THE Water Research FOUNDATION

PROJECT NO.
4993

Potential of Oilfield Produced Water for Irrigation in California

CALIFORNIA
Water Boards
STATE WATER RESOURCES CONTROL BOARD
REGIONAL WATER QUALITY CONTROL BOARDS

Potential of Oilfield Produced Water for Irrigation in California

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Co-sponsored by:
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Abstract and Benefits

Abstract:

Increasing water stress and scarcity in California are motivating interest in supply diversification and a need to better understand the magnitude of opportunities for using alternative supplies such as municipal recycled water and oilfield produced water (OPW). The formal use of municipal recycled water for agricultural irrigation in California dates back more than 100 years. Over this long history, much has been learned on how to safely manage the use of recycled water for agricultural irrigation. Relatively speaking, much less is known about the composition, risks, management, and treatment of OPW. This study was motivated by a desire to translate relevant lessons learned from recycled water into recommendations on the regulation of oilfield produced water in California and assess the relative potential for increasing reuse of oilfield produced water for agricultural irrigation. While there are locally significant opportunities for expanding OPW reuse, this study found that more research and data on OPW are needed to match the scientific basis of California's current recycled water policy.

Benefits:

- Supply diversification is an important characteristic of resilient water systems with alternative supplies at the center of a diversified supply portfolio.
- The use of oilfield produced water is gaining increased attention in California, but many basic knowledge gaps remain.
- Lessons learned in the recycled water sector can help inform future policies around OPW reuse in agriculture.
- Roughly 100,000 to 227,000 AFY of lower salinity OPW is potentially available for reuse. This is approximately 5 to 10 percent of the volume of recycled water potentially available for reuse.
- Current OPW reuse in Kern County demonstrates potential for locally significant demand for additional OPW reuse in this area.
- Additional basic research and data are needed to develop a regulatory framework for OPW that mirrors California's current recycled water policy.

Keywords: Oilfield produced water, Municipal recycled water, Title 22, Fit-for-purpose, Risk assessment, Reuse potential, Agricultural irrigation

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Acronyms and Abbreviations

mg/L	Milligram per liter
µS/cm	MicroSiemens per centimeter
AFY	Acre-feet per year
ATSDR	Agency for Toxic Substances and Disease Registry
BCF	Bioconcentration factors
BOD	Biological oxygen demand
CDWR	California Department of Water Resources
CalGEM	California Division of Geologic Energy Management
CASRN	Chemical Abstract Service registry numbers
CCST	California Council on Science and Technology
CECs	Chemicals/Contaminants of emerging concern
COD	Chemical oxygen demand
COIs	Contaminant of Interest
CIWQS	California Integrated Water Quality System Project
CT	Contact time
CVRWQCB	Central Valley Regional Water Quality Control Board
DOGGR	Division of Oil and Gas and Geothermal Resources
ds/m	Deci-siemens per meter
EC	Electrical conductivity
eSMR	Electronic Self-Monitoring Report
EDC	Endocrine disrupting chemicals/compounds
FAO	Food and Agriculture Organization
FSMA	Food safety modernization act
GHS	Globally harmonized system
ID	Insufficient data
IPIECA	International Petroleum Industry Environmental Conservation Association
IWMS	Irrigation Water Management Survey
MAFY	Million acre-feet per year
MCLs	Maximum contaminant levels
MPN	Most probable number
MRL	Minimal risk level
ND	Non-detect
NORMs	Naturally occurring radioactive materials
NPDES	National Pollutant Discharge Elimination System
NTU	Nephelometric turbidity unit
O&G	Oil and gas
OPW	Oilfield produced water
OSF	Oral slope factor
PAHs	Polycyclic aromatic hydrocarbons
PRC	Public Resources Code

RWQCB	Regional Water Quality Control Board
SAR	Sodium adsorption ratio
SB	Senate Bill
SGMA	Sustainable Groundwater Management Act
SWRCB	State Water Resources Control Board
TDS	Total dissolved solids
TSS	Total suspended solids
USDA	United States Department of Agriculture
WDR	Waste discharge requirements
WQO	Water quality objectives

Executive Summary

ES.1 Introduction

Current research shows that climate change is driving greater hydrologic extremes in California, including more severe and prolonged droughts (Swain et al. 2018). Historically, agricultural communities have turned to groundwater during periods of surface water scarcity, but groundwater levels are declining faster than they're recharging, and the Sustainable Groundwater Management Act (SGMA) will curtail future withdrawals. Increasingly dry conditions, coupled with decreased access to groundwater, have motivated increased interest in supply diversification, as well as a need for a better understanding of opportunities for using alternative supplies such as municipal recycled water, oilfield produced water (OPW), and stormwater (SWRCB 2018; CDWR 2014). Past work by the California Council on Science and Technology (CCST) SB 1281 study, 'Assessment of Oil and Gas Water Cycle Reporting in California' (Shimabuku, Abraham, and Feinstein 2019), and the Central Valley Regional Water Quality Control Board (CVRWQCB) Food Safety Project (Mahoney, Asami, and Stringfellow 2021) highlighted the current state of knowledge surrounding produced water[1] use and identified substantive knowledge and data gaps. The two primary objectives of this project include:

- Objective 1: Evaluate Title 22 Recycled Water Regulations as a Science and Policy Template for Oilfield Produced Water
- Objective 2: Geospatial Model and Map of Potential for Oilfield Produced Water Reuse

The following sections describe key findings related to each these objectives with additional detail and discussion in the main body of the report.

ES.2 Scientific and Procedural History of Title 22 Recycled Water Regulations

The formal use of recycled water for agricultural irrigation in California dates back more than 100 years. California currently uses approximately 728,000 AFY[2] of recycled water, of which 195,000 AFY is used for agricultural irrigation. Recent estimates identified roughly 1.8-2.1 million acre-feet per year (MAFY) of treated wastewater potentially available for additional reuse (Cooley et al. 2022). Management, monitoring, and regulation of recycled water use has evolved significantly over the years into California's current risk-based, fit-for-purpose[3] approach to mitigating and managing potential public health risks associated with the use of recycled water. Recycled water use in California is authorized, regulated, and managed via the Porter-Cologne Water Quality Act, Titles 17 and 22 in the California Code of Regulations, the State Recycled Water Policy and water quality criteria. Current standards for recycled water used for agricultural irrigation are composed of five primary elements:

- Definition of four water quality-based classes of Title 22 recycled water

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[1] Produced water is water that is extracted alongside oil and gas during extraction activities. It includes water, residual oil and gas, and chemicals (both naturally occurring and those used in production activities).

[2] AFY = acre-feet per year; 1 AFY = 325,851 gallons/year

[3] Fit-for-purpose approaches match the quality of recycled water to be reused and with allowable beneficial uses (e.g., irrigation of food crops consumed raw). In Title 22, classes of recycled water are defined based on treatment performance and risk assessments.

- Specifications on the types of crops that can be grown with each of the different classes of Title 22 recycled water
- Treatment requirements (e.g., oxidation, disinfection)
- Water quality monitoring requirements and standards for process indicators - total coliform and turbidity (disinfected tertiary only)
- Title 22 engineering report and anti-degradation analysis

Recycled water quality criteria were designed to minimize risk and assess whether treatment processes are performing in a manner that is adequately protective of public health. These standards are underpinned by detailed risk assessments (Olivieri et al. 2014) and numerous research studies assessing how well treatment processes perform in removing actual pathogens and other constituents of concern in recycled water (Sheikh et al. 1990; Williams et al. 2007).

ES.3 Review of Scientific Literature and Identification of Data Gaps on Oilfield Produced Water

The uncharacterized, complex, and variable chemical makeup of oilfield produced water has sparked concerns surrounding its long-term use for irrigating food crops. In general, produced water has higher concentrations of chemicals and other constituents, both naturally occurring and chemical additives used in oil and gas production, including salts (e.g., sodium, chloride), organics (e.g., aromatic hydrocarbons, polycyclic aromatic hydrocarbons [PAHs]), trace elements and heavy metals (e.g., arsenic, boron, cadmium), and naturally occurring radioactive materials (NORMs) relevant to human, crop, and soil health. Many are toxic to humans and are known carcinogens (e.g., arsenic and cadmium), mutagens, and endocrine disrupting chemicals (e.g., PAHs) that have the potential to form compounds with increased toxicity, become phytoavailable, and potentially enter the food chain and cause chronic illnesses. Accumulations in soils may also have negative consequences to plants and soil health including stunted growth, decreased biomass and yield, plant death, and reduced soil biodiversity.

Notable gaps on the chemical makeup, toxicity, and transformation products; fate and transport; and plant uptake and accumulation have been identified as prohibitive for conducting a rigorous risk assessment and drawing conclusive findings. Exposure routes are diverse (Figure ES-1) and chronic exposure to low concentrations of some of these chemicals may have effects not yet observed or measurable. More information is needed to fill these gaps including chemical mass or concentrations, frequency of use, and the impacts on crops and soil ecosystems to fully assess the human health and agronomic risks associated with the long-term for agricultural irrigation.

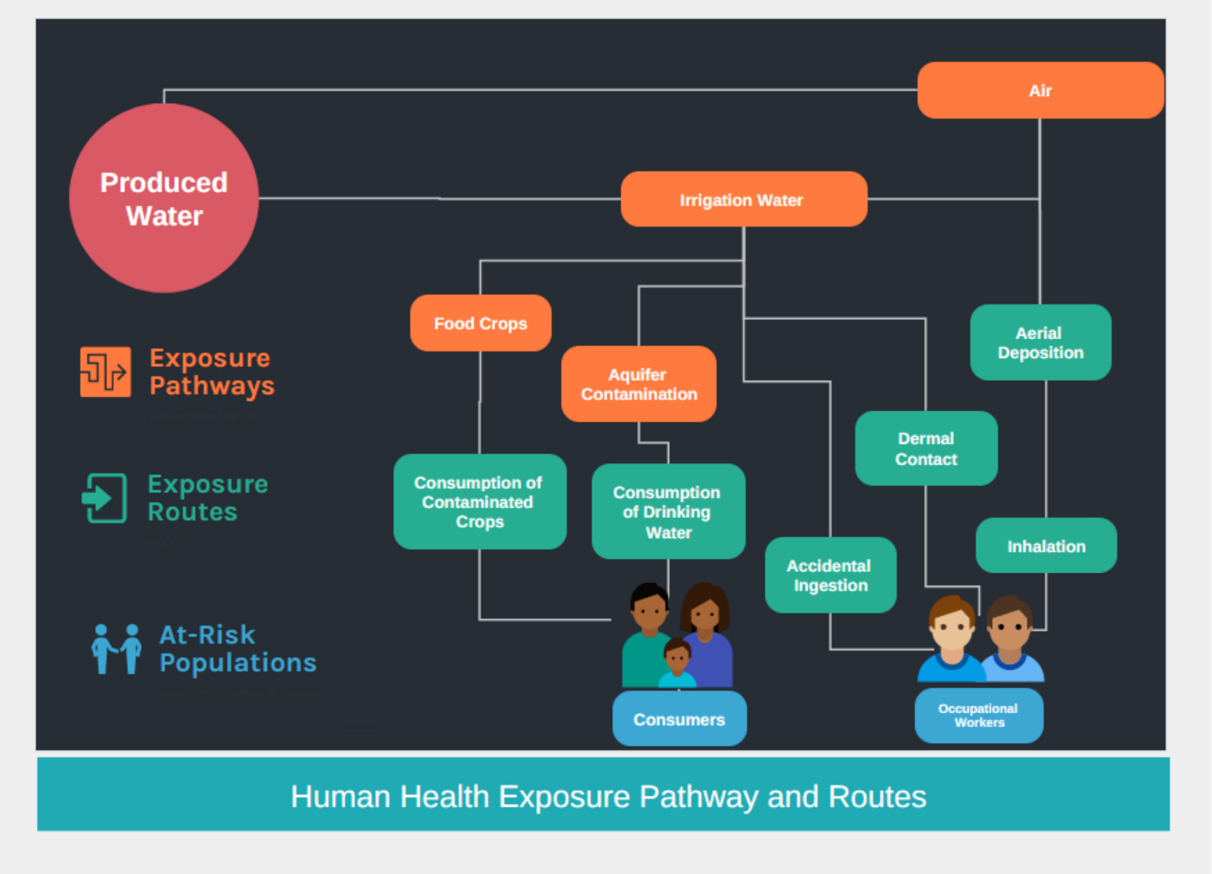

Figure ES-1. Potential Exposure Pathways and Routes for COIs that May be Present in Oilfield Produced Water.

ES.4 Reuse of Oilfield Produced Water in California

Two recent research efforts, the CCST SB 1281 study and the Food Safety Project, were initiated to evaluate current use and knowledge of oilfield produced water used for agricultural irrigation and to answer key questions on the safe use of oilfield produced water in California. Using a variety of data sources obtained from monitoring and reporting programs (e.g., SB 1281 reporting and waste discharge requirements, WDRs) and independent research, each study identified significant gaps.

Attempts by the CCST SB 1281 study to identify opportunities for expanding reuse in agriculture were challenged by inconsistencies and errors in reporting methods, poor characterizations, and redundancies in reporting data. Data on the quality and treatment methods used for produced water was reported as insufficient for determining suitability and safety of produced water. In addition, there is a general lack of data on chemical fate and transport, phyto-availability, and accumulation of many of the chemicals of interest in agronomic settings.

There was substantial alignment between many of the findings of the two studies including recommendations to continue, refine, and expand current OPW monitoring programs such as SB 1281 reporting and additive disclosure programs. Both studies found that many chemicals present in OPW lack standardized analytical methods, toxicity data, or were unidentifiable due to trade secrets. The CCST SB 1281 study indicates that oilfield produced water in California is likely to contain toxic and carcinogenic chemicals, and that available data is insufficient to fully assess the safe use. In addition to concentrations of chemicals of interest in water, the Food Safety Project also assessed concentrations of select chemicals in food crops. The Food Safety Project found that the chemical composition of crops irrigated with oilfield produced water were similar to those irrigated with conventional (surface or groundwater) sources, but significant limitations in analytical methods, transformation products, and general challenges in capturing a representative sample were noted. Due to these limitations, the Food Safety Panel recommended discontinuing food crop sampling to focus on increased water and soil sampling.

ES.5 Prioritize Data Needed in Support of an Oilfield Produced Water Fit-for-Purpose Classification Framework

To date, reuse of OPW for irrigation is a fairly limited practice in California that has not been subject to the same level of rigorous scientific and regulatory scrutiny as municipal recycled water (Heberger and Donnelly 2015). One of the basic hypotheses motivating this study was that there are unrealized opportunities to apply learnings from California's regulation and management of the recycled water for agricultural irrigation to the use of OPW for agricultural irrigation.

A risk-based approach underpins California's current Title 22 Water Quality Criteria which are then operationalized as a fit-for-purpose approach to managing the use of recycled water for agricultural irrigation (Figure ES-2).

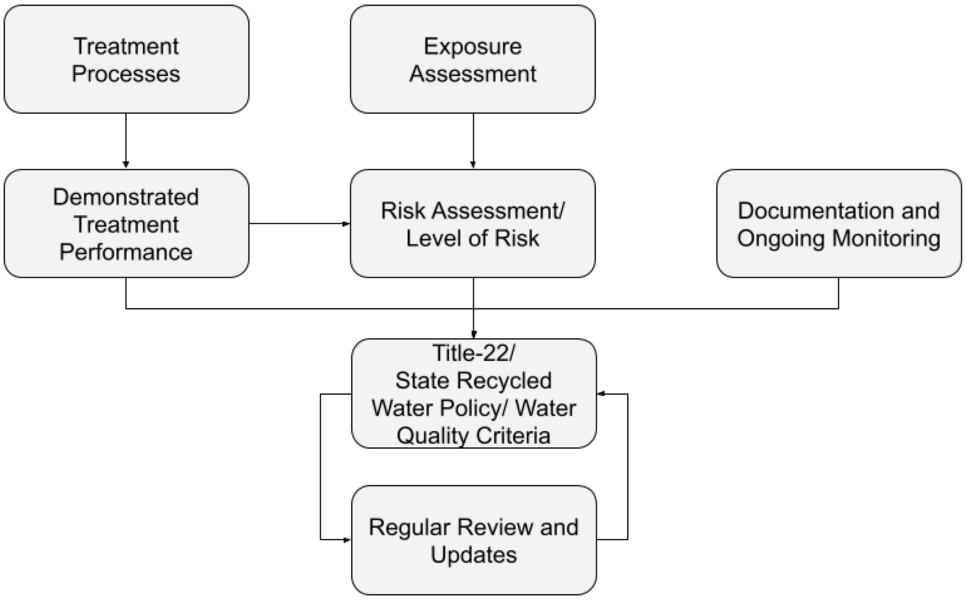

Figure ES-2. Summary of Risk Assessment and Management Activities Informing Development and Updates of California's Recycled Water Policy.

Potential water quality-related risks associated with both recycled water and OPW are diverse and variable. The maturity of our understanding of the composition of these waters and the efficacy of standard treatment processes varies widely across different constituents of concern. Understanding both overall water quality and how it varies over time and space is an essential component in understanding and managing potential risks associated with the use of alternative water supplies. Substantive basic knowledge gaps surrounding the composition, toxicity, and use of produced water were identified in this and other studies (Shimabuku, Abraham, and Feinstein 2019; Mahoney, Asami, and Stringfellow 2021). Without additional research, data, and risk assessments of produced water reuse, the potential for direct adoption and operationalization of many of the risk-based principles underpinning Title 22 is limited.

ES.6 Geospatial Model of Potential for Expanded Reuse of Oilfield Produced Water

In California's agricultural regions where water is increasingly scarce, OPW may have a larger role to play in reducing water stress. However, challenges still exist to expanding reuse of OPW for irrigation. A geospatial model was developed to help assess several factors that influence the potential for expansion of OPW reuse at a regional level. Results of the model are focused on the southern Central Valley, an area where oil and gas fields are co-located with agricultural fields, and there is ongoing, high-water stress. Here, potential for expanded OPW reuse from 19 oil and gas fields in Kern County is possible (Figure ES-3). Available water quality and quantity data indicates there may be 227,650 AFY of OPW suitable for irrigation (likely with treatment and/or blending) of at least some crops found in the region. Of this volume, 100,177 AFY is located in oilfields where average total dissolved solids (TDS) concentrations are below the maximum threshold for tolerant crops (5360 mg/L). Unfortunately, significant data gaps create challenges to understanding the certainty and strength of these findings. Data gaps identified include: Crop type and crop location, crop sensitivities based on irrigation types, OPW water quality (in amount of analytical samples, type of constituents included, and age of sample data), OPW water quantity estimates, location and capacity of infrastructure for transporting and storing OPW for reuse by irrigators, soil characteristics that impact water suitability, costs of alternatives and how these costs are expected to change in the future and/or vary under different scenarios such as drought, existing and predicted future regulatory barriers and hurdles, and sociological and political factors of key stakeholder groups. In so much as the model and its output can be used, they are intended to support regional-level decision making only; more site-specific opportunities will need to be explored in future work.

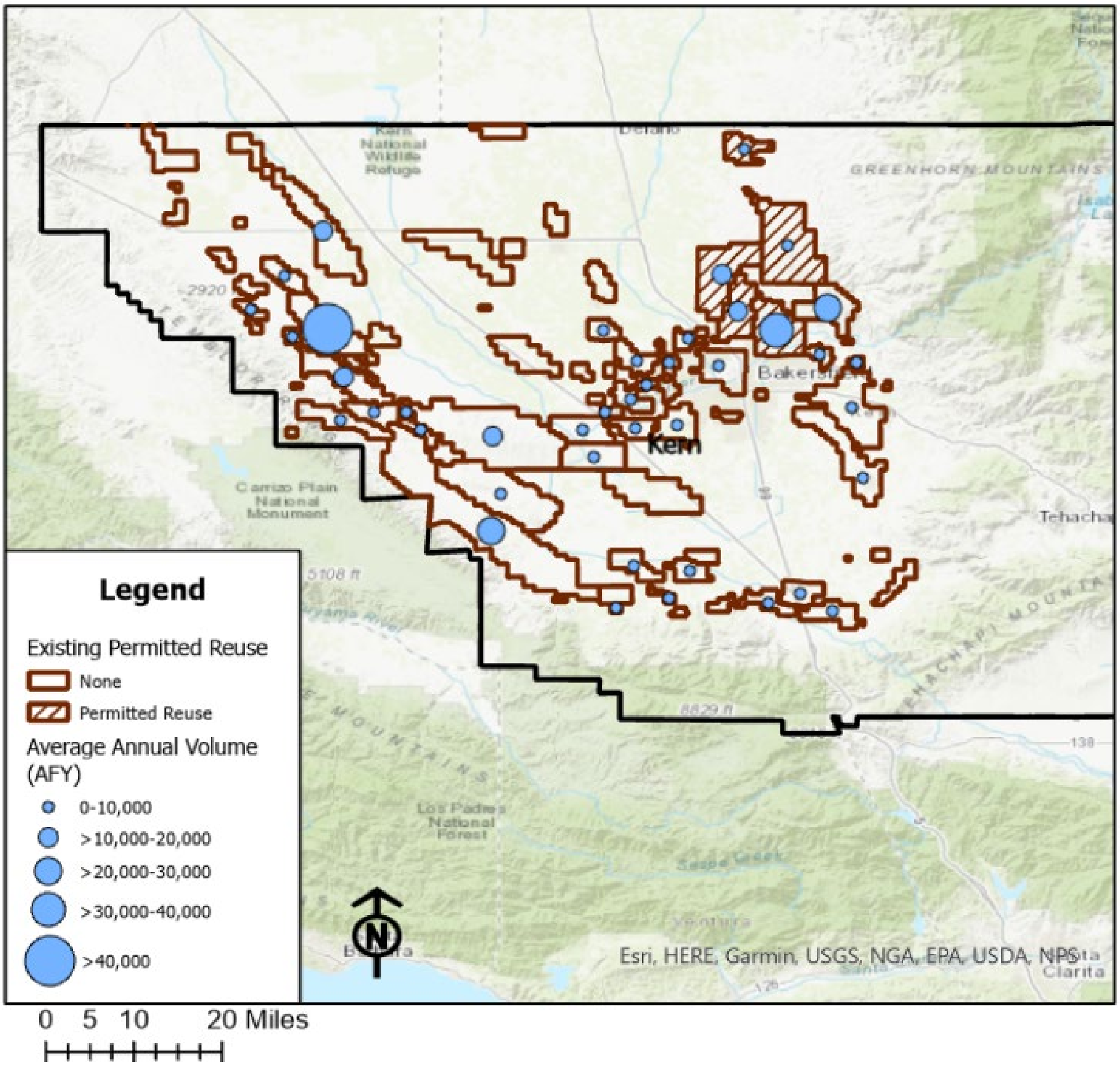

Figure ES-3. Map of Western Kern County Oil and Gas Fields with Average Annual Volume (AFY) of OPW.

ES.7 Conclusions

Regular, sustained droughts, curtailments on groundwater withdrawals with SGMA, and other stressors constrain the quantity of supply available to support California's economic, environmental, and societal needs. The State Water Plan identified the use of alternative supplies as a critical strategy in meeting the State's water demand now and in the future. California's long history using municipal recycled water for agricultural irrigation provides important insights into the benefits and challenges of monitoring, regulating, and managing the use of alternative supplies. OPW presents several unique challenges relative to recycled water including greater uncertainty on water composition (including temporal and spatial variability) and differences in the level of information available to support quantitative risk assessments. Fit-for-purpose approaches operationalize complex information on risk and treatment performance into practicable design, operation, and monitoring requirements. The knowledge gaps discussed in this report and other recent studies (CCST SB 1281 and Food Safety Project) point to several key areas where additional research, data and monitoring, risk assessments, and other information are needed to develop a regulatory framework for OPW that mirrors the approach and fit-for-purpose best practices adopted in regulations on the use of recycled water in California.

ES.8 Related WRF Research

- Agricultural Reuse- Impediments and Incentives (4775)
- Addressing Impediments and Incentives for Agricultural Reuse (4956)
- Assessing the State of Knowledge and Impacts of Recycled Water Irrigation on Agricultural Crops (4964)

CHAPTER 1

Introduction

1.1 Motivation and Background

As of May 2022, California is in the third year of a prolonged drought with more than 95 percent of the state, including prime agricultural regions in the Central Valley, experiencing severe, extreme, or exceptional drought (National Drought Mitigation Center n.d.). This drought follows on the heels of California's record breaking 2012-16 drought. Current research shows that climate change is driving greater hydrologic extremes in California, including more severe and prolonged droughts (Swain et al. 2018). To date, many agricultural regions have turned to groundwater when surface water supplies were curtailed during droughts (Howitt et al. 2015; Cooley et al. 2015). However, California's Sustainable Groundwater Management Act (SGMA) will curtail future groundwater withdrawals for agricultural irrigation in many regions. Increasingly dry conditions coupled with decreased access to groundwater have motivated increased interest in supply diversification and better understanding opportunities for using alternative supplies such as municipal recycled water, oilfield produced water, and stormwater (SWRCB 2018; CDWR 2014). In parallel, the oil and gas industry is facing greater regulation and restrictions on other avenues of produced water disposition, such as Class II Underground Injection wells and percolation pits. This is pushing operators to seek alternative means of disposal. Specifically, 2014 regulations prohibited the use of pits for produced water from hydraulically fractured wells, and underground Injection well permits are being reviewed and selectively revoked (CA Public Resources Code Section 1786; and CA DOGGR 2018).

While the reuse of oilfield produced water for agricultural irrigation has been permitted on an ad hoc, regional basis for more than 30 years, our understanding of the practice and the maturity of regulations is comparatively limited relative to the use of municipal recycled water for agricultural irrigation. This has prompted greater scrutiny from regulators and environmental groups while also motivating two state-funded projects assessing current information and understanding of the health and agronomic risks and knowledge gaps surrounding the use of produced water for agricultural irrigation. The findings of these two studies, the Central Valley Regional Water Quality Control Board (CVRWQCB, or Board) Food Safety Project (FSP) and the California Council on Science and Technology (CCST) study "An Assessment of Oil and Gas Water Cycle Reporting in California" (CCST SB 1281 Study) are discussed at length throughout this report.

1.2 WRF 4993 Project Objectives and Report Overview

This combination of factors served as the impetus motivating WRF 4993 "Potential of Oilfield Produced Water for Irrigation in California." The primary objectives and sub-objectives of this project include:

Objective 1. Evaluate Title 22 Recycled Water Regulations as a Science and Policy Template for OPW

- Objective 1.1 Review Scientific and Procedural History of Title 22 Recycled Water Regulations
- Objective 1.2 Review Scientific Literature and Identify Data Gaps on OPW Reuse
- Objective 1.3 Prioritize Data Needed in Support of an OPW Fit-For-Purpose Classification Framework

Objective 2. Geospatial Model and Map Potential for OPW Reuse

- Objective 2.1. Bring Together Spatial Information to Inform Map
- Objective 2.2. Generate Map Showing Potential for Reuse of OPW
- Objective 2.3 Create an Online, Interactive Version of Map to Support Decision Makers

Objective 1 was motivated by the identification for potential opportunities to learn from California's 100+ year process of developing and revising its recycled water regulations on agricultural use of recycled water. Chapter 2 summarizes the history and current state of recycled water regulations in California (Objective 1.1). Chapters 3 and 4 review current data and research on the quality of produced water, risks, and potential impacts on human and agronomic health (Objective 1.2). These chapters include discussion of data or knowledge gaps surrounding the reuse of produced water. Chapter 5 pulls together knowledge on recycled water and produced water to discuss data needs for development of a fit-for-purpose classification of produced water (Objective 1.3).

A basic assessment of the potential for produced water reuse in California was conducted as part of the CCST SB 1281 report. Objective 2 was motivated by recognition of additional opportunities for developing more granular assessments of 'potential' and a need to make the analysis products more accessible via online mapping platforms. The methods and results from this analysis are discussed in Chapter 6.

1.3 What is Produced Water?

Subsurface formations are permeated with a mixture of water and petroleum hydrocarbon products (PHCs) that make up oil and gas (US EPA n.d.). Over time, the hydrocarbons migrate towards the surface of the earth through porous sedimentary rock to form hydrocarbon reservoirs where they can be recovered. Conventional recovery methods use natural pressure or pumping to bring hydrocarbons to the surface through a vertically drilled borehole and can be classified as primary, secondary, or tertiary methods (enhanced oil recovery) (DOE n.d.). Unconventional recovery relies on other methods, including horizontal and directional drilling or hydraulic fracturing (fracking) of bedrocks using pressurized liquids for extraction and are more complex and expensive than conventional methods (Hart Energy n.d.).

During conventional primary recovery, a well is drilled down to reach the reservoirs and natural pressure brings the hydrocarbons to the surface (Hart Energy n.d.). As the well ages, the natural pressure is no longer enough to bring the hydrocarbons to the surface and secondary recovery is needed. During this process, water or gas is injected into the wellbore to recover an additional 20 to 40 percent of the original volume (DOE n.d.). Enhanced oil recovery (EOR) uses thermal recovery, gas injection, or chemical injections to recover even greater volumes, between 30 to 60 percent of the original oil from the reservoir (DOE n.d.).

Unconventional oil and gas recovery is capable of extracting hydrocarbons that are difficult to access. After the wellbore is drilled to the target location, pressurized water, proppants, and other chemicals are then pumped into the well to fracture the geologic formation targeted for production at economic levels, releasing the recoverable quantities of hydrocarbons and associated produced water to the surface to be recovered (Jackson et al. 2014).

Hydraulic fracturing practices in California differ from other states due to the unique geology of the reservoirs. On average, drilling generally occurs at shallower depths (less than 600 meters deep as compared to several kilometers in other states) and requires less volume of water, approximately

140,000 gallons per well [4] (CCST and LBNL 2015; Jackson et al. 2014). The majority of the hydraulically fractured wells in California are drilled vertically or directional and more than 95 percent of fracking activities use a crosslinked gel as the stimulation fluid (CCST and LBNL 2015). While an advantage to using gel-based fluids is that a reduced volume of water is required to produce simple fractures with wider openings, there are typically higher concentrations of chemicals used in the process (CCST and LBNL 2015).

During these processes, water and other liquids are brought to the surface. These oil and gas produced waters (Figure 1-1) can be classified as either 'recovered fluids' or 'produced water' and are distinguished by the origin, composition, timing, volume, and flowrate. While they are distinct, similarities in chemical composition of produced waters do exist and allowable end uses may vary accordingly. For example, oilfield produced water containing stimulation fluids are not allowed for reuse in agricultural irrigation, and a thorough chemical analysis may be needed to differentiate the two.

Recovered fluids, or flowback water, are the fluids that have been injected into the well during hydraulic fracturing and then recovered at the surface before the well is in production. These fluids can contain residual oil and gas, stimulation fluids, clays and sand, chemical additives and transformation products, well cleanout fluids, dissolved metals, and other dissolved solids (Termine Group n.d.). The majority of the recovered flowback, between 20 and 40 percent of what was injected, occurs within the first 10 to 30 days after fracturing and at a much higher flowrate than the produced water.

After the well is in production, the naturally occurring water that exists within the formations is brought to the surface along with the oil and gas. This is the produced water and contains the naturally occurring formation water consisting of salts, trace elements, organics, and naturally occurring radioactive materials (NORMs). It may also contain other chemicals and transformation products used during the extraction process as well as residual oil or gas. The composition of produced water depends on the type of hydrocarbon being produced (gas or oil), geographical location, age of the well, and the chemicals used during the extraction process (Veil et al. 2004). The produced water flows over a much longer time frame than recovered fluids, generally throughout the life of the well, but at a lower flowrate than flowback water (Termine Group n.d.).

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[4] Average water use per well varies considerably in the U.S due to several factors. These include the geologic formation and age of well, drilling direction (vertical, horizontal, or directional), the stage of production, operator, and whether water is recycled during the process. These volumes can range between 140,000 gallons (California) to 16 million gallons. For example, horizontal wells in the Eagle Ford Formation in Texas use approximately 4.3 million gallons (CCST and LBNL 2015).

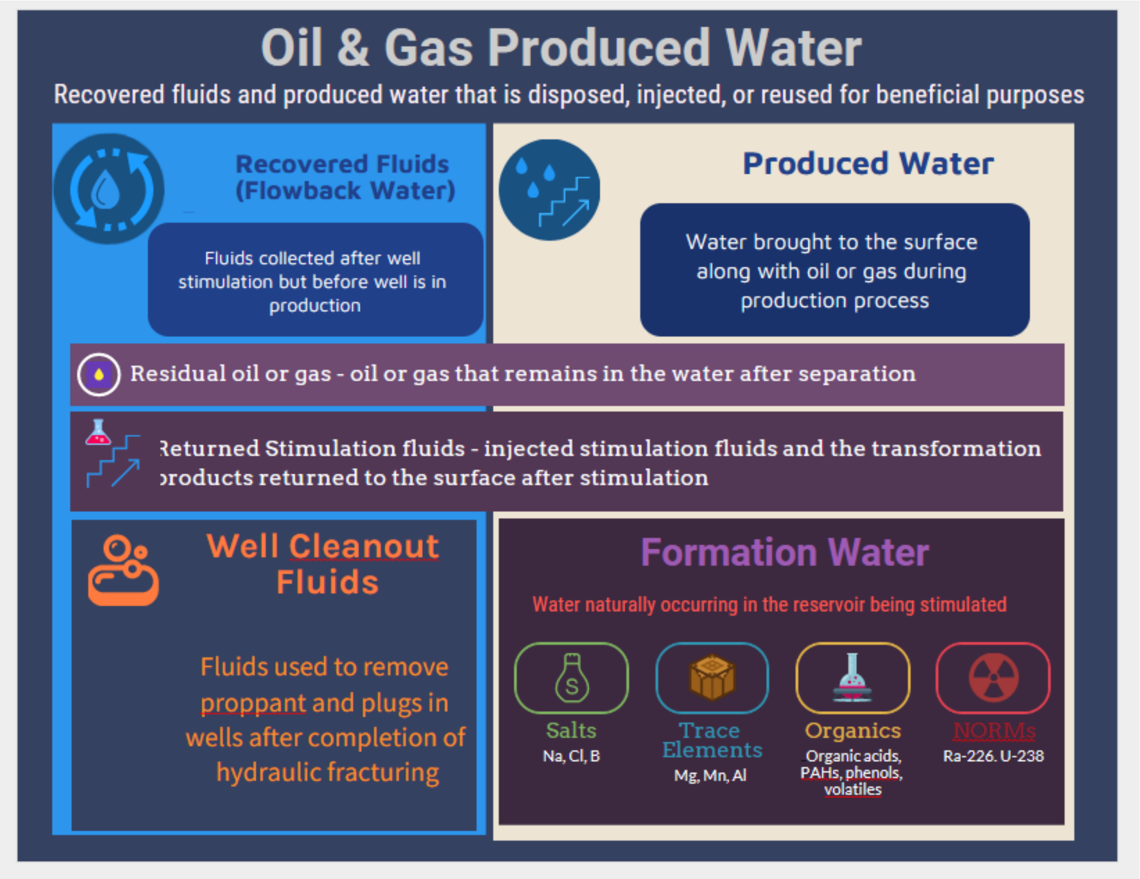

Figure 1-1. Major Constituents of Oil and Gas Produced Water.
Source: Adapted from CCST 2015.

1.4 Overview of Recent Synthesis Reports on Produced Water Use in California

Reports were recently published from two projects (Food Safety Project and CCST SB 1281 Study) evaluating the safety of using produced water for agricultural irrigation and identifying knowledge and data gaps surrounding this practice in California. The scope and approach of these projects are described in this section. The relevant findings from these two projects are included in pertinent sections throughout this report and discussion. The scope of these projects has substantial overlap with certain chapters in this report. As such, this report seeks to synthesize and summarize the findings of these reports plus other research on OPW quality and reuse then discuss these findings in the context of current knowledge of and regulatory approaches for recycled water.

1.4.1 California Council on Science and Technology Assessment of Oil and Gas Water Cycle Reporting in California

Prior to the signing of Senate Bill (SB) 1281 in 2014, reporting requirements under Section 3227 of the California Public Resources Code (PRC) mandated well owners to provide the Division of Oil, Gas, and

Geothermal Resources (DOGGR)[5] with monthly statements containing information on the volume of water, oil, and gas produced from each well. However, to better manage the State's water resources, decision makers needed a deeper understanding of the life cycle and quality of water used in the oil and gas fields. The SB 1281 data, reported on a quarterly basis, expands on the monthly reporting required by the PRC at finer detail. A standardized format, separated into four reports: 1. Production, 2. Injection, 3. Other Allocation, and 4. Well-to-Well Allocation, facilitates the collection of information on water volumes, water treatments, water quality, storage and disposition, and the reuse of water in production activities going into and out of wells.

DOGGR commissioned CCST to conduct a third-party assessment on the utility and effectiveness of the SB 1281 data, either alone or in conjunction with other data sets and provide decision makers with information to better inform policy and guide research. The study directly assessed several components of the SB 1281 data, in addition to other publicly available datasets, to evaluate the overall ability of the data collected within these reports to answer questions on water resources, public health, and the environment related to OPW production, current reuse, and potential for reuse expansion. Specifically, the study sought to identify the sources, volumes, and quality of water used in the production of oil and gas, estimate potentially available volumes for agricultural reuse, and understand how these vary across the state over time. The research team assessed how treatment technologies impact water availability; what hazards, risks, and impacts to humans and the environment exist or potentially exist as a result of discharging OPW into the environment; and the potential to expand OPW reuse opportunities outside of the oilfields.

From the SB 1281 data, the research team estimated approximately 413,000-acre feet per year (AFY) of water is produced within the five major California basins. Based on the single water quality parameter collected in the SB 1281 report, for a threshold of total dissolved solids (TDS) < 10,000 mg/L, an average annual 11,000 AFY (of the 413,000 AFY produced) was estimated to be available for agricultural reuse. Using water quality data from additional reports and placing thresholds for TDS (< 2,000 mg/L) and boron (< 3.0 mg/L) based on guidelines for agricultural irrigation waters (Ayers and Westcot 1985), an annual average of 64,000 AFY of produced water requiring minimal treatment was estimated as potentially available for agricultural reuse. The large differences in estimations could be the result of over and under – estimations due to how data is collected and reported in these reports.

Gaps in data collection and methods, practices, and knowledge related to the SB 1281 data and other publicly accessible data sets were identified and outlined in the SB 1281 final report (Shimabuku, Abraham, and Feinstein 2019). Recommendations to improve data collection and reporting as well as areas for future research based on the findings were also provided to DOGGR to help fill the identified gaps.

1.4.2 Central Valley Regional Water Quality Control Board Food Safety Project

The Food Safety Project was initiated by the Board in response to health-related concerns from the public and environmental groups surrounding the use of oil and gas produced water in agricultural irrigation. To provide a third-party assessment, the Board commissioned a consultant, GSI, to evaluate the safe use of produced water to irrigate food crops. The Board also convened a Food Safety Expert

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[5] DOGGR is now the California Geologic Energy Management Division (CalGEM).

Panel to review the findings. The three-pronged approach first identified and prioritized a list of chemicals that are known to be present, or have the potential to be present, in oil and gas produced water. These chemicals of interest (COIs) included both naturally occurring chemicals and those used as additives in the production of oil and gas. A variety of published sources were used to prioritize COIs for further evaluation primarily based on available oral toxicity and biodegradation information. The second phase, Task 2, included a literature review focused on the COIs identified in Task 1 as they related to produced water in agricultural irrigation and to identify other potential irrigation sources of these chemicals. Task 3[6] was a continuation of chemical analyses of sampled crops[7] grown with and without produced water. Task 3 ran concurrent with Tasks 1 and 2, and the results were used to inform the identification of the COIs from Task 1.

Throughout the length of the Project, the Food Safety Expert Panel held working groups to provide insight and technical recommendations. After the completion of the project, the Panel evaluated GSI's findings to provide the Board with answers to key health and safety questions related to oilfield additives, the potential for immediate or long-term health effects, and if the current waste discharge requirement permits (WDRs) are adequate to protect public health or if additional conditions should be placed on produced water used to irrigate food crops.

1.5 WRF 4993 Report Overview

The following sections in this report summarize key gaps in data collection, reporting, practices, and the current state of knowledge identified in the Food Safety Project reports, CCST SB 1281 study, and other resources.

- Chapter 2 provides a brief history of California's Title 22 recycled water regulations
- Chapter 3 is a review of the scientific literature and data gaps on oilfield produced water
- Chapter 4 summarizes current reuse of oilfield produced water in California
- Chapter 5 prioritizes data needed for a 'fit-for-purpose' approach for reuse of oilfield produced water
- Chapter 6 shares findings from a geospatial model assessing where reuse of oilfield produced water has the potential to expand in California based on water availability, irrigation needs, and water quality

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[6] Existing data from water, produced water, and blended produced water were considered when GSI reviewed the thirteen factors but were not the primary tool used to identify the COIs (GSI 2020).

[7] Task 3 built upon previously sampled crops from 2017, prior to the start of this project. Data collected during both the 2017 and Task 3 sampling events were used as a reference point for concentrations of chemicals likely to be detected in crops irrigated with blended produced water (GSI 2020).

CHAPTER 2

Scientific and Procedural History of Title 22 Recycled Water Regulations

2.1 Introduction

To date, reuse of OPW for irrigation is a fairly limited practice in California that has not been subject to the same level of rigorous scientific and regulatory scrutiny as municipal recycled water (Heberger and Donnelly 2015). As public pressure to investigate and oversee OPW reuse grows, it is evident that the careful scientific vetting and policy procedures employed to develop Title 22 recycled water regulations may provide useful insights into the development of harmonized regulations on the reuse of OPW for agricultural irrigation. This chapter aims to:

- Summarize the current state of agricultural reuse in California;
- Describe the history of how contemporary Title 22 recycled water regulations were developed and revised, both from the perspective of scientific investigation and public processes; and
- Discuss the thinking and rationale behind the regulations that were enacted, and how they balanced health and environmental stewardship with technical and financial feasibility.

Subsequent chapters provide additional background on OPW, its use in irrigated agriculture, and similarities and differences in regulatory approaches for municipal recycled water and OPW.

2.2 Current State of Agricultural Water Reuse in California

2.2.1 SWRCB Volumetric Annual Reporting

As of 2019, the State Water Resources Control Board (SWRCB) mandated the annual collection of data on wastewater production and reuse by all municipal wastewater and/or recycled water National Pollutant Discharge System (NPDES) and WDR permit holders in California. California currently reuses 728,000 AFY of recycled water of which 195,000 AFY is used for agricultural irrigation. The scale and distribution of current agricultural reuse varies widely across the state, ranging from small projects with a single grower through large, complex projects with large irrigation districts (Figure 2-1). Existing reuse of OPW is not included in the SWRCB volumetric annual reporting data.

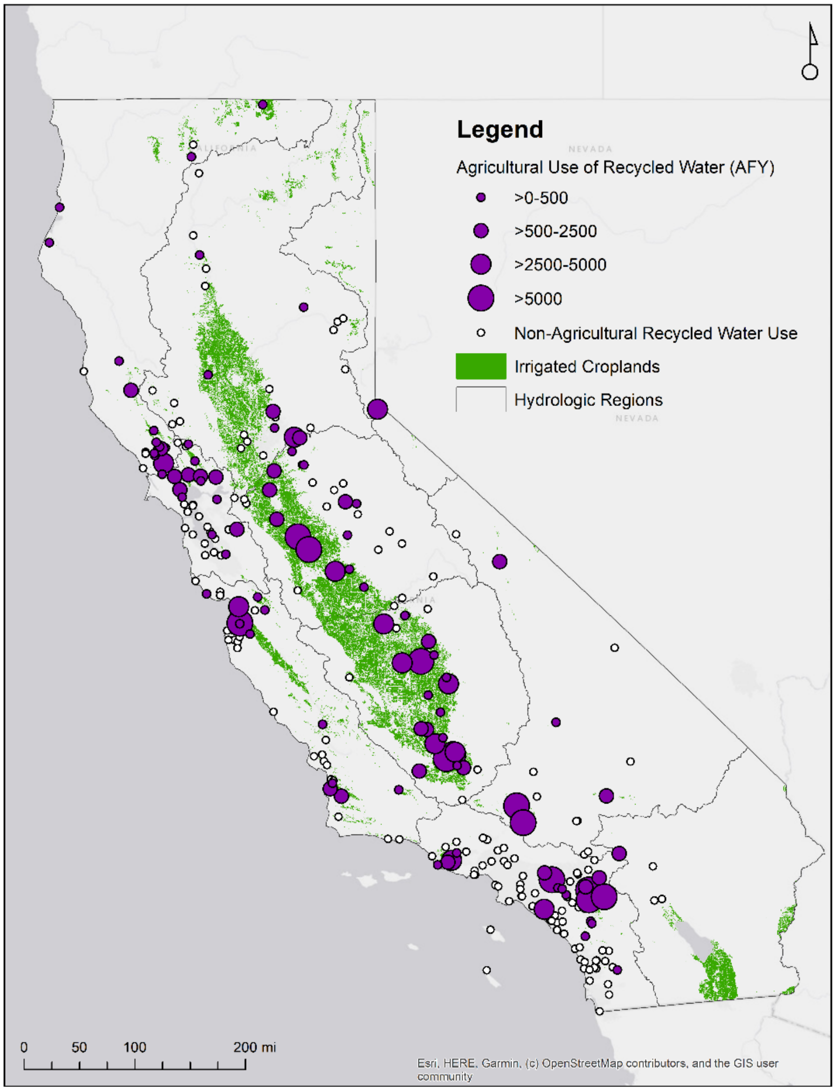

Figure 2-1. Current Agricultural Use of Municipal Recycled Water in California and Existing Irrigated Croplands.

2.2.2 USDA Irrigation Water Management Survey

The USDA Census of Agriculture collects information on the use of alternative water supplies for agricultural irrigation via the Irrigation Water Management Survey (IWMS) (formerly the Farm and Ranch Irrigation Survey). A key difference between the IWMS and SWRCB Volumetric Annual Reporting data is the inclusion of multiple on and off farm sources of reclaimed water. Farms in California report using a broad range of alternative supplies (Figure 2-2) in the USDA IWMS data. In the 2018 IWMS survey, 777 farms irrigating 261,000 acres reported using 378,000 AFY of reclaimed water[8] for irrigation

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[8] The USDA IWMS defines reclaimed water more broadly that the California's Recycled Water Policy. In the USDA IWMS reclaimed water is defined as "Reclaimed water is wastewater that has been treated for non-potable reuse

in California (USDA 2018b). For comparison, there were 42,093 farms in California that reported using irrigation. These farms irrigated 8.4 million acres and used 24.5 million acre-feet of water in 2017. Since most OPW that is reused is treated then blended with normal canal water, a portion of this reuse is likely captured in the total amount of water used for irrigation reported to USDA but is underrepresented in estimates of reclaimed water since the growers responding to the survey likely do not know what portion of delivered water is sourced from OPW.

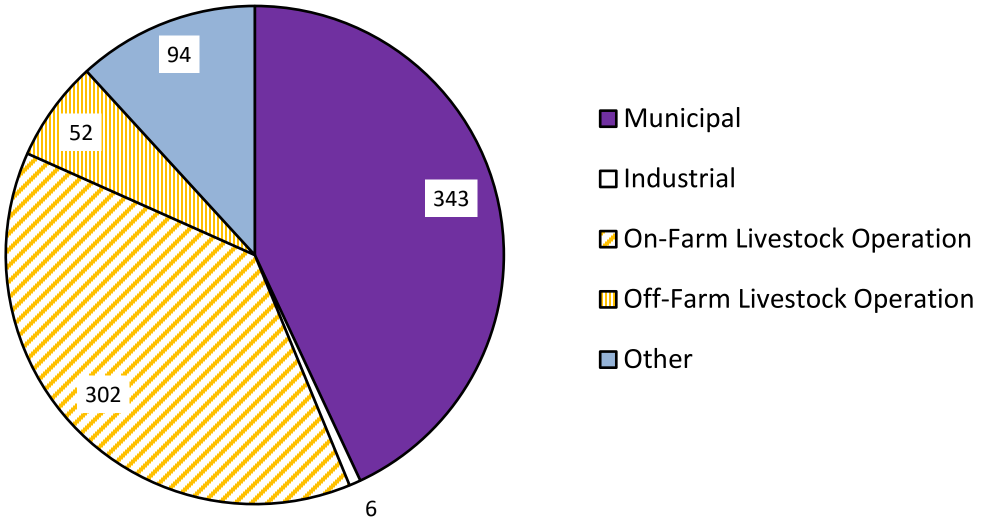

Figure 2-2. Sources of Reclaimed Water California and Number of Farms Reporting Use (in 2017).
Data Source: USDA 2018a.
Notes: Numbers indicate number of farms reporting using a particular source. Some sources reported multiple sources while others did not report the source of their reclaimed water. Data on the specific volume of each source of reclaimed water used by farms was not collected.

2.3 Summary of Water-Related Regulations Impacting Agricultural Water Reuse in California

Multiple sets of inter-related regulations related to water quality and quantity directly and indirectly impact the use of recycled water and other alternative supplies for agricultural irrigation.

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purposes. Sources include municipal, industrial, off-farm livestock operations, and other reclaimed water sources. Water from off-farm livestock facilities, municipal, industrial, and other reclaimed water sources were reported as off-farm supplies. While reclaimed water from on-farm livestock facilities were reported as on-farm surface water.” (USDA 2018a)

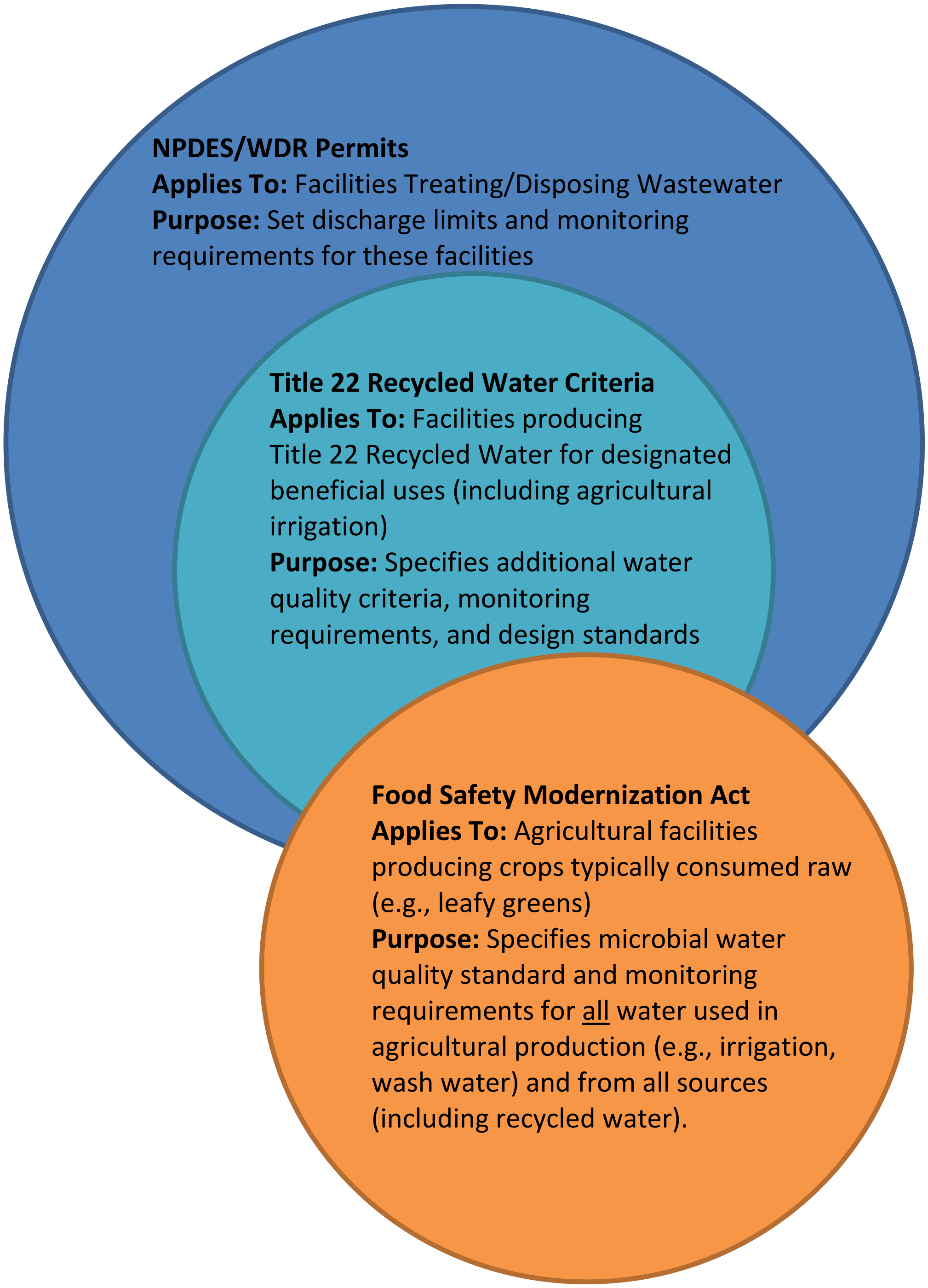
2.3.1 Water Quality

The discharge of treated wastewater to water or land in California is governed via NPDES permits (for discharges to surface water) and WDR permits (for land discharges). Both classes of permits are issued by the local Regional Water Quality Control Board. Discharges of both municipal wastewater and produced water are subject to NPDES/WDR permitting requirements. Similarities and differences in how NPDES/WDR permitting is managed for municipal wastewater and produced water is discussed at greater length in Chapter 5.

State and Federal Anti-Degradation Policies

A key component of all NPDES/WDR permits and the State's recycled water policy is compliance with federal and state anti-degradation policies. These policies mandate that the storage and discharge of treated wastewater and the use of recycled water should not negatively impact the quality of surface and groundwater resources relative to the designated water quality standards for that source. Water quality standards are set based on the designated beneficial uses (e.g., drinking water supply, cold water fishery) and ambient water quality of the receiving water(s).

The use of Title 22 recycled water for agricultural irrigation (and other beneficial uses) in California is governed by the State's Recycled Water Policy (Title 22 Recycled Water Criteria). These regulations apply only to the beneficial use of treated wastewater and are in addition to any requirements included in a facility's NPDES/WDR permit. This chapter focuses primarily on the State's Recycled Water Policy. The 2011 federal Food Safety Modernization Act is currently going through final rulemaking and develops additional microbial water quality standards for water used in the production of crops consumed raw (such as leafy greens). These three sets of inter-related regulations are summarized in Figure 2-3.



NPDES/WDR Permits
Applies To: Facilities Treating/Disposing Wastewater
Purpose: Set discharge limits and monitoring requirements for these facilities

Title 22 Recycled Water Criteria
Applies To: Facilities producing Title 22 Recycled Water for designated beneficial uses (including agricultural irrigation)
Purpose: Specifies additional water quality criteria, monitoring requirements, and design standards

Food Safety Modernization Act
Applies To: Agricultural facilities producing crops typically consumed raw (e.g., leafy greens)
Purpose: Specifies microbial water quality standard and monitoring requirements for all water used in agricultural production (e.g., irrigation, wash water) and from all sources (including recycled water).

Figure 2-3. Water Quality Regulations Impacting Agricultural Irrigation.

2.4 History and Evolution of California's Title 22 Recycled Water Regulations

California has a long history of using recycled water for agricultural irrigation and regulating the use of this water (Table 2-1). California was the first U.S. state to develop the guidance (1907) and regulations (1918) on the use of municipal wastewater (sewage) to irrigate agricultural crops (Olivieri et al. 2020).

Over the past century, California's recycled water regulations have evolved substantially. The regulations initial focus (1900-1930s) was on minimizing health risks associated with agricultural reuse and did so by creating restrictions on the use of wastewater for irrigation and developed guidance on on-farm management strategies (e.g., waiting times between irrigation and harvest). By the 1930-1950s, basic treatment and better understanding of pathogens were developing. Regulations developed at that time established some of the first bacterial standards for wastewater used for reuse. The 1960s brought major policy updates that established the legal authority of the State and Regional Water Resources Control Boards to develop and enforce reclaimed water standards (and manage water quality more broadly across the state). The 1970s brought multiple noteworthy events in water reuse in California. First, scientists and regulators found that wastewater treatment facilities were not reliably treating effluent to the intended standards which led to the development of updated treatment reliability criteria. The 1970s were also the decade where water reuse was established as a state priority and state water reuse policies were updated to include a broader range of beneficial uses (groundwater recharge and landscape irrigation). The 1980-2000s were a period of substantial research on recycled water and included significant advances in fundamental research, multiple demonstration projects, and advances in treatment. In 1991, the State set its first volumetric targets for increasing the use of recycled water within the state. The advances of the 80s and 90s set the foundation for the rapid growth in recycled water use that occurred in California over the past 30 years. In the 2000s, the State conducted a major update of its recycled water policy and developed strategies for scaling reuse. In the 2010s, the State convened a number of expert advisory panels focused on emerging contaminants, updated state recycled water policies and volumetric targets, and expanded regulations to allow for indirect potable reuse. The State continues to advance water reuse with continued investments in expert advisory panels and the development of new regulations on potable reuse and the use of onsite systems for non-potable reuse. Specific policies and details are summarized in Table 2-1.

Table 2-1. Evolution of and Summary of Water Reuse Laws, Policies, Expert Panels, and Other Significant Events in California Recycled Water Policy.

Scope/ Theme	Law/Policy/Expert Panel/Other	Year	Notes
Minimizing health risks by limiting reuse. Focus on agricultural reuse.	State Board of Health Bulletin	1907	Advisory notice on the use of sewage to irrigate raw food crops
	Regulation Governing Use of Sewage for Irrigation Practices	1918	Prohibited use of raw sewage for crop irrigation (with some exceptions). Limited use of treated effluent to non-food crops and crops cooked before consumption. Developed guidance on irrigation practices (e.g., time between irrigation and harvest).
Early development of science-based standards.	Regulations on the Use of Sewage for Irrigating Crops	1933	Updated 1918 regulations to include prohibitions on the use of sewage sludge and developed early water quality standards for reuse. Wastewater could be used for irrigation of food crops consumed raw if the wastewater was "well oxidized, nonputrescible, and reliably disinfected or filtered" to meet a bacterial standard approximately equivalent to drinking water standards at that point in time.
	Regulations Relating to Use of Sewage for Irrigating Crops	1953	Updated 1933 regulations.
Establishing the legal frameworks for	Updates to California Water Code	1967	Formally established/clarified state agencies legal authority in developing and enforcing reclaimed water standards.

Scope/ Theme	Law/Policy/Expert Panel/Other	Year	Notes
managing and regulating reuse.	Statewide Standards for the Safe Direct Use of Reclaimed Water for Irrigation and Impoundments	1968	Developed statewide, application specific water quality requirements with a focus on ensuring that the use of reclaimed water would not pose undue risks to public health.
	Porter-Cologne Water Quality Act	1969	Law that governs water quality regulation in California, including point and non-point sources of pollution. Established state and regional water boards.
Treatment reliability and expansion of beneficial uses.	Multiple water quality and treatment reliability studies.	1970s	Found that wastewater treatment plants had a poor record of reliability. (Crook 1976; California Department of Public Health 1973)
	Water Reuse Law of 1974	1974	Establishes water reuse as a priority in state water resources management. Law states, "It is hereby declared that the primary interest of the people of the state in the conservation of all available water resources requires the maximum reuse of reclaimed water in the satisfaction of requirements for beneficial uses of water."
	Wastewater Reclamation Criteria	1975	Updated 1968 standards to include treatment reliability requirements.
	Update of Water Reclamation Criteria	1978	Updated to include standards to include groundwater recharge and multiple classes of landscape irrigation.
Fundamental research and demonstration of safety of recycled water.	Research and work to update 1978 Water Reclamation Criteria	1978-2000	Research, demonstration projects, advances in treatment, and consideration of a broader range of types of reuse.
Expanded recognition of reuse as a state water priority.	Water Recycling Act of 1991	1991	Established a statewide goal to recycle 700,000 acre-feet of water per year by the year 2000 and 1,000,000 acre-feet of water per year by the year 2010
Strategies for scaling recycled water use.	Water Recycling Criteria	2000	Major update of 1978 Water Reclamation Criteria. Expands approved types of reuse and updates treatment and quality criteria.
	Recycled Water Task Force Report	2002	Series of recommendations on strategies for increasing the use of recycled water in California.
	Recycled Water Policy	2009	Develops state recycled water policy including state-level targets, priorities around constituents of emerging concern, salt and nutrient management plans, criteria for streamlining recycled water permitting, and many other topics. Establishes state-level goal of recycling an additional 200,000 AFY by 2020 and 300,000 AFY by 2030.
Science and data for decision making.	Science Advisory Panel for Recycled Water	2010	Published report 'Monitoring Strategies for Chemicals of Emerging Concern (CECs) in Recycled Water'

Scope/ Theme	Law/Policy/Expert Panel/Other	Year	Notes
	Water Recycling in Landscaping Act	2010	Government code update codifying recycled water use and water efficient landscaping as state priorities.
	Water Recycling Act of 2012	2012	Established a statewide goal to recycle 1.5 million acre-feet of water per year by the year 2020 and 2.5 million acre-feet of water per year by the year 2030
	2013 Recycled Water Policy Update	2013	Requirements added for indirect potable reuse (via groundwater replenishment)
	Expert Panel on Constituents of Emerging Concern (CECs) in Recycled Water	2018	Updated findings from 2010 panel with new research findings to release updated report 'Monitoring Strategies for Constituents of Emerging Concern (CECs) in Recycled Water'
	2018 Recycled Water Policy Update	2018	Requirements added indirect potable reuse (via surface water augmentation)
	SB 966 Onsite treated non-potable water systems	2018	Develops requirement to develop risk-based standards for onsite non-potable reuse and transfers the regulation of onsite non-potable reuse to local programs by late-2022.
Potable reuse. Continued update of policy and goals with new knowledge. Direct measurement methods.	Expert Panel on the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse	2020	Published report 'Evaluation of the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse'

2.5 California's Current Title 22 Regulations for Agricultural Water Reuse

A risk-based approach underpins California's current recycled water quality criteria and regulations on agricultural water reuse. Practically this means that recycled water quality criteria were set based on assessments evaluating water quality thresholds where the potential risks posed by recycled water were below generally accepted thresholds and would not significantly increase public health risk (Olivieri et al. 2014). California's recycled water regulations divide water used for irrigation into four major classes of water–undisinfected secondary, disinfected secondary–23, disinfected secondary-2.2, and disinfected tertiary. For each class of water, the regulations specify what crops can be irrigated with the water, level of treatment, allowable concentrations of water quality parameters, monitoring requirements, and other factors. All recycled water projects are also required to submit an engineering report demonstrating that the proposed treatment will meet all applicable recycled water quality standards plus (in many cases) an anti-degradation analysis to ensure that the use of recycled water will not negatively impact groundwater quality (SWRCB 2018). California's four classes of recycled water used for agricultural irrigation are summarized in Table 2-2. The remainder of this section discusses the details and rationale behind each of these components of the recycled water criteria.

Table 2-2. Classes of Title 22 Recycled Water Used for Agricultural Irrigation.

Recycled Water Class	Undisinfected Secondary		Disinfected Secondary-23	Disinfected Secondary-2.2	Disinfected Tertiary
Crops that Can be Irrigated	Food crops that must undergo commercial pathogen-destroying processing before being consumed by humans; Orchards and vineyards where recycled water does not come in contact with edible portion; Fodder and fiber crops and pasture for animals not producing milk for human consumption; Seed crops not eaten by humans; Non-food-bearing trees, nursery stock, and sod if there is no irrigation for 14-days before harvest/sale/public access.		Ornamental nursery stock/sod; Pasture for animals producing milk for human consumption	Food crops where the edible portion is produced above ground and not contacted by the recycled water	Food crops, including all edible root crops, where the recycled water comes into contact with the edible portion of the crop
Level of Treatment and Treatment Performance	Oxidized wastewater		Oxidized and disinfected	Oxidized and disinfected	Oxidized, filtered, and disinfected
Turbidity	Not Specified		Not Specified	Not Specified	2 NTU*
Pathogen Indicators	Indicator Organism	Not Specified	Total Coliform	Total Coliform	Total Coliform
	7-day Median (MPN/100 ml)	Not Specified	23	2.2	2.2
	Max in any one sample within a 30-day period (MPN/100 ml)	Not Specified	240	23	23
	No sample to exceed (MPN/100 ml)	Not Specified	Not Specified	Not Specified	240

* Regulations require coagulation and/or continuous monitoring of filter influent with additional treatment if various turbidity thresholds are exceeded (see CA regulations for details).

2.5.1 Crops that Can be Irrigated

Each class of Title 22 recycled water specifies the types of crops that can be irrigated with water of that quality. Crops such as highly processed food crops or orchard crops where there is not contact between the edible portion and recycled water (e.g., almonds) are considered lower risk than crops where there is direct contact between the crop and recycled water (e.g., strawberries, leafy greens). Lower risk crops are allowed to be irrigated with lower quality water (e.g., undisinfected secondary) while higher risk crops require higher quality classes of recycled water such as disinfected tertiary.

2.5.2 Level of Treatment and Treatment Performance

Each class of Title 22 recycled water specifies a minimum level of treatment required and ranges from oxidized wastewater (undisinfected secondary) through oxidation, filtration, and disinfection (disinfected tertiary). The regulations provide details on the specific types of treatment required and/or allowed. For example, the requirements for disinfected tertiary recycled water must meet the following criteria for filtration,

“(a) Has been coagulated* and passed through natural undisturbed soils or a bed of filter media pursuant to the following:

(1) At a rate that does not exceed 5 gallons per minute per square foot of surface area in mono, dual or mixed media gravity, upflow or pressure filtration systems, or does not exceed 2 gallons per minute per square foot of surface area in traveling bridge automatic backwash filters; and

(2) So that the turbidity of the filtered wastewater does not exceed any of the following: (A) An average of 2 NTU within a 24-hour period; (B) 5 NTU more than 5 percent of the time within a 24-hour period; and (C) 10 NTU at any time. (b) Has been passed through a microfiltration, ultrafiltration, nanofiltration, or reverse osmosis membrane so that the turbidity of the filtered wastewater does not exceed any of the following: (1) 0.2 NTU more than 5 percent of the time within a 24-hour period; and (2) 0.5 NTU at any time.”

and disinfection

“(a) The filtered wastewater has been disinfected by either:

(1) A chlorine disinfection process following filtration that provides a CT (the product of total chlorine residual and modal contact time measured at the same point) value of not less than 450 milligram-minutes per liter at all times with a modal contact time of at least 90 minutes, based on peak dry weather design flow; or

(2) A disinfection process that, when combined with the filtration process, has been demonstrated to inactivate and/or remove 99.999 percent of the plaque forming units of F-specific bacteriophage MS2, or polio virus in the wastewater. A virus that is at least as resistant to disinfection as polio virus may be used for purposes of the demonstration.”

The SWRCB ‘Alternative Treatment Technology Report for Recycled Water’ provides a list of approved alternative technologies that have been demonstrated to meet the above criteria for filtration and disinfection (SWRCB 2014). Treatment technologies on the Alternative Technologies list have been demonstrated to provide treatment equivalent to those specified in the Title 22 regulations.

2.5.3 Turbidity

Real-time monitoring of turbidity, a measure of water clarity, is included in the Title 22 Regulations as a process indicator for disinfected tertiary recycled water. In this case, turbidity is used to provide ongoing insights into whether filtration systems are operating effectively and as a leading indicator of potential breakthrough of actual pathogens. While California only includes turbidity in the criteria for disinfected tertiary recycled water, some other states include turbidity standards for a broader range of classes of recycled water.

2.5.4 Pathogen Indicators

California's water reuse regulations have historically focused on the protection of human health with an emphasis on the removal and/or inactivation of human pathogens. Measuring concentrations of actual pathogens is an ongoing challenge due to low concentrations in treated effluent (e.g., viruses), limitations of measurement methods, cost of direct measurement and other factors. As such, California's Title 22 Regulations use a combination of treatment specifications and total coliform (indicator bacteria) as a means of assessing treatment adequacy and performance. Total coliform serves as a conservative indicator of fecal contamination and metric for assessing whether treatment processes are performing as designed. Of the four classes of recycled water used for agricultural irrigation, three set total coliform limits (Table 2-2).

The measurement and regulation of contaminants of emerging concern in recycled water is an area of ongoing research with the SWRCB convening multiple expert panels on the topics. Current recycled water regulations do not include limits on contaminants (or chemicals) of emerging concern (CECs) though these it is likely that these constituents may be monitored and managed in the future, particularly in recycled water used for direct or indirect potable uses. Potential agronomic impacts of recycled water have not typically been a major factor in the development of recycled water criteria which has led to the underrepresentation of these parameters in current recycled water regulations in the U.S. though inclusion of agronomic parameters is more common in Middle Eastern countries (Sheikh et al. 2019; Shoushtarian and Negahban-Azar 2020). Additional discussions of these topics are included in later sections of this report.

2.5.5 Engineering Reports and Anti-Degradation Analysis

California's recycled water policy requires projects to submit an engineering report prior to project implementation. Engineering reports detail how the recycled water project will comply with the Water Recycling Criteria and "assure the regulatory agencies that the degree and reliability of treatment is commensurate with the requirements for the proposed use, and that the distribution and use of the recycled water will not create a health hazard or nuisance" (G. Davis 2001). Pursuant to State and Federal anti-degradation policies in the Porter-Cologne Water Quality Control Act (1968) and Federal Clean Water Act (1972) facilities are required to demonstrate that they will not adversely impact surface and groundwater quality. In many regions of the state, a recycled water project's coordination with the regional salt and nutrient management plan is an important component of the anti-degradation analysis. The State Recycled Water Policy includes salt and nutrient management planning requirements to limit potential groundwater quality impacts and promote basin-scale management of salts and nutrients in groundwater. Salt and nutrient plans are required to include the following components (from the State Recycled Water Policy (SWRCB 2018)):

> "a) A basin/sub-basin wide monitoring plan that includes an appropriate network of monitoring locations to determine whether concentrations of salt, nutrients, and other constituents of concern are consistent with applicable water quality objectives.

b) A provision for annual monitoring of Emerging Constituents/Constituents of Emerging Concern

c) Water recycling and stormwater recharge/use goals and objectives.

d) Salt and nutrient source identification, basin/sub-basin assimilative capacity and loading estimates, together with fate and transport of salts and nutrients.

e) Implementation measures to manage salt and nutrient loading in the basin on a sustainable basis.

f) An antidegradation analysis demonstrating that the projects included within the plan will, collectively, satisfy the requirements of the Antidegradation Policy (Resolution No. 68-16)."

2.6 Conclusions

The use of recycled water for agricultural irrigation has a 100+ year history in California. Regulations on the use of treated wastewater for agricultural irrigation have generally focused on protection of public health and evolved significantly over the years as our knowledge around the risks and benefits of the use of recycled water have grown. Current Title 22 regulations take a risk-based, fit-for-purpose approach to managing the use of recycled water for agricultural irrigation and other beneficial uses. This approach develops treatment-based standards rooted in demonstrated levels of pathogen inactivation by different types of treatment and the expected levels of risk posed by consumption of different classes of produce irrigated with recycled water. There are substantive similarities and differences in the composition of recycled water and oilfield produced water, data and knowledge gaps, and the regulatory structures surrounding the use of different alternative water supplies. The following chapters in this report summarize current knowledge on produced water and discusses opportunities and considerations for aligning the regulation of produced water reuse with recycled water.

CHAPTER 3

Review of Scientific Literature and Identification of Data Gaps on Oilfield Produced Water

3.1 Introduction

Oil and gas produced water has been identified as a potential source for agricultural water to supplement existing supplies. While produced water reuse occurs globally, potential risks to humans and crops have gained recent attention initiating further research into identifying hazards to aid in the development of mitigation strategies. Chemicals associated with produced water that pose a risk to human health arise from the underlying geology, the extracted oil and gas, and additives used in various stages of production. The primary concerns with these chemicals include both acute and chronic toxicity including cancer, oral and inhalation toxicity, and reproductive toxicity. Little is understood on the potential risks of irrigating food crops with treated produced water, thus reuse opportunities outside of the oil and gas sector are currently limited.

Historically, concerns surrounding food safety have been focused on acute illnesses resulting from biological contamination (e.g., bacteria, viruses, and parasites). Regulations and guidelines for recycled water provide water quality standards for indicator organisms (e.g., *Escherichia coli*, *E. coli*) or total coliform bacteria) when using recycled water for activities including agricultural irrigation. The recent Food Safety Modernization Act (FSMA) establishes water quality standards for agricultural irrigation water and has developed best practices for irrigating crops based on a number of factors, including source water type, crop type, and timing of irrigation to minimize food borne illnesses. CECs and other constituents (e.g., organics and inorganics) that are likely present in produced water and may be hazardous to humans are not currently included in current regulations on the use of recycled water for agricultural irrigation.

Human health risk assessment is a core public health tool used to assess the relative risks posed by exposure to chemicals, pathogens, and other substances with acute and/or long-term health impacts and is typically comprised of four main steps – hazard identification, dose-response assessment, exposure assessment, and risk characterization (US EPA 2014). Human health risk assessment is used extensively in California to develop and evaluate regulations on the use of recycled water (SWRCB 2018; Olivieri et al. 2014). However, the quantity and quality of data required to rigorously assess risk presents challenges when a given source of risk and/or exposure is poorly characterized or understood.

A literature review conducted by Danforth et al. (2020) revealed that 86 percent of chemicals and compounds used in oil and gas production have insufficient data to conduct risk assessments and 56 percent have not been studied for safety or toxicological effects (Danforth et al. 2020). Long-term exposure to constituents that are present, or may be present, in produced water is not well understood. These include CECs, salts, heavy metals and other inorganic compounds, and organic contaminants. Some chemicals used in the production of oil and gas and constituents found in oilfield produced water are known endocrine disrupting chemicals (EDCs), carcinogens, and mutagens.

Assessing risks to humans, crops, and the environment is complex and first requires sufficient data to identify hazards, such as potentially toxic chemicals and compounds. There are considerable gaps in knowledge related to the chemical makeup, chemical concentrations, and toxicity of chemicals present in oilfield produced water (OPW). Knowledge regarding detection, monitoring, and treatment methods as well as plant uptake and accumulation are also lacking. Additional information is needed to fill these gaps in order to assess the long-term risks and the safe use of OPW for irrigating crops (Shariq 2013; Shimabuku et al. 2019; McLaughlin et al. 2020; Kassotis et al. 2018; Nagel et al. 2020; Danforth et al. 2020; Echchelh et al. 2018; Zhao et al. 2010; Shariq 2019; Tao et al. 2009).

Water quality suitability for agricultural irrigation is another area of active research associated with the use of alternative supplies broadly and OPW, more specifically. Salinity concentrations in produced water are commonly elevated and may make the water quality unfit for agricultural irrigation without additional treatment or blending (IPIECA 2020). Order of magnitude scale differences in water quality parameters are common even within narrow geographies and depend on local geology and other factors (Scanlon et al. 2020). Produced water is commonly blended with other conventional water sources such as surface or groundwater to dilute salinity and extend supplies. In the Central Valley of California, low salinity produced water has been used for agricultural irrigation for over thirty years (Mahoney et al. 2021). Here, crops irrigated with produced water are regulated by the CVRWQCB through the WDR program. Individual permits set numeric limits on electroconductivity, chloride, boron, priority pollutants, oil and grease in effluent discharges and periodic monitoring for other constituents to protect human and crop health. Currently, there are approximately 95,000 acres of farmland in eastern Kern County (CA) irrigated with treated produced water and blended produced water (Mahoney et al. 2021).

Concerns over the short and long-term health and agronomic impacts of OPW use for irrigation motivated two recent studies focused on the use of produced water for agricultural irrigation in California. The CCST was tasked with assessing multiple datasets, including those required via SB 1281, to answer emerging questions related to health risks and potential for expansion of OPW reuse within the State. The Central Valley RWQCB also initiated a Food Safety Project using a three-phased approach to identify and prioritize chemicals of interest (COIs) and to answer similar questions to the CCST SB 1281 study. While the main focus of the two studies was to assess the safe use of produced water, the CCST SB 1281 study also evaluated the suitability and potential availability of produced water for agricultural irrigation based on salinity. The geographic focus of the CCST SB 1281 study covered the State of California, while the Food Safety Project focused on produced water generated within the Central Valley.

This chapter explores the current state of knowledge on produced water and the limitations for assessing risks to humans and crop health. The discussion includes summaries of the characteristics and common constituents of produced water relevant to agronomic and human health, current regulations, treatment technologies, and current research related to irrigating food crops with treated and blended OPW.

3.2 Public Health Concerns

3.2.1 Risk Assessment Overview

Human health risk assessment is a multi-step process that includes thoughtful consideration of both the constituents posing a potential risk and expected nature and duration of exposure. The following text highlights some core steps and considerations relevant to a human health risk assessment of OPW. While much of the following text is focused on assessment of risks to human health, many of the same principles are relevant to assessment of potential agronomic risks associated with the use of produced water for agricultural irrigation.

Identifying at-risk populations, such as agricultural workers, including irrigators, consumers of crops irrigated with produced water, soil biota, and the crops themselves is a key step in scoping any human health risk assessment. This includes characterizing **exposure pathways** (water sources, air, food), **exposure routes** (dermal, inhalation, ingestion, aerial deposition), **level of exposure** (e.g., length of exposure, accumulations in soils, plant uptake, how much contaminated produce has been consumed), and **consumer susceptibility** (age[9], gender, cultural or ethnic practices, underlying health conditions, and genetics).

To evaluate risks associated with using produced water for agricultural irrigation, the first step is to **identify and prioritize COIs**. Chemical behaviors and interactions with biotic and abiotic factors influence **environmental fate** such as persistence, degradation, movement, and the potential to enter food systems (e.g., plant uptake and accumulation). Chemical-chemical interactions may have greater or less toxicity or reactivity than the individual reactions. In some cases, a COI or COI-complex may mobilize an otherwise neutral substance in the environment thus creating a new hazard or exacerbate an existing one.

Toxicity of substances depends on a variety of complex factors including a chemical's concentration and properties; interactions with extrinsic factors that may alter the chemicals behavior or create dangerous by-products. Knowing how populations may be exposed is important for evaluating potential health effects as substances may have different toxicity levels or promote different health risks (e.g., carcinogenic or respiratory illness) depending on the exposure route.

The **dose-response**, or the relationship between the concentration of the substance and the observed effect, can vary between different substances, exposure routes, species, and populations within species. For example, those with auto-immune diseases may have a lower dose-response than other populations. Some plants may be more sensitive to chlorides than others, even between different genotypes within a species.

3.2.2 Exposure Routes Associated with OPW

Exposure pathways link a contaminated source or hazard to the at-risk populations and include air, irrigation water, groundwater, soils, and food. Exposure routes are the ways in which the hazard enters the at-risk population, and generally include inhalation, ingestion/uptake, or through dermal contact. The potential routes of exposure associated with produced water are diverse (Figure 3-1) with at-risk populations including agricultural workers including irrigators, soils and soil biota, crops, and consumers of crops irrigated with produced water. Consumers of produce irrigated with OPW, farmworkers, and local residents are the groups most likely to be exposed to the COI in OPW, though exposure routes and levels of exposure vary widely.

For occupational workers, exposure can occur directly via dermal contact, inhalation, or accidental ingestion of contaminated water or aerosolized contaminated particles. Plants, soils, and the soil biota[10] (including microorganisms, soil animals, and soil plants), may be exposed to COIs through direct contact with irrigation water or via aerial deposition, where they may persist and accumulate in soils over time.

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[9] For example, children are at a higher risk compared to average adults due to their lower body weight, ability to metabolize chemicals, increased expression of mutations as a result of higher frequency of cell division, and limited functions of immune system among others (US EPA 2005).

[10] The soil biota includes microorganisms, macrofauna, mesofauna, and microfauna, plants.

While some COIs are readily taken up by plants, others may, under certain conditions, transform into bioavailable forms that can be taken up into plants with the potential to accumulate. Consumer exposure can occur through consuming contaminated crops or from drinking groundwater that has been contaminated as a result of infiltration into aquifers.

Irrigation practices, including the application method and the timing of application, each provide a different level of risk for contaminating crops. The application method with the highest risk for contamination is overhead, or sprinkler, followed by furrow (flood), and drip methods (Steele and Odumeru 2004; Stine et al. 2005; AZLGMA 2021; CALGMA 2021). Overhead irrigation poses the greatest risk of contamination as the water comes into direct contact with the edible portion. Timing of irrigation events has been identified as an important factor in reducing food-borne illnesses related to microbial contaminated irrigation water (AZLGMA 2021; CALGMA 2021) but may be less relevant to more persistent contaminants. As the time between irrigation event and harvest decreases, risk increases. This is especially true when overhead irrigation is used and water comes into direct contact with the edible portion of the crop. While pathogenic microorganisms are a major concern to food safety, especially for crops eaten raw, there is the potential for COIs present in produced water to be deposited, adhere to, or be taken up by crops intended for human consumption. These topics are discussed at greater length later in Chapter 3.

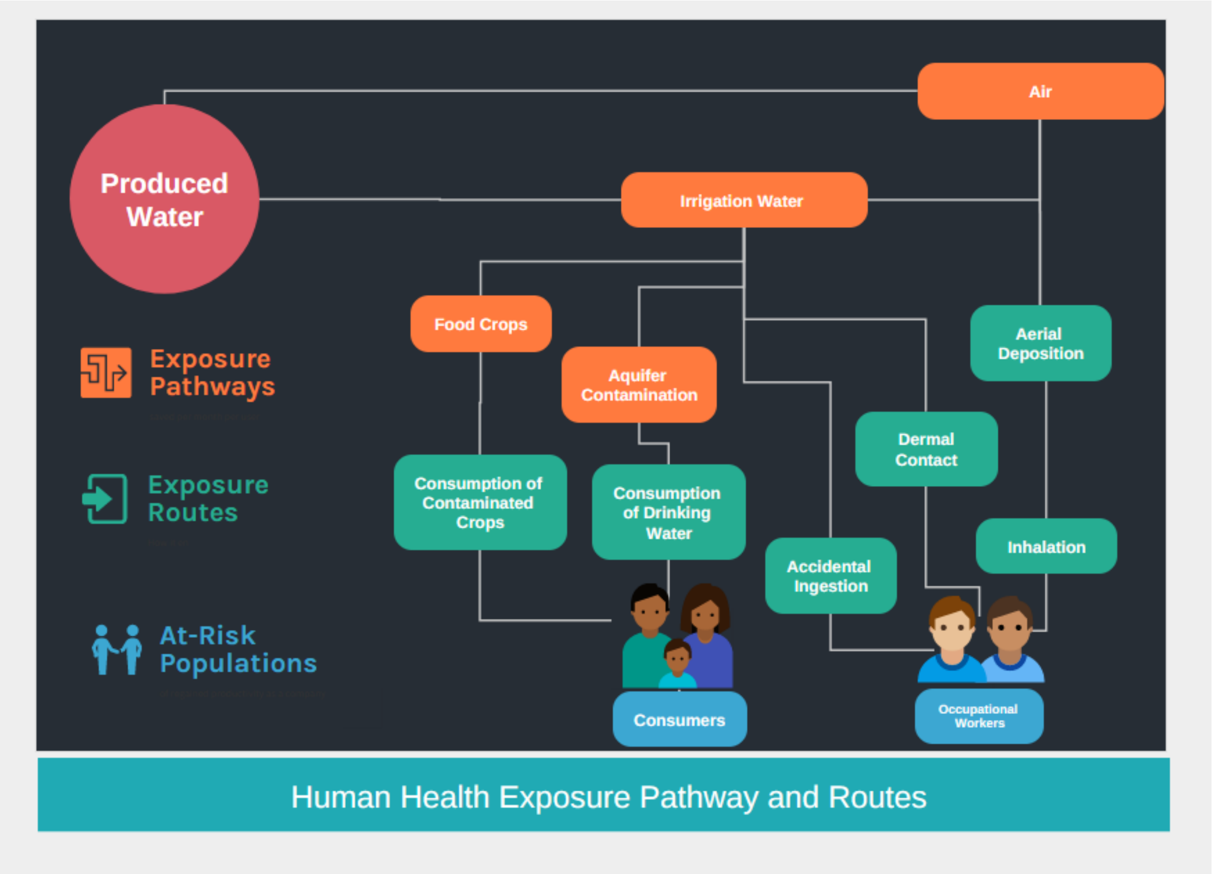

Figure 3-1. Potential Exposure Pathways and Routes for COIs That May Be Present in Oilfield Produced Water.

3.2.3 Identifying Chemicals of Interest in Oilfield Produced Water

Both the CCST SB 1281 study and Food Safety Project surveyed existing monitoring and research data to identify chemicals known to be in produced water and assess current information on the toxicity of these chemicals. This information was then used to develop lists of chemicals of interest in produced water. It is important to note that both of these studies were focused on evaluating potential human health risks and/or exposure. While many of the identified chemicals could impact crop health, detailed assessment the toxicity of most chemicals from an agronomic perspective was beyond the scope of both the CCST and Food Safety Project reports. The following sections describe the approaches taken by both studies to identify chemicals of interest and concludes with the identification of some key knowledge gaps.

3.2.3.1 CCST SB 1281 Study

The CCST SB 1281 report compiled physical, chemical, biological, and toxicological data for OPW chemical additives obtained from a variety of databases[11] and past research (Shimabuku, Abraham, and Feinstein 2019). Of the 1,119 identified chemicals, 630 had identifiable Chemical Abstract Service Registry Numbers[12] (CASRN) and were further assessed for toxicity. While most chemicals had acute toxicity data, chemicals with chronic toxicity data are scarce (154 out of 630). Table 3-1 provides a summary of the CCST findings for the chemicals where toxicity information could be found. Nearly forty of the chemicals were identified as being acutely toxic if ingested or inhaled; forty were identified as known probable carcinogens; and seven were identified as being toxic to reproductive systems.

Table 3-1. Number of CASRN Identified Chemicals Potentially Found in Produced Water with Known Toxicity.
Data Source: CCST 2019.

Toxicity Category	# of Chemicals Identified
Acute oral and inhalation toxicity (GHS Category 1 or 2)	38
Acute aquatic toxicity (GHS Category 1 or 2)	203
Hazardous air pollutants	51
CARB 'Hot Spots' list	74
Known or possible/probable carcinogens	40
Reproductive toxicity[A]	7
Not readily biodegradable[B]	125

[A] As identified on the California Prop 65 List.

[B] Likely to persist in the environment according to Organisation of Economic Co-operation and Development (OECD) standards, and therefore pose an increased risk of exposure to humans and wildlife.

3.2.3.2 Central Valley RWQCB Food Safety Project

The Food Safety Project identified a total of 399 chemicals potentially present in gas and oilfield produced water from the San Joaquin Valley (using California Division of Geologic Survey (CalGEM) chemical additive disclosure data), of which 143 were identified as COIs for further evaluation (GSI

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[11] These datasets include the Irrigation 13267 (reported by operators), AB 1328 (reported by operators and chemical suppliers), SCAQMG, DOGGR chemical, and FracFocus.

[12] A CASRN is a "unique identifier that provides an unambiguous means to distinguish chemical substances or molecular structures when there are many possible systematic, generic, proprietary or otherwise trivial names" (American Chemical Society n.d.).

2020). Due to a lack of analytical methods, 91 of the chemicals present are not monitored and the majority had insufficient toxicity information needed to conduct a hazard assessment or to establish toxicity thresholds (Mahoney et al. 2021). The Board also identified 45 naturally occurring inorganic compounds likely to be in produced water, three of which are NORMs (GSI 2020). Approximately 26 sources for toxicity factors were used to prioritize the list of chemicals (See Box). Persistence and degradation of COIs in irrigation water and toxicity potentials were used to further steer the selection process of these chemicals in Task 1. Chemical degradation and sorption to soils can inhibit plant uptake and were used to eliminate some chemicals from the COIs list. Elemental metals remained of interest as they are known to persist and, under certain circumstances, transform into bioavailable forms able to be taken up by plants (Mahoney, Asami, and Stringfellow 2021). For the COIs identified in Task 1, and based on available toxicity information, the Board then conducted a literature review to better understand how these chemicals move through the agricultural environment including fate and transport and the potential for plant uptake.

Assessing Chemical Toxicity in the Food Safety Project

Chronic mammalian toxicity was given priority followed by carcinogenicity, teratogenicity, and degradation. Teratogenicity is an agent that can harm or cause malformations to a developing fetus. A total of thirteen factors were initially considered for the selection process by GSI, many of which are not well understood or could not, with certainty, eliminate a chemical from further assessments. These included: dermal toxicity, toxicities of degradation by-products, plant uptake, frequency and concentrations chemicals are used in the field, chemicals that persist or bioaccumulate, chemicals that were detected in any water analysis of irrigation water with maximum measured irrigation water concentration above available risk-based water screening levels (EPA drinking water screening levels or California Public Health Goals), ambient concentrations in air and water that may have resulted from practices outside of produced water reuse, if the chemical occurs naturally in the environment, and other sources of the chemical in the environment and the specificity of the chemical to application of produced water for irrigation (GSI 2020).

3.2.3.3 Knowledge Gaps in Identifying Chemicals of Interest

The composition of OPW varies across geologic regions, over time, within an oilfield, and between operators. Interactions between geologic formations, environmental factors, chemical additives, the stage of production, and the age of the well all affect the makeup. Because of this variability and inconsistency, studies indicate that compositions from one geographic location at a particular time cannot necessarily be applied to other sites or at different times – even within the same field (McLaughlin et al. 2020).

A variety of different chemicals are used during oil and gas (O&G) production, and operators may use different mixtures and concentrations of chemicals. Chemical additives reported in O&G operations cannot always be identified or are not well-described due to proprietary trade secrets or a lacking CASRN (US EPA 2016; US EPA 2019). While oil companies, chemical manufacturers, and chemical distributers are required to provide a list of chemical additives used in oil and gas[13] production activities,

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[13] The CVRWQCB uses this information to create and update the Oilfield Additive List.

the specificity of the type of chemicals listed may be vague (e.g., aromatic amines used as a classification[14]) with inadequate information for assessing toxicity.

Without a CASRN, chemicals cannot be analyzed for toxicity or biodegradability. The frequency and volumes in which they are used, and the chemical masses are also not reported by producers. Some of these unknown chemicals may exist as, or degrade into, endocrine disrupting chemicals (EDC) or other degradation and daughter products with unknown toxicities (Mahoney et al. 2021; GSI 2020). At low concentrations EDCs are known to cause a number of human health concerns. Such information would be useful to identify, prioritize, and evaluate potential hazards; assess risks; predict potential impacts; and to prescribe efficacious treatment protocols.

3.2.4 Classes of Chemicals of Interest in Produced Water

3.2.4.1 Inorganics

Inorganics include trace elements and heavy metals, such as arsenic, cadmium, lead, and mercury. They are non-biodegradable and tend to persist and accumulate in soils (Ayers and Westcot 1985). Many of these may be present in produced water in trace amounts (Jiménez et al. 2018) that do not cause acute illness. However, because inorganics have the potential to transform and become biologically available to plants, plant uptake and accumulation may occur (Emamverdian et al. 2015).

Plants are known to uptake nonessential heavy metals along with essential ones through plant uptake systems (Rogers et al. 2000). Some of these heavy metals may be carcinogenic, mutagenic, or teratogenic (Alshatwi et al. 2014) and can accumulate in crops at higher concentrations than what is considered to be safe levels for human consumption yet at lower toxicity thresholds for crops (Grant et al. 2008). However, because other factors are at play, such as crop type and farming practices, concentrations in soils may not be a direct indicator of concentrations in crops.

Two inorganics in particular are of global concern - arsenic and cadmium. They are known carcinogens and uptake and accumulation in crops has long been an area of concern and reported in the literature (Zhao et al. 2010; Shariq 2019; Shariq et al. 2021). Long term exposure to cadmium and arsenic via water, soil, and food is a global health problem linked to cancers and organ system toxicity (Rafati Rahimzadeh et al. 2017; Yan et al. 2021). The major health concern for arsenic and cadmium accumulations are from the consumption of staple crops, such as rice, wheat, and potato (Grant et al. 2008; Shariq et al. 2021).

While the uptake of naturally occurring arsenic is an ongoing area of research, recent studies have indicated that wheat irrigated with concentrations found in produced water can increase the carcinogenic risk for humans by 6.5-fold (Shariq 2019). While this study focused on wheat irrigated with concentrations found in unconventional produced water (hydraulic fracturing flowback), and not specifically conventional produced water, many of the same chemicals and constituents, such as arsenic and cadmium, are present in produced water from both methods. The Agency for Toxic Substances and Disease Registry (ATSDR) reports that exposure to arsenic can occur through eating crops that have been irrigated with irrigation water and is a concern as elevated concentrations have been reported (ATSDR 2021a). Arsenic in drinking water is linked to deaths due to respiratory and cardiovascular

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[14] A number of specific and toxic chemicals, known to cause a wide range of symptoms from headaches to cancer, are included in the chemically ambiguous classification ‘aromatic amine’.

diseases as well as cancer (ATSDR 2021a). Significant correlations have also been observed between concentrations of arsenic in crop and soils and birth defects (ATSDR 2021a; J. Wu et al. 2014). The chronic-duration oral minimal risk level (MRL) toxicity listed by ATSDR is 0.003 mg/kg/day for arsenic (ATSDR 2021a).

Cadmium is known to bioaccumulate at all trophic levels including in poultry and cattle (Alloway et al. 1990; Kalac et al. 1996). Generally, accumulation occurs in the leaves and risks to humans increase when contaminated leafy vegetables are consumed, however, accumulations in commercially grown crops including sunflower, flax, wheat, and rice have also been identified (Alloway et al. 1990; Grant et al. 2008). Targets of cadmium through oral exposure have been identified as bone and kidneys, although evidence does suggest developing organs may also be at risk (ATSDR 2021b). The chronic-duration oral MRL toxicity listed by ATSDR is 0.0001 mg/kg/day for cadmium (ATSDR 2021b).

3.2.4.2 Radionuclides and NORMs

NORMs are ubiquitous in the Earth's crust. The type, variability, and concentration of NORMs in produced water are highly variable, depend on the geology, and are often positively correlated with TDS, boron, and salinity (GSI 2021b; Rosenblum et al. 2017; DOGGR 1996). In general, radionuclides behave similarly to other inorganics in fate, transport, and movement in soils, their behavior is also affected by radioactive decay (GSI 2021b). Similar to other inorganics, plant uptake and accumulation depends on many factors, including physico-chemical characteristics and crop type. For example, plants in the Asteraceae family (e.g., sunflowers) are efficient at taking up radionuclides and heavy metals and are used radio-phytoremediation (Gupta et al. 2016)

3.2.4.3 Organics

Many organics, including aromatics, phenols, and polycyclic aromatic hydrocarbons (PAHs) are known to be highly toxic (carcinogenic and mutagenic) to both humans and animals (Shariq 2019; Kassotis et al. 2014; Veil et al. 2004). Transfer from irrigation water to crops, higher trophic levels, and into human food systems is of concern when using produced water for agricultural irrigation. Some organics are known EDCs (e.g., phenols) while others may degrade into them (e.g., surfactants). In addition, chemical toxicity due to chemical interactions can be greater than the individual chemicals themselves (Veil et al. 2004).

Plant uptake and translocation of organics depend on chemical and plant properties, soil and plant microorganisms, and climate (more information is provided in Section 3.4.2). As chemicals move through the environment and into plants (via soil or atmosphere) chemical transformations also occur due to natural chemical degradation, plant, and microbial processes (Doucette et al. 2018). Evidence indicating that plants are able to take up hydrophobic organic compounds, including PAHs via soil and air has been shown in a variety of crops including zucchini, pumpkins, spinach, lettuce, and dandelion, (Huelster et al. 1994; White 2001; Mattina et al. 2000; Lee et al. 2003). Much like sensitivities to salts and trace elements, translocation and accumulation can vary across and within species. For examples, certain cultivars of zucchini (*Cucurbita pepo*, subspecies *pepo*) are able to move and accumulate hydrophobic organics from roots to shoots more efficiently than other cultivars or crops (Huelster et al. 1994; Inui et al. 2008; Saito et al. 2011; White et al. 2003).

3.2.4.4 Endocrine Disrupting Chemicals

Endocrine disrupting chemicals (EDCs) are substances or mixtures of substances that can disrupt any aspect of hormone actions including hormone production, reproduction, and development in organisms and their offspring, even at very low concentrations (Zoeller et al. 2012; NTP 2001). Many of which have been identified in produced water (Colborn et al. 2011). In 2010, The Endocrine Disrupting Exchange

TEDX identified 632 chemicals reported as ingredients to products used in oil and gas production (only a fraction of what is potentially present in produced water) of which 353 had CASRN. Of these, 37 percent were identified as EDCs (Colborn et al. 2011).

The SB 1281 study identified three chemicals from the sub-list of chemical additives with a CASRN, as having combined evidence of endocrine disrupting activity (two for humans and one for wildlife) and only one, (poly[oxy-1,2-ethandiyl], a-[nonylphenyl]-w-hydroxy-; CASRN: 9016-45-9) was identified as relevant to agriculture (Shimabuku et al. 2019). The sensitivity of the endocrine system to such chemicals, at concentrations less than parts-per-billion (ppb), and the delayed and often unpredictable health effects make identifying hazards and potential risks to humans difficult. These chemicals may have long-term health effects that may not become immediately evident. Chemical mixtures and products may also transform to highly toxic EDCs.

3.2.5 Knowledge Gaps on COI Toxicity and Biodegradability

There may be toxicological risks to humans when OPW is used to irrigate food crops. Unique exposure pathways to humans and the environment exist outside of typical pathways in O&G production. Risks to humans can occur either indirectly through the consumption of food crops or contamination of ground water, and directly if occupational workers are exposed. Agronomic and environmental risks can occur through deposition of contaminated irrigation water onto agricultural fields where the potential to impact soils may occur. This in turn can affect crops and crop production.

Factors affecting these risks include the mass and frequency of chemical use; toxicity, persistence, and accumulation; transformation products; irrigation method; and the amount and rate of ingestion (Shimabuku et al. 2019). Exposure to toxins can be categorized as either acute (oral, inhalation, and aquatic) or chronic. Acute toxicity can be defined as the adverse outcomes after short-term exposure while chronic toxicity are the adverse outcomes from repeated or long-term exposure. End points for chronic toxicity include effects to developmental, neurological, respiratory, or reproductive systems; increased occurrence of cancer and tumors; and a decrease in lifespan. More information exists on acute toxicity for chemicals than for chronic toxicity, and data are generally reported for single chemicals or compounds, rather than for mixed compounds.

A lack in toxicity data for chemical mixtures was identified by both studies (the SB 1281 study and the Food Safety Project) as a gap and a limiting factor in the ability to assess hazards for the use of OPW in agricultural. A common approach used to evaluate the effects of mixtures is to sum the toxicity of all individual constituents to estimate the overall toxicity (European Commission 2012). However, this practice does not capture the full range of possible toxic effects that can occur from interactions between constituents, transformation and daughter products, degradation products, and disinfection by-products.

Testing for toxicity and specific chemicals in blended produced water is challenged by the variations in the source water, the produced water, and the combination of the two. One strategy, Whole Effluent Testing (WET), assesses toxic effects when exposed to low concentrations of chemical mixtures within water sources (whole water testing) without identifying specific chemicals. However, many of these methods are targeted at aquatic, non-mammalian species with very few relevant to humans. In addition, results in the literature from in vitro methods used to test whole effluent toxicity are from produced water from hydraulic fracturing (fracking), and may not necessarily be extrapolated for conventional oilfield produced water, although many of the same chemicals are used in both methods (Crosby et al. 2018; Hull et al. 2018; Kassotis et al. 2014; Kassotis et al. 2018; Payne et al. 2015). Because there are chemical overlaps and similarities between all oilfield activities (e.g., routine activities, fracking, conventional production, and stimulation treatments), research from (Stringfellow et al. 2017) indicate there is likely an underestimation of risks when regulations and risk assessments do not account for all activities.

Of the 365 chemical additives relevant to agricultural irrigation of food crops identified in the Irrigation 13267 and AB 1328 datasets by the CCST SB 1281 study, 80 (22%) were reported as proprietary with no CASRN and could not be assessed. From the remaining chemicals with valid CASRN, there was not adequate information to establish acute oral toxicity for 118, acute inhalation toxicity for 211, acute aquatic toxicity for 78, and chronic toxicity for 196 of the chemical additives (Shimabuku et al. 2019). The Food Safety Project identified 86 COIs that do not have analytical methods or toxicity information.

In addition to toxicity, information on biodegradability is lacking for many of the chemicals and substances in OPW. Biodegradability is an important factor in the phyto-availability of organic chemicals of interest. However, to assess for toxicity and biodegradation, a better understanding of the chemical additives is an important first step. Similar to toxicity information, degradation data generally exists for single chemicals and compounds rather than chemical mixtures.

The SB 1281 study identified 14 chemical additives that are likely to persist in the environment and 31 likely to persist in the environment using computational estimates and thus may pose an increased risk of exposure to humans. There were 53 chemical additives with inadequate information to establish biodegradability (Shimabuku et al. 2019). Without degradation information, environmental persistence of chemicals and chemical mixtures in OPW cannot be discerned (Shimabuku, Abraham, and Feinstein 2019).

While data gaps on toxicity and degradation do exist for many chemical additives present in OPW, available data does indicate the presence of significant air, aquatic, and carcinogenic hazards. Concerns remain surrounding a lack of information on toxicological risks to humans (Shariq et al. 2021; McLaughlin et al. 2020; Israel et al. 2015), crops (Sedlacko et al. 2019; Miller et al. 2019), soils (Echchelh et al. 2018; Tasker et al. 2018) and the environment (McLaughlin et al. 2016). For the widespread use of OPW for food crop irrigation, additional research is needed to better understand the human, agronomic, and environmental toxicological impacts (Cooper et al. 2022)

Further research on chemical fate, degradation and persistence, plant uptake, and accumulation in soils and plants is needed. Without chemical masses or concentrations and frequency of use, hazards, risks, and impacts cannot be fully assessed.

3.3 Agronomic Concerns

3.3.1 Overview

The long-term impacts to crops and soil health are of concern when using produced water for irrigation. Similar to public health concerns, agronomic concerns have expanded beyond the historical suitability criteria to include additional water quality parameters. Suitability of irrigation water is generally based on salts, salinity, and infiltration (sodium adsorption ratio, SAR). Ion toxicity (e.g., calcium (Ca^{2+}), sodium (Na^{+}), chloride (Cl^{-}), magnesium (Mg^{2+}), and boron (B)) and miscellaneous effects including pH, bicarbonate, and nutrients are also important agronomic considerations (Ayers and Westcot 1985). The general guidelines for agricultural irrigation water quality from the Food and Agricultural Organization (FAO) are provided in Table 3-2.

Table 3-2. Guidelines for Evaluating Water Quality Suitability for Agricultural Irrigation.
Source: Adapted from Ayers and Westcot 1985 Table 1, citing original work from University of California Committee of Consultants 1974.

Parameter	Units	Degree of Restriction on Use		
		None	**Slight to moderate**	**Severe**
ECW	dS/m	<0.7	0.7-3.0	>3.0
TDS	mg/L	<450	450-2000	>2000
Sodium	SAR	<3	3-9	>9
Sodium*	me/L	<3	>3	-
Chloride*	me/L	<4	4-10	>10
Boron	mg/L	<0.7	0.7-3.0	>3.0
Nitrogen	mg/L	<5	5-30	>30
Bicarbonate	me/L	<1.5	1.5-8.5	>8.5

me=milliequivalents; * = surface irrigation.

While these are still major issues for irrigation water, CECs including organics and inorganics[15] can have long-term consequences including phytotoxicity, decreased crop yields, plant death, and soil degradation and may limit reuse opportunities. Plant tolerances to these can vary widely between and within crop species. Knowing the quality of produced water is an essential first step in determining its suitability for irrigation and selecting compatible crops. While many successful examples of irrigating crops with treated produced water exist globally, there have been cases when projects have been discontinued when the quality was not sufficient for the end-use. In these examples, removing said constituents was a technical issue that could not be overcome (GSI 2021b).

Phytotoxicity in response to organics and inorganics in produced water and soils is cited throughout the literature. Deleterious effects to crops include decreased photosynthesis, oxidative stress, delayed germination, stunted growth, and leaf deformation have been reported due to exposure to salts, heavy metals and other inorganics, and a myriad of organics including PAHs (Ding et al. 2017; Brdar-Jokanović 2020; Riyazuddin et al. 2021; Ayers and Westcot 1985; Grant et al. 2008; Irfan et al. 2013). While these are certainly concerns for the protection of public health, consideration to crop loss, decreased yields, and long-term food security must be considered.

3.3.2 Salinity and Sodium

Salinity, often measured as electrical conductivity (EC) or total dissolved solids (TDS), is used to describe irrigation water or soils and is, in general, the primary water quality concern to growers. EC and TDS are

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[15] Inorganic chemicals present in OPW mostly originate from geological formations but can also come from chemical additives used in O&G operations.

useful metrics to assess suitability of irrigation water, and over time saline irrigation waters can accumulate in soils leading to two main types of issues, salinity issues or sodium issues (Ayers and Westcot 1985). Saline soils around the root zone prevents plants from accessing water from the surrounding soil and limits plant water uptake. Other negative effects include ion toxicity (e.g., Cl- and B), disruption to nutritional balances, and effects to soil permeability (Corwin and Yemoto 2020).

Plants tend to have lower tolerance levels to concentrations of salts in irrigation water than to salts in soils. The general guidelines from the FAO place minimal restrictions when concentrations of TDS in irrigation water are between 450 mg/L and 2,000 mg/L and severe restrictions when concentrations exceed 2,000 mg/L (Ayers and Westcot 1985). Maximum values recommended for EC in irrigation water vary depending on crop tolerances, but values ranging from 750 to 2,000 µmhos (750 to 2,000 µS) are generally considered acceptable with appropriate management strategies (e.g., leaching) (Fipps 2021). Build-up of salts can occur due to poor water quality of irrigation water, poor drainage, low soil permeability, or irrigation practices. Management strategies, such as leaching, may be employed to flush these accumulations from around the root zone, however, this method requires the use of additional water and may not be a viable option in water stressed areas.

The SAR is a measure of excess sodium relative to calcium and magnesium ions and contributes to decreased infiltration rates and sodic soils. Elevated SAR values (> 26; (Fipps 2021) contribute to decreased infiltration rates, formation of soil crusting, high pH, increased risk of plant disease, decreased nutrient availability, soil erosion, and a general degradation of soil health (Fipps 2021). Characteristics and impacts of sodic soils include soil crusting, high soil pH, decreased overall soil health and nutrient phytoavailability, and an increased risk of disease (Fipps 2021; L. Wu et al. 2009; Rhoades, Kandiah, and Mashali 1992).

Studies show that treated produced water or blended produced water with lower concentrations of salinity and TDS are more suitable for long-term irrigation (GSI 2020). Research has also shown that plants have sustained negative effects to nutrient uptake, toxicities, or other undesirable effects (e.g., decreased biomass) from being irrigated with oil and gas produced water in both greenhouse and field settings, but treating (reverse osmosis) and blending with freshwater sources minimized negative effects (Sousa et al. 2016; F. Martel-Valles et al. 2014; J. F. Martel-Valles et al. 2013). When produced water is used long-term, soil salinity issues (elevated concentrations of sodium) and increased pH have also been reported (Hirayama et al. 2002; Burkhardt et al. 2015; Sintim et al. 2017).

3.3.3 Inorganics - Trace Elements and Heavy Metals

Some trace elements, such as boron, calcium, chloride, copper, potassium, magnesium, and sodium are essential for plant growth. Others, such as arsenic, cadmium, lead, and mercury, are considered non-essential heavy metals and can be toxic to plants at low doses (Ding et al. 2017). While many are naturally occurring in soils and are often present in conventional irrigation water sources (groundwater and surface water), they may be found in higher concentrations in produced water. Crop specific requirements and sensitivities vary considerably, and some minerals may have a narrow range between deficient and toxic concentrations. Toxicity symptoms and severity also vary depending on the crop. Some crops may exhibit chlorosis and necrosis while others may exhibit leaf deformation or decreased emergence (Brdar-Jokanović 2020). Accumulation of heavy metals in soils from irrigating with OPW can lead to soil degradation and damaged crops such as stunted growth or death (Riyazuddin et al. 2021).

Boron is a significant agricultural concern, next to salinity and sodium, and may be a barrier for agricultural reuse of OPW (and recycled water in general). Boron is also reported to be positively correlated with chloride, and concentrations in OPW are typically higher than in freshwater sources

(Kondash et al. 2020). Over time boron can accumulate in soils where it is difficult to manage or remove (Kondash et al. 2020; Yau and Ryan 2008). Plant tolerances to boron can vary widely with minimal restrictions when concentrations are between 0.7 and 3.0 mg L^{-1} (Ayers and Westcot 1985).

Chloride, while essential for plant growth, is another major agronomic concern. It is very mobile and is easily taken up by crops where it can accumulate in the leaves. In chloride sensitive plants, it can cause leaf burn, drop, and drying, but like most trace elements toxic concentrations depend on crop type. If concentrations in irrigation water used in overhead applications exceed crop thresholds, leaf and crop damage via direct contact and absorption through leaves can occur. Maximum concentrations for chloride in irrigation water[16] for sensitive crops such as strawberries and summer raspberries are approximately 3.3 meq/L[17] (117 mg/L) while more tolerant crops like the Sunki mandarin can tolerate concentrations up to 16.6 meq/L (588 mg/L) (Ayers and Westcot 1985). The FAO recommends slight to moderate degree of restriction when chloride concentrations in irrigation water are between and 4 and 10 meq/L (142 – 355 mg/L) (Ayers and Westcot 1985).

Screening value limits are provided in the WDRs for a number of these inorganic trace elements and heavy metals monitored in treated produced and blended produced waters. For example, limits for boron in irrigation waters (1.0 to 1.6 mg/L, as an annual average) are provided in the WDRs. Recommended concentrations for the short-term use of recycled water limit concentrations to boron in irrigation water to 2 mg/L and long-term use to 0.75 mg/L (Fipps 2021; Ayers and Westcot 1985). The WDR maximum contaminant level (MCLs) stated in the WDRs for copper is 1.3 mg/L while in soils, toxicity to roots may occur when total copper exceeds 50 mg/L for sandy soils or 150 mg/L for clay (Taariq-Sidibe et al. 2020).

Other metals, such as cadmium and arsenic can be detrimental to some crops. Excess concentrations of cadmium can lead to toxicity, oxidative stress, and nutrient deficiencies which can inhibit photosynthesis and limit growth (Grant et al. 2008; Irfan et al. 2013). In some crops (e.g., rice) arsenic has been shown decrease seed germination and reductions in shoot and root growth (Hasanuzzaman et al. 2015). Because metals tend to persist and accumulate in soils, more research is needed on how concentrations in irrigation water affect soil concentrations over time in order to establish risk-based ranges for acceptable concentrations in irrigation water.

3.3.4 Organics

Concerns surrounding organics are generally focused on the impacts to human, animals, and environmental health. However, PAHs are known to be phytotoxic, and because they are persistent and available for plant uptake, they are of agronomic importance as well. Toxic effects of PAHs have been cited throughout the literature and effects vary at different growth stages. For example, anthracene, fluoranthene, fluorene, and phenanthrene (and mixtures of these) in early development can delay germination and reduce root and shoot elongation in corn and rice (Somtrakoon and Chouychai 2013); acrylamide has been shown to stunt growth and reduce biomass of lettuce (Mroczek et al. 2014); fluorine can induce oxidative stress, decrease rates of seed germination and growth, and delay root and shoot elongation in wheat, sunflower, and alfalfa (Salehi-Lisar and Deljoo 2015); and phenanthrene has been shown to affect exo and endo-dermal development in maize roots which may inhibit access to

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[16] Irrigation water applied at the surface, does not apply for overhead applications.

[17] Milliequivalent per liter, sometimes written as me/L.

nutrients (Dupuy et al. 2016). Many of these are known to be present in California produced water (see Chapter 4).

3.3.5 Soil Organisms

Soil ecosystems are important for a myriad of important agronomic and ecosystem functions including nutrient cycling processes, mineral sequestration, disease prevention, soil remediation and degradation of pollution (Vadakattu, Leonard, and Neate 1998). Disruptions from pollutants, excess nutrients, and salts can cause changes in soil characteristics and soil biota - important in many of these ecosystem services.

As noted earlier, produced waters tend to have higher concentrations of salts, organics, and inorganics (e.g., boron and radium). Distribution and fate depend on soil, water, and chemical properties, including pH, temperature, humidity or water content, chemical compositions, and physicochemical properties of the water (Santos, Hildenbrand, and Schug 2019). While few studies specifically investigate the effects of oilfield produced water on soil health, including diversity and abundance of soil organisms, saline soils are known to increase soil stress which can lead to reductions in soil microorganisms (Borneman et al. 1996; Ibekwe et al. 2010). Studies report an overall decrease in abundance, diversity, and species richness over time in response to interactions between salinity, pH, and boron in soils (Ibekwe et al. 2010; Nelson and Mele 2007). Other studies have shown increases in EC and SAR and decreases in infiltration rates (Vance, King, and Ganjegunte 2008; Johnston, Vance, and Ganjegunte 2008); increased sodium levels, soil degradation, and decreases in crop yield (Sintim et al. 2017); elevated salts and boron accumulation (Kondash et al. 2020).

Salt accumulation in soils will continue to be an agronomic issue and is especially salient in arid regions where decreased precipitation and increased temperature will result in higher rates of evaporation and higher concentrations of salts in soils. Even small changes in sodium content of irrigation water can lead to accumulation in soils over time (Kondash et al. 2020). Soil organisms play a critical role in maintaining the physical and chemical quality of the soil. Because soil health is vital for crop production, the potential effects of produced water for irrigation, especially long-term use, should be considered. Disruptions to the balance in the soil ecosystem can result in degradation and a decline in soil and plant health as well other nutrient cycling processes important for life (Brussaard, de Ruiter, and Brown 2007). More research is needed to better understand the long-term effects on soil quality, physics, crop yields, and the soil biota (Mahoney, Asami, and Stringfellow 2021; Kondash et al. 2020). Research into soil remediation, crop rotations, and other soil amendments that can be used as management practices should also be explored (Sintim et al. 2017).

Issues related to soil salinity may need to be addressed when produced water is used as a long-term source of irrigation water (Hirayama et al. 2002; Burkhardt et al. 2015; Sintim et al. 2017; Kondash et al. 2020). Accumulation of metals, organics, and salts in soils, as a result of irrigating with OPW has been reported over time and may pose long-term effects on soil and plant health such as soil degradation and stunted growth or death (Santos, Hildenbrand, and Schug 2019; Riyazuddin et al. 2021).

Research is needed on the effects of produced water derived metals and other inorganics on soil quality and soil biota as a result of irrigating crops with produced water (Mahoney, Asami, and Stringfellow 2021). Gaps in knowledge surrounding biotic and abiotic interactions, accumulations of COIs, metals, and other substances; disruptions to nutrient cycling and other geomicrobiological transformations; and loss of diversity, abundance, and species richness (or changes to dominant species). While few studies specifically focused on the effects salinity/pH/boron and salinity/boron interactions on soil organisms, there are reported decreases in abundance and diversity over time, more studies on effects of other COIs and water quality parameters are needed.

3.3.6 Irrigation Method and Timing

Irrigation method, timing, and frequency can be managed to reduce accumulations of salts in soils and root zones and minimize damage to sensitive crops. For example, because flood and sprinkler irrigation methods tend to result in salts accumulating in the lower root zone, increasing irrigation frequency and decreasing the duration can help reduce salinity build up and decrease water stress (Ayers and Westcot 1985). Other strategies to overcome salinity issues include leaching and blending saline water with fresh water supplies, which dilute salts and can increase the volume of available water. However, leaching does require additional water and in water stressed regions, this may not be a viable option.

Crop sensitivities to chemicals and salts is not limited to root uptake from soil systems. Aerial deposition via overhead sprinkler irrigation can also cause damage to foliage in sensitive crops, and tolerances and sensitivities may vary between crops. For example, almonds, apricots, and citrus are more sensitive when chloride and sodium in irrigation water are greater than 177 mg/L and 115 mg/L, respectively. Cauliflower, cotton, and sugar beets are more tolerant and can withstand concentrations of chloride greater than 700 mg/L and sodium greater than 460 mg/L. Table 3-3 summarizes the susceptibility of leaf damage to sodium and chloride of select food crops when saline irrigation water is used in overhead sprinklers.

Some constituents, such as organic chemicals can also be internalized by plants through leaves. This is especially important in arid regions when evapotranspiration is greater. Selecting crops compatible with the irrigation water quality, soil type, and irrigation method can be important management practices to mitigate crop damage and loss of yields.

Table 3-3. Susceptibility of Select Crops to Leaf Damage Due to Saline Water Used for Overhead Irrigation.
Data Source: Adapted from Ayers and Westcot 1985 Table 18, citing original work by Maas 1984.

	Level of Crop Sensitivity [B]			
	1	**2**	**3**	**4**
Na or Cl (mol/m^3) [A]	***5***	***5 - 10***	***10 - 20***	***20***
Chloride (Cl) (mg/L)	*< 177*	*177-355*	*355-709*	*709*
Sodium (Na) (mg/L)	*< 115*	*115-230*	*230-460*	*460*
	Almond	Grape	Alfalfa	Cauliflower
	Apricot	Pepper	Barley	Cotton
	Citrus	Potato	Corn	Sugar Beet
	Plum	Tomato	Cucumber	Sunflower
			Safflower	
			Sesame	
			Sorghum	

[A] Based on direct accumulation of salts through the leaves.

[B] Presented as guidelines, injury to leaves is variable based on cultural practices and environmental conditions.

3.4 Additional Knowledge Gaps and Emerging Research

3.4.1 Detection Methods

Due to the complex and variable nature of produced water, application of standard analytical methods used to identify analytes is challenging and an area of ongoing research (Mahoney, Asami, and Stringfellow 2021). Often, methods are unreliable when performed in high saline or in chemically complex matrices. Pre-treating samples to remove salts and to remove interferences within the matrix is necessary to isolate analytes of interest (Santos, Hildenbrand, and Schug 2019). EPA approved analytical methods exist for drinking water, however, these methods have not been validated for use in waters with high salinity or TDS, and no standardized methods for produced waters currently exist (Gray 2020).

Detection methods generally in use include chemical specific (targeted) or non-targeted analytical methods, such as bioanalytical assays (bioassays). While targeted methods are useful for detecting known analytes, produced water may contain proprietary chemicals used in oil and gas production, protected by trade-secrets, and therefore may not be detected using targeted methods. Bioassays are capable of assessing CECs potential effects on human health, indicate if a physiological response will occur, identify unknown CECs, and narrow the type of CEC. These methods have significant relevance in detection and monitoring for unknown chemicals in produced water. Studies using bioassays have indicated that exposure to chemicals found in produced water may have detrimental health effects to aquatic life, but more research is needed to understand the potential effects to humans (Hu et al. 2022; Santos, Hildenbrand, and Schug 2019). One such non-targeted method, high-resolution mass spectrometry (HRMS) with liquid chromatography, is capable of identifying compounds by mass and has been used to characterize unknown compounds in produced water (Santos, Hildenbrand, and Schug 2019).

Within the public health field, there is growing evidence that exposure to combinations of chemicals can also be more harmful than exposure to a single chemical (Garner et al. 2016). Non-specific testing capable of characterizing toxic effects when exposed to chemical mixtures (e.g., WET) can help bridge this gap. Many chemicals transform, degrade, mix with other chemicals or compounds, or change due to environmental conditions and may be more toxic than the single constituent. An approach using both targeted and non-targeted approaches is needed to ensure complete coverage of chemical analytes.

The studies highlighted in this report, the CCST SB 1281 study and the Food Safety Project, recognized that many of the COIs are not routinely monitored due to a lack of available analytical methods. Standardized chemical analytic methods are needed to characterize OPW and to evaluate the safe use of OPW in agriculture (Shimabuku, Abraham, and Feinstein 2019; GSI 2021b; Cooper et al. 2022; McLaughlin et al. 2020). Physical, chemical, and toxicological data is needed to fully assess the hazards, risks, and impacts to humans, crops, and the environment. While the water quality data from all datasets is not sufficient to evaluate human and environmental impacts, available data obtained from these other data sets do suggest the presence of aquatic, carcinogenic, and air polluting chemicals in California OPW.

3.4.2 Fate, Transport, and Plant Uptake

3.4.2.1 Overview

Many factors influence how organics (e.g., PAHs) and inorganics (e.g., trace minerals, metallics and metalloids, and NORMs) move through soils, become available for plants to uptake, and are distributed and accumulated within plants. These factors include the characteristics of soils, irrigation water, crops, chemicals, and the environment. Bioconcentration factors (BCFs) describe the tendency for a chemical or compound to concentrate within a living organism. It is defined as the ratio of contaminants concentrated in the plant part of interest (e.g., root, leaf, shoot) to that of the medium it is exposed to (e.g., soil, soil porewater, air, or water). How, and at what concentrations, COIs are translocated and accumulate in plants is not well understood due to these complexities and therefore, uptake and accumulation of chemicals and compounds may expose humans to hazards when these crops are consumed.

Data indicates that complex organic chemicals, such as EDCs, PCP, and pharmaceuticals, may be phytoavailable, taken up, and accumulate in some crops, including corn, leafy greens, wheat, and root vegetables (Cooper et al. 2022; Shariq et al. 2021; Zhang et al. 2017; Dodgen et al. 2013; Paz et al. 2016; Malchi et al. 2014). While these specific chemicals are more likely to be present in municipally treated wastewater than OPW, this does provide insight on the potential for complex organic chemicals present in OPW to be taken up and accumulate in crops, as little data exist on their effects on plant community dynamics, plant uptake, and accumulation (Vance, King, and Ganjegunte 2008).

While the fate and transport of organics and inorganics in soils and water may be generally understood, knowledge gaps remain surrounding the long-term impacts on soil and plant health, generally, and as the topics relate to produced water use, more specifically. A majority of the organic COIs identified in the Food Safety Project do not have relevant phytoavailability data and over half (56 of 101) did not have sufficient data on environmental fate and transport, constituting a large data gap. The current state of knowledge limits the ability to determine which COIs will be taken up by plants, at what concentrations, and to establish chemical limits in irrigation water to prevent concentrations in the edible portion from reaching levels of concern to human health. The following sub-sections describe current research on fate, transport, and uptake for specific classes of COI.

3.4.2.2 Organics

The fate of organics in environmental settings, including irrigation water, soils, and plants, is highly complex. Solubility, molecular weight, volatility, biodegradability, plant uptake, sorption to organic matter, and soil characteristics among others are important factors affecting environmental fate. This includes both chemical specific properties as well as the multitudes of interactions between chemicals, chemical mixtures, and the environment. While lighter weight molecular organics may in general be more water soluble than heavier hydrocarbons (Veil et al. 2004) this is only one factor in determining water solubility and is not true for all organic compounds. For example, 2,2-Dibromopropanediamide has a molecular weight of 259.89 g/mol yet is water soluble with an estimated water solubility log ratio of 0.37 (US EPA 2015).

Information on uptake, translocation, and accumulation of organics, especially those found in produced water, within plants is less understood. Organic chemicals can be taken up either by roots (through the soil) or through the leaves through aerial deposition (Doucette et al. 2018). Studies on factors influencing uptake and translocation of organics in plants provide two perspectives (Shariq 2016). Some indicate that only compounds with both hydro and lipophilic properties are able to translocate from roots to leaves via xylem, while others report that highly soluble compounds are also able to translocate from roots to leave, although potentially following a slightly different pathway (Doucette et al. 2018; Dettenmaier, Doucette, and Bugbee 2009; Shariq 2016).

Studies report organic compounds, including PAHs, diethanolamine, and tetramethylammonium chloride (TMAC) (among others) can be taken up by plant roots of zucchini and pumpkin (Mattina, Iannucci-Berger, and Dykas 2000; Lee et al. 2003; Huelster, Mueller, and Marschner 1994), spinach, lettuce, and dandelion (Mattina, Iannucci-Berger, and Dykas 2000; Lee et al. 2003), and wheat (Tao et al. 2009; Shariq et al. 2021). Translocation and accumulation also depend on the crop variety, where chlordane (a persistent organic pollutant (POPs)) accumulates in the edible root tissues of carrots, beets and potatoes; the edible aerial tissues of spinach, lettuce, and zucchini; and the non-edible tissues of tomatoes, peppers, and corn (Mattina, Iannucci-Berger, and Dykas 2000).

3.4.2.3 Inorganics

All of the inorganics identified in the Food Safety Projects as COIs in produced water are also found as naturally occurring in soils, in conventional irrigation water, and in soil amendments and fertilizers (GSI 2021b). Crop type, extrinsic factors and environmental conditions, characteristics and concentrations of COIs, and soil composition and characteristics are important factors in the mechanisms responsible for uptake and concentration of inorganics within plants (GSI 2021b). Soil properties that influence fate and transport include pH, oxidation/reduction (redox) potential, clay and organic matter, cation exchange capacity, and acid content (humic or fulvic acids) (Antoniadis et al. 2017). Mobility and availability of inorganics, which are likely the most mobile components in soil, are most influenced by the redox potential and pH of the soil (Antoniadis et al. 2017; GSI 2021b).

Irrigation waters with high biological oxygen demand (BOD) have been shown to decrease soil pH, reduce levels of nitrates formed, and increase the level of oxygen stress (Nashikkar 1993). In acidic soils (low pH), positively charged species called cations (formed by metal atoms such as sodium, calcium, magnesium, iron, and ammonium) are more mobile and available to plants than negatively charged anions (formed by non-metal atoms such as chloride, bromide, nitrates, phosphates, and sulfates). The redox potential describes a chemical species affinity to exchange electrons. Oxidation occurs under aerobic conditions while reduction occurs under anaerobic conditions. As redox potential increases, pH decreases (becomes more acidic) and metallics become more soluble and available for plant uptake (Antoniadis et al. 2017). Alkaline soils (above pH of 7) generally contain more sodium, calcium, and magnesium. In these conditions, metals have decreased mobility and are less available to plants (Soares, Quina, and Quinta-Ferreira 2015). In addition, metals can create complexes with substances in soils, either increasing or decreasing plant uptake. When complexed with organic materials, metals become immobilized making them less phytoavailable, however, when metals complex with ligands (humic or fulvic acids) phytoavailability is increased (Evangelou, Daghan, and Schaeffer 2004). While ligands are naturally occurring in soils, they are also additives used in the production of oil and gas produced water (GSI 2021b). Soils with clay colloids can increase availability to plants, as the metal becomes more mobile as colloid-metal complexes and is released.

While plant uptake of inorganics occurs at the roots, they tend to concentrate in the roots, leaves, and stem, rather than in the edible portions (GSI 2021b). If concentrations of heavy metals, for example, become toxic, this can lead to physiological, morphological, and metabolic consequences resulting in poor plant health (e.g., chlorosis, protein degradation) or death. Plants employ a variety of defense mechanisms to counter these effects by protecting important metabolic functions that can be affected by inorganics. These include immobilization, formation of and elimination of complexes, and symbiotic associations with microbes (Emamverdian et al. 2015). Another strategy employed by plants is the sequestration of contaminants to areas of less importance (Emamverdian et al. 2015), such as skin and the non-edible portions, which supports the Board’s findings of higher concentrations detected in the non-edible parts of certain plants.

3.4.3 Data Gaps and Emerging Topics

Current data for bioaccumulation of organic chemicals and BCFs in plants is highly variable. Complex interactions between COIs, soils, plants, climate, and microorganisms challenge the ability to make accurate predictions on plant uptake, translocation, and accumulation. Site specific factors coupled with too many gaps in chemical fate and transport, plant uptake, and chemical translocation within a plant make it difficult to calculate the concentration of each chemical in each crop (GSI 2021a).

Current knowledge and data are insufficient to predict where COIs (both inorganic and organic) may accumulate (roots, leaves, or fruit) and at what concentrations using models based on concentrations found in irrigation water or soils. Numeric limits for COIs in irrigation water, therefore, cannot be established to ensure that concentrations in the edible portions of crops are well below oral toxicity values.

This general lack in knowledge and data related to plant uptake and accumulation was a significant gap identified in both the SB 1281 study and the Food Safety Project and was prohibitive in making conclusive statements on COIs (especially inorganics) found in OPW and the potential for them to accumulate in crops. Continued monitoring of water quality parameters and soil composition was also noted as a way to bridge gaps and are necessary to understand the fate, transport, and uptake of COIs in soil systems and within crops.

Due to the complexities involved in predicting translocation and bioaccumulation, new research using machine learning to help predict root concentration factors (RCFs) may be a promising approach. In a study conducted by Gao et al. (2022) from Yale and Columbia Universities, four machine learning models were used to predict how common crops uptake and accumulate organic contaminants from soil systems. The use of machine learning models may facilitate decisions around integrated management approaches that consider key factors for uptake and accumulation (e.g., lipid content of root systems, organic matter in soils, molecular size and characteristics of contaminants, crop species, and soil and water quality) to mitigate risks to humans (Gao et al. 2022).

Another research study collated data from nearly 156 peer-reviewed articles with over 7,000 entries on plant bioaccumulation metrics (112 plant species and 310 organic chemicals) to create a database. Efforts to collate current research to develop a database of bioaccumulation and BCFs are difficult to accomplish due to variations in research studies. Inconsistent and non-standardized testing methods and reporting make such analyses difficult. To add, differences in environmental and climactic conditions and crop characteristics are important variables in establishing BCFs, but studies reporting on these factors is limited (Doucette et al. 2018). Providing technical guidance to the scientific community on standardized methods and models is key to improving exposure assessments.

CHAPTER 4

Reuse of Oilfield Produced Water in California

4.1 Overview of Regulations, Monitoring, and Reporting Programs

Oil and gas operations are subject to state and federal regulations developed and enforced by a diverse range of agencies. In California, the Division (DOGGR) (now CalGEM) oversees the drilling, operation, maintenance, and abandonment of oil and gas wells. State and Regional Water Quality Control Boards regulate the management of wastewater produced by oil and gas operations. Through these agencies and others, several key data collection efforts on the quantity and quality of produced water and disclosures on chemical usage in oil and gas production are occurring. Links to current WDR permits for reuse of produced water for agricultural irrigation are available on the CVRWQCB website.[18] Notably, the CCST SB 1281 report also identified instances where facilities reported disposition of produced water via agricultural irrigation in the SB 1281 reporting data that were not captured in current WDR permits (Shimabuku, Abraham, and Feinstein 2019).

With recent changes in reporting requirements, more is known publicly about water and chemical use, wastewater production, and wastewater treatment than at any point in the past. However, these programs also have several key limits in their utility for addressing the public health and agronomic concerns and knowledge gaps summarized in the previous chapter. These gaps motivated two significant, recent research efforts – CCST SB 1281 study and Central Valley RWQCB Food Safety Project - to better understand the suitability of OPW for agricultural water reuse. This chapter focuses on presenting the data and findings from these studies on the suitability of produced water available for agricultural reuse in California while also discussing limitations of existing monitoring and reporting programs.

4.2 Research and Synthesis Reports on OPW Reuse in California

Ongoing questions about the suitability of produced water for agricultural irrigation in California prompted two recent studies evaluating data gaps and potential health risks associated with the use of produced water for agricultural irrigation in California. An introduction to these two studies was included in Chapter 1. The objectives, data sources, and main conclusions of each study are summarized in Table 4-1. This chapter begins with a summary of each study, shares findings from water quality and crop monitoring evaluation efforts, discusses the role of treatment, current assessments of the potential for reuse, and concludes with key findings and recommendations from each study.

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[18] Current Adopted and/or Issued Orders (including OPW WDRs by County) (CVRWQCB n.d.)

Table 4-1. Comparison of the CCST SB 1281 Study and Food Safety Project Objectives, Data Sources and Years, and Main Conclusions.

Data Sources: CCST 2019 tables 2.4 and 3.2; GSI 2021.

Topic	CCST SB 1281 Project	GSI Food Safety Project
Geographic Area	California – Oil Producing Counties	California - Central Valley
Assessment of	Produced water – before treatment	• Produced water - after treatment or after treatment and blending • Crops irrigated with produced water compared to crops grown with conventional sources
Main Objective	To assess the SB 1281 dataset to answer questions on water resources, public health, and the environment, and to identify opportunities for improvement.	To evaluate the effects and health risks associated with the use of treated produced water for irrigating food crops – to investigate and develop additional knowledge to address public concerns
Secondary Objectives	Sources, volumes, and quality of water used in and off of oilfields	Select chemicals of interest (COIs) from a list of known chemical additives as well as naturally occurring chemicals in produced water
	Variability of characteristics and quality of produced water across the state	Conduct literature review of the COIs and to identify other potential sources of these chemicals
	Impact of treatment to the availability of produced water availability as a potential resource	Fate and transport, phytoavailability, and plant uptake of COIs
	Identify 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	Sample and chemical analysis of crops irrigated with produced water and other crops irrigated with conventional irrigation water sources

Topic	CCST SB 1281 Project	GSI Food Safety Project
Data Sources and years for total dissolved solids, sodium, chloride, and boron, physico-chemical, and toxicological properties of oilfield produced water	1. SB 1281 dataset[A] CalGEM Quarterly Reports: Q1 2015 to Q4 2017 2. USGS Federal Database: 1930 - 1996 3. Division Monitoring 2015-2018 4. Davis et al. 2016: November 2014 5. Gannon et al. 2018: 2016-2017 6. Gans et al. 2018: 1958 – 2013 7. WST Disclosures 8. WDR Monitoring: 1997 to 2018 9. Gillespie et al. 2016: 1939-1997 10. Metzger et al. 2018: 1932-2014	1. Waste Discharge Reports (WDRs): 1967 to 2019[B], 2. Crop chemical analysis – samples collected between 2017 -2019
Main Conclusions	1. The SB 1281 dataset and other datasets do not provide enough information to fully assess the safe use of produced water for irrigating food crops 2. Produced water in California is likely to contain chemicals that are toxic and carcinogenic chemicals	1. The overall chemical concentration profiles between crops irrigated with produced water were similar to those irrigated with conventional sources 2. Typical consumption does not pose a health hazard

WST = Well Disclosure Treatment; WDR = Waste Discharge Requirements.

[A] Primary Data Source.

[B] The majority of WDRs obtained were from 2014 to 2019.

4.2.1 Findings from the California Council on Science and Technology (CCST) Report

While the O&G industry has tracked water produced from and injected into wells for over 45 years, the passing of the 2015 Senate Bill (SB) 1281 requires additional quarterly reporting on water used in O&G production. SB 1281 requires operators to provide information related to the sources, destinations, volumes, quality, storage, and water treatments related to oil and gas operations with more specificity than was previously required. In addition, monthly reports, developed by DOGGR are also required and include information related to water used in the production process.

CCST was commissioned as an independent party to assess the quality and utility of the SB 1281 dataset as compared to the monthly reports. More specifically, CCST was tasked with evaluating whether the data provided within the SB 1281 was sufficient to answer critical questions regarding the safe use of and the potential to expand the current use of produced water in agricultural irrigation. The study used the SB 1281 reporting data, the DOGGR monthly reports, WDR and NPDES permits, and other available data to evaluate the volume of reuse that is already occurring and where it is being used as a basis to determine potentially available volumes. The water quality parameters contained in the reports were used to assess the human and agronomic risks of using produced water for agricultural irrigation.

While the SB 1281 data does provide more detailed information than has been collected before on water used in O&G production, an accurate assessment of the SB 1281 dataset was challenged by a lack of consistency in reporting, invalid data entries, reporting errors, insufficient water quality data, and vague definitions and characterizations. The water quality data provided in the SB 1281 is limited to TDS, where operators report concentrations as either greater than or less than 10,000[19] mg/L. The first part of the study used this criterion alone to estimate the volume of produced water that could be potentially available. However, the recommended threshold for TDS in irrigation is much lower than this, with severe restrictions when concentrations are above 2000 mg/L. Thus, the single water quality parameter measured in the SB 1281 is not enough to categorize water into suitable or unsuitable categories that can then be used to estimate volumes potentially available for reuse (CCST 2019). Further analysis using the information on TDS concentrations could inform where future and more detailed assessments should focus, (i.e., fields where TDS was below the reporting threshold). The only water quality parameter measured in the SB 1281 is TDS, and even then, the actual concentration is not required in the reporting. The CCST SB 1281 report concluded there is not sufficient data to adequately assess the safe use of California produced water based entirely on the SB 1281 as it pertains to human health or the environment (CCST 2019).

Information on physico-chemical and toxicological properties of California produced water was also collated from five additional datasets. In all, CCST evaluated data from 1,707 samples of produced water and 127 chemistry parameters and identified 1,119 chemical additives commonly used in the production of oil and gas. The CCST SB 1281 report conducted a review on two classes of data evaluating produced water quality: 1) Datasets measuring the quality of produced water directly; and 2) Reporting data on the chemical additives that were used in oil and gas production.

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[19] This threshold value was provided by the State Water Board for categorizing produced water that could potentially be reused. Plant thresholds for TDS are generally well below these concentrations (<2000 mg/L).

While the SB 1281 dataset does provide more detailed information than what was previously collected on water used in O&G production, an accurate assessment of the SB 1281 dataset was challenged by a lack of consistency in reporting, invalid data entries, reporting errors, insufficient water quality data, and vague definitions and characterizations. The study found that the SB 1281 dataset was insufficient at estimating the volume of potentially available produced water for agricultural irrigation.

Further assessment of the historical data obtained from the five datasets also identified poor reporting habits, entries that lacked important information on standard analytical methods and detection limits, missing values, and data that could not be independently verified. In addition, many of the chemicals did not have CASRN and were therefore unable to be identified and could not be fully evaluated for toxicity. The CCST SB 1281 study concluded that, based on available data, produced water in California is likely to contain aquatic, air polluting, and carcinogenic chemical hazards. The findings indicate too many unknown variables exist surrounding the chemical make-up and variability in composition and concentrations, interactions between chemicals, degradation products, and daughter products to develop a thorough risk assessment at this time (Shimabuku, Abraham, and Feinstein 2019). Additional data and knowledge gaps identified in the CCST Review are summarized in the appropriate sections.

The overall findings of the CCST SB 1281 report indicate that the SB 1281 datasets alone are not sufficient to provide enough information on the availability of produced water for agricultural irrigation. The additional datasets did provide more useful information on water quality and could be used in conjunction with the SB 1281 datasets, with modifications to data collection and reporting requirements, to provide deeper understanding of the quality and quantity of produced water potentially available for agricultural reuse. Their findings also indicate that California produced water is likely to contain toxic and carcinogenic chemicals, but more research is needed to understand the chemical makeup, interactions and toxicity, and plant uptake and accumulation of these chemicals in agricultural environments.

In general, the CCST SB 1281 study identified major gaps in reporting that made distinguishing current end-locations, end-uses and activities, and the volumes already allocated for reuse difficult. Different reporting styles, redundancies, and complicated reporting classifications were noted as limitations and gaps.

4.2.2 Findings from the Central Valley RWQCB Food Safety Project

To address agronomic and human health concerns on the use of crops irrigated with produced and blended produced water, the Central Valley RWQCB initiated a three-phase approach to identify and prioritize COIs that have the potential to be present in produced water. The objective of Task 1 was to conduct a hazard assessment of chemicals that are known to exist or are likely to exist in oilfield produced water and to prioritize a list of chemicals for further study. Naturally occurring substances found in produced water were identified from the literature while additive chemicals used in the production of produced water were identified from compulsory reporting by oil and gas producers and chemical manufacturers. Task 2 built upon Task 1 with a literature review on the properties and occurrence of the identified COIs. Task 3 tested a variety of crops irrigated with blended produced water and conventional water to assess and compare chemical profiles between the water source types. Sampling work in Task 3 was a continuation of previous studies in the Cawelo Water District on crops irrigated with produced water and was used to inform Task 1. While this data was collected prior to the start of the project, sampling continued throughout Task 1 and the monitoring data was considered in the development of Task 1 list of chemicals in addition to the literature review (GSI 2020; Mahoney, Asami, and Stringfellow 2021).

A Food Safety Expert Panel was also commissioned to provide technical guidance on the work of GSI with a main goal of evaluating the safe use of irrigating food crops intended for human consumption with OPW and make recommendations based on the findings. The Expert Panel provided technical guidance on 1) the identification of chemicals used in oil and gas production, 2) determining ingestion toxicity of these chemicals in order to prioritize and rank COIs, 3) understanding the persistence, degradation, and plant uptake of COIs to edible portions of crops, and 4) the evaluation and implementation of water quality monitoring programs for the safe use of OPW for irrigating food crops (Mahoney, Asami, and Stringfellow 2021).

The overall conclusions of the Food Safety Project indicate that there were no significant differences between crops irrigated with produced water and those irrigated with conventional sources. GSI also concluded that typical consumption of crops irrigated with produced water do not pose a public health hazard. More research on chemical interactions, toxicity, and plant uptake was noted as an area of much needed research.

While the overall findings of the Food Safety Project indicate there were no significant differences between these two sets of crops, the study focused on known chemicals used in the production of oil and gas or those naturally occurring. Chemical mixtures, which may be more toxic than individual chemicals, and chemical transformations were not taken into account. There were also a number of COIs lacking in toxicity information or lacked analytical methods. Crop sampling was also identified as a limitation due to chemical transformations that occur during plant uptake and analytical methods used do not take this into account. Additional data and knowledge gaps identified in the Food Safety Project are summarized in the appropriate sections.

To assess risks to humans, crops, and soil health from using produced water for agricultural irrigation, WDR reporting data on treated produced water and treated produced water blended with conventional irrigation sources (blended produced water) were analyzed for COIs. Samples of treated produced and blended produced water were collected between 1967 and 2019. However, samples collected prior to 1985 did not include any of the COIs. Risk-based concentrations for each COI were based on concentrations safe for drinking water or California Public Health Goals and builds upon existing toxicity information, degradation, persistence, and by-product formation, and other sources (GSI 2020). Because there is a lack of toxicity data published for a number of chemicals associated with produced water, GSI developed surrogate toxicity levels for a number of COIs in the study (GSI 2020).

Based on an analysis of chemical residues of 113 constituents (18 metals and 95 organic compounds), the study concluded that the overall chemical profiles were similar between the treatment and the control groups. Concentrations of inorganics in produced water were measured and compared to those found in blended produced water. In general, the mean concentrations of the COIs were lower in blended produced water than in produced water with the mean ratios generally less than two. Six analytes, beryllium, cobalt, copper, lead, nitrite, and vanadium were reported more frequently and at higher concentrations in blended produced water than in treated produced water.

Often, the maximum contaminant levels (MCLs) for water quality objectives (WQOs) were equal to drinking water MCLs. Arsenic was the exception, regularly detected above drinking water standards, but consistent with conventional irrigation water currently used to irrigate crops (GSI 2020). Over half of the samples collected from blended produced water contained arsenic at concentrations exceeding WQO limits. These concentrations found in produced water were similar to what was observed in conventional sources used for irrigation. Copper and phenanthrene concentrations were higher than conventional water sources (but lower than drinking water standards and did not exceed current standards for water quality (GSI 2021b). In the absence of understanding potential exposure to these chemicals, the assumption that the irrigation water would be consumed as drinking water was used to estimate health risks, which may overestimate the exposure from consuming crops (GSI 2021b)

4.3 Composition of Produced Water and Food Crop Sampling Results

4.3.1 Overview

Produced water has a complex makeup, varying widely in types of constituents and concentrations, sometimes by orders of magnitude, across space and time. Produced water typically has elevated levels of salinity but can contain other inorganics and organics as well. Common constituents identified in produced water include trace amounts of inorganic compounds including salts, metals or metalloids, and radionuclides or NORMs; organic compounds and gases; dissolved and volatile organic compounds; oil and grease; bacteria; and additives required for hydrocarbon production (Gray 2020). Inorganics predominantly originate from the geologic formations surrounding the oil reservoir but may also be introduced from the chemicals used in the production process (GSI 2021b; Veil et al. 2004). Organics can occur naturally or from chemicals used in the production of oil and gas.

Typically, produced water has increased concentrations of salts, TDS, and BOD than fresh water supplies. While chloride (Cl^-) and sodium (Na^+) are the most prevalent inorganic salt ions, magnesium, sulfate, bromide, potassium, iodide, and bicarbonates are also abundant in produced water with high salinity (Rosenblum et al. 2017; Al-Ghouti et al. 2019; GSI 2021b). Trace elements, radionuclides, and other inorganics also may be found in produced water at varying concentrations as well as naturally occurring and additive organic compounds. Appendix A shows a full suite of constituents found in California OPW.

Assessment of potential risks associated with the use of produced water is further complicated by questions on what matrices are most appropriate for assessing risk (e.g., produced water after treatment, produced water after blending, soil, and/or edible crops) and limitations in current analytical methods. The results summarized in this chapter includes treated produced water (CCST and FSP), produced water that has been treated and blended (FSP), and edible crop irrigated with produced water (FSP). Table 4-4 provides a summary of some of the organics present in produced water, and Table 4-3 provides a snapshot of inorganics relevant to agronomic settings, Appendix A provides additional data on the full suite of constituents and concentrations measured in California oilfield produced water and compiled by the CCST SB 1281 study and Food Safety Project. Specific sources of data are noted with individual tables and generally sourced from either the CCST SB 1281 or Food Safety Project reports.

4.3.2 Temporal and Spatial Variation in Produced Water Quality

Variability in the characteristics, composition, and volume of produced water result from geographic location, the age and depth of the geologic formation, geochemistry, the processes used to extract the hydrocarbon product, the type of produced hydrocarbon (for example, oilfield produced discharges are less toxic than gas produced discharges), and the duration of the production period (temporal variations) (Rosenblum et al. 2017; Al-Ghouti et al. 2019; GSI 2020). Extrinsic factors, including temperature, oxygen levels and exposure, pressure, and treatment options also affect the overall composition. Differences in composition and volume can occur across large scales, differing between countries or continents. For example, Africa and the Middle East typically have lower salinity levels and concentrations of TDS (704 - 1,370 mg/L) (Camarillo and Stringfellow 2018) as compared to other locations, such as parts of North America where TDS ranges from 40 to > 450,000 mg/L (IPIECA 2020).

Even narrow geographic regions are known to produce water of different qualities and characteristics. For example, two separate geologic formations within an oilfield, the eastern fields (Fruitvale Field) and western fields (Lost Hills and Belridge fields) of the San Joaquin Valley in California produce water with different concentrations of salinity, chloride, and radium. In the western fields of the SJV, concentrations of salinity and NORMs in produced water are higher than what is produced in the eastern fields. Metals and metalloids also vary depending on location and on occasion are found in higher concentrations (by 100 to 100,000 times) than sea water (Rosenblum et al. 2017; GSI 2021b; Jiménez et al. 2018).

Table 4-2 highlights the differences in water quality of produced fields within Kern County, California from the east side of San Joaquin Valley and the McKittrick Oilfields (western field). In the eastern fields, produced water tends to have a higher quality than what is produced in the western fields (McKittrick Oilfield) and is used for agricultural irrigation. The low salinity of produced water from the east side of the San Joaquin Valley allows for it to be used for agricultural irrigation without treatment to remove salts though blending is common. Measured parameters in treated and blended OPW from the eastern fields are roughly equivalent to or below current State drinking water standard thresholds (Table 4-2).

Water quality characteristics and concentrations of constituents differ temporally with the age of the geologic formation and throughout the production process. Research by Rosenblum et al (2017) observed that fluctuations and variability in water quality stabilizes (for most parameters) after the first few days of flowback[20] during the well production period. Within the first four days, the total suspended solids (TSS) decreased by 59%, levelled off, then decreased by another 40% between days 55 and 80 (Rosenblum et al. 2017). Several studies show that the concentration of TDS generally increase throughout the production process while the chemical oxygen demand (COD) decreases (Rosenblum et al. 2017; Oetjen et al. 2018). This could play an important role in deciding which treatment technologies to employ and when to employ them in order to achieve the level of quality required for the end use.

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[20] Flowback is recovered fluid from a treated well prior to production of oil and gas. For the purposes of this report, flowback fluid is considered as part of produced water.

Table 4-2. Produced Water Quality from Two Oilfields in Kern County and Compared to Drinking Water Standards.

Source: Mahoney et al. 2021.

Parameters	Units	Treated, Blended Produced Water Reused for Irrigation from the East Side of the San Joaquin Valley	Produced Water from the McKittrick Oilfield (western field)	Drinking Water Standards[21]
Total Dissolved Solids	mg/L	524	15,250	500 *
Electrical Conductivity	umhos/cm	751	20,333	900 *
Boron	mg/L	0.84	59.75	NA
Chloride	mg/L	94	8,325	250 *
Copper	ug/L	1.83	5.70	1,300
Sodium	mg/L	143	5,000	NA
Benzene	ug/L	0.88	2.21	1
Xylenes, Total	ug/L	2.39	10.10	1,750
Toluene	ug/L	1.29	89.25	150

mg/L = milligrams per liter; umhos/cm = micromhos per centimeter; ug/L = micrograms per liter.

* = Secondary Drinking Water Standard.

Due to the lack of data on characteristics and composition of produced water, regional, geographical, and site-specific studies over time are needed to identify and prioritize chemicals CECs and COIs of human and agronomic concern to maximize successful water reuse programs (Al-Ghouti et al. 2019). Geologic characteristics affect quantity and quality of water produced thus individual formations within an oilfield should be evaluated rather than composite assessments (CCST 2018).

4.3.3 Concentrations of Chemicals of Interest in Produced Water

4.3.3.1 Salts

In agricultural settings, TDS concentrations (mg/L) or EC (reported as µS/cm or ds/cm) are commonly used to estimated salinity in irrigation water or soils (GSI 2021b; Veil et al. 2004). Total dissolved solids, often referred to as total salinity are a measure of combined ion particles smaller than 2 microns (0.0002 cm), including salt ions and dissolved organic solutes. EC is a measurement of the ability to pass electrical flows and is directly related to the ion concentrations.

In North America, produced water can have concentrations of TDS ranging from 40 to >450,000 mg/L while chloride concentrations range from 1 to 300,000 mg/L (IPIECA 2020; GSI 2021b). In comparison, salinity and EC in the eastern fields of the San Joaquin Valley is of a much higher quality with lower

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[21] State drinking water standards are from the California Code of Regulations and referenced in Title 22, Division 4, Chapter 15. The secondary standards (*) are based on aesthetic or cosmetic properties such as taste, odor, color or for the potential to cause discoloration of skin or teeth (Mahoney, Asami, and Stringfellow 2021).

average concentrations of TDS (524 mg/L), EC (751 uS/cm), sodium (143 mg/L), chloride (94 mg/L), and boron (0.84 mg/L) (Mahoney, Asami, and Stringfellow 2021). These concentrations are lower than in the neighboring McKittrick Oilfield where TDS exceeds 15,000 mg/L and are summarized in Table 4-2.

4.3.3.2 Trace Elements and Other Inorganics

A wide range of metals, metalloids, and other trace elements including barium (Ba), boron (B), chromium (Cr), iron (Fe), manganese (Mn), magnesium (Mg); mercury (Hg), nickel (Ni), strontium (Sr), and zinc (Zn) may also be present in produced water. In general, most dissolved inorganics are positively correlated with chloride and salinity. This is observed where high salinity produced waters also report higher concentrations of other inorganics, such as boron.

Reduced inorganic metals (Fe) and additive chemicals can contribute to high BOD levels, or the amount of oxygen microorganisms consume as they break down, or decompose, organic matter. As the BOD rises, the amount of available oxygen decreases, creating low oxygen, or anoxic, environments. Sulfates, commonly found in OPW and introduced via sulfate-containing seawater or existing naturally, can contribute to environmental, treatment, and operational challenges. In anoxic environments, anaerobic bacteria reduce sulfites to sulfides, such as hydrogen sulfide and polysulfides, known to be highly toxic, and contribute to scaling and microbially mediated corrosion (Rosenblum et al. 2017; Basafa and Hawboldt 2019).

The concentrations of inorganics found in California produced water also vary based on location. These differences are observed between produced water samples collected from the Central Valley California (used in the Food Safety Project) and samples from multiple oil-producing regions throughout California (used in the CCST SB 1281 study). For example, boron concentrations in produced water from multiple regions in California are well above the FAO recommendations for irrigation water (0.5 mg/L to 602 mg/L, mean of 92 mg/L), yet within the maximum thresholds for samples collected from oilfields inside the Central Valley (0.1 and 2.2 mg/L, mean of 0.86 mg/L). In contrast, the mean concentration of manganese reported in the CCST SB 1281 report is lower (39 mg/L) than what is reported by the Food Safety Project (87 mg/L).

Water quality data from produced water collated from both the CCST SB 1281 study and the Food Safety Project are presented and compared to the FAO guidelines in Table 4-3. The mean concentrations for inorganics (with the exception of manganese) in samples of produced water in the Central Valley assessed as part of the Food Safety Project fall below the FAO guideline values for the long-term use of recycled water for agricultural irrigation. Complete lists of analytes assessed in both the CCST SB 1281 study and Food Safety Project are provided in Appendix A.

Table 4-3. Summary of Produced Water Quality Data from the Food Safety Project and CCST SB 1281 Study and Comparison to FAO Recommendations for the Long-Term Agricultural Irrigation with Recycled Water.

Sources: Ayers & Westcot 1985 Table 21; CCST 2019 Table A3.1; GSI 2021 Tables 7 and 9.

Note: The parameters included in this table were selected for their agronomic significance, though some also pose human health risks. Data on additional water quality parameters is included in Appendix A and other tables. NT = not tested, ND = no data

Study	Chemical Analyte	Recommended Maximum Concentration for Irrigation [A] (mg/L)	Total No. of Samples [B]	No. of Detects [C]	Min (mg/L)	Mean/ Median [D] (mg/L)	Max (mg/L)
FSP	Aluminium	5	NT	NT	NT	NT	NT
CCST			-	32	0.01	0.5	17
FSP	Arsenic	0.1	159	142	0.0001	0.037	0.091
CCST			-	56	0.008	0.3	5
FSP	Beryllium	0.1	71	2	0.000081	0.000087	0.000092
CCST			-	31	0.001	0.01	0.1
FSP	Boron[E]	1.0 - 1.6	66	66	0.1	0.86	2.2
CCST			-	1,628	0.05	92	602
FSP	Cadmium	0.01	72	0	ND	ND	ND
CCST			-	3	0.0004	0.01	0.03
FSP	Chromium (VI)	0.1	37	7	0.000034	0.0016	0.0086
CCST			-	274	0.004	0.05	1.2
FSP	Cobalt	0.05	60	3	0.00011	0.00013	0.00017
CCST			-	38	0.002	0.04	0.1
FSP	Copper	0.2	63	25	0.00011	0.0016	0.0045
CCST			-	376	0.003	0.04	33
FSP	Fluoride	1	38	30	0.41	1	2.4
CCST			-	240	0.03	1.2	53
FSP	Iron	5	NT	NT	NT	NT	NT
CCST			-	1,128	0.01	15	660
FSP	Lithium	2.5	55	37	0.015	0.05	0.074
CCST			-	1,382	0.004	6	460
FSP	Manganese	0.2	107	94	0.0026	1.9	87
CCST			-	1,199	0.01	0.5	39
FSP	Molybdenum	0.01	63	41	0.00028	0.0069	0.015
CCST			-	111	0.002	0.04	0.3
FSP	Nickel	0.2	74	34	0.0003	0.00091	0.0026

CCST			-	158	0.008	0.07	2
FSP	Nitrite	-	6	1	1	1	1
CCST			-	-	-	-	-
FSP	Selenium	0.02	67	21	0.0003	0.00089	0.0028
CCST			-	140	0.03	0.4	15
FSP	Vanadium	0.1	53	3	0.0011	0.002	0.0027
CCST			-	31	0.01	0.07	0.9
FSP	Zinc	2	67	32	0.0018	0.0097	0.036
CCST			-	1,628	0.05	92	602

[A] Recommended limits for the long-term use of reclaimed water. Modified from Ayers and Westcot, 1985 and Fipps 2021.

[B] The CCST data was collected between 1930 and 2018 from many regions in CA and total number of samples for each parameter was not provided. FSP data was collected between 1985 and 2019 in the Central Valley.

[C] The number of detections for the FSP were calculated from the frequency of detection.

[D] The Food Safety Project (FSP) provided the mean while the CCST SB 1281 report provided the median of samples.

[E] Annual average

4.3.3.3 Naturally Occurring Radionuclides

There are six radionuclides identified as COIs in produced water. They include four metal radionuclides radium-226 (Ra-226), radium-228 (Ra-228), thorium-232 (Th-232), uranium-238 (U-238) and two noble gas radionuclides, krypton-85 (Kr-85), and xenon-133 (Xe-133). The most common NORM found in produced water is radium (226 and 228) and is known to co-precipitate with barium sulfate, calcium sulfate, and calcium carbonate (Stephenson 1992). Produced water from Kern and Tulare counties in California have been found to contain the presence of potassium-40, radium-226, radium-228, uranium-235, uranium-238, and cesium-137 in produced water (DOGGR 1996), however, P-40 is not considered a COI as concentrations found in produced water are an order of magnitude lower than typical daily intake (GSI 2021b; DOGGR 1996).

Recent studies in the southern San Joaquin Valley in California reported significantly lower concentrations of radium in the eastern fields than in the western fields where reported median concentrations were 1.3 Bq/L[22] and 3.5 Bq/L, respectively. This is expected as salinity and chloride concentrations are also lower in the eastern fields (Cl=110 mg/L) than in the western fields (Cl=23,000 mg/L) (Mahoney, Asami, and Stringfellow 2021; Kondash et al. 2020). This supports findings correlating higher concentrations of TDS and salinity with NORMs and other inorganics. Kondash et al. (2020) found that soils irrigated with raw or blended produced water were similar to that of soils irrigated with groundwater, indicating that NORM accumulation did not increase as a result of irrigating with OPW. However, regions where produced water has a higher salinity than the San Joaquin Valley, which typically has low saline produced water, may show different results.

4.3.3.4 Organics

Organics are also known to be present at higher concentrations in oilfield produced water (Camarillo and Stringfellow 2018; McMahon et al. 2018; Veil et al. 2004; Vengosh 2014). Naturally occurring organics include organic acids, PAHs, phenols, and volatiles, many of which are toxic to humans (Veil et al. 2004). Accumulation of PAHs has been well documented in the literature and can accumulate in plants with the potential of entering the food chain.

Table 4-4 shows the number of detections and summary statistics on select organic chemicals identified in California produced water from the CCST SB 1281 study. The number of samples available within existing datasets for each constituent varied widely. Data on the sampling location within the production lifecycle (e.g., individual wells, before or after treatment) was mixed and often limited. Within a given location, the number of samples varied (i.e., sites with a higher number of samples may be overrepresented). Likewise, the underlying data only reflect detections. Information on the total number of samples collected was not available.

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[22] Bq is the SI unit to measure radioactivity where one becquerel (Bq) is equal to one radioactive decay per second.

Table 4-4. Organic Constituents in Produced Water Identified in the CCST SB 1281 Study.

Source: Adapted from CCST 2019, Table A3.1.

Constituent	No. of Detections	Min	Med	Max	Units
1,2,4-Trimethylbenzene	2	0.3	0.3	0.3	mg/L
Benzene	1,175	0.0003	0.8	25	mg/L
Dibromofluoromethane	1	0.01	0.01	0.01	mg/L
Ethylbenzene	1,172	0.0006	0.3	5.3	mg/L
Guar gum	38	30	125	3,500	mg/L
m-Xylene	29	0.2	0.8	2.1	mg/L
o-Xylene	1,163	0.001	0.4	6	mg/L
p-Bromofluorobenzene	1	0.01	0.01	0.01	mg/L
Phenols	3	0.05	0.2	0.2	mg/L
Toluene	1,179	0.004	2	61	mg/L
Xylenes	1,178	0.004	1.3	19	mg/L
Xylenes, Isomers m & p	1,136	0.002	0.8	13	mg/L

Organic constituents from The Food Safety Project are summarized in Table 4-5 and include detection frequency and summary statistics from blended produced water. These data were sourced from WDR permit reporting. This table also includes toxicity values (mg/kg/d)[23] and phytoavailability scores. Phytoavailability scores were determined based on volatilization, sorption to organic materials, and biodegradation where a value of one indicates a low potential for organics to be taken up by plants and a value of eight indicates the greatest potential (GSI 2021b). Four of the chemicals had phytoavailability scores above five, nine chemicals had values of four, one chemical had a value of two, and two chemicals did not have phytoavailability scores.

Complete lists of analytes from the CCST SB 1281 study and the Food Safety Project are presented in Appendix A. It should be noted that there is minimal overlap between the analytes measured in each of the studies.

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[23] Oral slope factor (OSF) for the increased risk of cancer from oral exposure over a lifetime.

Table 4-5. Compilation of Food Safety Project Data on Organic Chemicals in Blended Produced Water, Relative Toxicity and Phyto-availability Score, and Comparison to Drinking Water Standards.

Sources: Modified from GSI 2021b, tables 8,9,13, and 14.

Organic Chemical Analyte [A]	Toxicity Value [B] (mg/kg/d)	Drinking Water [C] Equivalent Conc. (mg/L)	Phyto-Availability score	No. of samples	Detection Frequency	Min Conc.	Mean Conc.	Max Conc.
							(mg/L)	
1,4-Dioxane	0.0001	0.0038	7	9	0.22	0.00052	0.00075	0.00098
2-Naphthylamine	NA	NA	NA	0	NA	NA	NA	NA
Acenaphthene	0.06	3.3	4	61	0.15	0.00003	0.00015	0.00061
Acrylamide	0.5D	-	6	4	0	ND	ND	ND
Aniline	0.0057[D]	-	ND[E]	10	0	ND	ND	ND
Anthracene	0.3	17	4	60	0	ND	ND	ND
Benz(a)anthracene	0.000008	0.00031	4	60	0.02	0.00003	0.00003	0.00003
Benzo(a)pyrene	0.000003	0.00012	4	60	0	ND	ND	ND
Benzo(b)fluoranthene	0.000008	0.00031	4	60	0.02	0.00011	0.00011	0.00011
Bis(2-chloroethyl) ether	0.000004	0.00015	7	12	0	ND	ND	ND
Chlorobenzene	0.02	1.1	6	69	0	ND	ND	ND
Chrysene	0.00008	0.0031	4	60	0.03	0.000039	0.000041	0.000042
Dibenz(a,h)anthracene	0.000002	-	4	59	0	ND	ND	ND
Fluoranthene	0.04	2.2	5	74	0	ND	ND	ND
Indeno(1,2,3-c,d) pyrene	0.000008	0.00031	4	61	0.02	0.000091	0.000091	0.000091
Phenanthrene	ID	ID	4	60	0.18	0.000029	0.00011	0.00029
Pyrene	0.03	1.7	5	60	0.02	0.00004	0.00004	0.00004
Stoddard Solvent	ID	ID	2	1	1	0.025	0.025	0.025

[A] Samples collected between 1985 and 2019 from WDR permit reporting. Data are from nine sites currently or previously reusing OPW in the Central Valley.

ND – Non-detect; ID – Insufficient Data.

[B] As provided in GSI 2021b table 14, unless otherwise noted.

[C] Toxicity Value Drinking Water Equivalent Concentration.

[D] EPA IRIS Oral Slope Factor for quantitative estimate of carcinogenic risk from oral exposure.

[E] While no phytoavailability score is available for aniline, it is water soluble with an estimated water solubility log ratio of 1.08 and a measured log ratio of 0.9.

4.3.4 Results from Food Safety Project Crop Sampling

Concentrations of COIs were also measured from samples taken from thirteen different crops collected during the 2017-2019 growing season irrigated with blended produced water and were compared to those of market crops irrigated with conventional sources in other geographic regions (GSI 2021b). Table 4-6 provides a summary of crops with at least one detection of each of the target analytes performed in Task 3. In general, the concentrations of the majority of the COIs were consistent with the ranges observed in the marketplace crops (those irrigated with conventional irrigation water sources) (GSI 2021a).

In the thirteen crops tested (Carrots, potato, garlic, tomato, lemon, mandarin, navel and, Valencia oranges, apples, cherries, grapes, almonds, and pistachios), strontium was the only analyte detected in all crops at least once. Concentrations of antimony and chromium in some crops was found to be higher than what is reported in the literature, but concentrations were consistent between irrigation with blended produced water and conventional sources and may likely be linked to crop type or variety, air quality (aerial deposition), or soil composition (GSI 2021b). Arsenic concentrations in crops irrigated with produced water were also comparable to those typically reported in food crops (GSI 2021b).

All of the COIs detected in Task 3 crops were also found in soil, air, and conventional irrigation water indicating that these chemicals are not unique to produced or blended produced water and could have origins outside of irrigation water (GSI 2021b). Results of the food crop sampling indicated no significant differences between crops irrigated with blended produced water and crops irrigated with conventional sources. Based on these findings, the Food Safety Panel recommended ceasing crop sampling and focusing on water and soil sampling. However, it is important to clarify that this was not a judgement call on risk or lack thereof posed by these crops, but instead, a pragmatic assessment of the limitations current analytical methods, uncertainties around transformation products, and allocation of limited resources (Mahoney, Asami, and Stringfellow 2021). The Food Safety Panel recommended increased sampling and research on chemical concentrations in soil and water in lieu of additional food crop sampling.

Table 4-6. Number of Crops with at Least One Detection for Each Analyte Analyzed.

Source: GSI 2021, Table 4.

Type of Chemical	Target Analytes	Number of crops
Metal	Strontium	13
Metal	Copper	12
Metal	Barium	7
Metal	Zinc	3
Metal	Antimony	2
Metal	Cadmium	2
Metal	Molybdenum	2
Metal	Nickel	2
Metal	Arsenic	1
Metal	Chromium	1
Metal	Lead	1
Organic	Acetone	11
Organic	Acrolein	7
Organic	Ethyl acetate	6
Organic	p-Isopropyltoluene	5
Organic	Bis(2-ethylhexyl)phthalate	2
Organic	2-Butanone	1
Organic	2-Chloroethyl vinyl ether	1
Organic	2-Hexanone	1
Organic	Bromomethane	1
Organic	Chloromethane	1
Organic	Methyl tert-butyl ether (MTBE)	1
Organic	sec-Butylbenzene	1
Alcohols	Methanol	5

4.3.5 Data Gaps and Limitations – Produced Water Quality and Food Safety

Understanding the movement and fate of COIs, including trace elements, heavy metals, NORMs, and organic chemicals in agronomic settings, from irrigation water to food crops, is needed to assess risks and impacts to humans. While movement, fate, and transport of organics and inorganics is generally better understood, much of the existing data is on single compounds or elements, and not mixtures. Some organic chemicals that are known to be carcinogenic or toxic to humans are known to be taken up and accumulate in crops intended for human consumption. Because metals tend to persist and accumulate in soils, more research is needed to understand how concentrations in irrigation water affect soil concentrations over time in order to establish risk-based ranges for acceptable concentrations in irrigation water. Long-term studies on concentrations accumulated in crops and the effects of long-term exposure to low concentrations are needed to fully understand the potential negative health effects on humans. General findings on these knowledge gaps are included in Chapter 3 while this section focuses on specific gaps identified by the CCST SB 1281 report and Food Safety Project.

4.3.5.1 CCST SB 1281 Study

The CCST review of the (existing) produced water monitoring datasets found these data to have poor reporting habits lacking key information on standard analytical methods and detection limits. The reports had limited number of analytes and lacked sufficient information to assess toxicity, such as a CASRN. Reporting data on chemical additives (outside of the SB 1281) provided more specific details on the chemicals that were being used (though a significant proportion of the chemicals identified were listed as ‘proprietary’). Information was not available on the mass/concentration of chemicals used by sites (again proprietary), but nonetheless, the authors of the CCST SB 1281 report were able to use the available information to assess the relative toxicity of a subset of chemicals commonly used in oil in gas production and likely to end up in produced water. The report concluded that produced water likely contains toxic chemicals and that too many unknown variables exist to conduct a full risk assessment (Shimabuku, Abraham, and Feinstein 2019).

4.3.5.2 Food Safety Project

While the Food Safety Project did not find evidence that inorganics and metals accumulate substantially in crops, information on soil uptake factors for specific COIs found in OPW for specific crops is lacking, and predictions on concentrations of inorganics, metallics, and NORMs in crops based on concentrations in irrigation water cannot be made (GSI 2021b). The findings indicated no significant differences between the two types of crops (irrigated with produced water vs. conventional water). However, there are several factors that should be taken into consideration. First, this study focused on known chemicals that are used in oil and gas production or are naturally occurring. The chemical analyses looked for specific chemicals only and did not include daughter products or degradation by-products that can be produced during chemical transformations that occur in the environment as well as within plants in the analyses (for water samples or for crop samples) (GSI 2021a; Mahoney, Asami, and Stringfellow 2021). Mixtures of chemicals and transformation products may also have increased toxicity than single chemicals (Nagel et al. 2020; Kassotis, Nagel, and Stapleton 2018; Shimabuku, Abraham, and Feinstein 2019).

Data constraints limited the study to potentially hazardous chemicals known to be present in oilfield produced water. COIs were selected and prioritized as the best indicators to potentially impact health when used for agricultural irrigation (GSI 2021b). Therefore, the potential for additional and unknown CECs to be present in produced water, and in concentrations hazardous to humans, is possible. The majority of COIs assessed had few relevant studies and the current toxicology data that does exist, and is relevant to oilfield produced water, was limited (e.g., 86 chemicals identified in produced water that do not have analytical methods or toxicity information) (GSI 2021b; Mahoney, Asami, and Stringfellow 2021). To estimate toxicity for chemicals that had missing or incomplete toxicity data, GSI developed surrogate toxicity values for twelve COIs, mostly using animal studies (GSI 2021b; Mahoney, Asami, and Stringfellow 2021).

Another limitation is related to crop analyses where small sample sizes and a lack of controls were noted as gaps (GSI 2021a; Mahoney, Asami, and Stringfellow 2021). Likewise, details on sampling methodologies did not allow for deeper understanding of the proportion of a produce sampling location's irrigation water budget composed of produced water vs. other supplies (i.e., potential variability in the level of exposure crops had to produced water). Chemical analyses of crops were considered to be unreliable as compared to soil and water analyses due to chemical mixtures and transformation products – which can occur in the environment and during plant uptake. Analytical methods used did not account for these changes and do not provide a full picture of the potential toxicity that may exist in irrigation water or crops. It was therefore recommended that crop analysis be discontinued. This reasoning for discontinuing crop analysis was not due to a lack of detecting CIOs, but due to the unreliability of crop testing in general.

4.3.5.3 Summary of Data Gaps and Limitations

Produced water quality varies significantly across spatial and temporal scales. Future monitoring and/or research efforts should be designed to better understand these variations. For instance, water quality and quantity should be monitored over time and throughout production at sufficiently small-time intervals between samples to establish temporal profiles. Likewise, given variability within and across geologic regions, more site and formation specific sampling and monitoring is needed.

Both the CCST SB 1281 study and the Food Safety Project identified inclusion of additional water quality parameters and specifics on chemical use as key knowledge gaps in fully assessing the safe long-term use of oilfield produced water. Of particular significance is the lack of information on the mass of chemicals used as oilfield additives. Because many chemicals and their specific usage are proprietary or trade secrets, they could not be fully analyzed (Shimabuku, Abraham, and Feinstein 2019; Mahoney, Asami, and Stringfellow 2021). A lack of data on actual chemical use and make-up (outside of general water quality parameters) and chemicals without a CASRN does not allow for full risk assessments. Additionally, current water quality data on CECs and COIs identified in the study may be outdated and limited to only a select group of constituents that may no longer be relevant to modern production practices. The CCST SB 1281 study highlighted how more accurate and quantitative monitoring (e.g., reporting actual values for TDS) and inclusion of additional analytes of agronomic importance (e.g., boron, SAR, pH) to existing monitoring programs (e.g., SB 1281) would capture more accurately the potentially available volumes of OPW suitable for irrigation (Shimabuku, Abraham, and Feinstein 2019).

4.4 Treatment and Blending of Produced Water in California

Prior to irrigation, produced water is first treated to meet specific discharge requirements set forth under the WDRs. Deoiling using a water oil separator and/or pond systems were the most common types of treatment identified in WDR permits. More detailed information on treatment methods is provided in the 'Treatment Technologies and Detection Methods section' below. 'Dischargers' must monitor the discharge at specific locations and set frequencies before transferring the produced water from the oil company to a wastewater management company, or 'irrigators' through a conveyance system (Mahoney, Asami, and Stringfellow 2021). After receiving the treated produced water, the irrigation districts will generally blend it with surface or groundwater before delivery to the growers. The CCST SB 1281 report identified substantive gaps in reporting that made distinguishing current end-locations, end-uses and activities, and the volumes already allocated for reuse difficult. Different reporting styles, redundancies, and complicated reporting classifications were noted as limitations and gaps. These gaps make detailed understanding of full-cycle the management and treatment of all produced water within a facility challenging.

While most produced water is considered to be very saline, and unsuitable for irrigation of certain crops due to plant sensitivities, blending is commonly used to dilute salts and produce a quality of water acceptable for agricultural irrigation (from a salinity perspective). Blending also expands the water resource, creating a larger volume of water available to growers. Table 4-7 highlights the differences between treated produced and blended produced water from WDR monitoring data from samples collected in the Central Valley between 1985 and 2019. These values are compared to the recommended maximum concentrations for the long-term use of recycled water used for agricultural irrigation (Ayers and Westcot 1985).

Six analytes, beryllium, cobalt, copper, selenium, vanadium, and zinc were measured in higher concentrations in the blended produced water than what was measured in the treated produced water. Two analytes, fluoride and manganese, were measured in higher concentrations in the treated produced water than what is recommended for agricultural irrigation. None of the analytes in the blended produced water exceed the recommended maximum concentrations for agricultural irrigation water.

Table 4-7. Comparison of Recommended Maximum Concentrations of Trace Elements in Irrigation Water to Concentrations Reported in Treated Produced Water and Blended Produced Water from the Food Safety Project.

Data Sources: Ayers & Westcot 1985; GSI 2021b.

Element	Recommended Maximum Concentration [A] (mg/L)	Mean of Detected Concentration [B] (mg/L) Treated Produced Water	Mean of Detected Concentration [B] (mg/L) Blended Produced Water
Al (aluminum)	5.00	Not tested	Not tested
As (arsenic)	0.10	0.03690	0.01390
Be (beryllium)	0.10	0.00009	0.00294
B (boron) (annual average)	1.0 - 1.6[C]	0.86400	0.54700
Cd (cadmium)	0.01	ND	0.00400
Co (cobalt)	0.05	0.00013	0.00126
Cr (chromium)	0.10	0.00158	0.00006
Cu (copper)	0.20	0.00161	0.00893
F (fluoride)	1.00	1.02000	0.45200
Fe (iron)	5.00	Not tested	Not tested
Li (lithium)	2.50	0.04980	0.02170
Mn (manganese)	0.20	1.92000	0.04580
Mo (molybdenum)	0.01	0.00691	0.00324
Ni (nickel)	0.20	0.00091	0.00207
Pd (lead)	5.00	Not tested	Not tested
Se (selenium)	0.02	0.00089	0.00111
V (vanadium)	0.10	0.00197	0.00325
Zn (zinc)	2.00	0.00968	0.01340

[A] Recommended limits for the long-term use of reclaimed water. Modified from Ayers and Westcot, 1985 and Fipps 2021.

[B] Modified from GSI 2021b from samples collected between 1985 and 2019.

[C] Values for boron from the WDRs represent an annual average.

4.4.1 Treatment Technologies

Over the last decade, production technologies and operations have become increasingly efficient at achieving a higher quality of produced water. These advancements help to reduce the high costs and energy requirements associated with treatment and have created more opportunities for reuse. In produced waters, dischargers in California treat water in two phases. First, deoiling methods separate the oils from the water in wash tanks and the oil is sent to temporary storage tanks (Mahoney, Asami, and Stringfellow 2021). The secondary phase is generally used if the produced water is going to be use for agricultural purposes and generally consists of dissolved air flotation, filters, and ponds. These processes further remove residual oils and solids. Table 4-8 provides a summary of the treatment methods employed for produced water prior for use in agriculture.

While treatment technologies may be capable of achieving a quality of water sufficient for agricultural irrigation, human health and agronomic concerns exist. Treatment options are selected based on quality of the water, end-uses, and regulations. It is therefore essential to understand what chemicals are present in the produced water in order to determine the level and method of treatment required to produce a quality appropriate for the intended end-use. Because produced water typically has elevated levels of salinity, most scenarios require treatment to reduce salinity for use in agricultural (GSI 2021b). It also may be likely that removal of CECs is necessary for agricultural irrigation. However, the energy and financial costs of technologies capable of achieving this (e.g., desalination) are high. In some cases, treated produced water can be blended with other water sources such as surface or groundwater to further reduce salinity and dilute CECs. Current treatment technologies focus on physical-chemical treatments as they are straightforward and effective. However, disadvantages to these methods include high capital costs, production of brine waste, and challenges in removing trace contaminants.

Treatment trains are often employed in phases, each phase using a different technology appropriate for the end-use (CCST 2018). The level of treatment needed is based on the composition of the feed water, regulatory requirements, and the intended end-use (Gray 2020; GSI 2020). Primary and secondary treatments separate the oil and gas from the water while polishing methods using physical, biological, and chemical technologies further improve the quality to meet levels required for irrigation (GSI 2021b). Factors including type of contaminant, removal efficacy, energy needs, reagent consumption, impacts on the environment, and costs determine the most effective treatment method (GSI 2021b).

Table 4-8. Oilfield Produced Water Treatment Method, Description and Examples from SB 1281.
Source: Adapted from CCST 2019.

Treatment method	Description	Examples
Deoiling	Separation of hydrocarbons from water by use of gravity, physical, chemical, filtering, and/or absorption processes	Gravity/corrugated plate, centrifuge, hydrocyclone, gas flotation, chemical extraction, oxidizer introduction, absorption, media filtration
Disinfection	Treatment of water for microbial contamination; often used for domestic use or disposal.	Chlorination, ultraviolet (UV) light or ozone exposure
Desalination	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	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	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

While membrane technologies are efficient at removing a variety of contaminants, scaling and biofouling can reduce treatment efficacy and create costly problems due to the higher oxygen demand of produced water (Camarillo and Stringfellow 2018). Biological treatments have long been used in wastewater treatment and research into alternative treatment options (including biological methods) specific to oil and gas produced water is growing globally. Types of biological treatment technologies include fixed-film, membrane bioreactors, wetland ponds, activated sludge, anaerobic, and bio-electrochemical methods. A review by Camarillo and Stringfellow (2018) shows that biological treatments are effective at reducing a variety of water quality parameters including oxygen demand (OD), nutrients, metals, and trace contaminants and are able to function under extreme environmental conditions (e.g., pH, temperature, and salinity).

Studies show that biological treatments, especially as part of a larger treatment train are effective at removing 73% of COD when TDS values are below 50,000 mg/L but decreases to 54% removal as the TDS levels exceed 50,000 mg/L. While more research is needed to better understand the mechanisms underlying the temporal fluctuations and the factors affecting these variabilities that occur throughout the production period, findings from Rosenblum (2017) and Oetjen (2018) could play an important role in treatment technologies and management options (e.g., on-site vs centralized facilities or timing of treatment) (Rosenblum et al. 2017; Oetjen et al. 2018). For example, higher concentrations of TDS (>50,000 mg/L) were shown to decrease treatment efficacy of OPW (Rosenblum et al. 2017; Camarillo and Stringfellow 2018). Thus, identifying when TDS values are at optimal concentrations for increased treatment efficacy may be of great value in determining when, where, and which type(s) of treatments technologies to employ.

4.4.2 Treatment Knowledge Gaps

The CCST SB 1281 study also identified limitations and gaps related to treatment of produced water. The treatment categories provided in the SB 1281 data are poorly grouped and only require that one group is selected – deoiling, disinfection, desalination, membrane treatment, or ‘other’. Operators only need to report a binary ‘yes’ or ‘no’ if a method used falls into one of the categories but reporting does not require specifics beyond that. Not all chemicals, salts, and compounds are removed with any one treatment method. To prescribe an efficacious treatment method fit for the end-use, the composition of the water must be better understood as some treatment methods may also create toxic by-products. In general, a need for reporting specific treatment methods used and the sequence of methods within the treatment train are lacking and needed. Additional insights into treatment practices are provided in the WDR permits but monitoring for treatment efficacy is infrequent and only covers a limited number of parameters.

4.5 Conclusions

Large gaps in our understanding of oilfield produced water in California were highlighted in both the CCST SB 1281 study and the Food Safety Project. These range from unknown chemical composition, treatment methods used, and treatment efficacy to the long-term effects of exposure to low concentrations of COIs to humans, soil ecosystems, and crops. Overall, both studies indicate a lack of sufficient data required to assess the long-term safe use of OPW for agricultural irrigation.

The CCST SB 1281 study concluded that the monthly and quarterly water quality data (mostly salinity measured as TDS either above or below 10,000 mg/L) currently reported is inadequate to evaluate the suitability or safe use of OPW in agriculture. Systemic reporting challenges identified included missing data, inconsistent reporting, and errors in reporting data. There was also noted gaps in chemical toxicity information and many of the analytical methods used were not standardized or could not be independently verified.

The Food Safety Project indicated no significant differences between crops irrigated with produced water and crops irrigated with conventional sources. However, a full risk assessment was limited by several factors. The study focused on known chemicals used in oil and gas production, or those that are naturally occurring, and therefore many chemicals or chemical mixtures may not have been accounted for. Many chemicals were not listed due to trade secrets or had missing CASRN and did not have toxicity information. The analytical methods used for both water and crop samples did not account for increased toxicity of chemical interactions and transformation products, including microbially mediated transformations in soils or those that occur during plant uptake.

Throughout the literature, plant uptake and accumulation of COIs (both organic and inorganic constituents) have been well documented. Some of the chemicals present in OPW have been identified as endocrine disruptors, carcinogens, or mutagens and have been known to concentrate in edible portions of crops (e.g., PAHs, heavy metals). This is especially relevant, and of global importance, in staple crops such as wheat, rice, sunflower, and potatoes. Declines in crop and soil health have also been observed with decreased diversity in soil biota; reductions in growth, germination, and plant biomass; and decreased crop yields.

The chemical makeup and toxicity of OPW is not well understood and due to the complex variations, interactions, and composition that occurs across geographical locations and over time, more data is needed to fully assess the safe use of OPW in long-term agricultural settings. Additional water quality data, beyond salinity, such as concentrations or mass of chemicals and frequency of use, are needed. Non-targeted chemical detection methods, such as bioassays, should be used in addition to targeted (chemical-specific) detection methods to account for toxicity.

CHAPTER 5

Prioritize Data Needed in Support of an Oilfield Produced Water Fit-For-Purpose Classification Framework

5.1 Introduction

One of the basic hypotheses motivating this study (WRF 4993) was that there are unrealized opportunities to apply learnings from California's regulation and management of the recycled water for agricultural irrigation to the use of OPW for agricultural irrigation. Chapter 2 provided a summary of current regulations governing the use of recycled water for agricultural irrigation in California. Chapter 3 summarized current research on public health and agronomic concerns associated with produced water use in agriculture and knowledge gaps surrounding these topics. Chapter 4 summarized current information on characteristics and treatment of OPW in California including the identification of knowledge gaps in data collection and monitoring. Chapter 5 brings together the findings from Chapters 2, 3, and 4 to discuss where there 1) are opportunities for alignment between recycled water and OPW and 2) fundamental differences or knowledge gaps of significance in developing a parallel regulatory approach. Discussion of similarities and differences between municipal recycled water and produced water is divided into six sections – water quality; regulations and permitting processes; treatment and monitoring; addressing scientific uncertainty; the quantity of water available for reuse; and additional considerations.

5.2 Water Quality

Potential water quality-related risks associated with both recycled water and OPW are diverse and variable. The maturity of our understanding of the composition of these waters and the efficacy of standard treatment processes varies widely across different constituents of concern. Understanding both overall water quality and how it varies over time and space is an essential component in understanding and managing potential risks associated with the use of alternative water supplies. This section focuses explicitly on the composition of the source water available for reuse. Latter sections in the chapter discuss the role of treatment and blending in managing water quality.

5.2.1 Comparison of Source Water Composition and Variability

5.2.1.1 Municipal Wastewater and Recycled Water

Title 22 recycled water is sourced from municipal wastewater and typically composed of used water from residential and business settings (e.g., toilets, graywater), effluent from local commercial and industrial facilities, stormwater runoff (in areas with combined sewer systems), and inflow and infiltration into sewer systems (groundwater and stormwater). Given the large number of sources of wastewater within a sewer system, pollutants from any one source are typically diluted. Municipal wastewater tends to be stable in terms of the pollutants that are present though concentrations can change seasonally with influxes of stormwater and long-term shifts in indoor water use patterns.

Wastewater from certain commercial and industrial operations can contain high levels of fat, oil, and grease (FOG), heavy metals, copper, lead, and other industrial pollutants. Pre-treatment programs develop on-site treatment requirements targeted at removing these pollutants from wastewater prior to conveyance to and treatment at a publicly owned treatment works (POTW). Pre-treatment programs are tailored to meet local needs based on the capacity of local treatment facilities and processes and state/federal regulations. Current SWRCB requirements require POTW's treating more than 5 MGD and/or those with industrial operations to implement a pre-treatment program (SWRCB 2022).

Typical concentration ranges of common water quality parameters in raw wastewater are summarized in Table 5-1. Reported values in the NPDES permits for municipal wastewater treatment plants in Bakersfield, California (a Kern County city adjacent to many oilfields) fall within these ranges. Minimizing exposure to pathogens, avoiding adverse ecological impacts, and managing influent quality to match the capacity of local treatment facilities are some of the primary water quality management concerns associated with untreated municipal wastewater. Concentrations of metals and other industrial-origin pollutants vary significantly depending on the types of industries present and local pre-treatment programs. Dilution with graywater (from laundry, bathing, etc.), stormwater flows, and infiltration of groundwater all impact the concentration of water quality parameters in municipal wastewater. Municipal water supplies in California are typically sourced from a combination of surface and groundwater sources with additional supply augmentation with recycled water for non-potable and indirect potable uses in many areas. The chemistry of these source waters sets baseline levels of certain water quality parameters in wastewater influent.

Table 5-1. Typical Composition of Untreated Municipal Wastewater.
Data Sources: Adapted from Metcalf and Eddy 2003; US EPA 2012.

Water Quality Parameter	Typical Concentration Range	Units
Total Coliform	10^6 -10^{10}	#/100 ml
Fecal Coliform	10^3-10^8	#/100 ml
BOD5	110-350	mg/l
COD	250-800	mg/l
Nitrogen (as N)	20-70	mg/l
Phosphorous (as P)	4-12	mg/l
Fat, Oil, Grease (FOG)	50-150	mg/l
TS	390-1230	mg/l
TSS	120-400	mg/l
TDS	270-860	mg/l
Chlorides	30-90	mg/l
Boron*	0.1-0.2	mg/l

*Concentration above source water levels.

5.2.1.2 Produced Water

Oil and gas wastewater includes water extracted with oil and/or natural gas and a wide range of chemicals used for well stimulation, production, and cleanout (see chapters 3 and 4). Typically, the extracted water is a mix of water and chemicals injected into the well during well stimulation and completion operations and groundwater that naturally co-occurs within the oil and gas reservoirs. Concentrations of these chemicals varies widely with chemical usage, stage of production, local geology, and a host of other factors. Additional discussion of the quality of produced water and related uncertainties were discussed in the previous chapter. This variability coupled with monitoring limitations results in produced water being poorly characterized (relative to municipal wastewater).

5.2.1.3 Discussion

The source water characteristics of municipal wastewater and OPW are fundamentally different in ways that have important implications for developing parallel regulatory frameworks. The level of uncertainty around the quality and composition of produced water is substantially higher than the municipal wastewater typically used to produce recycled water for agricultural irrigation. The sources of municipal wastewater received by a POTW are generally well documented via customer databases and NPDES permitting. Where appropriate, waste streams from commercial and industrial sources are typically managed and monitored via pre-treatment programs. While reporting and monitoring programs for OPW are evolving, they continue to provide an incomplete picture of quantity and quality of produced water, the sources of this water, the full range of chemicals used in oil and gas production, and concentrations of these chemicals or their transformation products in wastewater from oil and gas production facilities. Strategies for managing this uncertainty through monitoring, reporting, and treatment are discussed in subsequent sections of this chapter.

5.2.2 Comparison of Human Health Concerns

5.2.2.1 Municipal Wastewater and Recycled Water

Pathogens: Historically, water quality criteria governing the use of recycled water for agricultural irrigation have focused on the removal or inactivation of pathogens of concern to human health (see Chapter 2 for additional discussion). Current recycled water regulations in California use a risk-based approach to minimize exposure to pathogens through specifications on the crops that can be irrigated with a given quality of water, level of treatment required and treatment performance, and monitoring requirements for turbidity and total coliform (a pathogen indicator organism). In most cases, the pathogens present in untreated wastewater present an acute health risk, such as diarrheal disease.

Metals: Metals can be present in municipal wastewater due to point sources such as industrial facilities not covered by pre-treatment programs and/or stormwater runoff containing road dirt, tire debris, and other pollutants. Standard wastewater treatment practices such as activated sludge are not specifically designed to remove metals, but, in practice, metals are often concentrated in the sludge fraction rather than the treated effluent or recycled water (Asano et al. 2007). Depending on the compound, concentration and duration of exposure, metals can pose both acute and chronic health risks.

Emerging Contaminants: With the development of direct and indirect potable reuse regulations and projects, there are a number of emerging contaminants gaining increased attention in the recycled water sector. Examples of emerging contaminants include pharmaceuticals and their metabolic byproducts, microplastics, endocrine disrupting compounds, disinfection byproducts, antibiotic resistance genes/bacteria, and legacy chemicals such as PFAS. There is a limited amount of research evaluating plant uptake of these compounds, transformation products, and the degree to which these contaminants pose a potential threat to human health. Concentrations of specific emerging contaminants in recycled water vary with the level of treatment and specific treatment processes used. At present, the SWRCB’s emerging contaminant efforts are focused on the development of potable reuse regulations, but the lessons learned may prove relevant to future regulations on agricultural uses of recycled water. The SWRCB’s current work on emerging contaminants includes efforts evaluating bioassays and other detection methods, consideration of the transformation products and byproducts associated with human consumption, treatment transformation, and compound toxicities associated with consumption of low levels of multiple contaminations.

5.2.2.2 Produced Water

From a public health perspective, the primary constituents of concern associated with OPW include inorganics, such as arsenic, radionuclides and NORMs**,** organics, and endocrine disrupting chemicals. While there can be acute toxicity impacts when concentrations of these chemicals exceed certain thresholds, many of the health impacts of concern are related to long-term, chronic exposure. Chapter 3 included detailed discussion on the constituents while Chapter 4 summarized specific findings on OPW quality in California.

5.2.2.3 Implications for Regulation

The challenges posed by emerging contaminants in recycled water are perhaps most analogous to the challenges and uncertainties surrounding emerging contaminants present in recycled water. In both cases (emerging contaminants in recycled water and the composition of produced water, generally) historical water quality monitoring criteria present an incomplete picture of the quality of water being used for irrigation. Measuring these constituents is challenged by limitations in existing analytical methods, detection in complex sample matrices, and general uncertainty regarding what chemicals are present/transformation products. At the root of this issue is the question of whether these chemicals pose acute or long-term risks to human or agronomic health. The CCST SB 1281 report concluded that existing data is insufficient to conduct a thorough human health risk assessment on the use of produced water. Risk assessments of the use of recycled water have been conducted for individual constituents (Hamilton et al. 2006; Weber, Khan, and Hollender 2006) (e.g., pathogens, metals, organics), but there is also a growing body of research on assessing composite risks associated with recycled water (Garner et al. 2016) that is of particular relevance to produced water.

5.2.3 Comparison of Agronomic Concerns

5.2.3.1 Municipal Wastewater and Recycled Water:

Typical wastewater treatment processes (e.g., activated sludge, settling) do not have significant impacts on the salinity of effluent. Incorporation of membrane processes into recycled water treatment trains can reduce concentrations of dissolved ions. However, given the higher cost of these treatment processes, they are typically reserved for producing recycled water used for indirect potable or other sensitive uses and not required by Title 22 for agricultural uses of recycled water. Concentrations of TDS in wastewater influent typically range from 270 to 860 mg/l. Standard disinfection processes (e.g., chlorination, UV) are highly effective in inactivating pathogens, though the economic and reputational risks of pathogen contamination remain a concern for some growers considering using recycled water (Sheikh et al. 2019). Agronomic impacts related to the fate and transport of emerging contaminants in recycled water remains an area of ongoing research.

5.2.3.2 Produced Water

Assessments of the suitability of irrigation water have historically focused on salinity, though the potential agronomic impacts of chemicals and other substances potentially present in OPW are gaining attention. Constituents of concern can be naturally occurring, such as bromide, calcium, chloride, magnesium, sulfate, and NORMs, or chemical additives used in the production, stimulation, and maintenance involved in O&G production (See Chapters 3 and 4 for additional details).

The quality of the OPW is known to change throughout the production process and with the age of the formation. For wells that produce water suitable for agricultural reuse, continued monitoring and analyses is therefore needed to ensure the quality remains sufficient for irrigation. Additional and quantitative water quality parameters should include, at a minimum, TDS, boron, and SAR. Additional chemicals and substances of agronomic concern may also be important to assess suitability, which is discussed further in the previous chapters.

Deoiling is the most common type of treatment used for produced water in California, but its primary aim is removing recoverable hydrocarbons and does not significantly reduce concentrations of the above constituents. Desalination can help reduce salinity but is energy intensive and not commonly utilized. As discussed in the previous chapter the salinity of water from some fields is adequate for agricultural irrigation.

5.3 Risk-Based Approach

5.3.1 Municipal Wastewater and Recycled Water

Olivieri et al. (Olivieri et al. 2014) conducted a quantitative microbial risk assessment (QMRA) evaluating whether California's current treatment-based regulations on the use of recycled water for food crop irrigation were adequately protective of public health. QMRA is a statistically based risk assessment approach that estimates an annual risk of infection (as a function of typical exposure, infectious dose, treatment efficacy, and other pathogen specific parameters, in this assessment). The Olivieri et al. assessment included four common waterborne pathogens – Giardia spp., Cryptosporidium species, Rotavirus, and *E. coli* O157:H7 - and found that, for a typical consumer, the annualized median risk of infection associated with consuming produce irrigated with recycled water in California was in the range of 10^{-5} to 10^{-9} (cases per year). For comparison, the estimated annual incidence of diarrheal disease in high-income countries ranges from 0.2 to 0.72 cases per year (Olivieri et al. 2014). This finding aligns with other studies assessing risks associated with the use of appropriately treated recycled water (Hamilton et al. 2006; Gonzales-Gustavson et al. 2019; Alegbeleye and Sant'Ana 2021). The risk of gastrointestinal illness associated with recycled water use in California is several orders lower than the baseline risk of gastrointestinal illnesses which led to the conclusion that the use of recycled water for agricultural irrigation does not impose a significant additional health burden above baseline. There are no known instances of outbreaks of waterborne disease associated with recycled water in California. Assessments of health risks posed by metals, emerging contaminants, and other constituents of concern are more limited (relative to pathogen studies), but still fairly extensive (for example, see (Lin et al. 2020; Shi et al. 2022; Garner et al. 2021; 2016; Debroux et al. 2012; Weber, Khan, and Hollender 2006). Broadly speaking, these studies found that the level of additional risk associated with the use of recycled water for irrigation is low to minimal.

5.3.2 Produced Water

The CCST SB 1281 Study concluded that current data is insufficient for conducting a comprehensive risk assessment of all known and suspected toxics (Shimabuku, Abraham, and Feinstein 2019). This is due to gaps in monitoring, chemicals lacking toxicity data, and general uncertainty around the chemicals present in produced water (see Chapter 3). Nonetheless, there are still opportunities to conduct more narrowly scoped risk assessments that are constrained to specific chemicals of interest and gain insights into specific elements of the safety and risks of produced water use. However, to date, there has been a general lack of publicly available, peer-reviewed evaluations of the risks associated with OPW use for irrigation (Redmon et al. 2021).

Redmon et al. recently conducted one of the first probabilistic risk assessments of produced water reuse for irrigation (focused on inorganic contaminants). Water quality data was sourced from a combination of direct sampling and historical data on produced water quality. Their initial assessment included more than 20 constituents with a focus on chemicals where concentrations in OPW either exceeded drinking water standards (aluminum, antimony, arsenic, iron, manganese) or were known carcinogens (arsenic, chromium VI, lead). Concentrations of water quality constituents varied widely (i.e., 2-4x difference between min and max concentrations). It is also important to note that the Redmon et al. study focused on areas with low-salinity produced water. Areas with higher salinity typically have poorer quality water for other constituents as well. Based on these data, Redmon et al. concluded that a person eating a vegetarian diet and consuming produce irrigated with blended produced water from the study area could face an increased risk of cancer (90th percentile risk exceeds the 10^{-6} level of concern[24]) due to arsenic exposure. Other modelled constituents were all below acceptable risk thresholds.

Risk assessments evaluating the use of produced water for agricultural irrigation are substantially more limited in number and scope relative those that have been conducted evaluating the use of recycled water for agricultural irrigation. Risk management in the produced water sector in California is conducted via mandatory chemical disclosure programs through CalGEM and quarterly monitoring of a list of known priority chemicals via WDR monitoring requirements.

5.3.3 Comparison of Risk-Based Approaches

Risk-based approaches are widely accepted as best practice for developing the theoretical underpinnings of regulations on the use of alternative water supplies. Olivieri et al. (2014) confirmed that current regulations on the use of recycled water for agricultural irrigation are adequately protective of public health, relative to baseline levels of gastrointestinal illness while other risk assessment studies provide insights into risks posed by metals, emerging contaminants, and other constituents of concern. This is still an ongoing area of research for recycled water, but comparatively mature relative to our understanding of the potential risks posed by the use of produced water for agricultural irrigation. In both cases, there is growing concern that traditional risk assessment methods fall short in assessing the composite risk when multiple constituents of concern are present in a water supply. To date, this has been of greater concern in the potable reuse sector where anticipated levels of exposure are generally higher than via consumption of crops. However, there will likely be interesting and relevant insights that come out of the State Water Board’s potable reuse expert panel on measuring and assessing risks posed by emerging contaminants that may be relevant to future updates to the state recycled water policy.

5.4 Similarities and Differences in Permitting and Reporting Requirements

5.4.1 Overview

While the baseline permitting program (NPDES/WDR) for produced water and municipal wastewater is the same, there are several key differences in how health risk management and monitoring are managed. These differences are summarized in Table 5-2 and discussed below.

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[24] 10^{-4} (1 in 10,000) to 10^{-6} (1 in a million) levels of risk are common thresholds used in public health risk assessment for defining ‘acceptable’ levels of risk.

Table 5-2. Comparison of Similarities and Differences Between Produced Water, Municipal Wastewater and Recycled Water Permitting, Monitoring, Reporting, and Management.

Item	Municipal Wastewater/ Recycled Water	Produced Water
Point Source Management	NPDES/WDR Permits	NPDES/WDR Permits
Managing Health Risks and Exposure, Risk-Based Management	Title 22 Recycled Water Quality Criteria; Expert Panels	Expert Panels
Water Quality Monitoring Information	Permit Monitoring Data; Title 22 Reporting	Permit Monitoring Data; CalGEM Well Stimulation Disclosures[A]
Monitoring Upstream Chemical Use[B]	Pre-Treatment Programs	CalGEM Chemical Additive Disclosure Dataset
Quantity of Water Used/Availability	Volumetric Annual Reporting Requirements	SB 1281 Water Cycle Reporting
Process for Updating Regulations	Periodic updates to State Recycled Water Policy; NPDES/WDR permit updates	NPDES/WDR permit updates

[A] CalGEM requires monitoring of the composition of recovered fluids within 60 days following the cessation of a well stimulation treatment.

[B] Pre-treatment programs require upstream management/treatment of target chemicals while disclosure requirements only require disclosure (not management/treatment) of added chemicals.

5.4.2 Point Source Management

The federal Clean Water Act and California's Porter-Cologne Water Quality Control Act regulate the point source discharge of pollutants via the NPDES and WDR (California specific) permitting programs. Produced water, municipal wastewater, and recycled water are subject to regulation under these programs. Discharges to surface water are managed via the NPDES system while discharges to land are managed through the WDR system. Both classes of permits are issued by the RWQCB. The NPDES/WDR permits specify discharge limits, monitoring requirements, and demonstrate compliance with state and federal anti-degradation policies. At a basic level, facilities are required to monitor regularly for a standard set of physico-chemical parameters, pathogen indicators (municipal wastewater), priority pollutants, and other locally significant water quality constituents (e.g., arsenic, nitrate). While there are similarities, NPDES/WDR permits are ultimately tailored to individual facilities depending on the location of the facility, local surface and groundwater quality issues, and the quantity and quality of discharge.

5.4.3 Managing Health Risks and Exposure

In addition to the standard NPDES/WDR permitting requirements, recycled water is required to comply with the Title 22 Water Quality Criteria. These requirements differ based on the class of Title 22 Recycled Water (e.g., undisinfected secondary, disinfected secondary 2.2, disinfected tertiary) and include specifications on the types of crops that can be irrigated, level of treatment and treatment performance standards, allowable levels of turbidity and total coliform, and provision of an acceptable engineering design report. Chapter 2 provides additional details on the requirements of Title 22. There is not an analogous risk-based regulatory framework for produced water aimed at setting treatment-based performance standards. This topic is discussed at greater length at the end of this chapter.

California's State and Regional Water Resource Control Boards regularly convene expert panels to review current science and develop recommendations on water quality criteria, adequacy of current regulations, and other relevant topics. Expert panels have been convened for both recycled water and produced water, but the practice is much more established for recycled water relative to produced water where only one panel (CVRWQCB Food Safety Panel) has been convened thus far.

5.4.4 Water Quality Monitoring Information

Both municipal wastewater and produced water are required to periodically report on water quality monitoring efforts as specified in their NPDES/WDR permit specifications via the California Integrated Water Quality System Project (CIWQS) electronic self-monitoring report (eSMR) system. Facilities supplying recycled water provide additional information on recycled water monitoring and data. Produced water facilities are also required to report to CalGEM on the composition of fluids recovered from wells for 60 days following cessation of a well stimulation treatment. What parameters are captured in a given dataset depends on a facility's permit requirements and reporting on the chemical additives used during a site's oil and gas production activities.

5.4.5 Monitoring Upstream Chemical Use

Facilities treating municipal wastewater typically manage upstream use of toxics and FOG through pre-treatment programs. These programs rely on on-site treatment and/or waste separation to limit the pollutants reaching conventional wastewater treatment plants (which are often not designed to treat these pollutants). Due to the different natures of the waste streams, pre-treatment programs are not a perfect analogue for produced water facilities given the single source nature of produced water vs. municipal wastewater. CalGEM requires oil and gas operations in California to disclose additives used in oil and gas production activities and monitor recovered fluids for 60 days following cessation of a well stimulation treatment. This provides some information on chemicals that may be/are present in produced water but does not actively manage discharges into water that is ultimately used for irrigation. Naturally occurring constituents and chemicals mobilized or formed as a byproduct of extraction practices would not be captured.

5.4.6 Quantity of Water Used/Availability

Both produced water and municipal wastewater/recycled water have (recently updated) reporting programs in place to track water use and reuse in their respective sectors. The SWRCB's volumetric annual reporting program tracks information on influent and monthly discharges of treated wastewater, level of treatment, current reuse by beneficial use, and other facility level information such as discharge location and local instream flow requirements (SWRCB 2021). While the data are well organized, care is required to avoid double counting flows when wastewater and recycled water are managed by separate facilities (Cooley et al. 2022). SB 1281 mandated more comprehensive water cycle reporting tracking water use by the oil and gas sector across all stages of operations. Additional discussion on the findings of these reporting efforts is summarized in Chapters 4 and 6.

5.5 Treatment and Monitoring

5.5.1 Treatment Processes

5.5.1.1 Municipal Wastewater and Recycled Water

Depending on the end use, municipal wastewater is treated to meet the specifications of one of four classes of Title 22 recycled water (Table 2-2). Standard wastewater treatment practices include primary and secondary treatment, filtration, and/or disinfection. Primary treatment removes material that will settle by gravity or float using screens and settling basins. In secondary treatment, trickling filters, activated sludge processes, or other approved approaches are used to remove biodegradable organic matter from the wastewater. Disinfection is required in three of four classes of Title 22 recycled water and used to inactivate pathogens. Commonly used methods of disinfection include various forms of chlorination and UV disinfection. Filtration is required in all cases where there is direct contact between the recycled water and edible portion of the food crop. Filtration captures smaller particles and, in the case of the Title 22 regulations, typically includes practices such as slow sand and granular media filters. The size and types of particles captured by filtration depends on the characteristics of the filtration media and particles being captured. In certain cases, membrane filtration is used to exclude sub-micron sized particles (such as viruses and certain chemical contaminants). California's approved technologies list identifies technologies that have been demonstrated to consistently provide a required level of treatment. Facilities wishing to use technologies not on this list must demonstrate their efficacy in removing viruses and other constituents of concern.

5.5.1.2 Produced Water

Five main classes of treatment of produced water were reported in recent data collected in response to SB1281 – deoiling, disinfection, desalinization, membrane treatment, and other treatment. Additional details on each of these treatment methods is included in Chapter 3. The types of treatment practiced vary by location and discharge location, but data on the specifics of actual the treatment technologies used (e.g., ion exchange, three-phase separator) are not included in reporting data. Likewise, operators are only required to report 'yes' or 'no' if the treatment technology used falls within one of the five categories (above) and does not capture if multiple treatments are used. Individual facilities NPDES and/or WDR permits provide additional details and specifications on the types of treatment and quality of effluent required for discharge/disposal/reuse from a given facility.

To assess potential and likely hazards, risks, and impacts, an understanding of the chemical makeup of produced water is necessary. This is also critical for prescribing treatment technologies efficacious of removing a targeted substance or substances. While treatment technologies are capable of treating water to sufficient levels for intended end-uses, not all methods are effective at removing all types of constituents. Some chemicals used in O&G production may not be adequately removed or may produce disinfection by-products as a result of some treatment methods (US EPA 2016). For example, heavy metals and EDCs are not removed through conventional or secondary treatments and require advanced methods for removal (US EPA 2012).

5.5.2 Treatment Performance and Monitoring

5.5.2.1 Municipal Wastewater and Recycled Water

Research studies of municipal wastewater treatment plants in the 1960s and 70s found that many treatment facilities were not providing reliable treatment which led to the development of more stringent, performance-based design standards and monitoring protocols. Detailed requirements for monitoring methods, frequency, parameters, and reporting requirements are included in a WWTP's NPDES or WDR permit issued by the RWQCB. Specific requirements vary based on facility characteristics, local context, and other factors, but typically includes at least flow, standard physico-chemical parameters (e.g., pH), nitrogen species (e.g., nitrates, ammonia), BOD_5, TSS, general minerals, and priority pollutants.

5.5.2.2 Produced Water

Due to OPW typically having elevated TDS concentrations, treatments to reduce salts (and other constituents, such as boron) will likely be needed in agronomic settings where soil and plant health are of concern (Cooper et al. 2022). In addition, many unregulated chemical additives are likely to be present in OPW, and research suggests that some of these chemicals may still be present after treatment (Cooper et al. 2022; Danforth et al. 2020; Camarillo, Domen, and Stringfellow 2016; Pichtel 2016). While many treatment technologies are efficient at removing many chemicals, not any single treatment method or can remove all chemicals of concern in OPW (Cooper et al. 2022). Selecting treatment methods as part of a treatment train efficient at removing constituents of concern for specific end-uses is impaired by the lack of chemical, physical, and additive mass data, concentration of chemical additives in produced water, chemical-chemical interactions and transformation products, and a lack of understanding on how chemical interactions may affect treatment efficacy or produce disinfection by-products. Variability in quality and quantity of OPW across landscapes and over time further challenges selecting standardized efficient treatment methods or treatment trains (Cooper et al. 2022). Treatment technologies and trains employed will be site and end-use specific. Data on treatment trains at O&G facilities, level of treatment, and treatment performance remain substantial knowledge gaps (as compared to municipal wastewater and recycled water).

5.6 Quantity of Water Available for Reuse

5.6.1 Municipal Wastewater and Recycled Water

California has conducted surveys of recycled water use since the 1970s and, with the 2018 Recycled Water Policy update, instituted a mandatory annual reporting requirement for all NPDES and WDR permitholders treating municipal wastewater. The new volumetric annual reporting requirements for municipal wastewater require facilities to report details on the facility (e.g., discharge location, contact information), monthly volumes of influent and effluent, level of treatment, and recycled water production volumes including the end uses of that recycled water. California currently produces approximately 3 MAFY of wastewater effluent of which about 728,000 AFY is currently recycled. A recent assessment found that roughly 2 MAFY of municipal wastewater is potentially available for reuse (Cooley et al. 2022).

5.6.2 Produced Water

California has required the O&G industry to track water produced from and injected into oil and gas wells since at least 1977. A limitation of past O&G water data collection efforts has been that they only captured a portion of water use in the O&G industry, leaving an incomplete picture of O&G water use (Feinstein, Shonkoff, and Lindsey 2021). SB 1281 updated oil and gas reporting requirements to try to capture a more comprehensive picture of how water is used in the oil and gas industry. The data collection efforts arising from SB 1281 aim to capture a lifecycle view of water use and disposal within the O&G industry and includes information on all inputs, outputs, and other applications of water in oil and gas operations. The SB 1281 dataset includes information on water use both on and off of the oilfields with quarterly reporting. Data on current (onsite) reuse is captured via the ‘other applications’ dataset within the SB 1281 reporting data. Monthly production and injection data is also collected by DOGGR. The CCST Phase II report compared the DOGGR and SB 1281 O&G datasets from 2015 Q4 – 2017 Q1 and found the SB 1281 data capture 95% of produced water production reported to DOGGR during that time period, though more discrepancies were noted in some earlier and later quarters and in minor basins. Over the three-year reporting period (2015-17), the CCST data indicated that roughly 1.2 MAF of produced water was generated and 1.0 MAF was injected (Feinstein, Shonkoff, and Lindsey 2021).

The CCST SB 1281 report authors also used a water cycle analysis approach to attempt to understand reuse within the O&G industry and determine whether the O&G industry was a net consumer or user of water. The CCST assessment was challenged by limitations in the SB 1281 data (e.g., subsurface injection combines injection for both enhanced oil recovery and stimulation as well as for disposal) and uncertainties around water quality data, but preliminary estimates were developed using supplemental information from the DOGGR data (Feinstein, Shonkoff, and Lindsey 2021). Approximately 72,000 AF (of mostly saline water) was reused[25] by O&G facilities and approximately 11,000 AF was discharged[26] each quarter. The CCST SB 1281 report includes many recommendations on improving the accuracy and usability of the SB 1281 reporting data.

While numerous data limitations were noted, the CCST SB 1281 project was able to develop two coarse estimates of the quantity of produced water potentially available for reuse. The first estimate subtracted the volume of produced water already allocated for agricultural reuse from the total volume of water produced from that field. Data were then analyzed further to only include fresh/brackish water with TDS concentrations less than 10,000 mg/l. That analysis found 11,337 AFY of produced water meeting these criteria and potentially available for reuse. As noted earlier in this report, TDS concentrations well below 10,000 mg/l are not suitable for agricultural irrigation and it is likely that some portion of this water would require desalination to be suitable for agricultural reuse. Underestimations based on the SB 1281 water quality thresholds are likely to have occurred due to misreporting or underreporting by operators. This is supported by large declines in reported volumes beginning in 2017. The authors of the CCST SB 1281 report also used their combined water quality dataset (see Chapter 5 for included datasets) to develop an expanded assessment reuse potential using TDS limits of <2000 mg/l and boron concentrations of <3.0 mg/l. This assessment found an upper bound of 64,272 AFY potentially available for reuse, though fields were classified as meeting the water quality criteria if thirty percent of samples (from individual wells within a field) were below the threshold. This approach overlooks well-to-well variability and variability overtime which could lead to both over and undercounting volumes. In both cases substantial data limitations were noted and summarized below. Chapter 5 refines the assessments conducted as part of the CCST B 1281 study and discussed the methodologies used in more detail.

5.6.2.1 Produced Water Quantity Data Limitations

To track how water moves through the oilfield, from production well to injection well, operators report volumes, end-location, and end-uses of water moving between these locations. Sources and destinations of water are captured with defined categories; however, the well-to-well reporting under SB 1281 does not accurately capture the correct volume of water as it moves from production well, to treatment facilities, and back to injection wells. The structure of the data sets also does not allow for straightforward calculations of volumes of water inputs, outputs, applications, reuse, and demands due to fragmentation of data reporting, duplicate reporting, and variability in reporting styles and structures.

Broad categories within the two disposition codes (‘Agricultural and Recharge’ and ‘Surface Water Discharge’) only provided vague and incomplete data. Further, without referencing the associated WDRs or NPDES permits, the water reported in the Agriculture and Recharge category was not identified as

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[25] Quantitative estimates of reuse in the CCST Phase II report are constrained to water reused onsite for ancillary oil and gas operations (e.g., operations, drilling) and enhanced oil recovery and well stimulation. Water that is currently reused for agriculture is captured under ‘discharge’ though not all discharged water is reused.

[26] Discharge includes percolation pits, surface water or land, public wastewater systems, and reuse for irrigation or recharge. Disposal via injection wells and evaporation from lined pits is included in a separate accounting category ‘disposal’.

being used directly, indirectly, or incidentally. The WDRs and NPDES permits were the primary source for end-uses but were not always available or did not exist. Distinguishing between direct use and indirect use is also an important factor to assess risks to humans, crops, soils, and the environment, as direct use can pose a higher risk. Determining the volumes currently being used for agricultural reuse, and thus the volume potentially available, was difficult as a result of the missing and incomplete data on end-locations and end-uses.

5.6.3 Comparison of Assessments of the Quantity of Water Available for Reuse

Recent legislation and policy updates have mandated and/or updated reporting requirements on municipal wastewater and produced water production and reuse. Good quality data on the quantities of effluent or produced water available, discharge locations, and timing are essential for understanding the current state of and potential for agricultural reuse. Both the volumetric annual reporting (municipal wastewater) and SB 1281 data (produced water) require additional analysis to assess their reuse potential in the agricultural sector. In both cases, water follows a complex pathway from its point of use to where it is ultimately reused. Careful analysis and accounting are required to avoid double counting flows of water.

Preliminary estimates of both the potential for increasing recycled water use (~2 MAFY) and produced water (~11,000-64,000 AFY) use in agriculture have been developed (Shimabuku, Abraham, and Feinstein 2019; Cooley et al. 2022). While there are uncertainties with both noted in their respective reports, the identified potential for recycled water use is roughly 30 to 180 times greater than the potential scale of produced water reuse. In both cases, a water cycle approach is used to track water flows. The database structure for recycled water tracking appears more robust, but care is still required to avoid double counting flows. Also important to note, there is significant onsite reuse already occurring in the oil and gas sector. These uses are discussed at greater length in the CCST SB 1281 report and are outside of the scope of this report.

5.7 Fit-for-Purpose Approach

5.7.1 Overview

A risk-based approach underpins California’s current Title 22 Water Quality Criteria which are then operationalized as a fit-for-purpose approach to managing the use of recycled water for agricultural irrigation (Figure 5-1). Details on the specific requirements for each class of Title 22 recycled water and the rationale behind each component of California’s fit-for-purpose framework are discussed in Chapter 2. The following sections 1) discuss the applicability (or lack thereof) of each component of California’s fit-for-purpose framework for recycled water to produced water; and 2) describe additional unique characteristics of produced water that are relevant to the development of a fit-for-purpose framework for produced water.

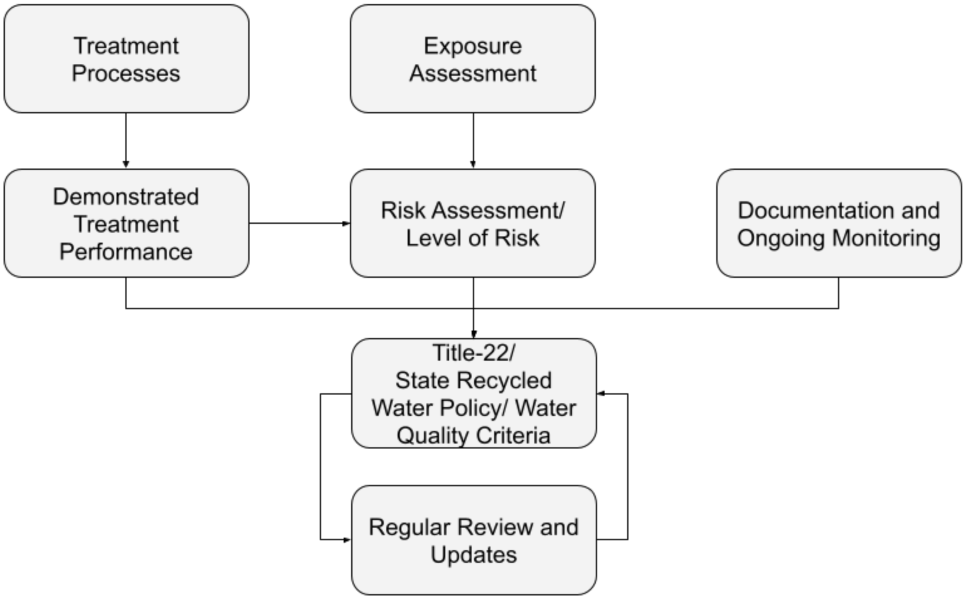

Figure 5-1. Summary of Risk Assessment and Management Activities Informing Development and Updates of California's Recycled Water Policy.

5.7.2 Components of Title 22 Fit-for-Purpose Approach and Applicability to Produced Water

5.7.2.1 Crops that Can be Irrigated

Crop classes in California's recycled water fit-for-purpose framework are defined based on the risk of exposure to pathogens (i.e., food crops typically eaten raw typically require a higher quality of recycled water). Current crop classes do not account for plant uptake of other constituents of concern. Produced water is different from recycled water in that the public health issues at the fore are related to long-term health impacts (vs. acute impacts such as gastrointestinal illness). Early results on chemicals of interest in the edible portions of crops are available from the Food Safety Project (Mahoney et al. 2021, Kondash et al. 2020), and others. However, there are substantial gaps in both the constituents that were monitored and current detection methods (Feinstein, Shonkoff, and Lindsey 2021). Additional research would be needed to develop health risk-based classes of crops analogous to those in recycled water's fit-for-purpose framework.

High levels of salinity, boron, and other chemicals of agronomic significance are common in produced water, though there are significant regional differences across California (see Chapter 4). Chapter 6 presents a series of crop tolerance classes for salinity and boron and maps current croplands relative to these classes as part of a broader assessment of the potential for produced water reuse in California.

5.7.2.2 Level of Treatment and Treatment Performance

California's recycled water fit-for-purpose framework includes three levels of treatment – oxidized, oxidized and disinfected, and oxidized, filtered, and disinfected which are loosely analogous to secondary and tertiary treatment. California's recycled water policy provides specific treatment performance criteria for each class of treatment. Each individual treatment technology must demonstrate compliance with these standards, either through past research studies or inclusion on the

State's Alternative Treatment Technologies list.[27] The SB 1281 reporting data's inclusion of treatment processes is an important step in understanding the broad classes of treatment utilized but falls short of the recycled water policy's treatment performance standards. To match what is currently in the State's recycled water policy, more research is needed to systematically assess and document the efficacy of existing produced water treatment technologies in removing constituents of concern for human and/or agronomic health. Current treatment technologies are primarily focused on removing hydrocarbons and do not address salinity and other water quality issues. Blending with groundwater or canal water is a common practice for managing the quality of produced water to reduce salinity to levels suitable for irrigating crops.

5.7.2.3 Monitoring for Turbidity and Pathogen Indicators

Turbidity and total coliform are used as process indicators to monitor whether treatment processes are operating as designed. Additional discussion on the rationale for using process indicators vs. monitoring for specific constituents is discussed in Chapter 2. At present, current research has not indicated a need for additional water quality criteria for agricultural irrigation. However, the State Recycled Water Policy is updated at regular intervals to incorporate advances in science and knowledge. The Direct Potable Reuse Criteria Expert Panel is currently advising the SWRCB on monitoring and water quality requirements for potable reuse. Some of the lessons learned from this effort, particularly around operationalizing the use of bioassays and other non-specific monitoring methods may be of relevance to produced water. At this time, there are substantial knowledge gaps around treatment efficacy and produced water composition. These gaps make recommendations on specific process indicators inappropriate within the context of this report.

5.7.2.4 Engineering Reports and Anti-Degradation Analysis

Title 22 requires submission of an acceptable engineering report that includes details on how the facility will comply with the State's Recycled Water Criteria including treatment performance standards, state and federal anti-degradation policies, and other requirements (See Chapter 2). Information in the Title 22 engineering reports goes above and beyond what is required for issuance of standard NPDES/WDR permits though it is important to note that anti-degradation assessments are a key component of NPDES/WDR permits for both produced water and municipal wastewater. First steps in developing a parallel 'engineering report' requirement for produced water include the development of standardized treatment performance standards for produced water and improved monitoring of produced water quality.

5.7.3 Additional Considerations in Developing a Fit-for-Purpose Framework for Produced Water

This report has discussed the current state of knowledge and knowledge gaps surrounding the use of produced water for agricultural irrigation. While there are elements of California's Title 22 Recycled Water Regulations that provide useful insights, there are also some fundamental differences in produced water that warrant additional consideration when scoping a fit-for-purpose framework for produced water. Additional factors to consider including in a fit-for-purpose framework for produced water are highlighted below.

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[27] SWRCB 2014.

5.7.3.1 Underlying Geology

Current water quality monitoring data shows that produced water quality substantially varies with differences in underlying geology. For instance, geologic formations with higher levels of arsenic tend to have higher concentrations of arsenic in produced water. Additional research is needed to classify the 'risk level' posed by different geologic formations.

5.7.3.2 Well Age

Typically, the longer the time a well has been in operation, the higher the ratio of water to oil (Feinstein, Shonkoff, and Lindsey 2021). This directly impacts the quantity and quality of water received by on-site treatment facilities. While this is typically a change that occurs over time, changes in source water composition are an important consideration in managing treatment performance. Information on well age may be available from CalGEM, though additional monitoring data is needed to understand the quality of produced water extracted from a given well.

5.7.3.3 Facility Characteristics

There are multiple configurations through which produced water is reused. In some instances, there is a single well and water is of sufficient quality to be used directly (or nearly so). However, in other (most) instances water from multiple wells is piped to a centralized treatment facility. The composition of wells (e.g., where they are located within a geologic formation, well age) can impact the quality of water received by the treatment facility and may change over time as wells come on/offline.

5.7.3.4 Recent Stimulation/Other Chemical Uses

Well stimulation and other activities use chemicals to increase yields from wells. The use of chemical additives and quality of produced water are monitored for 60 days following stimulation activities and reported to CalGEM. Many of the chemicals used in these activities are known to be toxic while others lack the information to assess their toxicity. Time-series assessment of the CalGEM and additional monitoring data could provide insights into how recent stimulation activities might be addressed in a fit-for-purpose framework addressing produced water reuse for irrigation.

5.7.3.5 Blending

Blending of produced water with local surface or ground water is a common management strategy used to manage the quality of produced water via dilution. Recycled water permits are typically written to reflect of the quality of the water as supplied by the WWTP/recycled water supplier. There are instances where blending does occur with recycled water (typically when recycled water is blended with canal water), but this does not impact the requirements for meeting the Title 22 Recycled Water Quality Criteria.

5.8 Conclusions and Recommendations

5.8.1 Conclusions

The use of OPW and municipal recycled water for agricultural irrigation in California are both long-standing practices. The use of these waters provides locally significant water supply benefits including helping irrigation districts diversify their supply portfolios and build resilience to droughts and other supply challenges. However, questions remain on how to most effectively and efficiently regulate the use of these waters to ensure adequate protection of public health and the environment. The history of recycled water use in California dates back more than 100 years and provides helpful insights into approaches that have worked, not worked, and lessons learned that are directly relevant to the comparatively new (30 year old) field of produced water reuse.

There are substantive similarities and differences in how the use of these two alternative supplies are regulated, managed, and monitored. In both cases, discharges to surface waters or land are regulated via the NPDES/WDR permit system. Additional regulation or monitoring of OPW occurs on a more ad hoc basis and generally tied to specific pieces of legislation and research projects, such as the SB 1281 reporting data and the Food Safety Project. The regulation and use of recycled water is more structured. Title 22, the State Recycled Water Policy, and water quality criteria detail allowable uses of recycled water and specific details on treatment, treatment performance, monitoring, and quality. California's Recycled Water Policy is regularly reviewed and updated to ensure the policy reflects the best available science and add additional beneficial uses (such as potable reuse) when the science is sufficiently mature to ensure acceptable protection of public health. Relative to recycled water, the knowledge base surrounding produced water is more limited. Substantive gaps in data availability, water composition, interactions between chemicals, toxicity, and other factors relevant to conducting risk assessments were identified in this study and others (Feinstein, Shonkoff, and Lindsey 2021; Mahoney, Asami, and Stringfellow 2021). Without additional research, data, and risk assessments of produced water reuse, the potential for direct adoption and operationalization of many of the risk-based principles underpinning Title 22 is limited. Nonetheless, there are opportunities to improve data collection and monitoring programs to facilitate more comprehensive risk assessments and tailor basic research to better address knowledge gaps. A subset of these opportunities are summarized below as recommendations.

5.8.2 Recommendations

5.8.2.1 Current Monitoring and Data Collection

1) **Use the findings of the CCST SB 1281 study to develop a plan for addressing current gaps and limitations in existing OPW monitoring programs.**
   The CCST SB 1281 study provides a comprehensive list of recommendations surrounding current data collection and monitoring programs on produced water in California. This document is a key resource in streamlining and disentangling the many overlapping data collection and monitoring programs. Developing and accurate understanding of what is in produced water and how much available, where is a key first step in developing a modern regulatory approach based on risk-based best practices.
2) **Conduct additional monitoring and/or research to better understand spatial and temporal variability in OPW quality and the drivers of these differences.**
   Data on many key water quality constituents is lacking in quantity, quality, and coverage. Given the high levels of temporal and spatial variation in produced water quality, additional research and/or monitoring at the site level is needed to characterize this variation. Research should be designed to ensure sampling plans address these knowledge gaps.

5.8.2.2 Risk Assessment

1) **Use the findings for the SB 1281 Study to guide the development of research and/or monitoring programs to provide more insights into the full composition of OPW in priority regions within California.**
   Substantive barriers to conducting comprehensive risk assessment of the use of produced water were noted by both the CCST SB 1281 and Food Safety Project studies. Information on the composition of produced water was one noted knowledge gap. Implementing recommendations from the CCST SB 1281 report would help address some of the knowledge gaps.

2) **Convene an expert advisory panel focused on assessing the strengths and weaknesses of analytical methods used in the characterization and assessment of OPW.**

Limitations of current analytical methods were another knowledge gap identified by the CCST SB 1281 and Food Safety Project studies. Convening an expert panel focused on evaluating the strengths, weaknesses, and limitations of different analytical methods for monitoring produced water quality could help identify specific research needs, provide a path forward for overcoming barriers, and develop future water quality criteria for produced water. The approach used by the SWRCB with the Direct Potable Reuse Expert Panel could prove to be a helpful model for a similar expert panel focused on produced water.

3) **Ensure any future fit-for-purpose framework for OPW incorporates consideration of unique, OPW specific factors impacting the quality of OPW (e.g., well age, geology).**
The 'additional considerations' highlighted in section 5.7.3 (e.g., geology, well age, recent chemical use) are material to the level of risk posed by produced water. These types of variables are unique to produced water and should be incorporated into a future fit-for-purpose framework for produced water either directly or indirectly via treatment performance criteria that account for the uncertainty and variability in water quality these factors introduce.

4) **Future studies on OPW reuse should include a broader range of potential exposure routes, including potential impacts of treatment facilities on local groundwater.**
This study focused specifically on the use of produced water for agricultural irrigation. However, many of the topics covered in this report (e.g., development of appropriate analytical methods, toxicity information, produced water composition) are relevant to risk assessments of produced water broadly. Future work should consider the full range of exposure pathways including potential groundwater contamination, farmworker exposure, management of treatment facilities, and other issues.

5.8.2.3 Treatment and Treatment Performance Criteria

1) **Conduct additional research to develop robust, risk-based treatment performance standards for treatment facilities supplying OPW for reuse.**
Underperforming treatment systems were a key issue that arose in the regulation of wastewater treatment systems in California. This is also an important issue in recycled water where there is a greater risk of exposure. Research studies identified these gaps in the 1960s and 70s and regulations were updated to include more stringent design and monitoring requirements. Current recycled water quality criteria address treatment performance through a risk-based approach and use of (treatment) process indicators (e.g., total coliform, turbidity). The efficacy of treatment systems is an area of active research in produced water. Oil and water separation to capture recoverable hydrocarbons is common, but, relative to recycled water, comparatively little is understood about the removal or transformation of other contaminants in produced water. Understanding treatment performance is further hindered by a lack of understanding of what chemical constituents and/or transformation products are present in produced water and how concentrations of constituents vary over time and space.

2) **Using the SB 1281 Study for guidance, improve reporting formats and procedures to better understand specifics on the types of treatment currently occurring.**
SB 1281 initiated the collection of additional information on the treatment of produced water, though there are serious limitations in the data (discussed elsewhere in this report and the CCST SB 1281 study). Better information on both the treatment processes and technologies in use and details on their performance generally and when faced with variable water quality is needed. As a precursor to defining treatment performance criteria, more information on the quality of produced

water is needed such that the water quality aims of treatment for reuse can be better defined beyond what is required by anti-degradation policies.

5.8.2.4 Fit-for-Purpose Framework

1) **Additional basic research is needed to begin defining a series of fit-for-purpose classes of OPW similar to what has been developed for municipal recycled water.**
   The agricultural irrigation portion of California's current fit-for-purpose framework for recycled water specifies, among other things, four classes of recycled water and the types of crops that can be irrigated with each class of water. These classes are defined based on risk assessments and incorporate considerations such as whether a type of produce is typically consumed raw vs. cooked (i.e., provides additional pathogen inactivation). These classes do not map especially well to produced water. Current research is starting to provide some insights into where COIs accumulate within crops, but significant gaps in analytical methods, basic knowledge around chemical transformations, and understanding of which specific chemicals to monitor for in crops remain. These limitations led to the Food Safety Panel's recommendation that current sampling efforts focus on soil and water quality. Better understanding of concentrations and the transformation of COI in produce is a barrier to defining specific fit-for-purpose classes akin to what is used in the current recycled water fit-for-purpose framework.

2) **Conduct additional research exploring whether constituents such as TDS could serve as a reliable, proxy indicator for other COI in OPW.**
   At least anecdotally, higher levels of TDS in produced water are associated with higher concentrations of COIs. Further research is needed to better understand these relationships and assess what role real-time TDS monitoring could play in future water quality criteria for produced water reuse and management of temporal variation in OPW quality.

3) **Explore whether there are relevant lessons that can be learned from other regulatory programs focused on minimizing adverse health and/or environmental impacts associated with long-term chronic exposures.**
   The recycled water regulations for agricultural irrigation focus on minimizing acute health impacts associated with pathogens. Produced water is different in that the primary health concerns are associated with chronic, long-term exposure. Other regulations such as those for air quality and/or drinking water quality that focus on minimizing health risks associated with long-term, chronic exposure may provide a more relevant or helpful additional analog for produced water. Likewise, there may be constructive lessons to learn from the process and findings of the SWRCB Direct Potable Reuse Criteria Expert Panel.

CHAPTER 6

Geospatial Model of Potential for Expanded Reuse of Oilfield Produced Water

6.1 Introduction

Reuse of oilfield produced water (OPW) for irrigation of agricultural crops is already occurring in different parts of California. In the southern Central Valley, for example, the estimated annual volume of permitted agricultural reuse is 31,246 acre feet per year (AFY), servicing approximately 95,000 acres of farmland (Shimabuku, Abraham, and Feinstein 2019; Mahoney, Asami, and Stringfellow 2021). This indicates that there is demand within the agricultural industry for OPW, therefore, exploring future expansion of reuse may be warranted. Another reason for analyzing the potential for expansion of OPW reuse is the continued water stress in the state, causing once productive agricultural land to be idled. For example, during the last major drought in California, as a direct response to surface water shortages and the high cost or unsuitable alternatives there was a 45% increase in idle agricultural land in 2015 (Lund et al. 2018).

For OPW to be a feasible source of water for agricultural producers it must overcome economic, regulatory, environmental, social, and corporate policy-related challenges (IPIECA 2020). These challenges are not trivial and are commonly site-specific, requiring customized analysis and solutions for each new opportunity. However, with growing challenges in securing reliable sources of water in agricultural regions in the state, OPW may be a desirable and viable supply source for certain irrigators.

In this chapter, the main goal is to build a geospatial model that can be used to evaluate a variety of key factors influencing the potential for expansion of OPW reuse in California. The model and its output are intended to support decision-making regarding further exploration of OPW reuse in California at a regional level. The model is not intended to be used for making well- or field-level decisions on suitability for OPW reuse, as more information is necessary for local, site-specific decisions.

This model was built using data sets that are available statewide, but the analysis and results focus on the southern Central Valley (specifically the area contained in Kern County) (Figure 6-1). The reason for this focus is twofold. First, produced water has been used for irrigation of food crops in Kern County for more than 30 years (Mahoney, Asami, and Stringfellow 2021), and it is currently the main location in the state of California where oil companies and irrigators are actively partnering to reuse OPW. Therefore, it is a good testing-ground for the model’s usefulness at identifying regional-scale opportunities for expanding reuse. Second, a report by CCST (2019) that used water quality and the SB 1281 dataset to determine potential for OPW reuse in California found that the potential for expanded reuse existed entirely in Kern County. Future work may wish to analyze other regions of the state and should be able to do so using the model developed here.

Figure 6-1. State of California with County Boundaries, Highlighting Kern County as the Focus Area for this Analysis.

The key objectives of this section include:

- Identify locations in the study area where OPW reuse could be expanded based on key factors such as quality of OPW water before treatment, volume, crop requirements, and potential demand from agricultural growers as determined by metrics of regional water scarcity;
- Estimate the volume of OPW suitable for expanded agricultural reuse;
- Identify data gaps that exist for meeting these stated objectives; and
- Provide recommendations for filling these gaps.

6.2 Methods

Here, a description of the data and methods used for development of a spatial model to predict where in California OPW reuse could be expanded is provided.[28] Factors included in the model are location and area of crops tolerant of key water quality constituents for crop health, water quality characteristics of OPW relevant to crop health, location and volume of OPW potentially available for expanded reuse, location/adjacency of irrigation districts that could provide for delivery of OPW, and indicators of regional water scarcity. These factors were chosen based on data availability and usefulness for meeting the research objectives outlined above. As stated previously, while the analysis and results are focused on the southern Central Valley in Kern County, much of the data and methods used are applicable across California. Furthermore, statewide data will be included for use in the online, publicly available spatial model (link to be included with the final report).

6.2.1 Key Factors for Predicting OPW Reuse Potential

6.2.1.1 Crop Tolerance

Review of crop tolerance information from relevant literature (Chapter 3) suggests crop sensitives to salinity and boron can be useful in developing criteria for irrigation water suitability. To assess crop tolerance, crop information was first collected from the California Department of Water (CDWR) Resources Crop Mapping spatial dataset of land use type which covers the entire state's irrigated agricultural area (CDWR 2018). From this shapefile a table was extracted with crop type information for the study area, Kern County. Next, data from the Food and Agriculture Organization of the United Nations (Ayers and Westcot 1985) was used to identify the tolerance levels of each crop to soil salinity (as EC_e) and boron.[29] Based on tolerance levels for a desired yield of 100%, a rating system was developed for assessing crop tolerance to irrigation water salinity and boron and was applied it to each agricultural crop area in the mapping space (Tables 6-1 and 6-2). For both rating systems, the lower scores correspond to more sensitivity (i.e., less tolerance) for the respective analyte. A "zero" rating was applied to cases where crop tolerance information for a particular analyte was not available. In some cases, up to four different crops were listed for a single agricultural field (as farmers can rotate crops throughout the growing season on a single field), and in these cases, the most sensitive crop type was used to rate the field. Also, some crops did not have tolerance ratings for salinity and/or boron in the literature reviewed. Altogether, this approach provided a conservative estimate of crop tolerance for each field.[30]

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[28] For the spatial model, all work was done using ArcGIS Pro v2.9.3.

[29] For categorizing crop tolerance and comparing it to OPW water quality, EC_e (ds/m) was converted to EC_w (ds/m) following the equation $EC_e = 1.5EC_w$ (Ayers & Westcot 1985). Boron crop tolerance is based on soil-water or saturation extracts, which are approximately equal to or slightly less than irrigation water (Ayers & Westcot 1985).

[30] Appendix B contains the complete list of each crop's specific tolerance ratings, both for achieving a 100% and 75% yield.

Table 6-1. Rating System for Assessing Crop Tolerance to Salinity Used for Spatial Model.
Data sources: Ayers & Westcot 1985 Tables 4 and Table 5, citing original work from Maas and Hoffman 1977 and Maas 1984.

Crop Tolerance Rating	EC_w (ds/m)	Tolerance Category
1	< 0.87 ds/m	Sensitive
2	0.87 – 2.0 ds/m	Moderately Sensitive
3	< 2.0 – 4.0 ds/m	Moderately Tolerant
4	< 4.0 – 6.7 ds/m	Tolerant
0	NA	No Data

EC_w = Electrical Conductivity of irrigation water in deci-siemens per meter (ds/m).

Table 6-2. Rating System for Assessing Crop Tolerance to Boron Used for Spatial Model.
Source: Based on Ayers & Westcot, 1985, Table 16; Maas 1984.

Crop Tolerance Rating	B mg/L	Tolerance Category
1	≤0.5	Extremely sensitive
2	>0.5 - 0.75	Very sensitive
3	>0.75 – 1.0	Sensitive
4	>1.0 – 2.0	Moderately sensitive
5	>2.0 – 4.0	Moderately tolerant
6	>4.0 – 6.0	Tolerant
7	>6.0 – 15.0	Very tolerant
0	NA	No Data

6.2.1.2 OPW Water Quality and Water Volume

A primary factor affecting the potential for reuse of OPW for irrigation is crop tolerance to the qualities and characteristics of that water. While in many cases OPW is blended with alternative sources of water and/or treated prior to application to crops, crop sensitives can constrain the practical and economic feasibility of these approaches, making certain treatment and blending options insufficient relative to the desired application (NRC 2008). Therefore, these methods were developed to identify irrigation water suitable for irrigation with little to no treatment.

This work builds on the work of Shimabuku et al. (2019) who estimate the total potential OPW available at the field level for reuse for irrigation in California. To identify oilfields where water quality and quantity may make OPW potentially available for reuse Shimabuku et al. evaluated measured concentrations of TDS (mg/L) and boron (mg/L) in produced water samples from eight different sources

(Table 6-3).[31] Of the 1,954 OPW analytical samples from (Shimabuku, Abraham, and Feinstein 2019), 1,829 were from oilfields in Kern County and used in this analysis. For this study, four additional samples were added to the dataset from two WDR permits issued in 2019 by the CVRWQCB (CVRWQCB 2019a; 2019b).

Table 6-3. Sources of Produced Water Analytical Data.
Source: Adapted from CCST 2019 Table 2.4.

Number	Data Source	Reference	Number of Samples
1	USGS Produced Waters Dataset	(US Geological Survey (USGS) 2018)	67
2	WST Disclosures	(California Department of Conservation, Geologic Energy Management Division, CalGEM 2018b)	1,141
3	Davis et al. 2016	(T. A. Davis, Kulongoski, and McMahon 2016)	4
4	Gannon et al. 2018	(Gannon et al. 2018)	15
5	Gans et al. 2018	(Gans et al. 2018)	31
6	Gillespie et al. 2016	(Gillespie, Kong, and Anderson, 2016)	54
7	Metzger et al. 2018	(Metzger et al. 2018)	512
8	WDR Irrigation Permits	Multiple, see references cited.	9
Total Samples			1,833

To include a sample in the analysis, it at minimum required a measurement of TDS, or it's surrogate, EC_w; boron concentrations were also included in the analysis when available. TDS and boron are key indicators of irrigation water suitability, according to the United Nations FAO Water Quality for Agriculture irrigation guidelines (Ayers and Westcot 1985). 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 (Yau and Ryan 2008; Fipps 2021). Boron concentrations were available for 1,205 of the 1,833 samples (65.7%).

Average and minimum OPW concentrations of TDS and boron by oil and gas field were calculated and used to rate and compare each field in the study area to crop tolerance ratings (Tables 6-4 and 6-5). Lower ratings correspond to lower concentrations of the analytes, and therefore, to oil and gas fields where OPW is potentially more suitable for irrigation of sensitive crops. If only one sample were

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[31] If measured concentrations of TDS were not available, Shimabuku et al. converted EC_w to TDS following instruction from the University of California, Division of Agriculture and Natural Resources (n.d.).

available, the singular concentration value was used in place of an average. Two additional ratings were included for oil and gas fields where averages were above the highest crop tolerance category. In the case of TDS, an oil and gas field was given a rating of 5 if the average was above all categories, but the minimum value was within range or below category 4. An oil and gas field was given a rating of 6 if the average and minimum TDS values were both above all crop tolerance categories. For boron, an oil and gas field was given a rating of 8 if the average was above all categories, but the minimum value was within range or below category 7. And an oil and gas field was given a rating of 9 if the average and minimum boron values were both above all crop tolerance categories. These final two categories distinguish oil and gas fields where OPW may be available for reuse but will likely need treatment and/or to be blended with other water supplies before use.

Table 6-4. Rating System for Oil and Gas Fields Based on OPW Salinity (Measured as TDS) Used for the Spatial Model.

Data Source: Ayers & Westcot, 1985; University of California, Division of Agriculture and Natural Resources n.d.

Oil and Gas Field Rating	TDS (mg/L)	Crop Tolerance Category Match
1	<557	Sensitive
2	558-1,280	Moderately Sensitive
3	1,281-3,200	Moderately Tolerant
4	3,201-5,360	Tolerant
5	NA	NA; Average above all categories, but minimum value within range or below category 4 TDS values
6	NA	NA; Average and minimum values are both above all categories
0	NA	No Data

Table 6-5. Rating System for Oil and Gas Fields Based on OPW Boron (B) Concentrations Used for the Spatial Model.

Data sources: Ayers and Westcot 1985 Table 16, citing data from Maas 1984.

Oil & Gas Field Rating	B mg/L	Crop Tolerance Category Match
1	≤0.5	Extremely sensitive
2	>0.5 - 0.75	Very sensitive
3	>0.75 – 1.0	Sensitive
4	>1.0 – 2.0	Moderately sensitive
5	>2.0 – 4.0	Moderately tolerant
6	>4.0 – 6.0	Tolerant
7	>6.0 – 15.0	Very tolerant

Oil & Gas Field Rating	B mg/L	Crop Tolerance Category Match
8	NA	NA; Average above all categories, but minimum value within range or below category 7 B values
9	NA	NA; Average and minimum values are both above all categories
0	NA	No Data

To estimate potential volume of OPW available for reuse by oil and gas field, Shimabuku et al. (2019) used quarterly volumetric data from SB 1281 (DOGGR 2018). They extracted well-level, produced water disposal data, aggregated it to field level, from Quarter 4 (Q4) of 2015 through Quarter 1 (Q1) of 2017. Then they used Equation 6.1 to estimate the average annual volume of produced water disposed of, in Acre-Foot per Year (AFY), at each field.

$$Average\ Annual\ Volume = 4 * \frac{\sum V_{Q4\ 2015}, V_{Q1\ 2016}, V_{Q2\ 2016}, V_{Q3\ 2016}, V_{Q4\ 2016}, V_{Q1\ 2017}}{6} \qquad \text{(Equation 6.1)}$$

where V is the volume, in AF, reported by the oil or gas operator for the quarter identified in the subscript.

To account for existing agricultural reuse, the volume of water at each field coded in the SB 1281 dataset under the two disposition codes used by existing, permitted OPW reuse for agricultural purposes, was removed from the average annual volume. [32] This provided a more conservative estimate of the volume potentially available for expanded reuse at each field.

Oil and gas field boundaries were obtained from the California Department of Conservation, Geologic Energy Management Division via California' Open Data Portal (CalGEM 2022). For the spatial analysis, the dataset was clipped to the study area boundaries, leaving 100 oil and gas fields. Of these 100, 21 that were labeled as "abandoned" were also removed from the analysis, leaving 79 oil and gas fields.

6.2.1.3 Water District Boundaries

Water district boundary location data is maintained by the CDWR, including agricultural water districts and other water retailers that sell water. All water districts located in Kern County (n = 171) are included in the spatial model, however, some of these districts may not serve agricultural customers and would need to be screened further to distinguish which may have interest in buying OPW. Additionally, it should be noted that district boundaries may not be reflective of existing water district infrastructure, but rather of the service area of each district, both existing and future.

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[32] The two disposition codes were "Sale/Transfer-Domestic Use" (Method 11) and "Surface water discharge – Ocean, lake, pond, etc." (Method 3). Sale/Transfer-Domestic Use is defined as water "used for agriculture, irrigation, water replenishment, water banking, livestock, etc."(CalGEM 2018a). 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" (CalGEM 2018a).

6.2.1.4 Water Scarcity

Water scarcity is when there is a shortage of water to meet a specified demand. In some parts of California, water scarcity may contribute to demand for OPW for irrigation. For this analysis, groundwater basin status from the SGMA Basin Prioritization map was used as a proxy for water scarcity. The dataset containing the boundary for each of California's 515 groundwater basins along with each basin's priority status was used in the spatial analysis to identify locations across the study area where groundwater basins have been unsustainably tapped as a water source (i.e., priority "High" or "Medium") and, therefore, where water scarcity is likely high (CDWR 2022).

6.2.1.5 Data Gaps and Uncertainty

A variety of data gaps and factors contributing to uncertainty of this analysis are important to recognize. Here is a list of the most important data gaps and sources of uncertainty in this analysis. It is not meant to be a list of data and information necessary for making site-specific decisions, but rather focuses on data gaps for regional-scale analyses.

- Crop type and crop location: While the dataset used to identify crop type and location reports better than a 95% accuracy rate, the data was collected in 2018 and therefore changes made at the agricultural field level since then are not captured in this analysis (Land IQ 2018).
- Other crop characteristics not included in this analysis: Crops can be sensitive to some chemical constituents based on the irrigation method used. Information on irrigation type is included in the crop spatial dataset but was not analyzed here due to time constraints.
- OPW water quality: While salinity and boron are two of the more common parameters for assessing crop tolerance, there are several other major water quality characteristics of concern for irrigated crops. These include calcium, sodium, chloride, and SAR (Ayers & Westcot 1985). These were not available in enough of the sample data to warrant their use here, but if available, could help to further refine OPW suitability for irrigation. Furthermore, OPW can contain other constituents that are harmful and/or toxic to plants and/or humans, such as hydrocarbons, radioactive material, heavy metals, and other chemical additives from the oil and gas industry (see Chapter 3 for further discussion). These constituents were not available for most samples in the analysis but could also be useful in further constraining opportunities for expanding reuse.
- OPW water quantity: Due to time constraints as well as concerns about the quality of newer volumetric data, this analysis relied on volumetric estimates from the CCST (2019) report. This report provided annual and average annual OPW volumes from quarterly data from Q4 2015-Q1 2017. As described in the report, SB 1281 quarterly data are problematic for several reasons, including, duplicate reporting, under-reporting, and general challenges caused by confusing and misaligned data categories within the sub-components of the dataset (Abraham, Feinstein, and Czolowski 2021). Furthermore, produced water volumes do not remain constant over time; over the lifetime of an oil or gas well, the water-to-oil ratio tends to increase (Clark and Veil 2009). This means that the volumetric estimates provided here could be lower than actual volumes, assuming the same wells have remained in production.
- Infrastructure for transporting and storing OPW for reuse by irrigators: For this analysis, specific information on infrastructure available for OPW transport and storage was unobtainable. Water district boundaries only provide approximations of where infrastructure could be and therefore, there is significant uncertainty in the need for additional or new infrastructure for expanded OPW reuse.
- Soil characteristics: Soil qualities and characteristics also impact water suitability, as well as longer-term potential for reuse of certain types of water; this information would be needed on a finer scale than was intended for this analysis but could potentially alter the results in a significant way.

- Costs of alternatives relative to the cost of OPW: Demand for OPW will in part be determined by the cost compared to the cost of other alternatives, such as imported water. Due to high variability in water prices on an annual basis and the complexity of predicting future cost of water, this factor was not included in the analysis.
- Regulatory issues: Water reuse for irrigation of crops is regulated by the California State Water Resources Control Board, and other state, local, and federal entities. Regulations commonly impact feasibility for reuse by adding additional cost and other barriers to obtaining necessary permits. It was beyond the scope of this analysis to incorporate regulatory factors affecting the potential for expanding OPW reuse.
- Public and agricultural community perspectives: Due to concerns for the health and well-being of humans and the environment, reuse of OPW for growing crops is a contentious issue. It was beyond the scope of this analysis to incorporate human sociological or political factors into the analysis.

6.3 Results

6.3.1 Locations where OPW reuse could be expanded

6.3.1.1 OPW Water Quality

Due to low sample numbers of OPW analytical measurements and lack of crop tolerance information for a high proportion of the total crop area in the study region, it is difficult to draw strong conclusions around where OPW reuse could be expanded. For locations where samples and crop tolerance information were available, Figures 6-2 and 6-3 provide maps of salinity and boron tolerance ratings by field, along with sample counts by analyte. While the SB 1281 dataset maintained by CalGEM) includes a parameter that identifies whether OPW is above or below 10,000 TDS, this is insufficient for evaluations of suitability for agricultural reuse and therefore was not included in the analysis (Shimabuku, Abraham, and Feinstein 2019).

Salinity is a common first order factor used for evaluating irrigation water suitability. Based on salinity measurements, two (3%) oil and gas field, Kern Bluff and Kern Front, had OPW samples with average salinity values suitable for “moderately sensitive” crops (Figure 6-2, Table 6-6). Five (6%) other fields, Edison, Jasmin, Kern River, Mount Poso, and Poso Creek, had OPW samples with average salinity values suitable for “moderately tolerant” crops. Of these, Kern Bluff and Edison are the only oil and gas fields that do not currently have any operators permitted for OPW reuse for agricultural purposes (Table 6-6). Three (4%) fields had OPW samples with average salinity values suitable for “tolerant” crops, including Ant Hill, Fruitvale, and Round Mountain. None of these oil and gas fields currently contain operators permitted for reuse of OPW for agriculture. 11 (14%) oil and gas fields had average salinity values above the crop tolerance thresholds, but minimum values within the range of values suitable for at least the most tolerant crops. 21 (27%) oil and gas fields had OPW samples where even the minimum salinity values were above thresholds for water suitable for the most tolerant crops. In these locations, OPW would not be suitable for reuse without blending or treatment and therefore reuse from these fields may be cost-prohibitive. No salinity measurements were identified for nearly half (47%) of all oil and gas fields in Kern County.

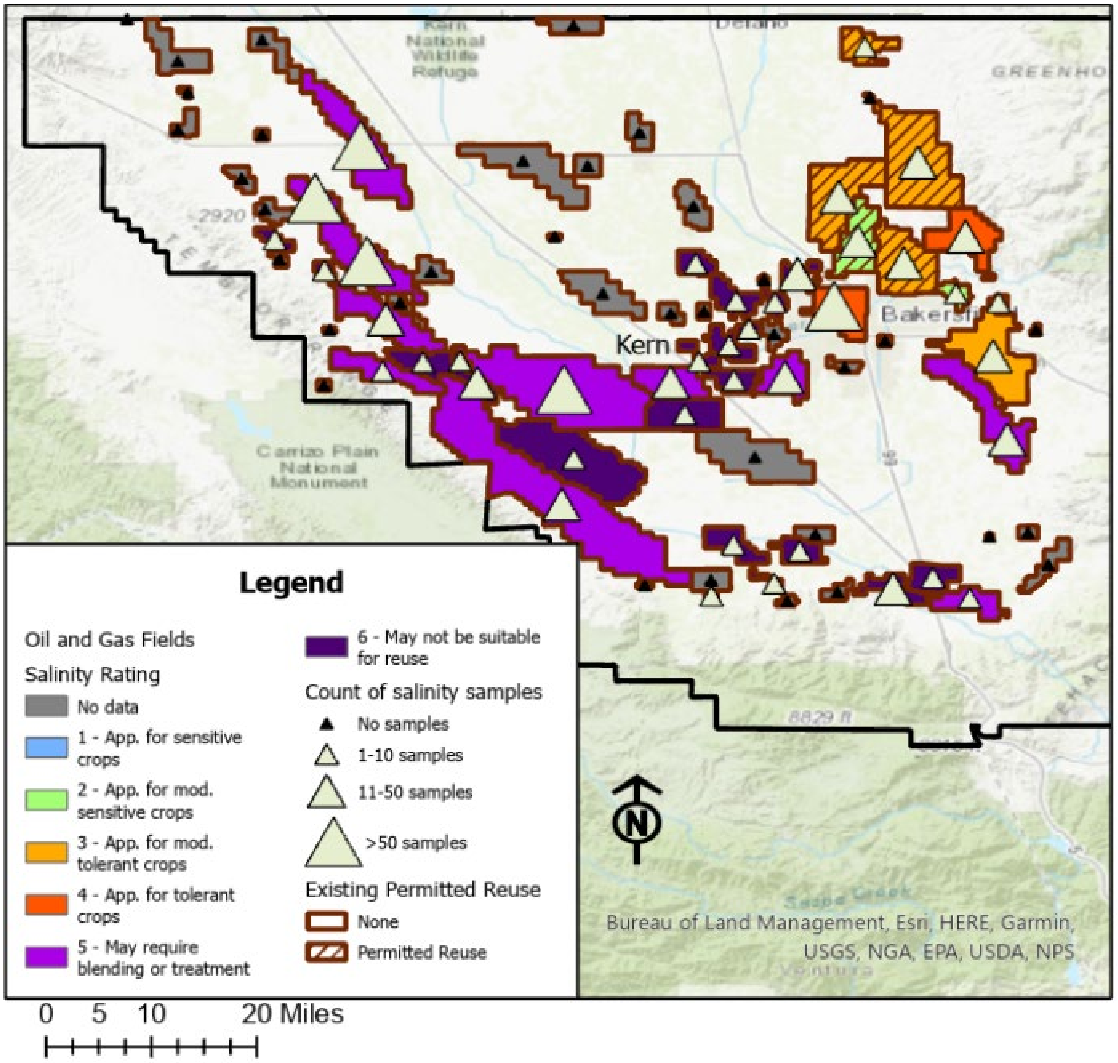


Figure 6-2. Map of Oil and Gas Fields with Permit Status, Salinity Rating to Match Crop Tolerance, and Salinity Sample Count, in Western Kern County.

Oil and gas field rating system displayed using blue and green colors where OPW salinity shows suitability for the most sensitive crops; orange and red colors where OPW salinity shows suitability for tolerant crops; and purple where OPW may need treatment or may not be suitable for agricultural reuse. Grey is used for fields that did not have salinity samples in the dataset.

Four (5%) oil and gas fields (Jasmin, Kern River, Mount Poso, and Poso Creek) had OPW with average boron concentrations that could be potentially applied crops that rate as "sensitive" to boron (Figure 6-3, Table 6-6). All of these fields already contain operators permitted for agricultural reuse of OPW. Four (5%) additional fields contain samples of OPW where average boron concentrations could be applied to crops that rate from "moderately sensitive" up to "very tolerant." These fields include Ant Hill, Fruitvale, Kern Front, and Mountain View. Kern Front already has operators permitted to reuse OPW for agriculture, however, the other three do not currently have permitted reuse occurring (See Table 6-6). Six (8%) additional oil and gas fields had OPW with minimum boron concentrations at or below the range suitable for "tolerant" crops, but average concentrations too high to be suitable for agricultural reuse without treatment. Six (8%) other oil and gas fields had OPW where samples measuring boron were all above the thresholds for even the most tolerant crops. While blending or treatment could potentially make this OPW suitable for reuse, cost of treatment will likely be a significant barrier in these locations. There were 59 (75%) oil and gas fields in Kern County that lacked data for assessing OPW water quality with regards to boron.

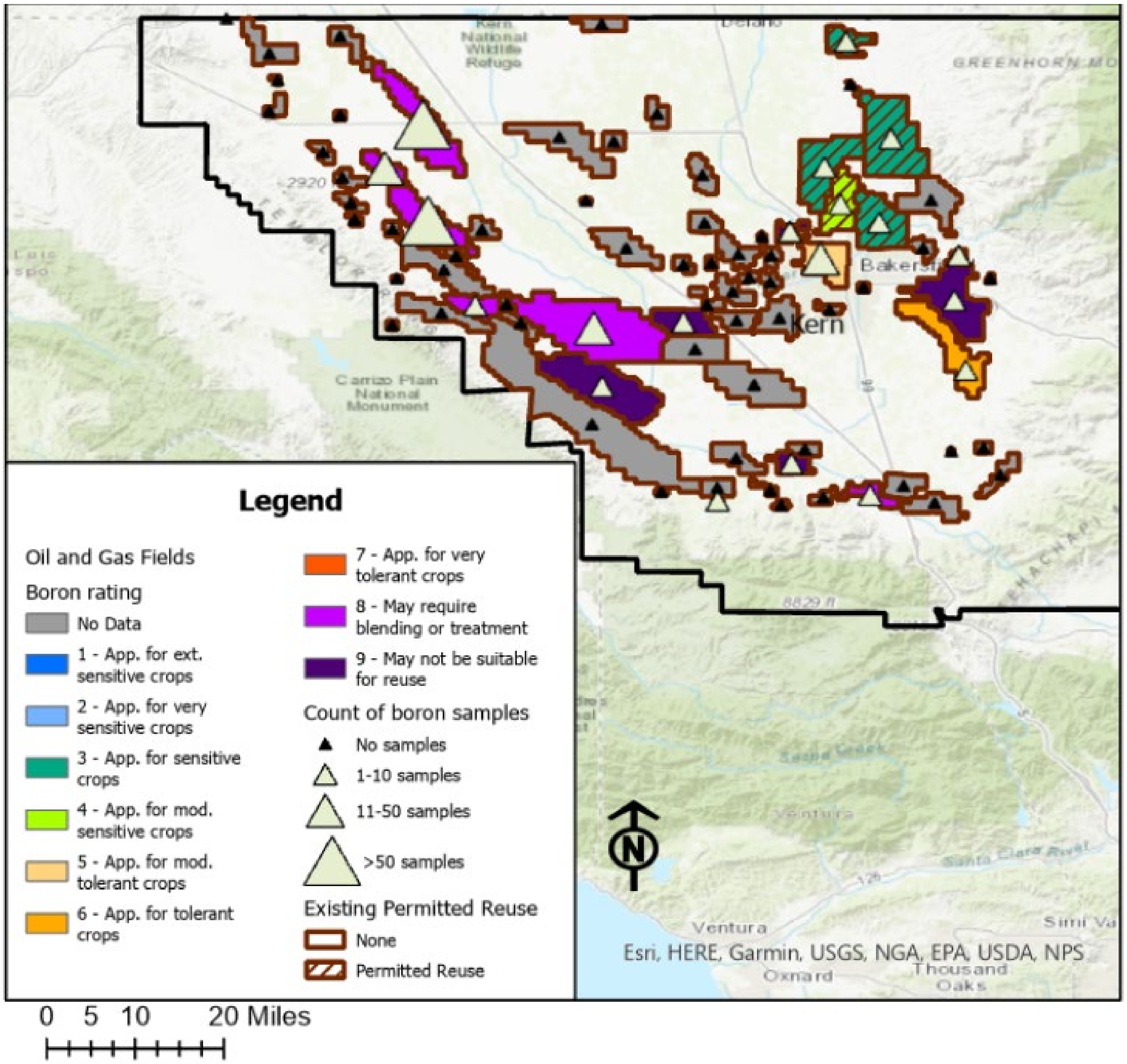


Figure 6-3. Map of Oil and Gas Fields with Permit Status, Boron Rating to Match Crop Tolerance, and Boron Sample Count, in Western Kern County.

Oil and gas field rating system displayed using blue and green colors where OPW concentrations of boron show suitability for sensitive crops; orange and red colors where OPW concentrations of boron show suitability for tolerant crops; and purple for fields where OPW may need treatment or may not be suitable for agricultural reuse. Grey is used for fields where there were no boron samples in the dataset.

Table 6-6. List of Oil and Gas Fields with OPW Potentially Suitable for Agricultural Reuse, Including Boron and TDS Analytical Sample Information, Tolerance Ratings, and Permit Status.

Field Name	No. of B Samples	Avg. B (mg/L)	Max. B (mg/L)	Min. B (mg/L)	No. of TDS Samples	Avg. TDS (mg/L)	Max. TDS (mg/L)	Min. TDS (mg/L)	B Tolerance Rating	Salinity Tolerance Rating	Existing Permitted Reuse of OPW for Ag?
Kern Bluff	0	-	-	-	4	661	782	572	-	2	N
Kern Front	2	1.1	1.1	1.1	27	1,052	2,318	491	4	2	Y
Jasmin	4	0.8	1.1	0.6	7	1,281	6,090	435	3	3	Y
Kern River	1	0.8	0.8	0.8	40	3,033	25,500	269	3	3	Y
Mount Poso	1	0.8	0.8	0.8	26	1,615	4,224	366	3	3	Y
Poso Creek	2	0.9	1.0	0.8	46	1,699	13,100	370	3	3	Y
Round Mountain	0	-	-	-	13	3,591	16,300	1,750	-	4	N
Fruitvale	20	2.6	9.3	0.2	60	4,380	20,520	904	5	4	N
Ant Hill	3	12.4	15.1	9.0	4	3,707	4,734	2,670	7	4	N
Belgian Anticline	0	-	-	-	7	13,454	20,253	2,347	-	5	N
Canfield Ranch	0	-	-	-	14	22,386	38,141	2,902	-	5	N
Cymric	0	-	-	-	12	17,698	29,000	5,201	-	5	N
Midway-Sunset	0	-	-	-	26	19,135	34,791	1,007	-	5	N
Tejon	0	-	-	-	9	6,856	16,210	1,084	-	5	N

Field Name	No. of B Samples	Avg. B (mg/L)	Max. B (mg/L)	Min. B (mg/L)	No. of TDS Samples	Avg. TDS (mg/L)	Max. TDS (mg/L)	Min. TDS (mg/L)	B Tolerance Rating	Salinity Tolerance Rating	Existing Permitted Reuse of OPW for Ag?
Mountain View	2	5.0	6.0	4.0	25	9,579	39,900	900	6	5	N
Belridge, North	24	79.5	96.0	12.0	51	31,298	52,000	560	8	5	N
Belridge, South	954	97.1	230.0	0.5	965	47,193	890,000	700	8	5	N
Elk Hills	15	73.4	140.0	4.8	116	28,817	45,988	4,500	8	5	N
Lost Hills	145	85.7	200.7	1.0	163	43,481	360,000	3,600	8	5	N

6.3.1.2 Crop Tolerance

Within Kern County, 895,269 acres of agricultural crops were evaluated for tolerances to different levels of salinity and boron. Of those, 28% were determined to be sensitive to salinity, and 9% were determined to be moderately sensitive (Table 6-7). Only 3% of crops were determined to be tolerant and 7% were determined to be moderately tolerant. Salinity tolerance for 53% of the crop area in Kern County could not be determined, creating uncertainty in locations for potentially expanding reuse of OPW.

Table 6-7. Acres of Crop by Salinity Tolerance Category for Kern County.

Tolerance Category	Acres	Percent
1 - Sensitive	251,047	28%
2 – Moderately Sensitive	81,526	9%
3 – Moderately Tolerant	66,656	7%
4 - Tolerant	24,075	3%
0 – No Data	471,965	53%
Sum Total	895,269	100%

Boron crop tolerance information was even more sparse. Table 6-8 contains a summary of the total area of crops, in acres, by their boron tolerance category. Of the total crop area evaluated in Kern County, less than 1% of the crop area was determined to extremely sensitive; 2% and 8% were determined to be very sensitive and sensitive, respectively. Only 3% of the crop area was determined to be moderately sensitive, and 1% was determined to be moderately tolerant. 7% of the crop area was determined to be tolerant to boron and 3% was determined to be very tolerant. The majority of the area, 78%, did not have data on tolerance to boron.

Table 6-8. Acres of Crop by Boron Tolerance Category for Kern County.

Tolerance Category	Acres	Percent
1 – Extremely Sensitive	1,101	0%
2 – Very Sensitive	14,434	2%
3 – Sensitive	68,755	8%
4 – Moderately Sensitive	23,540	3%
5 – Moderately Tolerant	6,015	1%
6 – Tolerant	62,506	7%
7 – Very Tolerant	22,603	3%
0 – No Data	696,315	78%
Sum Total	895,269	100%

Figure 6-4 provides a visual representation of the distribution of crop area with salinity tolerance ratings superimposed with oil and gas field locations.

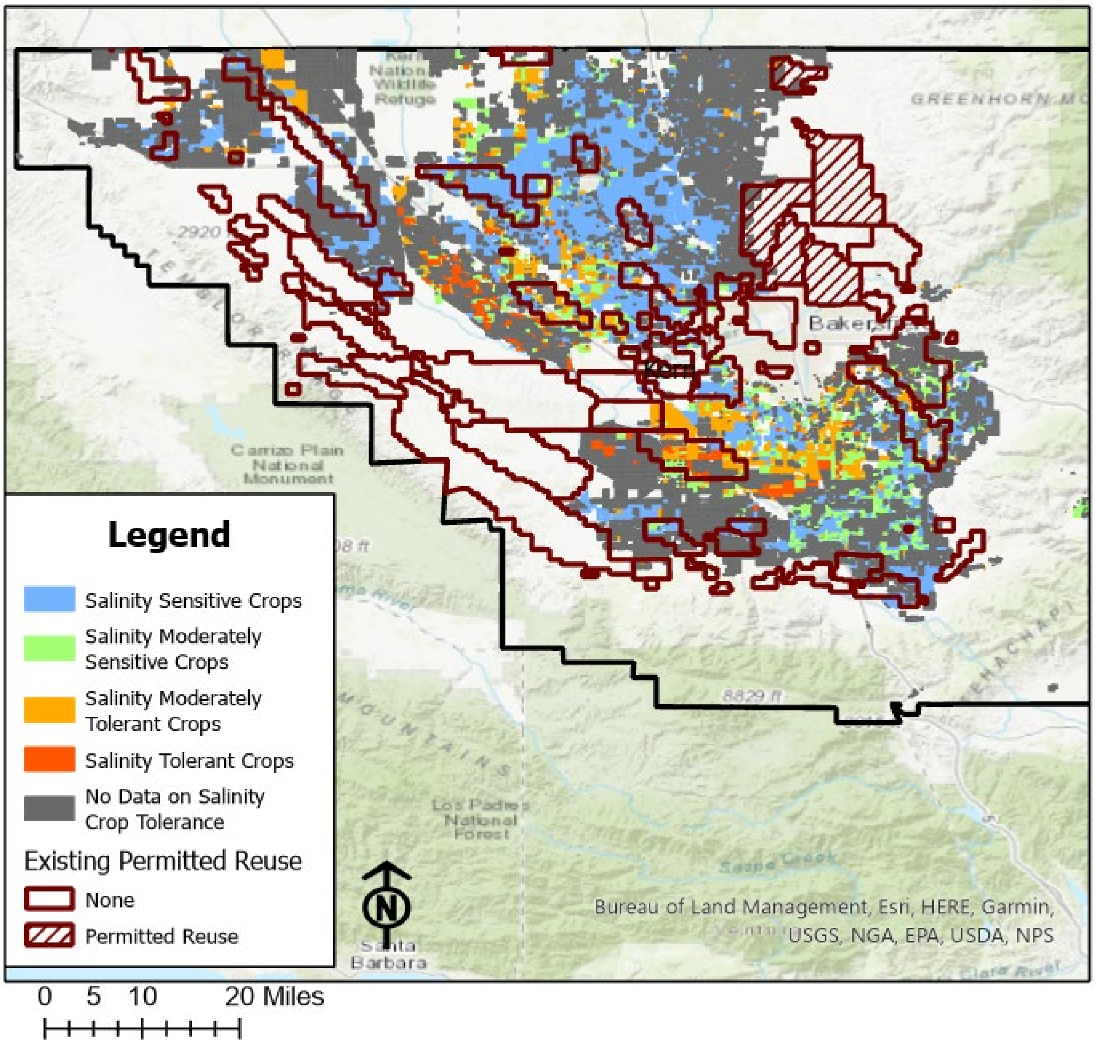


Figure 6-4. Map of Crop Area by Salinity Tolerance Overlaid with Oil and Gas Fields with Permit Status in Western Kern County.

Four categories of crop tolerance to salinity are included, from sensitive (blue) to tolerant (red). Grey indicates no data was available on the salinity tolerance of crops in those areas.

The distribution of boron tolerant crops in Kern County is shown in Figure 6-5. The main finding from the spatial analysis is that more data and information is needed for boron tolerance of crops in the northern portion of study area.

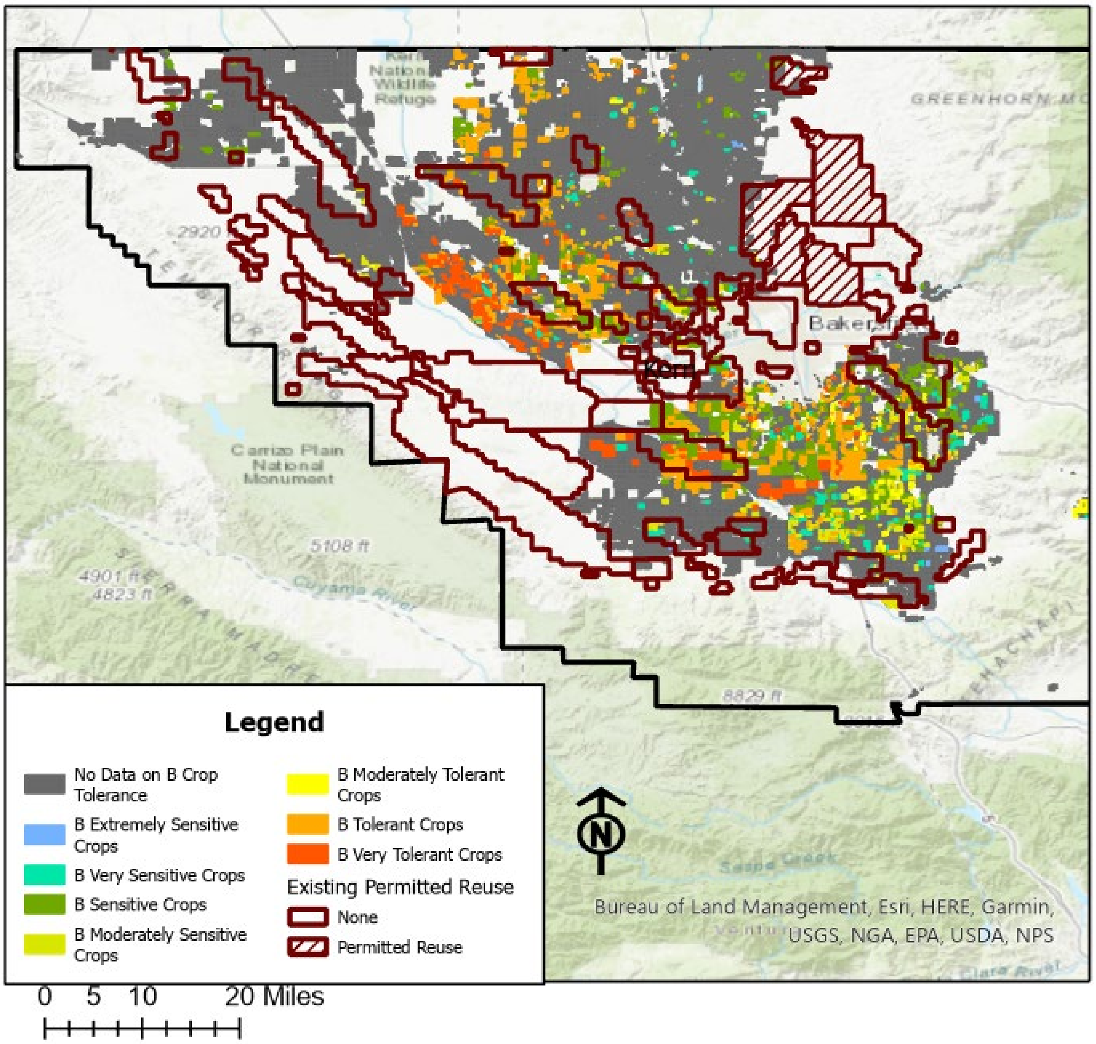
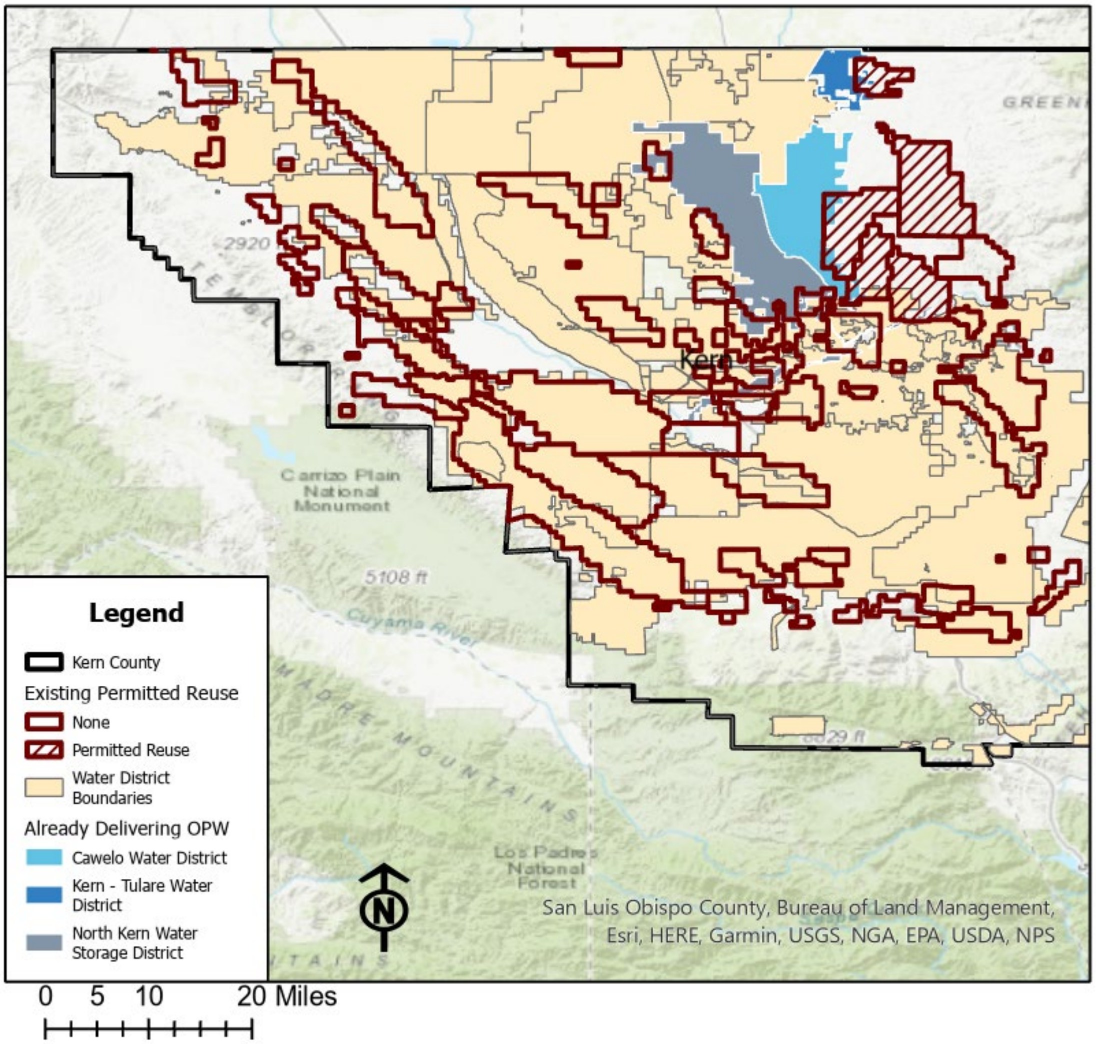


Figure 6-5. Map of Crop Area by Boron Tolerance Overlaid with Oil and Gas Fields with Permit Status in Western Kern County.

Seven categories of crop tolerance to boron are included, from extremely sensitive (blue) to very tolerant (red). Grey indicates no data was available on the boron tolerance of crops in those areas.

6.3.1.3 Water District Locations

A key factor in assessing OPW reuse potential for agriculture is understanding where infrastructure (e.g. canals and pipes) may exist that could be used to transport water from oil and gas fields to places where agricultural demand may exist. Figure 6-6 shows a map of existing water districts in western Kern County, three of which already transfer OPW to agricultural fields (in blue).[33]



San Luis Obispo County, Bureau of Land Management, Esri, HERE, Garmin, USGS, NGA, EPA, USDA, NPS

Figure 6-6. Map of Water District Boundaries Overlaid with Oil and Gas Fields with Permit Status in Western Kern County.

Water district boundaries likely indicate a district's current and potential future service area, not necessarily extent of existing infrastructure. The boundaries for one water district that is a regional water wholesaler, Kern County Water Authority, was removed from the map because its service area covers almost the entire extent of the area shown and would therefore would have hidden other boundary areas.

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[33] A fourth water district in the region, Jasmin Mutual Water District, also currently transports water for Jasmin oil and gas field to agricultural users (Central Valley Regional Water Quality Control Board (CVRWQCB) 2019b), but it's boundaries were not included in the water district dataset from the Department of Water Resources.

Water district boundaries depict each district’s service area, both present and potential future. Overlap between an oil and gas field and a water district does not guarantee that water infrastructure is available for transporting OPW to irrigators but can provide interested parties with initial information on potential partners for OPW reuse.

6.3.1.4 Water Scarcity

Water scarcity is a major challenge in the study area. As shown in Figure 6-7, nearly all of the oil and gas fields in Kern County are underlain by a designated “high priority” groundwater basin, the San Joaquin basin. This indicates that the groundwater level underlying this area is in decline, and that there are other factors contributing to high water stress. These are good indicators of likelihood for demand for alternative sources of water in this region.

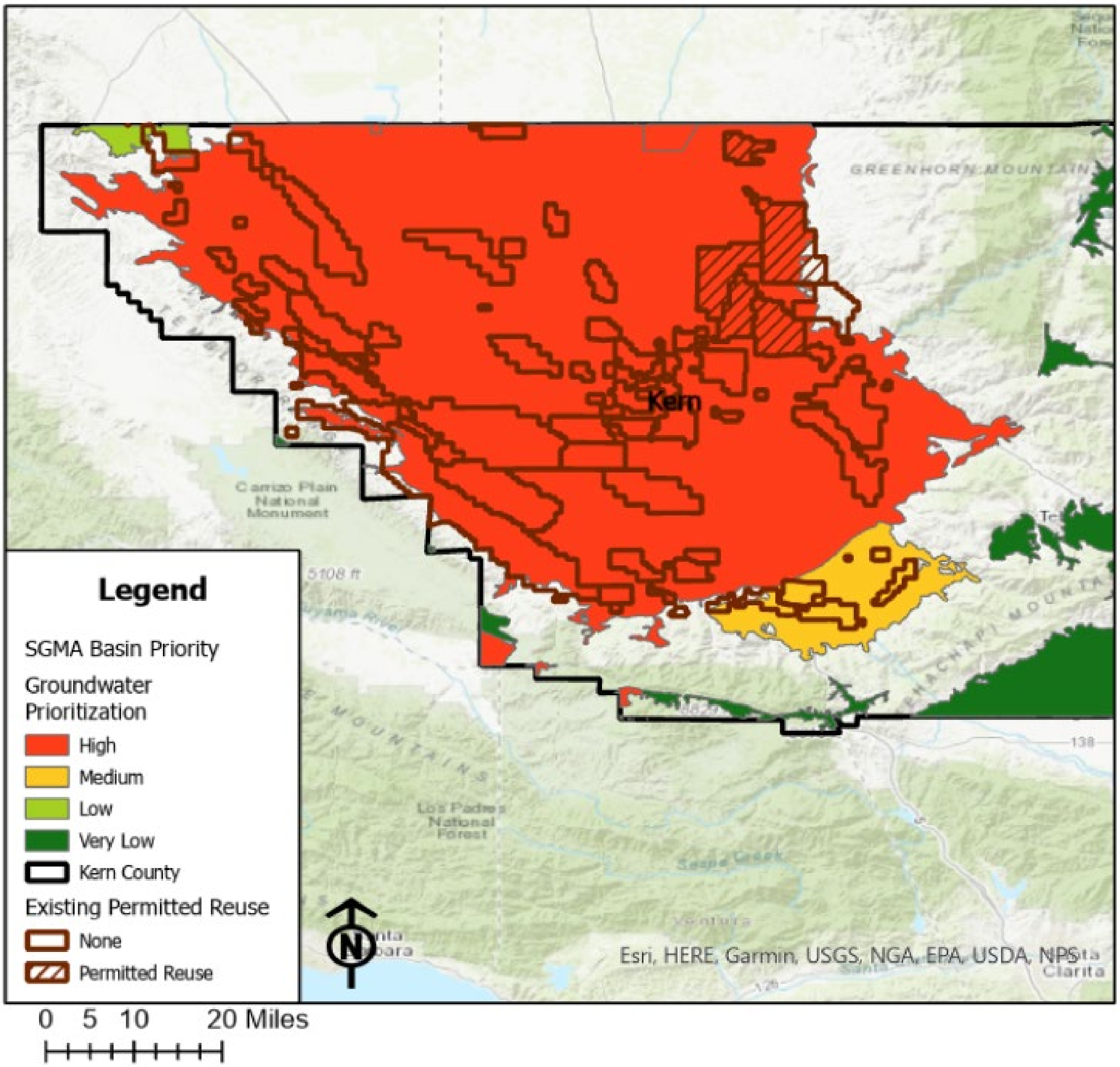

Figure 6-7. Map of SGMA Groundwater Basins with Prioritization Overlaid with Oil and Gas Fields with Permit Status in Western Kern County.

6.3.2 Quantity of OPW Potentially Available for Agricultural Reuse

The average annual volume of OPW by field was calculated from the SB 1281 dataset during theQ4 2015-Q4 2017 timeframe. Figure 6-8 depicts the average annual volume of OPW by field, after removing the volume of water reported as already being reused for agriculture. Table 6-9 provides a list of the estimated average annual volume of OPW by field. Fields that did not have analytical chemistry data were not considered in this analysis. Of the oil and gas fields where there are existing permits for agricultural reuse, all were estimated to have at least 1,367 AFY of additional OPW, beyond what was reported as already going toward reuse. Kern River oil and gas field was estimated to have 33,900 AFY of additional OPW for reuse, and Kern Front field was estimated to have an additional 19,986 AFY. Belridge, South field, Midway-Sunset, and Round Mountain, were estimated to have the highest average annual volume of fields without existing permits for agricultural reuse.

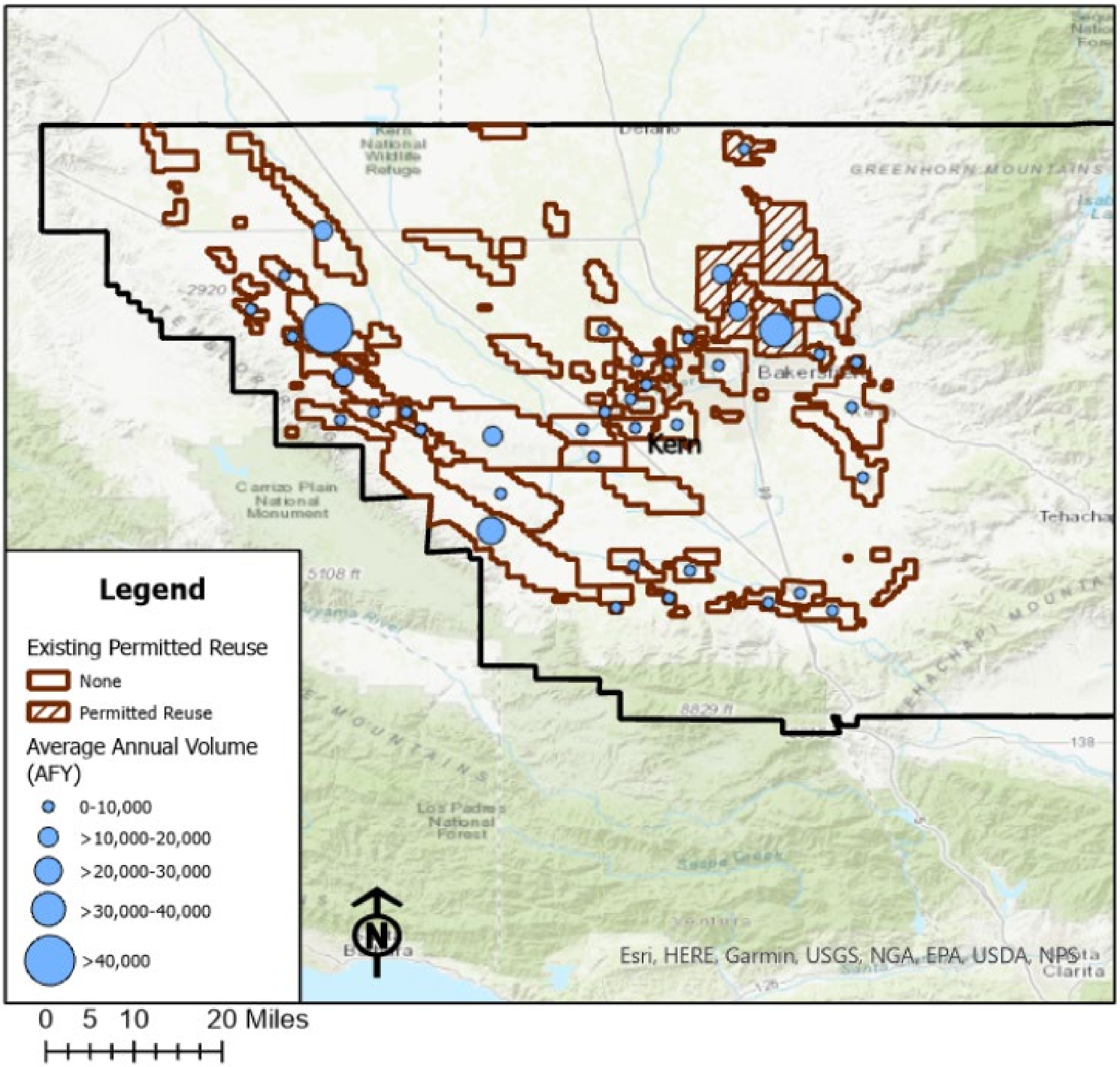

Figure 6-8. Map of Western Kern County Oil and Gas Fields with Average Annual Volume (AFY) of OPW.

In total, an estimated 227,650 AFY of OPW may be available for expanded reuse in the study area (Table 6-9). Of this volume, 100,177 AFY of OPW was within fields where average TDS was below the upper threshold for tolerant crops (5360 mg/l) (shaded rows in Table 6-9). However, it is important to note that data on TDS are scarce, spatially and temporally variable, and unlikely to accurately reflect accurately produced water suitability (Table 6-6). In the state of California, the total annual water use for agriculture ranged from 25.7 to 37.0 million AFY between 1960 and 2015 (Cooley 2020); therefore, this volume represents less than 1% of agricultural use in the state.

Table 6-9. Average Annual Volume (AFY) of OPW from Oil and Gas Fields Where Salinity and Boron in OPW may be Suitable for Agricultural Reuse.

An * indicates field has existing permitted reuse for agriculture. †Permitted reuse occurring at Poso Creek oil and gas field was not occurring in the Q4 2015-Q1 2017 timeframe used here to calculate average annual volume potentially available for reuse, therefore, the volume of OPW potentially available for reuse may be less than what is presented here. Shading indicates fields where average TDS concentrations were below the upper threshold for 'tolerant' crops.

Field Name	Average Annual Volume (AFY)
Belridge, South	40,789
Kern River*	33,900
Midway-Sunset	29,030
Round Mountain	22,207
Kern Front*	19,986
Elk Hills	19,580
Poso Creek*	17,728†
Lost Hills	15,562
Cymric	15,544
Belridge, North	4,127
Mount Poso*	3,646
Tejon	2,733
Jasmin*	1,367
Fruitvale	809
Ant Hill	414
Kern Bluff	120
Canfield Ranch	47
Mountain View	47
Belgian Anticline	13
Total (All Fields)	227,650
Total (Fields Where Average TDS <5360 mg/L) *	100,177

* A TDS levels of 5360 mg/L is the upper threshold for 'tolerant' crops. Most crops tolerance of TDS in irrigation water is significantly below this threshold.

6.4 Conclusions and Recommendations

In California's agricultural regions where water is increasingly scarce, OPW may have a role to play in reducing water stress. In a small number of places, OPW is already being used for agricultural purposes, supporting the assumption that there is demand for water from this source. However, challenges and hurdles still exist to expanding reuse of OPW for irrigation. At this point in time, some of the challenges include understanding where opportunities may exist, how different factors affecting the opportunity for reuse vary in time and space, and what data gaps exist. A geospatial model with a subset of key factors that influence the potential for expansion of OPW reuse, was used to identify some opportunities for reuse in the southern Central Valley. The model and its output are intended to support regional-level decision making only; more site-specific opportunities will need to be explored in future work.

The results of the analysis point to a potential for expanded reuse of OPW for agriculture. In the southern Central Valley, Kern County contains at least 19 oil and gas fields where water quality and quantity indicate that there is potential for reuse, albeit likely with blending or treatment. Crops grown in this region vary in sensitivity to the chemical analytes evaluated, but some are relatively tolerant to common constituents found in OPW. Furthermore, water districts in the region may be amendable to partnering on delivery of OPW to places with demand, as evidenced by the four that already do.

Unfortunately, significant data gaps create challenges with understanding the certainty and strength of these findings. Data gaps identified included: Crop type and crop location, crop sensitivities based on irrigation types, OPW water quality (in amount of analytical samples, type of constituents included, and age of sample data), OPW water quantity estimates, location and capacity of infrastructure for transporting and storing OPW for reuse by irrigators, soil characteristics that impact water suitability, costs of alternatives and how these costs are expected to change in the future and/or vary under different scenarios such as drought, existing and predicted future regulatory barriers and hurdles, and sociological and political factors of key stakeholder groups. For data to be useful in decision-making related to OPW reuse for agriculture it must be transparent, geographically specific, temporally current, and of a sufficient quantity that findings can be replicated, and margins of error are small and known. Unfortunately, these qualities are not found in most of the data currently available for assessing the potential for OPW reuse in California at the regional scale. This is true both for the area of focus of this analysis, as well as more broadly for the state. While the methods section lists the major data gaps of this analysis, the results from the analysis further highlight these critical gaps.

The following section provides a set of basic recommendations for remedying these gaps to allow for more reliable outputs for a regional-scale analysis of opportunities for expanding OPW reuse for agriculture.

6.4.1 Recommendations

6.4.1.1 More water quality data of untreated produced water is needed in locations identified as having potential for agricultural reuse.

While imperfect, results from this analysis and others could be used to design a targeted sampling approach to improve and strengthen the dataset required for analyzing OPW suitability for irrigation. Samples to assess OPW quality for agricultural reuse should be taken from the source from which it will be delivered to the irrigation district/agricultural field. At some oil and gas fields, produced waters from multiple wells are combined before being disposed. Samples from these mixed locations may be more relevant and therefore should be evaluated, rather than samples from single wells. If water will be blended with other sources, the combined source should be evaluated as well.

6.4.1.2 Perform a cost-benefit analysis comparing alternative water supply options and their co-benefits

OPW may be one option for reducing water stress in a region, but other benefits and tradeoffs beyond the water supply opportunity should be quantified and fairly evaluated against other supply or demand management options.

6.4.1.3 Knowledge of location and capacity of water transfer and storage infrastructure.

Knowing locations of existing water transfer and storage infrastructure would greatly enhance the ability of regional decision makers to evaluate costs of expanding OPW reuse. It is recognized that this may be difficult due to privacy considerations.

CHAPTER 7

Conclusions

There are roughly 9 million acres of irrigated farmland in California, using approximately 30 million acre-feet of water per year (CDWR 2014). Regular, sustained drought, curtailment of groundwater withdrawals with SGMA, and other stressors constrain the quantity of supply available to support California's economic, environmental, and societal needs. The State Water Plan identified the use of alternative supplies as a critical strategy in meeting the State's water demand now and in the future. The use of municipal recycled water and oilfield produced water for agricultural irrigation were two strategies considered, compared, and contrasted in the body of this report.

Recycled water use in California has a long history dating back more than 100 years. Regulations on the use of recycled water for agricultural irrigation have evolved significantly over that same time period as our basic knowledge and societal understanding of topics such pathogens, treatment performance, demand for recycled water, and other topics have grown in truly extraordinary ways. That said, there are still notable knowledge gaps surrounding the use of recycled water and California's regulations require regular updates that incorporate gains in scientific knowledge, demand for new beneficial uses of recycled water, and other pertinent information. Using California's Title 22 Regulations on the use of recycled water for agricultural irrigation as a template, this report sought to examine OPW reuse through the lens of recycled water to identify opportunities and knowledge gaps associated with current OPW reuse, make recommendations on aligning with Title 22, and assess the potential for additional OPW reuse in California. The key findings from these assessments are discussed in the following text. Specific recommendations were incorporated into relevant sections of the previous chapters.

While the use of oilfield produced water for agricultural irrigation has been ongoing over the past several decades (SWRCB 2016), recent concerns initiated several California studies between 2016 and 2019 investigating the safe use irrigating crops intended for human consumption - the SB 1281 Study, conducted by CCST, and the Food Safety Project, conducted by the CVRWQCB, GSI Environmental, and reviewed by a Food Safety Expert Panel. These studies found that the chemical composition of OPW is complex and inconsistent, varying across geologic and geographical locations and over time (Mahoney, Asami, and Stringfellow 2021; Al-Ghouti et al. 2019). Typical OPW has elevated concentrations of salts, organic and inorganic contaminants, metals, naturally occurring radioactive elements, and chemical additives used in the production of oil and gas (Vengosh 2014; Stringfellow and Camarillo 2019; Mahoney, Asami, and Stringfellow 2021). Many factors affect the compositional makeup of OPW, such as geologic formations, chemicals used in O&G production, the stage of production, and the age of the well. Many of the chemicals used in oil and gas production and the masses of chemicals used were identified as proprietary which further limits public understanding.

Thus, predicting water quality and chemical composition of OPW in one location based on another location, even within the same field, is not necessarily achievable. Substantive gaps in data collection, reporting requirements, produced water composition and toxicity, treatment practices, and other knowledge gaps discussed in this, and other reports, are substantial barriers to evaluating exposure, health and agronomic risks, and long-term human and environmental impacts from OPW reuse in agriculture.

Risk-based approaches underpin California's current regulations on the use of recycled water for agricultural irrigation and other beneficial uses. California's Recycled Water Policy is updated and reviewed regularly to incorporate new scientific knowledge on topics such as constituents of emerging concern and advances in risk assessment modeling. This is a sharp contrast with OPW reuse where the basic information is generally lacking to be able to conduct comprehensive risk assessments of OPW reuse. One of the first human health risk assessments of OPW reuse, conducted by Redmon et al. (Redmon et al. 2021), looked at human health risks associated with trace metals in reused OPW in the Central Valley, but noted many of the same limitations identified in the CCST SB 1281 study. Additional research is needed to assess risks posed by the broad range of chemicals common in OPW, but sufficient data are lacking to conduct many of these assessments.

The second major knowledge gap relevant to developing a Title 22 aligned fit-for-purpose framework for produced water was an overall lack of information on treatment practices and performance for OPW. Treatment performance is a foundational component in California's recycled water regulations. Treatment processes and technologies used to produce recycled water have been rigorously evaluated to ensure they provide an appropriate level of treatment under real-world conditions. This information is then used in risk assessment models to ensure the regulations under Title 22 and water quality criteria are sufficiently protective of public health. Additional research is needed to understand the level of treatment being provided in OPW operations and ensure that this treatment is adequately protective of public health for key COIs.

The quantity of OPW available for reuse is another important knowledge gap. This assessment found that upwards of 227,650 AFY of produced water may be available for reuse, though only 100,177 AFY is available within fields where average TDS concentrations are below the maximum threshold of crop tolerance. Data used in this assessment are subject to the constraints noted above with additional research and data needed to accurately understand potential within individual fields. Nonetheless, for context, the volume of OPW potentially available for reuse is roughly equal to five to ten percent of the total volume of municipal treated wastewater potentially available for reuse (Cooley et al. 2022). That said, OPW reuse is currently occurring and making locally significant contributions to agricultural water supplies in Kern County. This underscores the need for locally specific assessments of both risks and broader cost-benefit analyses.

The knowledge gaps discussed in this report and other recent studies point to several key areas where additional research, data and monitoring, risk assessments, and other information are needed to develop a regulatory framework for OPW that mirrors the approach and best practices adopted in regulation of the use of recycled water for agricultural irrigation in California. At this time, current data and knowledge gaps combined with fundamental differences in the composition of produced water (relative to recycled water) limit the direct adoption and operationalization of many of the risk-based principles underpinning California's Title 22 recycled water regulations. Studies such as the CCST SB 1281 study and Food Safety Project provide important insights and recommendations on how to improve current monitoring programs. Increasing our understanding of current OPW reuse is an important first step in developing regulatory approaches that match the level of rigor and best practices adopted into the regulation of the reuse of municipal recycled water in California.

APPENDIX A

Characterization of Produced Water Quality in California from the CCST SB 1281 Study and the Food Safety Project.

Table A-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

Source: CCST 2019, Table A3.1.

Constituent	No. of Detections	Min	Med	Max	5th	25th	50th	75th	95th	Unit
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

Constituent	**No. of Detections**	**Min**	**Med**	**Max**	**5th**	**25th**	**50th**	**75th**	**95th**	**Unit**
Major and Minor Ions / Trace Elements										
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

Constituent	No. of Detections	Min	Med	Max	5th	25th	50th	75th	95th	Unit
Major and Minor Ions / Trace Elements										
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
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

Constituent	No. of Detections	Min	Med	Max	5th	25th	50th	75th	95th	Unit
Major and Minor Ions / Trace Elements										
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

Constituent	No. of Detections	Min	Med	Max	5th	25th	50th	75th	95th	Unit

RADIOACTIVITY INDICATORS										
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

Constituent	No. of Detections	Min	Med	Max	5th	25th	50th	75th	95th	Unit
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
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

Constituent	No. of Detections	Min	Med	Max	5th	25th	50th	75th	95th	Unit
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

Table A-2. Water Quality Data for Blended Produced Water and Frequency of Samples Exceeding the Water Quality Objectives.

Source: GSI 2021b, Table 8.

CASRN	Chemical Analyte	Screening Value Type	Total Number of Samples	Frequency of Detection	Minimum of Detected [mg/L]	Mean of Detected [mg/L]	Maximum of Detected [mg/L]	Fraction of Samples Exceeding Water Quality Objective Concentration Limit
7440-36-0	Antimony	MCL	54	0.44	0.0001	0.0014	0.011	0.019
7440-38-2	Arsenic	MCL	132	0.86	0.0002	0.014	0.065	0.53
7440-39-3	Barium	MCL	61	0.87	0.0043	0.031	0.2	0
7440-41-7	Beryllium	MCL	53	0.04	0.00028	0.003	0.0056	0.019
7440-42-8	Boron [individual samples]	WQO	252	0.97	0.02	0.48	2.2	0.012
7440-42-8	Boron [annual average]	WQO	50	1	0.11	0.55	2.2	0.04
7440-43-9	Cadmium	MCL	54	0.02	0.004	0.004	0.004	0
18540-29-9	Chromium (VI)	MCL	24	0.12	0.000035	0.000055	0.000072	0
7440-48-4	Cobalt	Toxicity	53	0.3	0.000092	0.0013	0.01	0
7440-50-8	Copper	MCL	54	0.74	0.00064	0.0089	0.087	0
16984-48-8	Fluoride	MCL	13	0.69	0.17	0.45	0.91	0
20461-54-5	Iodide	Toxicity	4	0	ND	ND	ND	ND

CASRN	Chemical Analyte	Screening Value Type	Total Number of Samples	Frequency of Detection	Minimum of Detected [mg/L]	Mean of Detected [mg/L]	Maximum of Detected [mg/L]	Fraction of Samples Exceeding Water Quality Objective Concentration Limit
7439-92-1	Lead	MCL	53	0.47	0.000096	0.00086	0.0044	0
7439-93-2	Lithium	Toxicity	49	0.61	0.0068	0.022	0.053	0
7439-96-5	Manganese	Toxicity	95	0.86	0.003	0.046	0.61	0
7439-97-6	Mercury (total, including organic compounds)	MCL	52	0.13	0.000001	0.000042	0.000095	0
7439-98-7	Molybdenum	Toxicity	54	0.76	0.00038	0.0032	0.012	0
7440-02-0	Nickel	MCL	54	0.67	0.00036	0.002	0.02	0
14797-65-0	Nitrite	MCL	5	0.4	0.8	9.9	19	0.2
7782-49-2	Selenium	MCL	55	0.38	0.00019	0.0011	0.0075	0
7440-22-4	Silver	Toxicity	54	0	ND	ND	ND	ND
7440-24-6	Strontium	Toxicity	52	0.87	0.018	0.13	0.46	0
7440-31-5	Tin	Toxicity	1	0	ND	ND	ND	ND
7440-62-2	Vanadium	Toxicity	52	0.46	0.00099	0.0032	0.01	0
7440-66-6	Zinc	Toxicity	55	0.62	0.0018	0.013	0.1	0

CASRN	Chemical Analyte	Screening Value Type	Total Number of Samples	Frequency of Detection	Minimum of Detected [mg/L]	Mean of Detected [mg/L]	Maximum of Detected [mg/L]	Fraction of Samples Exceeding Water Quality Objective Concentration Limit
123-91-1	1,4-Dioxane	Toxicity	9	0.22	0.00052	0.00075	0.00098	0
134-32-7	2-Naphthylamine	Toxicity	0	NA	NA	NA	NA	NA
83-32-9	Acenaphthene	Toxicity	61	0.15	0.00003	0.00015	0.00061	0
79-06-1	Acrylamide	Toxicity	4	0	ND	ND	ND	ND
62-53-3	Aniline	NA	10	0	ND	ND	ND	NA
120-12-7	Anthracene	Toxicity	60	0	ND	ND	ND	ND
56-55-3	Benz(a)anthracene	Toxicity	60	0.02	0.00003	0.00003	0.00003	0
50-32-8	Benzo(a)pyrene	MCL	60	0	ND	ND	ND	ND
205-99-2	Benzo(b)fluoranthene	Toxicity	60	0.02	0.00011	0.00011	0.00011	0
111-44-4	Bis(2-chloroethyl) ether	Toxicity	12	0	ND	ND	ND	ND
108-90-7	Chlorobenzene	MCL	69	0	ND	ND	ND	ND
218-01-9	Chrysene	Toxicity	60	0.03	0.000039	0.000041	0.000042	0
53-70-3	Dibenz(a,h)anthracene	Toxicity	59	0	ND	ND	ND	ND
206-44-0	Fluoranthene	Toxicity	74	0	ND	ND	ND	ND

CASRN	Chemical Analyte	Screening Value Type	Total Number of Samples	Frequency of Detection	Minimum of Detected [mg/L]	Mean of Detected [mg/L]	Maximum of Detected [mg/L]	Fraction of Samples Exceeding Water Quality Objective Concentration Limit
193-39-5	Indeno(1,2,3-c,d)pyrene	Toxicity	61	0.02	0.000091	0.000091	0.000091	0
85-01-8	Phenanthrene	NA	60	0.18	0.000029	0.00011	0.00029	NA
129-00-0	Pyrene	Toxicity	60	0.02	0.00004	0.00004	0.00004	0
8052-41-3	Stoddard Solvent	NA	1	1	0.025	0.025	0.025	NA
13983-27-2	Krypton 851	NA	4	0	ND	ND	ND	NA
---	Radioactivity, Gross Alpha	MCL	32	0.69	0.2	3.3	20	0.031
---	Radioactivity, Gross Beta	MCL	11	0.91	0.89	3.3	7.3	0
---	Radium-226 plus Radium-228 (calculated by lab)	MCL	3	1	0.63	1.1	1.5	0

CASRN	Chemical Analyte	Screening Value Type	Total Number of Samples	Frequency of Detection	Minimum of Detected [mg/L]	Mean of Detected [mg/L]	Maximum of Detected [mg/L]	Fraction of Samples Exceeding Water Quality Objective Concentration Limit
---	Radium-226 plus Radium-228 (calculated from individual measurements)	MCL	30	0.83	0.32	1.8	9.4	0.033
7440-14-4	Radium-2261	NA	30	0.73	0.12	1.2	9.2	NA
15262-20-1	Radium-2281	NA	30	0.63	0.12	1	4.7	NA
7440-61-1	Uranium1	MCL	41	0.54	0.0001	0.64	8.6	0

Table A-3. Comparison of Blended Produced Water and Treated Produced Water.

CASRN	Chemical Analyte	Organic / Inorganic / Radionuclide	Frequency of Detection -Treated Produced Water	Frequency of Detection -Blended Produced Water	Frequency of Detection Ratio (Treated Produced / Conventional) A	Mean of Detected Concentration [mg/L] - Treated Produced Water B	Mean of Detected Concentrations [mg/L] - Blended Produced Water	Mean Detected Concentrations Ratio (Treated Produced Water/ Blended Produced Water)
7440-36-0	Antimony	Inorganic	0.44	0.44	1.00	2.66E-03	1.36E-03	1.96
7440-38-2	Arsenic	Inorganic	0.89	0.86	1.03	3.69E-02	1.39E-02	2.67
7440-39-3	Barium	Inorganic	0.67	0.87	0.77	5.32E-02	3.12E-02	1.70
7440-41-7	Beryllium	Inorganic	0.03	0.04	0.75	8.65E-05	2.94E-03	0.03
7440-42-8	Boron [individual samples]	Inorganic	1	0.97	1.03	8.44E-01	4.79E-01	1.76
7440-42-8	Boron [annual average]	Inorganic	1	1	1.00	8.64E-01	5.47E-01	1.58
7440-43-9	Cadmium	Inorganic	0	0.02	0.00	ND	4.00E-03	ND in TPW
18540-29-9	Chromium (VI)	Inorganic	0.19	0.12	1.58	1.58E-03	5.50E-05	28.64
7440-48-4	Cobalt	Inorganic	0.05	0.3	0.17	1.33E-04	1.26E-03	0.11

Source: GSI 2021b, Table 9.

CASRN	Chemical Analyte	Organic / Inorganic / Radionuclide	Frequency of Detection -Treated Produced Water	Frequency of Detection -Blended Produced Water	Frequency of Detection Ratio (Treated Produced / Conventional) A	Mean of Detected Concentration [mg/L] - Treated Produced Water B	Mean of Detected Concentrations [mg/L] - Blended Produced Water	Mean Detected Concentrations Ratio (Treated Produced Water/ Blended Produced Water)
7440-50-8	Copper	Inorganic	0.4	0.74	0.54	1.61E-03	8.93E-03	0.18
16984-48-8	Fluoride	Inorganic	0.79	0.69	1.14	1.02E+00	4.52E-01	2.25
20461-54-5	Iodide	Inorganic	0.14	0	ND in BIW	2.10E-01	ND	ND in BIW
7439-92-1	Lead	Inorganic	0.05	0.47	0.11	2.13E-04	8.62E-04	0.25
7439-93-2	Lithium	Inorganic	0.67	0.61	1.10	4.98E-02	2.17E-02	2.29
7439-96-5	Manganese	Inorganic	0.88	0.86	1.02	1.92E+00	4.58E-02	41.84
7439-97-6	Mercury (total, including organic compounds)	Inorganic	0.3	0.13	2.31	1.62E-04	4.19E-05	3.87
7439-98-7	Molybdenum	Inorganic	0.65	0.76	0.86	6.91E-03	3.24E-03	2.13
7440-02-0	Nickel	Inorganic	0.46	0.67	0.69	9.07E-04	2.07E-03	0.44
14797-65-0	Nitrite	Inorganic	0.17	0.4	0.43	1.00E+00	9.90E+00	0.10
7782-49-2	Selenium	Inorganic	0.31	0.38	0.82	8.94E-04	1.11E-03	0.81

CASRN	Chemical Analyte	Organic / Inorganic / Radionuclide	Frequency of Detection -Treated Produced Water	Frequency of Detection -Blended Produced Water	Frequency of Detection Ratio (Treated Produced / Conventional) A	Mean of Detected Concentration [mg/L] - Treated Produced Water B	Mean of Detected Concentrations [mg/L] - Blended Produced Water	Mean Detected Concentrations Ratio (Treated Produced Water/ Blended Produced Water)
7440-22-4	Silver	Inorganic	0	0	ND	ND	ND	ND
7440-31-5	Tin	Inorganic	0	0	ND	ND	ND	ND
7440-62-2	Vanadium	Inorganic	0.06	0.46	0.13	1.97E-03	3.25E-03	0.61
7440-66-6	Zinc	Inorganic	0.48	0.62	0.77	9.68E-03	1.34E-02	0.72
123-91-1	1,4-Dioxane	Organic	0.55	0.22	2.50	1.30E-03	7.50E-04	1.73
134-32-7	2-Naphthylamine	Organic	0	NA	ND in TPW	ND	not measured	ND in TPW
83-32-9	Acenaphthene	Organic	0.35	0.15	2.33	5.79E-04	1.49E-04	3.89
79-06-1	Acrylamide	Organic	0	0	ND	ND	ND	ND
62-53-3	Aniline	Organic	0	0	ND	ND	ND	ND
120-12-7	Anthracene	Organic	0.03	0	ND in BIW	1.15E-04	ND	ND in BIW
56-55-3	Benz(a)anthracene	Organic	0.01	0.02	0.50	3.10E-05	3.00E-05	1.03

CASRN	Chemical Analyte	Organic / Inorganic / Radionuclide	Frequency of Detection -Treated Produced Water	Frequency of Detection -Blended Produced Water	Frequency of Detection Ratio (Treated Produced / Conventional) A	Mean of Detected Concentration [mg/L] - Treated Produced Water B	Mean of Detected Concentrations [mg/L] - Blended Produced Water	Mean Detected Concentrations Ratio (Treated Produced Water/ Blended Produced Water)
50-32-8	Benzo(a)pyrene	Organic	0	0	ND	ND	ND	ND
205-99-2	Benzo(b)fluoranthene	Organic	0.04	0.02	2.00	5.63E-05	1.10E-04	0.51
111-44-4	Bis(2-chloroethyl) ether	Organic	0	0	ND	ND	ND	ND
108-90-7	Chlorobenzene	Organic	0	0	ND	ND	ND	ND
218-01-9	Chrysene	Organic	0.1	0.03	3.33	1.07E-04	4.05E-05	2.65
53-70-3	Dibenz(a,h)anthracene	Organic	0	0	ND	ND	ND	ND
206-44-0	Fluoranthene	Organic	0.05	0	ND in BIW	6.03E-05	ND	ND in BIW
193-39-5	Indeno(1,2,3-c,d)pyrene	Organic	0	0.02	ND in TPW	ND	9.10E-05	ND in TPW
85-01-8	Phenanthrene	Organic	0.33	0.18	1.83	5.34E-04	1.06E-04	5.02
129-00-0	Pyrene	Organic	0.1	0.02	5.00	1.17E-04	4.00E-05	2.93

CASRN	Chemical Analyte	Organic / Inorganic / Radionuclide	Frequency of Detection -Treated Produced Water	Frequency of Detection -Blended Produced Water	Frequency of Detection Ratio (Treated Produced / Conventional) A	Mean of Detected Concentration [mg/L] - Treated Produced Water B	Mean of Detected Concentrations [mg/L] - Blended Produced Water	Mean Detected Concentrations Ratio (Treated Produced Water/ Blended Produced Water)
8052-41-3	Stoddard Solvent	Organic	1	1	1.00	6.00E-02	2.50E-02	2.40
13983-27-2	Krypton 85	Radionuclide	0	0	ND	ND	ND	ND
---	Radioactivity, Gross Alpha	Radionuclide	0.62	0.69	0.90	3.20E+00	3.30E+00	0.97
---	Radioactivity, Gross Beta	Radionuclide	0.84	0.91	0.92	4.80E+00	3.31E+00	1.45
---	Radium-226 plus Radium- 228 (calculated by lab)	Radionuclide	0.86	1	0.86	1.42E+00	1.09E+00	1.30
---	Radium-226 plus Radium- 228 (calculated from individual measurements)	Radionuclide	0.92	0.83	1.11	1.57E+00	1.75E+00	0.90

CASRN	Chemical Analyte	Organic / Inorganic / Radionuclide	Frequency of Detection -Treated Produced Water	Frequency of Detection -Blended Produced Water	Frequency of Detection Ratio (Treated Produced / Conventional) A	Mean of Detected Concentration [mg/L] - Treated Produced Water B	Mean of Detected Concentrations [mg/L] - Blended Produced Water	Mean Detected Concentrations Ratio (Treated Produced Water/ Blended Produced Water)
7440-14-4	Radium-226	Radionuclide	0.72	0.73	0.99	6.60E-01	1.20E+00	0.55
15262-20-1	Radium-228	Radionuclide	0.7	0.63	1.11	1.40E+00	1.00E+00	1.40
7440-61-1	Uranium	Radionuclide	0.11	0.54	0.20	2.70E+00	6.38E-01	4.23

[A] ND – Non-detect; ND in BIW – Non-detect in blended produced water; ND in TPW – Non-detect in treated produced water

[B] Radionuclides reported in units of pCi/L

APPENDIX B

Crop Tolerance Ratings and Yield Potential to Salinity, Salts, and Boron in Soils and Irrigation Water.

Table B-1. Key for Relative Crop Tolerance Ratings[1] for Salinity in Soil Root Zones (EC_e) and Irrigation Water (EC_w).

Data sources: Ayers and Westcot 1985 Table 5 and Figure 10, citing data from Maas 1984.

Crop Tolerance Ratings[A]		EC_e[B] (ds/m)	EC_w[C] (ds/m)
No Data	0		
Sensitive	1	< 1.3	< 0.87
Moderately Sensitive	2	1.3 – 3.0	0.87 - 2
Moderately Tolerant	3	3.0 – 6.0	2 - 4
Tolerant	4	6.0 – 10.0	4 – 6.7

Notes: Electrical Conductivity (EC) is reported in deciSiemens per meter (dS/m) at 25°C. The relationship between soil salinity and water salinity ($EC_e = 1.5\ EC_w$) assumes a 15–20 percent leaching fraction and a 40-30-20-10 percent water use pattern for the upper to lower quarters of the root zone.

[1] These data serve only as a guide to the relative tolerance among crops. Absolute tolerances vary with climate, soil conditions and cultural practices.

[A] The relative tolerance ratings are defined by the boundaries in Ayers & Westcot 1985, Figure 10.

[B] Soil salinity (EC_e) at which yield loss begins. EC_e means average root zone salinity as measured by electrical conductivity of the saturation extract of the soil.

[C] Salinity of irrigation water (EC_w) at which yield loss begins.

Table B-2. Key for Relative Crop Tolerance Ratings to Boron in Soil-Water or Saturation Extract (B_e) Without Yield Reductions.

Data sources: Ayers and Westcot 1985 Table 16, citing data from Maas 1984.

Crop Tolerance Ratings [A]		B_e (mg/L)
Extremely sensitive	1	<0.5
Very sensitive	2	0.5 - 0.75
Sensitive	3	0.75 - 1
Moderately sensitive	4	1 - 2
Moderately tolerant	5	2 - 4
Tolerant	6	4 - 6
Very tolerant	7	6 - 15

[A] Maximum concentration in the irrigation water are approximately equal to these values or slightly less.

Table B-3. Crop Tolerance Ratings and Yield Potential Based on Irrigation Water Salinity (EC_w), Soil Salinity (EC_e), and Boron Concentrations (B_e) of Select Crops Grown in the Central Valley California.

Sources: Based on Maas 1984; Ayers & Westcot 1985 Tables 4, 5, and 16, and Figure 10; Crop data from California Statewide Crop Mapping Data (2018).

Crop	Boron Tolerance Rating A (Be)	Salinity Tolerance Rating B (ECw)	100% yield C ECe (ds/m)	100% yield D ECw (ds/m)	75% yield E ECw (ds/m)
Alfalfa & alfalfa mixtures	6	2	2	1.3	3.6
Almonds	-	1	1.5	1	1.9
Apples	-	1	-	-	-
Apricots	2	1	1.6	1.1	1.8
Artichokes	3	3	-	-	-

Crop	Boron Tolerance Rating A (Be)	Salinity Tolerance Rating B (ECw)	100% yield C ECe (ds/m)	100% yield D ECw (ds/m)	75% yield E ECw (ds/m)
Asian leafy vegetables (brassicaceae)	-	2	1.8	1.2	2.9
Asparagus	7	4	-	-	-
Avocados	2	1	-	-	-
Barley[1]	3	4	8	5.3	8.7
Beans (dry) (Phaseolus vulgaris)	3	1	1	0.7	1.5
Beans (green) (Phaseolus vulgaris)	-	1	1	0.7	1.5
Bermuda grass[3]	-	4	6.9	4.6	7.2
Blueberries	-	0	-	-	-
Brussels sprouts	-	2	-	-	-
Bush berries[4]	1	1	-	-	-
Cabbage	5	2	1.8	1.2	2.9
Carrots	4	1	1	0.7	1.9
Castor beans	-	2	-	-	-
Cauliflower	-	2	-	-	-
Celery	5	2	1.8	1.2	3.9
Cherries	2	1	-	-	-
Clover	5	3	1.5	1	3.9
Cole crops (mixture of 22 25) (Brassicaceae)	-	2	0.9	0.6	2.5
Corn (field & sweet)	-	2	1.7	1.1	2.5

Crop	Boron Tolerance Rating A (Be)	Salinity Tolerance Rating B (ECw)	100% yield C ECe (ds/m)	100% yield D ECw (ds/m)	75% yield E ECw (ds/m)
Cotton	7	4	7.7	5.1	8.4
Dates	-	4	4	2.7	7.3
Figs	2	3	-	-	-
Flax	-	2	1.7	1.1	2.5
Grain sorghum	-	3	6.8	4.5	5.6
Grapefruit	2	1	1.8	1.2	2.2
Greenhouse	-	0	-	-	-
Greenhouse	-	0	-	-	-
Hops (Humulus lupulus)	-	0	-	-	-
Hybrid sorghum/sudan	-	3	-	-	-
Induced high water table native pasture	-	0	-	-	-
Jojoba	-	4		-	-
Kiwis	-	0	-	-	-
Klein grass (Panicum coloratum)	-	0	-	-	-
Lemons	1	1	-	-	-
Lettuce (all types)	5	2	1.3	0.9	2.1
Lettuce or Leafy Greens grouped for remote sensing only	5	2	1.3	0.9	2.1
Melons, squash, and cucumbers (all types)[5]	4	2	2.5	1.7	2.9
Millet	-	2	-	-	-

Crop	Boron Tolerance Rating A (Be)	Salinity Tolerance Rating B (ECw)	100% yield C ECe (ds/m)	100% yield D ECw (ds/m)	75% yield E ECw (ds/m)
Miscellaneous deciduous	-	0	-	-	-
Miscellaneous field	-	0	-	-	-
Miscellaneous grain and hay	-	0	-	-	-
Miscellaneous grasses (tolerances 1, 2, & 3)	-	4	-	-	-
Miscellaneous subtropical fruit (jujube, papaya, pineapple)	-	3	-	-	-
Miscellaneous truck	-	0	-	-	-
Mixed (four or more)	-	0	-	-	-
Mixed deciduous	-	0	-	-	-
Mixed grain and hay	-	0	-	-	-
Mixed pasture	-	0	-	-	-
Mixed subtropical fruits	-	3		-	-
Oats (avena sativa)	5	3	-	-	-
Olives	-	3	-	-	-
Onions & garlic[6]	2	1	1.2	0.8	1.8
Oranges	2	1	1.7	1.1	2.2
Peaches and nectarines	2	1	1.7	1.1	1.9
Pears	-	1	-	-	-
Peas (pisum sativum)	4	0	-	-	-
Peppers (chili, bell etc.)[7]	4	2	1.5	1	2.2

Crop	Boron Tolerance Rating A (Be)	Salinity Tolerance Rating B (ECw)	100% yield C ECe (ds/m)	100% yield D ECw (ds/m)	75% yield E ECw (ds/m)
Pistachios	-	0	-	-	-
Plums	2	1	1.5	1	1.9
Plums Prunes or Apricots grouped for remote sensing only	-	1	1.5	1	1.9
Pomegranates	-	3	-	-	-
Potato or Sweet potato grouped for remote sensing only.	3	2	1.5	1	2.5
Potatoes	4	2	1.7	1.1	
Prunes	-	1	1.5	1	1.9
Rice (Oryza sativa)	-	2	3	2	3.4
Rye grass (perenial - Lolium perenne)	-	3	5.6	3.7	5.9
Safflower	-	3	-	-	-
Spinach	-	2	2	1.3	3.5
Strawberries	3	1	1	0.7	2.4
Sudan	-	3	2.8	1.9	5.7
Sugar beets	6	4	7	4.7	7.5
Sugar cane	-	2	1.7	1.1	4
Sunflowers	3	0	-	-	-
Sweet potatoes	3	2	1.5	1	2.5
Tomatoes (market)	6	2	2.5	1.7	3.4
Tomatoes (processing)	6	2	2.5	1.7	3.4

Crop	Boron Tolerance Rating A (Be)	Salinity Tolerance Rating B (ECw)	100% yield C ECe (ds/m)	100% yield D ECw (ds/m)	75% yield E ECw (ds/m)
Turf farms	-	0	-	-	-
Walnuts	2	0	-	-	-
Wheat1,2 (Triticum aestivum)	3	3	6	4	6.3
Wild Rice (Zizania)	-	4	-	-	-
Broccoli	-	2	2.8	1.9	3.7
Corn Sorghum or Sudan grouped for remote sensing only[8]	6	3	-	-	5.6
Eucalyptus	-	0		-	-
Flowers nursery & Christmas tree farms	-	0	-	-	-
Native pasture	-	0	-	-	-
Raisin grapes[9]	2	2	1.5	1	2.7
Table grapes[9]	2	2	1.5	1	2.7
Wine grapes[9]	2	2	1.5	1	2.7

Be = Boron concentration in soils (mg/L); ECe = Electrical Conductivity of soils; ECw = Electrical Conductivity of irrigation water; ds/m = deciSiemens per meter at 25°C.

[A] Crop tolerance rating for concentrations of boron in soils (Be) without yield reductions. Maximum concentrations in the irrigation water (ECw) are approximately equal to these values or slightly less. Ratings taken from Chapter 6.

[B] Crop tolerance rating for salinity (ECw) in irrigation water without yield reductions. Ratings taken from Chapter 6.

[C] Maximum salinity concentration in root zone of soil where no yield loss occurs.

[D] Maximum salinity concentration in irrigation water where no yield loss occurs.

[E] Maximum salinity concentration in irrigation water where a 75% yield loss occurs.

[1] Barley and wheat are less tolerant during germination and seeding stage; ECe should not exceed 4–5 dS/m in the upper soil during this period.

[2] Semi-dwarf, short cultivars may be less tolerant.

[3] Tolerance given is an average for Boer, Wilman, Sand and Weeping Lovegrass; Lehman Lovegrass seems about 50 percent more tolerant.

[4] Crop tolerance to boron based on blackberries only

[5] Crop tolerance to boron based on cucumbers only

[6] Crop tolerance to boron based on onions; garlic tolerance to boron is "3" which is more tolerant but because here they are listed together, the lowest tolerance was selected

[7] Crop tolerance to boron based on red pepper (Capsicum annuum)

[8] Crop tolerance to boron based on sorghum (Sorghum bicolor)

[9] Crop tolerance to boron based on grapes (Vitis vinifera)

References

Abraham, Sonali, Laura Feinstein, and Eliza Czolowski. 2021. "Chapter 1: Direct Assessment of the SB 1281 Dataset." California Council on Science and Technology.

Alegbeleye, Oluwadara O, and Anderson S Sant'Ana. 2021. "Risks Associated with the Consumption of Irrigation Water Contaminated Produce: On the Role of Quantitative Microbial Risk Assessment." Current Opinion in Food Science 41 (October): 88–98. https://doi.org/10.1016/j.cofs.2021.03.013.

*Al-Ghouti, Mohammad A., Maryam A. Al-Kaabi, Mohammad Y. Ashfaq, and Dana Adel Da'na. 2019. "Produced Water Characteristics, Treatment and Reuse: A Review." *Journal of Water Process Engineering* 28 (April): 222–39. https://doi.org/10.1016/j.jwpe.2019.02.001.

Alloway, Brian J., Andrew P. Jackson, and Hilary Morgan. 1990. "The Accumulation of Cadmium by Vegetables Grown on Soils Contaminated from a Variety of Sources." *Science of The Total Environment* 91 (February): 223–36. https://doi.org/10.1016/0048-9697(90)90300-J.

Alshatwi, Ali A., Tarique N. Hasan, Ali M. Alqahtani, Naveed A. Syed, Gowhar Shafi, Abdullah H. Al-Assaf, and Abdulrahmann S. Al-Khalifa. 2014. "Delineating the Anti-Cytotoxic and Anti-Genotoxic Potentials of Catechin Hydrate against Cadmium Toxicity in Human Peripheral Blood Lymphocytes." *Environmental Toxicology and Pharmacology* 38 (2): 653–62. https://doi.org/10.1016/j.etap.2014.07.013.

American Chemical Society. n.d. "CAS REGISTRY and CAS Registry Number FAQs." CAS. Accessed July 31, 2022. https://www.cas.org/support/documentation/chemical-substances/faqs.

Antoniadis, V., E. Levizou, Sabry M. Shaheen, Y. S. Ok, A. Sebastian, C. Baum, M.N.V. Prasad, W. W. Wenzel, and J. Rinklebe. 2017. "Trace Elements in the Soil-Plant Interface: Phytoavailability, Translocation, and Phytoremediation–A Review." *Earth-Science Reviews* 171 (August): 621–45. https://doi.org/10.1016/j.earscirev.2017.06.005.

Arizona Leafy Greens Marketing Agreement (AZLGMA). 2021. "Commodity Specific Food Safety Guidelines for the Production and Harvest of Lettuce and Leafy Greens." https://283b5790-0f10-43d8-a0fe-cbdf892578b5.filesusr.com/ugd/cdf4b0_00a96ec5bbcd4975b7e4236145659920.pdf.

Asano, Takashi, Franklin Burton, Harold Leverenz, Ryujiro Tsuchihashi, and George Tchobanoglous. 2007. *Water Reuse : Issues, Technologies, and Applications: Issues, Technologies, and Applications*. McGraw Hill Professional.

ATSDR. 2021a. "Arsenic | Toxic Substances | Toxic Substance Portal | ATSDR." 2021. https://wwwn.cdc.gov/TSP/substances/ToxSubstance.aspx?toxid=3.

———. 2021b. "Cadmium | Toxic Substances | Toxic Substance Portal | ATSDR." 2021. https://wwwn.cdc.gov/TSP/substances/ToxSubstance.aspx?toxid=15.

Ayers, R.S., and D.W. Westcot. 1985. *Water Quality for Agriculture*. Rome: Organization of the United Nations. https://www.fao.org/3/T0234e/T0234E00.htm.

Basafa, Mahsan, and Kelly Hawboldt. 2019. "Reservoir Souring: Sulfur Chemistry in Offshore Oil and Gas Reservoir Fluids." *Journal of Petroleum Exploration and Production Technology* 9 (2): 1105–18. https://doi.org/10.1007/s13202-018-0528-2.

Borneman, J, P W Skroch, K M O'Sullivan, J A Palus, N G Rumjanek, J L Jansen, J Nienhuis, and E W Triplett. 1996. "Molecular Microbial Diversity of an Agricultural Soil in Wisconsin." *Applied and Environmental Microbiology* 62 (6): 1935–43. https://doi.org/10.1128/aem.62.6.1935-1943.1996.

Brdar-Jokanović, M. 2020. "Boron Toxicity and Deficiency in Agricultural Plants." *International Journal of Molecular Sciences* 21 (4): 1424. https://doi.org/10.3390/ijms21041424.

Brussaard, L., P. C. de Ruiter, and G. G. Brown. 2007. "Soil Biodiversity for Agricultural Sustainability." *Agriculture, Ecosystems & Environment* 121 (3): 233–44. https://doi.org/10.1016/j.agee.2006.12.013.

Burkhardt, Andy, Archana Gawde, Charles L. Cantrell, Holly L. Baxter, Blake L. Joyce, C. Neal Stewart, and Valtcho D. Zheljazkov. 2015. "Effects of Produced Water on Soil Characteristics, Plant Biomass, and Secondary Metabolites." *Journal of Environmental Quality* 44 (6): 1938–47. https://doi.org/10.2134/jeq2015.06.0299.

Division of Oil, Gas, and Geothermal Resources (DOGGR). 2018. "Underground Injection Control Program Report On Permitting and Program Assessment January 25, 2018."

California Council on Science & Technology (CCST). 2018. "An Assessment of Oil and Gas Water Cycle Reporting in California: Preliminary Evaluation of Data Collected Pursuant to California Senate Bill 1281, Phase I."

———. 2019. "An Assessment of Oil and Gas Water Cycle Reporting in California Evaluation of Data Collected Pursuant to California Senate Bill 1281, Phase II Report." Sacramento, CA: California Council on Science and Technology.

California Council on Science & Technology (CCST), and Lawrence Berkeley National Laboratory (LBNL). 2015. "An Independent Scientific Assessment of Well Stimulation in California, Volume I: Well Stimulation Technologies and Their Past, Present, and Potential Future Use in California. Vol. I." Sacramento, California: California Council on Science and Technology and Lawrence Berkeley National Laboratory. https://ccst.us/wp-content/uploads/160708-sb4-vol-I.pdf.

California Department of Conservation, Geologic Energy Management Division (CalGEM). 2018a. "Data Dictionary for Water Report Form: Water Produced from, or Used in, Oil and Gas Fields." https://www.conservation.ca.gov/calgem/SB%201281/Documents/SB1281_DataDictionary-2018.pdf.

———. 2018b. "Well Stimulation Treatment Disclosure." 2018. https://www.conservation.ca.gov/calgem/Pages/WellStimulationTreatmentDisclosure.aspx.

———. 2022. "Oil and Gas Field Administrative Boundaries." Shapefile. California Department of Conservation, Geologic Energy Management Division. https://data.ca.gov/dataset/oil-and-gas-field-administrative-boundaries1.

California Department of Water Resources (CDWR). 2014. "California Water Plan, Update 2013. Volume 1, The Strategic Plan." Sacramento, CA: California Department of Water Resources. https://cawaterlibrary.net/wp-content/uploads/2017/05/CWP-Update-2013-Volume-1-Strategic-Plan.pdf.

———. 2018. "I15 Crop Mapping 2018." California Open Data. 2018. https://data.ca.gov/dataset/i15-crop-mapping-2018.

———. 2022. “I08 B118 SGMA 2019 Basin Prioritization.” California Natural Resources Agency. https://data.ca.gov/dataset/i08-b118-sgma-2019-basin-prioritization.

California Leafy Greens Marketing Agreement (CALGMA). 2021. “Commodity Specific Food Safety Guidelines for the Production and Harvest of Lettuce and Leafy Greens.” 2021. https://lgmatech.com/wp-content/uploads/2020/08/Current-version_August-2021-CA-LGMA-Metrics_FINAL-v20210818-clean-1262021.pdf.

Camarillo, Mary Kay, Jeremy K. Domen, and William T. Stringfellow. 2016. “Physical-Chemical Evaluation of Hydraulic Fracturing Chemicals in the Context of Produced Water Treatment.” *Journal of Environmental Management* 183 (December): 164–74. https://doi.org/10.1016/j.jenvman.2016.08.065.

Camarillo, Mary Kay, and William T Stringfellow. 2018. “Biological Treatment of Oil and Gas Produced Water: A Review and Meta-Analysis.” *Clean Technologies and Environmental Policy* 20 (6): 1127–46. https://doi.org/10.1007/s10098-018-1564-9.

Central Valley Regional Water Quality Control Board (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.” Central Valley Regional Water Quality Control Board (CVRWQCB). https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/#Discharge.

———. 2019b. “Order R5-2019-0043, Waste Discharge Requirements for Hathaway, LLC, Kern-Tulare Water District, and Jasmin Ranchos Mutual Water Company.” Central Valley Regional Water Quality Control Board (CVRWQCB). https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/#Discharge.

———. n.d. “Adopted / Issued Orders | Central Valley Regional Water Quality Control Board.” Accessed July 31, 2022. https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/#Discharge.

Clark, C. E., and J. A. Veil. 2009. “Produced Water Volumes and Management Practices in the United States.” ANL/EVS/R-09-1. Argonne National Lab. (ANL), Argonne, IL (United States). https://doi.org/10.2172/1007397.

Colborn, Theo, Carol Kwiatkowski, Kim Schultz, and Mary Bachran. 2011. “Natural Gas Operations from a Public Health Perspective.” *Human and Ecological Risk Assessment: An International Journal* 17 (5): 1039–56. https://doi.org/10.1080/10807039.2011.605662.

Cooley, Heather. 2020. “Urban and Agricultural Use in California, 1960-2015.” Oakland, CA: Pacific Institute. https://pacinst.org/wp-content/uploads/2020/06/PI_Water_Use_Trends_June_2020.pdf.

Cooley, Heather, Kristina Donnelly, Rapichan Phurisamban, and Madhyama Subramanian. 2015. “Impacts of California’s Ongoing Drought: Agriculture.” Oakland, CA: Pacific Institute.

Cooley, Heather, Anne Thebo, Sonali Abraham, Morgan Shimabuku, Peter Gleick, and Sarah Diringer. 2022. “The Untapped Potential of California’s Urban Water Supply: Water Efficiency, Water Reuse, and Stormwater Capture.” Oakland, CA: Pacific Institute. https://pacinst.org/publication/california-urban-water-supply-potential-2022/.

Cooper, Carolyn M., James McCall, Sean C. Stokes, Cameron McKay, Matthew J. Bentley, James S. Rosenblum, Tamzin A. Blewett, et al. 2022. “Oil and Gas Produced Water Reuse: Opportunities, Treatment Needs, and Challenges.” *ACS ES&T Engineering* 2 (3): 347–66. https://doi.org/10.1021/acsestengg.1c00248.

Corwin, D. L., and K. Yemoto. 2020. “Salinity: Electrical Conductivity and Total Dissolved Solids.” *Soil Science Society of America Journal* 84 (5): 1442–61. https://doi.org/10.1002/saj2.20154.

Crosby, L.M., Calin A. Tatu, Matthew Varonka, Kaylene M. Charles, and William H. Orem. 2018. “Toxicological and Chemical Studies of Wastewater from Hydraulic Fracture and Conventional Shale Gas Wells.” *Environmental Toxicology and Chemistry* 37 (8): 2098–2111. https://doi.org/10.1002/etc.4146.

Danforth, Cloelle, Weihsueh A. Chiu, Ivan Rusyn, Kim Schultz, Ashley Bolden, Carol Kwiatkowski, and Elena Craft. 2020. “An Integrative Method for Identification and Prioritization of Constituents of Concern in Produced Water from Onshore Oil and Gas Extraction.” *Environment International* 134 (January): 105280. https://doi.org/10.1016/j.envint.2019.105280.

Davis, Gray. 2001. “Guidelines for the Preparation of an Engineering Report for the Production, Distribution and Use of Recycled Water.” Department of Health Services. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/recharge/ERGUIDE2001.pdf.

Davis, T.A., J.T. Kulongoski, and P.B. McMahon. 2016. “Produced Water Chemistry Data for Samples from Four Petroleum Wells, Southern San Joaquin Valley, California.” U.S. Geological Survey. https://www.sciencebase.gov/catalog/item/57a50c48e4b0ebae89b6d87f.

Debroux, Jean-François, Jeffrey A. Soller, Megan H. Plumlee, and Laura J. Kennedy. 2012. “Human Health Risk Assessment of Non-Regulated Xenobiotics in Recycled Water: A Review.” *Human and Ecological Risk Assessment: An International Journal* 18 (3): 517–46. https://doi.org/10.1080/10807039.2012.672883.

Department of Energy (DOE). n.d. “Enhanced Oil Recovery.” Energy.Gov. Accessed May 22, 2022. https://www.energy.gov/fecm/science-innovation/oil-gas-research/enhanced-oil-recovery.

Dettenmaier, Erik M., William J. Doucette, and Bruce Bugbee. 2009. “Chemical Hydrophobicity and Uptake by Plant Roots.” Research-article. ACS Publications. American Chemical Society. World. 2009. https://doi.org/10.1021/es801751x.

Ding, Shen, Chaofeng Ma, Wenguang Shi, Wenzhe Liu, Yan Lu, Qifeng Liu, and Zhi-Bin Luo. 2017. “Exogenous Glutathione Enhances Cadmium Accumulation and Alleviates Its Toxicity in Populus × Canescens.” *Tree Physiology* 37 (12): 1697–1712. https://doi.org/10.1093/treephys/tpx132.

Division of Oil, Gas, and Geothermal Resources (DOGGR). 1996. *A Study of NORM Associated with Oil and Gas Production Operations in California*. Sacramento, Calif.: Dept. of Conservation, Division of Oil, Gas, and Geothermal Resources.

———. 2018. “Production and Injection (Quarterly Dataset).” Geologic Energy Management Division. https://www.conservation.ca.gov/calgem/for_operators/Pages/WellSTAR.aspx.

Dodgen, L.K., J. Li, D. Parker, and J.J. Gan. 2013. “Uptake and Accumulation of Four PPCP/EDCs in Two Leafy Vegetables.” *Environmental Pollution* 182 (November): 150–56. https://doi.org/10.1016/j.envpol.2013.06.038.

Doucette, William J., Chubashini Shunthirasingham, Erik M. Dettenmaier, Rosemary T. Zaleski, Peter Fantke, and Jon A. Arnot. 2018. “A Review of Measured Bioaccumulation Data on Terrestrial Plants for Organic Chemicals: Metrics, Variability, and the Need for Standardized Measurement Protocols.” *Environmental Toxicology and Chemistry* 37 (1): 21–33. https://doi.org/10.1002/etc.3992.

Dupuy, Joan, Pierre Leglize, Quentin Vincent, Ivan Zelko, Christian Mustin, Stéphanie Ouvrard, and Thibault Sterckeman. 2016. “Effect and Localization of Phenanthrene in Maize Roots.” Chemosphere 149 (April): 130–36. https://doi.org/10.1016/j.chemosphere.2016.01.102.

Echchelh, Alban, Tim Hess, and Ruben Sakrabani. 2018. “Reusing Oil and Gas Produced Water for Irrigation of Food Crops in Drylands.” Agricultural Water Management 206 (July): 124–34. https://doi.org/10.1016/j.agwat.2018.05.006.

Emamverdian, Abolghassem, Yulong Ding, Farzad Mokhberdoran, and Yinfeng Xie. 2015. “Heavy Metal Stress and Some Mechanisms of Plant Defense Response.” The Scientific World Journal 2015: 1–18. https://doi.org/10.1155/2015/756120.

European Commission. 2012. Toxicity and Assessment of Chemical Mixtures. LU: Publications Office. https://data.europa.eu/doi/10.2772/21444.

Evangelou, M.W.H., H. Daghan, and A. Schaeffer. 2004. “The Influence of Humic Acids on the Phytoextraction of Cadmium from Soil.” Chemosphere 57 (3): 207–13. https://doi.org/10.1016/j.chemosphere.2004.06.017.

Feinstein, Laura, Seth B.C. Shonkoff, and Brie Lindsey. 2021. “An Assessment of Oil and Gas Water Cycle Reporting in California Evaluation of Data Collected Pursuant to California Senate Bill 1281, Phase II Report.” Sacramento, CA: California Council on Science and Technology.

Fipps, G. 2021. “Irrigation Water Quality Standards and Salinity Management Strategies,” 11.

Gannon, R.S., J.F. Saraceno, J.T. Kulongoski, J.A. Teunis, P.H. Barry, R.L. Tyne, and S.L. Qi. 2018. “Produced Water Chemistry Data for the Lost Hills, Fruitvale, and North and South Belridge Study Areas, Southern San Joaquin Valley, California.” U.S. Geological Survey data release. https://doi.org/10.5066/F7X929H9.

Gans, Kathleen D., Loren F. Metzger, Janice M. Gillespie, and Sharon L. Qi. 2018. “Historical Produced Water Chemistry Data Compiled for the Fruitvale Oilfield, Kern County, California.” U.S. Geological Survey. https://doi.org/10.5066/F72B8X8G.

Gao, Feng, Yike Shen, J. Brett Sallach, Hui Li, Wei Zhang, Yuanbo Li, and Cun Liu. 2022. “Predicting Crop Root Concentration Factors of Organic Contaminants with Machine Learning Models.” Journal of Hazardous Materials 424 (February): 127437. https://doi.org/10.1016/j.jhazmat.2021.127437.

Garner, Emily, Marisa Organiscak, Lucien Dieter, Carley Shingleton, Madison Haddix, Sayalee Joshi, Amy Pruden, Nicholas J. Ashbolt, Gertjan Medema, and Kerry A. Hamilton. 2021. “Towards Risk Assessment for Antibiotic Resistant Pathogens in Recycled Water: A Systematic Review and Summary of Research Needs.” Environmental Microbiology 23 (12): 7355–72. https://doi.org/10.1111/1462-2920.15804.

Garner, Emily, Ni Zhu, Laurel Strom, Marc Edwards, and Amy Pruden. 2016. “A Human Exposome Framework for Guiding Risk Management and Holistic Assessment of Recycled Water Quality.” Environmental Science: Water Research & Technology 2 (4): 580–98. https://doi.org/10.1039/C6EW00031B.

Gillespie, J.M., D. Kong, and S. Anderson,. 2016. “Appendix 3. Oil and Gas Well Chemical Database.” California: Division of Oil, Gas and Geothermal Resources.

Gonzales-Gustavson, Eloy, Marta Rusiñol, Gertjan Medema, Miquel Calvo, and Rosina Girones. 2019. “Quantitative Risk Assessment of Norovirus and Adenovirus for the Use of Reclaimed Water to Irrigate Lettuce in Catalonia.” Water Research 153 (April): 91–99. https://doi.org/10.1016/j.watres.2018.12.070.

Grant, C.A., J.M. Clarke, S. Duguid, and R.L. Chaney. 2008. “Selection and Breeding of Plant Cultivars to Minimize Cadmium Accumulation.” Science of The Total Environment 390 (2–3): 301–10. https://doi.org/10.1016/j.scitotenv.2007.10.038.

Gray, Madeleine. 2020. “Reuse of Produced Water in the Oil and Gas Industry.” In Day 2 Tue, July 28, 2020, D021S004R001. Virtual: SPE. https://doi.org/10.2118/199498-MS.

GSI. 2020. “Identification of Chemicals of Interest Related to the Reuse of Produced Waters for Agricultural Irrigation of Edible Crops.” No. 4874. Fresno, California.: Central Valley Regional Water Quality Control Board. https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/data/white_paper/task1_report_final.pdf.

———. 2021a. “Comparison of Chemical Analyses Between Crops Irrigated with Produced Water and Crops Irrigated with Traditional Water Sources.” No. 4874. Fresno, California: Central Valley Regional Water Quality Control Board. https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/data/white_paper/finaltask3rpt.pdf.

———. 2021b. “Literature Review of Chemicals of Interest Related to the Reuse of Produced Waters for Agricultural Irrigation of Edible Crops.” No. 4874. Fresno, California: Central Valley Regional Water Quality Control Board. https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/data/white_paper/task2_report.pdf.

Gupta, D. K., S. Chatterjee, S. Datta, A. V. Voronina, and C. Walther. 2016. “Radionuclides: Accumulation and Transport in Plants.” In Reviews of Environmental Contamination and Toxicology Volume 241, edited by Pim de Voogt, 241:139–60. Reviews of Environmental Contamination and Toxicology. Cham: Springer International Publishing. https://doi.org/10.1007/398_2016_7.

Hamilton, Andrew J., Frank Stagnitti, Robert Premier, Anne-Maree Boland, and Glenn Hale. 2006. “Quantitative Microbial Risk Assessment Models for Consumption of Raw Vegetables Irrigated with Reclaimed Water.” Applied and Environmental Microbiology 72 (5): 3284–90. https://doi.org/10.1128/AEM.72.5.3284-3290.2006.

Hart Energy. n.d. “Conventional, Unconventional Drilling Go Hand In Hand.” Accessed May 22, 2022. https://www.hartenergy.com/opinions/conventional-unconventional-drilling-go-hand-hand-122267.

Hasanuzzaman, Mirza, Kamrun Nahar, Khalid Rehman Hakeem, Münir Öztürk, and Masayuki Fujita. 2015. “Arsenic Toxicity in Plants and Possible Remediation.” In Soil Remediation and Plants, 433–501. Elsevier. https://doi.org/10.1016/B978-0-12-799937-1.00016-4.

Heberger, Matthew, and Kristina Donnelly. 2015. Oil, Food, and Water: Challenges and Opportunities for California Agriculture. Oakland, California: Pacific Institute. http://pacinst.org/publication/oil-food-and-water-challenges-and-opportunities-for-california-agriculture/.

Hirayama, Akihiko, Masaki Maegaito, Masato Kawaguchi, Akira Ishikawa, Mark Sueyoshi, Ali Soud Al-Bemani, Ahmed Mushtaque, et al. 2002. “Omani Oil Fields Produced Water: Treatment and Utilization.” In . OnePetro. https://doi.org/10.2118/74413-MS.

Howitt, Richard, Duncan MacEwan, Josué Medellín-Azuara, Jay Lund, and Daniel Sumner. 2015. “Economic Analysis of the 2015 Drought For California Agriculture.” Davis, CA: UC Davis, Center for Watershed Sciences.

Hu, Lei, Wenbin Jiang, Xuesong Xu, Huiyao Wang, Kenneth C. Carroll, Pei Xu, and Yanyan Zhang. 2022. “Toxicological Characterization of Produced Water from the Permian Basin.” Science of The Total Environment 815 (April): 152943. https://doi.org/10.1016/j.scitotenv.2022.152943.

Huelster, Anke., Jochen F. Mueller, and Horst. Marschner. 1994. “Soil-Plant Transfer of Polychlorinated Dibenzo-p-Dioxins and Dibenzofurans to Vegetables of the Cucumber Family (Cucurbitaceae).” Environmental Science & Technology 28 (6): 1110–15. https://doi.org/10.1021/es00055a021.

Hull, Natalie M., James S. Rosenblum, Charles E. Robertson, J. Kirk Harris, and Karl G. Linden. 2018. “Succession of Toxicity and Microbiota in Hydraulic Fracturing Flowback and Produced Water in the Denver–Julesburg Basin.” Science of The Total Environment 644 (December): 183–92. https://doi.org/10.1016/j.scitotenv.2018.06.067.

Ibekwe, A.M., J.A. Poss, S.R. Grattan, C.M. Grieve, and D. Suarez. 2010. “Bacterial Diversity in Cucumber (Cucumis Sativus) Rhizosphere in Response to Salinity, Soil PH, and Boron.” Soil Biology and Biochemistry 42 (4): 567–75. https://doi.org/10.1016/j.soilbio.2009.11.033.

Inui, Hideyuki, Taketo Wakai, Keiko Gion, Yun-Seok Kim, and Heesoo Eun. 2008. “Differential Uptake for Dioxin-like Compounds by Zucchini Subspecies.” Chemosphere 73 (10): 1602–7. https://doi.org/10.1016/j.chemosphere.2008.08.013.

IPIECA. 2020. “Reuse of Produced Water from the Onshore Oil and Gas Industry: Evaluating Opportunities and Challenges.”

Irfan, Mohd, Shamsul Hayat, Aqil Ahmad, and Mohammed Nasser Alyemeni. 2013. “Soil Cadmium Enrichment: Allocation and Plant Physiological Manifestations.” Saudi Journal of Biological Sciences 20 (1): 1–10. https://doi.org/10.1016/j.sjbs.2012.11.004.

Israel, Andrei L., Gabrielle Wong-Parodi, Thomas Webler, and Paul C. Stern. 2015. “Eliciting Public Concerns about an Emerging Energy Technology: The Case of Unconventional Shale Gas Development in the United States.” Energy Research & Social Science 8 (July): 139–50. https://doi.org/10.1016/j.erss.2015.05.002.

Jackson, Robert B., Avner Vengosh, J. William Carey, Richard J. Davies, Thomas H. Darrah, Francis O’Sullivan, and Gabrielle Pétron. 2014. “The Environmental Costs and Benefits of Fracking.” Annual

Review of Environment and Resources 39 (1): 327–62. https://doi.org/10.1146/annurev-environ-031113-144051.

Jiménez, S., M.M. Micó, M. Arnaldos, F. Medina, and S. Contreras. 2018. “State of the Art of Produced Water Treatment.” Chemosphere 192 (February): 186–208. https://doi.org/10.1016/j.chemosphere.2017.10.139.

Johnston, Christopher R., George F. Vance, and Girisha K. Ganjegunte. 2008. “Irrigation with Coalbed Natural Gas Co-Produced Water.” Agricultural Water Management 95 (11): 1243–52. https://doi.org/10.1016/j.agwat.2008.04.015.

Kalac, P, M Niznanskiib, D Bevilaqua, and I Staiikova. 1996. “Concentrations of Mercury, Copper, Cadmium and Lead in Fruiting Bodies of Edible Mushrooms in the Vicinity of a Mercury Smelter and a Copper Smelter,” 8.

Kassotis, Christopher D, Susan C Nagel, and Heather M Stapleton. 2018. “Unconventional Oil and Gas Chemicals and Wastewater-Impacted Water Samples Promote Adipogenesis via PPARγ-Dependent and Independent Mechanisms in 3T3-L1 Cells.” Science of the Total Environment, 10.

Kassotis, Christopher D., Donald E. Tillitt, J. Wade Davis, Annette M. Hormann, and Susan C. Nagel. 2014. “Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region.” Endocrinology 155 (3): 897–907. https://doi.org/10.1210/en.2013-1697.

Kim, J., H. Hyung, M. Wilf, J.-S. Park, and J. Brown. 2009. “Boron Rejection by Reverse Osmosis Membranes: National Reconnaissance and Mechanism Study.” 127. Desalination and Water Purification Research and Development Program. US Department of the Interior, Bureau of Reclamation. https://www.usbr.gov/research/dwpr/reportpdfs/report127.pdf.

Kondash, Andrew J, Jennifer Hoponick Redmon, Elisabetta Lambertini, Laura Feinstein, Erika Weinthal, Luis Cabrales, and Avner Vengosh. 2020. “The Impact of Using Low-Saline Oilfield Produced Water for Irrigation on Water and Soil Quality in California.” Science of The Total Environment 733 (September): 139392. https://doi.org/10.1016/j.scitotenv.2020.139392.

Land IQ. 2018. “I15_Crop_Mapping_2018 Metadata.” California Department of Water Resources. https://data.ca.gov/dataset/i15-crop-mapping-2018.

Lee, Wen-Yee, William A. Iannucci-Berger, Brian D. Eitzer, Jason C. White, and MaryJane Incorvia Mattina. 2003. “Plant Uptake and Translocation of Air-Borne Chlordane and Comparison with the Soil-to-Plant Route.” Chemosphere 53 (2): 111–21. https://doi.org/10.1016/S0045-6535(03)00353-9.

Lin, Xiaohu, Jingcheng Xu, Arturo A. Keller, Li He, Yunhui Gu, Weiwei Zheng, Danyan Sun, et al. 2020. “Occurrence and Risk Assessment of Emerging Contaminants in a Water Reclamation and Ecological Reuse Project.” Science of The Total Environment 744 (November): 140977. https://doi.org/10.1016/j.scitotenv.2020.140977.

Lund, Jay, Josue Medellin-Azuara, John Durand, and Kathleen Stone. 2018. “Lessons from California’s 2012–2016 Drought.” Journal of Water Resources Planning and Management 144 (10): 04018067. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000984.

Maas, E.V. 1984. “Salt Tolerance of Plants.” In Handbook of Plant Science in Agriculture, B.R. Christie, ed. Cleveland, OH: CRC Press, Inc.

Maas, Eugene V., and Glenn J. Hoffman. "Crop salt tolerance—current assessment." Journal of the irrigation and drainage division 103, no. 2 (1977): 115-134.

Mahoney, J.G., R.T. Asami, and W.T. Stringfellow. 2021. “Food Safety Project White Paper On the Reuse of Oil Field Produced Water for Irrigation of Food Crops In Central Kern County, California.” White Paper.

Malchi, Tomer, Yehoshua Maor, Galit Tadmor, Moshe Shenker, and Benny Chefetz. 2014. “Irrigation of Root Vegetables with Treated Wastewater: Evaluating Uptake of Pharmaceuticals and the Associated Human Health Risks.” Environmental Science & Technology 48 (16): 9325–33. https://doi.org/10.1021/es5017894.

Martel-Valles, Fernando, Adalberto Benavides-Mendoza, Rosalinda Mendoza-Villarreal, Alejandro Zermeño-González, and Antonio Juárez-Maldonado. 2014. “Agronomic Use of Produced Water in Tomato Plants (Lycopersicon Esculentum L.) under Greenhouse Conditions,” 14.

Martel-Valles, José Fernando, Adalberto Benavides-Mendoza, Luis Alonso Valdez-Aguilar, Antonio Juárez-Maldonado, and Norma Angélica Ruiz-Torres. 2013. “Effect of the Application of Produced Water on the Growth, the Concentration of Minerals and Toxic Compounds in Tomato under Greenhouse.” Journal of Environmental Protection 04 (07): 138–46. https://doi.org/10.4236/jep.2013.47A016.

Mattina, Mary Jane Incorvia, William Iannucci-Berger, and Laure Dykas. 2000. “Chlordane Uptake and Its Translocation in Food Crops.” Journal of Agricultural and Food Chemistry 48 (5): 1909–15. https://doi.org/10.1021/jf990566a.

McLaughlin, Molly C., Jens Blotevogel, Ruth A. Watson, Baylee Schell, Tamzin A. Blewett, Erik J. Folkerts, Greg G. Goss, et al. 2020. “Mutagenicity Assessment Downstream of Oil and Gas Produced Water Discharges Intended for Agricultural Beneficial Reuse.” Science of The Total Environment 715 (May): 136944. https://doi.org/10.1016/j.scitotenv.2020.136944.

McLaughlin, Molly C., Thomas Borch, and Jens Blotevogel. 2016. “Spills of Hydraulic Fracturing Chemicals on Agricultural Topsoil: Biodegradation, Sorption, and Co-Contaminant Interactions.” Environmental Science & Technology 50 (11): 6071–78. https://doi.org/10.1021/acs.est.6b00240.

McMahon, Peter B., Justin T. Kulongoski, Avner Vengosh, Isabelle M. Cozzarelli, Matthew K. Landon, Yousif K. Kharaka, Janice M. Gillespie, and Tracy A. Davis. 2018. “Regional Patterns in the Geochemistry of Oil-Field Water, Southern San Joaquin Valley, California, USA.” Applied Geochemistry 98 (November): 127–40. https://doi.org/10.1016/j.apgeochem.2018.09.015.

Metcalf, and Eddy. 2003. Wastewater Engineering: Treatment and Reuse. 4th ed. McGraw Hill McGraw Hill Series in Civil and Environmental Engineering. New York: McGraw-Hill.

Metzger, L.F., T.A. Davis, M. Peterson, C. Brilmyer, and J. Johnson,. 2018. “Petroleum Well Data Used for Preliminary Regional Groundwater Salinity Mapping near Selected Oil Fields in Central and Southern California.” U.S. Geological Survey. https://doi.org/10.5066/F7RN373C.

Miller, Hannah, Pankaj Trivedi, Yuheng Qiu, Erin M. Sedlacko, Christopher P. Higgins, and Thomas Borch. 2019. “Food Crop Irrigation with Oilfield-Produced Water Suppresses Plant Immune Response.”

Environmental Science & Technology Letters 6 (11): 656–61. https://doi.org/10.1021/acs.estlett.9b00539.

Mroczek, E., P. Konieczny, T. Kleiber, and A. Waśkiewicz. 2014. “Response of Hydroponically Grown Head Lettuce on Residual Monomer from Polyacrylamide.” Food Additives & Contaminants: Part A 31 (8): 1399–1405. https://doi.org/10.1080/19440049.2014.926401.

Nagel, S.C., C.D. Kassotis, L.N. Vandenberg, B.P. Lawrence, J. Robert, and V.D. Balise. 2020. “Developmental Exposure to a Mixture of Unconventional Oil and Gas Chemicals: A Review of Experimental Effects on Adult Health, Behavior, and Disease.” Molecular and Cellular Endocrinology 513 (August): 110722. https://doi.org/10.1016/j.mce.2020.110722.

Nashikkar, V.J. 1993. “Effect of Reuse of High-BOD Wastewaters for Crop Irrigation on Soil Nitrification.” Environment International 19 (1): 63–69. https://doi.org/10.1016/0160-4120(93)90007-5.

National Drought Mitigation Center. n.d. “California.” U.S. Drought Monitor. Accessed May 26, 2022. https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?CA.

National Research Council (NRC). 2008. Desalination: A National Perspective. Washington, D.C.: The National Academies Press. https://doi.org/10.17226/12184.

National Toxicology Program (NTP). 2001. “National Toxicology Program’s Report of the Endocrine Disruptors Low-Dose Peer Review.” https://ntp.niehs.nih.gov/ntp/pressctr/mtgs_wkshps/2000/lowdosepeerfinalrpt.pdf.

Nelson, Darryl R., and Pauline M. Mele. 2007. “Subtle Changes in Rhizosphere Microbial Community Structure in Response to Increased Boron and Sodium Chloride Concentrations.” Soil Biology and Biochemistry 39 (1): 340–51. https://doi.org/10.1016/j.soilbio.2006.08.004.

Oetjen, Karl, Kevin E. Chan, Kristoffer Gulmark, Jan H. Christensen, Jens Blotevogel, Thomas Borch, John R. Spear, Tzahi Y. Cath, and Christopher P. Higgins. 2018. “Temporal Characterization and Statistical Analysis of Flowback and Produced Waters and Their Potential for Reuse.” Science of The Total Environment 619–620 (April): 654–64. https://doi.org/10.1016/j.scitotenv.2017.11.078.

Olivieri, Adam W., Brian Pecson, James Crook, and Robert Hultquist. 2020. “California Water Reuse—Past, Present and Future Perspectives.” In Advances in Chemical Pollution, Environmental Management and Protection, 5:65–111. Elsevier. https://doi.org/10.1016/bs.apmp.2020.07.002.

Olivieri, Adam W., Edmund Seto, Robert C. Cooper, Michael D. Cahn, John Colford, James Crook, Jean-François Debroux, et al. 2014. “Risk-Based Review of California’s Water-Recycling Criteria for Agricultural Irrigation.” Journal of Environmental Engineering 140 (6): 04014015. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000833.

Payne, Madeleine E., Heather F. Chapman, Janet Cumming, and Frederic D. L. Leusch. 2015. “In Vitro Cytotoxicity Assessment of a Hydraulic Fracturing Fluid.” Environmental Chemistry 12 (3): 286. https://doi.org/10.1071/EN14010.

Paz, Anat, Galit Tadmor, Tomer Malchi, Jens Blotevogel, Thomas Borch, Tamara Polubesova, and Benny Chefetz. 2016. “Fate of Carbamazepine, Its Metabolites, and Lamotrigine in Soils Irrigated with Reclaimed Wastewater: Sorption, Leaching and Plant Uptake.” Chemosphere 160 (October): 22–29. https://doi.org/10.1016/j.chemosphere.2016.06.048.

Pichtel, John. 2016. “Oil and Gas Production Wastewater: Soil Contamination and Pollution Prevention.” Applied and Environmental Soil Science 2016: 1–24. https://doi.org/10.1155/2016/2707989.

Rafati Rahimzadeh, Mehrdad, Mehravar Rafati Rahimzadeh, Sohrab Kazemi, and Ali-akbar Moghadamnia. 2017. “Cadmium Toxicity and Treatment: An Update.” Caspian Journal of Internal Medicine 8 (3): 135–45. https://doi.org/10.22088/cjim.8.3.135.

Redmon, Jennifer Hoponick, Andrew John Kondash, Donna Womack, Ted Lillys, Laura Feinstein, Luis Cabrales, Erika Weinthal, and Avner Vengosh. 2021. “Is Food Irrigated with Oilfield-Produced Water in the California Central Valley Safe to Eat? A Probabilistic Human Health Risk Assessment Evaluating Trace Metals Exposure.” Risk Analysis 41 (8): 1463–77. https://doi.org/10.1111/risa.13641.

Rhoades, J. D., A. Kandiah, and A. M. Mashali. 1992. The Use of Saline Waters for Crop Production. FAO Irrigation and Drainage Paper 48. Rome: Food and Agriculture Organization of the United Nations.

Riyazuddin, Riyazuddin, Nisha Nisha, Bushra Ejaz, M. Iqbal R. Khan, Manu Kumar, Pramod W. Ramteke, and Ravi Gupta. 2021. “A Comprehensive Review on the Heavy Metal Toxicity and Sequestration in Plants.” Biomolecules 12 (1): 43. https://doi.org/10.3390/biom12010043.

Rogers, Elizabeth E., David J. Eide, and Mary Lou Guerinot. 2000. “Altered Selectivity in an Arabidopsis Metal Transporter.” Proceedings of the National Academy of Sciences 97 (22): 12356–60. https://doi.org/10.1073/pnas.210214197.

Rosenblum, James, Andrew W. Nelson, Bridger Ruyle, Michael K. Schultz, Joseph N. Ryan, and Karl G. Linden. 2017. “Temporal Characterization of Flowback and Produced Water Quality from a Hydraulically Fractured Oil and Gas Well.” Science of The Total Environment 596–597 (October): 369–77. https://doi.org/10.1016/j.scitotenv.2017.03.294.

Saito, Takashi, Takashi Otani, Nobuyasu Seike, Hirotatsu Murano, and Masanori Okazaki. 2011. “Suppressive Effect of Soil Application of Carbonaceous Adsorbents on Dieldrin Uptake by Cucumber Fruits.” Soil Science and Plant Nutrition 57 (1): 157–66. https://doi.org/10.1080/00380768.2010.551281.

Salehi-Lisar, Seyed Yahya, and Somayeh Deljoo. 2015. “The Physiological Effect of Fluorene on Triticum Aestivum , Medicago Sativa , and Helianthus Annus.” Edited by Manuel Tejada Moral. Cogent Food & Agriculture 1 (1): 1020189. https://doi.org/10.1080/23311932.2015.1020189.

Santos, Inês C., Zacariah L. Hildenbrand, and Kevin A. Schug. 2019. “A Review of Analytical Methods for Characterizing the Potential Environmental Impacts of Unconventional Oil and Gas Development.” *Analytical Chemistry* 91 (1): 689–703. https://doi.org/10.1021/acs.analchem.8b04750.

Scanlon, Bridget R., Robert C. Reedy, Pei Xu, Mark Engle, J. P. Nicot, David Yoxtheimer, Qian Yang, and Svetlana Ikonnikova. 2020. “Can We Beneficially Reuse Produced Water from Oil and Gas Extraction in the U.S.?” *Science of The Total Environment* 717 (May): 137085. https://doi.org/10.1016/j.scitotenv.2020.137085.

Sedlacko, Erin M., Courtney E. Jahn, Adam L. Heuberger, Nathan M. Sindt, Hannah M. Miller, Thomas Borch, Andrea C. Blaine, Tzahi Y. Cath, and Christopher P. Higgins. 2019. “Potential for Beneficial Reuse of Oil and Gas–Derived Produced Water in Agriculture: Physiological and Morphological Responses in Spring Wheat (Triticum Aestivum).” *Environmental Toxicology and Chemistry* 38 (8): 1756–69. https://doi.org/10.1002/etc.4449.

Shariq, Linsey. 2013. “Uncertainties Associated with the Reuse of Treated Hydraulic Fracturing Wastewater for Crop Irrigation.” *Environmental Science & Technology* 47 (6): 2435–36. https://doi.org/10.1021/es4002983.

———. 2016. “Impacts of Irrigating Wheat Plants with Hydraulic Fracturing Chemicals on the Uptake of Toxic Metals, Nutrient Physiology, and Plant Morphology.”

———. 2019. “Health Risks Associated With Arsenic and Cadmium Uptake in Wheat Grain Irrigated With Simulated Hydraulic Fracturing Flowback Water.” *Journal of Environmental Health* 81 (6): 9.

Shariq, Linsey, Molly C. McLaughlin, Rachelle A. Rehberg, Hannah Miller, Jens Blotevogel, and Thomas Borch. 2021. “Irrigation of Wheat with Select Hydraulic Fracturing Chemicals: Evaluating Plant Uptake and Growth Impacts.” *Environmental Pollution* 273 (March): 116402. https://doi.org/10.1016/j.envpol.2020.116402.

Sheikh, Bahman, Robin P. Cort, William R. Kirkpatrick, Robert S. Jaques, and Takashi Asano. 1990. “Monterey Wastewater Reclamation Study for Agriculture.” *Research Journal of the Water Pollution Control Federation* 62 (3): 216–26. https://www.jstor.org/stable/25043824.

Sheikh, Bahman, Kara Nelson, Anne Thebo, Brent Haddad, Ted Gardner, Jim Kelly, Avner Adin, Ryujiro Tsuchihashi, Shannon Spurlock, and Naoyuki Funamizu. 2019. *Agricultural Use of Recycled Water: Impediments and Incentives.* Alexandria, VA: Water Research Foundation.

Shi, Qingyang, Yaxin Xiong, Parminder Kaur, Nathan Darlucio Sy, and Jay Gan. 2022. “Contaminants of Emerging Concerns in Recycled Water: Fate and Risks in Agroecosystems.” *Science of The Total Environment* 814 (March): 152527. https://doi.org/10.1016/j.scitotenv.2021.152527.

Shimabuku, Morgan, Sonali Abraham, and Laura Feinstein. 2019. “Reuse of Produced Water for Irrigation.” In *An Assessment of Oil and Gas Water Cycle Reporting in California Evaluation of Data Collected Pursuant to California Senate Bill 1281, Phase II Report*, 69–106. Sacramento, CA: California Council on Science and Technology.

Shoushtarian, Farshid, and Masoud Negahban-Azar. 2020. “Worldwide Regulations and Guidelines for Agricultural Water Reuse: A Critical Review.” *Water* 12 (4): 971. https://doi.org/10.3390/w12040971.

Sintim, Henry Y., Valtcho D. Zheljazkov, Michael E. Foley, and Roque L. Evangelista. 2017. “Coal-Bed Methane Water: Effects on Soil Properties and Camelina Productivity.” *Journal of Environmental Quality* 46 (3): 641–48. https://doi.org/10.2134/jeq2016.10.0403.

Soares, Micaela A.R., Margarida J. Quina, and Rosa M. Quinta-Ferreira. 2015. “Immobilisation of Lead and Zinc in Contaminated Soil Using Compost Derived from Industrial Eggshell.” *Journal of Environmental Management* 164 (December): 137–45. https://doi.org/10.1016/j.jenvman.2015.08.042.

Somtrakoon, K., and W. Chouychai. 2013. “Phytotoxicity of Single and Combined Polycyclic Aromatic Hydrocarbons toward Economic Crops.” *Russian Journal of Plant Physiology* 60 (1): 139–48. https://doi.org/10.1134/S1021443712060155.

Sousa, Adervan Fernandes, Lindbergue Araújo Crisostomo, Olmar Baller Weber, Maria Eugenia Ortiz Escobar, and Teógenes Senna De Oliveira. 2016. “Nutrient Content in Sunflowers Irrigated with Oil Exploration Water.” *Revista Caatinga* 29 (1): 94–100. https://doi.org/10.1590/1983-21252016v29n111rc.

State Water Resources Control Board (SWRCB). 2014. “Alternative Treatment Technology Report for Recycled Water.” Sacramento, CA: State Water Resources Control Board. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/dwdocuments/Alternative%20Treatment%20Technology%20Report%20for%20RW%2009_2014.pdf.

———. 2016. “Frequently Asked Questions About Recycled Oilfield Water for Crop Irrigation.” https://www.waterboards.ca.gov/publications_forms/publications/factsheets/docs/prod_water_for_crop_irrigation.pdf.

———. 2018. “Water Quality Control Policy for Recycled Water.” Sacramento, CA: State Water Resources Control Board. https://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2018/121118_7_final_amendment_oal.pdf.

———. 2021. “Volumetric Annual Report of Wastewater and Recycled Water -.” California Open Data. 2021. https://data.ca.gov/dataset/volumetric-annual-report-of-wastewater-and-recycled-water.

———. 2022. “NPDES - Pretreatment Program | California State Water Resources Control Board.” May 2022. https://www.waterboards.ca.gov/water_issues/programs/npdes/pretreat.html.

Steele, Marina, and Joseph Odumeru. 2004. “Irrigation Water as Source of Foodborne Pathogens on Fruit and Vegetables.” *Journal of Food Protection* 67 (12): 2839–49. https://doi.org/10.4315/0362-028X-67.12.2839.

Stephenson, M. T. 1992. “A Survey of Produced Water Studies.” In *Produced Water: Technological/Environmental Issues and Solutions*, edited by James P. Ray and F. Rainer Engelhardt, 1–11. Environmental Science Research. Boston, MA: Springer US. https://doi.org/10.1007/978-1-4615-2902-6_1.

Stine, Scott W., Inhong Song, Christopher Y. Choi, and Charles P. Gerba. 2005. “Application of Microbial Risk Assessment to the Development of Standards for Enteric Pathogens in Water Used To Irrigate Fresh Produce.” *Journal of Food Protection* 68 (5): 913–18. https://doi.org/10.4315/0362-028X-68.5.913.

Stringfellow, William T., and Mary Kay Camarillo. 2019. “Flowback Verses First-Flush: New Information on the Geochemistry of Produced Water from Mandatory Reporting.” *Environmental Science: Processes & Impacts* 21 (2): 370–83. https://doi.org/10.1039/C8EM00351C.

Stringfellow, William T., Mary Kay Camarillo, Jeremy K. Domen, and Seth B. C. Shonkoff. 2017. “Comparison of Chemical-Use between Hydraulic Fracturing, Acidizing, and Routine Oil and Gas Development.” *PLOS ONE* 12 (4): e0175344. https://doi.org/10.1371/journal.pone.0175344.

Swain, Daniel, Baird Langenbrunner, David Neelin, and Alex Hall. 2018. “Increasing Precipitation Volatility in Twenty-First-Century California.” *Nature Climate Change*, March. https://www.nature.com/articles/s41558-018-0140-y.

Taariq-Sidibe, Aminah, Murray B. McBride, Karl J. Czymmek, Joshua A. Putman, Paul E. Cerosalett, and Auirine Ketterings. 2020. “Agronomy Fact Sheet Series: Copper (Cu),” no. 113. http://nmsp.cals.cornell.edu/publications/factsheets/factsheet113.pdf.

Tao, Yuqiang, Shuzhen Zhang, Yong-guan Zhu, and Peter Christie. 2009. “Uptake and Acropetal Translocation of Polycyclic Aromatic Hydrocarbons by Wheat (Triticum Aestivum L.) Grown in Field-

Contaminated Soil." *Environmental Science & Technology* 43 (10): 3556–60. https://doi.org/10.1021/es803368y.

Tasker, T. L., W. D. Burgos, P. Piotrowski, L. Castillo-Meza, T. A. Blewett, K. B. Ganow, A. Stallworth, et al. 2018. "Environmental and Human Health Impacts of Spreading Oil and Gas Wastewater on Roads." *Environmental Science & Technology* 52 (12): 7081–91. https://doi.org/10.1021/acs.est.8b00716.

Termine Group. n.d. "What Is Flowback, and How Does It Differ from Produced Water?" Accessed May 22, 2022. https://www.termine.com/archives/494.

University of California Committee of Consultants. 1974. "Guidelines for Interpretation of Water Quality for Agriculture." http://s3-us-west-2.amazonaws.com/ucldc-nuxeo-ref-media/283f3d2c-2665-4f5f-a0f6-ad01a6b79ee6

University of California, Division of Agriculture and Natural Resources. n.d. "Salinity Measurement and Unit Conversion." n.d. https://ucanr.edu/sites/Salinity/Salinity_ Management/Salinity_Basics/Salinity_measurement_and_unit_conversions/.

US Department of Agriculture (USDA). 2018a. "2018 Irrigation and Water Management Survey." AC-17-SS-1.

———. 2018b. "Farms Using Recycled or Reclaimed Water: 2018 and 2013." https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris_1_0006_0006.pdf.

US Environmental Protection Agency (EPA). 2005. "Guidelines for Carcinogen Risk Assessment." EPA/630/P-03/001F. Washington, D.C.

———. 2012. "2012 Guidelines for Water Reuse."

———. 2014. "Human Health Risk Assessment." Collections and Lists. July 21, 2014. https://www.epa.gov/risk/human-health-risk-assessment.

———. 2015. "Compilation of Physicochemical and Toxicological Information About Hydraulic Fracturing-Related Chemicals (Draft Database)." Reports & Assessments. 2015. https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=308341.

———. 2016. "Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States - Executive Summary." EPA-600-R-16-236ES.

———. 2019. "Study of Oil and Gas Extraction Wastewater Management Under the Clean Water Act." EPA- 821-R19-001. Washington, D.C.: Engineering and Analysis Division, Office of Water. https://www.epa.gov/sites/default/files/2019-05/documents/oil-and-gas-study_draft_05-2019.pdf.

———. n.d. "What Are Total Petroleum Hydrocarbons (TPH)?" Overviews & Factsheets. Accessed July 30, 2022. https://www3.epa.gov/region1/eco/uep/tph.html.

US Geological Survey (USGS). 2018. "2017 Updates of the National Produced Waters Geochemical Database and Map Viewer." https://energy.usgs.gov/GeneralInfo/EnergyNewsroomAll/TabId/770/ArtMID/3941/ArticleID/1353/2017-Updates-of-the-National-Produced-Waters-Geochemical-Database-andMap-Viewer.aspx.

Vadakattu, G., E. Leonard, and S.M. Neate. 1998. *Life in the Soil: The Relationship between Agriculture and Soil Organisms*. Vol. 7. https://linkinghub.elsevier.com/retrieve/pii/S096098229770976X.

Vance, George F., Lyle A. King, and Girisha K. Ganjegunte. 2008. “Soil and Plant Responses from Land Application of Saline-Sodic Waters: Implications of Management.” *Journal of Environmental Quality* 37 (S5): S-139-S-148. https://doi.org/10.2134/jeq2007.0442.

*Veil, J A, M G Puder, D Elcock, and Redweik, R. J., Jr. 2004. “A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane.” ANL/EA/RP-112631, 821666. https://doi.org/10.2172/821666.

Vengosh, A. 2014. “Salinization and Saline Environments.” In *Treatise on Geochemistry*, 325–78. Elsevier. https://doi.org/10.1016/B978-0-08-095975-7.00909-8.

*Weber, S., S. Khan, and J. Hollender. 2006. “Human Risk Assessment of Organic Contaminants in Reclaimed Wastewater Used for Irrigation.” *Desalination*, Integrated Concepts in Water Recycling, 187 (1): 53–64. https://doi.org/10.1016/j.desal.2005.04.067.

White, Jason C. 2001. “Plant-Facilitated Mobilization and Translocation of Weathered 2,2-Bis(*p* -Chlorophenyl)-1,1-Dichloroethylene(*p,P′* -DDE) from an Agricultural Soil.” *Environmental Toxicology and Chemistry* 20 (9): 2047–52. https://doi.org/10.1002/etc.5620200925.

White, Jason C., Xiaoping Wang, Martin P. N. Gent, William Iannucci-Berger, Brian D. Eitzer, Neil P. Schultes, Michele Arienzo, and Mattina. 2003. “Subspecies-Level Variation in the Phytoextraction of Weathered *p,p′* -DDE by *Cucurbita Pepo*.” *Environmental Science & Technology* 37 (19): 4368–73. https://doi.org/10.1021/es034357p.

Williams, Gordon J., Bahman Sheikh, Robert B. Holden, Tom J. Kouretas, and Kara L. Nelson. 2007. “The Impact of Increased Loading Rate on Granular Media, Rapid Depth Filtration of Wastewater.” *Water Research* 41 (19): 4535–45. https://doi.org/10.1016/j.watres.2007.06.018.

Wu, Jilei, Chaosheng Zhang, Lijun Pei, Gong Chen, and Xiaoying Zheng. 2014. “Association between Risk of Birth Defects Occurring Level and Arsenic Concentrations in Soils of Lvliang, Shanxi Province of China.” *Environmental Pollution* 191 (August): 1–7. https://doi.org/10.1016/j.envpol.2014.04.004.

Wu, L., W. Chen, C. French, and A. Chang. 2009. *Safe Application of Reclaimed Water Reuse in the Southwestern United States*. University of California, Agriculture and Natural Resources. https://doi.org/10.3733/ucanr.8357.

Yan, Shiwei, Fan Wu, Song Zhou, Jianhao Yang, Xianjin Tang, and Wenling Ye. 2021. “Zinc Oxide Nanoparticles Alleviate the Arsenic Toxicity and Decrease the Accumulation of Arsenic in Rice (Oryza Sativa L.).” *BMC Plant Biology* 21 (1): 150. https://doi.org/10.1186/s12870-021-02929-3.

Yau, Sui Kwong, and John Ryan. 2008. “Boron Toxicity Tolerance in Crops: A Viable Alternative to Soil Amelioration.” Crop Science 48 (3): 854–65. https://doi.org/10.2135/cropsci2007.10.0539.

Zhang, Shichao, Hong Yao, Yintao Lu, Xiaohua Yu, Jing Wang, Shaobin Sun, Mingli Liu, Desheng Li, Yi-Fan Li, and Dayi Zhang. 2017. “Uptake and Translocation of Polycyclic Aromatic Hydrocarbons (PAHs) and Heavy Metals by Maize from Soil Irrigated with Wastewater.” Scientific Reports 7 (1): 12165. https://doi.org/10.1038/s41598-017-12437-w.

Zhao, Fang-Jie, Jacqueline L. Stroud, Tristan Eagling, Sarah J. Dunham, Steve P. McGrath, and Peter R. Shewry. 2010. "Accumulation, Distribution, and Speciation of Arsenic in Wheat Grain." Environmental Science & Technology 44 (14): 5464–68. https://doi.org/10.1021/es100765g.

Zoeller, R. Thomas, T. R. Brown, L. L. Doan, A. C. Gore, N. E. Skakkebaek, A. M. Soto, T. J. Woodruff, and F. S. Vom Saal. 2012. "Endocrine-Disrupting Chemicals and Public Health Protection: A Statement of Principles from The Endocrine Society." Endocrinology 153 (9): 4097–4110. https://doi.org/10.1210/en.2012-1422.

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