From: Victoria Bogdan Tejeda [mailto:vbogdantejeda@biologicaldiversity.org]
Sent: Tuesday, March 21, 2023 3:22 PM
To: CityClerk <CityClerk@longbeach.gov>
Subject: CBD Sources, Part 4.1

-EXTERNAL-

Attached:
Sumaila
Stringfellow
Stanford
Standard Oil

Victoria Bogdan Tejeda (*she/her*)
Staff Attorney, Climate Law Institute
Center for Biological Diversity
1212 Broadway, Suite 800
Oakland, CA 94612
Ph: 510.844.7103 ext. 303

Impact of the *Deepwater Horizon* well blowout on the economics of US Gulf fisheries

U. Rashid Sumaila, Andrés M. Cisneros-Montemayor, Andrew Dyck, Ling Huang, William Cheung, Jennifer Jacquet, Kristin Kleisner, Vicky Lam, Ashley McCrea-Strub, Wilf Swartz, Reg Watson, Dirk Zeller, and Daniel Pauly

Abstract: Marine oil spills usually harm organisms at two interfaces: near the water surface and on shore. However, because of the depth of the April 2010 *Deepwater Horizon* well blowout, deeper parts of the Gulf of Mexico are likely impacted. We estimate the potential negative economic effects of this blowout and oil spill on commercial and recreational fishing, as well as mariculture (marine aquaculture) in the US Gulf area, by computing potential losses throughout the fish value chain. We find that the spill could, in the next 7 years, result in (midpoint) present value losses of total revenues, total profits, wages, and economic impact of US\$3.7, US\$1.9, US\$1.2, and US\$8.7 billion, respectively. Commercial and recreational fisheries would likely suffer the most losses, with a respective estimated US\$1.6 and US\$1.9 billion of total revenue losses, US\$0.8 and US\$1.1 billion in total profit losses, and US\$4.9 and US\$3.5 billion of total economic losses.

Résumé : Les déversements de pétrole en mer nuisent généralement aux organismes à deux interfaces, soit près de la surface de l'eau et sur la côte. Cependant, à cause de la profondeur à laquelle s'est produite l'éruption de *Deepwater Horizon* en avril 2010, les zones plus profondes du golfe sont vraisemblablement affectées. Nous estimons les effets économiques négatifs potentiels de cette éruption et du déversement de pétrole sur les pêches commerciales et sportives, ainsi que sur la mariculture (aquaculture marine) dans la région du golfe aux É.-U., en calculant les pertes potentielles dans l'ensemble de la chaîne de valeur des poissons. Nous trouvons que le déversement pourrait, dans les 7 prochaines années, entraîner des pertes en valeur actuelle (point milieu) de revenus totaux, de profits totaux et de salaires et un impact économique de respectivement 3,7, 1,9, 1,2 et 8,7 milliards de \$US. Les pêches commerciales et sportives subiraient vraisemblablement les pertes les plus élevées, avec des pertes totales de revenu respectives de 1,6 et 1,9 milliards \$US, des pertes de profit total de 0,8 et de 1,1 milliards \$US et un impact économique total de 4,9 et de 3,5 milliards \$US.

[Traduit par la Rédaction]

Introduction

On 20 April 2010, the *Deepwater Horizon* (DH), an oil rig leased by British Petroleum (BP), exploded in the Gulf of Mexico (GOM) and began leaking oil from the seabed at a depth of over 1500 m. On Monday, 1 August 2010, the US government stated that BP's ruptured well had gushed an estimated 4.9 million barrels of oil (780 million L), making it the largest accidental marine oil spill in US waters (Levy and Gopalakrishnan 2010; Urriza and Duran 2010). In contrast, the 1989 *Exxon Valdez* oil spill, a major disaster in US history, amounted to less than 0.5 million barrels (80 million L). Given the likely economic and legal repercussions of this major pollution event, a rapid first-order estimation of the likely economic losses due to the oil leaks is required. Here, we present such a preliminary estimate using a top-down approach to set a baseline for future, hopefully more detailed, comprehensive economic assessments.

Besides obvious environmental effects, oil spills can have extensive socio-economic, psychological, and even cultural impacts, including effects on marine resource use and livelihoods (e.g., fisheries) and public health (Anonymous 1989; 1990*a*; Palinkas et al. 1993). Impacts on marine ecosystems can persist for extended periods and stem directly from the destruction of habitats, death and pollution of plants and animals, and changes to food web structure and function. For example, the environmental and economic effects of the 1989 *Exxon Valdez* spill in Prince William Sound, Alaska,

Received 24 November 2010. Accepted 7 October 2011. Published at www.nrcresearchpress.com/cjfas on 15 February 2012.
J2011-0046

Paper handled by Associate Editor Terrance Quinn III.

U.R. Sumaila, A.M. Cisneros-Montemayor, A. Dyck, L. Huang,* J. Jacquet, K. Kleisner, V. Lam, A. McCrea-Strub, W. Swartz, R. Watson, D. Zeller, and D. Pauly. Fisheries Centre, The University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada.
W. Cheung.[†] School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, United Kingdom.

Corresponding author: U. Rashid Sumaila (e-mail: r.sumaila@fisheries.ubc.ca).

*Present address: Department of Economics, University of Connecticut, 341 Mansfield Road, Unit 1063, Monteith Room 345, Storrs, CT 06269-1063, USA.
[†]Present address: Fisheries Centre, The University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada.

were still being felt in the early 2000s (Graham 2003). The impacts on marine ecosystems translate into impacts on the economy and livelihoods, including commercial fisheries, recreation, mariculture (marine aquaculture), tourism, and energy markets. Fish caught from contaminated areas or neighboring locations will raise concerns about food safety. These effects call for actions to mitigate, recover, and prevent the incidence of oil spills, which are costly to society.

The coast of the GOM is made up largely of saltwater marshes, mangroves, wetlands, and estuaries, which are important nursery and foraging areas for many marine species. Within these ecosystems, there are over 15 000 species of fauna and flora (Felder and Camp 2009), including whales, turtles, manatees, sharks and other fishes, shrimps, crabs, mollusks, birds, seagrasses, and mangroves. Many of these species are highly valued by commercial and recreational fisheries, including brown shrimp (*Farfantepenaeus aztecus*), blue crab (*Callinectes sapidus*), eastern oyster (*Crassostrea virginica*), red snapper (*Lutjanus campechanus*), Gulf menhaden (*Brevoortia patronus*), and bluefin tuna (*Thunnus thynnus*). Additionally, one of only two existing Atlantic bluefin tuna spawning grounds is located in the GOM. Large-scale pollution events, such as the DH spill, can result in impacts that are both direct (e.g., acute-phase mortality) and indirect (e.g., bioaccumulation through the food web). Indirect effects have been shown to persist for decades (Graham 2003).

Long-term studies on salt marsh habitat following the *Florida* barge spill in Wild Harbor, Massachusetts, USA, in 1969 demonstrate the persistence and impacts of oil within sediments (Culbertson et al. 2007, 2008*a*, 2008*b*). Buried hydrocarbons result in the destruction of seagrass root structure and subsequent losses of grass cover and increased erosion even 40 years later (Culbertson et al. 2008*a*).

Within tropical ecosystems, mangroves are considered to be among the most susceptible to impacts from oil spills (Shigenaka 2002). Studies of mangrove habitats after the 1986 spill of 50 000 barrels from the *Galeta* near the Panama Canal demonstrate the influence of sediments acting as long-term reservoirs of oil (Burns et al. 1993). The persistence of the oil was unexpected because of relatively warm tropical waters, which were thought to increase the rate of breakdown of the hydrocarbons. Short-term effects included dead mangroves along 27 km of coastline even 1½ years after the spill (Jackson et al. 1989) and the deterioration of surviving mangroves up to 6 years after the spill (Burns et al. 1993). Long-term effects were not only apparent in the mangroves themselves, but also detected in the species found associated with the root structure (i.e., bivalves).

Coral reefs are one of the most diverse marine ecosystems and host highly complex communities (Haapkyla et al. 2007). Besides obvious lethal effects of oil, sublethal effects such as reduced reproductive efficiency have also been demonstrated (Loya and Rinkevich 1980). Haapkyla et al. (2007) reviewed the impacts of oil and oil spills on corals and found that corals were negatively impacted, leading to decreases in coral cover, growth, reproductive output, and species diversity. Only in two cases were no or only minor effects found, these being the Arabian Gulf field experiment in 1989 (LeGore et al. 1989) and oil spills in the Arabian Gulf related to the Gulf War in 1991 (Downing and Roberts 1993; Price 1998).

Unlike the visually obvious and immediate effects on birds and mammals, the effects of oil on fisheries can be more difficult to detect, though they are no less devastating. Oil spreads through the marine ecosystem and damages coastal areas important as nurseries for juvenile fish and shrimp. Oil and hydrocarbons are taken up by plankton and other surface-dwelling species that link to aquatic food chains. Thus, oil moves through the food web and accumulates in food fishes, posing serious health concerns for consumers. Almost immediately following the DH spill, the region's key shrimp and oyster fishing areas were officially closed. According to the US National Marine Fisheries Service, 70% of the commercially caught shrimp and oysters in the US come from the GOM (National Oceanographic and Atmospheric Administration 2010).

Several studies have examined the effects of oil on fish and invertebrate species. The *Exxon Valdez* oil spill in Alaska in 1989 had notable effects on important fish species, such as Pacific herring (*Clupea pallasii*) and pink salmon (*Oncorhynchus gorbuscha*), including premature hatching, reduced growth rates, morphological and genetic abnormalities, and increased mortality (Bue et al. 1998; Rice et al. 2001). Adult Pacific herring showed evidence of liver lesions and increased disease due to depressed immune function (Moles et al. 1993; Carls et al. 2001). These effects contributed to increased natural mortality in adult Pacific herring over a 5-year period (Thorne and Thomas 2007). Research on biomarkers of hydrocarbon exposure in nine species of pelagic and demersal fish showed that 10 years after the *Exxon Valdez* spill, signs of exposure were still present (Jewett et al. 2002). Consequences have been shown to be more severe for invertebrates because of their sessile nature and close association with contaminated habitats, including declines in abundance, growth rate, and condition (Culbertson et al. 2007, 2008*a*). Sediments and intertidal mussel beds (*Mytilus trossulus*) showed evidence of contamination 6 years after the *Exxon Valdez* oil spill and were a source of chronic contamination for predatory species (Carls et al. 2001).

In addition to direct effects on individual species, food web interactions allow for the propagation of negative impacts to higher trophic levels. The impact of the *Tsesis* oil spill on benthic organisms in the Baltic Sea in 1977 resulted in food chain transfer of oil to flounder (*Platichthys flesus*; Elmgren et al. 1983).

The magnitude and duration of impacts will depend on the scale of the spill, the type of hydrocarbon, and the characteristics of the marine environment. Benthic and relatively sessile organisms (e.g., crabs, clams, mussels, and shrimps) suffer high initial mortalities, displacement, or contamination (becoming unmarketable) of up to 100% (Teal and Howarth 1984). Mobile fish species are generally subject to lower initial mortality rates, although those can quickly rise in large spills. For example, the 1979 *Ixtoc I* blowout, previously the largest accidental oil spill in history, is estimated to have caused 50%–70% fish mortality in adjacent coastal regions (Jernelov and Linden 1981).

There are many studies that examine the initial impacts of oil spills on species, yet few consider the time scale for marine organisms to recover from exposure. Recovery time is dependent on the length of exposure, water temperature, oceanographic features of the region, mobility, and ontogenetic stage of the species, as well as species-specific life history traits (e.g., feeding and reproductive patterns). The ability of critical habitats to act as long-term reservoirs of oil can extend exposure and subsequent recovery times. While habitat recolonization can begin within 3 to 6 months, it generally takes at least 1 year for pollutant concentrations in marine organisms to return to prespill conditions (Teal and Howarth 1984). This assumes that the spill has ended and most oil cleaned up, so the minimum duration of impacts can be well over 1 year. In fact, oil concentrations in sediment, where it is most persistent, have been detected up to 40 years after a spill (Culbertson et al. 2008*a*). All of these effects depend to a great extent on the type of ecosystem affected. In tropical systems like the GOM, impacts can be exacerbated by a high proportion of mangroves and marshes, which capture and retain oil for prolonged periods, affecting organisms that depend on these habitats for food, reproduction, and shelter (Jackson et al. 1989).

There are numerous economic assessments of oil spills, which can be adapted for the current assessment. Cohen (1995) estimated the social costs (i.e., cost to society as opposed to private cost to a firm or an individual) of the 1989 *Exxon Valdez* spill for the years 1990 and 1991 by examining the revenue difference between actual fisheries catches with and without the spill. García-Negro et al. (2009) studied the economic impact of the 2002 *Prestige* oil spill on the affected coastline in Spain, investigating the fisheries landings before and after the accident. The McDowe Group used business surveys to determine the economic effect of the *Exxon Valdez* spill on Alaska's tourism industry (Anonymous 1990*b*). A study by Advanced Resources International provided estimates of economic impacts for many oil spill accidents by dividing spills into three types: tanker, pipeline, and offshore platform, and determined the cost for clean-up, oil losses, environmental and resource damage per gallon (1 gallon = 3.785 L) of oil spilled to be US$260, US$1.71 and US$9.91–19.81, respectively (Anonymous 1993). Clean-up costs and environmental damage from tanker spills are highly variable, but can be particularly high if the spill occurs in remote and environmentally sensitive areas, as has occurred in the past. Offshore facilities have a relatively good safety record, so spill effects are more poorly defined. However, large blowouts close to sensitive coastal areas such as marshland or reefs can lead to substantial ecological and economic damages (e.g., *Ixtoc I*, 1979; *Union Platform A*, 1969); the DH blowout is unfortunately one such case.

An important consideration in this study is the potential market recovery times (i.e., the time required for market conditions for the affected fish species to return to prespill levels) of commercially important species in the GOM. There is a distinct difference between ecological and market recovery times. As mentioned above, ecological recovery can take decades, especially for organisms associated with sediments such as crustaceans and mollusks. Market recovery time, on the other hand, depends on the length of fisheries closures after a spill, public perceptions of seafood safety, and the degree of tainting (both visible and with respect to taste and smell of seafood; Moller et al. 1999).

The oil industry typically touts the quick recovery of organisms to an "untainted state" as evidence of the safety of seafood after an oil spill (e.g., Moller et al. 1999). However, after the *Exxon Valdez* spill, fisheries for salmon, herring, crab, shrimp, rockfish, and sablefish were closed, with some commercial fisheries remaining closed through 1990. Herring and salmon species in the region have never fully recovered ecologically or economically. One of the main reasons for this is the public perception of contamination from seafood (see http://useconomy.about.com/od/suppl1/p/Exxon_Valdez_Oil_Spill_Economic_Impact.htm).

Materials and methods

The GOM ecosystem supports considerable commercial and recreational fisheries, as well as mariculture, all of which are affected by spilled oil. To provide a broad picture of the economic effects of the spill on these three sectors, we estimate the potential losses in (*i*) total revenues; (*ii*) total profit (payment to capital plus resource rent); (*iii*) wages (payments to labor); (*iv*) number of jobs; and (*v*) economic impact throughout the wider economy. To provide conservative estimates of the economic effects of the oil spill, we use estimates of market recovery time rather than longer ecological recovery time horizons.

Total revenue is the product of ex-vessel price and catch in the case of commercial fisheries; the total expenditure in the case of recreational fisheries; and the product of ex-farm price and production quantity in the case of mariculture. Total profit is the sum of normal profit and resource rent. Normal profit (payment to capital) is the opportunity cost of the capital invested to run fisheries or mariculture. Resource rent is payment to the "owners" of marine resources (i.e., the American people in the case of commercial and recreational fisheries). Wages (payments to labor) are the amounts earned by people who expend their labor, skills, and expertise in the sector. The added value or impact through the fish value chain is the indirect economic effects of fisheries and mariculture because of their impact on activities such as boat building or maintenance, equipment supply, and the restaurant sector (Pontecorvo et al. 1980).

We assume that each economic indicator is related to landings (L) in the following manner:

$$(1)\qquad \text{total revenue} = L \cdot p$$

$$(2)\qquad \text{normal profit} = L \cdot \pi$$

$$(3)\qquad \text{wages} = L \cdot w$$

$$(4)\qquad \text{rent} = L \cdot p - L \cdot c$$

$$(5)\qquad \text{impact} = L \cdot p \cdot M$$

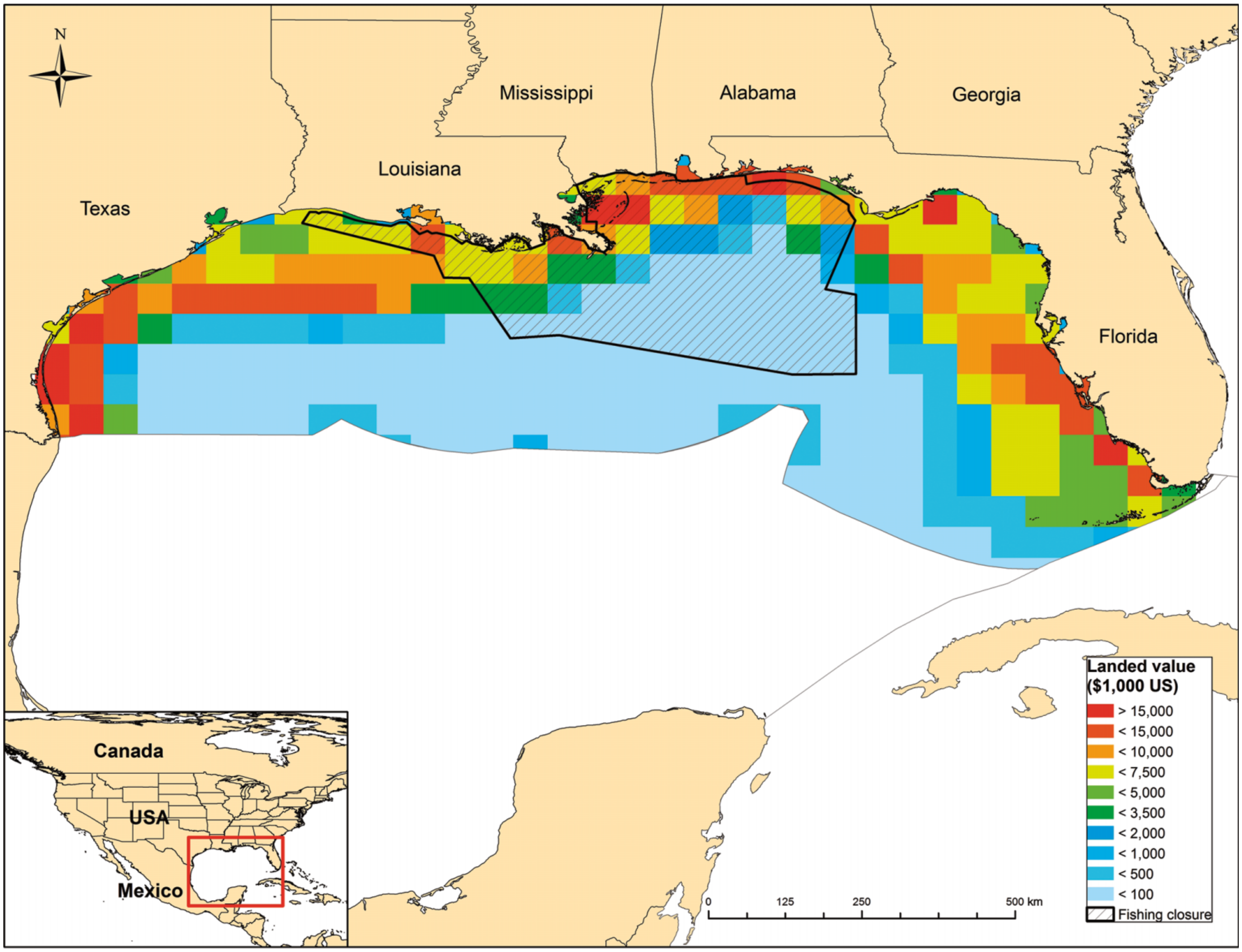
where p, π, w, and c represent price, profit, wages, and costs, respectively, per tonne. The parameter M represents the economic impact multiplier for fisheries of the US as estimated by Dyck and Sumaila (2010).

The present value of each indicator i over time t is expressed as

$$(6)\qquad \mathrm{PV}_i = \sum_{t=0}^{T} \delta_i^t X_{i,t}$$

where $X_{i,t}$ represents economic indicator i at time $t = 0 \ldots T$,

Fig. 1. Spatial distribution of the annual average landed value of the total commercial fisheries catch in the US Exclusive Economic Zone in the Gulf of Mexico (averaged for the 2000–2005 period). The area closed to commercial fishing (as of 22 July 2010) includes both federal waters and portions of western Florida, Alabama, Mississippi, and Louisiana state waters.



and the parameter δ is the discount factor determined using the appropriate rate of discount applicable to the US. The discount factor is calculated using a real discount rate of 3.0%.

Modeling oil spill impacts

We use the Sea Around Us Project (http://www.seaaroundus.org) global grid-map system of half degree latitude by half degree longitude cells of spatially assigned annual commercial catch (Watson et al. 2004) and landed values of catch (http://feru.org; Sumaila et al. 2007) taken by US fisheries in the US Gulf Exclusive Economic Zone (EEZ). We then overlay on this landed value map the area of the GOM that was closed to fishing at its largest extent (as of 22 July 2010), including federal and state waters (Fig. 1). Using this combination of spatial data, we calculate the likely proportion of landed value that is immediately unavailable to the fishing sector. This approach has also been applied in McCrea-Strub et al. (2011).

As foreign fishing vessels have been prohibited from operating within the US EEZ since 1991, fisheries closures are also assumed only to impact US fisheries. However, the GOM is a dynamic system, and oil and dispersants have not been confined to the sea surface, with subsurface plumes (50–1200 m) having been documented (Camilli et al. 2010). Most marine organisms, including those mentioned here, exhibit daily and seasonal, small- and large-scale migrations both laterally and vertically. Marine organisms may be directly impacted by physical contact with contaminants as well as indirectly affected via the fouling of important nursery and spawning habitats as well as food chain interactions. Therefore, it is unlikely that the effects of the spill will be spatially and temporally restricted to closed area boundaries and closure duration.

Estimates of loss in commercial, recreational, and mariculture fisheries are dependent on the combination of initial mortality of fish species due to the oil spill as well as the continued economic unmarketability that can result when consumers believe marine products from the GOM are less desirable because of real or perceived pollutants. In the case of the *Exxon Valdez* spill, full market recovery of the tourism and sport fishing sector in Alaska is reported to have occurred within 2 years after cleanup (Anonymous 1993); in the case of the *Amoco Cadiz* spill in Brittany, tourism activities returned to prespill levels 1 year after cleanup (Grigalu-

Table 1. Assumed impact gradient (%) for species group – state combinations in the area open to fishing (Area B) in the Gulf of Mexico.

Group	Florida (west)	Alabama	Mississippi	Louisiana	Texas
Mollusks	30	45	50	50	0
Crustaceans	30	45	50	50	0
Benthic fishes	15	23	25	25	0
Pelagic fishes	6	9	10	10	0

Table 2. Estimated annual catch and catch values before the Gulf of Mexico oil spill in the areas closed and open to fishing as of 22 July 2010.

	Closed area (A)		Open area (B)	
Group	Catch (t)	Value (million US$)	Catch (t)	Value (million US$)
Mollusks	13 357	13.4	52 219	53.3
Crustaceans	21 938	99.3	73 608	334.2
Benthic fish	2 648	7.8	10 825	30.7
Pelagic fish	79 869	22.8	331 405	94.7
Total	117 813	143.3	468 058	513.0

Table 3. Assumed initial unmarketability and market recovery time for key marine taxonomic groups targeted by commercial fisheries in the Gulf of Mexico.

Group	Includes	Initial unmarketability (%)	Market recovery time (years)
Mollusks	Clams, mussels, oysters	100	1–6[a,b]
Crustaceans	Shrimp, crabs, lobsters	100	1–7[b,c]
Benthic fish	Soles, flounders, rockfish	50	1–2[b,d,e,f]
Pelagic fish	Tunas, sharks, jacks, mullets	10–30	0.16–1[b,g,h]

Note: Initial mortality also includes displacement or contamination to unmarketable levels. Recovery time refers to a return to prespill biomass and begins once all visible oil has been cleaned or dissipated.

[a] Jackson et al. 1989.

[b] Teal and Howarth 1984.

[c] Teal et al. 1992.

[d] Jernelov and Linden 1981.

[e] Elmgren et al. 1983.

[f] Lee and Page 1997.

[g] Grigalunas et al. 1986.

[h] Cedre 2008.

nas et al. 1986). The market "recovery" times used for recreational fisheries are shorter than for commercial fisheries because of the inherent differences between recreational and commercial fishing, with the latter catching fish for consumption, while recreational fishers are not motivated by this factor alone and are likely to return to fishing sooner (Arlinghaus 2006; Fedler and Ditton 1986). Finally, we assume impact gradients in the currently closed area for the second and third years to be 50% and 25%, respectively, because we expect the impact of the spill to fade away with time (Table 1).

Commercial fishing

Using the spatial catch and value data displayed (Fig. 1), we estimate the average annual catch and landed values taken before the oil spill (2000–2005) within areas closed to fishing (Area A) and open to fishing (Area B; Table 2) by major species groups (see below for details on species groups). We assume that the economic indicators are affected differently in open versus closed areas as described below.

We use the equation below to estimate the loss in landings arising from areas closed (C^{closed}) and open (C^{open}) to fishing:

$$(7) \qquad \text{loss}_{g,s} = \left(C^{\text{closed}}_{g,s} + \mathbf{M}_{g,s} \cdot A_{g,s} \cdot C^{\text{open}}_{g,s}\right)$$

where the indices g and s refer to species groups and states, respectively. The matrix $\mathbf{M}$ represents the initial mortality of marine species groups due to the oil spill, and A denotes the proportion of landings for a given species group – state combination affected by the oil. For simplicity, the loss is assumed to be experienced throughout the length of the market recovery time, $t \in [1, T]$, for a given species group. A range of estimated recovery times (Table 3) are used to compute a range of estimates of the present value of each economic indicator calculated by substituting the loss in landings, $\text{loss}_{g,s}$,

Table 4. Preoil spill mariculture production in the Gulf of Mexico.

State	Product	Production (t)	Production value (million US$)	Employment (jobs)
Alabama	Shrimps	100	0.7	10
Florida	Clams	7 030	10.3	210
Louisiana	Oysters	51 400	41.5	250
Total		58 530	52.5	470

Note: Production values adjusted to 2010 US$.

into eqs. 1–5, summing across species groups and states, and using eq. 6 to compute the present value of economic effects.

Employment data for commercial fisheries in the Gulf are from National Marine Fisheries Service (2010). We collect direct, indirect, and induced employment data by state. By considering indirect and induced employment, we include jobs that are supported by marine fisheries throughout the region's economy. We estimate potential employment loss by assuming that a reduction in the value of marine landings will be followed by a proportional change in the number of workers employed.

Recreational fisheries

To estimate the economic indicators for recreational fisheries, we rely on surveys undertaken by the US Fish and Wildlife Service (Anonymous 2006*b*), which reports the number of recreational fishers (resident and nonresident) by state, as well as the expenditures by anglers. Under the assumption that the percentage of resident anglers has remained constant since 2006, we calculate the total number of resident anglers based on 2009 population projections (http://www.census.gov). We use the ratio of resident to nonresident anglers to estimate the total number of anglers per state and the total number of fishing trips. With regard to Florida's west coast, we use the proportion of recreational fishing that takes place along the west coast (Steinback et al. 2004).

To estimate the total expenditure (or total revenues generated by the sector) and the economic impact, we use reported expenditures (Steinback et al. 2004) converted to 2010 dollars based on the US consumer price index (http://www.bls.gov/CPI). These expenditures include payments for fishing-related items (gear, tackle, etc.) and travel costs to the fishing locations, including private, guided, and charter fishing trips. We exclude expenditure on durable items (i.e., second homes), assuming that these will not be substantially affected. We make the strong assumption that recreational fishing will continue in the area open to fishing (Area B) at the prespill level. For the closed area (Area A), first year economic effects of the spill are based on the spatial extent of the fishing closures (Fig. 1). The resource rent and profit share of total revenue is estimated by summarizing the literature on the topic (Carter 2003; Marshall and Lucy 1981; Galeano et al. 2004).

Losses due to the oil spill are then calculated using the following equation:

$$(8)\qquad \text{loss}_{s,t} = \left(1 - P_t^{\text{closed}}\right) X_s$$

where $\text{loss}_{s,t}$ is the change in an economic indicator, X_s, for state s at time t. The parameter P_t^{closed} represents the percentage of waters in the GOM closed to fishing at time t. At the time of writing, 24% of American waters in the GOM are closed to recreational fishing. We assume that the percentage of waters unavailable to recreational fisheries will decrease to zero after 3 years, with their share in the second and third years being 12% and 6%, respectively. Present values of loss for each of the economic indicators (except for employment) are estimated using eq. 6.

The economic impact of changes in total revenue due to the oil spill is estimated using eq. 9 (see Appendix A for more on impact multipliers):

$$(9)\qquad \text{impact} = \sum\nolimits_s \text{PV}_s \cdot M_s$$

where PV_s is the present value of total revenue in a given state s, and M_s is the state-specific economic multiplier as reported by Steinback et al. (2004). Employment is calculated based on information from Steinback et al. (2004), and it is assumed to change in proportion to changes in losses associated with the oil spill.

Mariculture

Mariculture in the GOM is focused on invertebrate species, particularly oysters. According to the 2005 US Census of Aquaculture (Anonymous 2006*a*), Louisiana accounts for the largest share in mariculture production (51 400 tonnes of oysters worth US$37 million in 2005) in the US, with further contributions from Florida (7000 tonnes of clams worth US$9 million) and Alabama (100 tonnes of shrimp worth US$630 000; Table 4). No mariculture has been reported for Texas.

Owing to the fact that mariculture in Florida, Louisiana, and Alabama is primarily for crustaceans and mollusks, we assume that the impacts of the spill on mariculture will be similar to those on commercial fisheries for crustaceans and molluscs, namely that the contamination will result in zero market recovery.

Based on the location of the current closure, we assume that 100% of mariculture operations in Louisiana and Alabama and 10% of operations in west Florida are affected. Moreover, since oyster mariculture occurs in 2-year cycles from seeding to harvesting, we assume that the exposure to the spill will result in 3 years of lost oyster harvest (2010, 2011, and 2012). However, assuming that sufficient oyster larvae can be recruited from uncontaminated broodstocks in 2011, we expect the industry to recover in early 2013. Here, we focus solely on the impact due to loss of harvest and ignore the potential long-term losses from a decrease in demand due to consumer fears over residual contamination risks.

Table 5. Predicted present value losses in economic indicators for commercial fisheries over the next 7 years in the US Gulf of Mexico area due to the *Deepwater Horizon* oil spill.

Group	Revenues (million US$)	Total profits[a] (million US$)	Wages (million US$)	Economic impact (million US$)	Employment (jobs)
Crustaceans	360–2307	155–987	79–507	1114–7151	—
Mollusks	53–297	67–369	53–297	165–920	—
Benthic Fish	22–43	18–35	2–4	68–133	—
Pelagic fish	35–58	26–43	8–14	106–176	—
Total	470–2705	266–1434	142–822	1453–8380	5250–8758[b]

[a] This is the sum of normal profits (payment to capital) and resource rent (payment to resource owners).

[b] Employment data are available only by state, not species. This number represents total employment loss for all of the US Gulf states. To produce a range, we calculate 7000 (±25%).

Table 6. Predicted present value loss in economic indicators for US Gulf states' recreational fisheries.

State	Total revenues (million US$)	Total profits (million US$)	Wages (million US$)	Economic impact (million US$)	Employment (jobs)
Florida	994–1 656	542–903	378–630	1 772–2 953	7 650–12 750
Alabama	111–185	60–100	38–64	195–325	900–1 500
Mississippi	59–98	32–53	17–28	119–198	375–625
Louisiana	278–464	152–253	95–159	473–788	2 025–3 375
All states	1 442–2 404	786–1 310	528–881	2 558–4 264	10 950–18 250

From our estimates of lost revenue, we compute the profit and wages lost. The cost structure of mariculture operations in the GOM region was not available to us; we therefore use information from oyster farming in Virginia (Lipton et al. 2006) to estimate the potential loss in profit (~47%) and wages (~20%) from total revenue. Because of the nature of mariculture (i.e., requiring input by operators to generate harvest), we assume that all of the profit is return to capital with no resource rent. As in commercial fisheries, the present value of the lost revenue, profit, and wages are calculated using eq. 1.

We assume the current level of output from mariculture to be similar to that reported in the 2005 US Census of Aquaculture (Anonymous 2006*a*), converted to 2010 US$ equivalent (Table 4). The employment figures are estimated from the state total using the ratio of mariculture farms to total number of aquaculture farms in each state (Anonymous 2006*a*).

The economic impact of losses in total mariculture revenue is estimated by adapting eq. 5 to mariculture production, changing it to

$$\text{impact} = \text{PV}_{\text{revenue}} \cdot M \quad (10)$$

where $\text{PV}_{\text{revenue}}$ is the present value of loss due to the oil spill, and M is the economic input–output multiplier from Dyck and Sumaila (2010).

Results

Commercial fisheries

The present value of total revenues that would be lost in the commercial fishing sector over the next 7 years, due to the DH well blowout, is estimated to be in the range of US$0.5–2.7 billion (Table 5). The equivalent losses in total profits, wages, and total economic impact are estimated at US$0.3–1.4, US$0.1–0.8, and US$1.5–8.4 billion, respectively. By far the largest losses are incurred among fishers targeting crustaceans such as shrimps, who would experience nearly 85% of the total estimated economic impact (Table 5). In addition, between 5000 and 9000 jobs may be lost by commercial fisheries in the US Gulf region (Table 5).

Recreational fisheries

The present value of losses in the recreational fishing sector are estimated to be US$1.4–2.4 billion in total revenues, US$0.7–1.3 billion in total profits, US$0.5–0.8 billion in wages, and US$2.5–4.2 billion in economic impact (Table 6). The recreational fishing sectors in Florida and Louisiana are predicted to suffer the largest impacts, with Florida accounting for most of the expected losses (Table 6). Between 11 000 and 18 000 jobs may also be lost in this sector (Table 6). Note that no losses have been predicted for Texas.

Mariculture

For the three mariculture states, Florida, Alabama, and Louisiana, the total loss in revenue is estimated to be US$94–157 million, with an economic impact of about US$293–488 million (Table 7). We estimate a loss of US$44–73 million in total profit and US$19–31 million in wages. The sector may lose well over 210 jobs, both full- and part-time (Table 7). Overall, the majority of economic losses will occur in oyster mariculture (Table 7).

Overall, the present value of (midpoint) losses in total revenues, total profits, wages, and economic impact from the three sectors considered here are about US$3.7, US$1.9, US$1.2, and US$8.7 billion over the next 7 years, respectively (Table 8). The likely largest losses can be expected from the commercial fisheries, while the recreational fishing sector may account for slightly more than a third of such

Table 7. Predicted present value losses in economic indicators for US Gulf mariculture.

Group	Revenues (million US$)	Normal profits (million US$)	Wages (million US$)	Economic impact (million US$)	Employment[a] (jobs)
Crustaceans	1.5–2.5	0.7–1.2	0.3–0.5	4.7–7.8	8–13
Mollusks	92–154	43–72	18.5–30	287.8–479.8	203–338
All species	94–157	44–73	19–31	293–488	211–351

[a] 25% error ranges on the median assumed.

Table 8. Predicted (midpoint) present value losses in economic indicators for all affected US Gulf states for commercial and recreational fisheries and mariculture sectors combined.

Sector	Total revenues (million US$)	Total profits (million US$)	Wages (million US$)	Economic impact (million US$)	Employment (jobs)
Commercial fisheries	1 577	823	469	4 888	7 000
Recreational fisheries	1 949	1 062	715	3 457	14 900
Mariculture	129	61	26	399	280
Total	3 655	1 946	1 210	8 744	22 180

losses. Furthermore, the region may lose over 22 000 jobs in fisheries-related sectors (Table 8).

Discussion

We focus exclusively on the potential economic impacts of the DH well blowout on commercial and recreational fisheries, as well as mariculture in US Gulf waters, and find that the impacts are quite significant. The blowout could, over the next 7 years, result in (midpoint) lost revenue, profit, wages, and total economic impact with a present value of US$3.7, US$1.9, US$1.2, and US$8.7 billion, respectively. We also find that over 22 000 jobs in the GOM economy may be lost. Therefore, our analysis suggests that the spill will result in considerable loss of income to households and businesses in the Gulf states because of losses in wages and profits, respectively. Our estimates include downstream and upstream indirect and induced economic impact to industries such as boat building, the restaurant sector, and fuel suppliers.

However, there are other potential economic impacts not covered here (see e.g., Boyd 2010), including (*i*) clean-up cost; (*ii*) value of lost oil; (*iii*) natural and environmental damage beyond fisheries impacts; (*iv*) other direct use impacts such as bird watching and other non-fish tourism (Oxford Economics (2010) suggests a potential loss in US tourism revenues at over US$22 billion); and (*iv*) non-use existence and option values. Additionally, 11 people died in the explosion and 17 were injured. These are unrecoverable losses to affected families and the US at large.

Even for the sectors we study, our estimates are not complete. For instance, we do not consider consumer impacts through increases in fish prices due to reduced supply caused by the spill. Also, we focus on the short-term (up to 7 years) impacts and losses, thereby ignoring long-term effects. Some unintended consequences of the spill may also exist (e.g., the potential benefits of a forced fishing moratorium may help rebuild some stocks in the medium to long term). Furthermore, a potential spill injury to the Gulf fisheries can arise in response not to actual contamination by oil but over public perception of potentially contaminated fish that can lead to closures so that demand remains high for other fishes or the same fishes from other areas, thereby affecting the economics of Gulf states fisheries. For instance, US demand for shrimp from Thailand increased right after the oil spill. Having said the above, it is worth noting that one consequence of the reduction in shrimping effort due to the oil spill is reduction in bycatch of groundfish species, which is a positive for fisheries targeting these species, and could mitigate the losses calculated in this contribution.

It is important for the reader to note that we used a number of models, each with underlying assumptions, which may affect the accuracy of our results, and this is the reason why our estimates have ranges. For example, the input–output analysis applied in this paper is not without criticism (e.g., Christ 1955; de Mesnard 2002); it is well known that input–output analyses rely on the stability of technical coefficients, which may not hold when used in forecasting situations that are greatly different than those described by the respective input–output table used. Furthermore, input–output analysis is fairly data intensive — a factor that can be problematic when studying regions with scattered high-quality data sources. These caveats notwithstanding, we believe that our findings, which are different from those presented by the Feinberg Commission, are likely more accurate because of the passage of time and the thoroughness of the review process.

Acknowledgements

Support for this study was provided by the Global Ocean Economics Project at the Fisheries Economic Research Unit, funded by the Pew Charitable Trusts of Philadelphia, USA, as well as the Sea Around Us Project, collaboration between The University of British Columbia and the Pew Environment Group.

References

Anonymous. 1989. The Exxon Valdez oil spill: a report to the President [online]. National Response Team. Government Printing Office, Washington, D.C. Available from http://www.epa.gov/aboutepa/history/topics/valdez/04.html [accessed June 2011].

Anonymous. 1990*a*. Economic, social, and psychological impact assessment of the Exxon Valdez oil spill: a report to the Oiled Mayors Subcommittee: Alaska Conference of Mayors. Impact Assessment, Inc., La Jolla, Calif.

Anonymous. 1990*b*. An assessment of the impact of the Exxon Valdez oil spill on the Alaska Tourism industry: Phase I, initial assessment. McDowe Group, Inc. A report to Preston, Thorgrimson, Shidler, Gates and Ellis, Seattle, Wash.

Anonymous. 1993. Economic impacts of oil spills: spill unit costs for tankers, pipelines, refineries, and offshore facilities. A report by Advanced Resources International, Inc. to US Department of Energy, Office of Domestic and International Energy Policy, Washington, D.C.

Anonymous. 2006*a*. Census of aquaculture 2005 [online]. Vol. 3. Special Studies Part 2 AC-02-SP-2. US Department of Agriculture, National Agricultural Statistics Service, Washington, D.C. Available from http://www.ntis.gov/search/product.aspx?ABBR=AC02SP2 [accessed June 2011].

Anonymous. 2006*b*. National survey of fishing, hunting and wildlife-associated recreation [online]. FHW/06-NATUS. Department of the Interior, Fish and Wildlife Service and US Department of Commerce, Bureau of the Census, Washington, D.C. Available from http://www.census.gov/prod/2008pubs/fhw06-nat.pdf [accessed June 2011].

Arlinghaus, R. 2006. On the apparently striking disconnect between motivation and satisfaction in recreational fishing: the case of catch orientation of German anglers. N. Am. J. Fish. Manage. **26**(3): 592–605. doi:10.1577/M04-220.1.

Boyd, J.W. 2010. How do you put a price on marine oil pollution damages? Resources, **175**: 21–23.

Bue, B.G., Sharr, S., and Seeb, J.E. 1998. Evidence of damage to pink salmon populations inhabiting Prince William Sound, Alaska, two generations after the *Exxon Valdez* oil spill. Trans. Am. Fish. Soc. **127**(1): 35–43. doi:10.1577/1548-8659(1998)127<0035:EODTPS>2.0.CO;2.

Burns, K.A., Garrity, S.D., and Levings, S.C. 1993. How many years until mangrove ecosystems recover from catastrophic oil spills? Mar. Pollut. Bull. **26**(5): 239–248. doi:10.1016/0025-326X(93)90062-O.

Camilli, R., Reddy, C.M., Yoerger, D.R., Van Mooy, B.A.S., Jakuba, M.V., Kinsey, J.C., McIntyre, C.P., Sylva, S.P., and Maloney, J.V. 2010. Tracking hydrocarbon plume transport and biodegradation at *Deepwater Horizon*. Science, **330**(6001): 201–204. doi:10.1126/science.1195223. PMID:20724584.

Carls, M.G., Babcock, M.M., Harris, P.M., Irvine, G.V., Cusick, J.A., and Rice, S.D. 2001. Persistence of oiling in mussel beds after the *Exxon Valdez* oil spill. Mar. Environ. Res. **51**(2): 167–190. doi:10.1016/S0141-1136(00)00103-3. PMID:11468815.

Carter, D.W. 2003. 2003 Gulf of Mexico red snapper rebuilding plan: economic analysis of the recreational sector. Working Paper Series SEFSC-SSRG-03. National Marine Fisheries Service, Southeast Fisheries Science Center, Miami, Fla.

Cedre. 2008. Amoco Cadiz [online]. Centre de Documentation, de Recherche et d'Experimentations sur les Pollutions Accidentelles des Eaux, Brest, France. Available from http://www.cedre.fr/en/spill/amoco/amoco.php [accessed July 2010; updated 29 February 2008].

Christ, C.F. 1955. A review of input-output analysis [online]. *In* Input–output analysis: an appraisal. Princeton University Press, Princeton, N.J. pp. 137–182. Available from http://www.nber.org/chapters/c2866.

Cohen, M.J. 1995. Technological disasters and natural resource damage assessment: an evaluation of the Exxon Valdez Oil Spill. Land Econ. **71**(1): 65–82. doi:10.2307/3146759.

Culbertson, J.B., Valiela, I., Peacock, E.E., Reddy, C.M., Carter, A., and VanderKruik, R. 2007. Long-term biological effects of petroleum residues on fiddler crabs in salt marshes. Mar. Pollut. Bull. **54**(7): 955–962. doi:10.1016/j.marpolbul.2007.02.015. PMID:17448504.

Culbertson, J.B., Valiela, I., Olsen, Y.S., and Reddy, C.M. 2008*a*. Effect of field exposure to 38-year-old residual petroleum hydrocarbons on growth, condition index, and filtration rate of the ribbed mussel, *Geukensia demissa.* Environ. Pollut. **154**(2): 312–319. doi:10.1016/j.envpol.2007.10.008. PMID:18045755.

Culbertson, J.B., Valiela, I., Pickart, M., Peacock, E.E., and Reddy, C.M. 2008*b*. Long-term consequences of residual petroleum on salt marsh grass. J. Appl. Ecol. **45**(4): 1284–1292. doi:10.1111/j.1365-2664.2008.01477.x.

de Mesnard, L. 2002. Note about the concept of net multipliers. J. Reg. Sci. **42**(3): 545–548. doi:10.1111/1467-9787.00271.

Downing, N., and Roberts, C. 1993. Has the Gulf War affected coral reefs of the Northwestern Gulf? Mar. Pollut. Bull. **27**: 149–156. doi:10.1016/0025-326X(93)90019-G.

Dyck, A.J., and Sumaila, U.R. 2010. Economic impact of ocean fish populations in the global fishery. J. Bioeconomics, **12**(3): 227–243. doi:10.1007/s10818-010-9088-3.

Elmgren, R., Hansson, S., Larsson, U., Sundelin, B., and Boehm, P.D. 1983. The "Tsesis" oil spill: acute and long-term impact on the benthos. Mar. Biol. **73**(1): 51–65. doi:10.1007/BF00396285.

Fedler, A.J., and Ditton, R.B. 1986. A framework for understanding the consumptive orientation of recreational fishermen. Environ. Manage. **10**(2): 221–227. doi:10.1007/BF01867360.

Felder, D.L., and Camp, D.K. (*Editors*). 2009. Gulf of Mexico: origin, waters, and biota. Vol. 1. Biodiversity, Texas A&M University Press, College Station, Texas, USA.

Galeano, D., Langenkamp, D., Levantis, C., Shafron, W., and Redmond, I. 2004. Economic value of charter and recreational fishing in Australia's eastern tuna and billfish fishery. ABARE eReport 04.10. Prepared for the Fisheries Resources Research Fund, Canberra, Australia.

García-Negro, M.C., Villasante, S., Carballo-Penela, A., and Rodríguez-Rodríguez, G. 2009. Estimating the economic impact of the Prestige oil spill on the Death Coast (NW Spain) fisheries. Mar. Policy, **33**(1): 8–23. doi:10.1016/j.marpol.2008.03.011.

Graham, S. 2003. Environmental effects of Exxon Valdez spill still being felt [online]. News report. Scientific American, 19 December 2003. Available from http://www.scientificamerican.com/article.cfm?id=environmental-effects-of.

Grigalunas, T.A., Anderson, R.C., Brown, G.M., Jr, Congar, R., Meade, N.F., and Sorensen, P.E. 1986. Estimating the cost of oil spills: lessons from the Amoco Cadiz incident. Mar. Resour. Econ. **2**(3): 239–262.

Haapkyla, J., Ramade, F., and Salvat, B. 2007. Oil pollution on coral reefs: a review of the state of knowledge and management needs. Vie Millieu, **57**(1/2): 91–107.

Jackson, J.B.C., Cubit, J.D., Keller, B.D., Batista, V., Burns, K., Caffey, H.M., Caldwell, R.L., Garrity, S.D., Getter, C.D., Gonzalez, C., Guzman, H.M., Kaufmann, A.H., Levings, S.C., Marshall, M.J., Steger, R., Thompson, R.C., and Weil, E. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. Science, **243**(4887): 37–44. doi:10.1126/science.243.4887.37. PMID:17780421.

Jernelov, A., and Linden, O. 1981. Ixtoc I: a case study of the world's largest oil spill. Ambio, **10**(6): 299–306.

Jewett, S.C., Dean, T.A., Woodin, B.R., Hoberg, M.K., and Stegeman, J.J. 2002. Exposure to hydrocarbons 10 years after the *Exxon Valdez* oil spill: evidence from cytochrome P4501A expression and billiary FACs in nearshore demersal fishes. Mar.

Environ. Res. **54**(1): 21–48. doi:10.1016/S0141-1136(02)00093-4. PMID:12148943.

Lee, R.F., and Page, D.S. 1997. Petroleum hydrocarbons and their effects in subtidal regions after major oil spills. Mar. Pollut. Bull. **34**(11): 928–940. doi:10.1016/S0025-326X(97)00078-7.

LeGore, S., Marszalek, D.S., Danek, L.J., Tomlinson, M.S., Hofmann, J.E., and Cuddebak, J.E. 1989. Effect of chemically dispersed oil on Arabian Gulf corals: a field experiment. *In* Proceedings of the 1989 International Oil Spill Conference, San Antonio, 13–16 February 1989. American Petroleum Institute, Washington, D.C. pp. 375–381.

Levy, J.K., and Gopalakrishnan, C. 2010. Promoting ecological sustainability and community resilience in the US Gulf Coast after the 2010 Deepwater Horizon oil spill. Journal of Natural Resources Policy Research, **2**(3): 297–315. doi:10.1080/19390459.2010.500462.

Lipton, D.W., Kirkley, J., and Murray, T. 2006. A background economic analysis for the programmatic environmental impact statement regarding the restoration of the Chesapeake Bay oyster fishery using the non-native oyster *Crassostrea ariakensis*. Final report to the Maryland Department of Natural Resources, Annapolis, Md.

Loya, Y., and Rinkevich, B. 1980. Effects of oil pollution on coral reef communities. Mar. Ecol. Prog. Ser. **3**: 167–180. doi:10.3354/meps003167.

Marshall, A.R., and Lucy, J.A. 1981. Virginia's charter and head boat fishery: analysis of catch and socioeconomic impacts. Special report in Applied Marine Science and Ocean Engineering No. 253. Virginia Sea Grant Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Va.

McCrea-Strub, A., Kleisner, K., Sumaila, U.R., Swartz, W., Watson, R., Zeller, D., and Pauly, D. 2011. Potential impact of the Deepwater Horizon oil spill on commercial fisheries in the Gulf of Mexico. Fisheries, **36**(7): 332–336. doi:10.1080/03632415.2011.589334.

Moles, A.D., Rice, S.D., and Okihiro, M.S. 1993. Herring parasite and tissue alterations following the Exxon Valdez oil spill. Proceedings of the 1993 Oil Spill Conference. American Petroleum Institute, Washington, D.C. pp. 325–328.

Moller, T.H., Dicks, B., and Goodman, C.N. 1989. Fisheries and mariculture affected by oil spills. *In* Proceedings of the 1989 International Oil Spill Conference, Seattle, Washington, 8–11 March 1999. American Petroleum Institute, Washington, D.C. pp. 693–699.

National Marine Fisheries Service. 2010. Seafood Industry Impact search routine of the Interactive Fisheries Economics Impacts Tools [online]. Available from https://www.st.nmfs.noaa.gov/apex/f?p=160:7:1836673894606153 [accessed 31 January 2012].

National Oceanographic and Atmospheric Administration. 2010. Fish stocks in the Gulf of Mexico [online]. Fact sheet. Available from http://gulfseagrant.tamu.edu/oilspill/facts_fishstocks.htm [accessed July 2010].

Oxford Economics. 2010. Potential impact of the Gulf oil spill on tourism [online]. US Travel Association. Available from http://www.ustravel.org/sites/default/files/page/2009/11/Gulf_Oil_Spill_Analysis_Oxford_Economics_710.pdf [accessed June 2011].

Palinkas, L.A., Downs, M.A., Petterson, J.S., and Russell, J.S. 1993. Social, cultural, and psychological impacts of the Exxon Valdez oil spill. Hum. Organ. **52**: 1–13.

Pontecorvo, G., Wilkinson, M., Anderson, R., and Holdowsky, M. 1980. Contribution of the ocean sector to the United States economy. Science, **208**(4447): 1000–1006. doi:10.1126/science.208.4447.1000. PMID:17779011.

Price, A.R.G. 1998. Impact of the 1991 Gulf War on the coastal environment and ecosystems: current status and future prospects. Environ. Int. **24**(1–2): 91–96. doi:10.1016/S0160-4120(97)00124-4.

Rice, S.D., Thomas, R.E., Carls, M.G., Heintz, R.A., Wertheimer, A. C., Murphy, M.L., Short, J.W., and Moles, A. 2001. Impacts to pink salmon following the *Exxon Valdez* oil spill: persistence, toxicity, sensitivity, and controversy. Rev. Fish. Sci. **9**(3): 165–211. doi:10.1080/20016491101744.

Shigenaka, G. 2002. Oil toxicity. *In* Oil spills in mangroves. Office of Response and Restoration, NOAA Ocean Service, NOAA, Seattle, Wash. pp. 23–35.

Steinback, S., Gentner, B., and Castle, J. 2004. The economic importance of marine angler expenditures in the United States [online]. US Department of Commerce, NOAA Professional Paper NMFS 2, La Jolla, California. Available from http://spo.nwr.noaa.gov/pp2.pdf [accessed 18 July 2011].

Sumaila, U.R., Marsden, A.D., Watson, R., and Pauly, D. 2007. A global ex-vessel fish price database: construction and applications. J. Bioeconomics, **9**(1): 39–51. doi:10.1007/s10818-007-9015-4.

Teal, J.M., and Howarth, R.W. 1984. Oil spill studies: a review of ecological effects. Environ. Manage. Health, **8**(1): 27–44.

Teal, J.M., Farrington, J.W., Burns, K.A., Stegeman, J.J., Tripp, B.W., Woodin, B., and Phinney, C. 1992. The West Falmouth oil spill after 20 years: fate of fuel oil compounds and effects on animals. Mar. Pollut. Bull. **24**(12): 607–614. doi:10.1016/0025-326X(92)90281-A.

Thorne, R.E., and Thomas, G.L. 2007. Herring and the "Exxon Valdez" oil spill: an investigation into historical data conflicts. ICES J. Mar. Sci. **65**(1): 44–50. doi:10.1093/icesjms/fsm176.

Urriza, M.S.G., and Duran, R. 2010. The Gulf oil spill: we have been here before. Can we learn from the past? Journal of Cosmology, **8**: 2026–2028.

Watson, R., Kitchingman, A., Gelchu, A., and Pauly, D. 2004. Mapping global fisheries: sharpening our focus. Fish Fish. **5**: 168–177.

Appendix A. More on input–output models

As a primary industry (i.e., activities focusing on extracting or processing natural resources, such as energy, minerals, and in this case food, for use elsewhere in the economy), fishing is the beginning of a productive value chain in an economy. The economic multiplier is used in fisheries research to emphasize that the industry has many linkages throughout the economy. Such multipliers are a factor by which we can multiply the value of final demand for an economic activity's output to obtain its total contribution to economic output, including activities directly and indirectly dependent on it.

More specifically, the multipliers used in this study are taken from Dyck and Sumaila (2010). The model configurations, presented in this reference, are briefly described below.

The method developed by Nobel laureate, Wassily Leontief, known as input–output analysis, is a tried and tested approach to analyzing the structure of the economy. Beginning as early as the late 1940s, Leontief used his method in a number of applications, including the well-known analyses of the potential economic impact of disarmament for the United States of America and tests of the Heckscher–Ohlin theory now known as the "Leontief Paradox" (Leontief 1953; Leontief et al. 1965). The definitive source on input–output methodology, his book on the subject is a collection of his earlier works and serves as an excellent foundation for using input–output analysis (Leontief 1966). There are, however, several additional sources for readers who are interested in the methodology as applied to fisheries (Heen 1989; Hoagland et al. 2005; Jin et al. 2003; Leung and Pooley 2001; Roy et al. 2009).

Input–output analysis uses interindustry transaction data to compute a technical coefficient matrix, **A**, which is composed of entries $a_{i,j}$ summarizing the output from industry *i* required to produce a unit of output for industry *j*. We compute this technical coefficient matrix for every maritime country of the world, expressing the economy of each country as a system of linear equations summarized by the following equation:

$$\text{(A.1)} \qquad \mathbf{A}\boldsymbol{x} + \boldsymbol{d} = \boldsymbol{x}$$

where **A** is the matrix of technical coefficients describing input requirements for each sector, $\boldsymbol{x}$ is a vector of sector inputs, and $\boldsymbol{d}$ is a vector of final demand. The above equation then simply states that the sum of intermediate demand ($\mathbf{A}\boldsymbol{x}$) and final demand ($\boldsymbol{d}$) is equal to supply ($\boldsymbol{x}$). It is then a simple problem of linear algebra to solve for the vector of inputs ($\boldsymbol{x}$) required to satisfy a given final demand vector ($\boldsymbol{d}$) using **I** as the identity matrix. This solution is expressed as

$$\text{(A.2)} \qquad \boldsymbol{x} = [\mathbf{I} - \mathbf{A}]^{-1}\boldsymbol{d}$$

We note that the vector $\boldsymbol{x}$ represents total output supported by the demand vector $\boldsymbol{d}$. It is important to keep this measure of economic activity separate from other measures such as value-added, which subtracts the value of inputs from the value of output. It is worth noting that it is not appropriate to make comparisons between estimates using input–output analysis and measures of value-added such as gross domestic product (GDP).

Type I & II output multipliers

Given the solution in eq. A.2 above, we calculate the change in output with respect to final demand. To do this, we take a partial derivative of eq. A.2 with respect to final demand ($\boldsymbol{d}$):

$$\text{(A.3)} \qquad \frac{\delta \boldsymbol{x}}{\delta \boldsymbol{d}} = [\mathbf{I} - \mathbf{A}]^{-1}$$

Equation A.3 describes a new relationship that proves to be very useful in macro-economic analysis. The right-hand side of this equation, $[\mathbf{I} - \mathbf{A}]^{-1}$, is also denoted as $\mathbf{L}^{-1}$, as it is commonly called the Leontief inverse or multiplier matrix. This square matrix is of such interest because each entry (denoted $\mathbf{l}_{i,j}$) describes the marginal inputs required from sector *i* when the output of sector *j* increases by one unit.

We calculate industry multipliers by computing the column sum of the Leontief inverse matrix $\mathbf{L}^{-1}$ as $\boldsymbol{M} = \sum_{j=1}^{N} \mathbf{L}_{i,j}$ where $\boldsymbol{M}$ is a row vector of Type I industry output multipliers. Each entry, $\boldsymbol{M}_j$, in this row vector is an output multiplier that allows us to compute the direct and indirect output required to support a unit of output for industry *j*. For example, in a sector with a multiplier of 1.5, we would estimate that US$100 in final demand from this sector supports US $150 of activity throughout the economy.

As we have shown, for a given economy with *n* industries, one calculates the Leontief inverse using a $n \times n$ technical coefficients matrix as described above. Multipliers calculated in this way account for the direct and indirect output supported by a given industry. In addition to these multipliers, often called Type I, a second set of multipliers, called Type II, may also be calculated. The advantage to using Type II multipliers is that they account for indirect as well as induced effects that occur, for example, when additional demand for a given sector increases household incomes that induce demand for additional output. With Type I multipliers, household consumption is part of the final demand sector and therefore assumed to be exogenous; with Type II multipliers, we treat household consumption as endogenous by adding it as an additional intermediate sector in the technical coefficients matrix **A**. When computing Type II output multipliers, a technical coefficients matrix with endogenous households will be $(n + 1) \times (n + 1)$ in dimension. Summing the multiplier matrix $\mathbf{L}^{-1}$ over *n* output sectors will produce Type II output multipliers that include the induced effect of endogenizing households without confusing output and income, which would occur if we added the last row of the multiplier matrix — also known as the income effect.

Researchers have adopted approaches to account for direct and indirect effects of fisheries in literature. A considerable amount of this previous work using economic impact methodology has been done for the USA (e.g., Seung and Waters 2006). Several methods used in such studies to analyze the economic impacts of fishing including input–output modeling, social accounting matrix (SAM) modeling, econometric input–output (EC-IO) modeling, fisheries economic assessment models (FEAM), and computable general equilibrium (CGE) models. Each of these techniques has its merits and demerits, which have been discussed in the literature at length (Loveridge 2004; Radtke et al. 2004).

Of these models, the input–output technique is well used in the study of fisheries, likely because of the relative ease of computation and accessibility of results (Bhat and Bhatta 2006; Hoagland et al. 2005; Leung and Pooley 2001). Results from an input–output study can be used to predict the outcome of a marginal change in demand for a particular good, and they can easily be interpreted and used in a practical manner.

For further reading on input–output tables, refer to references listed below.

References

Bhat, M.G., and Bhatta, R. 2006. Regional economic impacts of limited entry fishery management: an application of dynamic input–output model. Environ. Dev. Econ. **11**(6): 709–728. doi:10.1017/S1355770X06003238.

Dyck, A.J., and Sumaila, U.R. 2010. Economic impact of ocean fish populations in the global fishery. J. Bioeconomics, **12**(3): 227–243. doi:10.1007/s10818-010-9088-3.

Heen, K. 1989. Impact analysis of multispecies marine resource management. Mar. Resour. Econ. **6**(4): 331–348.

Hoagland, P., Jin, D., Thunberg, E., and Steinback, S. 2005. Economic activity associated with the northeast shelf large marine ecosystem: application of an input–output approach. Sustaining large marine ecosystems: the human dimension. Elsevier, Amsterdam, the Netherlands. pp. 159–181.

Jin, D., Hoagland, P., and Dalton, T.M. 2003. Linking economic and ecological models for a marine ecosystem. Ecol. Econ. **46**(3): 367–385. doi:10.1016/j.ecolecon.2003.06.001.

Leontief, W. 1953. Domestic production and foreign trade: the American capital position re-examined. Proc. Am. Philos. Soc. **97**(4): 332–349.

Leontief, W. 1966. Input–output economics. Oxford University Press, New York.

Leontief, W., Morgan, A., Polenske, K., Simpson, D., and Tower, E. 1965. The economic impact — industrial and regional — of an arms cut. Rev. Econ. Stat. **47**(3): 217–241. doi:10.2307/1927706.

Leung, P., and Pooley, S. 2001. Regional economic impacts of reductions in fisheries production: a supply-driven approach. Mar. Resour. Econ. **16**(4): 251–262.

Loveridge, S. 2004. A typology and assessment of multi-sector regional economic impact models. Reg. Stud. **38**(3): 305–317. doi:10.1080/003434042000211051.

Oosterhaven, J., and Stelder, D. 2002. Net multipliers avoid exaggerating impacts: with a bi-regional illustration for the Dutch transportation sector. J. Reg. Sci. **42**(3): 533–543. doi:10.1111/1467-9787.00270.

Pontecorvo, G., Wilkinson, M., Anderson, R., and Holdowsky, M. 1980. Contribution of the ocean sector to the United States economy. Science, **208**(4447): 1000–1006. doi:10.1126/science.208.4447.1000. PMID:17779011.

Radtke, H.D., Carter, C.N., and Davis, S.W. 2004. Economic evaluation of the northern pikeminnow management program. Report prepared for Pacific States Marine Fisheries Commission, Portland, Ore.

Roy, N., Arnason, R., and Schrank, W.E. 2009. The identification of economic base industries, with an application to the Newfoundland fishing industry. Land Econ. **85**(4): 675–691.

Seung, C.K., and Waters, E.C. 2006. A review of regional economic models for fisheries management in the U.S. Mar. Resour. Econ. **21**(1): 101.

Steinback, S., Gentner, B., and Castle, J. 2004. The economic importance of marine angler expenditures in the United States [online]. NOAA Professional Paper NMFS 2. US Department of Commerce, La Jolla, Calif. Available from http://spo.nwr.noaa.gov/pp2.pdf [accessed 18 July 2011].

RESEARCH ARTICLE

Comparison of chemical-use between hydraulic fracturing, acidizing, and routine oil and gas development

William T. Stringfellow[1,2], **Mary Kay Camarillo**[1,2], **Jeremy K. Domen**[1,2], **Seth B. C. Shonkoff**[3,4]*

1 Earth & Environmental Sciences Area, Lawrence Berkeley National Lab, Berkeley, CA, United States of America, **2** Ecological Engineering Research Program, School of Engineering & Computer Science, University of the Pacific, 3601 Pacific Avenue, Stockton, CA, United States of America, **3** PSE Healthy Energy, 1440 Broadway, Suite 205, Oakland CA, United States of America, **4** Department of Environmental Science, Policy and Management, University of California, Berkeley, Berkeley, CA, United States of America

* sshonkoff@psehealthyenergy.org

Abstract

The potential hazards and risks associated with well-stimulation in unconventional oil and gas development (hydraulic fracturing, acid fracturing, and matrix acidizing) have been investigated and evaluated and federal and state regulations requiring chemical disclosure for well-stimulation have been implemented as part of an overall risk management strategy for unconventional oil and gas development. Similar evaluations for chemicals used in other routine oil and gas development activities, such as maintenance acidizing, gravel packing, and well drilling, have not been previously conducted, in part due to a lack of reliable information concerning on-field chemical-use. In this study, we compare chemical-use between routine activities and the more closely regulated well-stimulation activities using data collected by the South Coast Air Quality Monitoring District (SCAQMD), which mandates the reporting of both unconventional and routine on-field chemical-use for parts of Southern California. Analysis of this data shows that there is significant overlap in chemical-use between so-called unconventional activities and routine activities conducted for well maintenance, well-completion, or rework. A comparison within the SCAQMD shows a significant overlap between both types and amounts of chemicals used for well-stimulation treatments included under State mandatory-disclosure regulations and routine treatments that are not included under State regulations. A comparison between SCAQMD chemical-use for routine treatments and state-wide chemical-use for hydraulic fracturing also showed close similarity in chemical-use between activities covered under chemical disclosure requirements (e.g. hydraulic fracturing) and many other oil and gas field activities. The results of this study indicate regulations and risk assessments focused exclusively on chemicals used in well-stimulation activities may underestimate potential hazard or risk from overall oil field chemical-use.

OPEN ACCESS

Citation: Stringfellow WT, Camarillo MK, Domen JK, Shonkoff SBC (2017) Comparison of chemical-use between hydraulic fracturing, acidizing, and routine oil and gas development. PLoS ONE 12(4): e0175344. https://doi.org/10.1371/journal.pone.0175344

Editor: John M. Senko, The University of Akron, UNITED STATES

Received: January 28, 2017

Accepted: March 26, 2017

Published: April 19, 2017

Data Availability Statement: Data are available from the South Coast Air Quality Monitoring District (http://www.aqmd.gov/). Additional data in Research Gate: DOI: 10.13140/RG.2.2.19128.55041.

Funding: This material is based upon work supported by the Department of Energy under Award Number DE-IA0000018. This study was supported in part by grants from The Broad Reach Fund and Laboratory Directed Research and Development (LDRD) funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH1123.

Competing interests: The authors have declared that no competing interests exist.

Introduction

Scientific, regulatory, and public debates on the environmental and public health dimensions of oil and gas development have been focused on hazardous chemicals used for hydraulic fracturing and other well-stimulation treatments, such as matrix acidizing, that are classified as "unconventional" oil and gas development methods [1–4]. Consequently, new regulations that govern oil and gas development require disclosure of chemical-use during well stimulation activities, but do not require disclosure of chemicals used for any other oil and gas field activities [1,2,4]. However, potentially hazardous chemicals are used throughout the entire oil and gas development process, not just during well stimulations [5–9], so there is interest in examining overall chemical-use on oil and gas fields and comparing chemical-use between regulated "unconventional" development activities and other oil and gas field activities.

Disclosure of chemical-use during well stimulation is considered an important requirement for the protection of human and environmental health, since knowledge of the types and amounts of chemicals used is fundamental to risk assessment [10]. Recent Federal and State regulations mandate chemical disclosures for well stimulations, including hydraulic fracturing and in some cases matrix acidizing and acid fracturing, but reporting chemical-use for other oil and gas field activities, such as well drilling, well completion, well maintenance, and well re-work is not required, unless pressures above the fracture gradient are used [1,2,4,11]. Given the public and scientific concern regarding the use and release of hazardous chemicals during the current oil and gas development boom [12] and the reuse of oil and gas field produced water for beneficial purposes in arid regions [13–15], it is important to evaluate the potential environmental and public health impacts of all chemical additives used in oil and gas development.

Chemicals are used routinely in oil and gas development as part of drilling and cementing of the well casing, repair of formation damage, wellbore clean-outs, scale and corrosion control, and for other production activities. Chemical additives are also used in enhanced oil recovery (EOR) to change fluid properties of oil (e.g. viscosity) and to otherwise increase production of oil within the formation [16]. During well construction, hazardous chemicals may be added to drilling fluids, drilling muds, and cements and are also used to remove debris from wellbores prior to cementing of the annular space between the steel casing and geological formations [9,17]. Chemical additives, including strong acids, are also used for well completion and rework to facilitate hydrocarbon production.

While large numbers and masses of chemical additives are used in routine oil and gas development activities, only a few surveys of routine chemical-use by the oil and gas industry have been conducted [5–8,18]. There is widespread use of potential chemicals of concern, including biocides, quaternary ammonium compounds, and corrosion inhibitors both off-shore and on-shore [5–8,18]. In contrast, several studies examined chemical-use during well stimulation activities, including hydraulic fracturing and matrix acidizing [19–24]. It has been established that chemicals used during well stimulation treatments have environmental pathways of exposure which include accidental spills, reuse of treated produced water, improper zonal isolation of fluids in the subsurface infrastructure and geologies, and discharge of wastewaters to aquatic ecosystems [3,21,24]. It is also known that produced water has similar exposure pathways, so it is of interest to determine overall oil and gas field chemical-use when evaluating the potential environmental and health impacts of oil and gas development.

The reuse of produced water for agricultural purposes is permissible in the western US and produced water is being reused for irrigation, watering livestock, aquifer recharge, and other purposes [13–15,24–26]. In California, produced water from oil fields is used for food crop irrigation, livestock watering, groundwater recharge, and for wetlands and other environmental purposes [15,27]. There are concerns that oil field chemicals or their degradation products will occur in produced water and that these chemicals may pose an unrecognized hazard or risk for produced water beneficial reuse, since potential exposure pathways from beneficial reuse include chemical uptake or deposition on food crops, contamination of regional aquifers through recharge, and the direct contact of farmworkers with produced water [15]. The hazard posed by oil and gas field chemicals would be in addition to other hazards associated with naturally occurring constituents of produced water, such as salts, metals, aromatic hydrocarbons, and naturally occurring radioactive material. The increased interest in reusing produced water [13,28] suggests that the hazards associated with oil and gas field chemicals should be evaluated.

The objective of this study is to assess chemical-use during routine oil and gas development and to compare chemical-use in routine production activities with chemical-use during well stimulation. To our knowledge, only one regulatory agency in the US, the South Coast Air Quality Management District (SCAQMD) in Southern California, requires mandatory disclosure of on-field chemical-use for well drilling, well completion, and well rework activities. These data were used by Abdullah et al. [19] to characterize chemical-use in acidizing. We use these data to compare chemical additive use between well-stimulation (hydraulic fracturing and matrix acidizing treatments) and routine oil field activities to determine similarities and differences in chemical-use. We summarize the chemicals used with respect to frequency of use, masses applied, and toxicity data. Similar data driven approaches have been used previously to evaluate hazards associated with hydraulic fracturing and matrix acidizing [19,21]. The results of our analysis are interpreted in the context of public and scientific concerns about hydraulic fracturing and the beneficial reuse of produced water.

Methods

Chemical-use data reported to the South Coast Air Quality Management District (SCAQMD) in southern California was analyzed in this study [29]. Under SCAQMD Rule 1148.2, which went into effect on June 4, 2013, operators and chemical suppliers are required to submit and make publicly available chemical usage data related to routine oil and gas activities (well drilling, well completion, and well rework) and well stimulation (hydraulic fracturing, matrix acidizing) in the California counties of San Bernardino, Orange, Riverside, and Los Angeles, including the City of Los Angeles [29]. These counties represent the second most productive oil and gas region in the third largest oil producing state in the United States. Chemical-use for enhanced oil recovery (EOR) and activities beyond upstream oil and gas development such as refining, transmission, and storage are not included in the SCAQMD datasets and are not included in this analysis.

Data on chemical type, mass injected, and water volumes used in oil and gas operations were downloaded from the SCAQMD database for the period of June 4, 2013 to September 2, 2015 [29]. The dataset used for this study consists of 51,514 entries from 1,207 oil and gas "events" conducted at 302 unique locations (identified by latitude and longitude). Events were categorized by operators as well drilling, completion, or rework activities. For completion, activities were further categorized as acidizing, gravel packing, hydraulic fracturing, maintenance acidizing, matrix acidizing, or acid fracturing. In order to focus on routine oil and gas activities, we separated well stimulation events (hydraulic fracturing, matrix acidizing and acid fracturing) from other routine events in our dataset. Entries were edited to standardize chemical names and to validate the assigned Chemical Abstracts Services Registry Number (CASRN). Changes to names of proprietary chemicals that could not be identified by CASRN were limited to correcting obvious spelling errors (e.g., aicd to acid, kerosine to kerosene), changing capitalization, and altering punctuation (e.g. removing dashes). Proprietary chemicals with singular and plural names that indicate chemical mixtures (e.g., ionic surfactant vs ionic surfactants) were maintained as separate entries. In cases where duplicate event IDs were reported, data were consolidated into one event ID entry. In cases where multiple chemical information documents were reported for the same event ID, data were individually assessed and duplicates, where apparent, were deleted.

For the chemical additives identified by CASRN, toxicological data were collected from online chemical databases [30–41]. Computational models within the U.S. EPA EPI Suite software (e.g., BIOWIN) were used to fill data gaps when experimental data were unavailable. Rat, mouse, and rabbit acute oral toxicity data and rat and mouse inhalation toxicity data were collected to represent and compare mammalian toxicity among the chemical constituents. To assess acute environmental toxicity, data for water flea (*Daphnia magna*), fathead minnow (*Pimephales promelas*), rainbow trout (*Oncorhynchus mykiss*), and green algae were collected. Mammalian median lethal dose (LD50) and median lethal concentration (LC50) were used to assess mammalian hazard. Median effective concentration (EC50) and LC50 data were used to assess aquatic species hazard. Toxicity ratings were assigned using the United Nations Globally Harmonized System (GHS) of Classification and Labelling of Chemicals [42]. In the GHS system, lower numbers indicate higher toxicity, with a designation of "1" indicating the most toxic category. When multiple GHS values were available for a given chemical, the lowest value was used. Chemicals for which the LD50, LC50, or EC50 exceeded the least toxic GHS category were classified as non-toxic.

Chemical were identified for further hazard assessment based on frequency of use, median mass of chemical-use per event, and available toxicity data. Frequency of use was calculated by dividing the number of events that utilized a given chemical by the total routine oil and gas events reported in the SCAQMD database. The median mass of chemical usage per event represents the median mass for all events containing that chemical. Where chemical mixtures were reported, individual chemical masses were calculated by multiplying the total mixture mass by the maximum individual chemical concentration. When multiple entries for a given chemical were reported for a single event, the chemical masses were summed within that event.

We compared the chemical-use in routine oil and gas activities in the SCAQMD dataset to hydraulic fracturing chemicals disclosed in the state of California via the voluntary FracFocus chemical disclosure registry, as summarized by Stringfellow et al. [21]. This dataset contains records of chemical use for 1,623 individual hydraulic fracturing operations conducted in California between January 30, 2011 and May 19, 2014. Stringfellow et al. [21] identified 338 unique additives based on name and CASRN combinations, of which 228 were reported with a CASRN and 110 were identified by chemical or common name only or had proprietary designations. The additives included chemicals, mineral proppants and carriers, and base fluids consisting of water, salt, and brine solutions. There were 326 unique additive names identified in the database [21].

Results and discussion

Chemical-use in the SCAQMD

In total, 548 chemical additives were used in the SCAQMD between June 2013 and September 2015, with 525 of these being used for routine oil and gas development activities. The most frequently used chemicals include solvents (e.g. methanol), petroleum products (e.g. distillates), and salts (e.g. sodium chloride) that are employed in formulating commercial blends of production chemicals (S1 Table). Also on the list of frequently used chemicals are carboxylic acids (e.g. citric acid and erythorbic acid) used for scale and iron control, biocides, and corrosion inhibitors. For routine acidizing (e.g., acid cleaning for well-maintenance), hydrochloric acid (HCl) and hydrofluoric acid (HF) were used extensively and in large quantities (mean masses

Table 1. Number of chemicals used and their summed masses per event for oil and gas development (does not include water)[a].

		Chemicals per event				Mass per event (kg)			
Pooled Activities	Events[a]	Mean	Median	Min	Max	Mean	Median	Min	Max
Acidizing	256	25	20	1	41	4,132	3,459	10	24,043
Gravel packing	169	6	3	1	65	24,655	6,297	61	710,722
Hydraulic fracturing	13	25	23	15	37	129,910	142,245	4,526	243,219
Maintenance acidizing	390	30	35	2	52	2,779	2,028	155	15,548
Maintenance acidizing and gravel packing	3	27	27	27	27	7,712	6,632	6,518	9,985
Matrix acidizing	7	21	20	20	23	4,210	3,055	1,970	10,791
Well completion and rework—type not specified	43	20	21	1	71	16,287	8,028	215	100,566
Well drilling	186	46	54	3	72	1,828,619	97,669	96	309,284,305
Well drilling with gravel packing	136	57	58	26	66	239,305	181,098	21,552	1,233,365

[a]There are 1,207 events in the data set but four events have only water listed so they are not included in this table (N = 1,203).

https://doi.org/10.1371/journal.pone.0175344.t001

of 1,791 and 161 kg per event, respectively). These quantities are consistent with the analysis by Abdullah et al. [19], who reported mean values of 1,908 kg HCl and 175 kg HF per acidizing event (also exclusive of matrix acidizing). Our values may differ due to the different study periods or deletion of duplicate entries by operators. Other additives used in the highest masses include minerals and other chemicals used for gravel packing (e.g. silica), cementing of well casings (e.g. Portland cement and additives), and sealing wells (e.g. bentonite) (S2 Table).

Table 1 is presented as an analysis of chemical use (numbers of chemicals used and masses) by reported activity. There were only a limited number of well-stimulation events in the SCAQMD during this period and no acid fracturing events were reported. Acidizing, maintenance acidizing, well drilling, and gravel packing accounted for the majority of the 1,207 events in the data set (Table 1). Chemical-use for these types of oil and gas field activities is only subject to mandatory reporting in the SCAQMD region.

Comparison of chemical-use between routine activities and well-stimulation treatments within the SCAQMD

Overall, a large number of constituents were used in both routine activities and well-stimulation activities and chemicals were applied in large masses (Table 1). The masses used in hydraulic fracturing were high because of the large quantities of proppants used. Similarly, well drilling uses large quantities of Portland cement and minerals for well construction. Comparison of the chemicals used for different on-field activities showed significant overlap in the chemicals used for hydraulic fracturing and routine oil and gas development operations (Fig 1). Only 23 (4.2%) chemicals were used exclusively for hydraulic fracturing in the SCAQMD. However, the SCAQMD dataset includes only a small number of hydraulic fracturing operations (13) and the degree of overlap in chemical use between different oil field operations may not be representative of other regions. A comparison of chemical use for routine oil and gas development as reported in the SCAQMD database and chemical use for fracturing in the whole state of California, indicates the degree of overlap is less.

Examining different types of acidizing within the SCAQMD, the median numbers of chemicals used in routine acidizing (20 for acidizing and 35 for maintenance acidizing) were similar in number to the median value of 20 used in matrix acidizing (Table 1). An analysis of chemicals used for acid treatments shows that there is considerable overlap in the chemicals used for the different applications of acid (Fig 2). The one compound used exclusively for matrix acidizing was identified only as "DDBSA salt," presumably a dodecylbenzenesulfonic acid salt, but

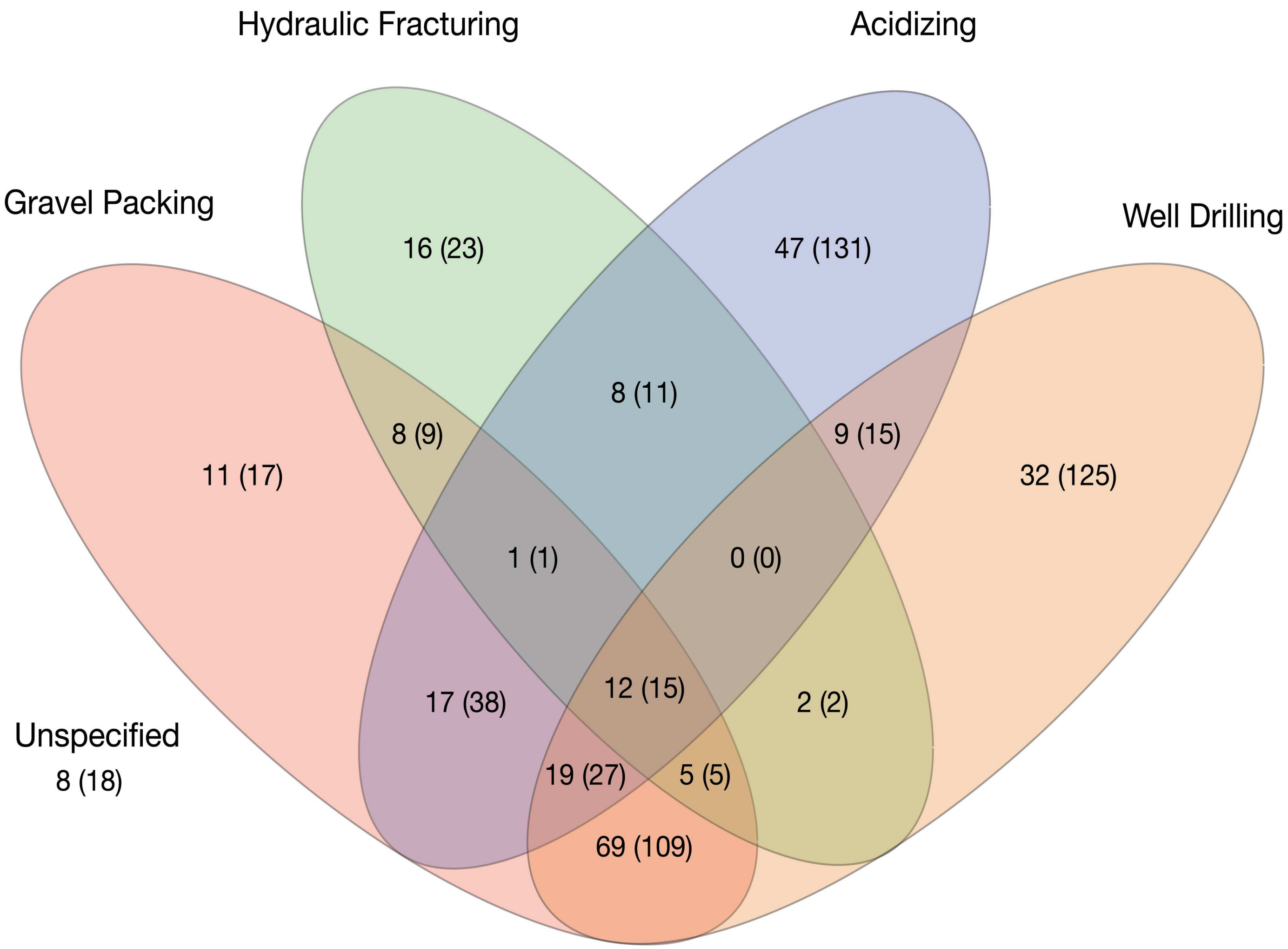


Fig 1. Venn diagram showing number of chemicals used in oil and gas production. The first number represents chemicals with CASRN and the number in parentheses represents the total number of reported chemicals. Does not include base fluids. Acidizing includes matrix acidizing, acidizing, and maintenance acidizing.

https://doi.org/10.1371/journal.pone.0175344.g001

without a corresponding CASRN, this identification is tentative. Maintenance acidizing used a lower median mass of chemicals (2,028 kg) than treatments reported as acidizing (3,459 kg) or matrix acidizing (3,055 kg). These quantities demonstrate that additives usage in other acidizing is not appreciably different than what is used in matrix acidizing (classified as well stimulation).

Concentrations of hydrochloric acid (HCl) and hydrofluoric acid (HF) used in all types of acidizing events were similar, as were the total masses of additives used (Figs 3 and 4). Hydrochloric acid concentrations ranged from approximately 0–15% (Fig 3) while HF concentrations were approximately 0–3% (Fig 4). In California, the distinction between routine acidizing and acid stimulation (matrix acidizing and acid fracturing) is based on calculation of the acid threshold volume that is determined based on wellbore volume and formation porosity [1]. The acid threshold volume cannot be calculated without site-specific information that is not reported to the publically available SCAQMD database. However, it is apparent that large quantities of acid and high concentrations are being used in all types of acidizing events. Since there is clear overlap in concentrations and amounts of acid used for events reported as

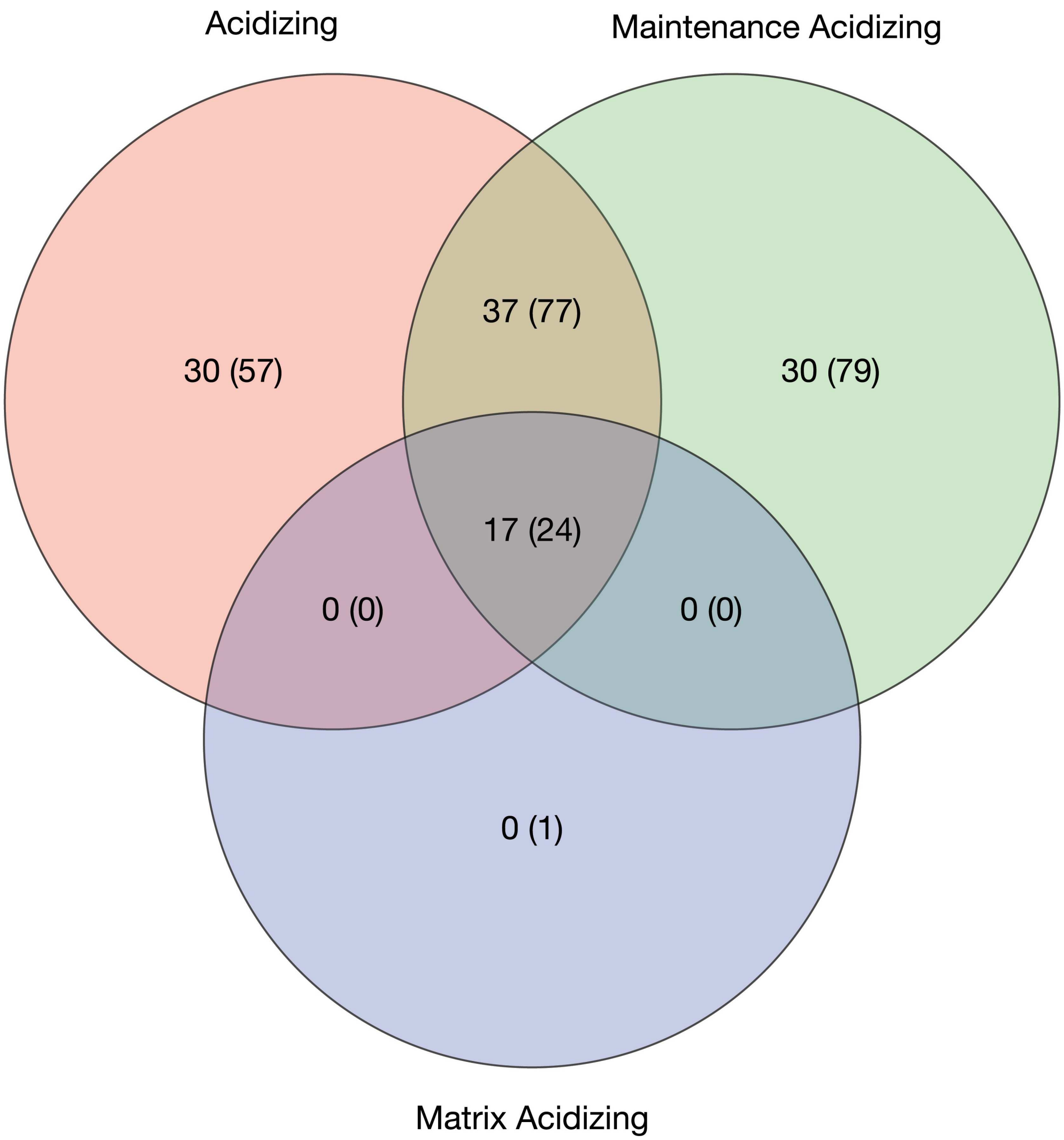


Fig 2. Venn diagram showing number of chemicals used for acidizing operations (routine and well stimulation). The first number represents chemicals with CASRN and the number in parentheses represents the total number of reported chemicals. Does not include base fluids.

https://doi.org/10.1371/journal.pone.0175344.g002

matrix acidizing, which are potentially regulated by state law, and routine maintenance acidizing (Figs 3 and 4), these results suggest that regulations focused only on disclosures of chemicals used in well stimulation events may not be sufficiently protective of public or environmental health.

Comparison of chemical-use between routine oil and gas development activities in the SCAQMD and hydraulic fracturing throughout California

The number of chemicals used in routine oil and gas development activities in the SCAQMD is as high or higher than the number of chemicals used for hydraulic fracturing throughout the State of California [21]. In Stringfellow et al. [21], 338 unique chemical additives were identified as used in hydraulic fracturing fluids in California, with 228 of these identified by CASRN.

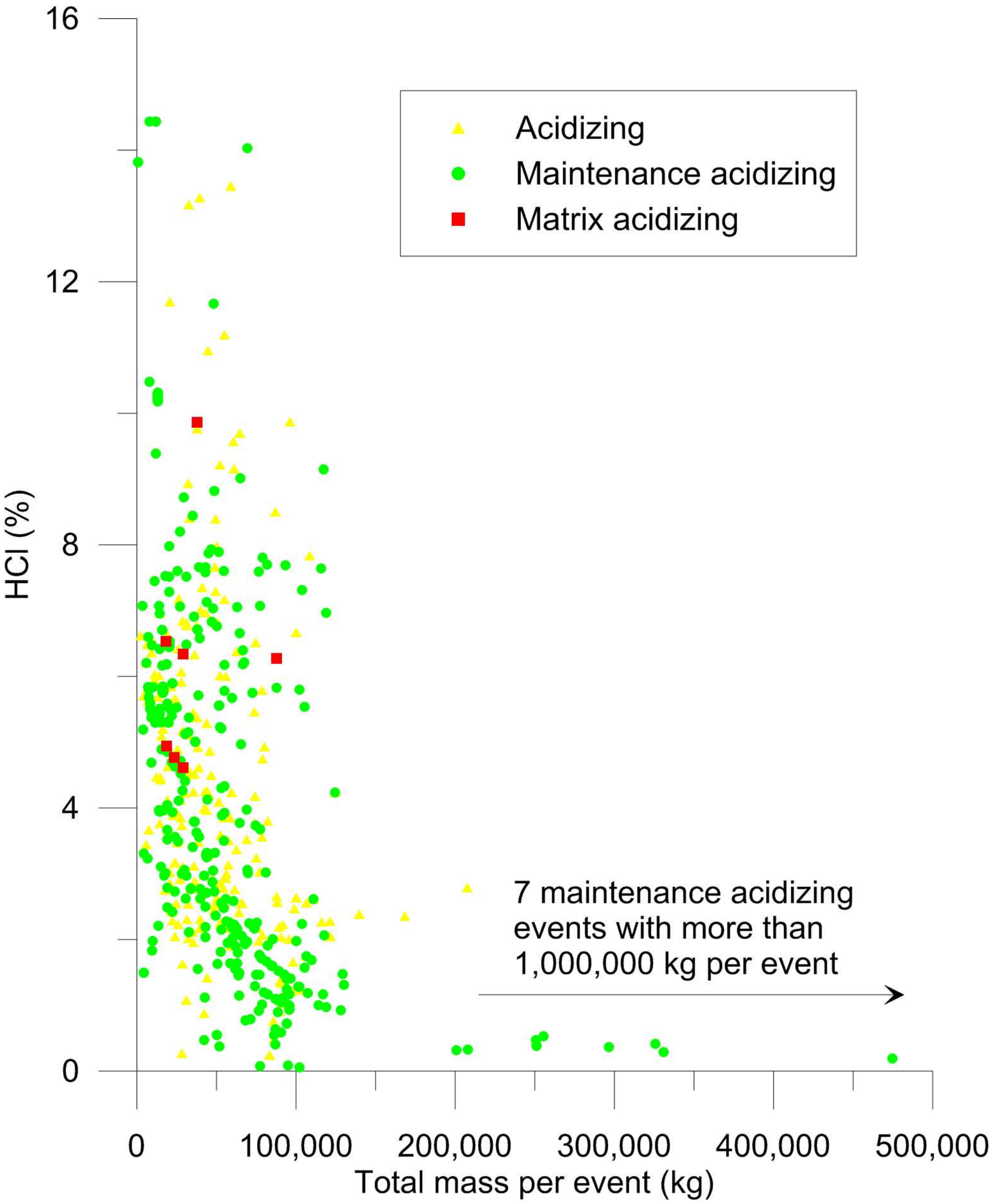


Fig 3. Concentrations of hydrochloric acid (HCl) used in acidizing. Sixteen events where water was not reported were excluded because the concentrations could not be calculated.

https://doi.org/10.1371/journal.pone.0175344.g003

These data were reported voluntarily by industry, but are believed to be representative of hydraulic fracturing as practiced in California [21,24,43,44]. Here, we identified 525 additives used in routine oil and gas production, with 249 identified by CASRN. In Stringfellow et al. [21], there was a median of 23 components per hydraulic fracturing treatment, inclusive of base fluids and proppants. In the SCAQMD, the number of additives per event varied by activity (Table 1). The median number of chemical additives was as low as three for gravel packing and the median number of chemical additives used in well drilling was much higher (54).

In the SCAQMD, the median mass used per hydraulic fracturing event was high (142,245 kg), but when water and quartz sand proppants were removed, the median mass of chemical additives was 6,725 kg. This is approximately three times higher than the value of 2,057 kg

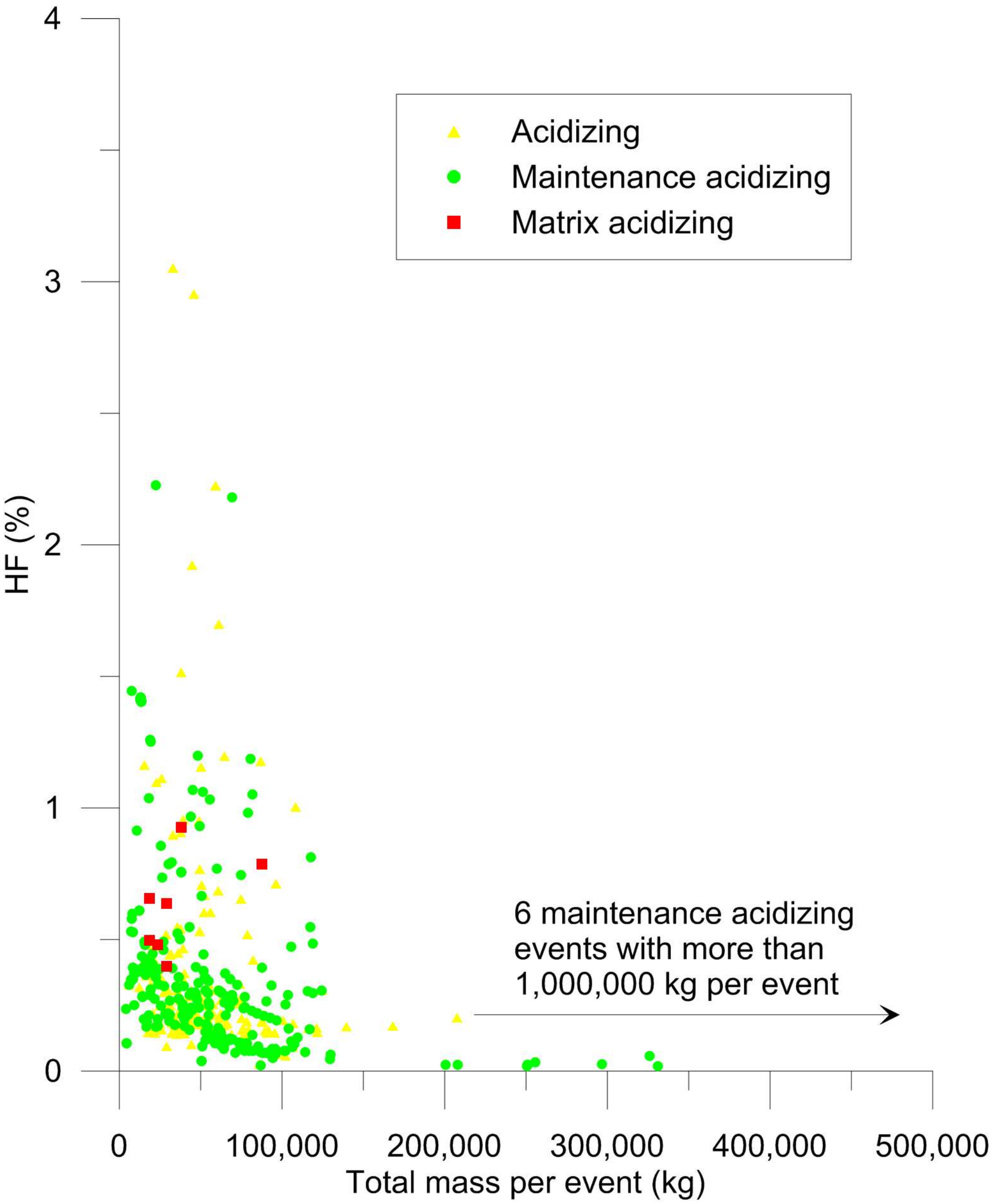


Fig 4. Concentrations of hydrofluoric acid (HF) used in acidizing. Sixteen events where water was not reported were excluded because the concentrations could not be calculated.

https://doi.org/10.1371/journal.pone.0175344.g004

obtained by Stringfellow et al. [21], who analyzed voluntarily reported data from the whole state of California. This difference may be attributed to differences in regional reservoir geology between the SCAQMD and the rest of California [44] and corresponding hydraulic fracturing practices: most of the data analyzed by Stringfellow et al. [21] was reported from Kern County, CA while the data here originated primarily from Orange and Los Angeles Counties.

Of the 249 chemicals identified by CASRN that are used for routine oil and gas development in the SCAQMD (Table 2), 124 (24%) were identified by Stringfellow et al. [21] as being used for hydraulic fracturing in California, further demonstrating overlap in chemical usage between hydraulic fracturing and routine activities. Further examination of the types of chemicals used in routine oil and gas development activities and in hydraulic fracturing yields both similarities and differences. As an example, ten biocides were identified in the hydraulic fracturing data set reported by Stringfellow et al. [21] while only six were identified here as used in routine activities. The biocides were used in 63% of routine activities conducted in the SCAQMD compared to 93% of hydraulic fracturing treatments [21]. In routine use, the most commonly used biocides were formaldehyde, used in 677 (57%) events, and glutaraldehyde, used in 274 (23%) events. In the hydraulic fracturing treatments, isothiazolones were used in 73% of treatments [21,24]. This demonstrates that biocides are used extensively in different types of oil and gas production activities.

Corrosion inhibitors were used more extensively in routine operations than in hydraulic fracturing treatments. Ten corrosion inhibitors were identified in both the current data set and in the hydraulic fracturing data set [21], although the numbers are likely higher since many chemicals used as corrosion inhibitors also have other functions in oil and gas production (e.g. surfactants). In routine operations in the SCAQMD, corrosion inhibitors were used in 894 events (75% of all events), but they were only used in 6% of the hydraulic fracturing treatments [21]. The prevalent use of corrosion inhibitors in the SCAQMD is not surprising given the common use of strong acids in well maintenance and completion activities.

The substantial overlap between chemicals used in hydraulic fracturing fluids and those used in routine oil and gas development processes clearly demonstrate that the regulatory focus on reporting chemical-use for well-stimulation activities (e.g. hydraulic fracturing) to the exclusion of routine maintenance activities (e.g. wellbore cleaning) does not fully address potential environmental and public health concerns from on field chemical-use, particularly in the context of beneficial reuse of produced water for agriculture [15]. A more complete understanding of chemical usage–including type; toxicity and environmental profile; and mass, timing, frequency used–in routine oil and gas development is needed to support decision making with respect to beneficial reuse of produced water and this study contributes to filling this data gap.

Comparison of chemical-use between routine oil and gas development activities in the SCAQMD and other oil and gas fields throughout the U. S. and World

It is difficult to determine with certainty if chemical use on oil fields in the SCAQMD is representative of chemical-use on oil fields throughout the U.S. or the world, since data on chemical-use is rarely collected by governments or published by industry. Hudgins analyzed and published chemical-use data provided voluntarily by off-shore operations in the Gulf of Mexico [7] and the North Sea [8]. Comparison of the Hudgins' studies with chemicals used in the SCAQMD shows that chemicals are used for common purposes, such as microbial control, scale control, and cleaning, at all locations [7,8]. Hudgins' studies did not identify chemicals by CASRN, but some chemicals were identified sufficiently by name to allow positive identification of 47 chemicals from the North Sea study [8] and 25 chemicals from the Gulf of Mexico study [7]. Thirty-five chemicals could be positively identified as being used in both the North Sea and in the SCAQMD and 15 were positively identified as being used in both the Gulf of Mexico and the SCAQMD. Overall, these results, combined with a review of industrial literature, patents, and other sources, suggests that many of the chemicals used on the SCAQMD, or closely related compounds, would be found on oil fields worldwide [5–8,19–22,45].

Analysis of chemical hazards using data science approaches

One of the important requirements of regulations directed at oil and gas development and production is the disclosure of the types and amounts of chemicals used on-field [1,2,4,11,46].

Table 2. Data availability for chemicals used in routine oil and gas development.

Number of chemicals	Proportion of all chemicals	CASRN	Mass data	Toxicity data
151	30%	Available	Available	Available[a]
1	0%	Available	Unavailable	Available[a]
97	18%	Available	Available	Unavailable[a]
43	8%	Unavailable	Available	Unavailable
233	44%	Unavailable	Unavailable	Unavailable

[a] Does not include EPI Suite computational estimates for green algae ecotoxicity

https://doi.org/10.1371/journal.pone.0175344.t002

Chemical disclosure is widely recognized as a fundamental prerequisite for the open and transparent analysis of the hazards and risks associated with chemicals [2,4,10,27,45,46]. Previous studies have shown that many oil and gas field chemicals are not expected to have negative environmental or health impacts, but that some compounds, including surfactants, biocides, and corrosion inhibitors may be harmful to the environment, and that in many cases there is insufficient information to confidentially evaluate the potential environmental impact of chemicals that are used in significant amounts on oil and gas fields [19–24,47,48].

A preliminary hazard assessment for oil field chemicals being used in the SCAQMD was conducted using data science methods applied against hydraulic fracturing chemicals [20,21]. As shown in Table 2, 52% of the chemicals used in the SCAQMD were reported without a CASRN and could therefore not be evaluated using a data science approach, which requires CASRN to match compounds with corresponding environmental and toxicity information. Of the 53 chemicals used most frequently (top 10%), 18 were reported without a corresponding CASRN. The top 10% of the chemicals used in the highest median masses per event also did not always have associated CASRN (S2 Table). For example, the fourth most commonly used additive is a proprietary chemical identified only as "polyoxyalkylenes," which could be any one of potentially hundreds of chemicals or chemical formulations. Compounds reported by CASRN mostly had corresponding mass-usage information, important for risk analysis, but 97 did not have toxicity profiles in the public databases used in this study (Table 2; S3 Table). Altogether, 70% of the chemical additives reported in the SCAQMD could not be fully evaluated using data-based hazard analysis approaches [20,21,47], suggesting that current reporting requirements may need to be strengthened, if the regulatory objective includes generating data needed for risk assessments.

Analysis of chemicals by mammalian toxicity revealed that five chemicals were classified as GHS Category 2 contaminants based on acute mammalian oral exposure and 13 were classified as GHS Category 1 or 2 for acute mammalian inhalation toxicity (Table 3). These results are similar to results found by Stringfellow et al. [21] for hydraulic fracturing operations. Several of the most toxic chemicals identified are biocides: 5-chloro-2-methyl-3(2H)-isothiazolone, DBNPA (2,2-dibromo-3-nitrilopropionamide), formaldehyde, and glutaraldehyde. Corrosion inhibitors are also represented on the list of most toxic chemical additives: propargyl alcohol and thioglycolic acid (Table 3). Mammalian toxicity data were unavailable for 105 (42%) of the 249 chemicals with CASRN.

Analysis of ecotoxicity characteristics of the chemicals revealed that 58 chemical additives were classified as GHS Category 1 or 2 (Table 4). Twenty-six of these classifications were determined using computational estimates from the U.S. EPA Ecological Structure Activity Relationships (ECOSAR) software for green algae ecotoxicity, available through EPI Suite. The remainder of the ecotoxicity determinations were made using experimental data. A wide range of chemicals were identified as being toxic to aquatic organisms. The list includes acids,

Table 3. Chemicals used in routine oil and gas development that are classified by the United Nations Globally Harmonized System (GHS) Categories 1 and 2 for acute mammalian toxicity[a].

Chemical name	CASRN	Oral toxicity ratings			Inhalation toxicity ratings		Frequency of use (% events)	Median mass per event (kg)
		Rat	Mouse	Rabbit	Rat	Mouse		
2-Butoxyethanol (Ethylene glycol butyl ether)	111-76-2	4	4	3	2	-	26.5%	545
5-Chloro-2-methyl-3(2H)-isothiazolone	26172-55-4	4	-	-	2	-	0.1%	5.2
DBNPA (2,2-dibromo-3-nitrilopropionamide)	10222-01-2	3	-	3	1	-	0.3%	4.1
Ethylene oxide	75-21-8	3	3	-	2	3	1.0%	<0.1
Ferric chloride	7705-08-0	2	4	-	-	-	0.5%	30
Formaldehyde	50-00-0	2	2	-	2	2	57.0%	<0.1
Glutaraldehyde	111-30-8	3	3	-	1	-	23.1%	75
Glycolic acid	79-14-1	4	4	-	1	-	0.1%	89
Hydrofluoric acid	7664-39-3	-	-	-	2	2	43.6%	96
Lithium hydroxide	1310-65-2	3	4	-	2	-	0.2%	22
Petroleum distillates	64741-44-2	-	-	-	2	-	0.1%	138,679
Propargyl alcohol	107-19-7	2	2	-	3	-	53.8%	3.7
Sulfuric acid	7664-93-9	5	-	-	2	-	2.1%	<0.1
Tetrasodium ethylenediaminetetraacetate	64-02-8	4	2	-	-	-	0.3%	<0.1
Thioglycolic acid	68-11-1	3	3	3	1	-	0.1%	98
Toluene	108-88-3	4	-	-	>4	2	1.4%	6.7
Zinc sulfate	7733-02-0	3	2	4	-	-	0.2%	50

[a]Only chemicals with valid CASRN could be evaluated.

https://doi.org/10.1371/journal.pone.0175344.t003

hydrocarbons, biocides, corrosion inhibitors, surfactants, and other industrial chemicals (e.g. tall oil). Experimental ecotoxicity data were unavailable for 146 (59%) of the 249 chemicals with CASRN; when ECOSAR estimates were included, ecotoxicity data were unavailable for 129 (52%) chemicals with CASRN.

Although a complete risk assessment is beyond the scope of this study, evaluation of the frequency of chemical use and the mass of chemical used can provide context for the potential risk associated with the use of hazardous chemicals. Of the 17 chemicals with high mammalian toxicity only four of these were used in more than 25% of events (Table 3). Quantities of the most toxic chemicals used varied. Seven of the toxic chemicals were used in median quantities of less than 10 kg per treatment, while nine were used in larger amounts. Glutaraldehyde (used in 23% of events) was applied with a median quantity per treatment of 75 kg. While formaldehyde was used more frequently (57% of events), the median quantity added was less than 1 kg per treatment. The complexity of toxicity information, paired with data on frequency of use and quantities applied (Table 3), suggest that while hazard assessments such as this as useful for characterizing chemical-use, more detailed risk assessments are needed.

Nine of the most toxic chemicals from an aquatic perspective were used in more than 25% of events (Table 4). The most frequently used chemicals on the list were hydrochloric acid, propargyl alcohol, ammonium chloride, and naphthalene, used in 48% of events or more. Propargyl alcohol and naphthalene were used in small quantities (median masses of less than 5 kg per treatment) although hydrochloric acid and ammonium chloride were used in much higher

Table 4. Chemicals used in routine oil and gas development that are classified by the United Nations Globally Harmonized System (GHS) in Categories 1 and 2 for ecotoxicity[a].

Chemical name	CASRN	Water Flea[b]	Fathead Minnow[c]	Rainbow Trout[d]	Green Algae[e]	Frequency of use (% events)	Median mass per event (kg)
1,2,3-Trimethylbenzene	526-73-8	-	-	-	2	0.3%	1.0
1,2,4-Trimethylbenzene	95-63-6	2	2	-	2	5.7%	1.6
1,3,5-Trimethylbenzene	108-67-8	2	-	-	2	0.3%	2.3
2-Mercaptoethyl alcohol	60-24-2	2	-	-	2	0.7%	2.5
2-Methyl-3(2H)-isothiazolone	2682-20-4	1	-	1	1	0.2%	2.6
5-Chloro-2-methyl-3(2H)-isothiazolone	26172-55-4	1	-	1	1	0.1%	5.2
Acrylamide	79-06-1	3	>3	>3	1	0.8%	<0.1
Alcohols, C10-14, ethoxylated	66455-15-0	-	-	-	1	0.6%	64
Aluminum	7429-90-5	-	-	1	-	16.5%	9.1
Ammonium chloride	12125-02-9	>3	2	>3	-	48.4%	454
Benzene, c10-c16 alkyl derivatives	68648-87-3	-	-	-	1	0.9%	<0.1
Benzene, tetrapropylene-	25265-78-5	-	-	-	1	0.1%	2.7
Benzoisothiazolinone	2634-33-5	1	-	1	1	0.1%	<0.1
Bis(isopropyl)naphthalene	38640-62-9	-	-	-	1	2.0%	1.8
Canola oil	120962-03-0	-	-	-	1	0.3%	92
Cocamidopropyl betaine	61789-40-0	2	-	-	>3	0.7%	<0.1
Cyclohexasiloxane, 2,2,4,4,6,6,8,8,10,10,12,12-dodecamethyl-	540-97-6	-	-	-	1	0.3%	<0.1
Cyclopentasiloxane, 2,2,4,4,6,6,8,8,10,10-decamethyl-	541-02-6	-	-	-	1	0.3%	<0.1
DBNPA (2,2-dibromo-3-nitrilopropionamide)	10222-01-2	1	1	1	1	0.3%	4.1
Dodecylbenzene	123-01-3	-	-	-	1	0.1%	5.4
Dodecylbenzene sulfonic acid	27176-87-0	2	-	2	3	1.4%	<0.1
Ethanesulfonic acid, 2-[methyl[(9z)-1-oxo-9-octadecen-1-yl]amino]-, sodium salt (1:1)	137-20-2	-	-	-	2	0.6%	53
Ethoxylated C14-15 alcohols	68951-67-7	1	1	1	1	1.3%	2.4
Ethoxylated hexanol	68439-45-2	2	-	2	>3	0.3%	16
Ethylbenzene	100-41-4	2	2	2	2	31.3%	2.9
Fatty acids, tall-oil	61790-12-3	>3	-	-	1	0.4%	7.1
Fatty acids, tall-oil, reaction products with triethanolamine	67784-78-5	-	-	-	2	1.3%	<0.1
Ferric chloride	7705-08-0	2	3	-	-	0.5%	30
Glutaraldehyde	111-30-8	1	2	2	2	23.1%	75
Glyoxal	107-22-2	>3	>3	0	2	23.0%	3.6

(*Continued*)

Table 4. (*Continued*)

Chemical name	CASRN	Water Flea[b]	Fathead Minnow[c]	Rainbow Trout[d]	Green Algae[e]	Frequency of use (% events)	Median mass per event (kg)
Hydrochloric acid	7647-01-0	1	-	2	-	54.8%	1,311
Hydrotreated light petroleum distillate	64742-47-8	-	3	2	1	32.9%	17
Isopropylbenzene	98-82-8	3	2	2	2	29.5%	0.3
Lecithins	8002-43-5	-	-	-	1	0.3%	1.4
Lithium hypochlorite	13840-33-0	1	-	1	-	0.2%	129
Naphtha (petroleum), heavy catalytic reformed	64741-68-0	-	-	-	2	0.2%	18
Naphthalene	91-20-3	1	1	1	2	48.4%	0.3
Octamethylcyclotetrasiloxane	556-67-2	-	-	-	1	0.3%	<0.1
Petroleum distillate-mineral oil grade	8002-05-9	1	-	-	1	0.1%	30
Petroleum distillates	64741-44-2	-	-	-	1	0.1%	138,679
Petroleum distillates	64742-46-7	-	-	-	1	0.1%	138,679
Poly(oxy-1,2-ethandiyl), a-(nonylphenyl)-w-hydroxy-	9016-45-9	2	-	2	2	13.2%	4.6
Polyethylene glycol monostearate	9004-99-3	-	-	-	1	1.3%	<0.1
Polypropylene	9003-07-0	-	-	-	1	1.1%	56
Polysiloxanes, di-Me	63148-62-9	3	-	-	1	1.6%	<0.1
Propargyl alcohol	107-19-7	-	2	-	>3	53.8%	3.7
Quinoline	91-22-5	3	1	-	3	18.8%	0.1
Sodium chloroacetate	3926-62-3	>3	-	-	1	0.3%	<0.1
Sodium hypochlorite	7681-52-9	1	1	1	>3	0.2%	2.3
Sodium silicate	1344-09-8	1	-	-	-	0.7%	72
Solvent naphtha, petroleum, heavy arom.	64742-94-5	1	3	2	2	39.0%	1.8
Solvent naphtha, petroleum, light arom.	64742-95-6	2	-	2	2	5.8%	1.7
Sorbitan monostearate	1338-41-6	-	-	-	1	1.3%	<0.1
Stearic acid	57-11-4	-	-	-	1	12.1%	150
Sulfonic acids, c14-16-alkane hydroxy and c14-16-alkene, sodium salts	68439-57-6	2	-	-	3	0.1%	5.4
Tall oil	8002-26-4	-	-	-	1	0.8%	13
Xylenes	1330-20-7	-	3	2	2	32.0%	1.5

(*Continued*)

Table 4. (*Continued*)

Chemical name	CASRN	Water Flea[b]	Fathead Minnow[c]	Rainbow Trout[d]	Green Algae[e]	Frequency of use (% events)	Median mass per event (kg)
Zinc sulfate	7733-02-0	1	1	1	-	0.2%	50

[a] Only chemicals with valid CASRN could be evaluated.

[b] Daphnia magna

[c] Pimephales promelas

[d] Oncorhynchus mykiss

[e] computational estimates from EPI Suite.

https://doi.org/10.1371/journal.pone.0175344.t004

amounts (median masses of 1,311 and 454 kg per treatment). The higher number of chemical additives posing ecotoxicity issues and the frequent use of these chemicals, suggests that the ecosystem risks need to be fully evaluated in produced water reuse projects.

Evaluation of chemical hazards using regulatory lists

To further investigate the potential hazards associated with chemicals used in routine oil and gas development activities, six regulatory lists were referenced (S4 Table). The result of the comparison with these regulatory lists was that twenty-two of the chemicals were on the California Toxic Air Contaminant List [41], 12 were on the California Proposition 65 List [40], 10 were on the U.S. EPA Drinking Water Standards and Health Advisories List [49], six were present on the U.S. EPA Contaminant Candidate List 4 [50], three were on the European Chemicals Agency Substance of Very High Concern Candidate List [51], and two were on the OSPAR List of Substances of Possible Concern [45]. These results demonstrate that some of the chemicals used in routine oil and gas development activities are chemicals of concern, as identified by multiple state, federal, and international environmental agencies due to their toxicities. However, the actual risk proposed by these chemicals would need to be determined in the context of their use and potential release into the environment.

It should be noted that comparison with regulatory lists also indicate that many of the chemicals used in the SCAQMD are expected to present little or no human health or ecotoxicity hazard, even if discharged into the environment. Of the chemicals reported with CASRN, 56 are on the OSPAR list of chemicals not expected to pose environmental harm [22]. These chemicals include inert minerals (e.g. silica, graphite, mica, diatomaceous earth), common salts (e.g. calcium carbonate, calcium chloride, sodium carbonate, etc.), chemicals that rapidly degrade in the environment (e.g. acetic acid, ethylene glycol, 1-butanol), and food additives (e.g. xanthan gum, guar gum, sodium erythorbate, starch).

Conclusions

In this study we compared routine oil and gas field chemical use, which is not typically subject to disclosure regulations, with chemical use for hydraulic fracturing and other well stimulation techniques that are subject to regulation mandating chemical disclosure. Our results indicate that there is substantial overlap between the chemicals used in well stimulation and those used in routine oil and gas development activities. Similarities were observed in the numbers of chemicals used, the masses in which they were applied, the frequency of use, and their toxicological profiles. Our analysis shows that hydraulic fracturing is just one of many applications of hazardous chemicals on oil and gas fields and suggests that limiting disclosure requirements for oil and gas field chemical-use to hydraulic fracturing and other well-stimulation events may not be fully protective of human and environmental health, especially in the context of beneficial reuse of produced water for irrigation, wildlife, livestock watering, and groundwater recharge.

Supporting information

S1 Table. Constituents used for routine oil and gas development activities (exclusive of well stimulation) in the SCAQMD, June 4, 2013 to September 2, 2015, sorted by frequency of use. Total number of events is 1,187.
(PDF)

S2 Table. The top 10% median masses of additives used in routine oil and gas development activities (exclusive of well stimulation) in the SCAQMD, June 4, 2013 to September 2, 2015. Total number of events is 1,187.
(PDF)

S3 Table. Chemicals reported to the SCAQMD and used in routine oil and gas production for which experimental toxicity information could not be located (N = 97).
(PDF)

S4 Table. Chemicals reported to the SCAQMD and used in routine oil and gas development activities considered chemicals of concern based on six reference lists consulted.
(PDF)

Acknowledgments

This material is based upon work supported by the Department of Energy under Award Number DE-IA0000018 (CERC-WET). This study was also supported by grants from The Broad Reach Fund and Laboratory Directed Research and Development (LDRD) funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH1123.

Author Contributions

Conceptualization: WTS SBCS MKC.

Data curation: MKC JKD WTS.

Formal analysis: MKC JKD WTS.

Funding acquisition: WTS SBCS.

Investigation: MKC JKD WTS SBCS.

Methodology: MKC JKD WTS.

Project administration: WTS SBCS.

Resources: WTS SBCS.

Supervision: WTS SBCS.

Validation: WTS MKC.

Visualization: JKD MKC WTS SBCS.

Writing – original draft: MKC JKD SBCS WTS.

Writing – review & editing: WTS MKC.

References

1. California Department of Conservation. SB 4 Well Stimulation Treatment Regulations, Final Text of Regulations, Chapter 4. Development, Regulation, and Conservation of Oil and Gas Resources, Subchapter 2. Environmental Protection. December 30; Sacramento, CA: Division of Oil, Gas, and Geothermal Resources; 2014.
2. Richardson N, Gottlieb M, Krupnick A, Wiseman H. The State of State Shale Gas Regulation. Washington, D.C.: Resources for the Future; 2013 June.
3. Brantley SL, Yoxtheimer D, Arjmand S, Grieve P, Vidic R, Pollak J, et al. Water resource impacts during unconventional shale gas development: The Pennsylvania experience. Int J Coal Geol. 2014; 126:140–56.
4. Bureau of Land Management. Oil and Gas; Hydraulic Fracturing on Federal and Indian Lands, Final Rule, 43 CFR Part 3160, RIN 1004–AE26. Washington, DC 2012.
5. Fink J. Petroleum Engineer's Guide to Oil Field Chemicals and Fluids. 2nd ed. Burlington, MA: Elsevier Science; 2015.
6. Kelland M. Production Chemicals for the Oil and Gas Industry. 2nd ed. Boca Raton, FL: CRC Press; 2014.
7. Hudgins CM. Chemical treatments and usage in offshore oil and gas production systems. J Pet Technol. 1992; 44(5):604–11.
8. Hudgins CM. Chemical use in North Sea oil and gas E&P. J Pet Technol. 1994; 46(1):67–74.
9. Economides MJ, Hill AD, Ehlig-Economides C, Zhu D. Petroleum Production Systems, 2nd ed. Upper Saddle River, NJ: Prentice Hall; 2013.
10. National Research Council. Science and Decisions: Advancing Risk Assessment. Washington, DC: The National Academies Press; 2009.
11. California Department of Conservation. Well Stimulation Treatment (WST) Sacramento, CA: Division of Oil, Gas, and Geothermal Resources; 2016 [cited 2016 July 29]. Available from: http://www.conservation.ca.gov/dog/Pages/WST.aspx.
12. Doman L. United States remains largest producer of petroleum and natural gas hydrocarbons. Washington, D.C.: U. S. Energy Information Administration; 2016 May 23.
13. Guerra K, Dahm K, Dundorf S. Oil and Gas Produced Water Management and Beneficial Use in the Western United States, S&T Report No. 157. Denver, CO: U.S. Department of the Interior, Bureau of Reclamation; 2011.
14. Veil J. U.S. Produced Water Volumes and Management Practices in 2012. Oklahoma City, OK: Ground Water Protection Council, 2015 April.
15. Heberger M, Donnelly K. Oil, Food, and Water: Challenges and Opportunities for California Agriculture. Oakland, CA: Pacific Institute; 2015 December.
16. Muggeridge A, Cockin A, Webb K, Frampton H, Collins I, Moulds T, et al. Recovery rates, enhanced oil recovery and technological limits. Phil Trans R Soc A. 2014; 372:20120320.
17. Nelson EB. Well cementing fundamentals. Oilfield Rev. 2012; 24(2):59–60.
18. OSPAR Commission. OSPAR Report on Discharges, Spills and Emissions from Offshore Oil and Gas Installations in 2013. London, UK; 2015. Available from: http://www.ospar.org/documents?v=33826
19. Abdullah K, Malloy T, Stenstrom MK, Suffet IHM. Toxicity of acidization fluids used in California oil exploration. Toxicol Environ Chem. 2017; 99(1):78–94.
20. Stringfellow WT, Domen JK, Camarillo MK, Sandelin WL, Borglin S. Physical, chemical, and biological characteristics of compounds used in hydraulic fracturing. J Hazard Mater. 2014; 275:37–54. https://doi.org/10.1016/j.jhazmat.2014.04.040 PMID: 24853136
21. Stringfellow WT, Camarillo MK, Domen JK, Sandelin WL, Varadharajan C, Jordan PD, et al. Identifying chemicals of concern in hydraulic fracturing fluids used for oil production. Environ Pollut. 2017; 220:413–20. https://doi.org/10.1016/j.envpol.2016.09.082 PMID: 27743793
22. OSPAR Commission. OSPAR List of Substances Used and Discharged Offshore which Are Considered to Pose Little or No Risk to the Environment (PLONOR). London, UK: OSPAR Commission; 2013 [updated June; cited 2015 Nov]. Available from: http://www.ospar.org/documents?d=32939.
23. Shonkoff S, Maddalena R, Hays J, Stringfellow W, Wettstein Z, Harrison R, et al. Chapter 6: Potential Impacts of Well Stimulation on Human Health in California. An Independent Scientific Assessment of

Well Stimulation in California, Volume II: Generic and Potential Environmental Impacts of Well Stimulation Treatments. Sacramento, CA: California Council on Science and Technology; 2015.

24. Stringfellow WT, Cooley H, Varadharajan C, Heberger M, Reagan M, Domen JK, et al. Chapter 2: Impacts of Well Stimulation on Water Resources. An Independent Scientific Assessment of Well Stimulation in California, Volume II: Generic and Potential Environmental Impacts of Well Stimulation Treatments. Sacramento, CA: California Council on Science and Technology; 2015.

25. Pattanayek M, DeShields B. Risk-Based Screening Levels for the Protection of Livestock Exposed to Petroleum Hydrocarbons, Publication Number 4733. Washington, D.C.: American Petroleum Institute; 2004 July.

26. Vengosh A, Jackson RB, Warner N, Darrah TH, Kondash A. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environ Sci Technol. 2014; 48(15): 8334–48. https://doi.org/10.1021/es405118y PMID: 24606408

27. Long JCS, Birkholzer JT, Feinstein LC. Summary Report: An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry. An Independent Scientific Assessment of Well Stimulation in California. Sacramento, CA: California Council on Science and Technology; 2015.

28. Shaffer DL, Chavez LHA, Ben-Sasson M, Castrillon SRV, Yip NY, Elimelech M. Desalination and Reuse of High-Salinity Shale Gas Produced Water: Drivers, Technologies, and Future Directions. Environ Sci Technol. 2013; 47(17):9569–83. https://doi.org/10.1021/es401966e PMID: 23885720

29. South Coast Air Quality Management District (SCAQMD). Notification and Reporting Requirements for Oil and Gas Wells and Chemical Suppliers Rule 1148.2: South Coast Air Quality Management District; 2013 [cited 2016 March 15]. Available from: http://www.aqmd.gov/home/regulations/compliance/1148-2.

30. Hazardous Substances Data Bank: A TOXNET Database [Internet]. Bethesda, MD: U.S. National Library of Medicine, National Institute of Health; 2015 [cited 2015 Nov]. Available from: http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB.

31. ChemIDplus Advanced: A TOXNET Database [Internet]. Bethesda, MD: U.S. National Library of Medicine, National Institute of Health; 2015 [cited 2015 Nov]. Available from: http://chem.sis.nlm.nih.gov/chemidplus/.

32. SciFinder [Internet]. Colombus, OH: American Chemical Society; 2014 [cited 2015 Nov]. Available from: https://scifinder.cas.org.

33. SRC I Physprop Database [Internet]. Syracuse, NY: SRC, Inc.; 2013 [cited 2015 Nov]. Available from: http://esc.syrres.com/fatepointer/search.asp.

34. World Health Organization. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans [Internet]. International Agency for Research on Cancer (IARC); 2015 [updated October 24; cited 2015 Nov]. Available from: http://monographs.iarc.fr/ENG/Classification/ClassificationsCASOrder.pdf.

35. Chemical Risk Information Platform (CHRIP) [Internet]. Tokyo, Japan: National Institute of Technology and Evaluation; 2015 [cited 2015 Nov]. Available from: http://www.nite.go.jp/en/chem/chrip/chrip_search/systemTop.

36. U.S. Environmental Protection Agency. EPI Suite™-Estimation Program, version 4.11,. Washington, D.C.: U.S. Environmental Protection Agency; 2012. Available from: https://www.epa.gov/tsca-screening-tools/epi-suitetm-estimation-program-interface.

37. Aggregated Computational Toxicology Resource (ACToR) Database [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; 2015 [cited 2015 Nov]. Available from: http://actor.epa.gov/actor/faces/ACToRHome.jsp.

38. ECOTOXicology Database (ECOTOX) Release 4.0 [Internet], Washington, D.C.: U.S. Environmental Protection Agency; 2015 [cited 2015 Nov]. Available from: http://cfpub.epa.gov/ecotox/quick_query.htm.

39. European Chemicals Agency. International Uniform Chemical Information Database (IUCLID) Year 2000 Edition [CD- ROM]. 2000.

40. Office of Environmental Health Hazard Assessment. Current Proposition 65 List. Sacramento, CA; 2015 [cited 2015 Nov]. Available from: http://oehha.ca.gov/prop65/prop65_list/Newlist.html.

41. California Air Resources Board. Toxic Air Contaminant (TAC) Identification List. Sacramento, CA; 2010 [cited 2015 Nov]. Available from: http://www.arb.ca.gov/toxics/cattable.htm.

42. United Nations. Globally Harmonized System of Classification and Labelling of Chemicals (GHS), 4th Revised Edition. New York and Geneva; 2013. Report No.: ST/SG/AC.10/30/Rev.5.

43. Long J, Birkholzer J, Feinstein L. Summary Report: An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry. Sacramento, CA: California Council on Science and Technology; 2015.

44. Long JCS, Feinstein LC, Birkholzer J, Jordan P, Houseworth J, Dobson PF, et al. An Independent Scientific Assessment of Well Stimulation in California, Volume I: Well Stimulation Technologies and their Past, Present, and Potential Future Use in California. Sacramento, CA: California Council on Science and Technology; 2015.

45. OSPAR Commission. List of Substances of Possible Concern. London, UK: OSPAR Commission; 2015 [cited 2015 Nov]. Available from: http://www.ospar.org/work-areas/hasec/chemicals/possible-concern/list.

46. OSPAR Commission. Common Interpretation on which Chemicals are Covered and not Covered by the Harmonised Mandatory Control System under OSPAR Decision 2000/2. London, UK: OSPAR Commission; 2002 [cited 2015 Nov]. Available from: www.ospar.org/documents?d=32731

47. Camarillo MK, Domen JK, Stringfellow WT. Physical-chemical evaluation of hydraulic fracturing chemicals in the context of produced water treatment. J Environ Manage. 2016; 183: 164–74. https://doi.org/10.1016/j.jenvman.2016.08.065 PMID: 27591844

48. Kahrilas GA, Blotevogel J, Stewart PS, Borch T. Biocides in hydraulic fracturing fluids: A critical review of their usage, mobility, degradation, and toxicity. Environ Sci Technol. 2015; 49(1): 16–32. https://doi.org/10.1021/es503724k PMID: 25427278

49. U.S. Environmental Protection Agency. 2012 Edition of the Drinking Water Standards and Health Advisories. Washington, D.C.; 2012 [cited 2015 Nov]. Report No.: EPA 822-S-12-001. Available from: http://water.epa.gov/action/advisories/drinking/upload/dwstandards2012.pdf.

50. U.S. Environmental Protection Agency. Contaminant Candidate List (CCL) 4 and Regulatory Determination. Washington, D.C.; 2015 [cited 2015 Nov]. Available from: http://www2.epa.gov/ccl/chemical-contaminants-ccl-4.

51. European Chemicals Agency. Candidate List of Substances of Very High Concern for Authorisation. Helsinki, Finland; 2015 [cited 2015 Nov]. Available from: http://echa.europa.eu/candidate-list-table.

Stanford News (http://news.stanford.edu/)

OCTOBER 12, 2021

Living near oil and gas wells increases air pollution exposure, according to Stanford research

Researchers found increased concentrations of air pollutants downwind from oil and gas wells in California, likely affecting millions of Californians who live near them.

BY DANIELLE TORRENT TUCKER

In a 14-year analysis of air quality across California, Stanford researchers observed higher levels of air pollutants within 2.5 miles of oil and gas wells, likely worsening negative health outcomes for nearby residents.

(https://news.stanford.edu/wp-content/uploads/2021/10/WellPollutants.jpg)

Oil wells operating in Signal Hill, a city in Los Angeles County, California. Researchers found that drilling and operating wells emits harmful levels of pollution that may affect the health of nearby residents. *(Image credit: David Gonzalez)*

The scientists analyzed local air quality measurements in combination with atmospheric data and found that oil and gas wells are emitting toxic particulate matter (PM2.5), carbon monoxide, nitrous oxide, ozone and volatile organic compounds (VOCs). The findings, which appear in the journal ***Science of the Total Environment* (https://www.sciencedirect.com/science/article/pii/S0048969721053754)**, will help researchers determine how proximity to oil and gas wells may increase the risk of adverse health outcomes, including preterm birth, asthma and heart disease.

"In California, Black and Latinx communities face some of the highest pollution from oil and gas wells. If we care about environmental justice and making sure every kid has a chance to be healthy, we should care about this," said lead author David Gonzalez, who conducted research for the study while a PhD student in Stanford's Emmett Interdisciplinary Program in Environment and Resources (E-IPER). "What's novel about our study is that we've done this at a population, state-wide scale using the same methods as public health studies."

The findings align with other smaller-scale studies that have measured emissions from a handful of wells. At least two million Californians live within one mile of an active oil or gas well.

“It’s really hard to show air quality impacts of an activity like oil and gas production at a population scale, but that’s the scale we need to be able to infer health impacts,” said senior study author Marshall Burke, an associate professor of Earth system science at Stanford’s **School of Earth, Energy & Environmental Sciences (http://earth.stanford.edu/)** (Stanford Earth). “While it’s not necessarily surprising that drilling and operating oil and gas wells emit air pollutants, knowing the magnitude of the effect improves our broader understanding of who is exposed to what and how to intervene to improve health outcomes.”

A global killer

The research reveals that when a new well is being drilled or reaches 100 barrels of production per day, the deadly particle pollution known as PM2.5 increases two micrograms per cubic meter about a mile away from the site. A recent study published in ***Science Advances* (https://www.science.org/doi/10.1126/sciadv.abd4049)** found that long-term exposure to one additional microgram per meter cubed of PM2.5 increases the risk of death from COVID-19 by 11 percent.

“We started in 2006 because that’s when local agencies started reporting PM2.5 concentrations,” said Gonzalez, who is now a postdoctoral researcher at the University of California, Berkeley. “We’re very concerned about particulate matter because it’s a leading global killer.”

The team evaluated about 38,000 wells that were being drilled and 90,000 wells in production between 2006 and 2019. They developed an econometric model incorporating over a million daily observations from 314 air monitors in combination with global wind direction information from the National Oceanic and Atmospheric Administration (NOAA) to determine if the pollutants were coming from the wells.

Other factors that could be contributing to elevated emissions were controlled for – such as wildfire smoke or industrial activities – and monitors located far from drilling sites were used to identify those factors unrelated to wells. They also analyzed locations with air quality data from both before and after a well was drilled.

“Sometimes the wind is blowing from the well, sometimes it’s not, and we found significantly higher pollution on days when the wind is blowing from the wells,” Gonzalez said. “As a control, we assumed wells that are downwind of the air monitor shouldn’t contribute any pollution – and that is indeed what we saw.”

The research also reveals that ozone – a powerful oxidant that can cause wheezing, shortness of breath and aggravated lung disease – was present up to 2.5 miles from wells. Children are at the greatest risk from exposure to ozone because their lungs are still developing, according to the Environmental Protection Agency (EPA).

Chronic exposure

The new study contributes to a growing body of evidence about the dangers of living near oil and gas wells that may help guide ongoing policymaking around residential setbacks from drilling sites. For example, LA County recently voted to phase out oil and gas drilling, citing issues of climate change, environmental impacts and equity, and other California cities are in discussion about neighborhood drilling regulations.

“Many of California’s oil fields have been operating for decades. People that live near them have been chronically exposed to higher levels of pollution – and a lot of these wells are located in neighborhoods that are already burdened by pollution,” Gonzalez said. “Our study adds to the evidence that public health policies are needed to reduce residents’ exposure to air pollution from wells.”

Although data for the research is from California, the co-authors say the findings are likely applicable to other regions with oil and gas operations.

“We’ve had earlier papers suggesting that proximity to oil and gas production worsens health outcomes, and the likely channel was through air pollutants, but we previously didn’t have a good way to demonstrate that was the case,” Burke said. “This new work is helping confirm that air pollution was the missing link between this type of energy production and the bad outcome that we cared about.

Burke is also deputy director of the ***Center on Food Security and the Environment*** **(https://fse.fsi.stanford.edu/)***, senior fellow at the* ***Freeman Spogli Institute for International Studies*** **(http://fsi.stanford.edu/)***, a member of* ***Bio-X*** **(http://biox.stanford.edu/)** *and a fellow with the* ***Stanford Institute for Economic Policy Research (SIEPR)*** **(https://siepr.stanford.edu/)***. Co-authors on the study include* ***Gary Shaw*** **(https://med.stanford.edu/profiles/gary-shaw)***, DrPH, a professor of pediatrics at the Stanford University* ***School of Medicine*** **(http://med.stanford.edu/)** *and member of* ***Bio-X*** **(http://biox.stanford.edu/)** *and the* ***Maternal & Child Health Research Institute (MCHRI)*** **(http://chri.stanford.edu/)***;* ***Mark Cullen*** **(https://profiles.stanford.edu/mark-cullen)***, MD, founding director of the Stanford Center for Population Health Sciences;* ***Michael Baiocchi*** **(https://profiles.stanford.edu/michael-baiocchi)***, an assistant professor of epidemiology and population health; and Christina Francis of Johns Hopkins University, who conducted research as part of the* ***Summer Undergraduate Research in Geoscience and Engineering Program*** **(https://earth.stanford.edu/dei/surge#gs.cfjcdy)** *(SURGE).*

The research was supported by the Ford Foundation Predoctoral Fellowship, the Vice Provost for Graduate Education at Stanford University and the Stanford School of Earth, Energy & Environmental Sciences.

To read all stories about Stanford science, subscribe to the biweekly ***Stanford Science Digest (http://eepurl.com/dLmCng)***.

Media Contacts

Marshall Burke, School of Earth, Energy & Environmental Sciences: (650) 721-2203; **mburke@stanford.edu (mailto:mburke@stanford.edu)**
David Gonzalez, University of California, Berkeley: (805) 714-6243; **djxgonz@berkeley.edu (mailto:djxgonz@berkeley.edu)**
Danielle Torrent Tucker, School of Earth, Energy & Environmental Sciences: (650) 497-9541; **dttucker@stanford.edu (mailto:dttucker@stanford.edu)**

(mailto:?
subject=An%20interesting%20article%20from%20Stanford%20News&body=I%20want%20to%20share%20this%

USPTO PATENT FULL-TEXT AND IMAGE DATABASE

Home Quick Advanced Pat Num Help

Bottom

View Cart Add to Cart

Images

(1 of 1)

United States Patent **4,291,772**
Beynet **September 29, 1981**

Drilling fluid bypass for marine riser

Abstract

Method and apparatus are described to reduce the tension required on a riser pipe used in offshore drilling between a floating vessel and a subsea wellhead. Heavy drilling fluid is circulated down a drill pipe and up the annulus between the drill pipe and the borehole wall to a point just above a subsea wellhead. From this point, a separate drilling fluid return conduit extends to the floating vessel. Means are provided to maintain a constant level of an interface between the heavy returning drilling fluid and the lightweight fluid which can be confined within the riser pipe.

Inventors:	**Beynet; Pierre A.** (Tulsa, OK)
Assignee:	**Standard Oil Company (Indiana)** (Chicago, IL)
Family ID:	**22459918**
Appl. No.:	**06/133,703**
Filed:	**March 25, 1980**

Current U.S. Class:	**175/5**; 175/25; 175/38; 175/40; 175/7
Current CPC Class:	E21B 21/08 (20130101); E21B 21/001 (20130101)
Current International Class:	E21B 21/00 (20060101); E21B 21/08 (20060101); E21B 007/12 (); E21B 017/01 (); E21B 021/08 ()
Field of Search:	;175/7,10,5,38,48,50,40,25 ;166/335,358,367,359

References Cited [Referenced By]

U.S. Patent Documents

3465817	September 1969	Vincent
3601187	August 1971	Tidwell
3791442	February 1974	Watkins
3815673	June 1974	Bruce et al.
3825065	July 1974	Lloyd et al.
4063602	December 1977	Howell et al.
4091881	May 1978	Maus

4099583	July 1978	Maus
4149603	April 1979	Arnold

Primary Examiner: Novosad; Stephen J.
Attorney, Agent or Firm: Gassett; John D.

Claims

What is claimed is:

1. A method of drilling a subsea well from a vessel floating on a body of water in which a drilling fluid is circulated down a drill pipe through a drill bit and returned up the annulus between a drill string and the borehole wall, the improvement which comprises:

providing a riser pipe from said wellhead to said vessel,

maintaining a lightweight fluid in said riser on top of the drilling fluid in said annulus, said lightweight fluid having a density less than said drilling fluid

maintaining a selected pressure on said lightweight fluid by use of pressure generating means; and

connecting the annulus below said lightweight fluid to a return conduit extending to said vessel.

2. A method as defined in claim 1 including the step of providing a pump in said return conduit.

3. A method as defined in claim 2 including providing an interface detector between said drilling fluid and said lightweight fluid and controlling the pumping of drilling fluid to the vessel external of said riser in response to the output of said interface detector.

4. A method as defined in claim 3 including providing a plurality of interface sensors at a plurality of elevations along said riser pipe and controlling said pump by a selected one of said interface sensors.

5. A method as defined in claim 3 in which said lightweight fluid is sea water.

6. A method as defined in claim 1 including

providing a seal in the upper end of said riser pipe through which said drill string can advance and rotate;

providing a pump in a conduit extending from the lower end of the annular space of said riser pipe and said drill string and the surface of the vessel.

7. A drilling system in which a subsea well is drilled from a floating vessel by circulating a drilling fluid down a drill pipe, the improvement which comprises:

a riser pipe having a slip joint at its upper end and connected at its lower end to said subsea well;

tensioning means supporting the top of said riser pipe in said vessel;

a seal sealing the annular space between said drill pipe and the internal side of said riser pipe below said slip joint;

a return conduit exterior said riser pipe and extending from the interior of the lower end of said riser pipe to said vessel;

a lightweight fluid in said annular space below said seal;

pump means to maintain said lightweight fluid under pressure; and

a pump in said return conduit.

8. A system as defined in claim 7 including a level control sensors to determine the interface between said lightweight fluid and said circulating drilling fluid and means to control said pump in said return conduit in response to said detected interface.

9. A system as defined in claim 7 including a plurality of interface sensors at a plurality of elevations along said riser pipe and means for connecting the output of a selected sensor to said pump.

10. A system as defined in claim 7 including means to maintain the upper level of said lightweight fluid at a selected elevation.

11. A method of drilling a subsea well from a vessel floating on a body of water in which a drilling fluid is circulated down a drill pipe through a drill bit and returned up the annulus between the drill string and the borehole wall, the improvement which comprises:

providing a riser pipe from said wellhead to said vessel;

maintaining a lightweight fluid in said riser on top of the drilling fluid in said annulus, said lightweight fluid having a density less than said drilling fluid;

connecting the annulus below said lightweight fluid to a return conduit extending to said vessel;

providing an interface detector between said drilling fluid and said lightweight fluid and controlling the pumping of drilling fluid to the vessel external of said riser in response to the output of said interface detector.

12. A method as defined in claim 11 including providing a plurality of interface sensors at a plurality of elevations along with said riser pipe and controlling said pump by a selected one of said interface sensors.

13. A method as defined in claim 11 in which said lightweight fluid is sea water.

14. A drilling system in which a subsea well drilled from a floating vessel by circulating a drilling fluid down a drill pipe, the improvement which comprises:

a riser pipe having a slip joint at the upper end and connected at its lower end to said subsea well;

tensioning means supporting the top of said riser pipe to said vessel;

a seal sealing the annuluar space between said drill pipe and the internal side of said riser pipe below said slip joint;

a return conduit exterior of said riser pipe and extending from the interior of the lower end of said riser pipe from said vessel;

a lightweight fluid in said annular space below said seal;

a pump in said return conduit;

level control sensors to determine the interface between said lightweight fluid and said circulating drilling fluid; and

means to control said pump and said return conduit in response to said detected interface.

15. A system as defined in claim 14, including a plurality of interface sensors at a plurality of elevations along said riser pipe and means for connecting the output of a selected sensor to said pump.

16. A drilling system in which a subsea well is drilled from a floating vessel by circulating a drilling fluid down a drill pipe, the improvement which comprises:

a riser pipe having a slip joint as its upper end and connected at its lower end to said subsea well;

tensioning means supporting the top of said riser pipe to said vessel;

a return conduit exterior said riser pipe and extending from the interior of the lower end of said riser pipe to said vessel;

a lightweight fluid in said annular space above said drilling fluid;

a pump in said return conduit;

means to maintain the upper level of said lightweight fluid at a selected elevation.

17. A method of drilling a subsea well from a vessel floating on a body of water in which a drilling fluid is circulated down a drill pipe to a drill bit and returned up the annulus between a drill string and the borehole wall, the improvement which comprises:

providing a riser pipe from said wellhead to said vessel;

maintaining a lightweight fluid other than air in said riser on top of the drilling fluid in said annulus;

said lightweight fluid having a density less than said drilling fluid; and

connecting the annulus below said lightweight fluid to a return conduit extending to said vessel.

18. A method as defined in claim 17 in which said lightweight fluid is sea water.

Description

This invention concerns the drilling of wells, particularly oil and gas, from a floating vessel. The most common method of drilling from floating vessels is by the use of a riser pipe which is a large diameter steel pipe, e.g., 20 inches, which extends from the floating vessel to a wellhead on the sea floor. The lower end is releasably connected to the wellhead by disconnect connectors which are commercially available, and the upper end is supported from the vessel by constant tensioning devices. As wells are drilled in deeper water it, of course, requires a longer riser pipe. When using a riser pipe in normal operations, a drilling fluid is circulated down a drill string through a drill bit and back up the annulus between the drill string and the borehole wall up through the annulus between the riser and the drill string.

When a drilling vessel drills in deep water and is using heavy mud, the marine riser has to be kept under very high tension to keep it from buckling. This tension supports the weight of the riser and the weight of the mud inside the riser. The weight of the mud inside the riser pipe is normally greater than the weight of the riser pipe itself. I disclose a system and method for greatly reducing the weight of the drilling mud within the riser pipe. A seal is provided at the top of the riser. The seal is of the type that permits the drill pipe to rotate and advance downwardly through it when it is not energized. I next provide a mud return conduit from the bottom interior of the riser pipe to the vessel. Above the drilling mud and in most of the riser pipe is a low-density fluid. Sufficient pressure is provided on this low-density fluid to prevent the drilling mud from rising substantially in the riser pipe. A pump is provided in the mud return conduit to pump the mud through the conduit to the vessel instead of up through the riser pipe, as is normally done. This permits the use of the required heavy or high-density drilling fluid, yet keeps the high-density drilling fluid from the riser pipe so that the tensioning on the riser pipe is much less than is normally the case.

Control means for the pump is provided and is responsive to the interface between the drilling fluid and the lightweight fluid in the riser annulus. This assists in maintaining the interface at a desired level. As will be explained hereinafter, by the use of the method described herein, I reduce the chances of fracturing a shallower formation when a heavy mud is required to control the well when drilling at a deeper depth.

A better understanding of the invention can be had from the following description taken in conjunction with the drawings.

DRAWINGS

FIG. 1 illustrates a drilling system using a riser pipe supported from a floating vessel to drill a subsea well in which the riser pipe is filled with a low-density fluid.

FIG. 2 is a pressure gradient chart illustrating pressure at various depths with and without the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Shown in FIG. 1 is a drilling vessel 10 floating on a body of water 12 with a bottom 14. A riser pipe 16 connects the vessel to a subsea wellhead 18 which is provided with blowout preventers and other necessary valves and is mounted on a casing 20 which extends into the seafloor 14. The upper end of the riser pipe is supported from the drilling vessel by cables or lines 22 connected to constant tensioning devices 24 in a known manner. A slip joint 26 is provided in the riser pipe 16 in its upper end and a drill string 28 is supported within the riser pipe from a derrick, not shown, on drilling vessel 10.

A seal 30 is provided in the upper end of riser pipe 16. Seal 30 can be a Hydril Bag Type BOP such as Type GL or GK shown in the 1978-79 Composite Catalog, Pages 36-40. To decrease the wear on seal 30, an optimal section or joint of polished drill pipe can be threaded into the drill string just below the kelley and kept in that position during the drilling of the well. A light-weight fluid conduit 32 is connected at point 34 to the interior of the riser pipe 16 and extends to a pump 36 and a supply of lightweight fluid not shown. A return mud flow line 38 connects into the annulus of the riser pipe 16 just above wellhead 18 and extends to mud return tanks and facilities 40 which are carried by vessel 10. The return mud line can be one of the "kill and choke" lines with appropriate bypass valving for the pump. A mud return pump 42 is provided in the lower end of mud return conduit 38.

In FIG. 1, the mud return pump 42 can be controlled by a level control means 43 to sense and control the interface 45 between the lightweight fluid 33 and the heavy drilling mud 35. This prevents a full head of heavy drilling fluid in conduit 38 from being applied to the drilling mud at depth. There can be a series of level control means 43, 43A along the riser pipe with output lines 41, 41A going to the surface where one can select which level 45, 45A, etc., is needed to obtain the desired pressure gradient. The output from the selected level control is used to send a control signal down line 39 to pump 42. The lightweight fluid upper level 45 is controlled by a level sensor 47 with a suitable circuit to average the heave effect. Level 45 is detected in container 49 which is connected to line 32. In the case where the lightweight fluid is a gas, it is controlled by a pressure regulator instead of level sensor 47. The output of liquid level control sensor 47 or of the pressure regular controls pump 36 so as to maintain a constant level 45 or selected pressure.

The lightweight fluid can be sea water, which weighs approximately 8.6 lbs/gal or it may be nitrogen gas. The heavy mud which it replaced may weigh as much as 18 lbs/gal or more. Without my system, the tension needed to be applied to riser 16 from the vessel 10 would typically be 400,000 lbs. With my system, using a lightweight fluid such as sea water, the tension which needs to be applied is only 200,000 lbs. This example is for a 16" riser with flotation, in 1260' of water, an 18 lbs/gal drilling fluid, 50 foot of vessel offset, 1 ft/sec current, 25 ft, 11-second waves, and maximum lower ball angle of 4.degree..

Attention is next directed to FIG. 2 which illustrates pressure gradients for the drilling mud in the borehole of the drilling mud at various depths. Shown thereon is a chart having depth versus pressure. The chart shows the water depth as D.sub.1. By using known technology in a given area for a depth D.sub.3 can be determined that the drilling mud should exert a pressure P.sub.3 on the formation in order to give proper control in accordance with good drilling practices. This would require a certain mud weight. If the riser pipe is filled with this mud, the pressure obtained with depth is indicated by line 44, which is much higher than the pressure indicated by line 46 which is obtained if we use a low-density fluid in the riser pipe. This is true for all points except at the surface and at depth D.sub.3. At the sea floor, the pressure in the conventional system is about twice what it is in our system. At depth D.sub.2, there is a .DELTA.P.sub.2 which is still substantial. The difference in pressure is illustrated by the shaded area 48. if the pressure P.sub.3, which is required at D.sub.3, is obtained, then the pressure at a point D.sub.2, as illustrated on line 44, might be sufficient to fracture the formation at depth D.sub.2. This, of course, could be hazardous. One way of combating this would be to set casing. However, this cannot always be done and frequently cannot be done economically. This becomes more and more true as the water depth D.sub.1 becomes greater and greater. As can be seen then with my system and the pump operational, I maintain a pressure gradient curve 46 which is much less than that of curve 44, yet at depth D.sub.3 we can obtain the required pressure P.sub.3. In order to obtain the required pressure P.sub.3, a slightly heavier drilling mud may be needed for the drilling fluid in order to obtain the pressure P.sub.3 because there is a head H.sub.2 of drilling mud and H.sub.1 of sea water instead of having heads H.sub.2 and H.sub.1 each of the drilling mud.

While the above description has been made in detail, it is possible to make variations therein without departing from the spirit or scope of the invention.

* * * * *

Images

View Cart Add to Cart

Top

Home Quick Advanced Pat Num Help