# An Independent Scientific Assessment of Well Stimulation in California

## Summary Report

### An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry

July 2015

CCST
CALIFORNIA COUNCIL ON SCIENCE & TECHNOLOGY

BERKELEY LAB
Lawrence Berkeley National Laboratory

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## An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry


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*July 2015*

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in the Oil and Gas Industry.

**About CCST**

CCST is a non-profit organization established in 1988 at the request of the California State Government and sponsored by the major public and private postsecondary institutions of California and affiliate federal laboratories in conjunction with leading private-sector firms. CCST's mission is to improve science and technology policy and application in California by proposing programs, conducting analyses, and recommending public policies and initiatives that will maintain California's technological leadership and a vigorous economy.

**Note**



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# Acronyms and Abbreviations

| | |
|---|---|
| CARB | California Air Resources Board |
| CASRN | Chemical Abstracts Service Registry Number |
| CCST | California Council on Science and Technology |
| CVRWQCB | Central Valley Regional Water Quality Control Board |
| DFE | (EPA) Designed for the Environment |
| DOGGR | (California) Division of Oil, Gas, and Geothermal Resources |
| EOR | Enhanced Oil Recovery |
| FOIA | Federal Freedom of Information Act |
| GHG | Greenhouse Gas |
| GHS | Globally Harmonized System of Classification and Labeling of Chemicals |
| HCl | Hydrochloric Acid |
| HF | Hydrofluoric Acid |
| HVHF | “High-volume” Hydraulic Fracturing |
| LBNL | Lawrence Berkeley National Laboratory |
| LLNL | Lawrence Livermore National Laboratory |
| $m^3$ | Cubic Meters |
| NAS | National Academies of Science |
| NIOSH | National Institute for Occupational Safety and Health |
| NPDES | National Pollutant Discharge Elimination System |
| OEHHA | Office of Environmental Health Hazard Assessment |
| OES | Office of Emergency Services |
| SB 4 | Senate Bill 4 |
| SB 1281 | Senate Bill 1281 |
| SCAQMD | South Coast Air Quality Management District |
| U.S. EIA | U.S. Energy Information Administration |
| U.S. EPA | U.S. Environmental Protection Agency |
| TAC | Toxic Air Contaminant |
| TDS | Total Dissolved Solids |
| UIC | Underground Injection Control |
| USDW | Underground Sources of Drinking Water |
| WET | Whole Effluent Toxicity |
| USGS | United States Geological Survey |
| VOC | Volatile Organic Compound |

# Abstract

Senate Bill 4 (SB 4) requires an independent study to assess current and potential future well stimulation practices in California, including the likelihood that these technologies could enable extensive new petroleum production in the state; impacts of well stimulation technologies (including hydraulic fracturing, acid fracturing and matrix acidizing); gaps in data that preclude evaluation; potential risks associated with current practices; and alternative practices that might limit these risks.

Publicly available information indicates the vast majority of well stimulations in California are hydraulic fracturing in four oil fields in the San Joaquin Valley. The California experience with hydraulic fracturing differs from that in other states because California wells tend to be shallow and the reservoirs more permeable. California operators generally do not conduct high-volume hydraulic fracturing from long-reach horizontal wells, and for this reason use far less water. Operators use hydraulic fracturing in a small number of offshore wells in state waters, but data on wells in federal waters is sparse. In the next few years, use of hydraulic fracturing in California will likely look much like today, both in terms of the stimulation practices and the expected number of operations. No reliable estimates exist of potential oil production using hydraulic fracturing or acid stimulation in the deep Monterey Formation source rock and the state should request a credible scientific assessment.

Direct impacts of hydraulic fracturing stem from unrestricted chemical use. These appear small but have not been investigated. Significant gaps and inconsistencies exist in available voluntary and mandatory data sources, both in terms of duration and completeness of reporting that limit assessment of the impacts of hydraulic fracturing. However, good management and mitigation measures can address the vast majority of potential direct impacts of well stimulation. The state should limit the use of the most hazardous chemicals and disallow the use of any chemical with unknown environmental characteristics in order to prevent possible environmental and health impacts. Operators currently dispose of wastewater from hydraulically fractured wells in percolation pits and also likely have occasionally injected wastewater contaminated with stimulation chemicals into protected groundwater. These practices should stop. We found no documented instances of hydraulic fracturing or acid stimulations directly causing groundwater contamination in California, but few studies examined this possibility. However, we did find that fracturing in California tends to be in shallow wells, and hydraulic fractures could possibly intersect protected groundwater in a few locations. Also, California reservoirs have many existing boreholes that warrant more attention to ensure they are not leakage pathways. We found the data insufficient to determine if there is a relationship between oil and gas-related fluid injection and any of California's numerous earthquakes, and this should be studied.

Most impacts associated with hydraulic fracturing are indirect and are caused by oil and gas production enabled by hydraulic fracturing. For example, oil and gas development in general causes habitat loss and fragmentation that should be mitigated and any production facility can incur air emissions. As hydraulic fracturing enables only 20-25% of production in California, only about 20-25% of any given indirect impact is likely attributable to hydraulically fractured reservoirs.

Oil production from hydraulically fractured reservoirs emits less greenhouse gas per barrel than other forms of oil production in California. Air pollutants and toxic air emissions from hydraulic fracturing are mostly a small part of total emissions in oil producing regions except for a few toxic air substances such as hydrogen sulfide and formaldehyde in the San Joaquin Valley. However, pollutants can be concentrated near production wells and present health hazards to nearby communities. California public health studies could determine the magnitude of this issue and the need for any mitigating policies. Studies done outside of California found workers in hydraulic fracturing operations were exposed to respirable silica and volatile organic compounds (VOCs), especially benzene, above recommended occupational levels, but confirmation of this issue awaits specific evaluation in California.

This study highlights many recommendations to change practice, collect data, and investigate risk factors for Californians. However, questions remain at the end of this initial assessment of the impacts of well stimulation in California that can only be answered by new research and data collection. Volumes II and III of this report series provide many detailed recommendations for filling data gaps and additional research.

## S.1. Introduction

In 2013, the California Legislature passed Senate Bill 4 (SB 4), setting the framework for regulation of hydraulic fracturing and acid stimulation technologies in California. SB 4 also requires the California Natural Resources Agency to conduct an independent scientific study of hydraulic fracturing and acid stimulation technologies in California to assess current and potential future hydraulic fracturing and acid stimulation practices, including the likelihood that these technologies could enable extensive new petroleum production in the state; evaluate the impacts of hydraulic fracturing and acid stimulation technologies and the gaps in data that preclude this understanding; identify potential risks associated with current practices; and identify alternative practices that might limit these risks. This scientific assessment addresses hydraulic fracturing and acid stimulation used in oil and gas production both on land and offshore in California.

Well stimulation enhances oil and gas production by making the reservoir rocks more permeable, thus allowing more oil or gas to flow to the well. The study evaluates three types of well stimulation as defined in SB 4 (Table S.1-1 and Volume I, Chapter 2). The first type is "hydraulic fracturing." To create a hydraulic fracture, an operator increases the pressure of an injected fluid in an isolated section of a well until the surrounding rock breaks, or "fractures." Sand injected into these fractures props them open after the pressure is released. The second type is "acid fracturing," in which a high-pressure acidic fluid fractures the rock and etches the walls of the fractures, so they remain permeable after the pressure is released. The third type, "matrix acidizing," does not fracture the rock; instead, acid pumped into the well at relatively low pressure dissolves some of the rock and makes it more permeable.

This study is issued in three volumes. Volume I, issued in January 2015, describes how well stimulation technologies work, how and where operators deploy these technologies for oil and gas production in California, and where they might enable production in the future. Volume II, issued in July 2015, discusses how well stimulation could affect water, atmosphere, seismic activity, wildlife and vegetation, and human health. Volume II reviews available data, and identifies knowledge gaps and alternative practices that could avoid or mitigate these possible impacts. Volume III, also issued in July 2015, presents case studies that assess environmental issues and qualitative risks for specific geographic regions. This Summary Report summarizes key findings, conclusions, and recommendations of all three volumes.

As specified by contract, these volumes assess issues with well stimulation in California from a scientific perspective. No economic analysis was requested, and none accompanies the recommendations. The report makes reference to regulations where appropriate, but authors did not perform a comprehensive analysis of regulatory adequacy. We have presented the recommendations in the report without priority, cost, trade-off analysis or, except in a few cases that appear urgent, specifications for timing.

*Table S.1-1. Well stimulation technologies included in SB 4.*

<table>
<tr><td colspan="3">Hydraulic Fracturing Stimulation<br>Common feature: All treatments create sufficient pressure in the well to induce fractures in the reservoir.</td></tr>
<tr><td colspan="2">Proppant Fracturing:<br>Uses proppant to hold the hydraulic fracture open</td><td>Acid Fracturing:<br>Uses acid instead of proppant</td></tr>
<tr><td>Traditional Fracturing: Creates long, narrower hydraulic fractures that extend deep into the formation in reservoirs that are not very permeable; proppant injected into fractures serves to prop fractures open.</td><td>Frac-Pack: Creates short, wider hydraulic fractures allowing oil to bypass damaged rock near a wellbore and prevents sand in the reservoir from entering the well.</td><td>Similar to traditional fracturing, but uses acid instead of proppant to etch, or “roughen” the fracture walls; used only in carbonate reservoirs.</td></tr>
</table>

<table>
<tr><td colspan="2">Acidizing Stimulation<br>Common feature: All treatments use acid to dissolve materials impeding flow</td></tr>
<tr><td colspan="2">Matrix Acidizing: Dissolves material near the well to make the reservoir rocks more permeable; typically only used for relatively permeable reservoirs that do not require traditional or acid fracturing</td></tr>
<tr><td>Sandstone Acidizing: Uses hydrofluoric acid in combination with other acids to dissolve minerals (silicates) that plug the pores of the reservoir; only used in reservoirs composed of sandstone or similar rocks</td><td>Carbonate Acidizing: Uses hydrochloric acid (or acetic or formic acids) to dissolve carbonate minerals, such as limestone, and bypass rock near a wellbore that has been damaged by drilling; only used in carbonate reservoirs</td></tr>
</table>

# Box S.1-1. History of Oil Production in California

Oil and gas production remains a major California industry. California hydrocarbon reservoirs have some of the highest concentrations of oil in the world. Commercial production started in the middle of the 19th century from hand-dug pits and shallow wells. In 1929, at the peak of oil development in the Los Angeles Basin, California accounted for more than 22% of total world oil production.[1] California's oil production reached an all-time high of almost 400 million barrels (64 million cubic meters [$m^3$]) in 1985 and has generally declined since then. Today California is the third highest producing state, with about 6% of U.S. production but less than 1% of global production. In 1960, almost as much oil was produced in California as was consumed, but by 2012 Californians produced only 32% of the oil they used (198 million barrels, or 31 million $m^3$, produced in the state[2] out of a total of about 621 million barrels consumed). Californian's made up the shortfall of about 423 million barrels (99 million $m^3$) mainly with oil delivered by tanker from Alaska, Saudi Arabia, Ecuador, Iraq, Colombia, and other countries.

Over the years, as California fields matured, operators have used water flooding, gas injection, thermal recovery, hydraulic fracturing, and other techniques to enhance oil and gas production. In the western San Joaquin Basin, diatomite (a rock that is not very permeable) reservoirs contain billions of barrels of oil. Production of this oil requires hydraulic fracturing. Production from the diatomite reservoirs now accounts for about 20% of California oil and gas production (see Volume I, Chapter 3). Most of the natural gas produced in the state is a co-product of oil production, which is known as "associated" gas production. Most of this production occurs in the San Joaquin Basin, including reservoirs that use hydraulic fracturing.

1. American Petroleum Institute, Basic Petroleum Data Book, Volume XIII, Number 2, 1993
2. From http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/total/use_tot_USa.html&sid=US and http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPCA1&f=M, accessed June 13, 2015

### S.1.1. CCST Committee Process

The California Council on Science and Technology (CCST) organized and led the study reported on here. Members of the CCST steering committee were appointed based on technical expertise and a balance of technical viewpoints. (Appendix B provides information about CCST's steering committee.) Under the guidance of the steering committee, Lawrence Berkeley National Laboratory (LBNL) and subcontractors (the science team) developed the findings based on original technical data analyses and a review of the relevant literature. Appendix C provides information about the LBNL science team and subcontractors who authored Volumes I, II, and III of this report.

The science team studied each of the issues required by SB 4, and the science team and the steering committee collaborated to develop a series of conclusions and recommendations that are provided in this summary report. Both science team and steering committee members proposed draft conclusions and recommendations. These were modified based on discussion within the steering committee along with continued consultation with the science team. Final responsibility for the conclusions and recommendations in this report lies with the steering committee. All steering committee members have agreed with these conclusions and recommendations. Any steering committee member could have written a dissenting opinion, but no one requested to do so.

SB 4 also required the participation of the California Environmental Protection Agency's Office of Environmental Health Hazard Assessment (OEHHA) in this study. OEHHA provided toxicity and other risk assessment information on many of the chemicals used in hydraulic fracturing, offered informal technical advice during the course of the study, and provided comments on drafts of Volumes II and III. OEHHA also organized a February 3, 2015, public workshop in Bakersfield in which representatives of CCST, LBNL, and subcontractors heard comments from attendees on the topics covered in the report.

This report has undergone extensive peer review. (Peer reviewers are listed in Appendix E, "Expert Oversight and Review"). Eighteen reviewers were chosen for their relevant technical expertise. More than 1,500 anonymous review comments were provided to the authors. The authors revised the report in response to peer review comments. In cases where the authors disagreed with the reviewer, the response to review included their reasons for disagreement. Report monitors, appointed by CCST, then reviewed the response to the review comments and when satisfied, approved the report.

### S.1.2. Data and Literature Used in the Report

This assessment reviewed and analyzed existing data including both voluntary and mandatory reporting of stimulation data, peer-reviewed scientific literature, as well as non-peer reviewed reports and documents if they were topically relevant and determined to be scientifically credible by the authors and reviewers of this volume. CCST solicited and reviewed nominations of literature from the public. Criteria for including the nominated literature are described in Volume I, Appendix E, "Review of Information Sources." The science team did not collect any new data, but did do original analysis of available data from a variety of sources.

Volumes I, II, and III of this report address issues that have very different amounts of available information and cover a wide range of topics and associated disciplines, which have well-established but differing protocols for inquiry. In Volume I, available data and methods of statistics, engineering, and geology allow the authors to present the factual basis of well stimulation in California. With a few exceptions, the existing data was sufficient to accurately identify the technologies used, analyze where and how often they are used, and evaluate where they are likely to be used in the future (see Volume I, Chapter 3).

The authors of Volume II faced the challenge of assessing and presenting the impacts of well stimulation. Since many impacts have never been thoroughly investigated, the authors drew on literature describing conditions and outcomes in other places, circumstantial evidence, and expert judgment to catalog an extensive list of potential impacts that may or may not occur in California. Volume II also identifies a subset of concerning situations—"risk factors" (summarized in Appendix F of the Summary Report and Table 6.2-1 of Volume II)—that warrant a closer look and perhaps regulatory attention.

Volume III largely extends the method of inquiry used in Volume II to location-specific issues for offshore production, the Monterey Formation, the Los Angeles Basin, and the San Joaquin Basin. The Offshore Case Study evaluates what we know and do not know about the use of stimulation technologies in that environment. The Monterey Formation Case Study identifies the geographic locations (or "footprint") of the parts of the Monterey Formation that could contain producible oil and gas in "source rock" (see Appendix G for a definition of source rock), and examines the implications if new production were to begin in those regions. Likewise, the San Joaquin Basin Case Study evaluates likely future production with hydraulic fracturing and examines the implications of that production.

The first part of the Los Angeles Basin Case Study describes the geologic basis of oil production and its implications for future oil and gas production using technology such as hydraulic fracturing. The second part evaluates sparse information about public health implications of oil and gas development in a densely populated mega-city. This study compensates for the lack of data documenting adverse health outcomes by investigating information that suggests, but does not confirm with certainty, the risks to human health. The precepts of the field of public health include an emphasis on the anticipation of potential problems even though specific problems have not been observed or proven to create risk. In this way, the public health chapter of Volume II and the public health analysis for the Los Angeles Basin Case Study differ from other parts of this report. A major goal of public health research is to anticipate and avoid harm rather than to observe and allocate cause for harm.

The authors of this report hope this flexible and appropriate use of different but well-established methods of inquiry, under highly variable conditions of data availability and potential impacts, serves useful to California.

### S.1.2.1. Data on Well Stimulation Practice and Stimulation Chemistry

A comprehensive understanding of well stimulation practice in California requires complete and accurate reporting, as directed by SB 4, and sufficient time for a representative number and type of operations to be reported. The analyses summarized in this report assess less than one year of well stimulation data collected under mandatory reporting starting on January 1, 2014.[3] Mandatory reporting under SB 4 includes submission of data to FracFocus, a website created by petroleum industry groups to disclose information about drilling and chemical use in hydraulic fracturing. SB 4 also requires submission of data to the California Division of Oil, Gas and Geothermal Resources (DOGGR), including the same drilling and chemical-use data submitted to FracFocus, as well as extended information about hydraulic fracturing operations. DOGGR provides access to all submitted data through its website.

Other sources of data collected under mandatory reporting include data from the South Coast Air Quality Management District (SCAQMD) since June 2013 and from the Central Valley Regional Water Quality Control Board (CVRWQCB) for 2012 and 2013. The SCAQMD and CVRWQCB data are limited to the Los Angeles Air Basin and the Central Valley Region, respectively.

Prior to mandatory reporting, DOGGR collected voluntary data on hydraulic fracturing operations including information submitted to FracFocus between 2011 and 2013, and well construction histories going back many years. These data help to provide a historical perspective, but remain incomplete and not fully verifiable.

California operators have deployed hydraulic fracturing since 1953, so most California operations occurred prior to the mandatory reporting requirement. Records of these operations vary from as little as simply indicating that a hydraulic fracturing operation occurred to as much as the times, flow rates, stages, fluid type, injection pressures, and proppant loading schedule for the operation (proppant consists of sand or similar material pumped into a hydraulic fracture to keep it open). In all cases, analyses summarized in this report only assess data available prior to 2015, and prior to July 2014 for many of the data sets considered starting in Volume I.

3. The cut-off date for including data in the analyses in the report varied from June 2014 to December 2014 depending on the topic as described in the report volumes. Time-consuming analyses, such as for chemistry, required earlier data cut-off dates and the analyses only include data reported as of June 2014. For less time-consuming analyses, such as characterizing the source and type of water used for stimulation and the geometric extent of stimulation, the analyses include data available as of December 2014.

Information from voluntary and mandatory reported data, scientific literature, government reports, and other sources (such as patents and industrial literature) support the conclusions about current hydraulic fracturing practice derived in this report. These multiple independent sources of information give largely consistent results. Consequently, the authors think the report conclusions about the practice of hydraulic fracturing are generally accurate and representative of well stimulation activities in California. Additional data in the future might change some of the quantitative findings about well stimulation practices in the report, but, absent some major external influence, it is unlikely these will fundamentally alter the report findings about the current and likely future use of well stimulation in California. In contrast to hydraulic fracturing, publicly-available data on chemical use during matrix acidizing prior to mandatory reporting (which started regionally in mid-2013 from SCAQMD and statewide in 2014 per SB 4) does not exist.

To evaluate the future potential use of hydraulic fracturing and acid stimulation in California, the study utilized high-quality scientific information on the geology of conventional resources in California. In contrast, only highly uncertain data support current estimates on the recoverable shale-oil resources in the deep Monterey Formation.

The report describes the limitations of the data throughout in order to transparently qualify the accuracy of the conclusions.

#### S.1.2.2. Information and Data on Well Stimulation Impacts

The stimulation completion reports recently required by SB 4 contain data that provide a basis for assessment of some potential environmental and health impacts of hydraulic fracturing and acid stimulation, such as the fracturing depth in the vicinity of groundwater resources. However, while mandatory reporting under SB 4 has clearly improved prior reporting practices, we found gaps and inconsistencies in the reporting suggesting that data quality issues still require attention. For many other impacts, only incomplete information and data exist, and questions remain that can only be answered with additional research and data collection. For example, few scientific studies of health and environmental impacts of well stimulation have been done to date, and the ones that have been done address other parts of the country where practices and regulations differ significantly from present-day practices in California. Generally, no environmental baseline data exists to document conditions in the vicinity of stimulation sites before stimulation. Analysts cannot easily determine if stimulation operations have changed groundwater chemistry or habitat if they have no knowledge of the conditions before stimulation. Likewise, studies do not typically include oil and gas sites developed without stimulation, so analysts cannot easily determine if impacts are caused by stimulation activity versus oil and gas production activities in general.

No records of contamination of protected water by hydraulic fracturing fluids in California exist, but few targeted studies have been conducted to look for such contamination. Data describing the quality of groundwater near hydraulic fracturing sites are not universally available. SB 4 partially addresses this issue by requiring monitoring when operators apply for a permit to conduct hydraulic fracturing near protected groundwater.[4] In cases where permit applications for hydraulic fracturing operations have been exempted from groundwater monitoring, we can presume that the operator has been able to demonstrate that no nearby, protected groundwater exists.

A complete analysis of the risks posed by well stimulation (primarily hydraulic fracturing) to water contamination, air pollution, earthquakes, wildlife, plants, and human health requires much more data than are available. However, the study authors were able to draw on their technical knowledge, data from other places, and consideration of the specific conditions in California to identify conditions in California that deserve more attention, and make recommendations for additional data collection, increased regulation, or other mitigating measures. These conditions, or "risk factors," have become the subjects of the conclusions and recommendations under the heading of "Impacts." Appendix F provides a summary of risk factors.

### S.1.3. The Use and Potential Impacts of Hydraulic Fracturing and Acid Stimulation in California

This study identified seven major principles required for safe hydraulic fracturing and acid stimulation in California. These principles include:

1. Maintain, expand and analyze data on the practice of hydraulic fracturing and acid stimulation in California.

2. Prepare for potential future changes in hydraulic fracturing and acid stimulation practice in California.

3. Account for and manage both direct and indirect impacts of hydraulic fracturing and acid stimulation.

4. Manage produced water from hydraulically fractured or acid stimulated wells appropriately.

5. Add protections to avoid groundwater contamination by hydraulic fracturing.

6. Understand and control emissions and their impact on environmental and human health.

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4. Protected groundwater according to the U.S. Environmental Protection Agency has fewer than 10,000 mg/L total dissolved solids (TDS). Aquifers with less than 10,000 mg/L TDS may be exempted from protection for several reasons, for example because they contain commercially producible minerals or hydrocarbons, or because they are too deep for economic recovery.

7. Take an informed path forward.

The sections below describe the major conclusions and recommendations of our report clustered under each of the seven principles. Section S.2 below provides information about the use of hydraulic fracturing and acid stimulation technologies in California, now and in the future (Principles 1 and 2). Section S.3 discusses the potential direct and indirect impacts of hydraulic fracturing and acid stimulation in California (Principles 3-6). Section S.4 focuses on how to improve the quality of scientific information on hydraulic fracturing and acid stimulation (Principle 7).

## S.2. Current and Potential Future Use of Hydraulic Fracturing and Acid Stimulation Technologies in California

This study first answers the questions: What use do operators make of hydraulic fracturing and acid stimulation technology on-shore and off-shore in California, and how does the California experience differ from other states? What hydraulic fracturing and acid stimulation technologies do operators use in California? How often and where do they use them and how much water do they require? Beyond current practice, could these technologies enable extensive new petroleum production in the state?

### Principle 1. Maintain, expand, and analyze data on the practice of hydraulic fracturing and acid stimulation in California.

Public records provide substantial information about the location, frequency of use, and water and chemical use for hydraulic fracturing and acid stimulation in California. Hydraulic fracturing supports about one quarter of California oil production. About one hundred and fifty wells per month undergo hydraulic fracturing primarily in the southwestern San Joaquin Valley, far fewer undergo matrix acidizing and practically none use acid fracturing. The average hydraulic fracturing operation in California uses a much smaller amount of water than in many other parts of the country because operators in this state fracture in relatively shallow vertical wells (less than 2,000 ft (600 m) deep).

**Conclusion 1.1. Most well stimulations in California are hydraulic fracturing and most hydraulic fracturing occurs in the San Joaquin Valley.**

*About 95% of reported hydraulic fracturing operations in California occur in the San Joaquin Basin, nearly all in four oil fields in Kern County. Over the last decade, about 20% of oil and gas production in California came from wells treated with hydraulic fracturing. Hydraulic fracturing accounts for about 90% of all well stimulations in California; matrix acidizing accounts for only 10%; and acid fracturing operations nearly none. Operators in California commonly use acid for well maintenance, but acid stimulation will not likely lead to major increases in oil and gas production due to the state's geology. Operators of dry (non-*

*associated)*[5] *gas wells located in Northern California rarely use hydraulic fracturing (Volume I, Chapter 3).*

In about 15% of California reservoirs (also called pools), almost all the wells are hydraulically fractured, while in about 80% of the reservoirs very little hydraulic fracturing takes place (Figure S.2-1). The majority of reservoirs use very little hydraulic fracturing, and the use of hydraulic fracturing is geographically concentrated in just a few reservoirs.

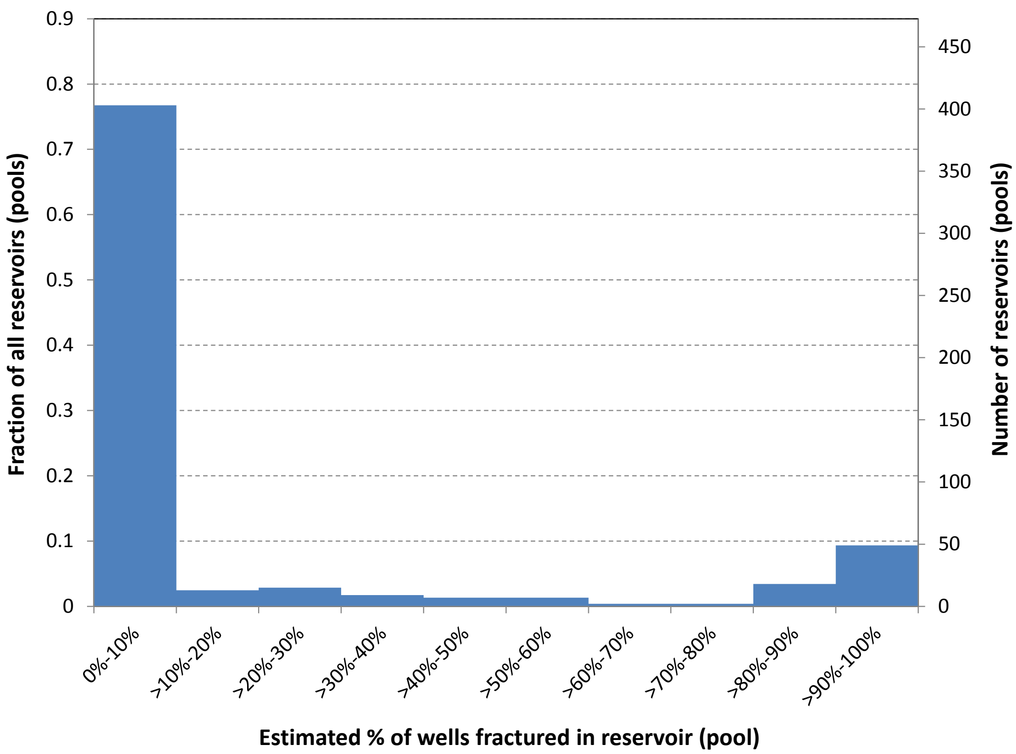



***Figure S.2-1. Distribution of reservoirs (pools) in California based on the estimated percent of wells that are hydraulically fractured in each reservoir.***

5. Petroleum wells are either classified as oil wells or gas wells. Oil wells predominantly produce oil, but they also produce some gas "associated" with the oil. In California, as elsewhere, this associated gas represents the majority of gas production in the state. "Dry" gas wells, or "non-associated" gas wells are wells that predominantly produce gas. In California, dry gas is predominantly produced in the Sacramento Valley, but this represents a minority of the gas produced in the state.

About 85% of the hydraulic fracturing in California occurs in four fields in the southwestern San Joaquin Basin, as shown in Figure S.2-2. Every well in some pools of these fields has been hydraulically fractured; we classify production from these pools as “hydraulic-fracturing-enabled” oil and gas development. For such heavily fractured reservoirs, production would likely not be economical without hydraulic fracturing. In the last decade, operators fractured about 125 to 175 wells of the approximately 300 new oil wells installed per month in California. This represents less than one-tenth of the number of hydraulic fracturing operations reported in the entire U.S. in 2012 and 2013 (Volume I, Chapter 3).

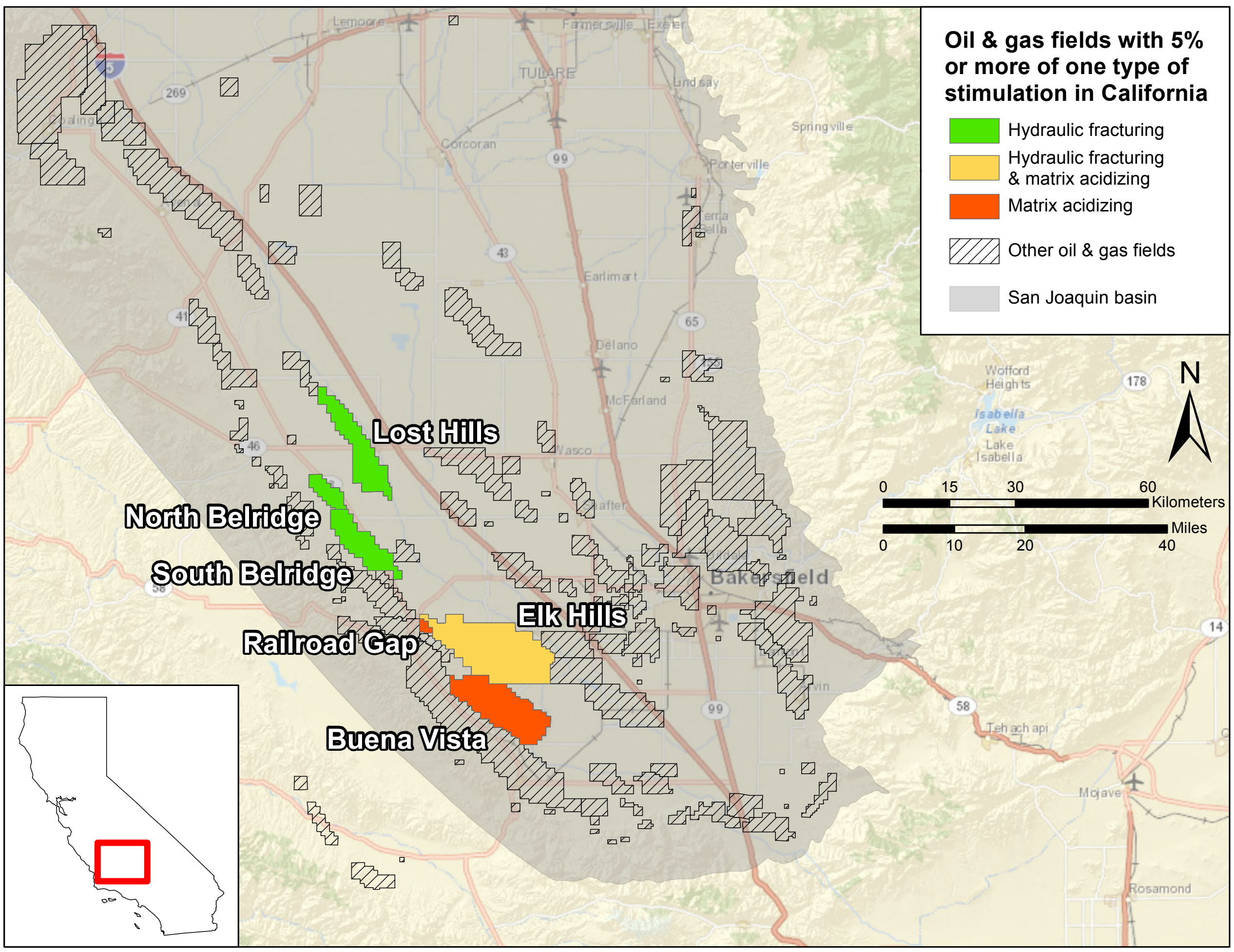



*Figure S.2-2. Oil and gas fields in California where altogether 85% of the reported hydraulic fracturing and over 95% of the reported matrix acidizing occur (figure from Volume I, Chapter 3).*

Figure S.2-3 provides basic statistics about the volume of oil and gas production from geologic basins in central and southern California from 2002 to 2014 and the proportion enabled by hydraulic fracturing. Northern California also produces gas, predominantly in the Sacramento Basin, but operators rarely use hydraulic fracturing in gas wells. An average of eight hydraulic fracturing operations per year took place in dry gas wells between 2002 through 2011 in the Sacramento Basin, and none since. However, most of the gas production in the state does not come from dry gas wells, but from wells that primarily produce oil, mostly in the San Joaquin Basin. About a fifth of gas production in the state comes from hydraulically fractured oil wells (Volume I, Chapter 3).

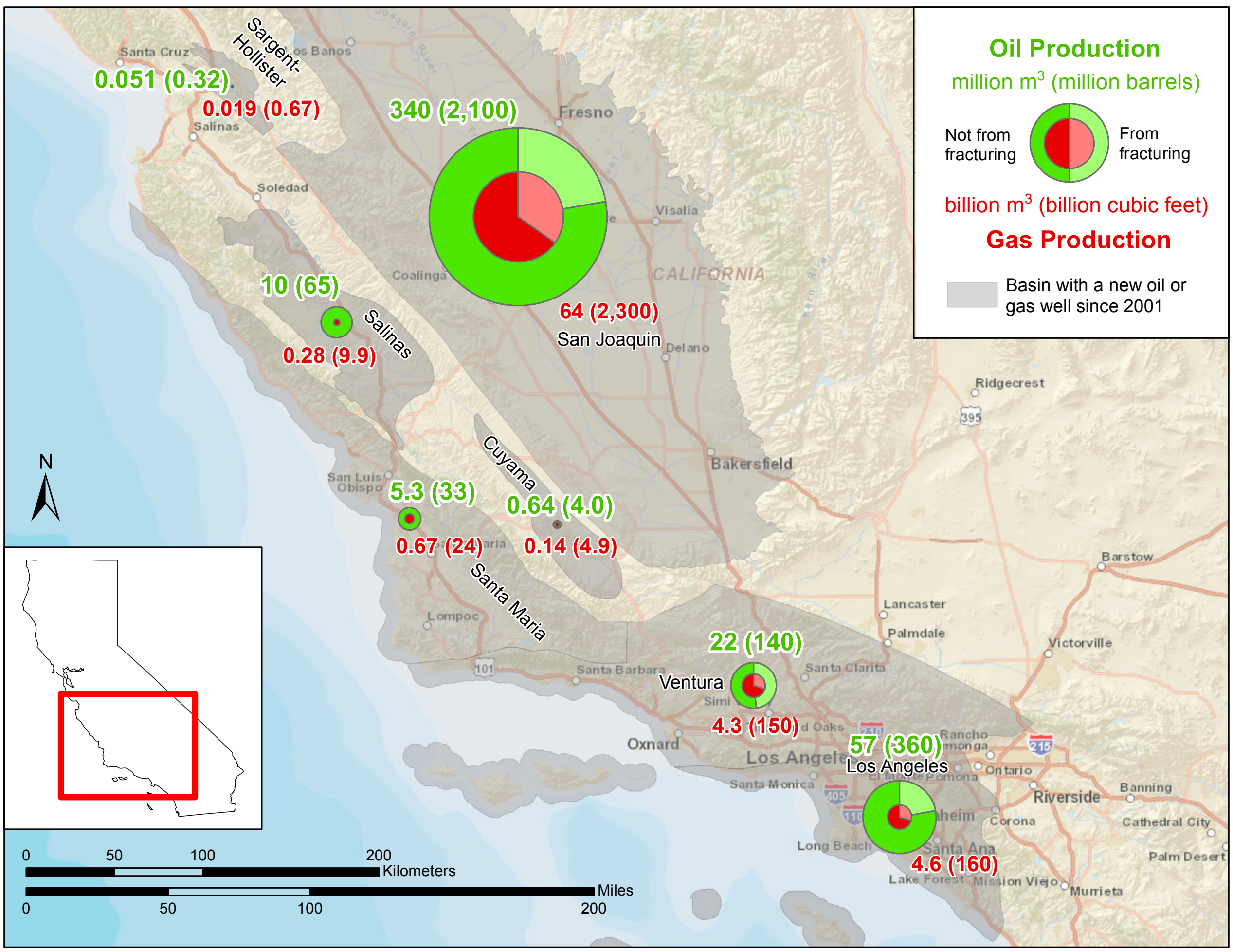



*Figure S.2-3. Production of oil and gas with and without hydraulic fracturing in each geologic basin in central and southern California from 2002 through May 2014. The area of each circle is proportional to the production volume in each basin. The green circles represent oil production and the red circles represent gas. The lighter shade represents the fraction of production from wells stimulated with hydraulic fracturing. The vast majority of production of both oil and gas in California comes from the San Joaquin Basin (figure modified from Volume I, Chapter 3).*

The vast majority of well stimulations conducted in California are onshore hydraulic fracturing operations, as shown in Figure S.2-4, with much less matrix acidizing and essentially no acid fracturing. Consequently, in California most of the potential impacts from well stimulation will be associated with hydraulic fracturing. We expect hydraulic fracturing onshore to continue as the main type of well stimulation in the state for the foreseeable future.

Various regulatory agencies use different definitions of acid stimulation and have different reporting requirements. Lack of commensurate data prevents a definitive assessment of the extent of matrix acidizing in California. Based on available data, operators use matrix acidizing in about 15–25 wells per month (out of approximately 300 wells installed per month in California), nearly all of these in the southwestern portion of the San Joaquin Basin.

Acid stimulations can make carbonate reservoirs (for example limestone) much more permeable because acid easily dissolves carbonate minerals. But carbonate reservoirs are rare in California, which explains why operators rarely use acid fracturing in California. We did not find reservoirs that require matrix acidizing for production. Currently, about 10% of stimulations in California are matrix acidizing, but given California geology, this technology will not likely enable major changes in production in the future (Volume I, Chapters 2 and 3).

Data available for this assessment do not delimit the amount of acid, including hydrochloric (HCl) and hydrofluoric acid (HF), used for oil and gas production in California. Starting July 1, 2015, DOGGR will require reporting of all acid use; this will result in a better understanding of the extent and volume of acid use in the future. In the Los Angeles Basin, the South Coast Air Quality Management District started requiring reporting on the use of chemicals used for drilling, well completion, and maintenance by the oil and gas industry in 2012. Their data suggests widespread and common use of acid for many applications in the industry. During 2013 and 2014, industry reported approximately twenty matrix-acidizing treatments per month to the Central Valley Regional Water Quality Control Board. Mandatory disclosure requirements for chemicals used in matrix acidizing operations went into effect under interim regulations pursuant to SB 4 in January 2014, which will improve our understanding of this practice in the future. Hydraulic fracturing operations have only infrequently incorporated acid use (11 voluntarily reported applications between January 2011 and May 2014).

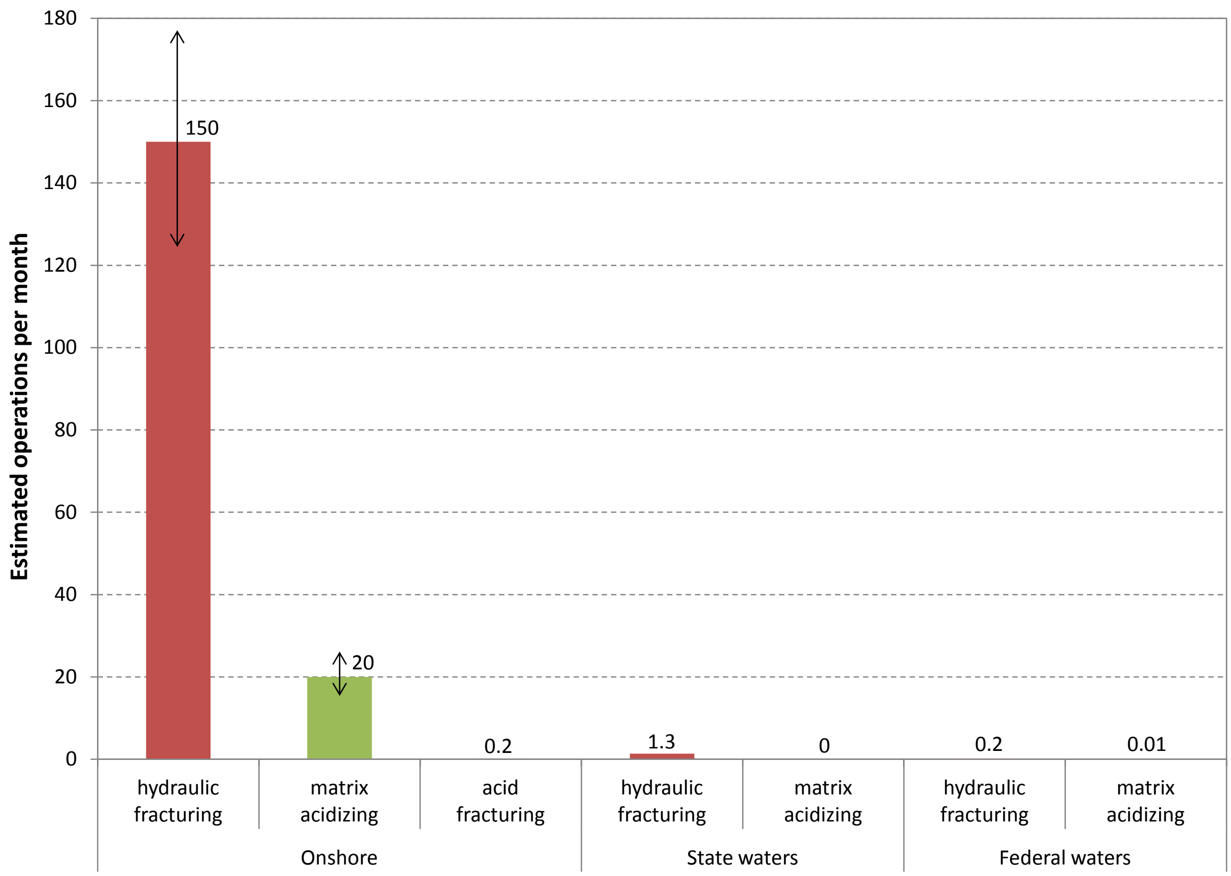



***Figure S.2-4. Estimated average number of stimulation operations per month, by type and location. The arrows represent the estimated uncertainty. About 90% of stimulations are onshore hydraulic fracturing and 10% are onshore matrix acidizing (figure modified from Volume I, Chapter 3).***

**Conclusion 1.2. The California experience with hydraulic fracturing differs from that in other states.**

*Present-day hydraulic fracturing practice and geologic conditions in California differ from those in other states, and as such, recent experiences with hydraulic fracturing in other states do not necessarily apply to current hydraulic fracturing in California.*

In the last few decades, significant innovation in the relatively old technology of hydraulic fracturing made economic production of oil and gas from deep, impermeable "source rocks"[6] possible. In reservoirs such as the Bakken Formation in North Dakota or the Eagle Ford Formation in Texas, operators now drill horizontal wells that can be many miles long (long-reach horizontal drilling) and use water mixed

6. Source rocks are rocks where oil and gas has formed and remains in place, see Appendix G.

with specialized chemicals to hydraulically fracture the rocks and produce the petroleum. Hydraulic fracturing of these wells requires a lot of water, because the operation must create many interconnected fractures to access the oil or gas, and because long horizontal wells may require ten to over a hundred separate hydraulic fracture events, or stages. This type of hydraulic fracturing is called “high-volume” hydraulic fracturing, or “HVHF.”

Although California operators have benefited from advances in hydraulic fracturing technology, the application of this technology in California differs from other states, primarily because the geology of the petroleum reservoirs differs. In California reservoirs in production today, the oil formed in the source rocks has migrated towards the surface until something in the geologic structure (known as a “trap”) prevents further migration. Today, operators produce this “trapped” petroleum. California reservoirs are shallower and more permeable than the shale source rocks being produced with HVHF. In California, the wells tend to be shorter and near-vertical as opposed to horizontal. The hydraulic fracturing operations require much less water per well, because the operations in California tend to produce a simple fracture that connects to natural fractures, and short wells require fewer fracture events (stages) per well. California hydraulic fracturing uses more concentrated chemicals in the water than hydraulic fracturing in other states. More concentrated chemicals allow the fluid to carry the additional proppant required to hold open a simple fracture. Consequently, the practices and impacts of hydraulic fracturing in other states do not necessarily apply to current hydraulic fracturing for petroleum production in California (Volume I, Chapter 3).

In California, a hydraulic fracturing operation consumes on average 140,000 gallons (over 500 $m^3$) of water per well, compared to about 4 million gallons (16,000 $m^3$) per well used in horizontal wells in the Eagle Ford Formation in Texas. Figure S.2-5 shows a histogram of water use per operation in California. Recently, the State of New York banned hydraulic fracturing operations using more than 300,000 gallons (one million $m^3$) of water per well. More than 90% of California operations use less than 300,000 gallons (one million $m^3$) of water per well. Consequently, if California were to enact the same ban on hydraulic fracturing as enacted in New York, the ban would make little difference to current hydraulic fracturing practice in California.

Hydraulic fracturing has application beyond enhancing oil production wells. Hydraulic fracturing can improve the function of injection wells used to flood the oil reservoir with water or steam (called water or steam flooding) and improve wells used to recharge geothermal reservoirs with water. Hydraulic fracturing helps to clean up underground contamination or dispose of waste fluids, and facilitates about a third of the subsurface storage of natural gas in the state. Hydraulic fracturing has also been used to improve water supply wells drilled into granite rock. While these applications use the same fundamental hydraulic fracturing technology, the amount of water and types of chemicals used differ from applications in oil and gas production (Volume I, Chapters 2 and 3).

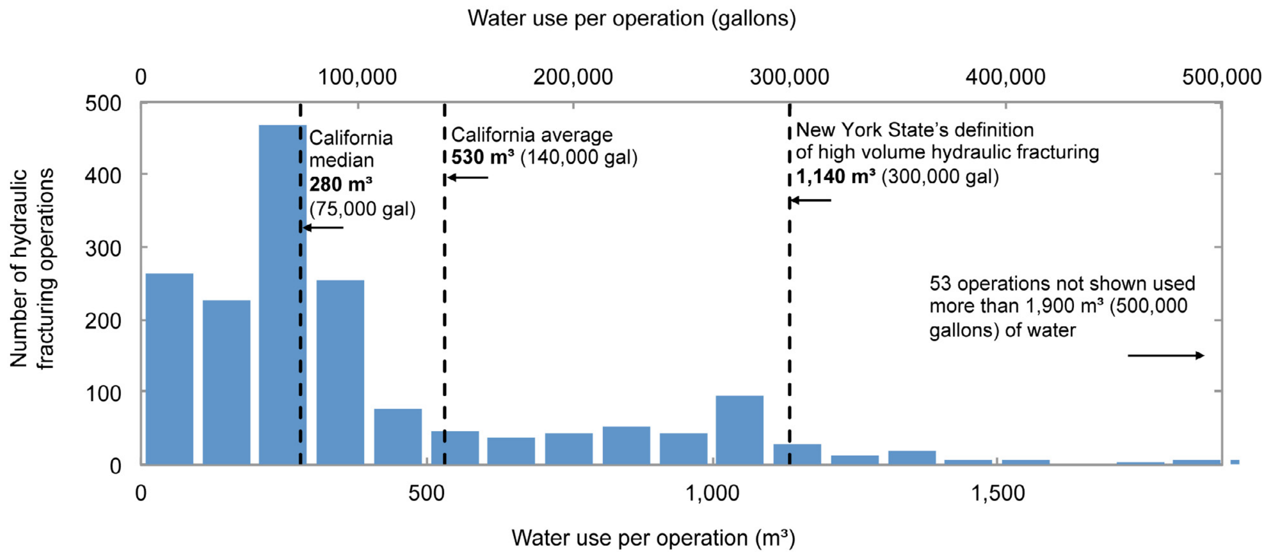



*Figure S.2-5. Histogram of water use per hydraulic fracturing operation based on SB 4 disclosures showing that almost all operations in California use less than the amount defined as high-volume hydraulic fracturing in New York. There are 53 operations not shown on the graph, including 17 that used over 1 million gallons (about 11,000 $m^3$), three of which used over about 4 million gallons (15,000 $m^3$) (figure modified from Volume I, Chapter 3).*

**Conclusion 1.3. Hydraulic fracturing in California does not use a lot of fresh water compared to other states and other human uses.**

*Operators in California use about 800 acre-feet (about a million $m^3$) of water per year for hydraulic fracturing. This does not represent a large amount of freshwater compared to other human water use, so recycling this water has only modest benefits. However, hydraulic fracturing takes place in relatively water-scarce regions. Other parts of the oil and gas production process, such as enhanced oil recovery via water flood or steam injection, require significantly more water than the hydraulic fracturing process. We estimate that in 2013, operators used 1,600 to 13,000 acre-feet (2 million to 14 million $m^3$) of freshwater for production using enhanced oil recovery just in hydraulically fractured fields. Where production was enabled by hydraulic fracturing, at least twice and possibly fourteen times as much fresh water was used for subsequent enhanced oil recovery using water or steam flooding than all the water used for hydraulic fracturing throughout the state. The state has recently begun requiring detailed reporting of water use and produced water disposal in California's oil and gas fields pursuant to Senate Bill 1281 (SB 1281). In the future, these data could help optimize oil and gas water practices, including water use, production, reuse, and disposal.*

Operators obtained 68% of the estimated 800 acre-feet (about one million $m^3$) of water needed for hydraulic fracturing from nearby irrigation districts, 13% from recycled produced water, 13% from operators' own wells, 4% from a nearby municipal water supplier, or 1 %

from a private landowner.

Hydraulic fracturing represents less than 0.2% of all human water uses in regions where stimulation occurs. If in the future high volume hydraulic fracturing becomes useful and common in California, the impacts on water use could change, and opportunities for water efficiency and conservation in hydraulic fracturing operations should be assessed. Currently, such efforts would have modest benefit.

Oil production in California often requires ongoing injection of water or steam into the reservoirs to push the oil towards a production well. Water or steam flood processes (or enhanced oil recovery or EOR) goes on for the life of the production well, whereas hydraulic fracturing goes on for about a day. Consequently, production requires much more water than hydraulic fracturing (Figure S.2-6).

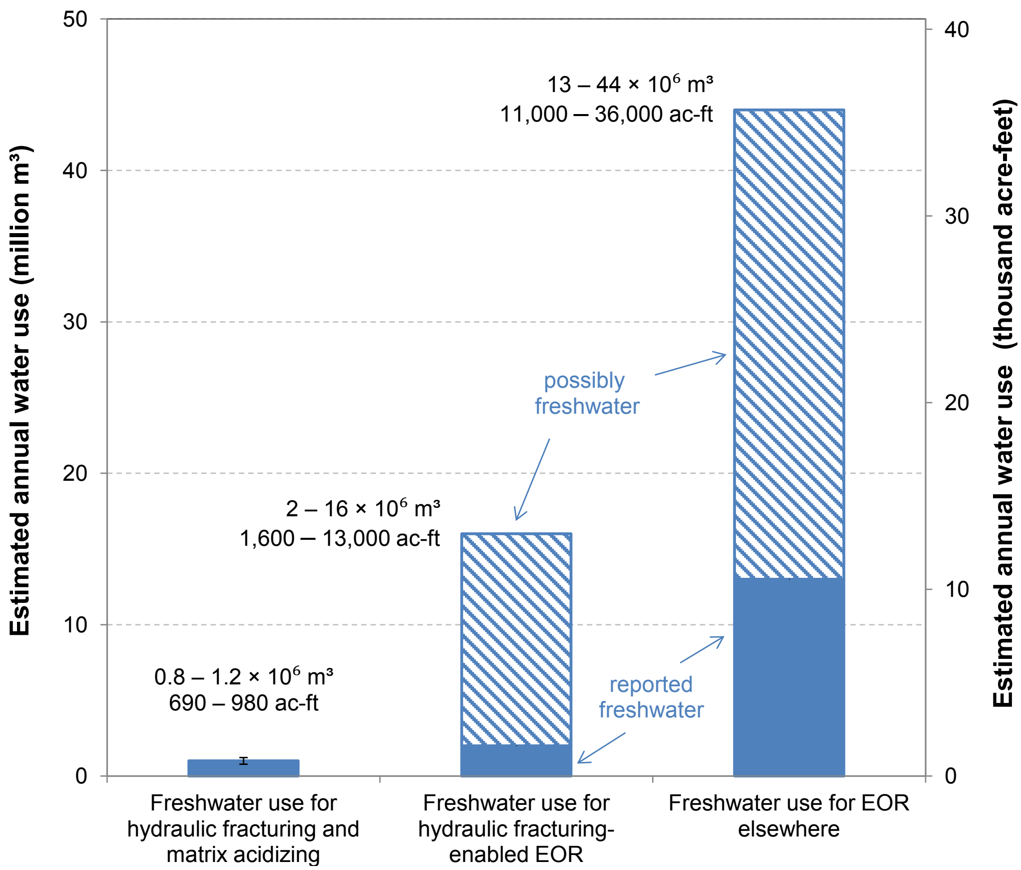



***Figure S.2-6. Estimated annual freshwater use in 2013 for hydraulic fracturing (left), production using enhanced oil recovery (EOR) in reservoir where most wells are hydraulically fractured (middle), and EOR in 2013 in other reservoirs (right). Hydraulic fracturing occurs before the well goes into production. EOR occurs throughout production (figure from Volume II, Chapter 2).***

Produced water, if appropriately treated, can also be used to satisfy water needs for hydraulic fracturing or other operations, such as water flooding and steam injection. This could be particularly useful on a regional basis, with produced water from adjacent fields substituting for freshwater used in another field. Focused efforts might overcome technical, infrastructure, and contractual barriers to matching sources and demands across numerous oil fields.

The state has recently begun requiring reporting of data concerning the source, quality, and treatment of water injected in oil and gas fields, and the disposition of produced water (SB 1281). This data will help to illuminate opportunities for water reuse and water practices that could be optimized or should be disallowed or controlled.

**Recommendation 1.1. Identify opportunities for water conservation and reuse in the oil and gas industry.**

*When roughly a year of water data becomes available from implementation of SB 1281, the state should begin an early assessment of this data to evaluate water sources, production, reuse, and disposal for the entire oil and gas industry. Early assessment will shed light on the adequacy of the data reporting requirements and identify additional requirements that could include additional information about the quality of the water used and produced. When several years of data become available, a full assessment should identify opportunities to reduce freshwater consumption or increase the beneficial use of produced water, and regularly update opportunities for water efficiency and conservation (Volume I, Chapter 3).*

**Conclusion 1.4. A small number of offshore wells use hydraulic fracturing.**

*California operators currently use hydraulic fracturing in a small portion of offshore wells, and we expect hydraulic fracturing to remain incidental in the offshore environment. Policies currently restrict oil and gas production offshore, but if these were to change in the future, production could largely occur without well stimulation technology for the foreseeable future.*

The majority of offshore production takes place without hydraulic fracturing. Most of the limited hydraulic fracturing activity is conducted on engineered islands (Figure S.2-7(a)) close to the Los Angeles coastline in state waters. According to our limited data sources, little hydraulic fracturing takes place on platforms in federal waters more than three nautical miles (5.6 kilometers [km]) offshore (Figure S.2-7(b)).

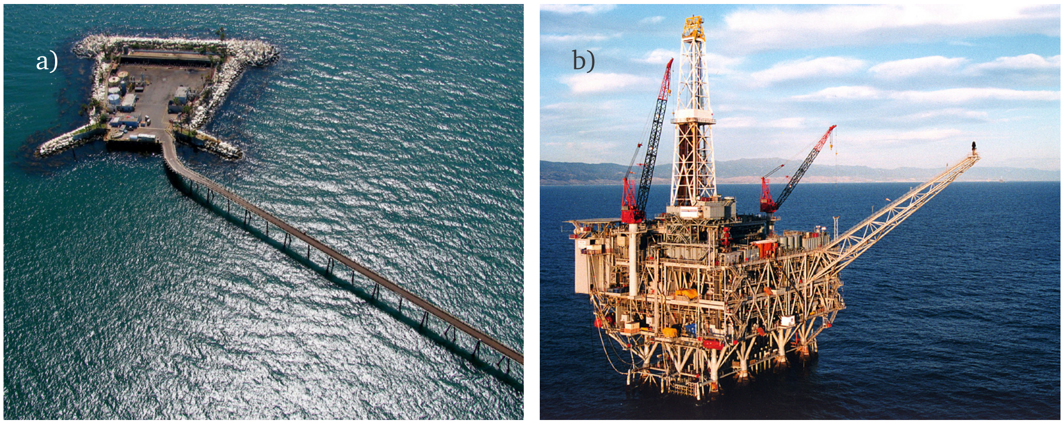



*Figure S.2-7. (a) The Rincon Offshore Artificial Island and causeway (b) Platform Heritage (1989)—the most recent platform installed in federal waters (figure from Volume III, Chapter 2 [Offshore Case Study]).*

Ninety percent of offshore fracturing operations in California waters occurred on dedicated islands in the Wilmington field. On these islands, operators conduct about 1-2 hydraulic fracturing operations in the 4-9 wells installed per month. Operations on close-to-shore, dedicated islands resemble onshore oil production activities.

Billions of barrels of potential oil reserves exist off the California coast, but both federal and state laws and policies restrict expansion of production into new areas. Current production from offshore platforms uses some hydraulic fracturing to marginally improve productivity, but most production does not require hydraulic fracturing. New production, if permitted, would likely resemble existing production. In the offshore environment, application of hydraulic fracturing would not affect production nearly as much as a change in current policies and regulations that now restrict new production offshore (Volume III, Chapter 2 [Offshore Case Study]).

**Conclusion 1.5. Record keeping for hydraulic fracturing and acid stimulation in federal waters does not meet state standards.**

*Current record-keeping practice on stimulations in federal waters (from platforms more than three nautical miles offshore) does not meet the standards set by the pending SB 4 well treatment regulations and does not allow an assessment of the level of activity or composition of hydraulic fracturing chemicals being discharged in the ocean. The U.S. Environmental Protection Agency's (U.S. EPA) National Pollutant Discharge Elimination System (NPDES) permits that regulate discharge from offshore platforms do not effectively address hydraulic fracturing fluids. The limited publicly available records disclose only a few stimulations per year.*

The federal government does not maintain a website or other public portal with data on the use of hydraulic fracturing from platforms in federal waters (federal waters are more than three nautical miles, or 5.6 km, from the coast) except for data that has been requested through the Federal Freedom of Information Act (FOIA). The FOIA records include about one hydraulic fracturing operation per year out of the 200 wells installed from 1992 through 2013, all but one of these operations were in the Santa Barbara-Ventura Basin (Volume I, Chapter 3). Through NPDES, EPA permits offshore facilities in federal waters to discharge recovered hydraulic fracturing fluids mixed with produced water to the ocean, subject to constraints on contaminant concentrations. However, the constraints do not include limits on hydraulic fracturing chemicals. EPA requires sampling of produced water discharge and testing these samples through a "whole effluent toxicity" or "WET" test that provides an integrated assessment of the toxicity of the effluent. However, these tests do not occur in coordination with any hydraulic fracturing operation, so they are likely to miss any impacts that hydraulic fracturing chemicals might cause.

> **Recommendation 1.2. Improve reporting of hydraulic fracturing and acid stimulation data in federal waters.**
>
> *The State of California should request that the federal government improve data collection and record keeping concerning well stimulation conducted in federal waters to at least match the requirements of SB 4. The U.S. EPA should conduct an assessment of ocean discharge and, based on these results, consider if alternatives to ocean disposal for well stimulation fluid returns are necessary (Volume III, Chapter 2 [Offshore Case Study]).*

**Principle 2. Prepare for potential future changes in hydraulic fracturing and acid stimulation practice in California.**

Additional oil and gas resources remain in and near reservoirs that are currently produced with hydraulic fracturing. Consequently, the near-term future for hydraulic fracturing will likely look much like the practice of today. On the other hand, a good estimate of the resource potential of the Monterey Formation source rock remains unavailable. The state should ask for a public scientific assessment of the potential of the Monterey Formation and keep track of exploration in this and similar geologic formations to be prepared for possible expansion of production via hydraulic fracturing or other stimulation technology.

**Conclusion 2.1. Future use of hydraulic fracturing in California will likely resemble current use.**

Future use of hydraulic fracturing will most likely expand production in and near existing oil fields in the San Joaquin Basin that currently require hydraulic fracturing.

The vast majority of hydraulic fracturing in the state takes place in the San Joaquin Basin in reservoirs that require this technology for economic production. A significant amount of oil remains in these reservoirs. Future additional development in these reservoirs would likely continue to use hydraulic fracturing (Volume I, Chapter 4; Volume III, Chapter 5 [San Joaquin Case Study]). Figure S.2-8 shows an example of how hydraulic-fracture-enabled production has expanded in the Cahn pool of the Lost Hills field in the San Joaquin Basin over time.

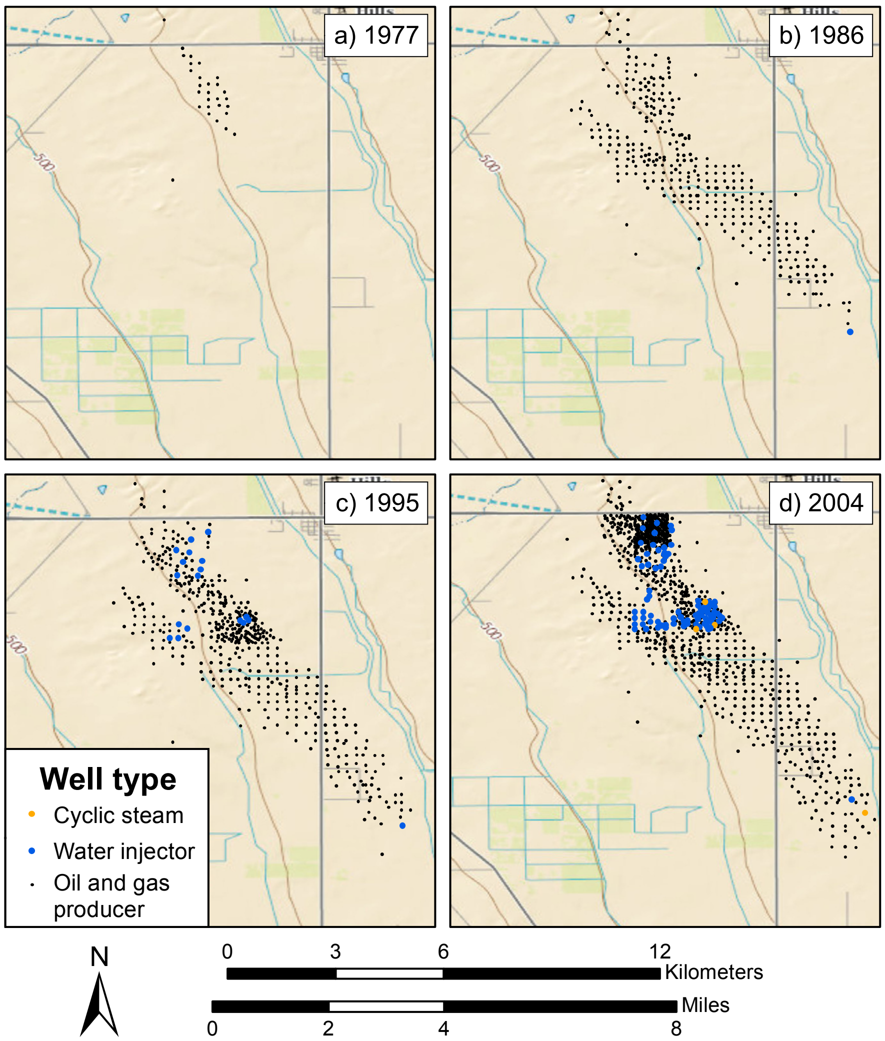



*Figure S.2-8. Growth in the number of wells operating over time in the Cahn pool in the Lost Hills field, one of the two pools in the field where hydraulic fracturing enables production. Data indicate that operators use hydraulic fracturing in almost all to all production wells in this field. Future growth in production would likely follow a similar pattern. The digital data on this field extends back to 1977. The primary well pattern reached nearly its full extent in 1986. By 1995, operators started infill drilling and by 2004, they were deploying water flooding (figure from Volume III, Chapter 5 [San Joaquin Case Study]).*

**Conclusion 2.2. Oil resource assessment and future use of hydraulic fracturing and acid stimulation in the Monterey Formation[7] of California remain uncertain.**

*In 2011, the U.S. Energy Information Administration (EIA) estimated that 15 billion barrels (2.4 billion* $m^3$*) of recoverable shale-oil resources existed in Monterey source rock. This caused concern about the potential environmental impacts of widespread shale-oil development in California using hydraulic fracturing. In 2014 the EIA downgraded the 2011 estimate by 96%. This study reviewed both EIA estimates and concluded that neither one can be considered reliable. Any potential for production in the Monterey Formation would be confined to those parts of the formation in the "oil window," that is, where Monterey Formation rocks have experienced the temperatures and pressures required to form oil. The surface footprint of this subset of the Monterey Formation expands existing regions of oil and gas production rather than opening up entirely new oil and gas producing regions. Significant unconventional gas resources (such as those of the Appalachian Basin Marcellus Shale or the Fort Worth Basin Barnett Formation which have been produced with large-scale hydraulic fracturing operations) probably do not exist in California.*

In 2011, the EIA reported that more than 15 billion barrels (2.4 billion $m^3$) of oil could be recovered from the "Monterey/Santos[8] (source rock) Play" across the state, presumably by means of hydraulic fracturing or acid stimulation. At the time, this estimate exceeded the estimated recoverable oil volume from source rock for the entire rest of the country. The EIA's projection, combined with widespread production using hydraulic fracturing of petroleum source rocks in North Dakota, Texas, and elsewhere, led to speculation and concern that similar development might be in the offing for California. Many Californians became concerned that California could experience a "boom-town" surge in oil production, i.e., activity in regions of the state that have not yet experienced oil production, unacceptable water use in a water-short state, water contamination, and health impacts. While no significant source-rock production has yet occurred in the state, future technical innovations might facilitate such development. A second EIA report, released in 2014, reduced the estimate of recoverable oil in Monterey source rocks to 0.6 billion barrels (0.1 billion $m^3$). Figure S.2-9 shows both these estimates. However, EIA provided little documentation to support either estimate. Consequently, neither of these estimates can be scientifically evaluated, and they do little to constrain the range of possible source rock oil resources in the Monterey Formation.

7. Appendix G provides an explanation of the terms Monterey Formation and Monterey Source Rock.

8. The 2011 and 2014 EIA assessments both use the term "Monterey/Santos" in describing the shale oil play in California. The "Santos" appears to be an erroneous reference to the Saltos shale of the Cuyama basin. Geochemical studies have not identified the Saltos shale as a significant source of hydrocarbons, so it is likely that the Monterey is the dominant source rock considered in the EIA evaluation.

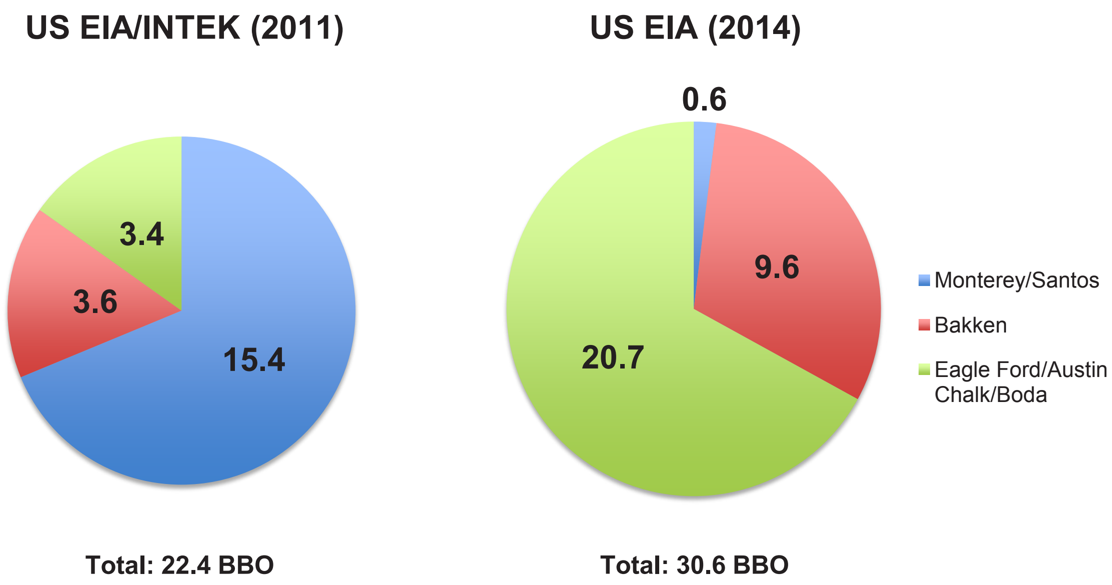



*Figure S.2-9. The Energy Information Administration 2011 and 2014 estimates of the potential of recoverable oil in source rock in the United States. The 2011 estimate for the Monterey/ Santos is more than 15 billion barrels (2.4 billion $m^3$), whereas the 2014 estimate decreases the Monterey estimate to about 4 % of the earlier estimate while increasing the total U.S. estimate by 30% (figure modified from Volume III, Chapter 1).*

The footprint of the oil and gas window of the Monterey Formation primarily expands the regions that currently produce oil and gas. No part of this footprint is more than 12 miles (~20 km) from existing production. Any potential future development of Monterey Formation source rocks would likely involve hydraulic fracturing or acid stimulation and would occur in the vicinity of current oil and gas producing regions with their existing infrastructure and economy (Figure S.2-10) (Volume III, Chapter 3 [Monterey Formation Case Study]).

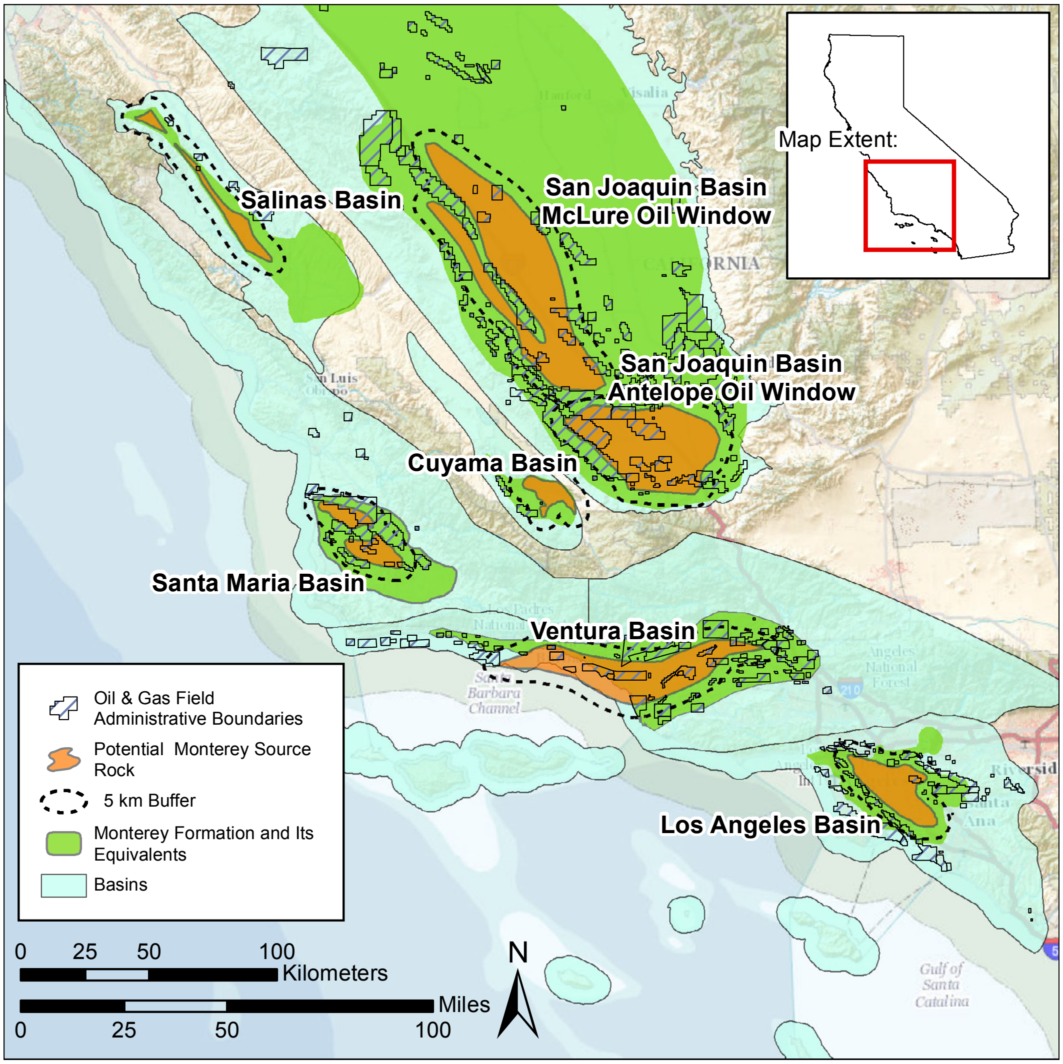



*Figure S.2-10. The approximate geographic footprint of those parts of the Monterey Formation in the oil and gas window (i.e. those parts that might be actively generating oil and gas) mapped along with current land use. Black hatching indicates the locations of existing oil fields. Thin black lines mark the footprint of the Monterey source rock oil window and dashed black lines mark a three-mile (~5 km) buffer to include uncertainty in the actual extent. Note that the boundaries of the Monterey source rock window are in the vicinity of existing oil and gas fields, but cover a larger area (Figure modified from Volume III, Chapter 3 [Monterey Formation Case Study]).*

The geological conditions in California do not likely include basin-wide gas accumulations. The Sacramento Basin, which contains the majority of dry gas reservoirs, does not exhibit the geological features of the Marcellus or Barnett Formations, or the Uinta-Piceance Basin, that would result in significant gas accumulations—at least at the depths that have been explored so far (Volume I, Chapter 4).

**Recommendation 2.1. Assess the oil resource potential of the Monterey Formation.**

*The state should request a comprehensive, science-based and peer-reviewed assessment of source-rock ("shale") oil resources in California and the technologies that might be used to produce them. The state could request such an assessment from the U.S. Geological Survey (USGS), for example.*

**Recommendation 2.2. Keep track of exploration in the Monterey Formation.**

*As expansive production in the Monterey Formation remains possible, DOGGR should track well permits for future drilling in the "oil window" of the Monterey source rocks (and other extensive source rocks, such as the Kreyenhagen) and be able to report increased activity (Volume I, Chapter 4; Volume III, Chapter 3 [Monterey Formation Case Study]).*

## S.3. Assessing Environmental and Health Impacts of Hydraulic Fracturing and Acid Stimulation in California

This scientific assessment of hydraulic fracturing and acid stimulation impacts covers the application of hydraulic fracturing and acid stimulation technology and resulting oil and gas production activities. The report considers impacts and potential impacts resulting from the development of a well pad and support infrastructure required to drill the well, hydraulic fracturing or acid stimulation and completion, production of oil and/or natural gas, and disposal or reuse of produced water. Figure S.3-1 shows the parts of the oil and gas system included in this assessment and examples of impacts for each.

This report excludes other stages in the development, production, refining, and use life cycle of oil and gas, including impacts of manufacturing of materials or equipment used in stimulation, impacts of transport of produced oil and gas to refineries or providers, impacts of refining, or impacts of combustion of hydrocarbons as fuel.

California regulations - including the state's new well stimulation regulations effective July 1, 2015 - address many of the areas of potential concern or risk raised in this study. This study does not address the effectiveness of the current regulatory framework in mitigating any potential risks associated with well stimulation technologies, but recommends that the state conduct such assessments in the future.

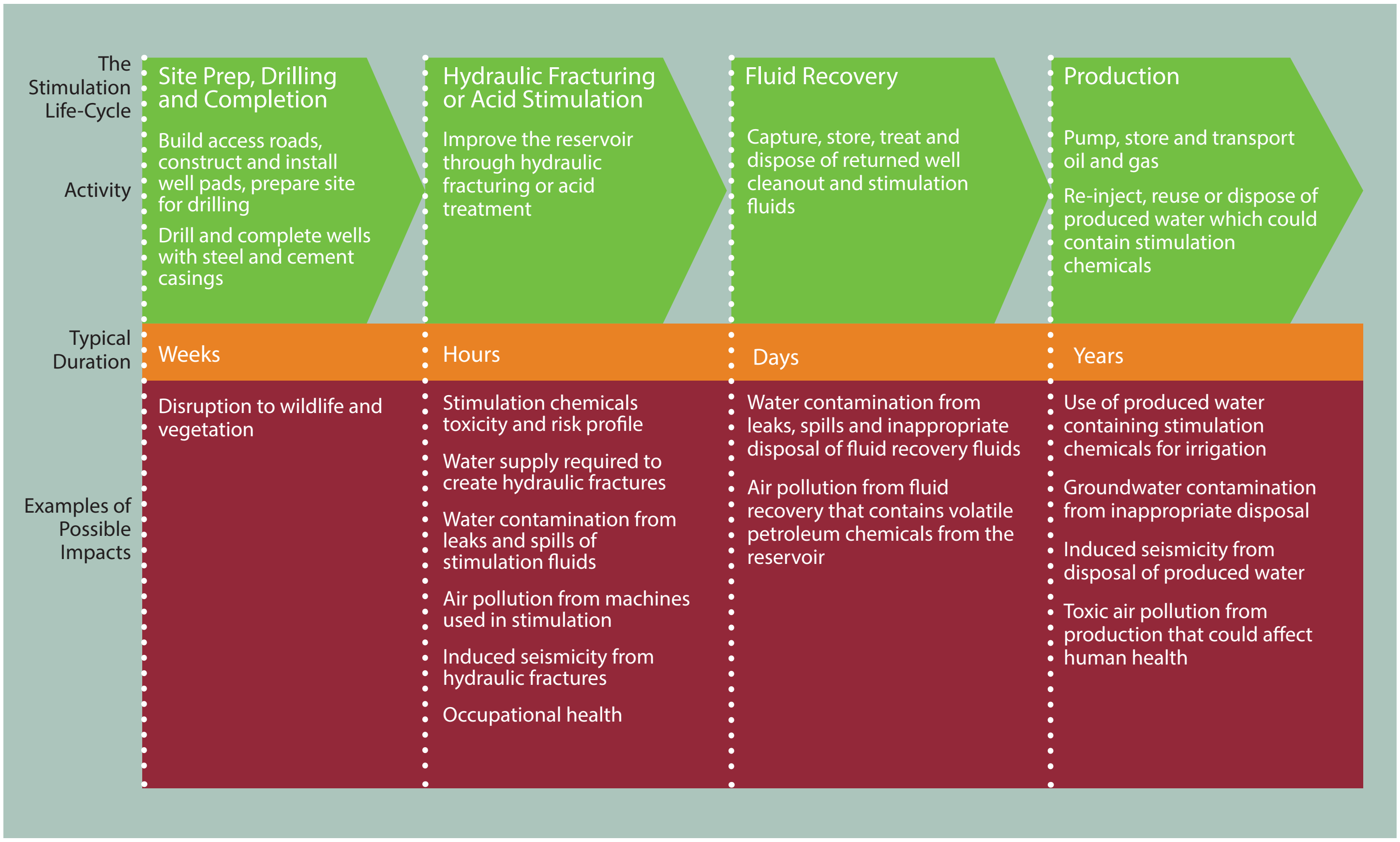



*Figure S.3-1. The sequential parts of the well stimulation system considered in this report (figure from Volume II, Chapter 1).*

**Principle 3. Account for and manage both direct and indirect impacts of hydraulic fracturing and acid stimulation.**

Hydraulic fracturing or acid stimulation can cause direct impacts. Potential direct impacts might include a hydraulic fracture extending into protected groundwater, accidental spills of fluids containing hydraulic fracturing chemicals or acid, or inappropriate disposal or reuse of produced water containing hydraulic fracturing chemicals. These direct impacts do not occur in oil and gas production unless hydraulic fracturing or acid stimulation has occurred. This study covers potential direct impacts of hydraulic fracturing or acid stimulation.

## Box S.3-1. Water Nomenclature

Water with specialized chemicals used to create a hydraulic fracture is called “hydraulic fracturing fluid” or “stimulation fluid.” The term “flowback” denotes the return of fluids used in the hydraulic fracturing operation, but there is no specific point in time when all hydraulic fracturing fluid returns. Some of this fluid reacts with the rock, and some is pushed into the rock and does not return for some time, if at all. Consequently, the term flowback has limited utility. Instead, we use the term “recovered” fluids to denote all fluids collected before oil production begins. Recovered fluids likely contain relatively high concentrations of hydraulic fracturing chemicals, but not necessarily all of the chemicals injected into the well. In California, the recovered fluids are typically stored in tanks at the well site prior to injection into Class II disposal wells. After the production of oil starts, water comes along with the oil, and this is called “produced water.” In California’s mature reservoirs, oil wells usually produce a mixture of about 10% oil and 90% water. Produced water from hydraulically fractured wells can contain hydraulic fracturing chemicals, their reaction products, salt, and other contaminants from the petroleum reservoir. Produced water can be disposed of, for example via injection into the underground, or may be treated and have beneficial reuse. For example, produced water could be injected back into the reservoir to maintain reservoir pressure or, if of low enough salinity, used in irrigation. The term “wastewater” refers collectively to produced water and recovered fluids. Wastewater that cannot be reused must be disposed of.

Hydraulic fracturing or acid stimulation can also incur indirect impacts, i.e., those not directly attributable to the activity itself. Some reservoirs require hydraulic fracturing for economic production. All activities associated with oil and gas production enabled by hydraulic fracturing or acid stimulation can bring about indirect impacts. Indirect impacts of hydraulic-fracturing-enabled oil and gas development usually occur in all oil and gas development, whether or not the wells are stimulated.

In some cases, we cannot separate direct and indirect impacts. For example, the inventory of emissions of hazardous air pollutants is for all oil and gas production and does not differentiate between hydraulically fractured and unfractured wells, so the data do not support differentiating direct and indirect impacts. However, as illustrated in the following examples, differentiating direct and indirect impacts can be important for framing investigations and policy.

An indirect impact common to all production, not just production enabled by hydraulic fracturing, means the impacts incurred by just the hydraulically fractured wells represent a small subset of the problem. For example, disposal of produced water through underground injection may carry the risk of inducing an earthquake. If this produced water comes from a hydraulically fractured reservoir, this potential impact would be an indirect impact. In California, about 20% of all produced waters come from stimulated reservoirs. Understanding induced seismicity requires looking at all the wastewater injections, not just those generated by hydraulically fractured wells. In this case, the indirect impact attributed to hydraulically fractured wells represents a minority part of a larger issue.

As another example, studies show elevated health risks near hydraulically fractured reservoirs attributable to benzene (Volume II, Chapter 6). But benzene use has been phased out in hydraulic fracturing fluids. These health risks probably occur due to processes associated with oil production, because oil contains benzene naturally. In this case, the health impacts do not occur because of hydraulic fracturing itself; they are indirect impacts that occur because of production. So the same health impacts could occur near any production, whether the wells have been fractured or not. Research that focuses only on benzene impacts near hydraulically fractured wells will likely result in a very poor understanding of both the extent of this problem and the possible mitigation measures. Concern about hydraulic fracturing might lead to studying health effects near fractured wells, but concern about the health effects from benzene should lead to study of all types of oil and gas production, not just hydraulically fractured wells.

As a final example, the activities associated with hydraulic fracturing or acid stimulation can add some new direct occupational hazards to a business that already has substantial occupational hazards. The drilling, completion, and production phases common to all oil and gas production incur significant risk of exposure to many toxic substances and accidents. In general, oil and gas production has significant occupational health issues, but these impacts are not directly attributable to well stimulation activity. In hydraulic fracturing, silica sand used for the proppant in hydraulic fracturing presents an additional occupational health hazard for serious lung disease (silicosis). Potential exposure to silica is a direct impact of hydraulic fracturing and a relatively small part of the total hazard profile for oil and gas development.

While this project was not tasked with a full assessment of the impacts of all oil and gas development in California, we have described indirect impacts in the context of all oil and gas production where the issue and associated data either allows or requires this. This report does include some recommendations for assessment of certain impacts for all oil and gas development in the future.

Table S.3-1 describes the potential direct impacts of hydraulic fracturing and acid stimulation, plus potential indirect impacts of hydraulic-fracturing-enabled oil and gas development covered in this report.[9] The table includes issues of concern that were named in the SB 4 legislation, raised by the public in the various forums around California and the U.S., or identified by expert judgment. A long list of features, events, and processes related to well stimulation and production could possibly lead to harmful impacts, but these are not all likely or equally likely. A long list of plausible hazards have been described in Volume II, but the reader is cautioned to treat these as a "checklist" of possible impacts, not at all a list of impacts that are generally occurring. Existing regulations prevent or mitigate many of these risks; however, an evaluation of the effectiveness of this regulatory framework was beyond the scope of this study.

Out of the possible plausible hazards, some emerge as especially relevant potential risk factors worthy of further attention through additional data collection or increased scrutiny. Appendix F presents a table of these risk issues, which are also the basis of the conclusions and recommendations in this section.

9. We do not include indirect impacts of acid stimulation because based on existing data, we did not find reservoirs that required acid stimulation for production.

*Table S.3-1. Examples of direct and indirect impacts considered in this study.*

| Issue | Possible Direct Impact Considered in This Study | Possible Indirect Impact Because of Hydraulic-Fracturing-Enabled Oil and Gas Development Considered in This Study |
|---|---|---|
| Stimulation Chemicals | Chemicals used in stimulation create the potential for introduction of hazardous materials into the environment. | N/A |
| Water Use[10] | Stimulation uses California fresh water supply. | Freshwater is sometimes used to produce oil in a previously stimulated reservoir, e.g., enhanced oil recovery via injection of water or steam. |
| Water Supply | Stimulation chemicals could enter produced water that is otherwise of sufficient quality for beneficial uses, such as irrigation, making treatment more complicated. | Additional production enabled by hydraulic fracturing can lead to additional produced water, which, with appropriate treatment, may be of sufficient quality for beneficial uses. |
| Water Contamination | Intentional or accidental releases of stimulation chemicals and their reaction products could lead to contamination of fresh water supply. Risk of hydraulic fractures acting as conduit for accidental releases of fluids; and risk of high-pressure injection affecting integrity of existing wells. | N/A |
| Air pollution | Equipment used in stimulation emits pollutants and greenhouse gases (GHGs). Retention ponds and tanks used to store stimulation fluids could contain off-gassing volatile organic compounds (VOC). | Oil and gas development activities cause emissions including VOC emissions from produced water. |
| Induced Seismicity | Hydraulic fracturing could cause earthquakes. | Disposal of wastewater from hydraulic fracture-enabled production in disposal wells classified by the EPA's Underground Injection Control (UIC) program as "Class II"[11] could cause earthquakes. |
| Human Health | Releases of stimulation chemicals that pollute water and air, as well as noise and light pollution from the stimulation operation could affect public health. | Proximity to any oil production, including stimulation-enabled production, could result in hazardous emissions to air and water, and noise and light pollution that could affect public health. |
| Wildlife and Vegetation | Introduction of invasive species; contamination of habitat or food web by stimulation chemicals; and water use for stimulation fluids could impact wildlife and vegetation. | Habitat loss and fragmentation, introduction of invasive species, and water use for enabled enhanced oil recovery could impact wildlife and vegetation. |

10. We cover water use in Section S.2 above as a characteristic of current practice, but water use is also an impact of hydraulic fracturing.

11. Class II wells are underground injection wells that inject fluids associated with oil and natural gas production. There are three types of Class II wells: enhanced recovery, wastewater disposal, and hydrocarbon storage. For more information, see http://water.epa.gov/type/groundwater/uic/class2/index.cfm.

**Conclusion 3.1. Direct impacts of hydraulic fracturing appear small, but have not been investigated.**

*Available evidence indicates that impacts caused directly by hydraulic fracturing or acid stimulation or by activities directly supporting these operations appear smaller than the indirect impacts associated with hydraulic-fracturing-enabled oil and gas development, or limited data precludes adequate assessment of these impacts. Good management and mitigation measures can address the vast majority of potential direct impacts of well stimulation.*

Hydraulic fracturing in California lasts a relatively short amount of time near the beginning of production—less than a day—and requires relatively small fluid volumes. In contrast, the subsequent oil and gas production phase lasts for years and involves very large volumes of fluid, with potential for long-term perturbations of the environment. Consequently, the production phase following well stimulation can have a much larger impact than the stimulation phase.

This study identifies a number of possible pathways for direct impacts from hydraulic fracturing and acid stimulation, such as accidental spills or leaks of hydraulic fracturing or acid fluids or emissions of volatile organic compounds (VOCs) from hydraulic fracturing fluids. Many, if not all, of these potential direct impacts can be addressed with good management practices or mitigation measures. These are described in Volumes II and III.

The recommendations below provide specific measures that could eliminate, avoid, or ameliorate direct impacts. These measures include limiting the use of toxic chemicals, avoiding inappropriate disposal, managing beneficial use of produced water containing stimulation chemicals, providing extra due diligence for shallow fracturing near protected groundwater, and using “green completions” to control emissions in oil and gas wells.

In California, existing or pending regulation already addresses many of these direct impacts. The state’s new well stimulation regulations, going into effect on July 1, 2015, will likely avoid or reduce many, but not all, of the impacts described in this report. The scope of this study did not include judging the adequacy of existing regulation, but this would make sense at some later time when significant experience can be assessed.

**Recommendation 3.1. Assess adequacy of regulations to control direct impacts of hydraulic fracturing and acid stimulations.**

*Over the next several years, relevant agencies should assess the adequacy and effectiveness of existing and pending regulations to mitigate direct impacts of hydraulic fracturing and acid stimulations, such as to: (1) reduce the use of highly toxic or harmful chemicals, or those with unknown environmental profiles in hydraulic fracturing and acid fluids; (2) devise adequate treatment and testing for any produced waters intended for beneficial reuse that may include hydraulic fracturing and acid fluids or disallow this practice; (3) prevent shallow hydraulic* *fractures from intersecting protected groundwater (Volume II); (4) dispose of produced waters that contain stimulation chemicals appropriately; and (5) control emissions, leaks and spills.*

**Conclusion 3.2. Operators have unrestricted use of many hazardous and uncharacterized chemicals in hydraulic fracturing.**

*The California oil and gas industry uses a large number of hazardous chemicals during hydraulic fracturing and acid treatments. The use of these chemicals underlies all significant potential direct impacts of well stimulation in California. This assessment did not find recorded negative impacts from hydraulic fracturing chemical use in California, but no agency has systematically investigated possible impacts. A few classes of chemicals used in hydraulic fracturing (e.g., biocides, quaternary ammonium compounds, etc.) present larger hazards because of their relatively high toxicity, frequent use, or use in large amounts. The environmental characteristics of many chemicals remain unknown. We lack information to determine if these chemicals would present a threat to human health or the environment if released to groundwater or other environmental media. Application of green chemistry principles, including reduction of hazardous chemical use and substitution of less hazardous chemicals, would reduce potential risk to the environment or human health.*

Operators have few, if any, restrictions on the chemicals used for hydraulic fracturing and acid treatments. The state's regulations address hazards from chemical use and eliminate or minimize many, but not necessarily all risks. Some of the chemicals used present hazards in the workplace or locally, such as silica dust or hydrofluoric acid. Other chemicals present potential hazards for the environment, such as biocides and surfactants that, if released, can harm fish and other wildlife. Many of the chemicals used can harm human health. If well stimulation did not use hazardous chemicals, hydraulic fracturing would pose a much smaller risk to humans and the environment. Even so, hazardous chemicals only present a risk to humans or the environment if they are released in hazardous concentrations or amounts, persist in the environment, and actually reach and affect a human, animal or plant. Even a very toxic or otherwise harmful chemical presents no risk if no person, animal or plant receives a dose of the chemical. Characterization of the risk posed by chemical use requires information on both the hazards posed by the chemicals and information about exposure to the chemicals (in other words, risk = hazard x exposure).

We have established a list of chemicals used in California based on voluntary disclosures by industry. In California, oil and gas production operators have voluntarily reported the use of over 300 chemical additives. New state regulations under SB 4 will eventually reveal all chemical use. However, knowledge of the hazards and risks associated with all the chemicals remains incomplete for almost two-thirds of the chemicals (Table S.3-2). The toxicity and biodegradability of more than half the chemicals used in hydraulic fracturing remains uninvestigated, unmeasured, and unknown. Basic information about how these chemicals would move through the environment does not exist. Although the probability of human and environmental exposure is estimated to be low, no direct studies of environmental or health impacts from hydraulic fracturing and acid stimulation chemicals have been completed in California. To the extent that any hydraulic fracturing and acid stimulation fluids can get into the environment, reduction or elimination of the use of the most hazardous chemicals will reduce risk.

***Table S.3-2. Availability of information for characterizing the hazard of stimulation chemicals used in hydraulic fracturing. The Chemical Abstracts Service Registry Number (CASRN) is a unique numerical identifier assigned to chemical substances. Operators do not provide CASRN numbers for proprietary chemicals.***

| Number of chemicals | Proportion of all chemicals | Identified by unique CASRN | Impact or toxicity | Quantity of use or emissions |
|---|---|---|---|---|
| 172 | 55% | Available | Available | Available |
| 17 | 5% | Available | Available | Unavailable |
| 6 | 2% | Available | Unavailable | Available |
| 121 | 38% | Unavailable | Unavailable | Available |

For this study, we sorted the extensive list of chemicals reported in California to identify those of most concern or interest and created tables identifying selected chemicals for each category contributing to hazard (see Appendix H and Volume II, Chapters 2 and 6). Chemicals used most frequently or in high concentrations rise to a higher level of concern, as do chemicals known to be acutely toxic to aquatic life or mammals. The assessment included chemicals used in hydraulic fracturing that can be found on the Toxic Air Contaminant Identification List, the Proposition 65 list of chemicals known to the State of California to cause cancer and reproductive harm, and the OEHHA list of chemicals with published reference exposure limits. Additional hazards considered include, flammability, corrosivity, and reactivity. These various criteria allow identification of priority chemicals to consider when reducing potential hazards from chemical use during well stimulation.

Strong acids, strong bases, silica, biocides, quaternary ammonium compounds, nonionic surfactants, and a variety of solvents are used frequently and in high concentrations in hydraulic fracturing and acid stimulation. Strong acids, strong bases, silica, and many solvents present potential exposure hazards to humans, particularly during handling, and of are of particular concern to workers and nearby residents. Use of appropriate procedures minimizes the risk of exposure and few incidences of the release of these materials during oil and gas development have been reported in California.

Biocides, quaternary ammonium compounds, nonionic surfactants, and some solvents present a significant hazard to aquatic species and other wildlife, particularly when released into surface water. The study found no releases of hazardous hydraulic fracturing chemicals to surface waters in California and no direct impacts to fish or wildlife. However, there is concern that well stimulation chemicals might have been released and potentially contaminated groundwater through a variety of mechanisms (see Conclusions 4.1, 4.3, 4.4, 5.1, 5.2 below). Many of the chemicals used in well stimulation, such as surfactants, are more harmful to the environment than to human health, but all of these chemicals are undesirable in drinking water. Determining whether chemicals that have been released pose an actual risk to human health or the environment requires further study, including a better understanding of the amounts of chemicals released and persistence of those chemicals in the environment.

Green Chemistry principles attempt to maintain an equivalent function while using less toxic chemicals and smaller amounts of toxic chemicals. It may be possible to forego or reduce the use of the most hazardous chemicals without losing much in the way of functionality. Chemical substitutions can present complications and can also introduce a new set of hazards and require a careful adaptive approach. For example, the use of guar in hydraulic fracturing fluids introduces food to bacteria in the reservoir, and this increases the need for biocides to prevent the buildup of toxic gases generated by bacterial growth. Operators moving to a less toxic but less effective biocide might also need to move away from guar to a less-digestible substitute. Then this choice could introduce new hazards instead of old hazards. For these reasons, the American Chemical Society currently sponsors a Green Chemistry Roundtable on the topic of hydraulic fracturing.

The state could also limit the chemicals used in hydraulic fracturing by disallowing certain chemicals or limiting chemicals to those on an approved list where approval depends on the chemical having an acceptable environmental profile. The latter approach reverses the usual practice, whereby an industry is permitted to use a chemical until a regulatory body proves that the chemical is harmful. Oil and gas production in the environmentally sensitive North Sea uses this pre-approval approach and might provide a model for limiting chemical risk in California. The EPA Designed for the Environment (DFE) list of chemicals may also be useful. Of course, any of these approaches requires that the operators report the unique identifier (CASRN number) of all chemicals.

**Recommendation 3.2. Limit the use of hazardous and poorly understood chemicals.**

*Operators should report the unique CASRN identification for all chemicals used in hydraulic fracturing and acid stimulation, and the use of chemicals with unknown environmental profiles should be disallowed. The overall number of different chemicals should be reduced, and the use of more hazardous chemicals and chemicals with poor environmental profiles should be reduced, avoided, or disallowed. The chemicals used in hydraulic fracturing could be limited to those on an approved list that would consist only of those chemicals with known and acceptable environmental hazard profiles. Operators should apply Green Chemistry principles to the formulation of hydraulic fracturing fluids, particularly for biocides, surfactants, and quaternary ammonium compounds, which have widely differing potential for environmental harm. Relevant state agencies, including DOGGR, should as soon* *as practical engage in discussion of technical issues involved in restricting chemical use with a group representing environmental and health scientists and industry practitioners, either through existing roundtable discussions or independently (Volume II, Chapters 2 and 6).*

**Conclusion 3.3. The majority of impacts associated with hydraulic fracturing are caused by the indirect impacts of oil and gas production enabled by the hydraulic fracturing.**

*Impacts caused by additional oil and gas development enabled by well stimulation (i.e. indirect impacts) account for the majority of environmental impacts associated with hydraulic fracturing. A corollary of this conclusion is that all oil and gas development causes similar impacts whether the oil is produced with well stimulation or not. If indirect impacts caused by additional oil and gas development enabled by hydraulic fracturing cause concern, these concerns in most cases extend to any oil and gas development. As hydraulic fracturing enables only 20% of production in California, only about 20% of any given indirect impact is likely attributable to hydraulically fractured reservoirs.*

Without hydraulic fracturing, oil and gas production from certain reservoirs would not be possible. If this oil and gas development did not occur, then the impacts of this development would not occur. Well stimulation is a relatively brief operation done after a well is installed, but oil and gas development goes on for years, involving construction of infrastructure and disruption of the landscape. Operators build roads, ponds, and well pads, and install pumps, field separators, tanks, and treatment systems in reservoirs that are stimulated and in those that are not. Surface spills and subsurface leakage may lead to impacts on groundwater quality as an impact of production. The life of a production well involves production of many millions of gallons of water that must be treated or disposed of properly. Production with or without stimulation can cause emission of pollutants over many years, often in proximity to places where people live, work, and go to school. Whereas the short-term injection of fluids for the purpose of hydraulic fracturing is unlikely to cause a felt or damaging earthquake (a direct impact), the subsurface disposal of millions of gallons of water produced along with oil over the life of a well can present a seismic hazard. The inappropriate disposal of produced water can contaminate protected groundwater, whether this water contains stimulation chemicals or not. All oil and gas development potentially incurs impacts similar to the indirect impacts of hydraulic fracturing.

**Recommendation 3.3. Evaluate impacts of production for all oil and gas development, rather than just the portion of production enabled by well stimulation.**

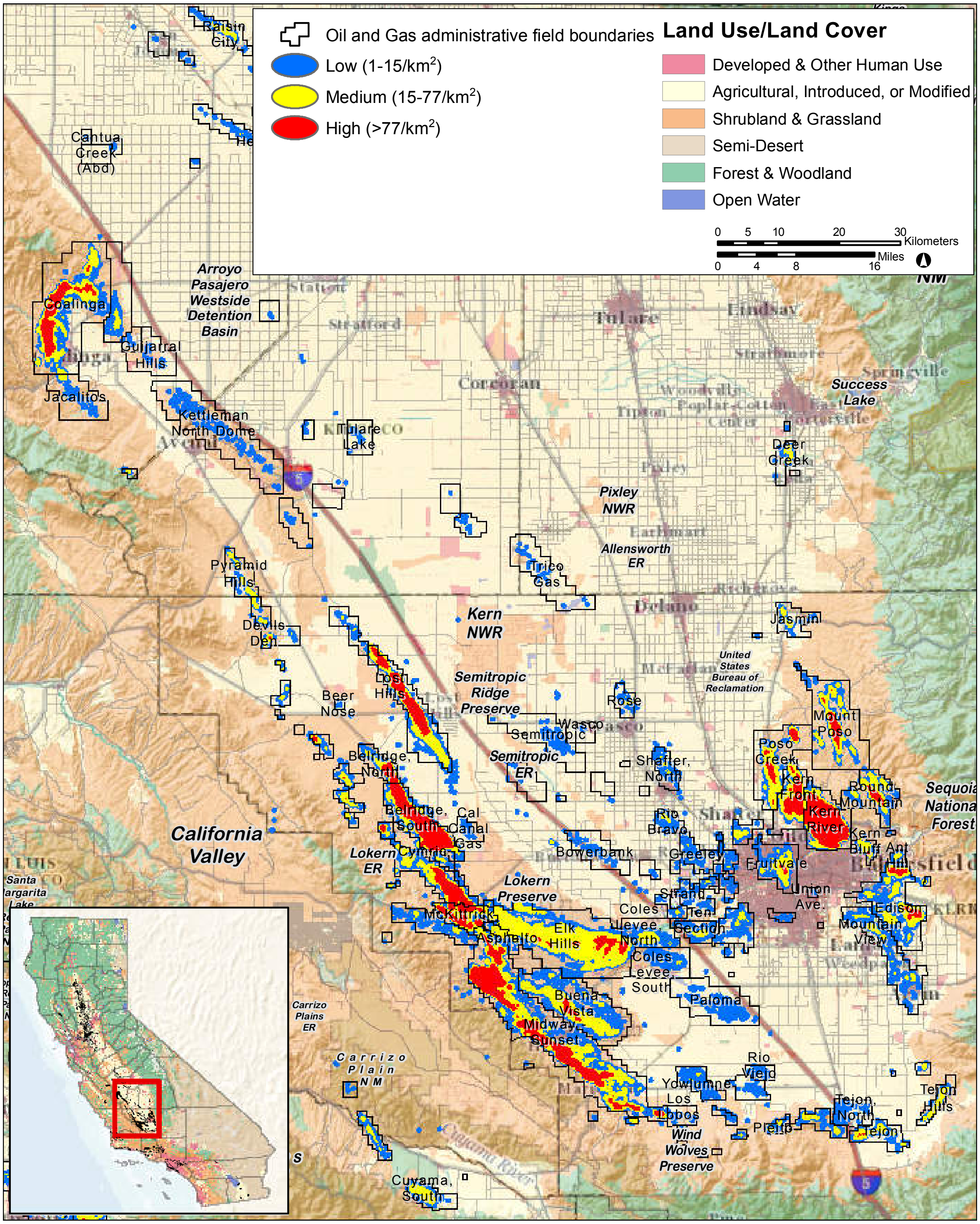
*Concern about hydraulic fracturing might cause focus on impacts associated with production from fractured wells, but concern about these indirect impacts should lead to study of all types of oil and gas production, not just production enabled by hydraulic fracturing. Agencies with jurisdiction should evaluate impacts of concern* *for all oil and gas development, rather than just the portion of development enabled by well stimulation. As appropriate, many of the rules and regulations aimed at mitigating indirect impacts of hydraulic fracturing and acid stimulation should also be applied to all oil and gas wells (Volume II, Chapters 5 and 6).*

**Conclusion 3.4. Oil and gas development causes habitat loss and fragmentation.**

*Any oil and gas development, including that enabled by hydraulic fracturing, can cause habitat loss and fragmentation. The location of hydraulic fracturing-enabled development coincides with ecologically sensitive areas in Kern and Ventura Counties.*

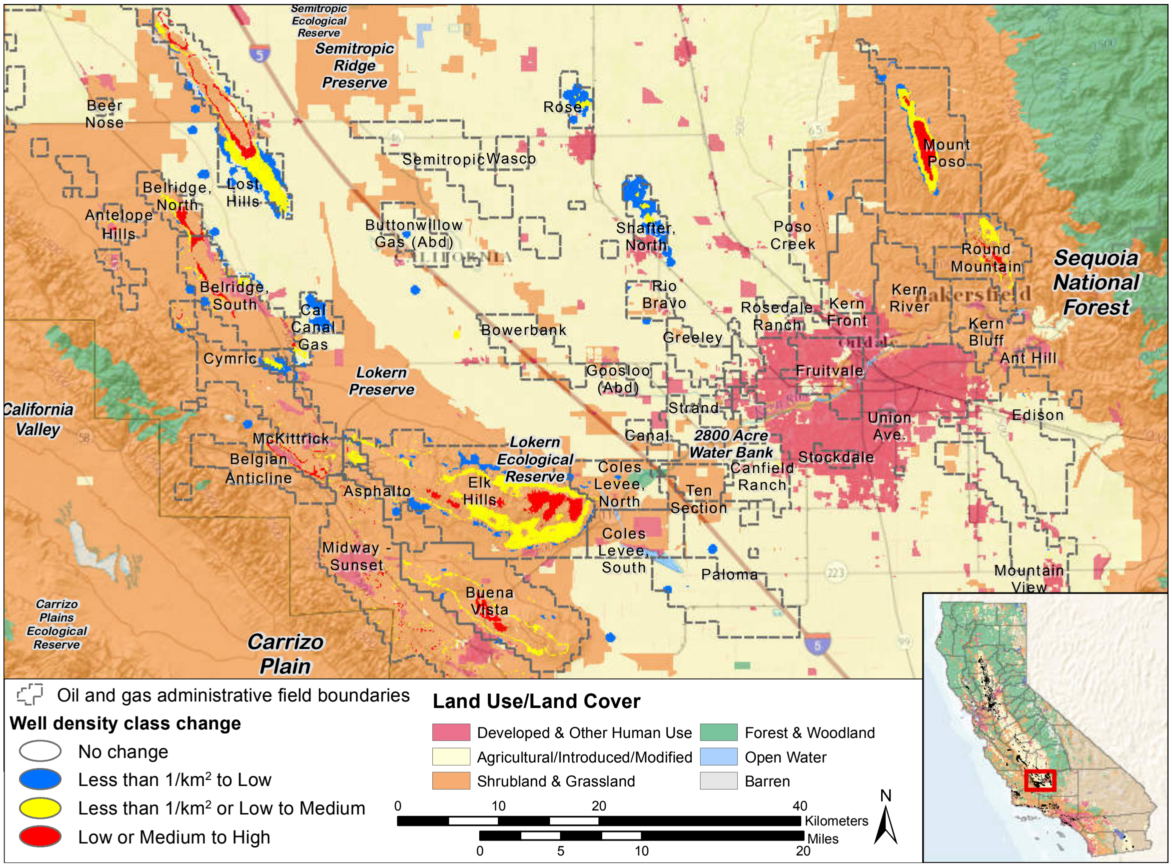
The impact to habitat for native wildlife and vegetation caused by increases in well density depends on the background land use. Some California oil and gas fields are already so densely filled with well pads that other human land uses and native species habitat cannot coexist. Other oil and gas fields have relatively sparse infrastructure interspersed with cities, farms, and natural habitat. The impact caused by increases in well density depends on the background land use. Oil wells installed into agricultural land (such as Rose and Shafter oil fields), or urban areas such as Los Angeles, create only minor impacts to native species. Increases in well density and habitat disturbance from well pads, roads, and facilities cause substantial loss and fragmentation of valuable habitat in those oil and gas fields inhabited by native wildlife and vegetation.

Elk Hills, Mt. Poso, Buena Vista, and Lost Hills fields in Kern County and the Sespe, Ojai, and Ventura fields in Ventura County host substantial amounts of hydraulic fracturing-enabled development as well as rare habitat types and associated endangered species. Portions of oil fields in Kern County are essential to support resident populations of rare species and serve as corridors for maintaining connectivity between remaining areas of natural habitat (including protected areas), and these are vulnerable to expanded production (Figure S.3 -2).



Oil and Gas administrative field boundaries
Low (1-15/km2)
Medium (15-77/km2)
High (>77/km2)
Land Use/Land Cover
Developed & Other Human Use
Agricultural, Introduced, or Modified
Shrubland & Grassland
Semi-Desert
Forest & Woodland
Open Water
0 5 10 20 30 Kilometers
0 4 8 16 Miles
Coalinga
Jacalitos
Kettleman North Dome
Arroyo Pasajero Westside Detention Basin
Pyramid Hills
Devils Den
Lost Hills
Belridge, North
Belridge, South
Cymric
McKittrick
Asphalto
Elk Hills
Buena Vista
Midway-Sunset
Kern NWR
Semitropic Ridge Preserve
Semitropic ER
Lokern ER
Lokern Preserve
California Valley
Carrizo Plain NM
Cuyama, South
Pixley NWR
Allensworth ER
Trico Gas
Jasmin
Mount Poso
Poso Creek
Kern Front
Kern River
Round Mountain
Kern Bluff
Edison
Mountain View
Fruitvale
Rosedale Ranch
Coles Levee, North
Coles Levee, South
Paloma
Yowlumne
Los Lobos
Wind Wolves Preserve
Tejon, North
Tejon
Tejon Hills
Rio Viejo
Rio Bravo
Greeley
Bowerbank
Shafter, North
Rose
Semitropic
Wasco
Beer Nose
Cal Canal Gas
Strand
Ten Section
Union Ave.
Deer Creek
Tulare Lake
Raisin City
Cantua Creek (Abd)
Guijarral Hills
Success Lake
Sequoia National Forest
United States Bureau of Reclamation
Carrizo Plains ER


a.




b.

*Figure S.3-2. a) Well density in the San Joaquin basin. Opaque blue, yellow and red indicate the density of all wells. b) The portion of wells that were hydraulically fractured. Opaque blue, yellow and red indicate areas that have greater well density because of hydraulic fracturing-enabled production. Increases in well density cause habitat loss and fragmentation. Hydraulic fracturing-enabled development causes a small portion of the habitat loss caused by oil and gas production in the state, although much of the hydraulic fracturing is concentrated in areas of valuable natural habitat. All wells that had recorded activity from January 1977 through September 2014 are shown. Background shading indicates land use and cover categories.*

Ecologically sensitive areas require the conservation of habitat to compensate for new oil and gas development. Currently, no regional planning strategy exists to coordinate habitat conservation efforts in a manner that would ensure continued viable populations of rare species. While possible to compensate only for habitat loss caused by hydraulic fracturing-enabled development, a more logical approach would account for habitat loss from oil and gas production as a whole. Maintaining habitat connectivity in the southwestern San Joaquin will likely require slowing or halting increases in well pad density in dispersal corridors. This type of planning, such as the Kern County Valley Floor Habitat Restoration Plan, has not succeeded in the past, but a renewed effort would safeguard the survival of threatened and endangered species.

**Recommendation 3.4. Minimize habitat loss and fragmentation in oil and gas producing regions.**

*Enact regional plans to conserve essential habitat and dispersal corridors for native species in Kern and Ventura Counties. The plans should identify top-priority habitat and restrict development of those areas. The plan should also define and require those practices, such as clustering multiple wells on a pad and using centralized networks of roads and pipes, which will minimize future surface disturbances. A program to set aside compensatory habitat in reserve areas when oil and gas development causes habitat loss and fragmentation should be developed and implemented (Volume II, Chapter 5; Volume III, Chapter 5 [San Joaquin Basin Case Study]).*

**Principle 4. Manage water produced from hydraulically fractured or acid stimulated wells appropriately.**

Large volumes of water of various salinities and qualities get produced along with the oil. Oil reservoirs tend to yield increasing quantities of water over time, and most of California's oil reservoirs have been in production for several decades to over a century. For 2013, more than 3 billion barrels (.48 billion $m^3$ or about 400,000 AF) of water came along with some 0.2 billion barrels (.032 billion $m^3$) of oil in California. Operators re-inject some produced water back into the oil and gas reservoirs to help recover more petroleum and mitigate land subsidence. In other cases, farmers use this water for irrigation; often blending treated produced water with higher-quality water to reduce salinity. Disposal or reuse of produced water without proper precautions can cause contamination of groundwater and more so, if this water contains chemicals from hydraulic fracturing and acid stimulation. Underground injection of produced water can cause earthquakes.

**Conclusion 4.1. Produced water disposed of in percolation pits could contain hydraulic fracturing chemicals.**

*Based on publicly available data, operators disposed of some produced water from stimulated wells in Kern County in percolation pits. The effluent has not been tested to determine if there is a measureable concentration of hydraulic fracturing chemical constituents. If these chemicals were present, the potential impacts to groundwater, human health, wildlife, and vegetation would be extremely difficult to predict, because there are so many possible chemicals, and the environmental profiles of many of them are unmeasured.*

A commonly reported disposal method for produced water from stimulated wells in California is by evaporation and percolation in percolation surface impoundments, also referred to as percolation pits, as shown in Figure S.3-3. Information from 2011 to 2014 indicates that operators dispose of some 40-60% of the produced water from hydraulically fractured wells in percolation pits during the first full month of production after stimulation. The range in estimated proportion stems from uncertainties about which wells were stimulated prior to mandatory reporting. Produced water from these wells may contain hazardous chemicals from hydraulic fracturing treatments, as well as reaction byproducts of those chemicals. We do not know how long hydraulic fracturing chemicals persist in produced water or at what concentrations or how these change in time, which means that hazardous levels of contaminants in produced water disposed into pits cannot be ruled out.

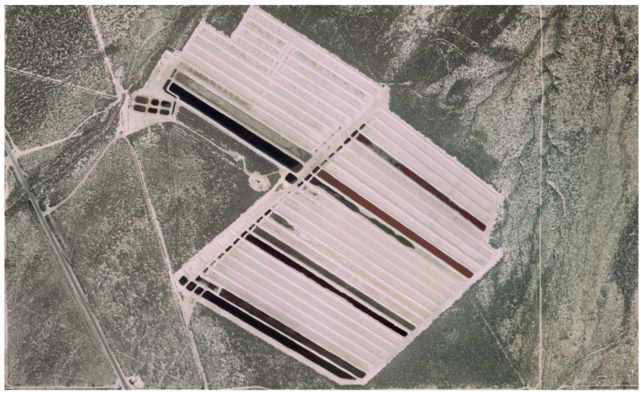


***Figure S.3-3. Percolation pits in Kern County used for produced water disposal (figure modified from Volume II, Chapter 1). Image courtesy of Google Earth***

The primary intent of percolation pits is to percolate water into the ground. This practice provides a potential direct pathway to transport produced water constituents, including returned hydraulic fracturing fluids, into groundwater aquifers. Groundwater contaminated in this way could subsequently intercept rivers, streams, and surface water resources. Contaminated water used by plants (including food crops), humans, fish, and wildlife could introduce contaminants into the food chain. Some states, including Kentucky, Texas and Ohio, have phased out the use of percolation pits for produced water disposal, because their use has demonstrably contaminated groundwater.

Operators have reported disposal of produced water in percolation pits in several California counties (e.g., Fresno, Monterey, and Tulare counties). However, records from 2011 to mid-2014 show that percolation pits received produced water from hydraulically fractured wells only in Kern County. Specifically, wells in the Elk Hills, South Belridge, North Belridge, Lost Hills, and Buena Vista fields were hydraulically fractured, and these fields disposed of produced water to percolation pits in the region under the jurisdiction of the CVRWQCB. An estimated 36% of percolation pits in the Central Valley operate without necessary permits from the CVRWQCB.

The data reported to DOGGR may contain errors on disposition of produced water. For example, DOGGR's production database shows that, during the past few years, one operator discharged produced water to percolation pits at Lost Hills, yet CVRWQCB ordered the closure of percolation pits at Lost Hills in 2009.[12]

Data collected pursuant to the recent Senate Bill 1281 (SB 1281) will shed light on the disposition of produced water and locations of percolation pits statewide. With the data available as of the writing of this report, we cannot rule out that some produced water from hydraulically fractured wells at other fields went to percolation pits and that this water might have contained chemicals used in hydraulic fracturing. Figure S.3-4 shows that many of these pits overlie protected groundwater. The pending well stimulation regulations, effective July 1, 2015, disallow fluid produced from a stimulated well from being placed in percolation pits.[13]

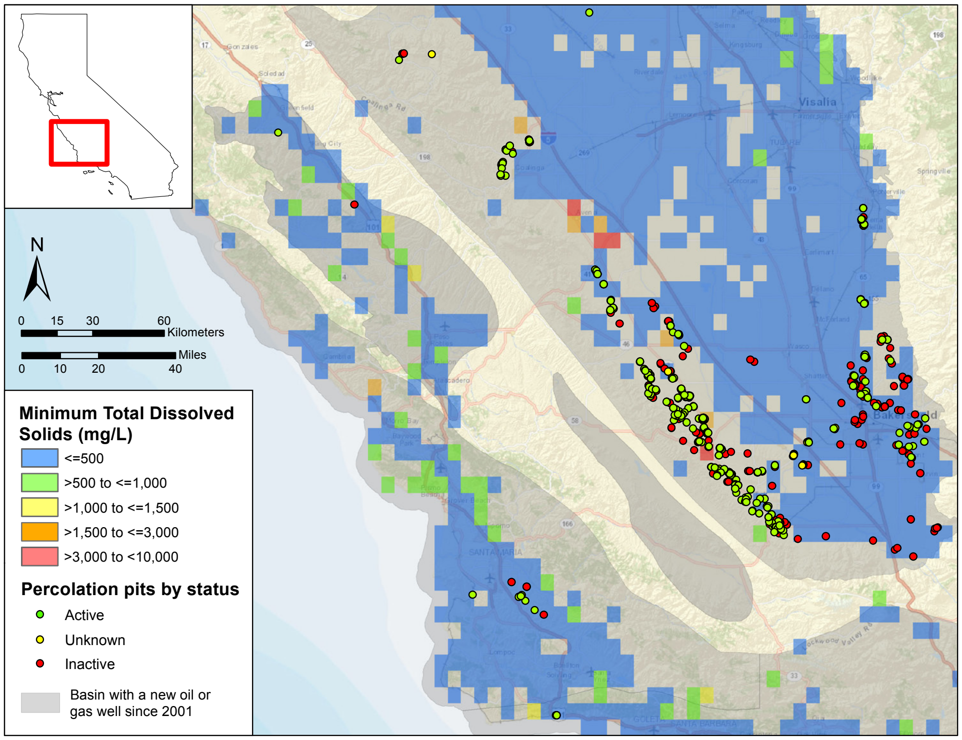



*Figure S.3-4. Location of percolation pits in the Central Valley and Central Coast used for produced water disposal and the location of groundwater of varying quality showing that many percolation pits are located in regions that have potentially protected groundwater shown in color (figure from Volume II, Chapter 2).*

12. Order R5-2013-0056, Waste Discharge Requirements for Chevron USA, Inc., Central Valley Regional Water Quality Control Board.

13. Title 14 California Code of Regulations, Section 1786(a)(4)

**Recommendation 4.1. Ensure safe disposal of produced water in percolation pits with appropriate testing and treatment or phase out this practice.**

*Agencies with jurisdiction should promptly ensure through appropriate testing that the water discharged into percolation pits does not contain hazardous amounts of chemicals related to hydraulic fracturing as well as other phases of oil and gas development. If the presence of hazardous concentrations of chemicals cannot be ruled out, they should phase out the practice of discharging produced water into percolation pits. Agencies should investigate any legacy effects of discharging produced waters into percolation pits including the potential effects of stimulation fluids (Volume II, Chapter 2; Volume III, Chapters 4 and 5 [Los Angeles Basin and San Joaquin Basin Case Studies]).*

**Conclusion 4.2. The chemistry of produced water from hydraulically fractured or acid stimulated wells has not been measured.**

*Chemicals used in each hydraulic fracturing operation can react with each other and react with the rocks and fluids of the oil and gas reservoirs. When a well is stimulated with acid, the reaction of the acid with the rock minerals, petroleum, and other injected chemicals can release contaminants of concern in the oil reservoirs, such as metals or fluoride ions that have not been characterized or quantified. These contaminants may be present in recovered and produced water.*

An average of about 25 different chemicals are used in each hydraulic fracturing operation. As discussed in Conclusion 3.2, some of these can be quite hazardous alone and chemical reactions can results in new constituents. Acids used in well treatments quickly react with rock minerals and become neutralized. But acids can dissolve and mobilize naturally occurring heavy metals and other pollutants in the oil-bearing formation. Neutralized hydrofluoric acid can release toxic fluoride ions into groundwater. Assessment of the environmental risks posed by hydraulic fracturing and acid use along with commonly associated chemicals, such as corrosion inhibitors, requires more complete disclosure of chemical use and a better understanding of the chemistry of treatment fluids and produced water returning to the surface. We found no characterization of the chemistry of produced water from wells that have been hydraulically fractured or stimulated with acid.

**Recommendation 4.2. Evaluate and report produced water chemistry from hydraulically fractured or acid stimulated wells.**

*Evaluate the chemistry of produced water from hydraulically fractured and acid stimulated wells, and the potential consequences of that chemistry for the environment. Determine how this chemistry changes over time. Require reporting of all significant chemical use, including acids, for oil and gas development (Volume II, Chapters 2 and 6).*

**Conclusion 4.3. Required testing and treatment of produced water destined for reuse may not detect or remove chemicals associated with hydraulic fracturing and acid stimulation.**

*Produced water from oil and gas production has potential for beneficial reuse, such as for irrigation or for groundwater recharge. In fields that have applied hydraulic fracturing or acid stimulations, produced water may contain hazardous chemicals and chemical byproducts from well stimulation fluids. Practice in California does not always rule out the beneficial reuse of produced water from wells that have been hydraulically fractured or stimulated with acid. The required testing may not detect these chemicals, and the treatment required prior to reuse necessarily may not remove hydraulic fracturing chemicals.*

Growing pressure on water resources in the state means more interest in using produced water for a range of beneficial purposes, such as groundwater recharge, wildlife habitat, surface waterways, irrigation, etc. Produced water could become a significant resource for California.

However, produced water from wells that have been hydraulically fractured may contain hazardous chemicals and chemical by-products. Our study found only one oil field where both hydraulic fracturing occurs and farmers use the produced water for irrigation. In the Kern River field in the San Joaquin Basin, hydraulic fracturing operations occasionally occur, and a fraction of the produced water goes to irrigation (for example, Figure S.3-5). But we did not find policies or procedures that would necessarily exclude produced water from hydraulically fractured wells from use in irrigation.

***Figure S.3-5. Produced water used for irrigation in Cawelo water district. Photo credit: Lauren Sommer/KQED (figure from Volume II, Chapter 1).***

The regional water quality control boards require testing and treatment of produced water prior to use for irrigation, but the testing does not include hydraulic fracturing chemicals, and required treatment would not necessarily remove hazardous stimulation fluid constituents if they were present. Regional water-quality control boards have also established monitoring requirements for each instance where produced water is applied to irrigated lands; however, these requirements do not include monitoring for constituents specific to, or indicative of, hydraulic fracturing.

Safe reuse of produced water that may contain stimulation chemicals requires appropriate testing and treatment protocols. These protocols should match the level of testing and treatment to the water-quality objectives of the beneficial reuse. However, designing the appropriate testing and treatment protocols to ensure safe reuse of waters contaminated with stimulation chemicals presents significant challenges, because so many different chemicals could be present, and the safe concentration limits for many of them have not been established. Hydraulic fracturing chemicals may be present in extremely small concentrations that present negligible risk, but this has not been confirmed.

Limiting hazardous chemical use as described in Recommendation 3.2 would also help to limit issues with reuse. Disallowing the reuse of produced water from hydraulically fractured wells would also solve this problem, especially in the first years of production. This water could be tested over time to determine if hazardous levels of hydraulic fracturing chemicals remain before transitioning this waste stream to beneficial use.

> **Recommendation 4.3. Protect irrigation water from contamination by hydraulic fracturing chemicals and stimulation reaction products.**
>
> *Agencies of jurisdiction should clarify that produced water from hydraulically fractured wells cannot be reused for purposes such as irrigation that could negatively impact the environment, human health, wildlife and vegetation. This ban should continue until or unless testing the produced water specifically for hydraulic fracturing chemicals and breakdown products shows non-hazardous concentrations, or required water treatment reduces concentrations to non-hazardous levels (Volume II, Chapter 2; Volume III, Chapter 5 [San Joaquin Basin Case Study]).*

**Conclusion 4.4. Injection wells currently under review for inappropriate disposal into protected aquifers may have received water containing chemicals from hydraulic fracturing.**

*DOGGR is currently reviewing injection wells in the San Joaquin Valley for inappropriate disposal of oil and gas wastewaters into protected groundwater. The wastewaters injected into some of these wells likely included stimulation chemicals because hydraulic fracturing occurs nearby.*

In 2014, DOGGR began to evaluate injection wells in California used to dispose of oil field wastewater. DOGGR found that some wells inappropriately allowed injection of wastewater into protected groundwater and subsequently shut them down. DOGGR's ongoing investigation will review many more wells to determine if they are injecting into aquifers that should be protected.

Figure S.3-6 is a map of the Elks Hills field in the San Joaquin Basin showing one example where hydraulically fractured wells exist near active water disposal wells. The DOGGR review includes almost every disposal well in this field for possible inappropriate injection into protected water. Some of the produced water likely came from nearby production wells that were hydraulically fractured. Consequently, the injected wastewater possibly contained stimulation chemicals at some unknown concentration.

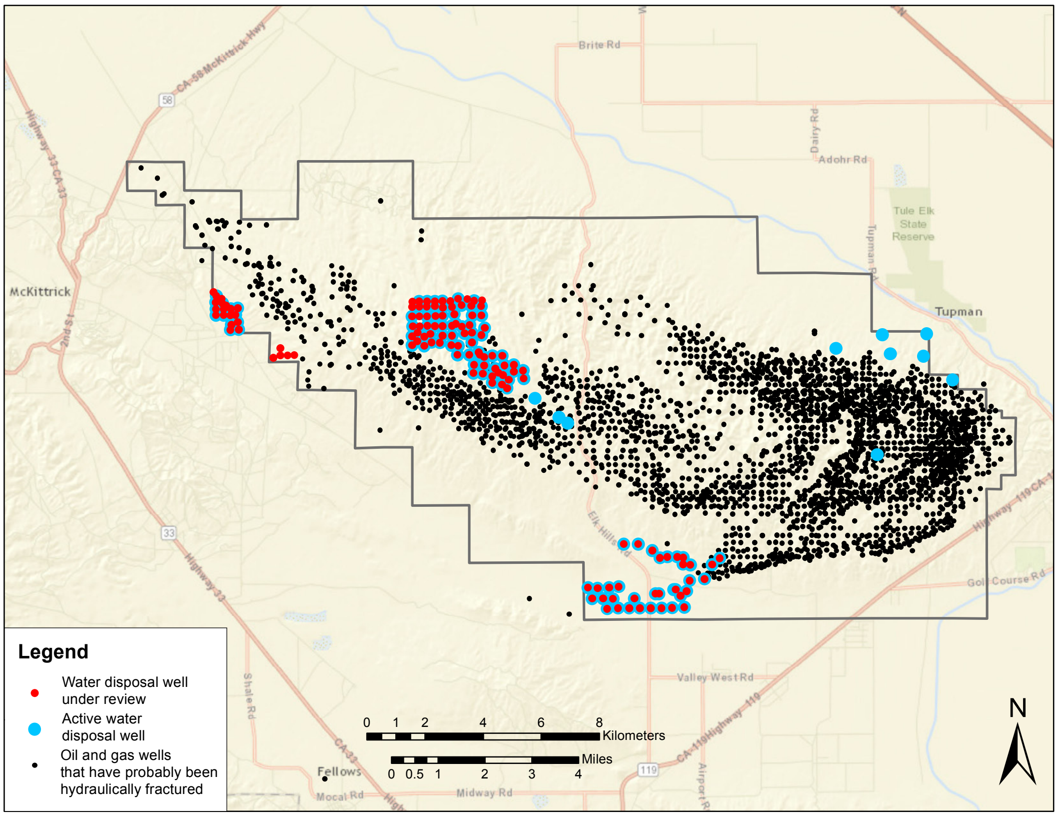



*Figure S.3-6. A map of the Elk Hills field in the San Joaquin Basin showing the location of wells that have probably been hydraulically fractured (black dots). Blue dots are the location of active water disposal wells, and blue dots with a red center are the location of disposal wells under review for possibly injecting into groundwater that should be protected (figure from Volume II, Chapter 1).*

**Recommendation 4.4. In the ongoing investigation of inappropriate disposal of wastewater into protected aquifers, recognize that hydraulic fracturing chemicals may have been present in the wastewater.**

*In the ongoing process of reviewing, analyzing, and remediating the potential impacts of wastewater injection into protected groundwater, agencies of jurisdiction should include the possibility that hydraulic fracturing chemicals may have been present in these wastewaters (Volume II, Chapter 2; Volume III, Chapter 5 [San Joaquin Basin Case Study]).*

**Conclusion 4.5. Disposal of wastewater by underground injection has caused earthquakes elsewhere.**

*Fluid injected in the process of hydraulic fracturing will not likely cause earthquakes of concern. In contrast, disposal of produced water by underground injection could cause felt or damaging earthquakes. To date, there have been no reported cases of induced seismicity associated with produced water injection in California. However, it can be very difficult to distinguish California's frequent natural earthquakes from those possibly caused by water injection into the subsurface.*

Hydraulic fracturing causes a pressure increase for a short amount of time and affects relatively small volumes of rock. For this reason, hydraulic fracturing has a small likelihood of producing felt (i.e., sensed), let alone damaging, earthquakes. In California, only one small earthquake (which occurred in 1991) has been linked to hydraulic fracturing to date (Volume II, Chapter 4).

Disposal into deep injection wells of water produced from oil and gas operations has caused felt seismic events in several states, but there have been no reported cases of induced seismicity associated with wastewater injection in California. The volume of produced water destined for underground injection could increase for a number of reasons, and disposal of increased volumes by injection underground could increase seismic hazards.

California has frequent naturally occurring earthquakes—so many that seismologists have a hard time determining if any of these earthquakes were actually induced by fluid injection. In areas like Kansas that do not have frequent earthquakes, it is much easier to find correlations between an earthquake and human activity. In the future, the amount of fluid requiring underground injection in California could increase locally due to expanded production or a change in disposal practice. Such change in practice might incur an unacceptable seismic risk, but understanding this possible risk requires a better understanding of the current correlation between injection and earthquakes, if any.

California also has many geologic faults. Figure S.3-7 shows a map of California earthquake epicenters, the location of wastewater disposal wells active since 1981 and faults in the USGS database in central and southern California. Across all six oil-producing basins, over 1,000 wells are located within 1.5 mile (2.5 km) of a mapped active fault, and more than 150 within 650 ft (200 m).

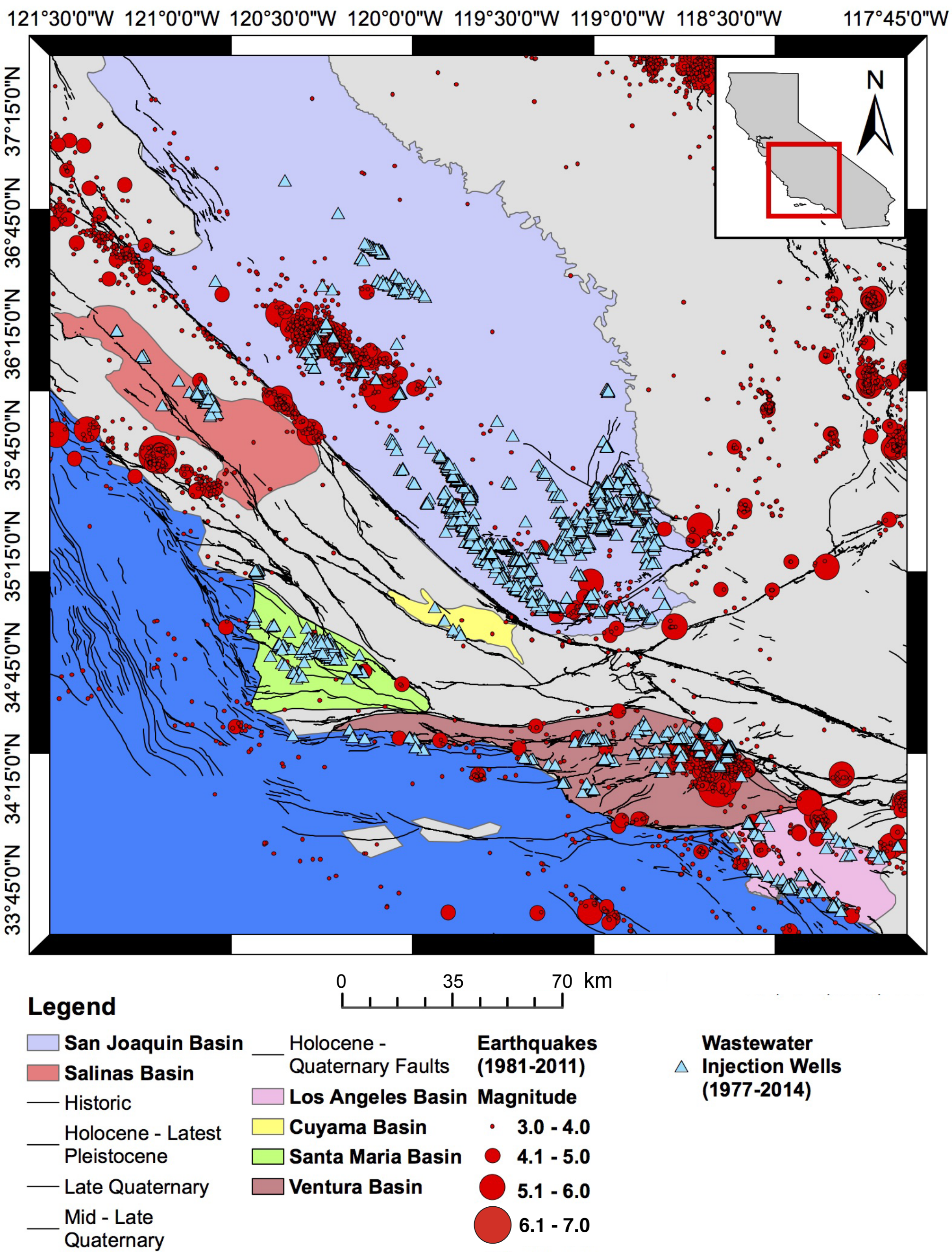



*Figure S.3-7. High-precision locations for earthquakes M≥3 in central and southern California during the period 1981-2011), and active and previously active water disposal wells from DOGGR (figure from Volume II, Chapter 4).*

A systematic regional-scale analysis of earthquake occurrence in relation to water injection would help identify if induced seismicity exists in California. This study should include statistical characterizations and geomechanical analysis for induced seismicity and will require more detailed data than that currently reported by industry on injection depth, variations in fluid injection rate, and pressure over time. Currently, operators report the volume of injected water and wellhead pressures only as monthly averages. Analysts will need to know more about exactly when, how, how much, where injection occurred to identify a potential relationship between earthquakes and injection patterns. A systematic study will also require geophysical characterization of oil field test sites, detailed seismic monitoring, and modeling of the subsurface pressure changes produced by injection in the vicinity of the well.

The state could likely manage and mitigate potential induced seismicity, by adopting protocols to modify an injection operation when and if seismic activity is detected. The protocol could require reductions in injection flow rate and pressure, and shutting down the well altogether if the risk of an earthquake rises above some threshold. Currently, ad hoc protocols exist for this purpose. Better protocols would require monitoring the reservoir and local seismic activity, and formal calculation of the probability of inducing earthquakes of concern.

> **Recommendation 4.5. Determine if there is a relationship between wastewater injection and earthquakes in California.**
>
> *Conduct a comprehensive multi-year study to determine if there is a relationship between oil and gas-related fluid injection and any of California's numerous earthquakes. In parallel, develop and apply protocols for monitoring, analyzing, and managing produced water injection operations to mitigate the risk of induced seismicity. Investigate whether future changes in disposal volumes or injection depth could affect potential for induced seismicity (Volume II, Chapter 4).*

**Conclusion 4.6. Changing the method of wastewater disposal will incur tradeoffs in potential impacts.**

*Based on publicly available data, operators dispose of much of the produced water from stimulated wells in percolation pits (evaporation-percolation ponds), about a quarter by underground injection (in Class II wells), and less than one percent to surface bodies of water. Changing the method of produced water disposal could decrease some potential impacts while increasing others.*

Figure S.3-8 shows the results of an analysis of disposal methods of produced water from known stimulated wells in the first full month after stimulation during the period from 2011 to 2014. As much as 60% of the water was sent to percolation pits, also known as evaporation-percolation ponds, as discussed in Conclusion 4.1 Second to this, produced water from stimulated wells was injected into Class II wells for disposal or enhanced oil recovery. With proper regulation, siting, construction, and maintenance, subsurface injection is less likely to result in groundwater contamination than disposal in percolation pits.

However, increasing injection volumes could increase the risk of induced seismicity, discussed in Conclusion 4.5. Also, concerns have recently emerged about whether California's Class II underground injection control (UIC) program provides adequate protection for underground sources of drinking water (USDWs), as discussed in Conclusion 4.4, USDWs are defined as groundwater aquifers that currently or could one day supply water for human consumption. The least common method of dealing with wastewater, disposal to surface bodies of water, can, for example, augment stream flows, but requires careful testing and treatment to ensure the water is safe, especially if stimulation chemicals could be present.

The DOGGR monthly production data either do not specify the disposal method or report as "other" for 17% of the produced water from known stimulated wells. This reporting category could include subsurface injection, disposal to a surface body of water, sewer disposal, or water not disposed of but reused for irrigation or another beneficial purpose, as described in Conclusion 4.3.

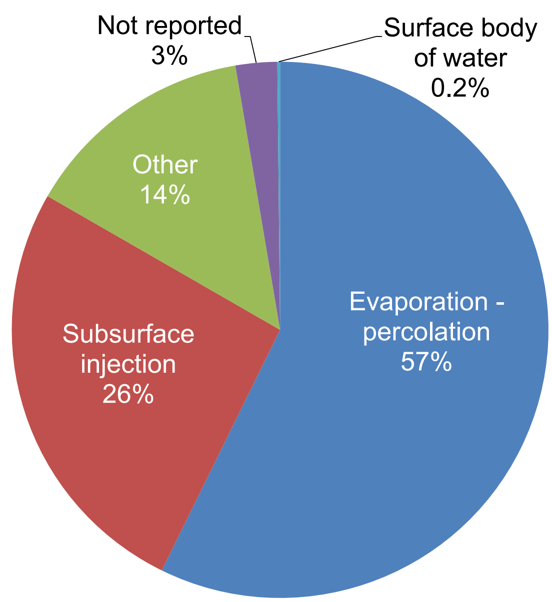



*Figure S.3-8. Disposal method for produced water from hydraulically fractured wells during the first full month after stimulation for the time period 2011-2014 based on data from the DOGGR monthly production database. Note: Subsurface injection includes any injection into Class II wells, which include disposal wells as well as enhanced recovery wells used for water flooding and steam flooding (figure from Volume II, Chapter 2).*

Changing the method of produced water disposal or reuse will incur tradeoffs. Any attempt to reduce one disposal method must consider the likely outcome that other disposal methods will increase. For example, eliminating disposal in evaporation–percolation pits can lead to an increase in other disposal methods to make up the difference. In particular, closure of percolation pits or injection wells found to be contaminating protected aquifers would increase the use of other disposal methods, and this will require careful planning and management on a regional basis.

**Recommendation 4.6. Evaluate tradeoffs in wastewater disposal practices.**

*As California moves to change disposal practices, for example by phasing out percolation pits or stopping injection into protected aquifers, agencies with jurisdiction should assess the consequences of modifying or increasing disposal via other methods (Volume II, Chapter 2; Volume II, Chapter 4).*

**Principle 5. Add protections to avoid groundwater contamination by hydraulic fracturing.**

Hydraulic fracturing operations could contaminate groundwater through a variety of pathways. We found no documented instances of hydraulic fracturing or acid stimulations directly causing groundwater contamination in California. However, we did find that fracturing in California tends to be in shallow wells and in mature reservoirs that have many existing boreholes. These practices warrant more attention to ensure that they have not and will not cause contamination.

**Conclusion 5.1. Shallow fracturing raises concerns about potential groundwater contamination.**

*In California, about three quarters of all hydraulic fracturing operations take place in shallow wells less than 2,000 ft (600 m) deep. In a few places, protected aquifers exist above such shallow fracturing operations, and this presents an inherent risk that hydraulic fractures could accidentally connect to the drinking water aquifers and contaminate them or provide a pathway for water to enter the oil reservoir. Groundwater monitoring alone may not necessarily detect groundwater contamination from hydraulic fractures. Shallow hydraulic fracturing conducted near protected groundwater resources warrants special requirements and plans for design control, monitoring, reporting, and corrective action.*

Hydraulic fractures produced in deep formations far beneath protected groundwater are very unlikely to propagate far enough upwards to intersect an aquifer. Studies performed for high-volume hydraulic fracturing elsewhere in the country have shown that hydraulic fractures have propagated no further than 2,000 feet (ft; 600 m) vertically, so hydraulic fracturing conducted many thousands of feet below an aquifer is not expected to reach a protected aquifer far above. In California, however, and particularly in the San Joaquin Basin, most hydraulic fracturing occurs in relatively shallow reservoirs, where protected groundwater might be found within a few hundred meters (Figure S.3-9). A few instances of shallow fracturing have also been reported in the Los Angeles Basin (Figure S.3-10), but overall much less than the San Joaquin Basin. No cases of contamination have yet been reported, but there has been little to no systematic monitoring of aquifers in the vicinity of oil production sites.

Shallow hydraulic fracturing presents a higher risk of groundwater contamination, which groundwater monitoring may not detect. This situation warrants additional scrutiny. Operations with shallow fracturing near protected groundwater could be disallowed or be subject to additional requirements regarding design, control, monitoring, reporting, and corrective action, including: (1) pre-project monitoring to establish a base-line of chemical concentrations, (2) detailed prediction of expected fracturing characteristics prior to starting the operation, (3) definition of isolation between expected fractures and protected groundwater, providing a sufficient safety margin with proper weighting of subsurface uncertainties, (4) targeted monitoring of the fracturing operation to watch for and react to evidence (e.g., anomalous pressure transients, microseismic signals) indicative of fractures growing beyond their designed extent, (5) monitoring groundwater to detect leaks, (6) timely reporting of the measured or inferred fracture characteristics confirming whether or not the fractures have actually intersected or come close to intersecting groundwater, (7) preparing corrective action and mitigation plans in case anomalous behavior is observed or contamination is detected, and (8) adaption of groundwater monitoring plans to improve the monitoring system and specifically look for contamination in close proximity to possible fracture extensions into groundwater.

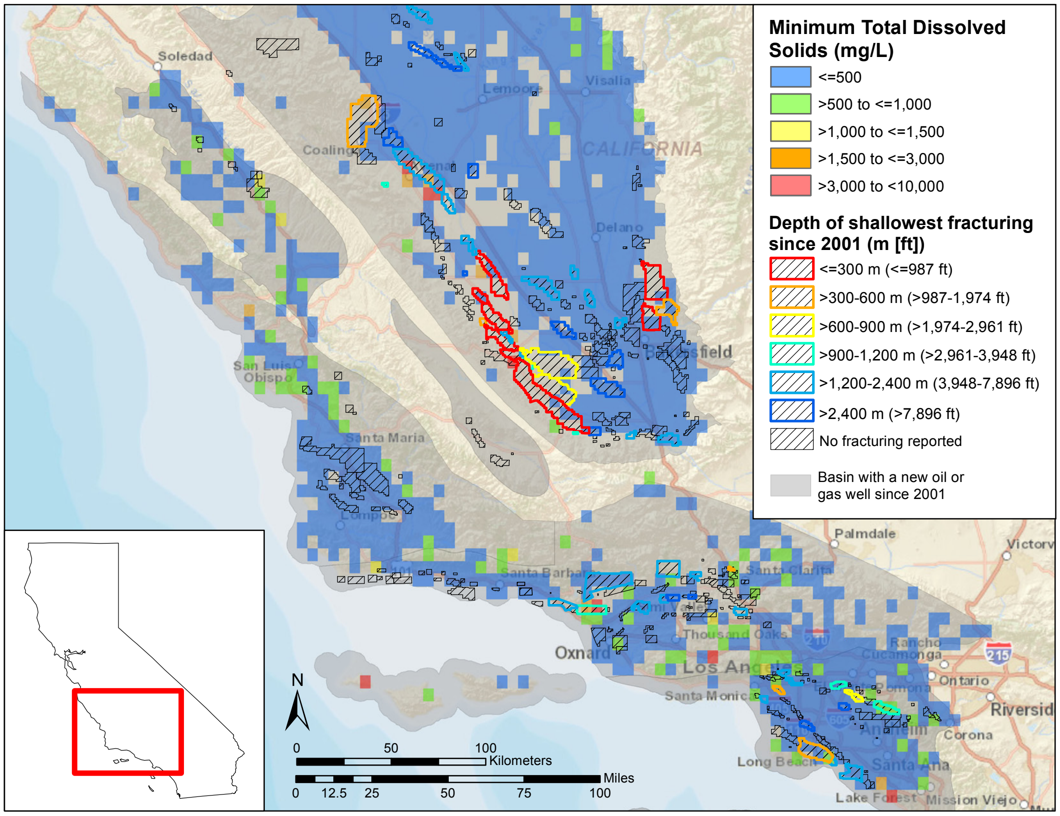



*Figure S.3-9. Shallow fracturing locations and groundwater quality in the San Joaquin and Los Angeles Basins. Some high quality water exists in fields that have shallow fractured wells (figure from Volume II, Chapter 2).*

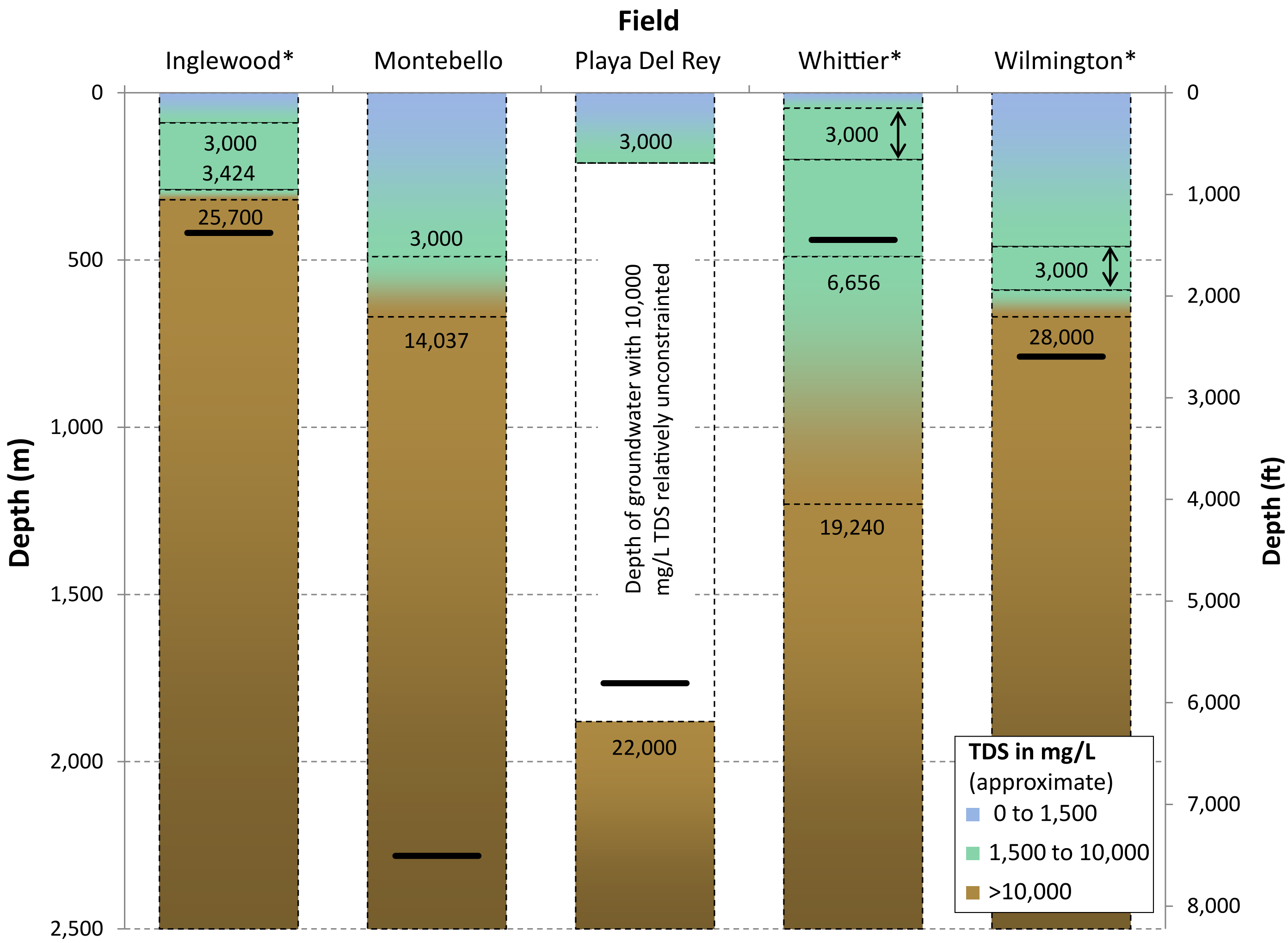



*Figure S.3-10. Depths of groundwater total dissolved solids (TDS) in mg/L in five oil fields in the Los Angeles Basin. The numbers indicate specific TDS data and the colors represent approximate interpolation. The depth of 3,000 mg/L TDS is labeled on all five fields. Blue (<3,000 mg/L) and aqua (between 3,000 mg/L and 10,000 mg/L) colors represent protected groundwater. Depth of 10,000 mg/L TDS is uncertain, but it is estimated to fall in the range where aqua transitions to brown. The heavy black horizontal line indicates the shallowest hydraulically fractured well interval in each field. (Asterisks denote the fields of most concern for the proximity of hydraulic fracturing to groundwater with less than 10,000 mg/L TDS.) (figure from Volume III, Chapter 4 [Los Angeles Basin Case Study]).*

The potential for shallow hydraulic fractures to intercept protected groundwater requires both knowing the location and quality of nearby groundwater and accurate information about the extent of the hydraulic fractures. Maps of the vertical depth of protected groundwater with less than 10,000 mg/L TDS for California oil producing regions do not yet exist. Analysis and field verification could identify typical hydraulic fracture geometries; this would help determine the probability of fractures extending into groundwater aquifers. Finally, detection of potential contamination and planning of mitigation measures requires integrated site-specific and regional groundwater monitoring programs.

The pending SB 4 well stimulation regulations, effective July 1, 2015, require operators to design fracturing operations so that the fractures avoid protected water, and to implement appropriate characterization and groundwater monitoring near hydraulic fracturing operations. However, groundwater monitoring alone does not ensure protection of water, nor will it necessarily detect contamination should it occur. The path followed by contamination underground can be hard to predict, and may bypass a monitoring well. Groundwater monitoring can give false negative results in these cases,[14] and does nothing to stop contamination from occurring in any case.

**Recommendation 5.1. Protect groundwater from shallow hydraulic fracturing operations.**

*Agencies with jurisdiction should act promptly to locate and catalog the quality of groundwater throughout the oil-producing regions. Operators proposing to use hydraulic fracturing operation near protected groundwater resources should be required to provide adequate assurance that the expected fractures will not extend into these aquifers and cause contamination. If the operator cannot demonstrate the safety of the operation with reasonable assurance, agencies with jurisdiction should either deny the permit, or develop protocols for increased monitoring, operational control, reporting, and preparedness (Volume I, Chapter 3; Volume II, Chapter 2; Volume III, Chapter 5 [San Joaquin Basin Case Study]).*

**Conclusion 5.2. Leakage of hydraulic fracturing chemicals could occur through existing wells.**

*California operators use hydraulic fracturing mainly in reservoirs that have been in production for a long time. Consequently, these reservoirs have a high density of existing wells that could form leakage paths away from the fracture zone to protected groundwater or*

14. Chemical tracers (non-reactive chemicals that can be detected in small concentrations) can be added to hydraulic fracturing fluids and, if groundwater samples contain these tracers, it is evidence that the stimulation fluid has migrated out of the designed zone. However, the use of tracers does not guarantee that leaks to groundwater will be detected. Groundwater flow can be highly channelized and it can be difficult to place a monitoring well in the right place to intersect a possible plume of contaminant. The use of tracers is good practice, but does not “solve” the problem of detecting contamination.

*the ground surface. The pending SB 4 regulations going into effect July 1, 2015 do address concerns about existing wells in the vicinity of well stimulation operations; however, it remains to demonstrate the effectiveness of these regulations in protecting groundwater.*

In California, most hydraulic fracturing occurs in old reservoirs where oil and gas has been produced for a long time. Usually this means many other wells (called “offset wells”) have previously been drilled in the vicinity of the operation. Wells constructed to less stringent regulations in the past or degraded since installation may not withstand the high pressures used in hydraulic fracturing. Thus, in California, as well as in other parts of the country, existing oil and gas wells can provide subsurface conduits for oil-field contamination to reach protected groundwater. Old wells present a risk for any oil and gas development, but the high pressures involved in hydraulic fracturing can increase this risk significantly. California has no recorded incidents of groundwater contamination due to stimulation. But neither have there been attempts to detect such contamination with targeted monitoring, nor studies to determine the extent of compromised wellbore integrity.

Historically, California has required placement of well casings and cement seals to protect groundwater with a salinity less than 3,000 mg/L total dissolved solids (TDS). Now, SB 4 requires more stringent monitoring and protection from degradation of non-exempt groundwater with less than 10,000 mg/L TDS. Consequently, existing wells may not have been built to protect groundwater between 3,000 mg/L and 10,000 mg/L TDS. For instance, there may be no cement seal in place to isolate the zones containing water that is between 3,000 and 10,000 mg/L TDS from deeper zones with water that is higher than 10,000 mg/L TDS.

The new well stimulation regulations going into effect in July 1, 2015 require operators to locate and review any existing well within a zone that is twice as large as the expected fractures. Operators need to design the planned hydraulic fracturing operation to confine hydraulic fracturing fluids and hydrocarbons within the hydrocarbon formation. The pressure buildup at offset wells caused by neighboring hydraulic fracturing operations must remain below a threshold value defined by the regulations.

The new regulations for existing wells are appropriate in concept, but the effectiveness of these requirements will depend on implementation practice. For example: How will operators estimate the extent of the fractures, and how will regulators ensure the reliability of these calculations? Is the safety factor provided by limiting concern to an area equal to twice the extent of the designed fractures adequate? How will regulators assess the integrity of existing wells when information about these wells is incomplete? How will regulators determine the maximum allowed pressure experienced at existing wells? Will the regulators validate the theoretical calculations to predict fracture extent and maximum pressure with field observations?

**Recommendation 5.2. Evaluate the effectiveness of hydraulic fracturing regulations designed to protect groundwater from leakage along existing wells.**

*Within a few years of the new regulations going into effect, DOGGR should conduct or commission an assessment of the regulatory requirements for existing wells near stimulation operations and their effectiveness in protecting groundwater with less than 10,000 TDS from well leakage. This assessment should include comparisons of field observations from hydraulic fracturing sites with the theoretical calculations for stimulation area or well pressure required in the regulations (Volume II, Chapter 2; Volume III, Chapters 4 and 5 [Los Angeles Basin and San Joaquin Basin Case Study]).*

**Principle 6. Understand and control emissions and their impact on environmental and human health.**

Gaseous emissions and particulates associated with hydraulic fracturing can arise from the use of fossil fuel in engines, outgassing from fluids, leaks, or proppants. These emissions have potential environmental or health impacts.

**Conclusion 6.1. Oil and gas production from hydraulically fractured reservoirs emits less greenhouse gas per barrel of oil than other forms of oil production in California.**

*Burning fossil fuel to run vehicles, make electricity, and provide heat accounts for the vast majority of California's greenhouse gas emissions. In comparison, publicly available California state emission inventories indicate that oil and gas production operations emit about 4% of California total greenhouse gas emissions. Oil and gas production from hydraulically fractured reservoirs emits less greenhouse gas per barrel of oil than production using steam injection. Oil produced in California using hydraulic fracturing also emits less greenhouse gas per barrel than the average barrel imported to California. If the oil and gas derived from stimulated reservoirs were no longer available, and demand for oil remained constant, the replacement fuel could have larger greenhouse emissions.*

Most oil-related greenhouse gas (GHG) emissions in the state come from the consumption of fossil fuels such as gasoline and diesel, not the extraction of oil. According to state emission inventories, GHG emissions from oil and gas production processes equal about four percent of total GHG emissions in California, although some studies conclude these emission inventories may underestimate true emissions. Fields with lighter oil result in low emissions per barrel of crude produced, while fields with heavier oil have higher emissions because of the need for steam injection during production as well as more intensive refining needed to produce useful fuels such as gasoline. Well stimulation generally applies to reservoirs with lighter oil and consequently smaller greenhouse gas burdens per unit of oil. Oil and gas from San Joaquin Basin reservoirs using hydraulic fracturing have a relatively smaller carbon footprint than oil and gas from reservoirs such as those in the Kern River field that use steam flooding (Figure S.3-11).

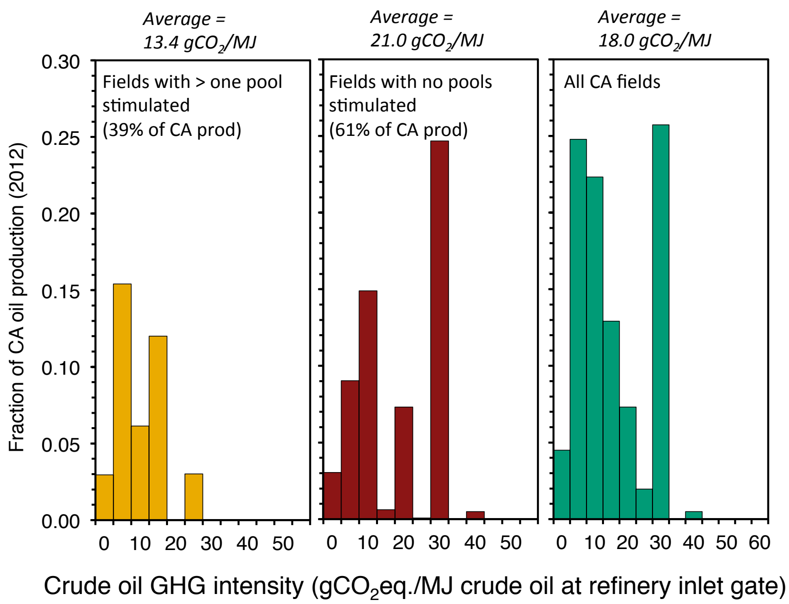



***Figure S.3-11. Distribution of crude oil greenhouse gas intensity for fields containing well-stimulation-enabled pools (left), those that are not stimulated (middle) and all California oilfields (right) (figure from Volume II, Chapter 3).***

If well stimulation were disallowed and consumption of oil and gas in California did not decline, more oil and gas would be required from non-stimulated California fields or regions outside of California, possibly with higher emissions per barrel. Consequently, overall greenhouse gas emissions due to production could increase if well stimulation were stopped in California. The net greenhouse gas change associated with the use of hydraulic fracturing requires knowing the carbon footprint of both in-state and out-of-state production, and understanding the scale of impact requires a market-informed life cycle analysis.

**Recommendation 6.1. Assess and compare greenhouse gas signatures of different types of oil and gas production in California.**

*Conduct rigorous market-informed life-cycle analyses of emissions impacts of different oil and gas production to better understand GHG impacts of well stimulation (Volume II, Chapter 3).*

**Conclusion 6.2. Air pollutants and toxic air emissions[15] from hydraulic fracturing are mostly a small part of total emissions, but pollutants can be concentrated near production wells.**

*According to publicly available California state emission inventories, oil and gas production in the San Joaquin Valley air district likely accounts for significant emissions of sulfur oxides ($SO_x$), volatile organic compounds (VOC), and some air toxics, notably hydrogen sulfide ($H_2S$). In other oil and gas production regions, production as a whole accounts for a small proportion of total emissions. Hydraulic fracturing facilitates about 20% of California production, and so emissions associated with this production also represent about 20% of all emissions from the oil and gas production in California. Even where the proportion of air pollutants and toxic emissions caused directly or indirectly by well simulation is small, atmospheric concentrations of pollutants near production sites can be much larger than basin or regional averages, and could potentially cause health impacts.*

In the San Joaquin Valley oil and gas production as a whole accounts for about 30% of sulfur oxides and 8% of anthropogenic volatile organic compound (VOC) emissions. VOCs in turn react with nitrogen oxides ($NO_x$) to create ozone. Eliminating emissions from oil and gas production would reduce, but not eliminate the difficult air pollution problems in the San Joaquin Valley. Oil and gas facilities also emit significant air toxics in the San Joaquin Valley. They are responsible for a large fraction (>70%) of total hydrogen sulfide emissions and small fractions (2-6%) of total benzene, xylene, hexane, and formaldehyde emissions (Figure S.3-12). Dust ($PM_{2.5}$ and $PM_{10}$) is a major air quality concern in the San Joaquin Valley, and agriculture is the dominant source of dust in the region. The amount of dust generated by oil and gas activities (including hydraulic fracturing) is comparatively very small.

15. Toxic air pollutants, also known as hazardous air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Criteria air contaminants (CAC), or criteria pollutants, are a set of air pollutants that cause smog, acid rain, and other health hazards.

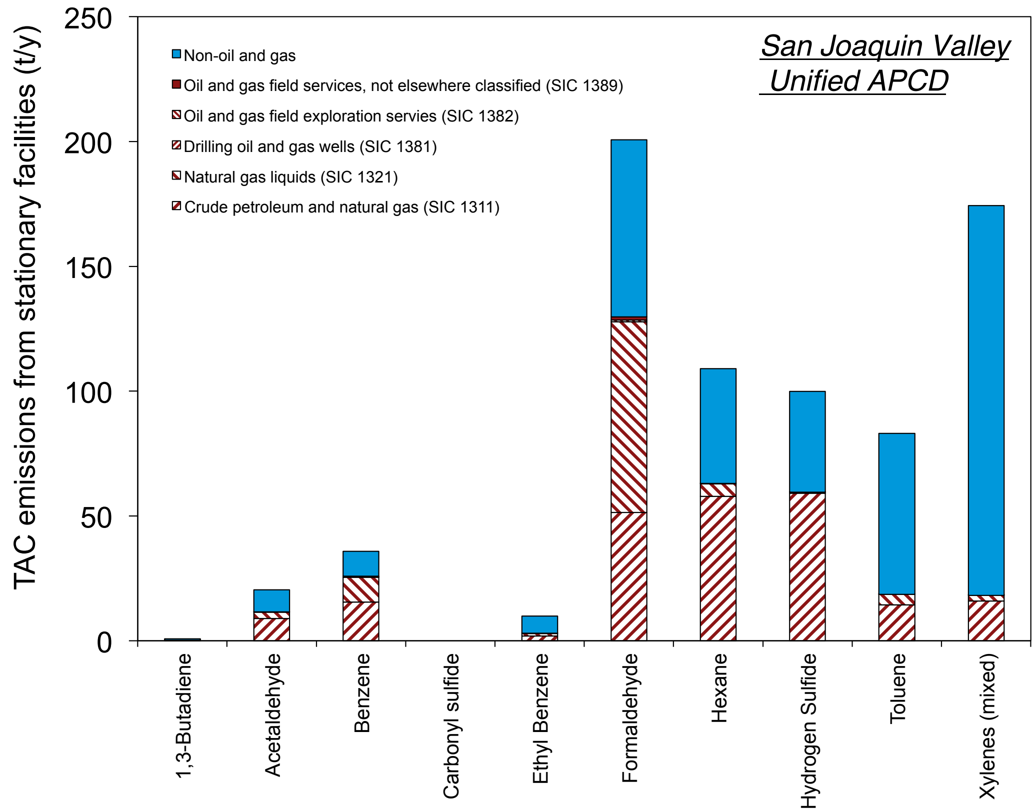



***Figure S.3-12. Summed facility-level toxic air contaminant (TAC) emissions in San Joaquin Valley air district). Facility-level emissions derived from a California Air Resources Board (CARB) facility emissions tool. Total emissions are emissions from all oil and gas facilities in the air district, including gasoline fueling stations (Volume II, Chapter 3) (figure from Volume II, Chapter 3).***

In the South Coast air district (including all of Orange County, the non-desert regions of Los Angeles and Los Angeles County, San Bernardino County, and Riverside County), upstream oil and gas sources represent small proportions (<1%) of criteria air pollutant and toxic air contaminant emissions due to large quantities of emissions from other sources in a highly urbanized area.

Produced gas can be emitted during recovery of hydraulic fracturing liquids and therefore be a possible source of direct air emissions from well stimulation. Regulation and control technologies can address these emissions with proper implementation and enforcement. Federal regulations already control emissions during fluid recovery from new gas wells using “green completions,” and California is developing similar regulations for oil wells.

Public data sources provide information about the emissions from all upstream oil and gas production, but do not include information that would allow separating out the contribution of emissions from hydraulically fractured wells. Because well stimulation facilitates or enables about 20% of California's oil recovery, indirect air impacts from well stimulation are likely on the order of one-fifth of total upstream oil and gas air impacts.

Even if upstream oil and gas operations are not a large part of basin-wide air pollution load, at the scale of counties, cities or neighborhoods, oil and gas development can have larger proportional impacts. Even in regions where well stimulation-related emissions represent a small part of overall emissions, local air toxic concentrations near drilling and production sites may be elevated. This could result in health impacts in densely populated areas such as Los Angeles, where production wells are in close proximity to homes, schools, and businesses. Public datasets do not provide specific enough temporal and spatial data on air toxics emissions that would allow any realistic assessment of these impacts.

**Recommendation 6.2. Control toxic air emissions from oil and gas production wells and measure their concentrations near productions wells.**

*Apply reduced-air-emission completion technologies to production wells, including stimulated wells, to limit direct emissions of air pollutants, as planned. Reassess opportunities for emission controls in general oil and gas operations to limit emissions. Improve specificity of inventories to allow better understanding of oil and gas emissions sources. Conduct studies to improve our understanding of toxics concentrations near stimulated and un-stimulated wells (Volume II, Chapter 3; Volume III, Chapter 4 [Los Angeles Basin Case Study]).*

**Conclusion 6.3. Emissions concentrated near all oil and gas production could present health hazards to nearby communities in California.**

*Many of the constituents used in and emitted by oil and gas development can damage health, and place disproportionate risks on sensitive populations, including children, pregnant women, the elderly, and those with pre-existing respiratory and cardiovascular conditions. Health risks near oil and gas wells may be independent of whether wells in production have undergone hydraulic fracturing or not. Consequently, a full understanding of health risks caused by proximity to production wells will require studying all types of productions wells, not just those that have undergone hydraulic fracturing. Oil and gas development poses more elevated health risks when conducted in areas of high population density, such as the Los Angeles Basin, because it results in larger population exposures to toxic air contaminants.*

California has large developed oil reserves located in densely populated areas. For example, the Los Angeles Basin reservoirs, which have the highest concentrations of oil in the world, exist within the global megacity of Los Angeles. Approximately half a million people live, and large numbers of schools, elderly facilities, and daycare facilities exist, within one mile of a stimulated well, and many more live near oil and gas development of all types (Figure S.3-13). The closer citizens are to these industrial facilities, the higher their potential exposure to toxic air emissions and higher risk of associated health effects. Production enabled by well stimulation accounts for a fraction of these emissions.

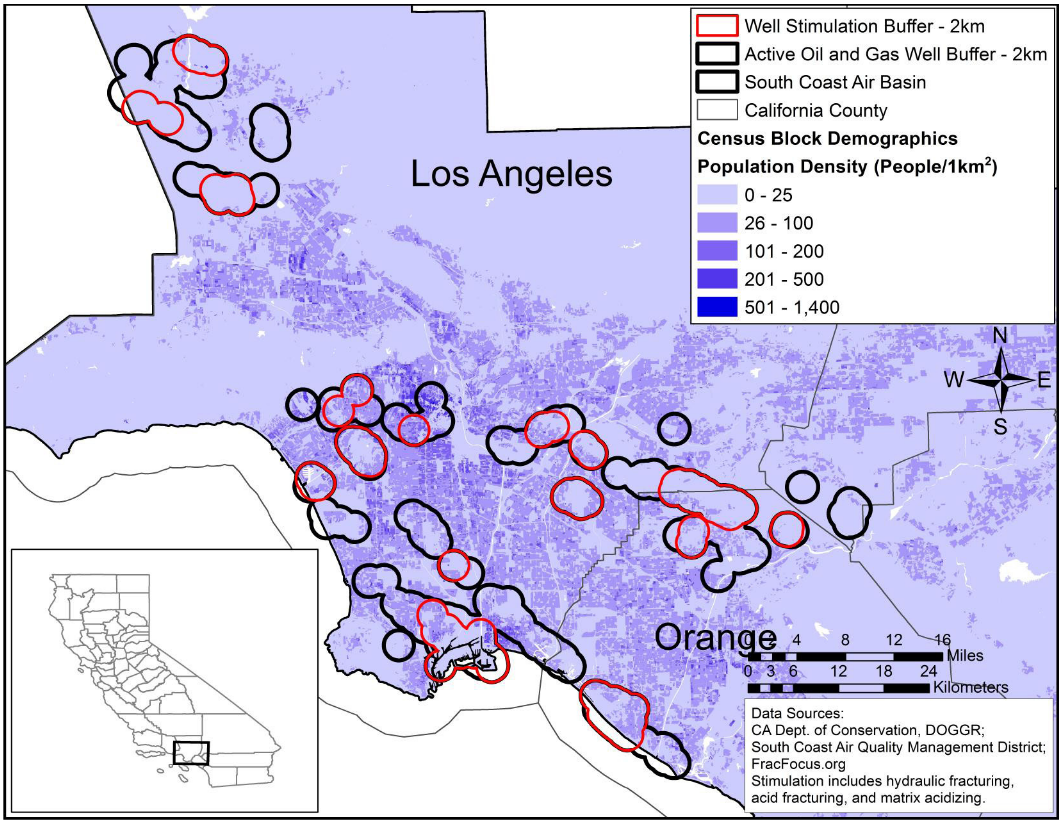



***Figure S.3-13. Population density within 6,562 ft (2,000 m) of currently active oil production wells and currently active wells that have been stimulated (figure from Volume III, Chapter 4 [Los Angeles Basin Case Study]).***

Studies from outside of California indicate that, from a public health perspective, the most significant exposures to toxic air contaminants such as benzene, aliphatic hydrocarbons and hydrogen sulfide occur within one-half mile (800 meters) from active oil and gas development. These risks depend on local conditions and the type of petroleum being produced. California impacts may be significantly different, but have not been measured.

**Recommendation 6.3. Assess public health near oil and gas production.**

*Conduct studies in California to assess public health as a function of proximity to all oil and gas development, not just stimulated wells, and develop policies such as science-based surface setbacks, to limit exposures (Volume II, Chapter 6; Volume III, Chapters 4 and 5 [Los Angeles Basin and San Joaquin Basin Case Studies]).*

**Conclusion 6.4. Hydraulic fracturing and acid stimulation operations add some occupational hazards to an already hazardous industry.**

*Studies done outside of California found workers in hydraulic fracturing operations were exposed to respirable silica and VOCs, especially benzene, above recommended occupational levels. The oil and gas industry commonly uses acid along with other toxic substances for both routine maintenance and well stimulation. Well-established procedures exist for safe handling of dangerous acids.*

Occupational hazards for workers who are involved in oil and gas operations include exposure to chemical and physical hazards, some of which are specific to well stimulation activities and many of which are general to the industry. Our review identified studies confirming occupational hazards directly related to well stimulation in states outside of California. The National Institute for Occupational Safety and Health (NIOSH) has conducted two peer-reviewed studies of occupational exposures attributable to hydraulic fracturing across multiple states (not including California) and times of year. One of the studies found that respirable silica (silica sand is used as a proppant to hold open fractures formed in hydraulic fracturing) was in concentrations well in excess of occupational health and safety standards (in this case permissible exposure limits or PELs) by factors of as much as ten. Exposures exceeded PELs even when workers reported use of personal protective equipment. The second study found exposure to VOCs, especially benzene, above recommended occupational levels. The NIOSH studies are relevant for identifying hazards that could be significant for California workers, but no study to date has addressed occupational hazards associated with hydraulic fracturing and other forms of well stimulation in California.

While both hydrochloric acid and hydrofluoric acid are highly corrosive, hydrofluoric acid can be a greater health risk than hydrochloric acid in some exposure pathways because of its higher rate of absorption. State and federal agencies regulate spills of acids and other hazardous chemicals, and existing industry standards dictate safety protocols for handling acids. The Office of Emergency Services (OES) reported nine spills of acid that can be attributed to oil and gas development between January 2009 and December 2014. Reports also indicate that the spills did not involve any injuries or deaths. These acid spill reports represent less than 1% of all reported spills of any kind attributed to the oil and gas development sector in the same period, and suggest that spills of acid associated with oil and gas development are infrequent, and industry protocols for handling acids protect workers.

Employers in the oil and gas industry must comply with existing California occupational safety and health regulations, and follow best practices to reduce and eliminate illness and injury risk to their employees. Employers can and often do implement comprehensive worker protection programs that substantially reduce worker exposure and likelihood of illness and injury. However, the effectiveness of these programs in California has not been evaluated. Engineering controls that reduce emissions could protect workers involved in well stimulation operations from chemical exposures and potentially reduce the likelihood of chemical exposure to the surrounding community.

**Recommendation 6.4. Assess occupational health hazards from proppant use and emission of volatile organic compounds.**

*Conduct California-based studies focused on silica and volatile organic compounds exposures to workers engaged in hydraulic-fracturing-enabled oil and gas development processes based on the NIOSH occupational health findings and protocols (Volume II, Chapter 6) .*

## S.4. Improving the Quality of Scientific Information on Hydraulic Fracturing and Acid Stimulation

In this section we address how to improve the quality of publicly available information on well stimulation in the state by implementing better practices on data gathering and management, and conducting research in key areas. We suggest establishing a committee of scientific advisors that can help interpret new information as it comes available.

**Principle 7. Take an informed path forward.**

This assessment faced significant challenges because of limited data available to answer the questions posed by SB 4. Either the records were incomplete, or data had never been gathered in the field. The following conclusions and recommendations address the need for better information and interpretation.

**Conclusion 7.1. Data reporting gaps and quality issues exist.**

*Significant gaps and inconsistencies exist in available voluntary and mandatory data sources, both in terms of duration and completeness of reporting. Because the hydrologic and geologic conditions and stimulation practices in California differ from other unconventional plays in this country, many data gaps are specific to California.*

Data on the past and current practices of well stimulation in California have been assembled from various sources and databases for this study. Mandatory reporting resulting from the implementation of SB 4 has proven very valuable, and this report includes data in the first six months since mandatory reporting was implemented on

January 1, 2014. It would make sense to reevaluate this assessment in a few years, after sufficient mandatory data have been collected to confirm analysis based on early data trends, and determine the overall adequacy of the mandatory reporting regime.

While mandatory reporting under SB 4 has clearly improved upon prior reporting practices, gaps and data quality issues in the reporting limited this analysis and may warrant the adoption of additional quality assurance, reporting and data handling requirements. Investigators found the quality, completeness, and availability of data from the South Coast Air Quality Management District particularly exemplary and useful. In contrast, much of the data reported to DOGGR is not available in an electronic format that can be searched and analyzed. Furthermore, inconsistencies exist between different data sources collected by various state and private institutions. Examples of questionable data quality in the stimulation completion reports include the number of stages per operation and the vertical extent of stimulation. All hydraulic fracturing completion reports list one hydraulic fracturing stage per operation, but well records indicate that operators rarely limit a treatment to only a single stage per operation. Operators are required to report the vertical extent of hydraulic fractures, but for more than half of the reports, this extent was exactly equal to the length of the well, which is highly unlikely. These inconsistencies indicate potential inaccuracies or errors in the data.

Examples of suggested additional reporting requirements include:

1. Operators collect basic data during the execution of hydraulic fractures that can indicate if the operation occurred as planned. These data, such as the injection rate, pressure, proppant loading, and fluid type as a function of time, are not currently reported to DOGGR as part of mandatory reporting requirements. Access to this information would facilitate evaluation of risk to protected groundwater.

2. Data on groundwater location, geological strata, depth, and quality (including spatial and temporal variation if available) in the treatment well and field area would provide a useful reference database and help to protect groundwater resources.

3. Methods for measurement and monitoring of potential water contaminants specific to hydraulic fracturing should be developed and implemented.

4. The composition of recovered and produced water should be analyzed to illuminate the possible ramifications of chemical contaminants on reuse or accidental or intentional releases to the environment. The composition of recovered fluids and produced water changes in time as the chemicals are consumed, adsorbed, or diluted, and necessitates a rationale for when and how to sample, and what to measure.

5. Data reported to the state on the destination of produced water is incomplete and possibly inaccurate. Implementation of SB 1281 will provide better information. Updated and corrected information on produced water disposition, including clear identification of that designated for beneficial reuse, would help to ensure appropriate outcomes.

6. Depths and injection intervals for Class II disposal wells and high-resolution temporal data on pressure, rate, and volume of injection would facilitate study of possible induced seismicity.

7. Mandatory reporting of spill data should include information about whether well stimulation chemicals are associated with the spill, to improve assessment of the hazards associated with the spills.

8. Complete information on chemicals used and their environmental profiles in both stimulated and un-stimulated wells would help to evaluate the marginal risk of chemical use in stimulation and oil production in general.

9. Reporting of offshore well stimulation and water disposal data in federal waters similar to state water reporting requirements would help to establish baseline information about the possible impacts of chemical use offshore.

**Recommendation 7.1. Improve and modernize public record keeping for oil and gas production.**

*DOGGR should digitize paper records and organize all datasets in databases that facilitate searches and quantitative analysis. DOGGR should also institute and publish data quality assurance practices, and institute enforcement measures to ensure accuracy of reporting. When a few years' reporting data become available, a study should assess the value, completeness, and consistency of reporting requirements for hydraulic fracturing and acid treatment operations—and as necessary, revise or expand reporting requirements. The quality and completeness of the data collected by the South Coast Air Quality Management District provides a good example of the completeness and availability the state should seek to emulate. The Department of Conservation should reevaluate well stimulation data trends after 3–5 years of reporting.*

**Conclusion 7.2. Future research would fill knowledge gaps.**

*Questions remain at the end of this initial assessment of the impacts of well stimulation in California that can only be answered by new research and data collection. Volumes II and III of this report series provide many detailed recommendations for filling data gaps and additional research. Some examples of key questions and suggested research to answer them include:*

*Has any protected groundwater been contaminated with stimulation chemicals in the past, and what would protect against this occurrence in the future? No records of groundwater contamination due to hydraulic fracturing were found, but there were also few investigations designed to look for contamination.*

- Identify oil fields in California where there has been significant hydraulic fracturing development at depths close to important groundwater resources, and evaluate these for groundwater contamination. If the study finds polluted groundwater caused by oilfield well stimulation operations, determine how and why and identify modifications to the state's pending well stimulation regulations that would prevent this problem from reoccurring. Simultaneously, develop a theoretical basis for limiting the likely maximum size of shallow hydraulic fractures to support appropriate regulations to prevent intersecting protected water.

- Evaluate the spatial relationship between protected groundwater resources (including depth and location of groundwater wells) and the reservoirs used for oil and gas production, as well as produced water disposal. If possible, develop local- to regional-scale simulation models for planning purposes that include shallow groundwater layers as well as deeper oil and gas reservoirs.

- Characterize legacy contamination due to percolation pits and wastewater injection disposal into groundwater that should have been protected. Determine the fate and transport of the inappropriately disposed contaminants and plans for remediation if necessary and possible.

- Characterize well integrity for stimulated wells and nearby "offset" wells to assess the likelihood of these becoming pathways to the environment.

- Evaluate the long-term integrity and leakage potential of decommissioned wells used for hydraulic fracturing.

*What environmental risks do stimulation chemicals pose, and are there practices that would limit these risks?*

- Systematically determine the environmental profile of all chemicals used in well stimulation, including their long-term impacts, chronic toxicity, environmental persistence, and tendency for bioaccumulation. The evaluation of toxicity and bioaccumulation should be based on the chemical concentrations used in oilfield operations, and account for various exposure pathways including consumption, adsorption, and dilution.

- Apply Green Chemistry principles to identify best practices with respect to chemical use in oil and gas production.

*Can water being produced from hydraulically fractured wells become a resource for California?*

- Assess the integrated toxicity of produced waters containing mixtures of stimulation chemicals and assess risks associated with reuse over the production life of wells.

- Determine the chemical reactions that might occur underground between stimulation fluids, formation rock, and formation fluids.

- Assess potential methods for detecting and treating contaminants in produced water, including those related to stimulation.

*How does oil and gas production as a whole (including that enabled by hydraulic fracturing) affect California's water system?*

- Quantify the sources and amounts of freshwater that are used in various forms of oil production processes.

- Conduct regional system-level analysis of the volumes and quality of waters that are produced along with oil and gas production and the disposition of this water.

- Evaluate opportunities for reuse of produced water.

- Characterize the impact of various production methods on the water system and identify opportunities to decrease impacts.

- Evaluate the impact on water resources of decommissioned wells used for hydraulic fracturing.

*Does California's current or future practice of underground injection of wastewater present a significant risk of inducing earthquakes?*

- Evaluate potential for induced seismicity from wastewater disposal injections through a regional analysis of the relationship between injection and seismicity coupled with mechanical interpretation.

- Identify potentially hazardous injection sites by characterizing faults in producing regions and installing dedicated seismic monitoring to support improved understanding of fault reactivation processes and seismic hazard potential.

*How can the public best be protected from air pollution associated with oil and gas production?*

- Obtain accurate air emissions inventories and collect air concentration data near oil and gas production sites, including those using hydraulic fracturing.

- Conduct community and occupational epidemiology studies specific to oil and gas development in the San Joaquin Basin and in the Los Angeles Basin.

*What are the ecological impacts of oil and gas development in California?*

- Data defining the ecological condition of abandoned well sites would provide a better understanding of the long-term impacts of oil and gas development. Key parameters to evaluate include, but are not limited to, the identity and number of native plants and animals that inhabit former well pad sites, and to what degree active restoration efforts alter ecological outcomes.

Many of the questions listed above might best be addressed through integrated research programs at dedicated hydraulic fracturing field study areas, where data collection and interpretative analysis can be much more intense and ubiquitous than is possible in general industry operations. The field study areas would be intensely monitored and enable testing of monitoring practices and determining the factors that control the risks and impacts of hydraulic fracturing (similar to the data collection at the Inglewood Oil Field reported in Cardno ENTRIX, 2012[16]). Such field study areas should be representative of the conditions in which well stimulation is conducted in California. Integrated research should include regional hydrologic characterization and field studies related to surface and groundwater protection, induced seismicity, and ecological condition of well sites. Field-based studies should also include air and health components. Field study areas should be located in Kern County in the San Joaquin Basin, where most of the state's hydraulic fracturing is conducted. Including other field study sites in Southern California, such as in the Los Angeles, Ventura, and Santa Barbara counties, would span the varying hydrogeological conditions and well stimulation characteristics experienced in California.

**Recommendation 7.2. Conduct integrated research to close knowledge gaps.**

*Conduct integrated research studies in California to answer key questions about the environmental, health, and seismic impacts of oil and gas production enabled by well stimulation. Integrated research studies should include regional hydrologic characterization and field studies related to surface and groundwater protection, induced seismicity, ecological conditions, as well as air and health effects.*

16. Cardno ENTRIX (2012), Hydraulic Fracturing Study - PXP Inglewood Oil Field. http://www.scribd.com/doc/109624423/Hydraulic-Fracturing-Study-Inglewood-Field10102012

**Conclusion 7.3. Ongoing scientific advice could inform policy.**

*As the State of California digests this assessment and as more data become available, continued interpretation of both the impacts of well stimulation and the potential meaning of scientific data and analysis would inform the policy framework for this complex topic.*

This study highlights many recommendations to change practice, collect data, and investigate risk factors for Californians. Each recommendation will take thought and more insight to implement. This report hardly represents the last word on the topic. More data will be collected and different issues, or modifications to issues, will arise. Continuing scientific advice via an advisory body would help to evaluate existing policies and support future changes in policy. As many of the impacts we found were impacts associated with all oil and gas development, this advisory body should be charged with providing scientific assessment of environmental, water, atmosphere, wildlife and vegetation, seismic, and human-health issues associated with the oil and gas development sector.

> **Recommendation 7.3. Establish a scientific advisory committee on oil and gas development.**
>
> *The State of California should establish a standing scientific advisory committee to support decisions on the regulation of oil and gas development.*

## Apendix A

# Senate Bill 4 Language Mandating the Independent Scientific Study on Well Stimulation Treatment

The following is the language from Senate Bill 4 (Pavley, Statutes of 2013) that required the independent scientific study on well stimulation treatments, of which this volume comprises the first installment.

3160. (a) On or before January 1, 2015, the Secretary of the Natural Resources Agency shall cause to be conducted, and completed, an independent scientific study on well stimulation treatments, including, but not limited to, hydraulic fracturing and acid well stimulation treatments. The scientific study shall evaluate the hazards and risks and potential hazards and risks that well stimulation treatments pose to natural resources and public, occupational, and environmental health and safety. The scientific study shall do all of the following:

1. Follow the well-established standard protocols of the scientific profession, including, but not limited to, the use of recognized experts, peer review, and publication.

2. Identify areas with existing and potential conventional and unconventional oil and gas reserves where well stimulation treatments are likely to spur or enable oil and gas exploration and production.

3. (A) Evaluate all aspects and effects of well stimulation treatments, including, but not limited to, the well stimulation treatment, additive and water transportation to and from the well site, mixing and handling of the well stimulation treatment fluids and additives onsite, the use and potential for use of nontoxic additives and the use or reuse of treated or produced water in well stimulation treatment fluids, flowback fluids and handling, treatment, and disposal of flowback fluids and other materials, if any, generated by the treatment. Specifically, the potential for the use of recycled water in well stimulation treatments, including appropriate water quality requirements and available treatment technologies, shall be evaluated. Well stimulation treatments include, but are not limited to, hydraulic fracturing and acid well stimulation treatments.

(B) Review and evaluate acid matrix stimulation treatments, including the range of acid volumes applied per treated foot and total acid volumes used in treatments, types of acids, acid concentration, and other chemicals used in the treatments.

4. Consider, at a minimum, atmospheric emissions, including potential greenhouse gas emissions, the potential degradation of air quality, potential impacts on wildlife, native plants, and habitat, including habitat fragmentation, potential water and surface contamination, potential noise pollution, induced seismicity, and the ultimate disposition, transport, transformation, and toxicology of well stimulation treatments, including acid well stimulation fluids, hydraulic fracturing fluids, and waste hydraulic fracturing fluids and acid well stimulation in the environment.

5. Identify and evaluate the geologic features present in the vicinity of a well, including the well bore, that should be taken into consideration in the design of a proposed well stimulation treatment.

6. Include a hazard assessment and risk analysis addressing occupational and environmental exposures to well stimulation treatments, including hydraulic fracturing treatments, hydraulic fracturing treatment-related processes, acid well stimulation treatments, acid well stimulation treatment-related processes, and the corresponding impacts on public health and safety with the participation of the Office of Environmental Health Hazard Assessment.

7. Clearly identify where additional information is necessary to inform and improve the analyses.

# Appendix B

# CCST Steering Committee Members and Staff

Full curricula vitae for Steering Committee members are available upon request. Please contact California Council on Science and Technology at (916)-492-0996.

**Jane Long, Ph.D.**

**Principal Associate Director at Large, Lawrence Livermore National Laboratory, Retired Steering Committee Chair**

Dr. Long recently retired from Lawrence Livermore National Laboratory, where she was the Principal Associate Director at Large, Fellow in the LLNL Center for Global Strategic Research, and the Associate Director for Energy and Environment. She is currently a senior contributing scientist for the Environmental Defense Fund, Visiting Researcher at UC Berkeley, Co-chair of the Task Force on Geoengineering for the Bipartisan Policy Center and chairman of the California Council on Science and Technology's California's Energy Future committee. Her current work involves strategies for dealing with climate change, including reinvention of the energy system, geoengineering, and adaptation. Dr. Long was the Dean of the Mackay School of Mines, University of Nevada, Reno, and Department Chair for the Energy Resources Technology and the Environmental Research Departments at Lawrence Berkeley National Laboratory. She holds a bachelor's degree in engineering from Brown University and Masters and Ph.D. from U.C. Berkeley. Dr. Long is a fellow of the American Association for the Advancement of Science and was named Alum of the Year in 2012 by the Brown University School of Engineering. Dr. Long is an Associate of the National Academies of Science (NAS) and a Senior Fellow and council member of the California Council on Science and Technology (CCST) and the Breakthrough Institute. She serves on the board of directors for the Clean Air Task Force and the Center for Sustainable Shale Development.

**Roger Aines, Ph.D.**

**Senior Scientist, Atmospheric, Earth, and Energy Division and Carbon Fuel Cycle Program Leader E Programs, Global Security, Lawrence Livermore National Laboratory**

Roger Aines leads the development of carbon management technologies at Lawrence Livermore National Laboratory, working since 1984 in the U.S. national laboratory system. Dr. Aines's work has spanned nuclear waste disposal, environmental remediation, applying stochastic methods to inversion and data fusion, managing carbon emissions, and sequestration monitoring and verification methods. Aines takes an integrated view of the energy, climate, and environmental aspects of carbon-based fuel production and use. His current focus is on efficient ways to remove carbon dioxide from the atmosphere and safer methods for producing environmentally clean fuel. He holds 13 patents and has authored more than 100 publications. Aines holds a Bachelor of Arts degree in Chemistry from Carleton College, and Doctor of Philosophy in geochemistry from the California Institute of Technology.

**Jens Birkholzer, Ph.D.**

**Deputy Director, Earth Sciences Division, Lawrence Berkeley National Laboratory**

Dr. Birkholzer joined Lawrence Berkeley National Laboratory in 1994 as a post-doctoral fellow and has since been promoted to the second-highest scientist rank at this research facility. He currently serves as the deputy director of the Earth Sciences Division and as the program lead for the nuclear waste program, and also leads a research group working on environmental impacts related to geologic carbon sequestration and other subsurface activities. His area of expertise is subsurface hydrology, with an emphasis on understanding and modeling coupled fluid, gas, solute and heat transport in complex subsurface systems, such as heterogeneous sediments or fractured rock. His recent research was mostly in the context of risk/performance assessment, e.g., for geologic disposal of radioactive wastes and for geologic $CO_2$ storage. Dr. Birkholzer has authored about 90 peer-reviewed journal articles and book chapters, and has over 230 conference publications and abstracts.

### Brian Cypher, Ph.D.

**Associate Director, Endangered Species Recovery Program,**
**California State University-Stanislaus**

Dr. Cypher received a PhD in Zoology from Southern Illinois University in 1991. Since 1990, he has been engaged in ecological research and conservation efforts on a variety of animal and plant species and their habitats. Much of this work has occurred in the San Joaquin Valley in central California and has involved extensive evaluations of the effects of hydrocarbon production and energy development on ecological processes and individual species. The information generated has been presented in numerous reports and publications, which have contributed to the development of conservation strategies and best-management practices that help mitigate environmental impacts from energy development activities.

### Jim Dieterich, Ph.D.

**Distinguished Professor of Geophysics, University of California, Riverside**

Dr. Dieterich's research interests have to do with the mechanics of deformation processes, particularly as they relate to earthquake and volcanic phenomena. Areas of emphasis include development of governing relations for earthquake nucleation and earthquake occurrence; estimation of earthquake probabilities; fault constitutive properties; and coupled interactions between magmatic activity, faulting, and earthquakes. Current research includes (1) numerical simulation of earthquakes processes in interacting fault systems, (2) origins of earthquake clustering including foreshocks and aftershocks, (3) application of seismicity rate changes to infer stress changes in volcanic and tectonic environments, and (4) laboratory investigation of fault constitutive properties and surface contact process.

**Donald L. Gautier, Ph.D.**

**Consulting Petroleum Geologist, DonGautier L.L.C.**

With a career spanning almost four decades, Dr. Donald L. Gautier is an internationally recognized leader and author in the theory and practice of petroleum resource analysis. As a principal architect of modern USGS assessment methodology, Gautier's accomplishments include leadership of the first comprehensive evaluation of undiscovered oil and gas resources north of the Arctic Circle, the first national assessment of United States petroleum resources to be fully documented in a digital environment, and the first development of performance-based methodology for assessment of unconventional petroleum resources such as shale gas or light, tight oil. He was lead scientist for the San Joaquin Basin and Los Angeles Basin Resource Assessment projects. His recent work has focused on the analysis of growth of reserves in existing fields and on the development of probabilistic resource/cost functions. Gautier is the author of more than 200 technical publications, most of which concern the evaluation of undiscovered and undeveloped petroleum resources. He holds a Ph.D. in geology from the University of Colorado.

**Peter H. Gleick, Ph.D.**

**President, Pacific Institute**

Dr. Peter H. Gleick is an internationally recognized environmental scientist and co-founder of the Pacific Institute in Oakland, California. His research addresses the critical connections between water and human health, the hydrologic impacts of climate change, sustainable water use, privatization and globalization, and international security and conflicts over water resources. Dr. Gleick was named a MacArthur "genius" Fellow in October 2003 for his work on water, climate, and security. In 2006, Dr. Gleick was elected to the U.S. National Academy of Sciences, Washington, D.C. Dr. Gleick's work has redefined water from the realm of engineers to the world of social justice, sustainability, human rights, and integrated thinking. His influence on the field of water has been long and deep: he developed one of the earliest assessments of the impacts of climate change on water resources, defined and explored the links between water and international security and local conflict, and developed a comprehensive argument in favor of basic human needs for water and the human right to water—work that has been used by the UN and in human rights court cases. He pioneered the concept of the "soft path for water," developed the idea of "peak water," and has written about the need for a "local water movement." Dr. Gleick received a B.S. in Engineering and Applied Science from Yale University and an M.S. and Ph.D. from the Energy and Resources Group of the University of California, Berkeley. He serves on the boards of numerous journals and organizations, and is the author of many scientific papers and ten books, including Bottled & Sold: The Story Behind Our Obsession with Bottled Water, and the biennial water report, The World's Water, published by Island Press (Washington, D.C.).

### A. Daniel Hill, Ph.D.

**Department Head, Professor and holder of the Noble Chair, Petroleum Engineering Department at Texas A&M University**

Dr. A. D. Hill is Professor, holder of the Noble Endowed Chair, and Department Head of Petroleum Engineering at Texas A&M University. Previously, he taught for 22 years at The University of Texas at Austin after spending five years in industry. He holds a B. S. degree from Texas A&M University and M. S. and Ph. D. degrees from The University of Texas at Austin, all in chemical engineering. He is the author of the Society of Petroleum Engineering (SPE) monograph, Production Logging: Theoretical and Interpretive Elements, co-author of the textbook, Petroleum Production Systems (1st and 2nd editions), co-author of an SPE book, Multilateral Wells, and author of over 170 technical papers and five patents. He has been a Society of Petroleum Engineers (SPE) Distinguished Lecturer, has served on numerous SPE committees and was founding chairman of the Austin SPE Section. He was named a Distinguished Member of SPE in 1999 and received the SPE Production and Operations Award in 2008. In 2012, he was one of the two inaugural winners of the SPE Pipeline Award, which recognizes faculty who have fostered petroleum engineering Ph.Ds. to enter academia. He currently serves on the SPE Editorial Review Committee, the SPE Global Training Committee, and the SPE Hydraulic Fracturing Technology Conference Program Committee. Professor Hill is an expert in the areas of production engineering, well completions, well stimulation, production logging, and complex well performance (horizontal and multilateral wells), and has presented lectures and courses and consulted on these topics throughout the world.

### Larry Lake, Ph.D.

**Professor, Department of Petroleum and Geosystems Engineering, University of Texas, Austin**

Larry W. Lake is a professor of the Department of Petroleum and Geosystems Engineering at The University of Texas at Austin and director of the Center for Petroleum Asset Risk Management. He holds B.S.E and Ph.D. degrees in Chemical Engineering from Arizona State University and Rice University. Dr. Lake has published widely; he is the author or co-author of more than 100 technical papers, the editor of 3 bound volumes and author or co-author of four textbooks. He has been teaching at UT for 34 years before which he worked for Shell Development Company in Houston, Texas. He was chairman of the Petroleum and Geosystems Engineering department twice, from 1989 to 1997 and from 2008-2010. He formerly held the Shell Distinguished Chair and the W.A. (Tex) Moncrief, Jr. Centennial Endowed Chair in Petroleum Engineering. He currently holds the W.A. (Monty) Moncrief Centennial Chair in Petroleum Engineering. Dr. Lake has served on the Board of Directors for the Society of Petroleum Engineers (SPE) as well as on several of its committees; he has twice been an SPE distinguished lecturer. Dr. Lake is a member of the U.S. National Academy of Engineers and won the 1996 Anthony F. Lucas Gold Medal of the SPE. He won the 1999 Dad's Award for excellence in teaching undergraduates at The University of Texas and the 1999 Hocott Award in the College of Engineering for excellence in research. He also is a member of the 2001 Engineering Dream Team awarded by the Texas Society of Professional Engineers. He is an SPE Honorary Member.

### Thomas E. McKone, Ph.D.

**Deputy for Research Programs in the Energy Analysis and Environmental Impacts Department, Lawrence Berkeley National Laboratory (LBNL)**

Thomas E. McKone is a senior staff scientist and Deputy for Research Programs in the Energy Analysis and Environmental Impacts Department at the Lawrence Berkeley National Laboratory (LBNL) and Professor of Environmental Health Sciences at the University of California, Berkeley School of Public Health. At LBNL, he leads the Sustainable Energy Systems Group. His research focuses on the development, use, and evaluation of models and data for human-health and ecological risk assessments and the health and environmental impacts of energy, industrial, and agricultural systems. Outside of Berkeley, he has served six years on the EPA Science Advisory Board, has been a member of more than a dozen National Academy of Sciences (NAS) committees including the Board on Environmental Studies and Toxicology, and has been on consultant committees for the Organization for Economic Cooperation and Development (OECD), the World Health Organization, the International Atomic Energy Agency, and the Food and Agriculture Organization. McKone is a Fellow of the Society of Risk Analysis and has received two major awards from the International Society of Exposure Analysis—one for lifetime achievement in exposure science research, and one for research that has impacted major international and national environmental policies.

### William A. Minner, P.E.

**Petroleum Engineer, Minner Engineering, Inc.**

Minner is an independent petroleum engineering consultant, with a primary focus on hydraulic fracture well stimulation technology and application. After receiving B.S. and M.S. degrees in mechanical engineering with a petroleum option from the University of California, Berkeley, Minner joined Unocal in 1980, and began to focus on hydraulic fracturing well stimulation in 1985. In 1995, he left Unocal to open an office for Pinnacle Technologies in Bakersfield. Pinnacle's focus was on the development and commercialization of hydraulic fracture mapping technologies; Minner's role was on engineering consulting, using fracture diagnostics and mapping results to assist clients with hydraulic fracture engineering design, execution, and analysis. His engineering consulting role continued after the fracture mapping business was sold in 2008 and the company name was changed to StrataGen Engineering, and after February 2015 when he left StrataGen to venture out in the independent engineering consulting arena. Minner is a registered Petroleum Engineer in California, and received Society of Petroleum Engineers regional awards in 2011 and 2015 for his contribution to technical progress and interchange. He has authored or coauthored 21 industry technical papers on hydraulic fracturing.

**Amy Myers Jaffe**

**Executive Director, Energy and Sustainability, UC Davis**

Amy Myers Jaffe is a leading expert on global energy policy, geopolitical risk, and energy and sustainability. Jaffe serves as executive director for Energy and Sustainability at University of California, Davis with a joint appointment to the Graduate School of Management and Institute of Transportation Studies (ITS). At ITS-Davis, Jaffe heads the fossil fuel component of Next STEPS (Sustainable Transportation Energy Pathways). She is associate editor (North America) for the academic journal Energy Strategy Reviews. Prior to joining UC Davis, Jaffe served as director of the Energy Forum and Wallace S. Wilson Fellow in Energy Studies at Rice University's James A. Baker III Institute for Public Policy. Jaffe's research focuses on oil and natural gas geopolitics, strategic energy policy, corporate investment strategies in the energy sector, and energy economics. She was formerly senior editor and Middle East analyst for Petroleum Intelligence Weekly. Jaffe is widely published, including as co-author of Oil, Dollars, Debt and Crises: The Global Curse of Black Gold (Cambridge University Press, January 2010 with Mahmoud El-Gamal). She served as co-editor of Energy in the Caspian Region: Present and Future (Palgrave, 2002) and Natural Gas and Geopolitics: From 1970 to 2040 (Cambridge University Press, 2006). Jaffe was the honoree for Esquire's annual 100 Best and Brightest in the contribution to society category (2005) and Elle Magazine's Women for the Environment (2006) and holds the excellence in writing prize from the International Association for Energy Economics (1994).

**Seth B. C Shonkoff, Ph.D., MPH**

**Executive Director, PSE Healthy Energy**
**Visiting Scholar, University of California, Berkeley**
**Affiliate, Lawrence Berkeley National Laboratory**

Dr. Shonkoff is the executive director of the energy science and policy institute, PSE Healthy Energy. Dr. Shonkoff is also a visiting scholar in the Department of Environmental Science, Policy and Management at UC Berkeley, and an affiliate in the Environment Energy Technology Division at Lawrence Berkeley National Laboratory in Berkeley California. An environmental and public health scientist by training, he has more than 15 years of experience in water, air, climate, and population health research. Dr. Shonkoff completed his PhD in the Department of Environmental Science, Policy, and Management and his MPH in epidemiology in the School of Public Health from the University of California, Berkeley. He is a contributing author to the Human Health chapter of The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). He has worked and published on topics related to the intersection of energy, air pollution, water quality, climate, and human health from scientific and policy perspectives. Dr. Shonkoff's research also focuses on the development of the effectiveness of anthropogenic climate change mitigation policies that generate socioeconomic and health co-benefits. Dr. Shonkoff's current work focuses on the human health, environmental and climate dimensions of oil and gas development in the United States and abroad.

**Daniel Tormey, Ph.D., P.G.**

**Principal, Ramboll Environ Corporation**

Dr. Daniel Tormey is an expert in energy and water and conducts environmental reviews for both government and industry. He works with the environmental aspects of all types of energy development, with an emphasis on oil and gas, including hydraulic fracturing and produced water management, pipelines, LNG terminals, refineries, and retail facilities. Dr. Tormey was the principal investigator for the peer-reviewed, publicly available "Hydraulic Fracturing Study at the Baldwin Hills" of southern California, on behalf of the County of Los Angeles and the field operator, PXP. He conducts projects in sediment transport, hydrology, water supply, water quality, and groundwater-surfacewater interaction. He has been project manager or technical lead for over two hundred projects requiring fate and transport analysis of chemicals in the environment. He has a Ph.D. in Geology and Geochemistry from MIT, and a B.S. in Civil Engineering and Geology from Stanford. He is a Principal at Ramboll Environ Corporation; was named by the National Academy of Sciences to the Science Advisory Board for Giant Sequoia National Monument; is a Distinguished Lecturer for the Society of Petroleum Engineers; is on the review committee on behalf of IUCN for the UNESCO World Heritage Site List and member of the IUCN Geoscientist Specialist Group; is volcanologist for Cruz del Sur, an emergency response and contingency planning organization in Chile; was an Executive in Residence at California Polytechnic University San Luis Obispo; and is a Professional Geologist in California. He has worked throughout the USA, Australia, Indonesia, Italy, Chile, Ecuador, Colombia, Venezuela, Brazil, Senegal, South Africa, Armenia and the Republic of Georgia.

**Samuel Traina, Ph.D.**

**Vice Chancellor of Research, University of California, Merced**

Dr. Traina is the Vice Chancellor for Research and Economic Development at the University of California, Merced, where he holds the Falasco Chair in Earth Sciences and Geology. He serves as a Board Member of the California Council of Science and Technology. Prior to joining UC Merced in 2002 as a Founding Faculty member and the Founding Director of the Sierra Nevada Research Institute, Dr. Traina was a faculty member for 17 years at the Ohio State University, with concomitant appointments in the School of Natural Resources and the Environment, the Department of Earth Science and Geology, Civil and Environmental Engineering, Microbiology and Chemistry. He has served on the National Research Council's Standing Committee on Earth Resources. In 1997–1998 he held the Cox Visiting Professorship in the School of Earth Sciences at Stanford University. Dr. Traina's past and current research has dealt with the fate, transformation, and transport of contaminants in soils and natural waters, with an emphasis on radionuclides, heavy metals, and mining wastes. Dr. Traina holds a B.S. in soil resource management and a Ph.D. in soil chemistry. He is a fellow of the Soil Science Society of American and of the American Association for the Advancement of Science, as well as a recipient of the Clay Scientist Award of the Clay Minerals Society.

**Laura Feinstein, Ph.D.**

**CCST Project Manager**

Laura Feinstein serves as the project manager and author for CCST on this report, and CCST's previous report on well stimulation prepared for the Bureau of Land Management. She previously served as a CCST Science and Technology Policy Fellow with the California Senate Committee on Environmental Quality. She was the director of the GirlSource Technology and Leadership Program, where she developed and ran a program teaching computer and job skills to low-income young women. She also was a web/media developer and researcher with the Center for Defense Information, a think-tank focusing on security issues. She was awarded a CalFED Bay-Delta Science fellowship for scientific research on ecological problems facing the Bay-Delta watershed, and a California Native Plant Society research scholarship. She has a Ph.D. in Ecology from University of California, Davis.

**Disclosure of Conflict of Interest: Professor Dan Hill**

In accordance with the practice of the California Council on Science and Technology (CCST), CCST makes best efforts to ensure that no individual appointed to serve on a committee has a conflict of interest that is relevant to the functions to be performed, unless such conflict is promptly and publicly disclosed and CCST determines that the conflict is unavoidable. A conflict of interest refers to an interest, ordinarily financial, of an individual that could be directly affected by the work of the committee. An objective determination is made for each provisionally appointed committee member regarding whether or not a conflict of interest exists, given the facts of the individual's financial and other interests, and the task being undertaken by the committee. A determination of a conflict of interest for an individual is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

We have concluded that for this committee to accomplish the tasks for which it was established, its membership must include among others, individuals with research and expertise in the area of acid treatments for petroleum wells who have studied oil and gas industry operations in the United States and are internationally recognized for this expertise. Acid treatment is of particular public concern in California and is the subject of regulation under SB 4.

To meet the need for this expertise and experience, Dr. Dan Hill is proposed for appointment to the committee, even though we have concluded that he has a conflict of interest because of investments he holds and research services provided by his employer.

As his biographical summary makes clear, Dr. Hill is a recognized expert in petroleum reservoir engineering with many publications to wit. He is also known as one of the world's key experts in acid treatment.

After an extensive search, we have been unable to find another individual with the equivalent combination of expertise in acid treatment as Dr. Hill, who does not have a similar conflict of interest. Therefore, we have concluded that this potential conflict is unavoidable.

**Disclosure of Conflict of Interest: William Minner**

In accordance with the practice of the California Council on Science and Technology (CCST), CCST makes best efforts to ensure that no individual appointed to serve on a committee has a conflict of interest that is relevant to the functions to be performed, unless such conflict is promptly and publicly disclosed and CCST determines that the conflict is unavoidable. A conflict of interest refers to an interest, ordinarily financial, of an individual that could be directly affected by the work of the committee. An objective determination is made for each provisionally appointed committee member regarding whether or not a conflict of interest exists, given the facts of the individual's financial and other interests, and the task being undertaken by the committee. A determination of a conflict of interest for an individual is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

We have concluded that for this committee to accomplish the tasks for which it was established its membership must include, among others, individuals with direct experience in the area of well stimulation practice, specifically in California. Well stimulation is of particular public concern in California and is the subject of regulation under SB 4. The practice in California is significantly different than in other states so we require someone with direct experience in the state.

To meet the need for this expertise and experience, William Minner is proposed for appointment to the committee even though we have concluded that he has a conflict of interest because of investments he holds and research services provided by his employer.

As his biographical summary makes clear, William Minner is a recognized expert in petroleum reservoir stimulation with a long history of practice in California as well as around the world. He is one of the most recognized experts in California well stimulation design and execution.

After an extensive search, we have been unable to find another individual with the equivalent combination of expertise as William Minner, who does not have a similar conflict of interest. Therefore, we have concluded that this potential conflict is unavoidable.

# Appendix C

# Report Authors

*Lead chapter authors are given in bold.*

| Author | Affiliation | Chapters |
|---|---|---|
| Corinne Bachmann | Lawrence Berkeley National Laboratory | Volume II: Ch. 4 |
| Jenner Banbury | California State University, Stanislaus | Volume II: Ch. 5 |
| **Jens T. Birkholzer** | Lawrence Berkeley National Laboratory | Summary Report<br>Volume I: Executive Summary, Introduction |
| **Adam Brandt** | Stanford University | Volume II: Ch. 3*<br>Volume III: Ch. 3, 4.3, 5 |
| Mary Kay Camarillo | Lawrence Berkeley National Laboratory | Volume II: Ch. 2 |
| Heather Cooley | Pacific Institute | Volume II: Ch. 2 |
| Brian L. Cypher | California State University, Stanislaus | Volume II: Ch. 5 |
| **Patrick F. Dobson** | Lawrence Berkeley National Laboratory | Volume I: Executive Summary, Introduction, Ch. 4* |
| Jeremy K. Domen | Lawrence Berkeley National Laboratory | Volume II: Ch. 2 |
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| Jacob G. Englander | Stanford | Volume II: Ch. 3 |
| **Laura C. Feinstein** | California Council On Science And Technology | Summary Report<br>Volume I: Executive Summary, Introduction<br>Volume II: Ch. 5*<br>Volume III: Ch. 3*, 5 |
| Kyle Ferrar | The Frac Tracker Alliance | Volume III: Ch. 4.3, 5 |
| **William Foxall** | Lawrence Berkeley National Laboratory | Volume II: Ch. 4*<br>Volume III: Ch. 3 |
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| Ben K. Greenfield | University of California, Berkeley | Volume III: Ch. 4.3 |
| Amro Hamdoun | University of California San Diego | Volume II: Ch. 2, 5 |
| Jake Hays | PSE Healthy Energy | Volume II: Ch. 6 |
| Robert J. Harrison | University of California, San Francisco | Volume II: Ch. 6 |
| Matthew G. Heberger | Pacific Institute | Volume I: Ch. 3<br>Volume II: Ch. 2<br>Volume III: Ch. 3, 4.3 |
| **James E. Houseworth** | Lawrence Berkeley National Laboratory | Volume I: Executive Summary, Introduction, Ch. 2*<br>Volume II: Ch. 2<br>Volume III: Ch. 2* |
| Michael L. B. Jerrett | University of California, Los Angeles | Volume III: Ch. 4.3 |
| Ling Jin | Lawrence Berkeley National Laboratory | Volume II: Ch. 3 |

| Author | Affiliation | Chapters |
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| **Preston D. Jordan** | Lawrence Berkeley National Laboratory | Volume I: Executive Summary, Introduction, Ch. 3*<br>Volume II: Ch. 2<br>Volume III: Ch. 4.3, 5* |
| Nathaniel J. Lindsey | Lawrence Berkeley National Laboratory | Volume II: Ch. 4<br>Volume III: Ch. 3 |
| **Jane C. S. Long** | California Council On Science And Technology | Summary Report*<br>Volume I: Executive Summary*<br>Volume II: Ch. 1*<br>Volume III: Ch. 1* |
| Randy L. Maddalena | Lawrence Berkeley National Laboratory | Volume II: Ch. 6<br>Volume III: Ch. 4.3 |
| **Thomas E. McKone** | Lawrence Berkeley National Laboratory | Volume II: Ch. 6*<br>Volume III: Ch. 4.3 |
| Dev E. Millstein | Lawrence Berkeley National Laboratory | Volume II: Ch. 3 |
| Sascha C.T. Nicklisch | University of California San Diego | Volume II: Ch. 2, 5 |
| Scott E. Phillips | California State University, Stanislaus | Volume II: Ch. 5<br>Volume III: Ch. 3, 5 |
| Matthew T. Reagan | Lawrence Berkeley National Laboratory | Volume II: Ch. 2 |
| Whitney L. Sandelin | Lawrence Berkeley National Laboratory | Volume II: Ch. 2, 6 |
| **Seth B. C. Shonkoff** | PSE Healthy Energy | Volume II: Ch. 6<br>Volume III: Ch. 4.3* |
| William T. Stringfellow | Lawrence Berkeley National Laboratory | Volume II: Ch. 2*, 6<br>Volume III: Ch. 2 |
| Craig Ulrich | Lawrence Berkeley National Laboratory | Volume III: Ch. 3 |
| Charuleka Varadharajan | Lawrence Berkeley National Laboratory | Volume II: Ch. 2 |
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*Denotes the chapter(s) for which an author served as the lead.

Full curricula vitae for authors are available upon request. Please contact California Council on Science and Technology (916) 492-0996

## Appendix D

# California Council on Science and Technology Study Process

The reports of the California Council on Science and Technology (CCST) are viewed as being valuable and credible, because of the institution's reputation for providing independent, objective, and nonpartisan advice with high standards of scientific and technical quality. Checks and balances are applied at every step in the study process to protect the integrity of the reports and to maintain public confidence in them.

**Study Process Overview—Ensuring Independent, Objective Advice**

For over 25 years, CCST has been advising California on issues of science and technology by leveraging exceptional talent and expertise.

CCST can enlist the state's foremost scientists, engineers, health professionals, and other experts to address the scientific and technical aspects of society's most pressing problems.

CCST studies are funded by state agencies, foundations, and other private sponsors. CCST provides independent advice; external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. Study committees gather information from many sources in public and private meetings, but they carry out their deliberations in private in order to avoid political, special interest, and sponsor influence.

**Stage 1: Defining the Study**

Before the committee selection process begins, CCST staff and members work with sponsors to determine the specific set of questions to be addressed by the study in a formal "statement of task," as well as the duration and cost of the study. The statement of task defines and bounds the scope of the study, and it serves as the basis for determining the expertise and the balance of perspectives needed on the committee.

The statement of task, work plan, and budget must be approved by CCST's Board chair. This review often results in changes to the proposed task and work plan. On occasion, it results in turning down studies that CCST believes are inappropriately framed or not within its purview.

**Stage 2: Committee Selection and Approval**

Selection of appropriate committee members, individually and collectively, is essential for the success of a study. All committee members serve as individual experts, not as representatives of organizations or interest groups. Each member is expected to contribute to the project on the basis of his or her own expertise and good judgment. A committee is not finally approved until a thorough balance and conflict-of-interest discussion is held, and any issues raised in that discussion are investigated and addressed. Members of a committee are anonymous until this process is completed.

Careful steps are taken to convene committees that meet the following criteria:

**An Appropriate Range of Expertise for the Task.** The committee must include experts with the specific expertise and experience needed to address the study's statement of task. A major strength of CCST is the ability to bring together recognized experts from diverse disciplines and backgrounds who might not otherwise collaborate. These diverse groups are encouraged to conceive new ways of thinking about a problem.

**A Balance of Perspectives.** Having the right expertise is not sufficient for success. It is also essential to evaluate the overall composition of the committee in terms of different experiences and perspectives. The goal is to ensure that the relevant points of view are, in CCST's judgment, reasonably balanced, so that the committee can carry out its charge objectively and credibly.

**Screened for Conflicts of Interest.** All provisional committee members are screened in writing and in a confidential group discussion about possible conflicts of interest. For this purpose, a "conflict of interest" means any financial or other interest which conflicts with the service of the individual because it could significantly impair the individual's objectivity or could create an unfair competitive advantage for any person or organization. The term conflict of interest means something more than individual bias. There must be an interest, ordinarily financial, which could be directly affected by the work of the committee. Except for those rare situations in which CCST determines that a conflict of interest is unavoidable and promptly and publicly disclose the conflict of interest, no individual can be appointed to serve (or continue to serve) on a committee of the institution used in the development of reports, if the individual has a conflict of interest that is relevant to the functions to be performed.

***Point of View is different from Conflict of Interest.*** A point of view or bias is not necessarily a conflict of interest. Committee members are expected to have points of view, and CCST attempts to balance these points of view in a way deemed appropriate for the task. Committee members are asked to consider respectfully the viewpoints of other members, to reflect their own views rather than be a representative of any organization, and to base their scientific findings and conclusions on the evidence. Each committee member has the right to issue a dissenting opinion to the report if he or she disagrees with the consensus of the other members.

**Other Considerations.** Membership in CCST and previous involvement in CCST studies are taken into account in committee selection. The inclusion of women, minorities, and young professionals are additional considerations.

Specific steps in the committee selection and approval process are as follows:

Staff solicits an extensive number of suggestions for potential committee members from a wide range of sources, then recommends a slate of nominees. Nominees are reviewed and approved at several levels within CCST. A provisional slate is then approved by CCST's Board. The provisional committee members complete background information and conflict-of-interest disclosure forms. The committee balance and conflict-of-interest discussion is held at the first committee meeting. Any conflicts of interest or issues of committee balance and expertise are investigated; changes to the committee are proposed and finalized. Committee is formally approved. Committee members continue to be screened for conflict of interest throughout the life of the committee.

**Stage 3: Committee Meetings, Information Gathering, Deliberations, and Drafting the Report**

Study committees typically gather information through:

- Meetings
- Submission of information by outside parties
- Reviews of the scientific literature
- Investigations by the committee members and staff.

In all cases, efforts are made to solicit input from individuals who have been directly involved in, or who have special knowledge of, the problem under consideration.

The committee deliberates in meetings closed to the public in order to develop draft findings and recommendations free from outside influences. The public is provided with brief summaries of these meetings that include the list of committee members present. All analyses and drafts of the report remain confidential.

**Stage 4: Report Review**

As a final check on the quality and objectivity of the study, all CCST reports—whether products of studies, summaries of workshop proceedings, or other documents—must undergo a rigorous, independent external review by experts whose comments are provided anonymously to the committee members. CCST recruits independent experts with a range of views and perspectives to review and comment on the draft report prepared by the committee.

The review process is structured to ensure that each report addresses its approved study charge and does not go beyond it, that the findings are supported by the scientific evidence and arguments presented, that the exposition and organization are effective, and that the report is impartial and objective.

Each committee must respond to, but need not agree with, reviewer comments in a detailed “response to review” that is examined by one or two independent report review “monitors” responsible for ensuring that the report review criteria have been satisfied. While feedback from the peer reviewers and report monitors is reflected in the report, neither group approved the final report before publication. The steering committee and CCST take sole responsibility for the content of the report. After all committee members and appropriate CCST officials have signed off on the final report, it is transmitted to the sponsor of the study and is released to the public. Sponsors are not given an opportunity to suggest changes in reports. All reviewer comments remain confidential. The names and affiliations of the report reviewers are made public when the report is released.

The report steering committee wishes to thank the oversight committee and the peer reviewers for many thoughtful comments that improved this manuscript.

# Appendix E

# Expert Oversight and Review

***Oversight Committee:***

Bruce Darling, National Academy of Sciences and National Research Council
Paul Jennings, California Institute of Technology
Robert F. Sawyer, University of California Berkeley

***Report Monitors:***

Maxine Savitz, Honeywell, Int. (Retired)
Robert F. Sawyer, University of California Berkeley

***Expert Reviewers:***

| **Name** | **Affiliation** | **Volumes Reviewed** |
|---|---|---|
| David Allen | University of Texas at Austin | Summary Report<br>Volume I<br>Volume II<br>Volume III |
| Ari Bernstein | Harvard T.H. Chan School of Public Health, Boston Children's Hospital | Summary Report<br>Volume II<br>Volume III |
| Jim Boyd | Cleantech Advocates | Volume I |
| Jerry Bushberg | University of California, Davis School of Medicine | Summary Report |
| Michael Ditmore | Novim Group – University of California, Santa Barbara | Summary Report |
| Ziyad Duron | Harvey Mudd College | Summary Report<br>Volume I<br>Volume II<br>Volume III |
| Graham Fogg | University of California, Davis | Summary Report<br>Volume II<br>Volume III |
| Tom Heaton | California Institute of Technology | Volume II |
| Gary Hughes | California Polytechnic State University, San Luis Obispo | Summary Report<br>Volume II<br>Volume III |

| | | |
|---|---|---|
| Tissa Illangaskare | Colorado School of Mines | Summary Report<br>Volume II<br>Volume III |
| Thom Kato | Lawrence Livermore National Laboratory | Volume II<br>Volume III |
| George E. King | George E. King Engineering | Summary Report<br>Volume I<br>Volume II<br>Volume III |
| Lisa McKenzie | University of Colorado, Denver | Summary Report<br>Volume II<br>Volume III |
| Peter McMahon | U.S. Geological Survey, Colorado Water Science Center | Summary Report<br>Volume II<br>Volume III |
| Mason Medizade | Cal Poly State University, San Luis Obispo | Summary Report<br>Volume II<br>Volume III |
| Charles Menzie | Exponent Inc. | Summary Report<br>Volume II<br>Volume III |
| William A. Minner | Minner Engineering, Inc. | Volume I |
| Larry Saslaw | Bureau of Land Management, Retired | Summary Report<br>Volume II<br>Volume III |

# Appendix F

# Summary of the Most Concerning Risk Issues

These risk issues are associated with hydraulic fracturing and acid stimulation in California as identified in this study.

*Table S.F-1 Risk issues.*

| **Risk Issue** | Description of the Issue | Possible Influence on Risk | Possible Mitigation | Loc. |
|---|---|---|---|---|
| **Number and toxicity of chemicals in hydraulic fracturing and acid stimulation fluids** | Operators have few restrictions on the types of chemicals they can use for hydraulic fracturing and acid stimulation. In California, oil and gas operators have reported the use of over 300 chemical additives. About 1/3 have not been assessed for toxicity. Of the chemicals for which there is basic environmental and health information, only a few are known to be highly toxic, but many are moderately toxic. There is incomplete information on which of the chemicals used have the potential to persist or bio-accumulate in the environment and may present risks from chronic low-level exposure. | If these chemicals are not released into usable water, including agricultural water, then the risk is minimal. However, if there are potential leakage pathways, then it is nearly impossible to assess the risk because of the large number of possible chemicals, incomplete knowledge about which chemicals are present, how long they persist, and what their environmental and human health impacts are. Researchers and the public need access to sufficient levels of information on all chemicals involved in well stimulation, to begin an assessment of the toxicity, environmental profiles, and human health hazards associated with hydraulic fracturing and acidizing stimulation fluids. | Invoke Green Chemistry principles to reduce risk—that is, use smaller numbers and amounts of less toxic chemicals, and avoid chemicals with unknown impacts. Mitigate exposure pathways. Limit the chemical use in hydraulic fracturing to those on an approved list that would consist only of those chemicals with known and acceptable toxicity profiles | Vol. II Ch. 2 |

| **Risk Issue** | Description of the Issue | Possible Influence on Risk | Possible Mitigation | Loc. |
|---|---|---|---|---|
| **Shallow fracturing** | The majority of hydraulic fracturing in California is conducted from shallow vertical wells. These operations present a larger probability of fractures intersecting near-surface groundwater compared to high volume fracturing from deep long-reach horizontal wells commonly used elsewhere. | The groundwater in the vicinity of much of the shallow hydraulic fracturing operations in California has high salinity and has no beneficial uses that might constitute environmental exposure pathways to humans.<br><br>The groundwater in the vicinity of some shallow fracturing is protected. Contamination of usable groundwater presents environmental public health risks. Groundwater monitoring requirements are likely insufficient to determine whether water has been contaminated by well-stimulation-enabled oil and gas development or not. | The focus of regulations should be on preventing contamination of aquifers, not just monitoring for it. Operators should be required to demonstrate that stimulations could not intersect usable groundwater to receive a permit. A higher level of scrutiny should be applied to shallow stimulations. Groundwater monitoring plans should be adapted as part of the corrective action, to improve the monitoring system and specifically look for contamination in close proximity to possible fracture extensions into groundwater. | Vol. I Ch. 3 & Vol. II Ch. 2 |
| **Hydraulic fracturing in reservoirs with long history of oil and gas production** | Many of the issues faced by other states arise because hydraulic fracturing has opened up oil and gas development in regions that previously had little or no experience with production. When the U.S. Energy Information Administration issued a report indicating that a large amount of such development was also possible in California from the Monterey Formation (subsequently revised dramatically downward), many were concerned about the development of oil and gas in new geographies. This assessment finds that the most likely future use of hydraulic fracturing is in and around the reservoirs where it is currently being used. | New production in developed fields can use the existing roads, platforms and infrastructure already in place. As a result, the impacts caused by construction and traffic are much less than in new, previously undeveloped regions.<br><br>Old reservoirs have many existing wells. If hydraulic fractures intersect or come near these old wells, the wells could form leakage pathways for stimulation fluids.<br><br>Older existing infrastructure (e.g., pipelines, storage tanks) may increase the likelihood of failures or leakage. | Existing infrastructure reduces the need for new pads, pipelines and other stationary infrastructure. Existing infrastructure can often transport fluids to and from the pad, reducing the need for truck trips. This reduces traffic accidents and the emission of diesel particulates and other health-damaging air pollutants.<br><br>Locate and seal old wells in the vicinity of hydraulic fracturing if they would provide leakage paths to air and usable groundwater.<br><br>Regulations should explicitly require an assessment of the integrity and leakage risk of existing wells that might be encountered by a hydraulic fracture, and remediation of wells which create a high risk of leakage into water less than 10,000 mg/L TDS. | Vol. II Ch. 2; Vol. III Ch. 5 |
| **Spills and leaks** | Surface spills and leaks are common occurrences in the oil and gas industry, and must be reported and cleaned up. | Information recorded on spills and leaks is insufficient to determine whether stimulation chemicals could be involved. | Require reporting about whether the source of the leak could contain well stimulation chemicals. | Vol. II Ch.2 |

| Risk Issue | Description of the Issue | Possible Influence on Risk | Possible Mitigation | Loc. |
|---|---|---|---|---|
| **Injection of recovered fluids and produced water into aquifers used for drinking, agriculture, and other direct and indirect uses by humans** | Produced water from stimulated fields has been injected into aquifers that are suitable for drinking water, irrigation, and other beneficial uses. | If water from contaminated aquifers is used, it could expose humans to unsafe concentrations of toxic compounds. | Prevent injection of well stimulation chemicals to usable groundwater in the future. In the process, of reviewing, analyzing and remediating the potential impacts of wastewater injection into protected groundwater, consider the possibility that stimulation chemicals may have been present in these wastewaters. | Vol. II Ch. 2 Vol. III Ch. 5 |
| **Beneficial use of produced water** | California is a water-short state, and California's oil reservoirs produce about 10 times more water than oil. Produced water is sometimes reused, for example to irrigate crops. If this produced water comes from stimulated wells or oil wells producing from a reservoir where stimulation was used, stimulation chemicals could be present in the produced water. | Well stimulation chemicals and their reaction products may be toxic, persistent or bioaccumulative. Current water district requirements for testing such waters before they are used for irrigation are not sufficient to guarantee that stimulation chemicals are removed, although some local treatment plants do use adequate protocols. If produced water used in irrigation water contains well stimulation and other chemicals, this would provide a possible exposure pathway for farmworker and animals, and could lead to exposure through the food chain. Currently, more than 60% of the fruits and vegetables consumed domestically come from the Central Valley. | Water districts in the San Joaquin Valley should explicitly disallow the use for irrigation of produced water from wells that have been hydraulically fractured or demonstrate that their monitoring and treatment methods ensure that hydraulic fracturing chemicals and other contaminants are not present in water destined for irrigation. | Vol. II Ch. 2 |
| **Disposal of water in percolation pits** | Wastewater disposed of in percolation pits infiltrates into the ground. The disposal of contaminated water in percolation pits is banned in nearly all other states, because this method of disposal results in the contamination of groundwater. Contaminants from percolation pits can move along with groundwater to reach wells or surface water where contamination can be a serious problem. Nearly 60% of wastewater from stimulated wells in California was disposed in percolation pits. | Well stimulation and naturally occurring chemical constituents can evaporate from these ponds or pits to the atmosphere as air pollutants, leak into aquifers, or migrate through the soil which could lead to food chain exposure to biota and humans. Chemicals in recovered fluids and produced water may be toxic, persistent, or bioaccumulative. | Test and appropriately treat water going in to percolation pits, or phase out the use of percolation pits in the San Joaquin Valley for wastewater disposal. | Vol. II Ch. 2 Vol. III Ch. 5 |

| **Risk Issue** | Description of the Issue | Possible Influence on Risk | Possible Mitigation | Loc. |
|---|---|---|---|---|
| **Acid use** | Operators in California commonly use mixtures of hydrochloric acid and hydrofluoric acid with other sources of fluoride anions as the most economical reagent for cleaning out wells or enhancing geological formation permeability. Reported use of hydrofluoric acid in the SCAQMD data lists the concentration (in percent mass of the ingredient) as 1%-3%. | Spills and leaks of undiluted acids may present an acute toxicity and corrosivity hazard. The use of acid can also mobilize naturally occurring heavy metals and other compounds that are known to be health hazards and these compounds could therefore be present in recovered fluids and produced water which humans could be exposed to if treatment and disposal is not sufficiently undertaken. | Evaluate the chemistry of recovered fluids and produced water for wells that have used acids and the potential consequences for the environment. Require reporting of significant chemical use for oil and gas development based on these results. | Vol. II Ch. 2 |
| **Oil and gas development near human populations** | California has large oil reserves located under densely populated areas primarily in the San Joaquin and Los Angeles Basins. In Los Angeles, oil and gas production developed simultaneously with the growth of the city. The Los Angeles Basin has world-class oil reservoirs, with the most concentrated oil in the world. Los Angeles is also a global megacity. | Proximity to production increases exposures to air pollutant emissions and other results of oil and gas development activities (e.g., dust, chemicals, noise, light). Households that use groundwater from private drinking water wells in close proximity to oil and gas development may be at increased risk of exposure to potential water contamination. | Identify and apply appropriate measures to limit exposure by residents and sensitive receptors (schools, daycare facilities, elderly care facilities)—such as scientifically based setback requirements. | Vol. II Ch. 6 |
| **Induced seismicity** | Disposal of wastewater by underground injection could cause felt or damaging earthquakes. | Disposal of wastewater from oil and gas operations into deep injection wells has caused felt seismic events in several states, although there have been no reported cases of induced seismicity associated with wastewater injection in California. Increased volumes of produced water, which if disposed of by injection underground could increase seismic hazards. | Develop and apply a protocol for managing injection wells to mitigate the risk of induced seismicity. Investigate whether future changes in disposal volumes or injection depth could affect potential for induced seismicity | Vol. II Ch. 4 |
| **Loss of habitat** | The location of hydraulic fracturing-enabled development coincides with ecologically sensitive areas in the southwestern San Joaquin Basin and Ventura County and causes habitat loss and fragmentation. | Portions of oil fields in the southwestern San Joaquin are essential corridors for connectivity between remaining areas of natural habitat and are vulnerable to expanded production. | Develop regional plans to conserve habitat and minimize fragmentation and compensate for new oil and gas development in ecologically sensitive areas. | Vo II Ch. 5 |

# Appendix G

# What to Call "The Monterey"

The Monterey Formation looms large in the public discourse about hydraulic fracturing, because a 2011 EIA report estimated that 15 billion barrels (2.4 billion $m^3$) of oil could be produced from the Monterey Formation using hydraulic fracturing, much like the "shale" oil that is being produced from the Bakken Formation in North Dakota and the Eagle Ford Formation in Texas. Some publications use the term "Monterey Shale" to identify the idea of having similar, "boom town"-type developments in California

This report uses more accurate terms than "Monterey Shale" in order to carefully describe the issues and potential of the Monterey. For over a hundred years, geologists have used the term *"Monterey Formation"* for rocks that were originally deposited off the coast of California between about 17.5 and 6 million years ago (middle to late Miocene Epoch). The Monterey Formation underlies much of California, but varies greatly from place to place in thickness and includes many different rock types, not just shale. Geologists identify rocks in the Monterey Formation as diatomite, porcelanite, chert, siliceous shale, highly organic-rich and phosphatic shale, marlstone, clay shale, sandstone, and volcanic rocks.

Generations of geologists have studied the Monterey and given it different names, leading to much confusion. For example, Antelope Shale, Devilwater Shale, Fruitvale Shale, Gould Shale, McDonald Shale, Modelo Formation, Monterey, Monterey Formation, Monterey Shale, Nodular Shale, Puente Formation, and Stevens Sandstone are just some of the names used to describe strata that could be considered as parts of the Monterey Formation. For simplicity, this report uses the terms "Monterey Formation" and "Monterey" interchangeably to describe all of these as a single class.

*The Monterey source rocks* are those parts of the Monterey Formation that are sources of petroleum. Oil can form in those parts of the formation that include concentrated organic material and that are in the "oil window". That is they have been buried deeply enough so that chemical reactions triggered by heat and pressure transform the organic matter into oil. Some of this oil formed in the oil window floats upwards (migrates by buoyancy) until it meets a barrier or "trap." The rest of the oil remains behind in the source rock.

Nearly all the petroleum so far produced in California has migrated from these prolific Monterey source rocks to the near-surface reservoirs that are now under production. But some oil, perhaps a lot and perhaps not much, may remain in the source rocks. The EIA based their estimate of potential new production on the idea that the oil remaining behind in the source rocks could also be produced.

# Appendix H

# Most Hazardous Chemicals

The following two tables list the most hazardous chemicals used in hydraulic fracturing in California from a human health perspective. Tables S.H-1 and S.H-2 give lists of the top ten most hazardous chemicals based on ranking, using acute toxicity data and chronic toxicity data respectively. The ranking is based on toxicity data as well as information as to how often and how much of the chemical is used. This list is incomplete, because it only applies to that fraction of the chemical database for which toxicity data were available. A full explanation of the ranking methodology is found in Volume II, Chapter 6.

***Table S.H-1. A list of the 12 substances used in hydraulic fracturing with the highest acute estimated hazard metric (EHMacute) values along with an indication of what factor(s) contribute most to their ranking (from high to low). WST = Well Stimulation Treatment.***

| Chemical Name | Reported frequency of use | Reported median mass fraction per WST (mg/kg) | Acute Toxicity |
|---|---|---|---|
| Distillates, petroleum, hydrotreated light paraffinic | ✔ | ✔ | |
| Isotridecanol, ethoxylated | ✔ | | ✔[1] |
| Hydrochloric acid | | ✔ | ✔[2] |
| Polyethylene-polypropylene glycol | ✔ | | ✔[3] |
| Sodium hydroxide | | | ✔[4] |
| Glyoxal | | ✔ | ✔[5] |
| Potassium carbonate | ✔ | ✔ | |
| Glutaraldehyde | | | ✔[6] |
| Ammonium Persulfate | ✔ | | ✔[7] |
| Hydrofluoric acid | | ✔ | ✔[8] |
| Sodium tetraborate decahydrate | ✔ | ✔ | |
| 5-Chloro-2-methyl-3(2H)-isothiazolone | ✔ | | ✔[9] |

*[1] Skin corrosion/irritation Globally Harmonized System of Classification and Labeling of Chemicals designation (GHS) = 1 per material safety data sheet (MSDS); [2] Skin sensitization and eye effects GHS = 1 per MSDS;[3] Inhalation LC50 (lethal concentration for 50 % of the test subjects) for rats of 45 ppm equivalent to GHS 1 from published data; [4] Skin corrosion/irritation GHS = 1 per MSDS; [5] Eye effects GHS = 1 per MSDS; [6] Inhalation equivalent to GHS 1 per published values and Eye effects GHS = 1 per MSDS; [7] Respiratory sensitization GHS = 1 per MSDS; [8] Inhalation equivalent to GHS 2 per published values and dermal, skin corrosion/irritation and eye effects per MSDS; [9] Inhalation equivalent to GHS 1 per published values.*

*Table S.H-2. A list of the 12 substances used in hydraulic fracturing with the highest chronic estimated hazard metric (EHM$_{chronic}$) values along with an indication of what factor(s) contribute most to their ranking (from high to low). WST = Well Stimulation Treatment.*

| Chemical Name | Reported frequency of use | Reported median conc. per WST (mg/kg) | Chronic[8] Toxicity |
|---|---|---|---|
| Proppant material | | ✔ | ✔[1] |
| Glutaraldehyde | ✔ | ✔ | ✔ |
| Zirconium oxychloride[2] | ✔ | ✔ | ✔[2] |
| Bromic acid, sodium salt (1:1) | | ✔ | ✔[3] |
| Hydrochloric acid | ✔ | ✔ | ✔ |
| Boron sodium oxide | ✔ | ✔ | ✔[4] |
| Ethylbenzene | | ✔ | ✔ |
| Naphthalene | ✔ | | ✔ |
| Sodium tetraborate decahydrate | ✔ | ✔ | ✔[5] |
| Boric acid, dipotassium salt | | ✔ | ✔[6] |
| Aluminum oxide | | ✔ | ✔[7] |
| Diethanolamine | | ✔ | ✔[6] |

*[1] Proppant materials reported that might include crystalline silica impurity (mullite, kyanite, silicon dioxide) use crystalline silica impurity as reference chemical for hazard screening (inhalation); [2] soluble zirconium compounds used as reference chemical for hazard screening (oral); [3] boric acid and bromate used as reference compound for hazard screening (oral) and (inhalation) respectively; [4] boric acid used as reference chemical for hazard screening (oral); [5] boric acid used as reference compound for hazard screening (oral); [6] boric acid used as reference chemical for hazard screening (oral); [7] The toxicity value used is only for non-fibrous forms of aluminum oxide, and does not apply to fibrous forms; [8] screening toxicity values for aluminum oxide, titanium oxide, propargyl alcohol, glyoxal, butyl glycidyl ether, hydrogen peroxide, and ethanol are available for occupational health criteria, but screening values are not provided because for each of these substances, there was an indication in the literature of possible mutagenicity or carcinogenicity such that the available occupational health criteria might not be sufficiently health protective of workers and the general population.*

## Appendix I

# Unit Conversion Table

| U.S. Customary Unit | International System of Units |
|---|---|
| 1 Oil Barrel | 0.158987 Cubic Meters ($m^3$) |
| 1 Foot (ft) | 0.304800 Meters (m) |
| 1 Gallon (gal) | 0.003785 Cubic Meters ($m^3$) |
| 1 Acre-Foot | 1,233.481855 Cubic Meters ($m^3$) |
| 1 Miles (mi) | 1.609344 Kilometers (km) |
| 1 Nautical Mile | 1.852000 Kilometers (km) |

# Appendix J

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