11138-66-2
Lecithins	8002-43-5		

Table A3.22. Chemical additives identified by The Endocrine Disruption Exchange (TEDX) as potential endocrine disrupting compounds for all datasets.

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
2,2 Dibromo-3-nitrilopropionamide	10222-01-2	Kerosene	8008-20-6
2,2''-oxydiethanol (impurity)	111-46-6	Lead	7439-92-1
2-Butoxyethanol	111-76-2	Lithium chloride	7447-41-8
2-Ethylhexan-1-ol	104-76-7	Lithium hydroxide	1310-65-2
2-Methyl-3(2H)-isothiazolone	2682-20-4	Magnesium chloride	7786-30-3
Acetaldehyde	75-07-0	Mercury	7439-97-6
Acetone	67-64-1	Methanol	67-56-1
Aluminum	7429-90-5	Methyl salicylate	119-36-8
Ammonium chloride	12125-02-9	Naphthalene	91-20-3
Ammonium sulfate	7783-20-2	Nickel sulfate	7786-81-4
Arsenic	7440-38-2	Octamethylcyclotetrasiloxane	556-67-2
Barium	7440-39-3	Oleic acid	112-80-1
Benzaldehyde	100-52-7	Petroleum distillate-mineral oil grade	8002-05-9
Benzene	71-43-2	Poly(oxy-1,2-ethandiyl), a-(nonylphenyl)-w-hydroxy-	9016-45-9
Benzoic acid	65-85-0	Poly(oxy-1,2-ethanediyl), alpha-(nonylphenyl)-omega-hydroxy-, branched	68412-54-4
Benzyl chloride	100-44-7	Portland cement	65997-15-1
Boric acid	10043-35-3	Potassium chloride	7447-40-7
Bromic acid, sodium salt (1:1)	7789-38-0	Propargyl alcohol	107-19-7
Cadmium	7440-43-9	Propionaldehyde	123-38-6
Chlorous acid,sodium salt	7758-19-2	Propylene glycol	57-55-6
Chromium	7440-47-3	Quinoline	91-22-5
Cinnamaldehyde	104-55-2	Sodium bicarbonate	144-55-8
Copper dichloride	7447-39-4	Sodium nitrite	7632-00-0
Cottonseed, flour	68308-87-2	Sodium silicate	1344-09-8
Cumene	98-82-8	Sodium tetraborate decahydrate	1303-96-4
Cyclopentasiloxane, 2,2,4,4,6,6,8,8,10,10-decamethyl-	541-02-6	Solvent naphtha, petroleum, light arom.	64742-95-6
Diethanolamine	111-42-2	Sorbitan monooleate, ethoxylated	9005-65-6
Diethylene glycol mono-n-butyl ether	112-34-5	Stearic acid	57-11-4
Ethanol	64-17-5	Sulfur dioxide	7446-09-5
Ethylbenzene	100-41-4	Tetrakis hydroxymethyl phosphonium sulfate	55566-30-8
Ethylene glycol	107-21-1	Thioglycolic acid	68-11-1
Ethylene oxide	75-21-8	Titanium oxide	13463-67-7
Formaldehyde	50-00-0	Toluene	108-88-3
Formamide	75-12-7	Tributyl phosphate	126-73-8

Chemical Name	**CASRN**	**Chemical Name**	**CASRN**
Glutaraldehyde	111-30-8	Triethanolamine	102-71-6
Humic acids	1415-93-6	Triethylene glycol	112-27-6
Hydroquinone	123-31-9	Xylenes	1330-20-7
Hydroxyethyl cellulose	9004-62-0	Zinc	7440-66-6
Iron	7439-89-6	Zinc chloride	7646-85-7
Isoquinoline	119-65-3		

Table A3.23. Chemical additives recognized as carcinogenic or possibly carcinogenic by IARC, CA Prop 65, and National Toxicity Program that are used in oil fields that send produced water for irrigation of food crops.

Chemical Name	**CASRN**	**IARC Group**	**National Toxicity Program**	**Prop 65 List**
Benzene	71-43-2	1	Known carcinogen	X
Beryllium	7440-41-7	1	Known carcinogen	X
Cadmium	7440-43-9	1	Known carcinogen	X
Crystalline silica (cristobalite)	14464-46-1	1	Known carcinogen[1]	X[1]
Crystalline silica (quartz)	14808-60-7	1	Known carcinogen[1]	X[1]
Ethanol	64-17-5	1[2]	Known carcinogen	X
Formaldehyde	50-00-0	1	Known carcinogen	X
Hydrochloric acid	7647-01-0	1[3]	NL[4]	NL
Nickel sulfate	7786-81-4	1[5]	Known carcinogen[5]	X[5]
Sulfuric acid	7664-93-9	1[3]	Known carcinogen[6]	X[6]
Xenon 133, radionuclide	14932-42-4	1[7]	Known carcinogen[7]	X[7]
Acrylamide	79-06-1	2A	RAHC[8]	X
Benzyl chloride	100-44-7	2A	NL	X
1,4-Dioxane	123-91-1	2B	RAHC	X
Acetaldehyde	75-07-0	2B	RAHC	X
Antimony trioxide	1309-64-4	2B	NL	X
Coconut diethanolamide	68603-42-9	2B	RAHC	X
Cumene	98-82-8	2B	RAHC	X
Diethanolamine	111-42-2	2B	NL	X
Ethyl acrylate	140-88-5	2B	NL	X

1. Listed as silica, crystalline (airborne particles of respirable size)

2. Listed as alcoholic beverages

3. Listed as acid mists, strong inorganic

4. NL – Not listed

5. Listed as nickel compounds (nickel compounds are Class 1, metallic nickel is Class 2B)

6. Listed as strong inorganic acid mists containing sulfuric acid

7. Listed as radionuclides

8. RAHC – Reasonably anticipated to be a human carcinogen

9. Listed for developmental toxicity

Chemical Name	CASRN	IARC Group	National Toxicity Program	Prop 65 List
Ethylbenzene	100-41-4	2B	NL	X
Furfuryl alcohol	98-00-0	2B	NL	X
Lead	7439-92-1	2B	RAHC	X
Naphthalene	91-20-3	2B	RAHC	X
Nickel	7440-02-0	2B	RAHC	X
Nitrilotriacetic acid	139-13-9	2B	RAHC	X
Chromium	7440-47-3	3	NL	X
Mercury	7439-97-6	3	NL	X[9]
Methyl chloride (chloromethane)	74-87-3	3	NL	X[9]
Sulfur dioxide	7446-09-5	3	NL	X[9]
Toluene	108-88-3	3	NL	X[9]
Crystalline silica (tridymite)	15468-32-3	NL	Known carcinogen[1]	X[1]
Ethylene glycol	107-21-1	NL	NL	X[9]
Lithium carbonate	554-13-2	NL	NL	X[9]
Methanol	67-56-1	NL	NL	X[9]
Nitrilotriacetic acid	139-13-9	NL	RAHC	X

1. Listed as silica, crystalline (airborne particles of respirable size)

2. Listed as alcoholic beverages

3. Listed as acid mists, strong inorganic

4. NL – Not listed

5. Listed as nickel compounds (nickel compounds are Class 1, metallic nickel is Class 2B)

6. Listed as strong inorganic acid mists containing sulfuric acid

7. Listed as radionuclides

8. RAHC – Reasonably anticipated to be a human carcinogen

9. Listed for developmental toxicity

Table A3.24. Chemical additives identified as toxic air contaminants by the Clean Air Act and CARB that are used in oil fields that send produced water for irrigation of food crops.

Chemical Name	CASRN	Clean Air Act Hazardous Air Pollutant	California Air Resources Board Hot Spots Program	California Air Resources Board TAC Category	Henry's Law Constant (atm m^3/ mol)
1,4-Dioxane	123-91-1	X	X	2a	4.80E-06
2-Butoxyethanol	111-76-2	[1]	X	2a	1.60E-06
Acetaldehyde	75-07-0	X	X	2a	1.67E-07
Acrolein	107-02-8	X	X	2a	1.22E-04

1. 2-butoxyethanol was removed from the list of hazardous air pollutants in November, 2004

2. Listed as antimony compounds

3. Listed as nickel compounds

4. Listed as copper compounds

5. NA = Not available

Chemical Name	CASRN	Clean Air Act Hazardous Air Pollutant	California Air Resources Board Hot Spots Program	California Air Resources Board TAC Category	Henry's Law Constant (atm m^3/mol)
Acrylamide	79-06-1	X	X	2a	1.70E-09
Acrylic Acid	79-10-7	X	X	2a	3.70E-07
Antimony trioxide	1309-64-4	X[2]	X[2]	2a[2]	NA5
Benzene	71-43-2	X	X	2a	5.55E-03
Benzyl chloride	100-44-7	X	X	2a	4.12E-04
Beryllium	7440-41-7	X	X	2a	NA
Cadmium	7440-43-9	X	X	2a	NA
Chromium	7440-47-3	X	X	2a	NA
Diethanolamine	111-42-2	X	X	2a	3.90E-11
Ethylbenzene	100-41-4	X	X	2a	7.88E-03
Ethylene glycol	107-21-1	X	X	2a	6.00E-08
Formaldehyde	50-00-0	X	X	2a	3.37E-07
Hydrochloric acid	7647-01-0	X	X	2a	4.98E-10
Hydrofluoric acid	7664-39-3	X	X	2a	1.04E-04
Lead	7439-92-1	X	X	2a	NA
Mercury	7439-97-6	X	X	2a	NA
Methanol	67-56-1	X	X	2a	4.55E-06
Naphthalene	91-20-3	X	X	2a	4.40E-04
Nickel	7440-02-0	X	X	2a	NA
Nickel sulfate	7786-81-4	X[3]	X[3]	2a[3]	NA
Toluene	108-88-3	X	X	2a	6.40E-03
Xylenes	1330-20-7	X	X	2a	5.18E-03
Copper	7440-50-8		X	2b	NA
Copper sulfate pentahydrate	7758-99-8		X[4]	2b[4]	NA
Glutaraldehyde	111-30-8		X	2b	2.40E-08
Isopropanol	67-63-0		X	2b	8.10E-06
Phosphoric acid	7664-38-2		X	2b	NA
Sodium hydroxide	1310-73-2		X	2b	8.45E-09
Sulfuric acid	7664-93-9		X	2b	NA
Zinc	7440-66-6		X	2b	NA
Non-crystalline silica (impurity)	7631-86-9			3	NA
Cumene	98-82-8	X	X	4a	1.15E-02

1. 2-butoxyethanol was removed from the list of hazardous air pollutants in November, 2004

2. Listed as antimony compounds

3. Listed as nickel compounds

4. Listed as copper compounds

5. NA = Not available

Chemical Name	**CASRN**	**Clean Air Act Hazardous Air Pollutant**	**California Air Resources Board Hot Spots Program**	**California Air Resources Board TAC Category**	**Henry's Law Constant (atm m³/ mol)**
Ethyl acrylate	140-88-5	X	X	4a	3.39E-04
Hydroquinone	123-31-9	X	X	4a	4.73E-11
Methyl chloride (chloromethane)	74-87-3	X	X	4a	8.82E-03
Propionaldehyde	123-38-6	X	X	4a	7.34E-05
Xenon 133, radionuclide	14932-42-4	X	X	4a	NA
1,2,4-Trimethylbenzene	95-63-6		X	4b	6.16E-03
Ammonium sulfate	7783-20-2		X	4b	NA
Barium	7440-39-3		X	4b	NA
Peracetic acid	79-21-0		X	4b	2.14E-06
Cyclohexanol	108-93-0		X		4.40E-06
Dipropylene glycol monomethyl ether	34590-94-8		X		1.07E-07
Trimethylbenzenes	25551-13-7		X		7.24E-03

1. 2-butoxyethanol was removed from the list of hazardous air pollutants in November, 2004

2. Listed as antimony compounds

3. Listed as nickel compounds

4. Listed as copper compounds

5. NA = Not available

Appendix 3.3. Potential treatment of chemicals used in oil and gas operations

Chemical additives used in oil and gas development operations in California were categorized according to reported and potential chemical functions. Chemical function data was available in the SCAQMD and FracFocus datasets, and consisted of broad categories including surfactants, solvents, clay control agents, acids and bases, biocides, and breakers. In cases where chemical function was not reported, chemical structure and formula was used to categorize chemicals when possible. For example, quaternary ammonium compounds (QACs), minerals, metals, salts, surfactants, and polymers are readily identifiable through chemical structure and formula. Peer reviewed literature, reports, and other sources were also used to categorize oil and gas chemicals according to chemical function whenever possible (Borchardt, 1989; Camarillo et al., 2016; Shonkoff et al., 2015a; Fink, 2012; King, 2012; Stringfellow et al., 2017a; U.S. EPA, 2015a; U.S. EPA, 2016). Chemicals that could not be categorized were labeled "unknown/unspecified."

Chemical additives were categorized according to chemical functions or chemical structure. A total of 198 (31%) chemicals could not be identified by chemical function or structure and were grouped together in the "unknown/unspecified" category (Table A3.16). A significant fraction of these "unknown/unspecified" chemicals (anywhere from 25-38%, depending on the treatment technology) had inadequate chemical and physical data, and could not be assessed for potential treatment and removal using the selected treatment technologies.

Table A3.25. Suitability of select treatment technologies for removal of various classes of chemical additives used in oil and gas operations in California.

Chemical Function	**Number of Chemicals**	**Inorganic**	**Number of chemicals appropriate for each treatment technology**					
			RO	**NF**	**Adsorption/ Oil-water separation**	**Organic adsorption media**	**Air stripping**	**Biological treatment**
Acids and Bases	29	18	14 (0)	4 (0)	1 (8)	1 (13)	0 (11)	11 (0)
Amine/amide	14	0	8 (1)	2 (1)	2 (1)	6 (1)	0 (1)	12 (1)
Ammonium compounds	2	2	0 (0)	0 (0)	0 (1)	0 (2)	0 (2)	0 (0)
Biocide	11	0	9 (0)	3 (0)	0 (0)	1 (1)	0 (1)	5 (1)
Boron compounds	1	1	0 (1)	0 (1)	0 (1)	0 (1)	0 (1)	0 (0)
Breaker	9	4	2 (3)	2 (3)	0 (7)	0 (7)	0 (6)	2 (2)
Carbohydrates	9	0	5 (4)	4 (4)	0 (8)	0 (8)	0 (8)	2 (7)
Carbonate compounds	2	2	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Carboxylic compounds	6	0	3 (1)	1 (1)	0 (1)	0 (1)	0 (1)	5 (1)
Carrier	21	8	9 (7)	6 (7)	6 (11)	7 (11)	7 (11)	1 (4)
Cement additive	1	1	0 (0)	0 (0)	0 (1)	0 (1)	0 (1)	0 (0)
Clay control	5	2	3 (1)	1 (1)	0 (1)	0 (3)	0 (2)	1 (1)
Coal	3	0	1 (2)	1 (2)	0 (3)	0 (3)	0 (3)	0 (3)
Corrosion inhibitor	6	0	1 (3)	1 (3)	0 (4)	0 (4)	0 (4)	2 (4)
Crosslinker	14	9	9 (1)	5 (1)	0 (7)	1 (9)	0 (10)	3 (1)
Defoamer	2	0	1 (1)	1 (1)	2 (0)	1 (0)	0 (0)	1 (0)
Diverting agent	1	0	0 (1)	0 (1)	0 (1)	0 (1)	0 (1)	1 (0)
Friction reducer	1	0	0 (0)	0 (0)	0 (1)	0 (1)	0 (1)	0 (1)
Gelling agent	1	0	1 (0)	1 (0)	0 (1)	0 (1)	0 (1)	0 (1)
Iron control	3	0	2 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3 (0)
Iron control, corrosion inhibitor	1	0	0 (0)	0 (0)	0 (0)	1 (0)	0 (0)	1 (0)
Iron control, scale inhibitor, corrosion inhibitor	4	0	4 (0)	3 (0)	1 (0)	0 (0)	0 (0)	3 (0)
Metals	10	10	4 (0)	2 (0)	0 (10)	0 (10)	0 (10)	0 (0)
Minerals	25	25	9 (11)	3 (11)	0 (23)	0 (23)	1 (24)	1 (3)
Nutrient mixtures	2	0	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)
Oils	3	0	0 (3)	0 (3)	3 (0)	3 (0)	2 (0)	3 (0)
Oxidizing agents	5	5	1 (0)	1 (0)	0 (4)	0 (5)	0 (4)	0 (0)
Phosphorus compounds	6	3	6 (0)	6 (0)	0 (3)	1 (3)	0 (3)	0 (0)

a The first number is the number of chemicals appropriate for removal and the number in parentheses is the number of chemicals in that chemical category for which data could not be located.

Chemical Function	**Number of Chemicals**	**Inorganic**	**Number of chemicals appropriate for each treatment technology**					
			RO	**NF**	**Adsorption/ Oil-water separation**	**Organic adsorption media**	**Air stripping**	**Biological treatment**
Polymers	25	0	13 (9)	10 (9)	2 (16)	7 (16)	2 (16)	3 (16)
Proppant	13	13	10 (1)	3 (1)	1 (11)	0 (11)	0 (13)	0 (0)
QAC	24	0	13 (11)	9 (11)	9 (11)	7 (14)	0 (11)	8 (10)
Reducing agent	3	2	2 (0)	0 (0)	0 (0)	0 (0)	0 (3)	1 (0)
Resin	6	0	2 (4)	0 (4)	0 (5)	0 (5)	0 (5)	1 (4)
Salt	21	21	16 (0)	2 (0)	0 (18)	0 (21)	1 (20)	0 (0)
Scale inhibitor	11	1	2 (6)	2 (6)	0 (7)	0 (8)	0 (8)	1 (6)
Solvent	63	0	29 (19)	6 (19)	38 (5)	19 (6)	25 (7)	47 (4)
Surfactant	68	0	21 (47)	17 (47)	38 (13)	33 (13)	12 (14)	37 (12)
Unknown/ Unspecified	199	25	112 (63)	70 (63)	71 (71)	65 (77)	26 (77)	66 (51)

a The first number is the number of chemicals appropriate for removal and the number in parentheses is the number of chemicals in that chemical category for which data could not be located.

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Appendix 4

4.1. Formations of Significance to Groundwater Resources

The San Joaquin Valley is a 700-km long oil and gas producing asymmetric (deepening to the west) basin that extends from the Stockton Arch to the north to the foothills of the Tehachapi and San Emigdio Mountains to the south, and from the San Andreas Fault and Coast Ranges to the west to the Sierra Nevada Mountains to the east (Hosford Scheirer & Magoon, 2007). More than 7.5 km of sedimentary rocks overlie igneous and metamorphic basement rock and provide a nearly continuous record of sedimentation over the past ~100 million years (Ma) (Hosford Scheirer & Magoon, 2007). However, the sedimentary sequences are complicated because of tectonic activity, lateral changes in depositional environment, and temporal variation in sea level. Few formations are continuous throughout the basin (Hosford Scheirer & Magoon, 2007).

Marine deposition was dominant throughout in the San Joaquin basin from Paleocene time (beginning ~66 Ma) to the beginning of Oligocene time (beginning ~34 Ma) (Figure A4.1) (Bertoldi et al., 1991). During early Oligocene time, marine deposition was restricted to the southern portion of the San Joaquin Valley (Bertoldi et al., 1991). During Miocene time (beginning ~23 Ma) (Figure A4.1), marine deposits were laid down along the west flank and throughout most of the southern portion of the San Joaquin Valley. Parts of the Central Valley remained inundated by the Pacific Ocean until late Pliocene time (~ 2 to 3 Ma) (Figure A4.1). By Pleistocene time (~2.6 Ma) (Figure A4.1), only continental or freshwater sediments were deposited throughout Pleistocene and Holocene time (10,000 years ago) (Figure A4.1) (Bertoldi et al., 1991).

There are places in the San Joaquin Valley where marine sediments have been sufficiently flushed by meteoric water to provide freshwater (generally regarded as having TDS level less than 3,000 mg/L) (Bertoldi et al., 1991). These areas are likely in the eastern portion of the Kern groundwater subbasin where these formations are uplifted and recharged near the surface. The oldest formations containing groundwater resources start with the Olcese and Santa Margarita Formations (Figure A4.1). The Olcese and Santa Margarita Formations contain non-saline (<10,000 mg/L TDS) water in the northeastern portion of the Kern subbasin, where they occur as confined aquifers. The Olcese Formation (~21 to 16.5 Ma) is of marine origin (Hosford Scheirer & Magoon, 2007) and consists primarily of sand (Hilton et al., 1963). The Santa Margarita Formation (11 to 6.5 Ma) is also of marine origin (Hosford Scheirer & Magoon, 2007) and consists of coarse sand (Hilton et al., 1963).

The Chanac Formation (9 to 6 Ma) is of nonmarine origin and is confined to a narrow band in the southeastern portion of the San Joaquin basin (Hosford Scheirer & Magoon, 2007). Oil is produced from the Chanac Formation in the Mountain View and Fruitvale Fields (Hosford Scheirer & Magoon, 2007).

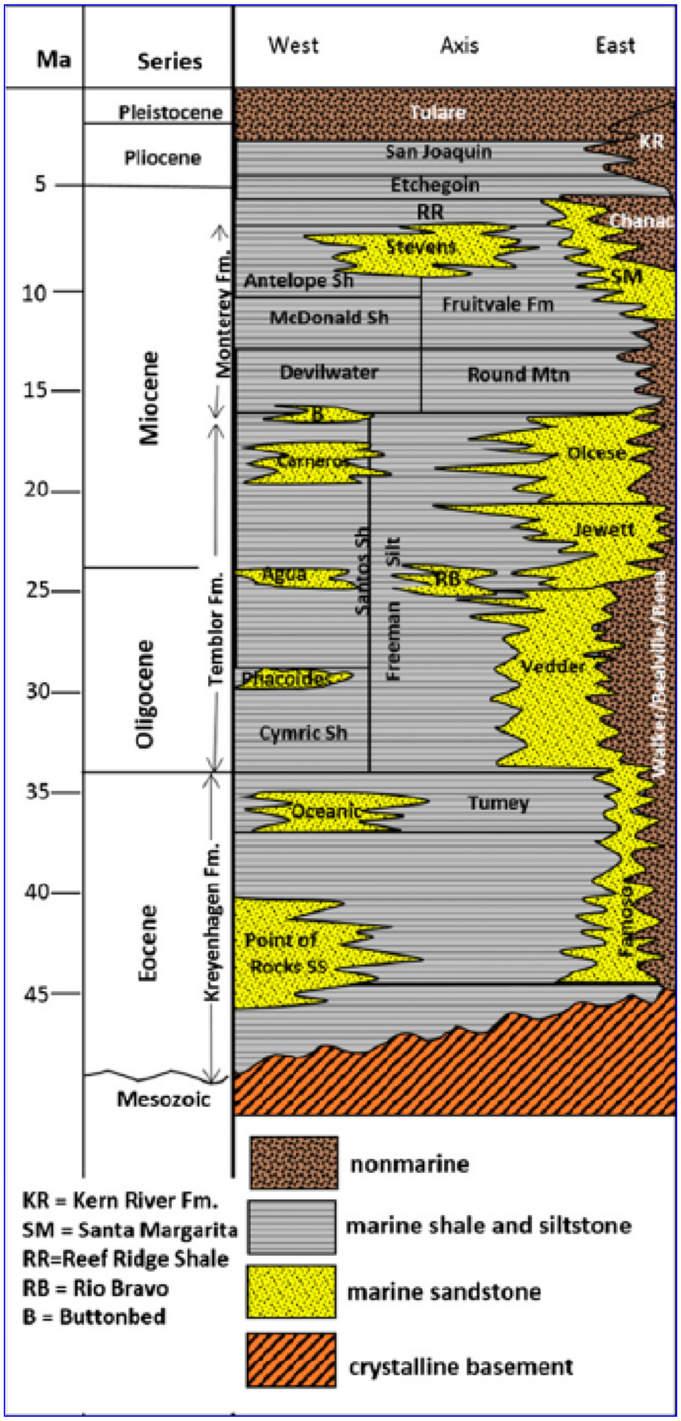

Figure A4.1. Generalized stratigraphic column depicting formations in the eastern and western southern San Joaquin Valley. Fm=Formation, Mtn=Mountain, Sh=Shale, SS=sandstone. Source: figure from Gillespie et al. (2017), modified from Gautier et al. (2003)

The Kern River Formation (8 to 6 Ma) is of nonmarine origin (Hosford Scheirer & Magoon, 2007). As discussed in the California Groundwater Bulletin (CGWB) for the Kern County groundwater subbasin, the Kern River Formation is an important source of municipal and domestic drinking water in the eastern portion of the subbasin (CGWB, 2006). The Kern River Formation includes poorly sorted, lenticular deposits of clay, silt, sand, and gravel derived from the Sierra Nevada Mountains. Sediments from the Sierra Nevada Mountains are often characterized as reduced (Croft, 1972). The Kern River Formation is moderately to highly permeable and yields moderate to large quantities of water to wells (Hilton et al., 1963).

The Etchegoin Formation (5.5 to 4.5 Ma) is of marine origin and is broadly distributed across the southern portion of the San Joaquin basin between the San Andreas Fault and the Bakersfield Arch (Hosford Scheirer & Magoon, 2007). The San Joaquin Formation (4.5 to 2.5 Ma) is a marine and brackish unit (Hosford Scheirer, 2007) with a subsurface expression similar to the underlying Etchegoin Formation except that it occupies a more westerly location (Hosford Scheirer & Magoon, 2007).

The Tulare Formation (2.5 to 0.6 Ma) is of nonmarine origin and was deposited at the end of the Pliocene to throughout the Pleistocene (Plio-Pleistocene). The Tulare Formation is present throughout most of the San Joaquin Valley (Hosford Scheirer, 2007). The formation increases in thickness toward the axis of the basin and south of the Bakersfield Arch. The Tulare Formation is a major source of municipal and domestic water in the south-central to south-western portion of the San Joaquin Valley. The Tulare Formation contains of interbedded, oxidized to reduced sands and gypsiferous clays and gravels derived predominantly from Coast Range sources (CGWB, 2006).

The Tulare Formation includes the Tulare Lake bed, which consists of fine-grained deposits interbedded with coarser stream channels in excess of 1,100 m, resting on Pliocene marine sediments (Page, 1986). The Tulare Lake fluctuated in size throughout its history and at one time occupied most of the San Joaquin Valley as Pleistocene glacial Lake Corcoran (Fujii & Swan, 1995). The lake is now extinct because of damming of rivers and tributaries from the Sierra Nevada Mountains for agriculture (Davis & Coplen, 1989). Lack of discharge from Tulare Lake has essentially resulted in the Tulare Lake basin being a hydrologically closed basin (Davis & Coplen, 1989).

During the Pleistocene, most of the San Joaquin Valley was inundated by lakes that accumulated up to 60 m of clay. The clay is often referred to as the E-clay or the Corcoran Clay member of the Tulare Formation (Faunt et al., 2009, 2010; Davis et al., 1959). The Corcoran Clay member formed between 740,000 to 615,000 years ago and is present throughout the central portion of the San Joaquin Valley (Hosford Scheirer & Magoon, 2007).

The Corcoran Clay is generally very fined-grained, however, isolated coarser-grained zones are present particularly when the clay is less than six m in thickness along the edges of the clay boundary (Page, 1986). Where the Corcoran Clay member is present, this clay layer generally divides the groundwater flow system into an upper semi-confined zone and a lower confined zone (Williamson et al., 1989; Belitz & Heimes, 1990). However, thousands of long large-diameter irrigation wells have perforated the Corcoran Clay and increased the hydraulic connection of aquifer systems above the and below the Corcoran Clay (Williamson et al., 1989; Bertoldi et al., 1991). Hence, it is unlikely that the Corcoran Clay forms a barrier to the downward migration of contaminants from produced water ponds. Except in the Westside subbasin area, sediments below the Corcoran clay are generally finer-grained than those above the Corcoran Clay (Faunt et al., 2009, 2010).

Older alluvial deposits overlie the Tulare and Kern Formations. These deposits are composed of Pleistocene-age lenticular deposits of clay, silt, sand, and gravel that are loosely consolidated to cemented and are exposed at the Kern subbasin margins. Coarse-grained areas are prevalent in many of the alluvial fan areas in the Sierra Nevada foothills (Faunt et al., 2009, 2010). Generally, fine-grained textural zones are present in distal floodplain areas (Faunt et al., 2009, 2010). These alluvial deposits are often indistinguishable from the Tulare and Kern Formations below and together with these underlying formations, form the principal aquifer body in the Kern County subbasin (CGWB, 2006). These deposits are moderately to highly permeable and yield large quantities of water to wells (Hilton et al., 1963; Wood & Davis, 1959; Wood & Dale, 1964).

Younger alluvial deposits vary in character and thickness in the Kern subbasin. At the eastern and southern subbasin margins, the unit is composed of interstratified and discontinuous beds of clay, silt, sand, and gravel. In the southwestern Kern subbasin, younger alluvial deposits are finer grained and less permeable as it grades into fine-grained flood basin deposits underlying the historic beds of Buena Vista and Kern Lakes in the southern subbasin (Hilton et al., 1963; Wood & Dale, 1964). Flood basin deposits consist of silt, silty clay, sandy clay, and clay interbedded with poorly permeable sand layers. These flood basin deposits are difficult to distinguish from underlying fine-grained older alluvium and the total thickness of both units may be as much as 330 meters (Wood & Dale 1964).

Groundwater in the eastern portion of the Kern subbasin is primarily calcium bicarbonate waters in the shallow zones, increasing in sodium with depth (CGWB, 2006). Streams and rivers originating in the Sierra Nevada historically provided most of the natural drainage into the basin prior to damming these rivers and tributaries for irrigation water. The two largest rivers entering the basin from the Sierra Nevada, the Kings and Kern Rivers, are characterized by relatively low salinity (< 150 mg/L TDS), calcium-bicarbonate- and sodium-bicarbonate-type waters (Fujii & Swain, 1995).

Bicarbonate is replaced by sulfate and lesser chloride in an east to west trend across the subbasin (CGWB, 2006). West-side waters are primarily sodium sulfate to calcium-sodium sulfate type (Hilton et al., 1963; Wood & Dale, 1964; Wood & Davis, 1959). Deposits from the Coast Range can contain significant concentrations of gypsum ($CaSO_4 \cdot H_2O$) and thenardite (Na_2SO_4), while deposits from the Sierra Nevada contain lower concentrations of salts and little or no gypsum (Fujii & Swain, 1995).

Ephemeral streams from the Coast Range are characterized as calcium/sodium-sulfate-type waters with higher salinity (~2,000 to 3,000 mg/L TDS), reflecting weathering of Cretaceous and Tertiary gypsiferous marine sediments (Fujii & Swain, 1995). High concentrations of sulfate could also be due to oxidation of iron sulfide minerals present in marine shales (Davis, 1961). Fujii & Swain (1995) also found elevated concentrations of boron in shallow groundwater in sediments from the Coast Range and San Emigdio Mountains, as compared to shallow groundwater in sediments from the Sierra Nevada. Fujii & Swain (1995) state that the distribution of boron was correlated to concentrations of TDS and appeared to behave conservatively in groundwater. In general, concentrations of TDS in groundwater increase from east to west across the basin.

The climate of the Tulare Lake basin is characterized by hot, dry summers with maximum temperatures in excess of 43°C and cool, moist winters with temperatures seldom below 0°C. Total precipitation averages only 10 to 20 cm per year which falls mostly in winter months. Levels of TDS in shallow (<6 m) groundwater can be high (>10,000 mg/L) in areas containing soils of marine origin and where groundwater is close enough to land surface to allow evaporation and evapotranspiration or where evaporation has resulted in highly concentrated irrigation drainage water (Fujii & Swain, 1995). Elevated TDS levels in shallow groundwater in proximity to Tulare Lake are likely due to evaporation of previous lake water and deposition of salts (Fujii & Swain, 1995).

Oil Accumulations in the Tulare and Kern River Formations

In addition to being sources of drinking water, the Tulare and Kern River Formations also contain substantial reservoirs of petroleum. To understand where groundwater resources occur in these formations, it is necessary to consider where and to what depths commercial accumulations of oil occur. Groundwater resources are present in the Tulare and Kern River Formations at depths above that used for commercial oil development. Also, groundwater resources are present in proximity to oil fields at depths used for commercial oil development. A preliminary analysis of locations where oil may exist below or in lateral proximity in formations containing groundwater resources is presented here. A more detailed or site-specific analysis is necessary to evaluate the presence of commercially extractable oil in specific unlined produced pond areas.

In the McLure Shale-Tulare USGS Petroleum Assessment Unit, the source rock for petroleum in the Tulare Formation north of the Bakersfield Arch is the McLure Shale of the Monterey Formation (Magoon et al., 2007). The largest accumulations are located near the deepest part of the source rock (in excess of 6,700 m in some areas) (Magoon et al., 2007). In decreasing volumes of production, the four largest fields associated with the McLure-Tulare Petroleum Assessment Unit are the South Belridge, Cymric, Lost Hills, and McKittrick fields. At these fields, oil and gas were expelled from the thermally McLure Shale member and subsequently migrated vertically upward to the Tulare Formation (Magoon et al., 2007).

The Antelope-Stevens USGS Petroleum Assessment Unit is located south of the Bakersfield Arch with the primary reservoir in the Stevens Sand and the source rock from the Antelope Shale of the Monterey Formation (Figure A4.1) (Magoon et al., 2007). Petroleum in the Stevens Sand constitutes 29.3% of expelled petroleum followed by the Kern River Formation (18.1%), Etchegoin Formation (7.1%), Jewett Sand (3.9%), and the Veddar Sand (3.9%) of the Temblor Formation (Figure A1) (Magoon et al., 2007). This pattern of petroleum occurrence suggests that oil and gas expulsion from thermally mature Antelope Shale source rock migrated into the adjacent Stevens sand and then migrated upward to the Kern River Oil Field to the north and to the Buena Vista, Elk Hills, and Midway Sunset oil field to the northwest (Magoon et al., 2007). In decreasing volumes, the four largest fields are Midway-Sunset, Kern River, Elk Hills, and Buena Vista fields (Magoon et al., 2007). As discussed for the Tulare Formation, groundwater resources may be present in the Kern River Formation above and in the vicinity of petroleum migration to this formation.

The Southeast Stable Shelf USGS Petroleum Assessment Unit of the Micocene Total Petroleum System is located along the southern margin of the San Joaquin basin. The source rock for oil in this system is fine-grained, biosiliceous, organic-rich facies of the Monterey Formation located along the basin’s southwestern margin (Gautier & Hosford Scheirer, 2007). During the Pliocene between 4 and 3 Ma, a stable shelf consisting entirely of nonmarine deposits was deposited on the basin’s southeastern margin during marine regression (Gautier & Hosford Scheirer, 2007).

The major reservoir in this unit is the Kern River Formation in the Kern River Field (Gautier and Hosford Scheirer, 2007). The Kern River Formation contains the largest volume of oil (2,100 million barrels) in the San Joaquin basin (Gautier & Hosford Scheirer, 2007). Petroleum associated with assessment unit also migrated to the nonmarine Chanac Formation at the Rosedale Ranch and Fruitvale Fields (Gautier & Hosford Scheirer, 2007). The lower portion of the Kern River Formation grades westward into the Etchegoin Formation whereas the upper portion of the Kern River Formation grades westward into the San Joaquin and Tulare Formations (Hosford Scheirer & Magoon, 2007; Gautier & Hosford Scheirer, 2007).

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Appendix A

Statement of Work

Study Process

The standard California Council on Science and Technology (CCST) process is tailored to the scope and timeline of this project. Our approach, modeled after the National Academies of Sciences' National Research Council process, is designed to ensure independent, objective, and nonpartisan advice with high standards of scientific and technical quality through the use of recognized experts and peer review. Checks and balances are applied at every step in the Study process to protect the integrity of the reports and to maintain public confidence in them.

Reports are researched and written by principal researchers under the guidance of and with feedback from a steering committee with an appropriate range of expertise, a balance of perspectives, and no conflicts of interest (unless a conflict is deemed unavoidable and is promptly and publicly disclosed). After these two groups come to agreement on a draft report, it is submitted to another set of experts that provide anonymous peer review. The review comments are addressed by the researchers under the oversight of the steering committee. The revised report draft and comment responses are subsequently assessed for adequacy by a fourth set of experts called the "report monitors." The researchers, again under the guidance of the steering committee, make further adjustments to address any response inadequacies identified by a report monitor.

CCST strives to produce reports through a transparent process to ensure that the final product is responsive to the questions of the sponsor, while maintaining full scientific independence. Transparency is achieved by engaging the sponsor in dialogue about the nature of the information they need and informing the sponsoring agency of our progress, typically with regular meetings and written updates.

More details on CCST's Study process are available at http://ccst.us/ccstinfo/process.php.

Preliminary Questions[1]

CCST will write a report with an executive summary, introduction, and 6 substantive chapters:

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[1] The degree to which the following questions can be addressed may be constrained by the timeframe and funding available for this Study.

Executive Summary: Findings, Conclusions, and Recommendations

Introduction

Chapter 1: Sources of Water Used for Oil and Gas Development and Production in California

Chapter 2: Produced Water Characteristics Across California

Chapter 3: Treated Produced Water as a Potential Resource

Chapter 4: Potential Impacts of Various Produced Water Dispositions

Chapter 5: Opportunities to Reduce Water Stress

Chapter 6: SB 1281 Dataset Assessment

Each chapter will consider a Secondary Evaluation Question posed in Phase I, and the selected Operational Questions relating to each, as determined in the beginning of Phase II. To the extent possible given resource constraints, additional questions identified in Phase I that lack sufficient data to answer directly but are significant enough to warrant further discussion and suggestions for improved data collection to address them, may be covered.

Secondary Questions and associated Operational Questions determined to be tractable and significant during Phase I are listed below and are expected to be considered for each chapter.[2]

Chapter 1: Secondary Evaluation Question 1 – What are the sources, volumes, and quality of water used for oil and gas development and production in California?

a. What are the gross water volumes, sources, and qualities used and generated on a per-operator, per-field basis? What are the net volumes of water imported and exported from oil and gas-producing reservoirs? How do these vary in space and time?

b. What are the water volumes, sources, and qualities used for different oil and gas production methods, e.g. hydraulic fracturing and enhanced oil recovery? How do these vary in space and time?

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[2] Additional refinement of these questions may occur as determined at the outset of Phase II.

Chapter 2: Secondary Evaluation Question 2 – What are the characteristics/quality of produced water across the state, and how do these vary over time?

a. What is the salinity of produced water across the state?

b. What are the sources and volumes of produced water recycled for use in oilfields in the state? On local and regional scales? Compared with other oil-producing states and regions?

c. What are the sources and volumes of produced water recycled for use in applications beyond the oilfield? How do these quantities compare with other oil-producing states and regions?

Chapter 3: Secondary Evaluation Question 3 – How does treatment impact produced water availability as a potential resource, both within and outside of oilfields?

a. What proportion of produced water is currently treated prior to disposal or any reuse application in California?

b. Of the quantities of produced water treated, what proportion is sent for disposal? What proportion is reused within the oilfield? What proportion is reused outside of the oilfield?

c. Which operators or areas of the state reuse the most produced water by volume and proportion?

d. What applications are currently the largest destinations for treated produced water?

Chapter 4: Secondary Evaluation Question 4 – What are the potential and actual hazards, risks and impacts to environmental and human health from various dispositions of reused water discharges to land, water, and subsurface injection?

a. Where are the locations of these percolation pits geographically with respect to groundwater that is currently used or in the future could be used for drinking, food crop irrigation and other activities with potential human exposure pathways?

b. What volume of produced water is discharged to water districts for food crop irrigation and livestock watering?

c. Where, geographically, is produced water sent for reuse in agricultural irrigation?

d. What volume of produced water is injected into UIC wells annually?

Chapter 5: Secondary Evaluation Question 5 – Are there unrealized opportunities to reduce stress on other water resources, including conservation and efficiency, improving and expanding direct and indirect reuse of produced water?

a. Where do physical proximity of (a) large amounts of irrigated agriculture, (b) scarcity of irrigation water, and (c) low-salinity produced water injected into disposal wells exist?

b. What technology and infrastructure barriers exist that affect the reuse of produced water?[3]

Chapter 6: What is the utility of the current SB 1281 dataset to answer important questions on water resources, public health, and the environment, and are there opportunities for improvement?

a. Is the dataset designed in a manner that facilitates answering the most important questions?

b. Are there sufficient quality control processes in place to ensure the data are accurate and have full coverage?

c. Are the data organized in a manner that facilitates connection with other important public datasets, both by the Division and by other agencies?

d. Would aligning Division data stewardship practices with other multi-agency practices, such as the California Open and Transparent Water Data Act (AB 1755), significantly improve the utility of the SB 1281 dataset?

e. What data gaps exist within the SB 1281 dataset, and what essential datasets do not currently exist, or are not publicly available?

f. Where important data are missing, which agencies would be best suited to collect that information?

Sources

This Study will be conducted as an original analysis and synthesis of existing available data including the results of currently ongoing or recently related studies, protocols, and proposed regulations. The quality of the assessment will depend on the quality of the information and time available for the study and the study will include an assessment of data adequacy. Every effort is made to use publicly available data where possible and appropriate.

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[3] This operational question may not be answerable through data analysis specifically, but will be discussed in context of background and looking forward.

Appendix B

CCST Steering Committee Members

The Steering Committee (SC) oversees the report authors, reaches conclusions based on the findings of the authors, drafts recommendations and writes an executive summary.

Full *curricula vitae* for the SC members are available upon request. Please contact CCST (916) 492-0996.

Steering Committee Members

- **Mike Kavanaugh**, Geosyntec Consultants, Inc. (Chair)
- **Stephen Weisberg**, Southern California Coastal Water Research Project Authority (Vice Chair)
- **Nicole Deziel**, Yale School of Public Health
- **Eric M.V. Hoek**, University of California, Los Angeles
- **Susan Hubbard**, Lawrence Berkeley National Laboratory and UC Berkeley
- **James McCall**, National Renewable Energy Laboratory
- **William Stringfellow**, University of the Pacific and Lawrence Berkeley National Laboratory

Steering Committee Members

Mike Kavanaugh, PhD, P.E., NAE,

Steering Committee Chair
Senior Principal
Geosyntec Consultants, Inc.

Mike Kavanaugh is a chemical and environmental engineer with more than four decades of consulting experience in a number of technical areas. Mike's professional practice started in the areas of municipal and industrial wastewater treatment, water quality management, and water reuse and drinking water treatment. He expanded his practice to include contaminated groundwater studies, particularly CERCLA-driven remedial investigations/feasibility studies (RI/FS), groundwater remediation, waste minimization and pollution prevention studies, pioneering technology development, as well as third-party peer review and strategic consulting on environmental management and compliance issues. He has also provided technology evaluations including patent reviews of environmental technologies.

As a testifying expert and a fact witness on engineering and hydrogeologic issues related to hazardous waste sites as well as on other issues related to his areas of expertise, Mike has been tapped more than 60 times by attorneys, arbitrators, judges, and government agencies to serve. He also has participated on several mediation and arbitration panels as a neutral technical expert as well as serving as an individual facilitator, mediator, arbitrator, court appointed expert, or "blue ribbon" expert panelist working on project-specific and policy-level issues.

To advance the state of the practice, Mike has contributed to over 80 technical publications and more than 150 presentations to audiences that included congressional and state committees. Currently, he is an instructor for the Princeton Groundwater Course and a consulting professor in the Stanford University Civil and Environmental Engineering Department. He also served on the Board of Directors for the Environmental Law Institute and was the chair of the National Research Council's Committee on Future Options for the Nation's Contaminated Groundwater Remediation Efforts. He was elected into the National Academy of Engineering in 1998.

Stephen Weisberg, PhD

Steering Committee Vice Chair
Executive Director,
Southern California Coastal Water Research Project Authority (SCCWRP)

Dr. Stephen Weisberg is Executive Director of the Southern California Coastal Water Research Project Authority, a research consortium formed by 14 leading water quality agencies in California to ensure a solid scientific foundation for their management activities. Dr. Weisberg's research emphasis is in developing tools to support implementation of, and data interpretation from, environmental monitoring programs. Beyond his research activities, Dr. Weisberg focuses on linking the needs of the management community with science. He serves on numerous advisory committees, including the State of California's Clean Beach Task Force, the California Ocean Protection Council Science Advisory Team, the California Sea Grant Program Advisory Council, and the California Water Quality Monitoring Council. Dr. Weisberg received his undergraduate degree from the University of Michigan and his Ph.D. from the University of Delaware.

Nicole Deziel, M.H.S., PhD

Assistant Professor of Epidemiology,
Yale School of Public Health

Nicole C. Deziel, M.H.S., Ph.D., is an Assistant Professor in the Department of Environmental Health Sciences. Her research involves applying existing and advanced statistical models, biomonitoring techniques, and environmental measurements to provide quantitative assessments of exposure to combinations of traditional and emerging environmental contaminants. Her exposure assessment strategies aim to reduce exposure misclassification for epidemiologic studies, advancing understanding of relationships between of exposure to environmental chemicals and risk of cancer and other adverse health outcomes. She has investigated several types of pollutants including pesticides, persistent organic pollutants, and polycyclic aromatic hydrocarbons.

Dr. Deziel's research also includes hydraulic fracturing, or "fracking," and how chemicals used in the process and released into the air or water may adversely affect communities of people living nearby. She is leading an inter-disciplinary team of investigators on a project entitled "Drinking water vulnerability and neonatal health outcomes in relation to oil and gas production in the Appalachian Basin." In this 3-year study funded by the Environmental Protection Agency (EPA), her team is evaluating whether exposure to water contaminants from the process of hydraulic fracturing ("fracking") is associated with adverse human developmental and teratogenic effects.

Eric M.V. Hoek, PhD

Professor, Department of Civil and Environmental Engineering,
California NanoSystems Institute and Institute of the Environment & Sustainability
University of California Los Angeles (UCLA)

Eric Hoek is an internationally recognized expert in water treatment, UCLA environmental engineering professor, founder of 4 successful water technology startups, and considered a thought leader in the water industry. He has worked on various aspects of water treatment including drinking water treatment, wastewater treatment, desalination, oil & gas produced water treatment, municipal and industrial water reuse and oil spill remediation. He has served as a consultant to municipal water authorities, water technology startups, hedge funds, venture capital funds, law firms, private research foundations, non-profit foundations, US federal, state and local agencies and foreign national research agencies. He has over 130 scientific publications, over 70 patents filed in the U.S. and internationally, and serves as the Editor-in-Chief of the Nature Publishing Group journal *npj Clean Water*. He is a graduate of Penn State (B.S.), UCLA (M.S.), Yale University (Ph.D.) and the Executive Management program at the UCLA Anderson School of Management.

Susan Hubbard, PhD

Associate Laboratory Director & Senior Scientist, LBNL
Adjunct Professor, Environmental Science, Policy and Management,
University of California, Berkeley

As the Associate Lab Director for Earth & Environmental Sciences Area at Berkeley Laboratory, Dr. Susan Hubbard leads a premier group of ~500 staff that has a significant research portfolio in climate science, terrestrial ecosystem science, environmental and biological system science, fundamental geoscience, and subsurface energy resources. Research within this Area of Berkeley Lab is tackling some of the most pressing environmental and subsurface energy challenges of the 21st Century. Dr. Hubbard is also an Adjunct Professor at UC Berkeley in the Department of Environmental Science, Policy and Management. Dr. Hubbard earned her PhD in Civil and Environmental Engineering at UC Berkeley, and prior to joining Berkeley Lab, she was a geologist at the US Geological Survey and a geophysicist in industry.

As a Senior Scientist at Berkeley Laboratory, Dr. Hubbard's research focuses on quantifying how terrestrial environments function, with a particular emphasis on the development of geophysical approaches to provide new insights about processes relevant to contaminant remediation, carbon cycling, water resources, and subsurface energy systems. She has been honored by the scientific community with several awards, including as an: American Geophysical Union (AGU) Fellow, Geological Society of America (AGU) Felow, receipent of the Society of Exploration Geophysicists (SEG) Frank Frischknecht Award for leadership and innovation in near-surface geophysics, the Birdsall Dreiss Distinguished Lecturer Award, Distinguished Alumni of UC Berkeley, and the SEG Harold Mooney Award for Near Surface Geophysics. Dr. Hubbard has served widely on many scientific boards and has served on the editorial boards of JGR-Biosciences, Water Resources Research, Vadose Zone Journal and the Journal of Hydrology.

James McCall, P.S.M.

Distributed Energy and Environment Analyst,
National Renewable Energy Laboratory (NREL)

James joined the Systems Modeling & Geospatial Data Science Group in the Strategic Energy Analysis Center in 2015. His interests include techno-economic analyses for various renewable technologies, economic and employment impacts, and systems analysis associated with the energy-water-food-nexus. Prior work experience was as a researcher at a utility law think tank at ASU and a project manager/facilities engineer for an upstream oil and gas producer.

William Stringfellow, PhD

Emeritus Professor, University of the Pacific
Research Engineer, LBNL

William T. Stringfellow, Ph.D. is an Emeritus Professor at the School of Engineering & Computer Science at the University of the Pacific in Stockton, CA and a Research Engineer in the Geochemistry Department, Earth & Environmental Sciences Area at Berkeley National Laboratory. He received his B. S. in Environmental Health from the University of Georgia (Athens, GA) in 1980 and his Master's Degree in Microbial Physiology and Aquatic Ecology from Virginia Tech (Blacksburg, VA) in 1984. He received his Ph.D. in Environmental Sciences and Engineering from the University of North Carolina at Chapel Hill in 1994 and worked as a Post-Doctoral Fellow in the Civil and Environmental Engineering Department at the University of California at Berkeley.

Professor Stringfellow is the first author on over 50 journal publications, has been the lead author on numerous government reports, and has made hundreds of presentations on the subjects of water quality, water treatment, and the microbiology of engineered systems. He has over 35 years research and consulting experience in wastewater treatment and management in both the US and Europe. Prof. Stringfellow's research interests include treatment and management of agricultural and industrial wastes. Prof. Stringfellow was the Water Group Leader for the SB-4 Study examining the environmental impacts of hydraulic fracturing in California and Lead Scientist on the Low Dissolved Oxygen Study investigating disuse pollution impacts on the San Joaquin River and Estuary. He is currently a member of the Food Safety Advisory Panel examining the beneficial reuse of produced water for irrigation. On-going projects include an extensive examination of water and chemical use during oil and gas development and the treatment and reuse of oil-field wastewater.

Appendix C

Science Team
Report Author Biosketches

Report Authors

Dr. Laura Feinstein from the Pacific Institute, Dr. Seth Shonkoff from PSE Healthy Energy, and Dr. Brie Lindsey from CCST, the report's lead authors, primarily researched and wrote the body of the report. In addition, the following individuals assisted in writing the report:

- Sonali Abraham, Pacific Institute
- Eliza Czolowski, PSE Healthy Energy
- Dominic DiGiulio, PSE Healthy Energy
- Jeremy Domen, Lawrence Berkeley National Laboratory
- Lee Ann Hill, PSE Healthy Energy
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EDUCATION

2012	PHD-ECOLOGY University of California, Davis, CA
1998	BA-ANTHROPOLOGY University of California, Berkeley, CA

CURRENT AND PAST POSITIONS

Since 2016	Senior Researcher Pacific Institute, Oakland, CA
2013-2016	Project Manager California Council on Science and Technology, Sacramento, CA
2012-2013	Science and Technology Policy Fellow California Senate Committee on Environmental Quality, Sacramento, CA
2006-2012	Graduate Student Researcher University of California, Davis, CA
2004-2006	Laboratory Technician University of California, Berkeley, CA

HONORS AND AWARDS

2013	California Senate Resolution on Service to State of California, 2013
2007	SeaGrant Delta Science Fellow
2007	National Science Foundation Interdisciplinary Graduate Research Training Grant

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EDUCATION

2012	PHD-ENVIRONMENTAL SCIENCE, POLICY AND MANAGEMENT, University of California, Berkeley, CA
2008	MPH-EPIDEMIOLOGY, University of California, Berkeley, CA
2003	BA-ENVIRONMENTAL STUDIES, Skidmore College, Saratoga Springs, NY

CURRENT AND PAST POSITIONS

Since 2012	Executive Director PSE Healthy Energy, Oakland, CA
Since 2012	Visiting Scholar Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA
Since 2014	Affiliate, Energy Technologies Area Lawrence Berkeley National Laboratory, Berkeley, CA
2011-2014	Contributing Author Intergovernmental Panel on Climate Change (IPCC), University of California, Berkeley, CA
2008-2012	Climate and Health Graduate Student Researcher University of California, Berkeley, CA
2010	Program Associate Berkeley Air Monitoring Group, Berkeley, CA
2007	Health Policy Analyst San Francisco Department of Public Health, San Francisco, CA
2007-2008	Molecular Epidemiology Graduate Student Researcher University of California, Berkeley, CA

2003-2006	Environmental Analyst San Francisco Estuary Institute, Oakland, CA

HONORS AND AWARDS

2017	Pioneer Under 40 in Environmental Public Health, Collaborative on Health and the Environment (CHE)
Since 2014	Emerging Leader, Emerging Leaders Fund, The Claneil Foundation
2012	Outstanding Graduate Student Instructor Award, University of California, Berkeley

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EDUCATION

2013	PHD-OCEANOGRAPHY, Oregon State University, Corvallis, OR
2002	BA-ENVIRONMENTAL SCIENCES, University of California, Berkeley, CA

CURRENT AND PAST POSITIONS

Since 2017	Senior Program Associate California Council on Science and Technology, Sacramento, CA
2014-2016	Research Scientist California Council on Science and Technology, Sacramento, CA
2013-2014	Science and Technology Policy Fellow California State Senate Office of Research, Sacramento, CA
2005-2013	Graduate Student Researcher Oregon State University, Corvallis, OR
2004-2005	Assistant Wildlife Biologist University of California, Berkeley, CA
2004-2005	Research Assistant Cordell Bank National Marine Sanctuary, Point Reyes, CA
2003	Assistant Plant Biologist University of Arizona, Tucson, AZ
2000-2002	Research Assistant University of California, Berkeley, CA

HONORS AND AWARDS

2019	Novim Epiphany Award for Science Inspiration, 2019
2014	California Senate Resolution on Service to State of California

2009	National Center for Atmospheric Research Advanced Study Program Awardee
2005-2007	Graduate Student Pipeline Fellow

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EDUCATION

Present	D.ENV-ENVIRONMENTAL SCIENCE AND ENGINEERING University of California, Los Angeles, CA
2014	MS-ENVIRONMENTAL ENGINEERING Johns Hopkins University, Baltimore, MD
2012	B.SC-CHEMISTRY HONORS St Stephens College, Delhi University, New Delhi, India

CURRENT AND PAST POSITIONS

Since 2018	Research Associate Pacific Institute, Oakland, CA
2017	Researcher and Project Lead Institute of the Environment and Sustainability, University of California, Los Angeles
2015	Researcher and Laboratory Manager Whiting School of Engineering, Johns Hopkins University
2014	Research Intern United Nations Environment Programme (UNEP), Washington D.C.
2013	Research Intern The Energy and Resources Institute (TERI), Bangalore, India
2010	Research Intern Abu Dhabi Food Control Authorities Laboratories, Abu Dhabi, UAE

HONORS AND AWARDS

2018	LASC Fellowship Award, Los Angeles Sustainability Collaborative
2018	Barbara Maida Award, University of California, Los Angeles

2017	AWWA Graduate Scholarship, American Water Works Association
2016	Pankaj Parekh Graduate Fellowship, University of California, Los Angeles
2012	Virendra Kumar Memorial Prize for Lab Proficiency, St. Stephens College, Delhi

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EDUCATION

2013	MS-PROFESSIONAL STUDIES IN ENVIRONMENTAL SCIENCE SUNY College of Environmental Science and Forestry, Syracuse, NY
2009	BS-ENVIRONMENTAL SCIENCE Allegheny College, Meadville, PA

CURRENT AND PAST POSITIONS

Since 2015	Program Associate, Energy-Environment Program PSE Healthy Energy, Ithaca, NY
2012-2015	Scientist 1 / Graphics Area Lead GZA Geoenvironmental Inc., East Syracuse, NY
2011-2012	GIS Specialist The Palmerton Group, LCC, East Syracuse, NY
2009-2010	Research Scientist, accuracy assessment of land use change maps, water quality Geographic Modeling Services, Jamesville, NY

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EDUCATION

1982	BS-Environmental Engineering, Temple University, Philadelphia, PA
1988	MS-Environmental Science, Drexel University, Philadelphia, PA
2000	PhD-Soil, Water, and Environmental Science, University of Arizona, Tucson, AZ

CURRENT AND PAST POSITIONS

Since 2017	Senior Research Scientist, PSE Healthy Energy, Oakland, CA
2015-2017	Environmental Engineer, Subsurface Gas Solutions, Ada, OK
2014-2015	Research Associate, Stanford University, Stanford, CA
1982-2014	Environmental Engineer, U.S. Environmental Protection Agency, Philadelphia, PA and Ada, OK
1975-1978	Enlisted, United States Marine Corps, Camp Pendleton, CA

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EDUCATION

2013	MS-ENGINEERING SCIENCE University of the Pacific, Stockton, CA
2010	BS-BIOENGINEERING University of the Pacific, Stockton, CA

CURRENT AND PAST POSITIONS

Since 2014	Research Associate, Earth and Environmental Sciences Area Lawrence Berkeley National Laboratory, Berkeley, CA
2011-2016	Research Assistant, Ecological Engineering Research Program University of the Pacific, Stockton, CA

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EDUCATION

2016	MS-PUBLIC HEALTH, ENVIRONMENTAL HEALTH SCIENCES University of California, Berkeley, CA
2013	BS-ENVIRONMENTAL SCIENCE Ithaca College, Ithaca, NY

CURRENT AND PAST POSITIONS

Since 2016	Associate, Environmental Health Program PSE Healthy Energy, Oakland, CA
2016	Research Assistant Office of Environmental Health Hazard Assessment, Oakland, CA
2015	Health Intern Natural Resources Defense Council, San Francisco, CA
2014	Environmental Laboratory Intern Ithaca Area Wastewater Treatment Facility, Ithaca, NY
2013	Water Quality Intern City of Ithaca Water Treatment Plant, Ithaca, NY
2013	Environmental Health Intern Tompkins County Health Department, Ithaca, NY

MORGAN SHIMABUKU

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EDUCATION

2013	MA-GEOGRAPHY, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO
2006	BA-ENVIRONMENTAL STUDIES AND GEOLOGY Whitman College, Walla Walla, WA

CURRENT AND PAST POSITIONS

Since 2018	Research Associate Pacific Institute, Oakland, CA
2012-2017	Senior Manager of Sustainability Programs & Research Associate Resource Central (formerly, Center for ReSource Conservation), Boulder, CO
2010	Stream Technician U.S. Forest Service, PIBO Effectiveness Monitoring Program, Logan, UT
2010	Researcher Montana State University Sustainability Center, Bozeman, MT
2008-2009	Staff Scientist S.S. Papadopulos & Associates, Portland, OR

HONORS AND AWARDS

2011	Young Investigators Award, BASIN Isotope Conference
2006	Leeds Prize for Honors and Excellence in Geology, Whitman College

Appendix D

Glossary

1281 Dataset – Quarterly reported dataset of water volumes related to production and injection for wells, required under California Public Resources Code §3227.

Applications – Overarching category, used in the O&G Industry Water Cycle, to refer to applications of water within the cycle. 'EOR and Stimulation' and 'Ancillary O&G Operations' make up this category, both defined below.

Ancillary O&G Operations – Applications category in the O&G Industry Water Cycle. Refers to activities within the O&G industry that do not include activities related to production and underground injection. Specific sources and destinations from the 1281 dataset make up this category. (See also: Destination and Source).

Beneficial Use – Beneficial Uses of the waters of the state that may be protected against quality degradation include, but are not limited to, domestic, municipal, agricultural and industrial supply; power generation; recreation; aesthetic enjoyment; navigation; and preservation and enhancement of fish, wildlife, and other aquatic resources or preserves (California Water Code § 13050(f)).

Destination – Refers to the end point of water handled by the oil and gas industry, and is one of twelve categories as defined in SB 1281. For example, sale/transfer for domestic use or surface water discharge. (See also: Disposition).

Direct Reuse – The intentional use of water that is delivered to the user directly from a wastewater treatment facility. This type of reuse is planned and typically requires a permit.

Discharge – Output category in the O&G Industry Water Cycle. Refers to water discharged by the O&G industry. The discharged water is available for use by downstream users. Specific destinations from the 1281 dataset make up this category.

Disposal – Output category in the O&G Industry Water Cycle. Refers to water disposed of by the O&G industry in Class II disposal wells through the Underground Injection Control program and evaporation from lined pits. This water is no longer readily available for use.

Disposition – The term used by the California Department of Oil, Gas and Geothermal Resources to refer to the end point of water handled by the oil and gas industry. In this report, we use the term destination to avoid implying that all water is disposed of when in fact much is reused. (See also: Destination).

Endpoint – The term used to designate the final location of a flow of water, as described by the water cycle. A single endpoint encompasses one or more destinations. For example, disposal, defined above. (See also: Destination).

Enhanced Oil Recovery (EOR) and Stimulation – Applications category in the O&G Industry Water Cycle that entail injection of fluids into oil and gas-producing zones to increase hydrocarbon recovery. EOR includes processes that inject water into the subsurface to recover more oil than would be possible with primary production, such as water and steam flooding ("Enhanced Oil Recovery," n.d.). Well stimulation refers to technologies such as hydraulic fracturing and matrix acidizing that inject fluids to increase the permeability of the production zone (CCST and LBNL).

External Source – Input category in the O&G Industry Water Cycle. Refers to water coming from sources external to the oil and gas industry, i.e. water that is entering the industry for the first time. Specific sources from the 1281 dataset make up this category.

Flows – Volume of water moving from a source to a destination.

Fresh/brackish – Water with a Total Dissolved Solids (TDS) value of 10,000 mg/L or less.

Hazard – Any biological, chemical, mechanical, environmental, or physical stressor that is reasonably likely to cause harm or damage to humans, other organisms, the environment, and/or engineered systems in the absence of control.

Impact – The particular harm, loss, or damage that is experienced if the risk-based scenario occurs.

Incidental Reuse – This is unplanned reuse that occurs when a downstream water user draws raw water from a source that receives water from an upstream wastewater discharge.

Indirect Reuse – The intentional use of water from a wastewater treatment facility that is first blended in the environment with other water(s) (e.g. river water). Indirect reuse also typically requires a permit.

Input – Overarching category, used in the O&G Industry Water Cycle, to refer to inputs to the water cycle. Multiple origins make up this category. (See Also: Origin)

Monthly Dataset – Monthly reported dataset of volumes of oil, gas, and water produced and injected for wells in California. Commonly referred to as "monthly production/ injection" data.

No Known Permit – A discharge of water to end uses defined as beneficial reuses by the California Water Code for which we were unable to find an associated Waste Discharge Requirement Permit. These reuses may be direct, indirect, or incidental.

O&G (Oil and Gas) water use – any interaction between the unit of interest (in this case, an oil field operator) and water. Producing and reinjecting water, extracting water from a water well for use in well stimulation, or purchase of water from a municipal supplier for interior use would all be cases of oil and gas operators using water. Water use includes reuse and diversions of water, and the eventual discharge and disposal of that water. The California Department of Water Resources refers to use of water as applied water, e.g. water is applied for energy production within a Hydrologic Region (DWR, 2018). Because "use" is such an ambiguous term, we also developed a number of more specifically defined terms for interactions with water, given in this section

Origin – The term used to designate the starting location or of a flow of water, as described by the water cycle. A single origin encompasses one or more sources. For example, external source, defined above. (See Also: Source).

Output – Overarching category, used in the O&G Industry Water Cycle, to refer to outputs from the water cycle. Multiple endpoints make up this category. (See Also: Endpoint).

"Produced Water and Flowback" – Input and applications category in the O&G Industry Water Cycle. Refers to water and flowback from a production well. This includes the 'produced water' and 'well stimulation recycled fluids' source category in the 1281 dataset.

Produced water – In cases where "produced water" is used without mention to "flowback," the term refers to water co-produced with oil and gas from a well, including flowback.

Risk – The probability that a given hazard plays out in a scenario that causes a particular harm, loss, or damage.

Saline – Water with a Total Dissolved Solids (TDS) value of more than 10,000 mg/L.

SB 1281 – Senate Bill 1281, enacted into statute in 2014 to amend California Public Resources Code §3226.3 and §3227.

Source – Refers to a specific source of injected water and is one of eleven categories as defined in SB 1281. For example, a domestic water system or surface water.

Suitable for Domestic or Irrigation Purposes – Term used in SB 1281. The phrase had no existing definition in statute or regulation, and as such California Water Board staff defined it in a Memorandum of Agreement as water of 10,000 mg/L TDS or less (Bishop, 2015).

Toxicity – The degree to which a substance (a toxin or poison) can harm humans or animals.

Appendix E

Review of Information Sources

This study was conducted as a synthesis of existing publicly available data including the results of many currently on-going or recently completed relevant studies, protocols, and proposed regulations. The quality of the assessment depended on the quality of the information and time available for the study. The study includes an assessment of data adequacy for questions posed herein.

Our scientists cited a given reference in the report if it met all three of the following criteria:

1. Fit into one of the seven categories of admissible literature (described in a-g below).
    a. Published, peer-reviewed scientific papers.
    b. Government data and reports including analysis of available data from The Division and other publicly available sources.
    c. Academic studies that are reviewed through a university process, textbooks, and papers from technical conferences.
    d. Studies generated by non-government organizations that are based on data, and draw traceable conclusions clearly supported by the data.
    e. Voluntary reporting from industry. This data is cited with the caveat that, as voluntary, there is no quality control on the accuracy or completeness of the data.
    f. Other relevant publications including reports and theses. We state the qualifications of the information used in the report.
    g. Additional authoritative sources including the expert opinion of the committee and scientific community.
2. Was relevant to the scope of the report.
3. Added substantive information to the report.

For this report, the authors reviewed many sources of public information, including some that are not easily accessible to all citizens, such as fee-based scientific journals. If a member of the public wishes to view a document referenced in the report, they may visit

CCST at 1130 K Street, Suite 280, Sacramento, CA 95814-3965. We cannot duplicate or electronically transmit copyright documents. Please make arrangements in advance by contacting CCST at (916) 492-0996.

Appendix F

California Council on Science and Technology Study Process

California Council on Science and Technology (CCST) studies are viewed as valuable and credible because of the organization's reputation for providing independent, objective, and nonpartisan advice with high standards of scientific and technical quality. Checks and balances are applied at every step in the study process to protect the integrity of the studies and to maintain public confidence in them.

Study Process Overview—Ensuring Independent, Objective Advice

For 30 years, CCST has been advising California on issues of science and technology by leveraging exceptional talent and expertise.

CCST enlists the state's foremost scientists, engineers, health professionals, and other experts to address the scientific and technical aspects of society's most pressing problems.

CCST studies are primarily funded by state agencies and foundations. CCST provides independent advice; external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. Authors and the Steering Committee gather information from many sources in public and private meetings, but they carry out their deliberations in private in order to avoid political, special interest, and sponsor influence.

Stage 1: Defining the Study

Before the author(s) and Steering Committee selection process begins, CCST staff, Board Members, Council Members and other relevant experts work with the study sponsors to determine the specific set of questions to be addressed by the study in a formal "statement of task," as well as the duration and cost of the study. The statement of task defines and bounds the scope of the study, and it serves as the basis for determining the expertise and the balance of perspectives needed for the study authors, Steering Committee members, and peer reviewers.

The statement of task, work plan, and budget must be approved by CCST's Project Director in consultation with CCST leadership. This review sometimes results in changes to the proposed task and work plan. On occasion, it results in turning down studies that CCST believes are inappropriately framed or not within its purview.

Stage 2: Study Author(s) and Steering Committee (SC) Selection and Approval

Selection of appropriate authors and SC members, individually and collectively, is essential for the success of a study. All authors and SC members serve as individual experts, not as representatives of organizations or interest groups. The size of the SC depends on the size and scope of the study. Each expert is expected to contribute to the project on the basis of his or her own expertise and good judgment. Each provisional SC member and author complete a conflict of interest (COI) form and submit current resumes. CCST staff send all of this information to outside counsel for a thorough COI review and then organize all results and recommendations from the outside counsel. CCST organizes an in-person meeting for the provisional SC and lead authors to discuss the balance of the committee and evaluate each person for any potential COIs based on the outside counsel feedback. Any issues raised in this discussion are investigated and addressed. CCST sends the list and COI information of the provisional SC and lead authors, including any recommendations or concerns from the in-person meeting, to the Oversight Committee (created by the Board and made up of two CCST Board Members and an outside expert) for final approval. While the lead authors attend the meeting for the discussion of their own potential COIs they do not contribute to the discussion of the provisional SC Member's COIs. Members of a SC and the lead author(s) are anonymous until this process is completed. The lead author(s) maintain continued communication with the SC as the study progresses through frequent updates and background meetings.

Careful steps are taken to convene SCs that meet the following criteria:

> **An appropriate range of expertise for the task.** The SC must include experts with the specific expertise and experience needed to address the study's statement of task. A major strength of CCST is the ability to bring together recognized experts from diverse disciplines and backgrounds who might not otherwise collaborate. These diverse groups are encouraged to conceive new ways of thinking about a problem. The size of the SC depends on the size and scope of the study.
>
> **A balance of perspectives.** Having the right expertise is not sufficient for success. It is also essential to evaluate the overall composition of the SC in terms of different experiences and perspectives. The goal is to ensure that the relevant points of view are, in CCST and the Oversight Committee's judgment, reasonably balanced so that the SC can carry out its charge objectively and credibly.
>
> **Screened for conflicts of interest.** All provisional SC members are screened in writing and in a confidential group discussion about possible conflicts of interest. For this purpose, a "conflict of interest" means any financial or other interest which conflicts with the service of the individual because it could significantly impair the individual's objectivity or could create an unfair competitive advantage for any person or organization. The term "conflict of interest" means something more than individual bias. There must be an interest, ordinarily financial, that could influence the work of

the SC or that could be directly affected by the work of the SC. Except for those rare situations in which CCST and the Board appointed Oversight Committee determine that a conflict of interest is unavoidable and promptly and publicly disclose the conflict of interest, no individual can be appointed to serve (or continue to serve) on a SC used in the development of studies if the individual has a conflict of interest that is relevant to the functions to be performed.

Point of View is different from Conflict of Interest. A point of view or bias is not necessarily a conflict of interest. SC members are expected to have points of view, and CCST attempts to balance these points of view in a way deemed appropriate for the task. SC members are asked to consider respectfully the viewpoints of other members, to reflect their own views rather than be a representative of any organization, and to base their scientific findings and conclusions on the evidence. Each SC member has the right to issue a dissenting opinion to the study if he or she disagrees with the consensus of the other members.

Other considerations. Membership in CCST are taken into account in SC selection. The inclusion of women, minorities, and young professionals are additional considerations.

Specific steps in the SC selection and approval process are as follows:

CCST staff solicit an extensive number of suggestions for potential SC members from a wide range of sources, then recommend a slate of nominees. Nominees are reviewed, as a provisional SC, at several levels within CCST. Prior to final approval, the provisional SC members complete background information and COI disclosure forms. The SC balance and COI discussion is held at the first SC meeting. Any COIs or issues of SC balance and expertise are investigated; changes to the SC are proposed and finalized. Finally, the provisional SC is presented to the Oversight Committee for formal approval. SC members continue to be screened for conflict of interest throughout the life of the committee.

CCST uses a similar approach as described above for SC development to identify study authors who have the appropriate expertise and availability to conduct the work necessary to complete the study. In addition to the SC, all authors, peer reviewers, and CCST staff are screened for COI.

Stage 3: Author and Steering Committee Meetings, Information Gathering, Deliberations, and Drafting the Study

Authors and the Steering Committee typically gather information through:

meetings;

submission of information by outside parties;

reviews of the scientific literature; and

investigations by the study authors and/or SC members and CCST staff.

In all cases, efforts are made to solicit input from individuals who have been directly involved in, or who have special knowledge of, the problem under consideration.

For larger reports, lead authors may request additional authors to ensure the appropriate expertise is included. Every author must be approved by the SC and CCST staff. Some of the additional authors may become section leads. The lead author reviews and approves the work of all other chapter authors, including section leads.

During the course of a report, authors' duties may shift which may change the lead author or section lead designations. Any such changes must be made in conjunction with CCST staff and the SC. If the reorganization of author responsibilities or the addition of a new author raises conflict of interest concerns, they are presented to and resolved by the Oversight Committee.

The authors shall draft the study and the SC shall draft the Executive Summary which includes findings, conclusions, and recommendations (FCRs). In some cases, the authors write the first draft of the FCRs to ensure they are based on the information and analysis contained in the full report. The draft FCRs are then edited and approved by the SC. The SC deliberates in meetings closed to the public in order to develop draft FCRs free from outside influences. All analyses and drafts of the study remain confidential.

Stage 4: Report Review

As a final check on the quality and objectivity of the study, all CCST full commissioned reports must undergo a rigorous, independent external peer review by experts whose comments are provided anonymously to the authors and SC members. CCST recruits independent experts with a range of views and perspectives to review and comment on the draft report prepared by the authors and the SC. The proposed list of peer reviewers is approved by the Oversight Committee to ensure all report sections are adequately reviewed.

The review process is structured to ensure that each report addresses its approved study charge, that the findings are supported by the scientific evidence and arguments presented, that the exposition and organization are effective, and that the report is impartial and objective.

The authors and the SC must respond to, but need not agree with, reviewer comments in a detailed "response to review" that is examined by one or more independent "report monitor(s)" responsible for ensuring that the report review criteria have been satisfied. After all SC members and appropriate CCST officials have signed off on the final report, it is transmitted to the sponsor of the study and the sponsor can release it to the public. Sponsors are not given an opportunity to suggest changes in reports. All reviewer comments and SC deliberations remain confidential. The names and affiliations of the report reviewers are made public when the report is released.

Appendix G

Expert Oversight and Review

Oversight Committee:

- **Richard C. Flagan**, California Institute of Technology, CCST Board Member
- **Samuel J. Traina**, University of California, Merced, CCST Board Member
- **Robert F. Sawyer**, University of California, Berkeley, External Member

Report Monitors:

- **Samuel J. Traina**, University of California, Merced, CCST Board Member

Expert Reviewers:

- **Preston Jordan**, Lawrence Berkeley National Laboratory
- **Meagan Mauter**, Carnegie Mellon University
- **Peter McMahon**, U.S. Geological Survey
- **Diane Saber**, REEthink, Inc.
- **David Shimabukuro**, California State University, Sacramento
- **Dan Tormey**, Catalyst Environmental Solutions Corp.
- **John Veil**, Veil Environmental
- **Nathaniel Warner**, Pennsylvania State University

Appendix H

Full List of Findings, Conclusions, and Recommendations

Findings, conclusions, and recommendations are defined as follows:

> ***Finding**: Facts the study team has found that could be documented or referenced and that have importance to the study.*

> ***Conclusion**: A deduction the study team made based on findings.*

> ***Recommendation**: A statement that recommends an action to be considered as a result of the report findings and conclusions.*

The committee process ensures conclusions are based on findings (facts), and recommendations are based on findings and conclusions. Both the authors and the Steering Committee members proposed draft conclusions and recommendations. These were modified based on peer review and discussion within the Steering Committee, along with continued consultation with the authors.

CHAPTER 1. Direct Assessment of the SB 1281 Dataset

FCR 1.1. Value of the SB 1281 dataset *(Chapter 1, Sections 1.1, 1.2.1)*

Finding 1.1.1. Prior attempts to collect data on water use by the O&G industry, such as the monthly and SB 4 datasets, captured only a subset of water handled by the industry.

Finding 1.1.2. The SB 1281 dataset provides unique value by encompassing all water handled by the O&G industry in its three reports, including previously unreported uses such as for dust suppression, equipment cleaning, drilling muds, and domestic water.

Finding 1.1.3. Much of the new information gained from the SB 1281 dataset is found in the Other Allocation report, which is the sole source of state information on water used by the industry that is neither produced nor injected.

Conclusion 1.1.1. The SB 1281 dataset, while imperfect, allows a fuller understanding of the O&G industry’s role in regional water balances than was previously possible. By capturing all inputs, outputs, and applications of water, the dataset enables calculations of metrics such as demand, reuse, and net impact to the surface water cycle, which were previously impossible to calculate.

Conclusion 1.1.2. Any revisions to the SB 1281 dataset should preserve and enhance its unique capacity to provide insight into the oil and gas water cycle and the impact of the industry to regional water balances.

FCR 1.2. Redundancy between the 1281 and monthly datasets *(Chapter 1, Sections 1.2.1, 1.2.2)*

Finding 1.2.1. The SB 1281 dataset includes three reports: Injection, Production, and Other Allocation, which have non-parallel sets of columns.

Finding 1.2.2. The monthly dataset includes three reports: Injection, Production, and California oil and gas wells. The Injection and Production reports give information on volumes of water (in addition to oil and gas where appropriate), and source/disposition and quality of water that are similar to information found in the SB 1281 dataset.

Conclusion 1.2.1. The Well-to-Well Allocation report seeks to itemize the movement of water from every production well to every injection well. In practice, however, water moves from production wells to centralized treatment facilities (e.g. oil-water separators) and back to injection wells, and these volumes cannot be accurately tracked in the way intended by this report.

Conclusion 1.2.2. Per-well reporting of produced and injected water in the SB 1281 dataset was largely redundant with existing reporting in the monthly dataset. At the same time, the Well-to-Well Allocation report was excessively complex and failed to accurately represent how water moves through an oil field.

Conclusion 1.2.3. The SB 1281 dataset provides better information on source, destination, and quality of water than the monthly dataset.

Conclusion 1.2.4. Redundancy between the SB 1281 dataset and the monthly dataset can be reduced by appropriately augmenting the monthly dataset to take over well-by-well reporting on production and injection from the SB 1281 dataset.

Conclusion 1.2.5. The SB 1281 dataset can be used to gather information at the lease scale or larger.

Conclusion 1.2.6. The monthly dataset appears to have more reliable information on volumes of produced and injected water than the SB 1281 dataset.

Recommendation 1.2.1. Make the monthly dataset the repository for volumes of water produced and injected; focus the SB 1281 dataset instead on flows of water into and out of the O&G industry.

Recommendation 1.2.2. The monthly dataset should adopt similar variables for source, destination, and quality as the SB 1281 dataset to eliminate the per-well reporting in the SB 1281 dataset; operators can be required to simply report on a per-lease basis to the SB 1281 dataset.

Recommendation 1.2.3. Add a column to the monthly production and injection dataset for operators to report the water treatment facility to which each production and injection well connects.

Recommendation 1.2.4. Instead of attempting to apportion flows of water between individual wells as is currently done in the Well-to-Well Allocation report, operators should simply include the water treatment facility or facilities connected to each production and injection well in the monthly dataset.

FCR 1.3. Using the SB 1281 dataset for insight into the water cycle *(Chapter 1, Section 1.3.2)*

Finding 1.3.1. Calculating water inputs, outputs, and applications by the O&G industry required extensive parsing, reorganizing, and compiling of data from three reports: Production, Injection, and Other Allocation.

Finding 1.3.2. The three reports contained similar variables but had slightly different structures, making it challenging to sum quantities across reports. For example, produced water used for well stimulation was reported in the Production report, whereas water from external sources used for well stimulation was found in the Other Allocations report.

Finding 1.3.3. The three reports also allowed for duplicate reporting of some flows of water. For example, produced water that was injected into a UIC well was reported in all three reports: once in the Production report with a destination of underground injection, once in the Injection report with a source of produced water, and once (erroneously) in the Other Allocations report with a source of produced water and destination of underground injection.

Conclusion 1.3. The SB 1281 dataset is not structured to facilitate straightforward calculations of water inputs, outputs, and applications by the O&G industry, key variables for understanding the impact of the O&G industry on regional water resources.

Recommendation 1.3.1. Collapse the three SB 1281 datasets (Injection, Production, Other Allocation) into one master All Flows report, as described in Recommendations 1.4.2 and 1.4.3.

Recommendation 1.3.2. Denote source and destination for every flow. Produced water should be a source, rather than a separate report. Likewise, water injected into a UIC well should be a destination, rather than a standalone report. Make Storage a source and a destination, rather than a separate variable.

Recommendation 1.3.3. Eliminate duplicate reporting across the three reports. In theory, collapsing the three reports into one should reduce the likelihood of duplicate reporting. Definitions of sources and destinations should also be revised as necessary to prevent ambiguity. For example, Destination 9, "Operator's Facilities," should not include onsite storage if the stored water is reported elsewhere.

Recommendation 1.3.4. The Division quarterly summary reports should give use, reuse, percentage reused, sources, and destinations per hydrologic region. This additional information would not replace sources and destinations, but would facilitate calculating larger, more integrative categories such as demand, reuse, total inputs from external sources, and total discharges to the surface.

FCR 1.4. Water reuse by the O&G industry *(Chapter 1, Section 1.3.3)*

Finding 1.4. The O&G industry meets much of its demand for saline water by reusing produced water.

Conclusion 1.4. Although the O&G industry reuses much of the saline water it produces, in certain basins, a substantial amount is either disposed of underground or discharged at the surface. A smaller proportion of industry fresh water demand is met by recycled water, because the majority of fresh/brackish water used by the O&G industry is water obtained from external sources rather than produced water.

FCR 1.5. Water use and discharges by the O&G industry *(Chapter 1, Section 1.3.3)*

Finding 1.5.1. For saline water, volumes discharged at the surface exceeded water diverted from external sources. For fresh/brackish water, volumes diverted from external sources exceeded what was discharged at the surface.

Finding 1.5.2. Net withdrawal of fresh/brackish water for the O&G industry is less than 0.1% of all water applied for human use in a hydrologic region.

Conclusion 1.5. The O&G industry is a net generator of saline water and a net consumer of fresh/brackish water.

FCR 1.6. Facilitating assessment of regional water impacts *(Chapter 1, Section 1.3.1)*

Finding 1.6. Hydrologic region can serve as a reasonable framework for assessing water budgets, but hydrologic region is not reported as a variable in the SB 1281 dataset.

Conclusion 1.6. Without hydrologic region reported, the SB 1281 dataset structure and data quality do not facilitate assessment of regional water availability and quality.

Recommendation 1.6.1. The SB 1281 dataset should be expanded to denote hydrologic region of each lease.

Recommendation 1.6.2. To enable the assessment of regional water availability, The Division quarterly summary reports should be expanded to provide use, reuse, sources, and destinations of water as a function of hydrologic region.

FCR 1.7. Data quality, organization, and reporting requirements in the SB 1281 dataset *(Chapter 1, Section 1.4)*

Finding 1.7. There were a large number of data quality problems in the SB 1281 dataset. Examples include:

- Much of the water quality reporting did not appear credible when considering the source or destination of the water, such as saline water from a municipal water supplier, or saline water discharged for agriculture and recharge.
- Blank fields could signify zeroes, not applicable, or failure to report.
- Multiple source and destination categories were vaguely defined or aggregated in groupings that are very different.
- Text fields with slight variants or misspellings (i.e. Smith Corp., smith corp., Smith corporation, and Smith corporation) created unintentional mismatches in the dataset.
- Invalid data entries, such as data of the wrong value type or outside the range of possible values, caused loss of information.

Conclusion 1.7.1. Data quality problems made accurate analysis challenging. In particular, water quality reporting that seems illogical undermines the ability to accurately assess impacts to water resources. Simple data validation fixes could make accurate analysis easier and faster.

Recommendation 1.7.1. Zero values should always be actively reported (not left blank) to enable accurate calculations of means.

Recommendation 1.7.2. Source and destination categories should be better defined to better elucidate the industry's impact on water resources.

Conclusion 1.7.2. The SB 1281 dataset could be improved with certain changes in data quality assurance to reduce the errors in the final dataset. Specific recommendations follow:

Recommendation 1.7.3. Update the terms and definitions for sources and destinations to better describe and distinguish the categories as described in Appendix 1.1. Key points to consider in renaming sources and destinations: a) "Domestic Use" should not be used to refer to reuse for agriculture or recharge; b) Oceans and surface water should be distinguished in sources and destinations, given the large quality differences; c) Constrain the definition of the "Other" category such that it explicitly excludes reporting water that could be reported in another, better-defined category; d) Create separate categories for injection in disposal wells versus injection in EOR wells; and e) Treat storage as a source and a destination, not a separate variable.

Recommendation 1.7.4. Reducing the number of sources and destinations reported by field would simplify reporting without functional loss of important information. For instance, Source 10, "Other Class II Recycled fluid source," along with Source 11, "Recycled Class II fluids from operator's drilling," and Source 5, "Industrial Waste – Class II fluid treated by 3rd party" could become one source defined simply as "Class II Fluids (other than produced water)."

Recommendation 1.7.5. Add columns to the reports to allow more detailed reporting on the identity and location of the source and destination. For example, external sources (such as municipal suppliers and municipal wastewater) should provide names of public water systems and their associated Public Water System Identification Number (PWSID), the tracking identification number used by the State Water Board. Discharges should identify the relevant permit, if applicable. Discharges to municipal wastewater systems should include PWSID.

Recommendation 1.7.6. Limit invalid data entry by requiring operators to choose from a drop-down list where appropriate and restrict the ability to leave fields blank. There should be pre-defined options for every field. Most text entry fields, such as operator and field names, should be selected from a drop-down menu to prevent alternative spellings.

Recommendation 1.7.7. Enact mechanisms to distinguish between zero, not applicable, and failure to report. All fields should require the reporter to select an option before submitting the report. If an operator fails to report information, that should be noted as "failure to report" in the master dataset, rather than blanks.

Recommendation 1.7.8. Beta test the form to observe how operators interpret the form. This would enable The Division to find opportunities to clarify the form.

Recommendation 1.7.9. Perform selective ground-truthing on the information reported in the dataset. Reports of large volumes of saline water from a water well, municipal water supplier, or municipal wastewater, as well as substantial discharges of saline water, should be flagged for closer inspection to verify that the reporting is accurate. Independent datasets on groundwater quality, such as GeoTracker GAMA, could be used to validate the SB 1281 dataset.

Recommendation 1.7.10. Perform further, in-depth data validation between information reported in the SB 1281 dataset and in the monthly dataset, and compare volumes reported for well stimulation with those reported in SB 4.

CHAPTER 2. Reuse of Produced Water for Irrigation

FCR 2.1. Reuse of produced water that is presently occurring *(Chapter 2, Section 2.4)*

Finding 2.1.1. Based on operator-reported produced water volumes in the SB 1281 dataset, an estimated total annual volume of 38,345 AFY was discharged from oil and gas fields in California to the destinations of Agriculture and Recharge or Surface Water Discharge between 2015 Q4 and 2017 Q1. Of this amount, 35,838 AFY originated from 11 fields in the San Joaquin basin. Only 2,508 AFY was discharged from a single field in each of the following basins: Sacramento, Santa Barbara-Ventura, Salinas, and Santa Maria.

Conclusion 2.1.1. Reuse of produced water for agriculture is predominantly occurring in the southeastern San Joaquin basin where the majority of agricultural production occurs in the state. The rest of the reuse is spread between four other basins across the state.

Finding 2.1.2. We were able to identify WDRs/NPDES permits associated with an estimated 33,753 AFY (88%) of the total volume reported as going to Agriculture and Recharge or Surface Water Discharge. We were not able to identify WDRs/NPDES permits for an estimated 4,592 AFY (12%) of the total volume reported as going to Agriculture and Recharge or Surface Water Discharge.

Conclusion 2.1.2. WDRs/NPDES permits are the main source of information on how the water is used after leaving the oil and gas field. By examining these permits, we identified a mixture of direct reuse for agriculture and indirect reuse via discharge to ground and surface water.

Recommendation 2.1.2. The SB 1281 dataset should require the operator to report the associated permit for discharges to Agriculture and Recharge and Surface Water Discharge.

Conclusion 2.1.3. For the water reported as going to Agriculture and Recharge or Surface Water Discharge for which we could not identify permits, we were unable to conclude whether the water is reused directly, indirectly, or incidentally by agricultural or other water users.

Recommendation 2.1.3.1. SB 1281 reporting requirements for operators should be updated to include information on the receiving entity, groundwater water system, or surface water body when reporting volumes of water under the Agriculture and Recharge or Surface Water Discharge destination codes.

Recommendation 2.1.3.2. For cases where we were not able to identify permits associated with discharges labeled as Agriculture and Recharge or Surface Water Discharge the relevant regional board should review operator records.

FCR 2.2. SB 1281 Destination Codes *(Chapter 2, Section 2.4)*

Finding 2.2.1. The current destination code of Agriculture and Recharge does not distinguish between direct and indirect reuse for agriculture.

Finding 2.2.2. From our inspection of WDRs/NPDES permits, we observed that this destination code was used for a wide variety of discharges. A few operators appear to be reporting what happens to the water one or more steps downstream, rather than simply reporting what happens to the water at the moment it leaves their custody.

Finding 2.2.3. Direct reuse for irrigation provides a more direct pathway of exposure for soil, crops, and human health than indirect reuse.

Conclusion 2.2.1. It is important to differentiate between direct and indirect reuse of produced water. Direct and indirect reuse are not mutually exclusive, making it difficult to distinguish them with a single reporting code.

Recommendation 2.2.1. To distinguish between direct and indirect produced water reuse applications SB 1281 should eliminate the Agriculture and Recharge code and replace it with three codes: “Water Supplier,” “Agriculture,” and “Groundwater Recharge.” If a discharge requires a permit, the operator should report such in a separate field associated with that discharge.

Recommendation 2.2.2. Operators should be responsible only for reporting what happens to the water at the moment it leaves their custody. The eventual fate of produced water after it leaves the hands of the operator should be traced via the permit, not the SB 1281 dataset.

FCR 2.3. Potential for expanded reuse of produced water for irrigation *(Chapter 2, Sections 2.5.1, 2.5.2)*

Finding 2.3.1. According to the SB 1281 dataset, 11,337 AFY of fresh/brackish water (≤ 10,000 mg/L TDS) not currently reused by agriculture was produced in the five major basins between 2015 Q4 and 2017 Q1.

Conclusion 2.3.1. Based solely on the criterion of having a TDS of < 10,000 mg/L, there may be as much as 11,337 AFY of fresh/brackish water available for reuse outside of the O&G industry.

Conclusion 2.3.2. The water quality information in the SB 1281 dataset is inadequate for a complete assessment of water suitability for agricultural reuse intended by the SB 1281 legislation. Additional water quality data are needed to better characterize the potential for expanded reuse of produced water for irrigation.

Recommendation 2.3.1. The Division should carry out the intent of SB 1281 to track water "suitable for domestic or irrigation purposes" by more accurately capturing relevant water quality parameters; at a minimum, quantitative TDS concentrations should be reported. Boron and SAR concentrations are also important for determining irrigation suitability.

Finding 2.3.2. Information to assess the potential for expansion of produced water for reuse was limited.

Finding 2.3.3. Based on available water quality data beyond the SB 1281 dataset, we estimate that there is approximately 64,000 AFY of additional produced water available for expanded reuse with minimal treatment. This potential resource originates from eight fields, all within the San Joaquin basin.

Finding 2.3.4. Where data were available, we found modest potential for expansion outside of the O&G industry for reuse by the agricultural industry. Of the eight fields where data supported a potential for reuse of produced water for agriculture, five currently have known permitted operations for agricultural reuse.

Recommendation 2.3.2. Where there are indications of substantial volumes of produced water with TDS values feasible for reuse, from fields that are in proximity to agricultural regions, the Division should commission a study to conduct a detailed assessment of reuse potential. Such an assessment would evaluate the quality of water produced from each pool in a field for, at a minimum, boron and SAR concentrations; and potentially might consider other analytes of concern for soil and crop health identified in the United Nations Food and Agriculture Organization guidelines (Table 2.3).

Finding 2.3.5. Produced water for reuse is typically obtained from centralized water-handling facilities.

Conclusion 2.3.3. Sampling and reporting requirements for SB 1281 could be simplified by allowing operators to report water quality at centralized water handling facilities when commingled water shows little variation in parameters of interest.

Recommendation 2.3.3. Water samples for assessing quality for agricultural reuse should be obtained from centralized water-handling facilities; in cases where there is significant variability in TDS (or EC), boron, and the SAR between wells, these samples should be taken from single wells.

Recommendation 2.3.4. Research should be undertaken that provides a greater understanding of the technical and economic reuse potential for produced water in California. The study should assess the quality of produced water in alignment with accepted guidelines for irrigation water, as well as the economic cost-benefit analysis of treating and transporting produced water, taking into consideration local conditions.

CHAPTER 3. California Produced Water Quality: Implications for Human Health and the Environment

FCR 3.1. Produced water quality in California *(Chapter 3, Section 3.2)*

Finding 3.1.1. Salinity is reported in SB 1281 as above or below 10,000 mg/L TDS. With the exception of salinity, produced water quality parameters are not reported to SB 1281.

Finding 3.1.2. Chemical constituents that are or may be in produced water (e.g., residual petroleum hydrocarbons, chemical additives, geogenic compounds, daughter products, and degradation byproducts of chemical transformations) are not required to be reported to SB 1281.

Conclusion 3.1. SB 1281 is inadequate in reporting water quality parameters. An understanding of produced water quality is essential to assess the potential for environmental and human health hazards, risks and impacts associated with produced water, to inform produced water management, and to identify opportunities for reuse outside of the oilfield.

Recommendation 3.1.1. Require the SB 1281 dataset to include reporting of actual TDS measurements for all produced water at the level of the oil-water separator or similar point of aggregation.

Recommendation 3.1.2. Priority water quality parameters and other approaches to water quality monitoring should be identified by a convened group of human and environmental health scientists with expertise in produced water quality and human and environmental health.

Recommendation 3.1.3. SB 1281 should require reporting of all priority health- and environmentally-relevant water quality parameters for produced water discharged to the surface (e.g., to agricultural irrigation and unlined produced water ponds).

FCR 3.2. Spatial tracking of produced water from production to disposal and reuse *(Chapter 3, Section 3.2)*

Finding 3.2. The SB 1281 dataset includes water disposition categories that are informative, but produced water disposition reporting lacks adequate spatial resolution. For instance, it may be reported that produced water from a given well in a particular oilfield and production zone was sent to an unlined produced water pond facility, but which pond facility is not clear.

Conclusion 3.2. The lack of spatially-explicit tracking of produced water in the SB 1281 dataset makes it difficult to assess and manage potential environmental, ecological, and human health hazards risks and impacts, at spatial scales relevant to human and environmental exposures.

Recommendation 3.2. Update the SB 1281 dataset requirements to enable regulators to trace the geographic and geological source and fate of produced water to support assessments of environmental and exposure pathways, particularly for produced water discharged to the surface. For example, the use of unique spatial identifiers should be considered: these could include latitude and longitude coordinates for specific produced water pond facilities or water recipient facility locations where water is intended for reuse (e.g. agricultural irrigation).

FCR 3.3. Other produced water quality datasets *(Chapter 3, Section 3.3)*

Finding 3.3.1. Analysis of existing produced water quality information in the State of California currently requires collation from multiple data sources and data formats.

Finding 3.3.2. The existing data may not sufficiently characterize produced waters to allow evaluation with respect to impacts on human and ecological health.

Conclusion 3.3. To assess and manage potential risks and opportunities for produced water discharged to the surface and reused outside of the oilfield, there is a need for a comprehensive and current produced water quality database in the State of California.

Recommendation 3.3. Agencies with jurisdiction should require comprehensive produced water quality monitoring information be disclosed and consolidated into an integrated, digitized, and publicly available database, especially for produced water that is discharged to the surface or reused outside of the oilfield. The SB 1281 dataset, in conjunction with Geotracker, may be a relevant repository for this information.

FCR 3.4. Chemical use in oil and gas operations *(Chapter 3, Section 3.4)*

Finding 3.4.1. The SB 1281 dataset lacks the water quality information necessary to conduct quantitative risk assessments. However, other publicly available datasets can be used in concert with the SB 1281 dataset to assess produced water quality, including chemical additives disclosed as used in O&G operations.

Finding 3.4.2. Chemical additives reported to be used in O&G operations cannot always be identified, and when they can be, they may not be well-described. In datasets supplemental to the SB 1281 dataset, 630 unique chemical additives were identified as used in oil and gas wells and associated operations in California from 2011 – 2018. Nearly half of the disclosed chemical additives could not be definitively identified due to lack of a unique Chemical Abstract Service Registry Numbers (CASRNs). An analysis of available physical, chemical, and toxicological properties of identified chemicals used in O&G operations in California shows that many are poorly characterized and lack important data required to assess health hazards, treatment potential, and environmental fate and behavior.

Conclusion 3.4.1. Available chemical data suggest there are aquatic, air pollution, and carcinogenic chemical hazards associated with produced water in California.

Conclusion 3.4.2. Chemical additives that are not disclosed using CASRN cannot be definitively identified and cannot be evaluated in terms of their potential human health and environmental hazards, risks, and impacts. Available chemical data suggest that there are potential human and ecological health risks associated with produced water where exposure pathways exist.

Recommendation 3.4. All chemical additives used in any type of O&G operation—not just for well stimulation—in California should be required to be disclosed to a publicly available, digitized database. Agencies with jurisdiction could consider phasing out the use of chemicals or chemical mixtures whose identities cannot be verified or disclosed. Submitted data including chemical names, CASRN, and usage data (frequency, mass, or concentration) should be validated and verified. Environmental and toxicological profiles should be developed for chemical additives and, to the extent possible, chemical additive mixtures used in O&G operations that lack any publicly available information.

FCR 3.5. The SB 1281 dataset on produced water treatment categories *(Chapter 3, Section 3.5)*

Finding 3.5.1. The treatment categories used in the SB 1281 dataset are not sufficiently specific; they do not provide the detail necessary to determine which treatment process is being applied. Thus, treatment level cannot be accurately assessed in the context of responsible produced water beneficial reuse potential.

Conclusion 3.5.1. More detailed and specific reporting regarding treatment technologies and treatment trains is required for risk management of produced water, in particular produced water that is discharged to the surface and reused outside of the oilfield.

Recommendation 3.5.1. The SB 1281 dataset on treatment should be modified to require detailed information on the specific treatment process or processes used. The current categories are overly broad and should be abandoned and replaced by detailed descriptions of the actual treatment technology applied (e.g., three-phase separator, WEMCO, ion exchange, walnut-shell filters). The sequence of technologies used to treat produced water should be identified, especially for produced water that is discharged to the surface or reused outside of the oilfield.

Finding 3.5.2. No one treatment technology can be expected to adequately remove all potential chemicals of concern that can exist in produced water, but treatment trains can be developed for functionally complete treatment. Of the screened technologies, reverse osmosis and biological treatment have the greatest potential to treat chemical additives of concern that may be found in produced water intended for reuse outside of the oilfield.

Conclusion 3.5.2.1. Certain chemical constituents are well-proven to be removed by state-of-the-art physical, chemical, and biological treatment approaches. However, some chemical additives reported as used in O&G development operations in California are not expected to be effectively removed by commonly-used physical, chemical, and biological treatment technologies.

Conclusion 3.5.2.2. Further research and applied investigations are warranted to assess the efficacy of removal of chemical additives and other chemical constituents, particularly for applications of produced water discharged and reused at the surface.

FCR 3.6. Evolving chemical landscapes and produced water reuse *(Chapter 3, Section 3.6)*

Finding 3.6.1. Produced water quality is highly heterogeneous across geographic and geological space and operators use a wide variety of chemical additives in their operations. While disclosure of chemicals is expected to result in significantly more information about chemical use, questions remain as to how these chemicals may transform under high temperature and pressure and in the presence of other chemical constituents in oilfield reservoirs and associated processes.

Finding 3.6.2. Produced water can meet traditional water quality standards and still pose toxicological, mutagenic, and carcinogenic risks when there is a human or ecological exposure pathway. These mechanisms are difficult to ascertain without non-targeted or bioanalytical testing.

Conclusion 3.6. Answering questions of produced water quality and associated public health and ecological risks is aided, but not satisfied by, chemical disclosure. While pollutant-by-pollutant chemical disclosure and monitoring is important, produced water reuse outside of the oilfield with human and ecological exposure potential could benefit from more holistic approaches to water quality testing (e.g., non-targeted chemistry and cell line assays) that are not directly focused on understanding all of the chemicals in the mixture. Existing water reuse frameworks that address evolving chemical landscapes (e.g., municipal wastewater) may inform produced water treatment, monitoring, and management.

Recommendation 3.6.1. Agencies with jurisdiction should ensure that the best available research informs their regulations. To this end, they should convene water quality and public health experts to conduct non-targeted water quality research on produced water that is currently or is being considered to be reused outside of oilfields with potential human and ecological exposure pathways (e.g., agricultural irrigation).

Recommendation 3.6.2. More holistic approaches to water quality testing (e.g., non-targeted chemistry and cell line assays) could be integrated into produced water discharge permit requirements as is being considered for municipal wastewater recycling for potable reuse.

CHAPTER 4. Potential Impact to Groundwater Resources from Disposal of Produced Water into Unlined Produced Water Ponds in the San Joaquin Valley

FCR 4.1. Reporting of disposal volumes into unlined produced water ponds pursuant to SB 1281 *(Chapter 4, Section 4.2)*

Finding 4.1.1. Reporting pursuant to SB 1281 indicates that 3,182 AFY of produced water is currently disposed into unlined produced water ponds in the San Joaquin Valley.

Finding 4.1.2. A review of discharge records at the McKittrick 1 & 1-3 Facility (a single facility) indicates that on average 3,152 AFY is disposed into unlined produced water ponds at this facility.

Conclusion 4.1. Because there are numerous active facilities of comparable size to the McKittrick 1 & 1-3 Facility in the San Joaquin Valley, including the McKittrick 1-1 Facility where 1,059 AFY of produced water is currently disposed into unlined produced water ponds, the accuracy of reported volumes pursuant to SB 1281 is in question.

Recommendation 4.1. All facility records should be reviewed to verify that reporting under SB 1281 accurately reflects volumes of disposal of produced water into unlined produced water ponds in the San Joaquin Valley.

FCR 4.2. Produced Water Disposal Method Codes in the SB 1281 dataset *(Chapter 4, Section 4.2)*

Finding 4.2.1. The volume of produced water reported disposed by “other” methods is more than twice the volume of produced water reported disposed into unlined produced water ponds.

Finding 4.2.2. The SB 1281 dataset includes a disposal method category “06 – Other,” which may include, but not be limited to, disposal to unlined produced water ponds, if those produced water ponds are managed by a commercial entity. It is unclear what portion, if any, of this produced water has been disposed of in unlined produced water ponds operated by commercial entities.

Conclusion 4.2. Categories such as “Other” may make parsing out relevant information challenging or impossible, rendering even some straightforward questions unanswerable.

Recommendation 4.2. At a minimum, the SB 1281 dataset should be modified to include “Transfer to Commercial Disposal” to the disposition codes. A more useful code in this case would include the specific method of disposal (e.g. “Commercial Disposal to Unlined Sump”).

FCR 4.3. Spatially-explicit information for produced water ponds: risk assessments *(Chapter 4, Section 4.2)*

Finding 4.3.1. The overall volume and categorical disposition (e.g., reuse, disposal) of produced water is currently reported under SB 1281, but not the spatially-explicit destination.

Conclusion 4.3.1. Without spatially-explicit destination information, it is not possible to trace produced water from a particular oil field or formation to a particular produced water pond, and volumes of produced water discharged to a particular unlined produced water pond cannot be ascertained.

Recommendation 4.3.1. Data reported under SB 1281 should include spatially-explicit destination information (e.g., facility name and latitude/longitude) in addition to disposition of produced water to improve the ability to assess the risk posed to groundwater resources from disposal of produced water into unlined produced water ponds.

Finding 4.3.2. Potential impact to groundwater resources from disposal of produced water into unlined produced water ponds is, in part, a function of annual and cumulative discharge volumes and the quality of discharged produced water.

Conclusion 4.3.2. Though this information is necessary to assess potential impacts of discharging to unlined ponds, data reported to SB 1281 is currently not useful to determine annual or cumulative discharge volumes to individual produced water pond facilities.

Recommendation 4.3.2. Annual and cumulative discharge volumes should be assessed at active produced water pond facilities.

FCR 4.4. Produced water ponds are in areas that have groundwater that is or could be fit for agricultural, municipal, or domestic use *(Chapter 4, Section 4.3)*

Finding 4.4.1. Reporting pursuant to SB 1281 provides information on the locations of produced water ponds and the volumes of produced water disposed in unlined produced water ponds in general.

Finding 4.4.2. Groundwater resources that are or could be used for agricultural, municipal, or domestic use exist in areas of unlined produced water ponds in the central, northwestern, and eastern portion of the Tulare basin. Groundwater resources that could be treated for these uses exist in the western portion of the Kern County subbasin of the Tulare basin. With the exception of the eastern portion of the Tulare basin, where deep groundwater resources are present, groundwater resources having beneficial use appear to be limited to surficial (less than 300 m in depth) deposits.

Conclusion 4.4.1. Due to their shallow depth, many groundwater resources in the Tulare basin with potential for beneficial use may be particularly vulnerable to contamination from unlined produced water ponds.

Conclusion 4.4.2. Discharge of produced water into unlined produced water ponds poses risks to groundwater resources that are currently used or could be used in the future for beneficial purposes.

Recommendation 4.4.1. Agencies with jurisdiction should continue to investigate the use of produced water ponds and require appropriate testing and treatment of any water discharged into produced water ponds.

Recommendation 4.4.2. These agencies should develop a risk prioritization system to designate which unlined produced water ponds require in-depth, site investigations to determine the nature and extent of historical, current, and future impacts from the discharge of produced water. Such a risk prioritization should start with produced water ponds having the greatest present or past cumulative discharge volumes and should also include criteria such as the presence of groundwater resources having agricultural, municipal or domestic uses or potential for use with treatment.

Recommendation 4.4.3. For high-priority produced water ponds, a facility-by-facility assessment should be undertaken to determine where impacts to groundwater resources have already occurred or are likely to occur if the practice continues.

Recommendation 4.4.4. Agencies with jurisdiction should promptly ensure through appropriate testing and treatment that any water discharged into produced water ponds does not contain concentrations of chemicals related to oil and gas development that could impact groundwater resources. Given the potential for impact to groundwater resources, it may be advantageous for these volumes to decrease over time and the agencies with jurisdiction should thoroughly consider alternatives to this practice in the future.

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