University of California
Agriculture and Natural Resources | California Institute for Water Resources

Hydraulic fracturing and water resources in California: Evaluating the emerging regulatory framework

Principal Investigators:
Brent M. Haddad (Principal Investigator)
University of California, Santa Cruz

Cameron Speir, Aaron Mamula,
Duran Fiack, and Audrey Levine
(Co-Investigators)
Southwest Fisheries Science Center, NOAA, Santa Cruz, California
Boston College

Technical Completion Report for project: NIWR2014CA323B
Project period: March 1, 2014 – October 27, 2017

Project Summary

Hydraulic fracturing: an established method for oil recovery

Technology advances in directional drilling and well stimulation have spurred interest in recovering oil and gas resources from deep subsurface formations. One technology, hydraulic fracturing (HF), enables access to oil and gas in unconventional formations such as shale, coalbeds, and tight sands. The ready availability of unconventional energy resources has been credited with improving the domestic economy and fueling a resurgence of U.S. manufacturing (Dumaine, 2015). It has also triggered concerns and research about environmental protection, public health, water resources, and air quality (e.g., Entrekin et al., 2011; Russell, 2013; Vengosh et al., 2014; Hedemark, 2015; USEPA, 2016; Brown, 2014, other articles and discussions in Environmental Health Perspectives and similar journals, and numerous NSF- and regionally-sponsored meetings and workshops).

HF is an established well-stimulation technology in California, with primary activity in Kern County. Statewide, over the period 2005-2015, of approximately 300 new wells installed per month, between 100 and 175 were fractured (Long et al., 2015a; CCST et al., 2016). In general, California's unconventional oil resources are embedded in the Monterey Shale Formation, a 1,750-square-mile oil reserve located in the southern San Joaquin Valley and Los Angeles Basin. The shale formation is between 1,000 and 3,000 feet thick and occurs at depths ranging from 8,000 to 14,000 feet (below ground surface). In 2011 recoverable tight oil in California's Monterey Formation was estimated at 15.4 billion barrels (USEIA 2011), equivalent to roughly 64% of all U.S. shale oil resources, and 7% of all U.S. technically recoverable oil resources. However, more detailed analysis yielded revised recoverable oil estimates of 21 million barrels (USGS 2015, Tennyson et al., 2015) in the San Joaquin Basin region, and 13 million barrels in the Los Angeles Basin region (Tennyson et al., 2016).

Neither of the Tennyson et al. reports was optimistic that a combination of hydraulic fracturing and horizontal drilling could yield substantial additional oil resources. The 2015 study attributed the drastic reduction in estimated resources to a better understanding of how shale oil was migrating upward through naturally-occurring fractures to form conventional deposits. In effect, the earlier, larger estimates of Monterey shale reserves were double-counting oil that had migrated from the shale and is now trapped or already recovered from overlying conventional reserves. Further, estimates of subsurface available resources can only be confirmed by actual drilling results, which turned out to be inconsistent with the more optimistic estimates of availability. HF can also be used to stimulate formations containing natural gas, however, currently this practice is not economically competitive in California (Long et al., 2015a).

Effective governance of oil and gas drilling is critical for maintaining a competitive domestic fossil fuel industry while protecting the environment and public health. In 2012 California began to actively review its fossil fuel production regulations to establish policies relevant to unconventional oil and gas production (Long et al., 2015a, 2015b; Stringfellow et al., 2015; CCST et al., 2016; DOGGR, 2015a and 2015b; Martin, 2014; Wilson, 2014; Kiparsky and Hein, 2013). Spurred by California Senate Bill 4 (Pavley, Chapter 313, Statutes of 2013), the California

Commission on Science and Technology (CCST) (Long et al., 2015a, 2015b, and Stringfellow et al., 2015) evaluated the locations and intensity of HF-induced unconventional energy production across California. Another CCST-led report (CCST et al., 2016), commissioned by the U.S. Bureau of Land Management, focused on the larger category of well stimulation technologies, which includes HF, acid fracturing, and matrix acid stimulation, and included an extensive section on potential negative impacts of well stimulation technologies on water resources. Since nearly all well stimulation in California involve HF (e.g., out of 669 total stimulations in 2014, 652 were HF stimulations according to the California Department of Conservation, 2016), HF is essentially synonymous with well stimulation in California.

The 2016 CCST et al. report makes a useful distinction between direct and indirect impacts of well stimulation technologies. The distinction was also noted in the California Division of Oil, Gas and Geothermal Resources (DOGGR) state wide Environmental Impact Report on well stimulation technologies (DOGGR, 2015b). Direct impacts are those that result during the three weeks to a few months time frame of the HF process. Indirect impacts relate to the aftermath of HF implementation and can include geochemical changes, fugitive gas emissions, surface spills, well integrity failures, drilling accidents, and other consequences of unconventional energy extraction. The chain of liability for indirect vs. direct potential harms is different in that companies that specialize in HF are not held liable for indirect impacts that can occur as a result of enhanced oil and gas recovery. Yet even with all the caveats just listed HF and its indirect impacts are linked and require consideration alongside direct impacts. To only focus on direct impacts, according to CCST et al. (2016, p. 34), is to examine a “very narrowly defined marginal change in risks” rather than the entire set of impacts related to the practice. A decade earlier, a USEPA study (2004) concluded that there were no direct impacts of HF on drinking water. This finding is now considered to have been technically accurate but misleading regarding the relationship between HF and aquifers that provide drinking water.

Research Program

Box 1

A principled analysis of hydraulic fracturing in light of its contribution to global warming

The CCST et al. report (2016, p. 33) focuses on direct impacts of hydraulic fracturing (HF), but notes that indirect impacts “may be significant” and should not be dismissed. Similarly, the certification cover memo for the statewide programmatic Environmental Impact Report notes the importance of indirect impacts (DOGGR 2015b). The most important long-term indirect impact of HF is its role in liberating additional subsurface hydrocarbons that, once combusted or volatilized, contribute to greenhouse gas loading to the atmosphere and global warming.

One could argue that any discussion or policy that facilitates hydrocarbon recovery adds to the problem of global warming and therefore cannot be justified. Based on this principle, one could conclude without further discussion any analysis of HF except for how to immediately end the practice. A paper such as this one is not consistent with this principle because it is addressing the further implementation of HF, not its curtailment.

An unprincipled basis on which to proceed with an analysis of HF would be to dismiss the premise that global warming is a major threat to the earth's social- and ecosystems. This entails the selective use of science: the same scientific methods and tools utilized in an analysis of HF risks must be rejected as illegitimate when applied to understanding impacts of greenhouse gas loading. One either accepts the legitimacy of scientific methods and the ways in which science self-evaluates and self-corrects, or one doesn't.

California has made a strong commitment to reducing greenhouse gas loading into the atmosphere. HF can help during the transition toward a sustainable energy future. The value of HF is in reducing the cost of oil and natural gas production, both superior to coal in their greenhouse gas creation per unit of energy. There is no reason to devote resources wastefully to the production of oil and gas while they are being phased out. HF contributes to cost reductions in oil and gas production, thereby providing a substitute for coal while enabling financial resources to be efficiently allocated. The principle of an efficient transition to a sustainable energy future justifies this kind of research.

This paper was commissioned by the Prosser Trust to explore basic issues concerning the protection of surface waters in California arising from HF, based on the assumption of rapid expansion of HF and a new era of hydrocarbon production in the state. California's anticipated unconventional oil and gas drilling boom turned out to be chimeric, with the rate of new well drilling remaining steady over the past 12 years (Long et al., 2015a). Meanwhile, many of the questions about HF's impacts on the waters of California and how to regulate them have been addressed by the large-scale research projects commissioned during this period. This paper provides a summary of the intensive period of research and regulation promulgation occurring over the past five years, followed by observations about where HF-related energy policy could turn next. After a brief introduction to the method of HF, this report provides an overview of HF activity in the U.S. and California. The report then reviews potential surface water and groundwater impacts that have been attributed to the practice of HF. The next section examines how HF is regulated in California. A concluding section summarizes what the next steps should be for HF regulation as well as what can be learned more broadly from the research on California's HF experience, including potential new directions in the relationship between hydrocarbon production and water resources in California.

Expansion of unconventional fossil fuel recovery in the United States

It is estimated that roughly half of all crude oil produced in the U.S. comes from hydraulically fractured wells (USEIA, 2016a). By 2015, more than 4.3 million barrels per day (b/d) were being produced from an estimated 300,000 hydraulically fractured wells. Conventional drilling dropped slightly from 2000-2015, while overall production rose from 5.8 million b/d to 9.4 million b/d. All of the rapid expansion of overall U.S. crude oil production can be attributed to hydraulically fractured wells.

Natural gas production nationally has shown a more striking trend, with marketed natural gas production from hydraulically fractured wells growing from 7% in 2000 to 67% in 2015 (USEIA 2016b). At the beginning of the period, 26,000 hydraulically fractured wells produced 3.6 billion cubic feet per day (Bcf/d), and by 2015 the numbers had grown to roughly 300,000 wells producing 53 Bcf/d.

Numerous factors have contributed to the rapid expansion of unconventional oil and gas recovery in North America. These include the discovery of extensive untapped resources, continuing demand for fossil fuels, depletion of conventional resources, a national desire for energy independence, and technological advancements that have reduced the cost and environmental risk of drilling. Unconventional oil and gas plays have been discovered and mapped in detail in the upper mid-west, Texas, the Rockies, and northeastern U.S.

Hydraulic fracturing in California: a common practice but no oil boom in sight

While overall crude oil production has seen a steady decline since the mid-1980s in California, the proportion of fractured wells has increased. By 2000, California produced 741 thousand barrels per day. Production rallied slightly from 2000-2005, but the overall trend reached 551 thousand b/d in 2015. California's share of national crude oil production has been falling, from nearly 13% in 2000 to nearly 6% in 2015.

There are more than 80,000 new and active oil and gas wells in California, of which, 2,572 have employed the practice of hydraulic fracturing to extract oil and natural gas (Table 1).[1] While the practice of hydraulic fracturing to extract oil and gas has been implemented in the state for decades (Figure 1), the state experienced a dramatic increase in the number of wells that have used the process to produce fossil fuels.

California wells are also shallower – closer to the earth's surface – compared to wells in other parts of the nation. The average depth to the top of the oil recovery horizon of new HF wells over a 2014-15 reporting period was 1,153 feet (DOGGR, 2015a, Table 33). Much of the planned hydraulic fracturing operations in California is expected to occur at depths of less than 305 meters (1,000 feet). (CCST et al., 2016) This is the elevation of oil-rich diatomite formations in the southern San Joaquin Valley. California's smaller wells produce less oil while using less water than

[1] This figure includes conventional oil and gas, dry gas, pressure maintenance, steam flood, water flood, and dry gas well types. Note that the dataset includes 5,750 wells that were recorded as new or active, but do not have a designated well type. Given that the dataset includes well types not associated with oil and gas production (e.g., gas disposal, water disposal, and water source), the 5,750 wells with no well type recorded were removed from the dataset.

wells in other parts of the U.S., resulting in California using roughly half the water in HF wells per unit of energy produced compared to other formations. (Tiedman et al., 2016).

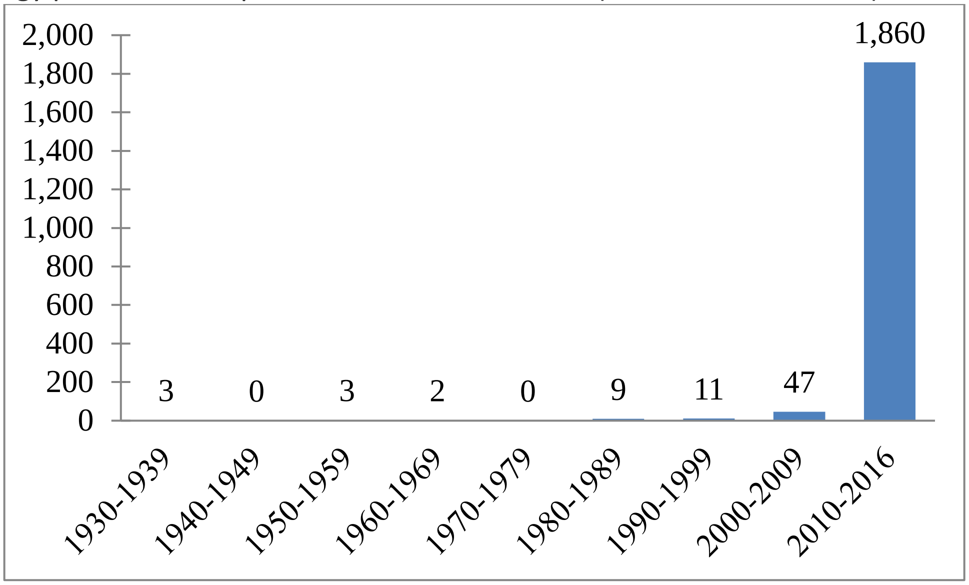

Figure 1: Hydraulically fractured wells completed in California by decade.
Completion is the process of making a well ready for production (or injection). Note: Of the 2,572 hydraulically fractured wells on record, 637 do not have completion dates on record.
Source: DOGGR 2017

Table 1: California counties with hydraulically fractured wells in operation, 2017, including offshore wells.
Source: DOGGR 2017

County	Number of Wells	Percentage of Wells
Kern	2,138	83.13
Ventura	323	12.56
Los Angeles	60	2.33
Orange	15	0.58
Sutter	14	0.54
Santa Barbara	8	0.31
Kings	4	0.16
Colusa	3	0.12
Santa Clara	3	0.12
Fresno	1	0.04
Glenn	1	0.04
Monterey	1	0.04
San Luis Obispo	1	0.04
TOTAL:	2,572	

Hydraulic fracturing and water supply: assessing the risks

Vengosh et al. (2014) provide a list of potential harms to surface and groundwater related to HF in shale gas formations. They include contamination of shallow aquifers with fugitive hydrocarbons or salinity via leaking natural gas wells or subsurface flows; surface and shallow groundwater contamination from spills, leaks, or disposal of inadequately treated wastewater; accumulation of toxic or radioactive elements in soils or streams near disposal or spill sites; and local shortages from overuse of water supplies for HF. This list was generated based on the HF experience in Pennsylvania, Texas, and North Dakota. Over the next two years, DOGGR completed its programmatic Environmental Impact Report (2015b), and CCST et al. (2016) completed its Bureau of Land Management-commissioned study of water-related risks of well stimulation technologies including HF. These latter studies focused exclusively on California, providing far more detail that re-prioritized and contextualized the risks California faces. The following discussion divides risks into those related to water supply and water quality impairment.

Water Supply Risks

The amount of water used for HF per well drilled in California, in the range of Long et al.'s (2015) 3,300 barrels and DOGGR's (2015a, Table 60) 2,545 barrels, or roughly one-third of an acre-foot, is small compared to other regions of the U.S. Still, one should investigate the possibility of localized water shortages in regions where HF takes place. According to California's first annual Well Stimulation Treatment Report (DOGGR, 2015a, Tables 53*ff*.), between January 2014 and September 2015, 78% of the water used as the base fluid for HF was supplied by regional water agencies, 15% came from oilfield produced waters, and 7% from private wells. The total amount of HF base fluid used was 2,608,729 barrels, or 306 acre-feet. These statistics cover a 20-month period. To put this amount of water into context, during an overlapping 12-month period, January to December 2015, 2 billion barrels, or 258,000 acre feet, of oil and gas field produced water were generated in Kern County (DOGGR, 2015c). That means that HF-base water requirements are equivalent to roughly 0.1% of produced water.

Since roughly 99% of California's HF occurs in Kern County, it is the only region in which a water shortage related to HF is possible. Located at the southern end of California's central valley, Kern County is a major agricultural producer (among the top five counties in the U.S.) with crops and livestock production valued at roughly $7 billion annually. Its annual water consumption is roughly 3.7 million acre feet, drawing upon local and imported sources. Local water sources include flows from the Kern River (21% of the total) and other local rivers (8%), as well as imports from two major water supply systems, the Central Valley Project (11%) and the State Water Project (23%). The county has a longstanding system of water storage in large aquifer system enabling excess wet year supplies to be banked for use in dry years and supplying 37% of annual water needs. Local precipitation provides less than one percent of water supply (KCWA, 2015).

Of the 3.7 million acre feet of annual water consumption in Kern County, 222,000 acre feet are used by the city of Bakersfield to support municipal and industrial activities. As noted above, of this amount, 306 acre feet were used as HF base fluid covering a slightly longer period. This analysis shows that for California, HF does not pose a competition risk for regional water supply.

Box 2 examines this issue at the even finer water agency scale and reaches the same conclusion. One can even identify situations in which produced water from oil fields, having been treated and blended, provides a reliable source of water for irrigation. Cawelo Water District, north of Bakersfield, receives 20-25% of its water supply from produced water sources and provides water to 34,000 irrigated acres, and up to 50% during drought periods (KEDC, 2015). One should note that the implication found in this paper, that risks of an HF-related water shortage regionally or state-wide are minimal, departs from the somewhat greater concern expressed in earlier risk studies.

Water Quality Risks

With respect to water quality risks three categories of water related to oil and gas drilling activities that employ HF can be identified: fracturing fluids, flowback, and produced water.

Fracturing fluids, or injection fluids, are pumped into the wellbore under heavy pressure in order to fracture the formations surrounding the well. CCST's 2015 report (Long et al., 2015a) provides a useful table listing common additives to aqueous fracture fluids, reproduced in Table 2. This list of additives provides a useful framework for surface and subsurface regulation of injection and flowback fluids. It is not an exhaustive list since some oil and gas recovery companies utilize proprietary chemicals and blends. A list generated in 2014-5 by California's DOGGR included 253 different chemical constituents added to the fracturing base fluid (DOGGR, 2015a). It is also possible that chemicals will mix, react, and transform during the high-pressure fracturing process, creating new chemicals with different risk profiles (Kahrilas et al., 2016).

Of the proppants and additives that along with water comprise fracturing fluid, most are considered non-toxic or of low toxicity. A few have been identified as toxic, including biocides (e.g., tetrakis (hydroxymethyl) phosphonium sulfate; 2,2-dibromo-3-nitrilopropionamide; and glutaraldehyde), corrosion inhibitors (e.g. propargyl alcohol), and mineral acids (e.g. hydrofluoric acid and hydrochloric acid) (CCST et al. 2016).

There are minor risks in the delivery and storage of fracturing fluid compounds (proppants and additives) at drilling sites. This risk can be related to major storm events that disrupt normal procedures (DOGGR 2015b). Injection fluid is not mixed until the fracturing process has begun. The mixed injection fluid is pumped directly to the wellbore so there is little surface spill risk related to mixed injection fluid.

Flowback is mostly the injected fracturing fluids returning to the surface after the fracturing process is complete. Between 15 and 40% of injected fluids return to the surface over a period of three weeks, primarily in the first 7-10 days following fracturing. Over this period, the return flows transition to produced water, depending on the formation characteristics. Flowback water contains all of the chemicals originally added to the fracture fluids, plus contaminants that are mobilized from the formation. Because one of the goals of well stimulation is to dissolve and remove salts and cement from the well and fractures, flowback water is likely to be high in salinity and total dissolved solids (TDS), with thousand-fold increases in concentrations possible (CCST et al. 2016, Table 5-4).

Flowback is stored onsite in tanks or in lined pits before being taken offsite for injection into Class II wells or reuse as fracturing fluid elsewhere. Class II wells are used for subsurface injection of fluids related to oil and gas recovery. They sequester flowback fluids and produced water while also enhancing oil recovery. For this reason Class II wells are commonly located in producing oil fields. During the period January 1, 2014 through September 30, 2015, 98% of recovered WST fluids were injected into Class II wells. The remainder was recycled (DOGGR, 2015a). In some cases, produced water is used as by the agricultural industry to irrigate crops. The Cawelo Water District, for example, has applied produced water to is agricultural fields for decades. However, the District's website emphasizes that it does not apply water generated from hydraulic fracturing (see: http://www.cawelowd.org/PrdWater.html, accessed September 8, 2017).

Produced waters are waters that commonly underlie or are interspersed with hydrocarbon formations. Produced water contains salinity, TDS, dissolved hydrocarbons, other local minerals, and traces of the chemicals introduced in the oil and gas operations. Oil fields produce far more water than hydrocarbons. Globally, the average ratio of water to oil produced is 3:1, meaning roughly 70% of all produced fluids is water (Fakhru'l-Razi et al., 2009). Roughly 95% of produced water can be returned to the original formation to enhance recovery, but the remaining produced water requires treatment prior to disposal or other beneficial use. Treatment technologies exist to improve the quality of produced water (Johnson, 2013). They involve multiple steps and the choice of steps depends on the nature of the produced waters and the intended use of the water after treatment. USEPA sets minimum standards for dissolved and dispersed hydrocarbons. Treating water to a quality that enables beneficial use of produced water is generally affordable by industrial and municipal entities but not for agriculture. The Cawelo Water District, which does purchase produced water for agricultural use, can afford it because the producer, Chevron, only charges for the 8.5 miles of piping the treated water, not the treatment itself. The nearby Belridge Water Storage District identifies oilfield wastewater (produced waters) as being produced in "considerable" amounts (BWSD, 2015:56). As a potential source of recycled water, BWSD notes that treatment and brine disposal costs exceed the agricultural region's ability to pay. However, an agreement to swap some of BWSD's SWP-contracted water, which arrives via the California Aqueduct, with an urban region also connected to the Aqueduct that has a greater ability to pay for water treatment could be possible. The urban region would take additional SWP water and pay for water treatment enabling BWSD to take the oilfield water.

There is a risk of surface spills throughout the handling of flowback and produced waters. Spills could include runoff from drilling sites or infiltration into shallow groundwater formations from leaking surface impoundments. There is also a risk of leakage of fracturing fluid through the wellbore into shallow aquifers. Risks from fracturing and flowback fluids stem from the presence of compounds found in Table 2, as well as any additional salts and other compounds added by the fracturing process. Risks associated with any oil and gas production include cross contamination with aquifers along the wellbore, oil spills that could harm surface or groundwater, and water pollution impacts from the refining process. As explained earlier, these are potential indirect impacts facilitated by HF but not directly caused by the HF process.

Box 2

Belridge Water Storage District: supplying agriculture and hydraulic fracturing in western Kern County

Kern County-located Belridge Water Storage District (BWSD) is a water agency providing water to roughly 80% of HF wells in California (CDC, 2016). The North and South Belridge Oil Fields are located in the western portion of the District (Figure 2). Within BWSD's boundaries, roughly 130,000 acre feet of water is provided to agriculture each year, focusing on almonds, pistachios, and citrus, all tree crops requiring regular irrigation. An additional 5,578 acre feet per year is contracted to industrial users, including oil production, of which roughly 1,600 acre feet are taken. This amounts to slightly over one percent of overall water allocation in a typical year (BWSD, 2015, Tables 23 and 28). The California drought of 2012-17 reduced BWSD's primary source of water, the State Water Project (SWP), significantly, but sufficient alternative sources were available to maintain agricultural output and industrial activities. The sufficiency of water available for HF in BWSD results from the combined availability of local groundwater and imported SWP supplies.

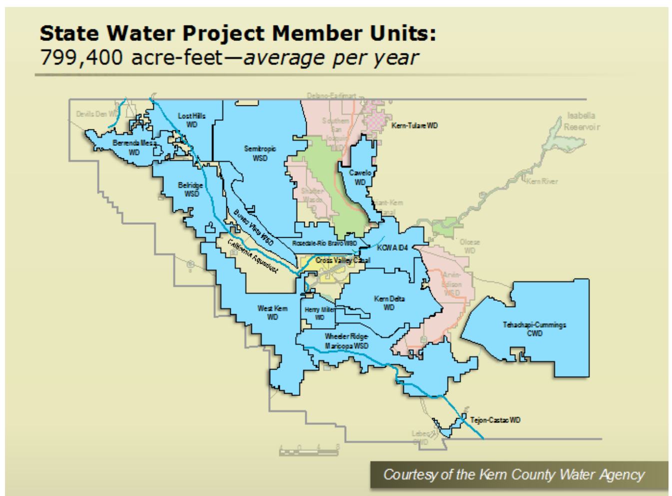

Figure 2: Belridge Water Storage District location. Located along the California Aqueduct in western Kern County, its western portion is the primary site of hydraulic fracturing in California.

The experience of BWSD suggests that California's oil producing regions have sufficient water resources to meet the anticipated demands of HF. Unlike other parts of the nation where HF requires far more water per well, available oil and gas resources are much larger, and there may not be an engineered system to store and deliver, California does not face HF-induced water scarcity problems. California's integrated network of water supply from captured snowmelt in the Sierra Nevada and northern mountain ranges also increases the ability of water-poor regions like Kern County to satisfy agricultural, urban, and industrial demands for water.

Table 2: Additives to Aqueous Fracture Fluids. Adapted from Table 2-2 in Long et al., 2015a, which provides as a source Table 5-6 of the New York State Department of Environmental Conservation 2011 *Revised Draft Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program*. Supplemental data from Table 2.7-4 from Long et al., 2015b, Vol. 3.

Additive Type	Description of Purpose	Examples of Chemicals
Proppant	"Props" open fractures and allows gas / fluids to flow more freely to the well bore.	Sand [Sintered bauxite; zirconium oxide; ceramic beads]; crystalline silica [quartz (SiO_2)]; up to 29%
Acid	Removes cement and drilling mud from casing perforations prior to fracturing fluid injection	Hydrochloric acid (HCl, 3% to 28%); muriatic acid; ammonium bifluoride
Breaker	Reduces the viscosity of the fluid in order to release proppant into fractures and enhance the recovery of the fracturing fluid.	Peroxydisulfates
Bactericide / Biocide / Antibacterial Agent	Inhibits growth of organisms that could produce gases (particularly hydrogen sulfide) that could contaminate methane gas. Also prevents the growth of bacteria which can reduce the ability of the fluid to carry proppant into the fractures.	Gluteraldehyde; 2,2-dibromo-3-ni-trilopropionamide
Buffer / pH Adjusting Agent	Adjusts and controls the pH of the fluid in order to maximize the effectiveness of other additives such as	Sodium or potassium carbonate; acetic acid (up to 1%)

	crosslinkers	
Clay Stabilizer / Control /KCl	Prevents swelling and migration of formation clays which could block pore spaces thereby reducing permeability.	Salts (e.g., tetramethyl ammonium chloride Potassium chloride (KCl)
Corrosion Inhibitor (including Oxygen Scavengers)	Reduces rust formation on steel tubing, well casings, tools, and tanks (used only in fracturing fluids that contain acid).	Methanol; ammonium bisulfate for Oxygen Scavengers
Crosslinker	Increases fluid viscosity using phosphate esters combined with metals. The metals are referred to as crosslinking agents. The increased fracturing fluid viscosity allows the fluid to carry more proppant into the fractures.	Potassium hydroxide; borate salts
Friction Reducer	Allows fracture fluids to be injected at optimum rates and pressures by minimizing friction.	Sodium acrylate-acrylamide copolymer; polyacrylamide (PAM); petroleum distillates
Gelling Agent	Increases fracturing fluid viscosity, allowing the fluid to carry more proppant into the fractures.	Guar gum; petroleum distillates; up to 0.25%
Iron Control	Prevents the precipitation of metal oxides which could plug off the formation.	Citric acid; up to 0.83%
Scale Inhibitor	Prevents the precipitation of carbonates and sulfates (calcium	Ammonium chloride (up to 5%); ethylene Glycol

	carbonate, calcium sulfate, barium sulfate) which could plug off the formation.	
Solvent	Additive which is soluble in oil, water and acid-based treatment fluids which is used to control the wettability of contact surfaces or to prevent or break emulsions	2-butoxyethanol (up to 2%); various aromatic hydrocarbons
Surfactant	Reduces fracturing fluid surface tension thereby aiding fluid recovery.	Methanol; isopropanol; ethoxylated alcohol

In its first annual report on well stimulation activities, DOGGR (2015a) reported no emergency responses, spills, or releases of any liquids or regulated substances associated with well stimulation technologies during the reporting period January 2014 through September 2015. This record is consistent with the CCST et al. (2016) findings that "the direct impacts of WST appear to be relatively limited for industry practice of today and will likely be limited in the future if proper management practices are followed."

Information Transfer/Outreach Program

Regulatory Oversight of Hydraulic Fracturing in California

DOGGR is the implementing agency for well stimulation technology regulations. The state agency oversees the drilling, operation, maintenance, and plugging and abandonment of oil, natural gas, and geothermal wells.

Various state and federal laws already require remediation and reporting of spills or releases of hazardous substances. In 2011, in response to Assembly Bill (AB) 1960, DOGGR implemented regulations for the safe management of oilfield fluids. The AB 1960 regulations require secondary containment features around fluid containers, regular testing and maintenance of tanks and pipelines, and operator implementation of a detailed spill contingency plan. In addition to these existing requirements, the regulations prohibit the storage of well stimulation fluids in unlined sumps or pits. The regulations also require operators to specifically include well stimulation treatment fluids in their spill contingency plans. And the regulations include the requirement to cleanup spills in accordance with all applicable statutes and regulations.

In 2013, the California Legislature passed SB 4, titled *Oil and gas: well stimulation*. It laid out a now-implemented procedure for research, interim regulations, and final regulations governing HF. Among the major provisions of SB 4 are:

- A permit requirement and application process for conducting a new well stimulation treatment. Approved permits are made publicly available by DOGGR and must be provided to overlying landowners and tenants prior to commencing the well stimulation treatment.

- Following the well stimulation treatment, the well operator must provide public information on the well stimulation fluid used.

- An annual report on well stimulation activities is required (the first report is referenced here as DOGGR 2015a).

- Coordination between DOGGR and the State Water Resources Control Board is mandated to develop groundwater monitoring plans prioritizing groundwater that is or could be used for drinking water. Groundwater monitoring and management plans will be part of well stimulation permits if necessitated by the proximity of groundwater formations.

A following bill, SB 1281 (2014), laid out reporting requirements for well owners, including monthly reports on (1) the amount of oil, natural gas, and water produced from each oil and natural gas well; (2) the source, volume, storage, and disposal status of all water used in or generated by oil and gas field activities; and (3) the ultimate use, disposal method, or method of recycling or reuse.

In carrying out its SB 4 and SB 1281 duties, DOGGR coordinates with several state and regional agencies. DOGGR consulted widely in the development of HF regulations and in producing an extensive state-wide Environmental Impact Report on the potential impacts of HF (DOGGR, 2015b). In carrying out ongoing HF oversight duties, further consultation occurs. For example, it is possible for produced water to be reinjected into aquifers intended for potable use. When this is proposed, DOGGR coordinates with Regional Water Quality Control Boards to affirm that the produced water quality after treatment and mixing is sufficient to allow reinjection. Another agency with which DOGGR coordinates is the California Office of Emergency Services. This is the lead office for spill reporting and response. The California Department of Toxic Substance Control also plays a role in regulating flowback fluids and produced water.

At the federal level, the Bureau of Land Management (BLM) holds jurisdiction over HF activities on federal lands. DOGGR and the BLM have a Memorandum of Understanding signed in 2012 describing how the two agencies share authority of HF in California. Federal water- and safety-related laws provide a broad regulatory framework for HF, including authority for site inspection and enforcement actions. Federal laws and agencies include the Clean Water Act (providing general water resource protection, spill prevention control and countermeasures, discharge requirements, and reporting requirements); Comprehensive Environmental Response, Compensation, and Liability Act, also known as Superfund (spill reporting and clean up); Emergency Planning and Community Right-to-Know Act (hazardous substance reporting); the Safe Drinking Water Act (water injection requirements); and the Occupational Safety and Health Administration (worker safety, and chemical disclosures).

A 2016 California Legislative Analyst's Office report (LAO, 2016) summarizes efforts to implement HF-related legislation. It found the research and regulation development process to be on track, as well as creation of online processes for permit applications and reporting.

Notable Achievements

Future Policy Directions: Short Term and Long Term

Two areas of ongoing policy interest, one short term and one long term, emerge from California's experience with HF. The first, a short-term perspective, involves integrating what has been and will soon be learned about HF into the newly-created well stimulation regulatory structure. DOGGR has anticipated this and expects to make adjustments to its regulatory and reporting systems. For example, DOGGR estimates that only 90% of all well stimulation activities have been properly reported thus far. For the non-reporting 10%, DOGGR is exercising newly-established processes of notice of violation and civil penalties (LAO, 2016). The success of these regulatory actions will inform how the program is adjusted in the future. DOGGR is also learning more about what chemicals are actually used and found in flowback fluid, what disposal practices are in use, what the potential environmental consequences might be, and feasible mitigation strategies. Recommendations and data gaps identified in Sections 2.8 and 2.9 of Volume II of CCST (Stringfellow, et al., 2015, pp. 143*ff*), and in Conclusion 5 in the Executive Summary of CCST et al. (2016), which identifies specific toxic chemicals used in HF, will help improve regulatory oversight. DOGGR will be able to compare actual behaviors and performance with categories developed through its state-wide EIR process, as well as with existing water quality standards and procedures, and adjust existing regulations accordingly. Regulations and guidelines will emerge or be refined related to monitoring, inspections, integrity testing, emergency response plans, baseline data, site management plans, and other aspects of HF.

The second area is developing a long term perspective. Millions of dollars and thousands of hours of effort went into studying HF between 2013 and 2016. The proximate outcome has been a finding that HF poses a relatively minor threat to California water supply and water quality. However, as has been noted in CCST et al. (2016) and the programmatic EIR (DOGGR 2015b; especially the comments on the limits of the EIR's programmatic analysis in Supervisor Bohlen's Certifying Statement), the focus on well stimulation technologies and HF misses a larger point. It is important to consider HF from an unconventional energy lifecycle perspective that includes exploratory drilling, wellboring, fuel recovery, storage, transport, site management, along with closure and post-closure activities. It would be prudent to leverage the approaches that are used in management and remediation of hazardous waste sites to provide a comprehensive risk assessment framework.

California's energy economy remains deeply dependent on fossil fuels. In 2015, 77% of statewide total energy consumption (7676 trillion Btu) came from oil, natural gas, and coal, not counting fossil fuels' contribution to imported electricity production. In terms of equilibrating state-wide production and consumption, California consumes about three times the energy it produces (USEIA 2016c). In addition, over half of the petroleum consumed in California originates in foreign nations, a ratio that continues to grow.

Fossil fuel's continued predominance in California's energy sector imposes the burden of short- and long-term environmental and public health impacts, as well as the global political problems associated with securing fossil fuel imports and associated greenhouse gas emissions. As a practical policy response, a two-pronged strategy has emerged in California. In the short run, regulations that maintain the viability of HF as a technology that enables fossil fuel recovery and storage are being pursued, including online reporting and detailed systems to protect fracturing fluid trade secrets. HF regulations are facilitative, not punitive, focusing on disclosure and proper disposal of flowback fluids. Incentivizing the use of 'green' environmentally 'friendly' chemicals is also feasible along with advances in water use efficiency and site management.

Simultaneously, a slower and more complex policy-driven transition to a sustainable energy economy is underway in California. This transition includes changing how Californians produce, transport, store, and consume energy. It reaches across all sectors of the economy. It also engages how other major resource-dependent sectors connect with energy, including water, food production, and other systems (e.g., Bazilian et al., 2011). The focus of SB4 and BLM-sponsored research on HF's impact on water resources is part of a growing recognition that improvements in the performance of one resource sector need to take into consideration its interactions with other resource sectors.

A single-sector focus misses too many opportunities for beneficial co-management. SB4 is expanding water and energy co-management in subsurface regions. For example, the law requires permit applicants to model HF-stimulated wells and their potential impact on local potable groundwater formations prior to receiving a well stimulation permit. Additionally, permit holders must follow reporting requirements and other restrictions on the reinjection of flowback fluids. These efforts are consistent with the ongoing initiatives to harmonize California's energy and water regulations. More opportunities may emerge. Recent legislation to restore California's groundwater basins, cumulatively known as the Sustainable Groundwater Management Act of 2014 (AB 1739, SB 1319, SB 1168, and SB 13), recognize the importance of California's subsurface waters to the state's long term economic and public health.

This longer-term policy process of reforming the state's energy sector is vastly more complex and encompassing than the regulation of well stimulation technologies. With intellectual roots in the

1970s (Lovins, 1976), the energy sector transition process is frustratingly slow. The extensive public interest in HF, which led many cities and counties to pass their own prohibitions (see, e.g., http://www.cafrackfacts.org/policy/local-regulations/), can be understood as an expression of a broadly-held belief that California's existing energy sector, including both its production and consumption practices, is not the state's desired energy sector.

While the sustainability of the fossil fuel economy is not practical, a transition period is needed to implement alternative fuel sources and supporting infrastructure. If carefully regulated, HF can be justified as part of an efficient transition of California's fossil fuel-dependent economy.

With SB4, the state is implicitly adopting the position that fossil fuel production will be phased out when alternative energy sources and general reductions in demand for energy are phased in. Market forces will then phase out oil and gas production and consumption. This represents a practical trade-off: HF's enabling regulatory structure exists as part of a broader commitment to a sustainable energy future (e.g., CEC, 2015). The regulatory structure deals with the localized and immediate risks of HF while broader efforts are made to transition the overall energy economy. California's leadership in alternative energy development and in energy efficiency indicates ongoing effort to fulfill this commitment (e.g., AB 32 of 2006).

Although its purpose is to regulate HF, SB4 also represents an important step in the sustainable co-management of multiple resource systems, in this case energy and water. SB4 requires both state energy and water regulators to work together to manage the surface and subsurface resource systems in tandem. A broader transition to an economy supported by sustainable resource systems will be achieved in part by identifying and pursuing beneficial co-management opportunities of multiple resource systems, such as water-energy, food-energy, energy-coastal systems, and others. SB4 is a promising example of this larger process.

While HF is an effective well stimulation technology, it is likely to have a finite lifespan in California as alternative energy sources become more available and cost-competitive. California's HF regulations connect crucial dots between energy and water management and can serve as an example for future multi-resource regulatory harmonization.

References

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Geilen, D., Steduto, P., Mueller, A., Komor, P., Tol, R., and Yumkella, K. 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* 39:7896-7906.

Belridge Water Storage District (BWSD), 2015. 2012 Agricultural Water Management Plan; 2015 Update. McKittrick, CA: Belridge Water Storage District. Downloaded August 30, 2017, from http://www.belridgewsd.com/awmp .

Brown, V., 2014. "Radionuclides in Fracking Wastewater: Managing a Toxic Blend". Environmental Health Perspectives. p. A50.

California Council on Science and Technology (CCST), Lawrence Berkeley National Laboratory, and Pacific Institute, 2016. Advanced Well Stimulation Technologies in California: An Independent Review of Scientific and Technical Information. Commissioned by U.S. Bureau of Land Management. Downloaded August 21, 2017 from http://ccst.us/projects/hydraulic_fracturing_public/BLM.php

California Department of Conservation (CDC), 2016. Website: Well Stimulation Treatment – Frequently Asked Questions. Accessed September 1, 2017, at: http://www.conservation.ca.gov/dog/Pages/WST_Faq.aspx#regulation

California Energy Commission (CEC), 2015. 2015 Integrated Energy Report. Downloaded September 11, 2017, from: http://www.energy.ca.gov/2015_energypolicy/.

Division of Oil, Gas, and Geothermal Resources (DOGGR), 2015a. Well Stimulation Treatment: First Annual Report. Downloaded September 1, 2017, at: http://www.conservation.ca.gov/dog/pubs_stats/annual_reports/Pages/annual_reports.aspx

——— 2015b. Environmental Impact Report on Analysis of Well Stimulation Treatments in California (July 1). Downloaded September 11, 2017 from: http://www.conservation.ca.gov/dog/Pages/SB4_Final_EIR_TOC.aspx.

——— 2015c. Well count and production of oil, gas, and water by county. Downloaded September 8, 2017 from *ftp://ftp.consrv.ca.gov/pub/oil/annual_reports/2015/County_Production_2015.pdf.*

——— 2017. All Wells Online Dataset. Downloaded September 29, 2017, at: ftp://ftp.consrv.ca.gov/pub/oil/GIS/ExcelTables/

Dumaine, B. 2015. "U.S. Manufacturing costs are almost as low as China's, and that's a very big deal." *Fortune* 6-26-2015. http://fortune.com/2015/06/26/fracking-manufacturing-costs/. Downloaded 11-2-16.

Entrekin, S., Evans-White, M. Johnson, B and Hagenbuch, E. 2011. Rapid expansion of natural gas development poses a threat to surface waters. *Frontiers in Ecology and the Environment*. 9(9): 503-511.

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L., Biak, D., Madaeni, S., and Abidin, Z., 2009. Review of technologies for oil and gas produced water treatment. *Journal of Hazardous Materials.* 170 (2-3): 530-551.

Hedemark, J. 2015 Taming the West: Senate Bill 4 and California's Struggle to Regulate Fracking. *Golden Gate University Environmental Law Journal* 8(1): 119-154. http://digitalcommons.law.ggu.edu/gguelj/vol8/iss1/8
Johnson, A. 2013. Sustainable Water Management. *Oil and Gas Financial Journal Digital Magazine* (Nov. 12). Downloaded September 8, 2017, from: http://www.ogfj.com/articles/print/volume-10/issue-11/features/sustainable-water-management.html

Kern County Water Agency (KCWA), 2015. Comprehensive Annual Financial Report for the fiscal year ended June 30, 2015. Downloaded September 8, 2017 from: https://emma.msrb.org/ES777404-ES611120-ES1006828.pdf

Kern Economic Development Corporation (KEDC), 2015. Kern: Oil & Water Mix. Downloaded September 8, 2017, from: http://kedc.com/kern-county-oil-water-mix/

Kahrilas, G., Blotevogel, J., Corrin, E., and Borch, T. 2016. Downhold transformation of the hydraulic fracturing fluid biocide Glutaraldehyde: Implications for flowback and produced water quality. *Environmental Science and Technology* 50 (20): 11414–11423.

Kiparsky, M., and Hein, J. 2013. Regulation of Hydraulic Fracturing in California: A Wastewater and Water Quality Perspective. Center for Law, Energy, & the Environment Publications. Paper 27. Downloaded August 25, 2017, at http://scholarship.law.berkeley.edu/cleepubs/27

Legislative Analyst's Office (LAO), 2016. Hydraulic Fracturing: How it works and recent state oversight actions. (December 1). Downloaded September 11, 2017 at http://www.lao.ca.gov/Publications/Report/3513.

Long, J., Feinstein, L, Birkholzer, J., Jordan, P., Houseworth, J., Dobson, P., Heberger, M., and Gautier, D. 2015a. Well Stimulation Technologies and their Past, Present, and Potential Future Use in California (January). Volume 1 of An Independent Scientific Assessment of Well Stimulation in California ISBN Number: 978-1-930117-97-6. Report updated July 2016.

Long, J., Feinstein, L, Birkholzer, J., Foxall, W., Houseworth, J., Jordan, P., Lindsey, N., Maddalena, R., McKone, T., Stringfellow, W., Ulrich, C., Heberger, M., Shonkoff, S., Brandt, A., Ferrar, K., Gautier, D., Phillips, S., Greenfield, B., and Jerrett, M. 2015b. Case Studies of Hydraulic Fracturing and Acid Stimulations in Select Regions: Offshore, Monterey Formation, Los Angeles Basin and San Joaquin Basin. Volume III in 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, ISBN Number: 978-1-930117-76-1.

Lovins, A. 1976. Energy Strategy: the Road Not Taken? *Foreign Policy* (October).

Martin, P. 2014. Hydraulic Fracturing in California: An Overview. California Research Bureau Short Subjects S-14-001 (March).

Russell, C. 2013. Fracking our Farmland, Our Families, and Our Future: A New Toxic Legacy. *The Bulletin 19(5):* 8-13.

Stringfellow, W., Cooley, H., Varadharajan, C., Heberger, M., Reagan, M., Domen, J., Sandelin, W., Camarillo, M., Jordan, P., Donnelly, K., Nicklisch, S., Hamdoun, A., and Houseworth, J. 2015. Impacts of Well Stimulation on Water Resources. Chapter two of 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, ISBN Number: 978-1-930117-76-1.

Tennyson, M., Charpentier, R., Klett, M., Brownfield, M., Pitman, J., Gaswirth, S., Hawkins, S., Lillis, P., Marra, K., Mercier, T., Leathers, H., Schenk, C., and Widden, K. 2015. Assessment of Undiscovered Continuous Oil and Gas Resources in the Monterey Formation, San Joapuin Basin Province, California, 2015. Fact Sheet 2015-3058 (September). Downloaded August 21, 2017 from: https://pubs.er.usgs.gov/publication/fs20153058

Tennyson, M., Charpentier, R., Klett, M., Brownfield, M., Pitman, J., Gaswirth, S., Hawkins, S., Le, P., Lillis, P., Marra, K., Mercier, T., Leathers-Miller, H., and Schenk, C. 2016. Assessment of undiscovered continuous oil and gas resources in the Monterey Formation, Los Angeles Basin Province, California, 2015. Fact Sheet 2016-3036. Downloaded August 21, 2017 from https://pubs.er.usgs.gov/publication/fs20163036.

Tiedman, K., Yeh, S., Scanlon, B., Teter, J., and Mishra, G. 2016. Recent Trends in Water Use and Production for California Oil Production. 2016. *Environmental Science and Technology* 50(14):7904-7912.

U.S. Energy Information Administration (USEIA), 2011. Review of Emerging Resources: U.S. Shale Gas and Shale Oil Plays. Washington, D.C.: U.S. Department of Energy.

——— 2016a. Hydraulic fracturing accounts for about half of current U.S. crude oil production. (March 15). Downloaded August 18, 2017 from https://www.eia.gov/todayinenergy/detail.php?id=25372

——— 2016b. Hydraulically fractured wells provide two-thirds of U.S. natural gas production. (May 5). Downloaded August 18, 2017 from https://www.eia.gov/todayinenergy/detail.php?id=26112

——— 2016c. California State Profile and Energy Estimates. Downloaded September 11, 2017, from: https://www.eia.gov/state/data.php?sid=CA#ReservesSupply .

U.S. Environmental Protection Agency (USEPA), 2004. Evaluation of impacts to underground sources of drinking water by hydraulic fracturing of coalbed methane reservoirs [EPA Report]. (EPA/816/R-04/003). Washington, D.C.: U.S. Environmental Protection Agency, Office of Solid Waste.

——— 2016. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/236F.

U.S. Geological Survey (USGS), 2015. USGS Estimates 21 Million Barrels of Oil and 27 Billion Cubic Feet of Gas in the Monterey Formation of the San Joaquin Basin, California. (October 6). Download August 21, 2017 from https://www.usgs.gov/news/usgs-estimates-21-million-barrels-oil-and-27-billion-cubic-feet-gas-monterey-formation-san

Vengosh, A., Jackson, R. Warner, N., Darrah, T., and Kondash, A. 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology* 48: 8334-8348.

Wilson, E. 2014. Regulating Fracking in California: An Overview. *Western City: the Monthly Magazine of the League of California Cities* (September). Dowloaded August 21, 2017 from http://www.westerncity.com/Western-City/September-2014/Regulating-Fracking-in-California-An-Overview/