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Effect of Hydrofracking on Aquifers

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<http://dx.doi.org/10.5772/intechopen.72327>

Abstract

Geologists have understood the presence of shale gas and shale oil since the early twentieth century but always considered it unattainable due to shale's low permeability. The shale gas revolution in the USA, brought about by the combination of horizontal drilling and hydraulic fracturing, has proven the feasibility of economically accessing this resource and significantly increasing the world's proven reserve. As we enter the era of application of this technology worldwide, countries will have to weigh the promise of increased energy independence and hydrocarbon revenue against the potential damage to water supplies. Hydrofracking's voracious thirst for water and potential to pollute will impact surface water bodies and aquifers. We review the basic technique, and potentially contaminating fracking fluid additives. We examine the potential damage to water quality and the potential effect on water availability in China, Mexico, South Africa, and Algeria.

Keywords: aquifer, hydrofracking, shale gas, water resources, water

1. Introduction

Hydrofracking is a simple technique that has revolutionized oil and gas production and transformed the USA into the world's largest oil producer, and yet the technique remains controversial. Along with the promise of increased production comes the real threats of surface water and groundwater pollution. An additional threat is posed by the release of methane, a potent greenhouse gas. Modern hydrofracking combines horizontal drilling through thousands of feet of hydrocarbon-bearing rock with a formation fracturing injection of high-pressure fracking fluid. The fracking fluid is both the elixir that unlocks the tightly held hydrocarbons and the source of potential pollution. It is a mixture of millions of liters of water under extreme pressure to fracture the rock, sand grains to prop the new fractures open, lubricants to decrease friction and better deliver the pressurized water to the rock, and toxic chemicals to

prevent microbial growth. There is a worldwide debate related to the environmental impact of hydrofracking causing some countries to ban the practice, and some countries to declare a moratorium on hydrofracking. Even in the USA, where hydrofracking was invented, there are states and even counties within states that have banned hydrofracking.

One of the many risks and concerns of hydrofracking is methane releases and its impact on climate change, but the biggest concern expressed in both the popular press and scientific journals is the contamination of groundwater. One aspect of the debate related to the contamination of groundwater to be explored in this chapter in more detail is the argument that the hydrofracking is happening kilometers below the ground level, and therefore the hydrofracking layer is separated from usable aquifer layers by more than a 1000 meter of impermeable bedrock. In this chapter the authors will lay out the history of hydrofracking and the technological improvements that have optimized the process. The authors will describe the real and perceived threats to the environment and communities within the path of the hydrofracking boom.

2. History of hydrofracking technique

What is called hydrofracking in the popular vernacular is actually two technologies. It is a combination of horizontal drilling and high-volume hydraulic fracturing. The first is horizontal drilling, in which the well drills horizontally through the oil- or gas-bearing rock layer. The second is high-volume hydraulic fracturing in which highly pressurized water is used to fracture the oil- or gas-bearing rock formation and sand transported with the high-pressure water props the fractures open.

Neither is an entirely new technology. Directional drilling was used to drill for offshore oil in southern California in the 1920s. Drillers would drill vertically from an onshore location and then cause the drill bit to angle west to tap formations below the ocean [1]. From that time the technology has steadily advanced until the present day where drillers have excellent control of the depth and angle of the turn from vertical, the ultimate depth of the horizontal portion, and the 3D orientation of the drilling.

3. Purpose of hydrofracking and typical geologic targets

Horizontal drilling followed by high-volume hydraulic fracturing is an expensive, heavy technology, potentially polluting activity, so why has it become popular? Comparing the process to conventional drilling explains the overwhelming benefits of the technique in the appropriate geologic setting.

In a conventional oil or gas production setting, a well would be advanced from the ground surface vertically down through overlying sediment and rock layers and ultimately through the oil- or gas-bearing formation. Typically, the target would be an oil- and/or gas-bearing sandstone or limestone layer of rock possibly tens to hundreds of feet thick. The portion of the well casing within the hydrocarbon-rich zone would be perforated or screened. The relatively large pores in the sandstone or limestone would allow the fluid to flow toward the well.

The limits to fossil fuel production in such a well are the thickness of the formation that is screened, tens to hundreds of feet, and the ability of the hydrocarbons to flow through the solid rock. To glean natural gas or oil from a shale formation offers a unique challenge due to the size of the rock's pores. Normally, reservoir rocks have pore throat openings in the range of 2 μm or more. Hydrocarbon-rich shales have pore throat openings in the range of 0.1–0.005 μm [2].

These inherent limits on production of hydrocarbons from shale are overcome with the combination of horizontal drilling and high-volume hydraulic fracturing. In this technique, a well is drilled vertically down to a few hundred feet above the top of the reservoir rock then bored in an arc towards horizontal, then continuing as a horizontal borehole. The horizontal borehole is positioned to be somewhere in the middle of the depth of the reservoir rock and extended thousands of feet horizontally through the formation. The entire length of the horizontal borehole through the reservoir rock will eventually be screened and open for hydrocarbon flow. To overcome the low pore size and porosity of the shale, portions of horizontal well casing will be perforated, and then the rock surrounding the well bore will be fractured using high-pressure water. The fracturing creates interconnected secondary porosity that allows hydrocarbons to flow toward the thousands of feet of horizontal well. This combination of horizontal drilling and high volume hydraulic fracturing is what has converted shale gas into a recoverable resource.

4. Effect of hydrofracking in the USA and worldwide oil and gas proven reserve

The rapid rise of combined horizontal drilling and high-volume hydraulic fracturing has opened up large, previously unavailable natural gas and oil resources within the lower 48 states of the USA. The opening-up of unconventional "tight gas" formations to exploration and production has greatly increased estimates of technically recoverable US shale gas reserves. Geologists at the US Geological Survey, US Energy Information Administration, as well as in academic settings and energy producers have known the vast natural gas resource locked within the tight shale formations. It is only with the development of horizontal drilling and the perfection of hydrofracking that portions of this resource have been converted to proven reserves, that is, portions of the resource that are able to be economically extracted. **Figure 1** shows the increase in shale gas as a percentage of all natural gas produced in the USA between 2000 and 2015 and indicates the dramatic rise from less than 3% of US natural gas production in 2003 to over 65% of US natural gas production in 2015.

The technological revolution that has increased US natural gas production in the USA has spilled over into and dramatically increased US oil production as well. Oil exploration and extraction are a mature industry in the USA, having begun in the 1860s. US oil production, as well as US proven reserves, had been in a long-term steady decline since 1970. That decline was reversed in 2008, and since 2014 more than half of the oil production in the USA comes from hydrofracked wells. In fact US oil production increased from under 5 million barrels per day in 2008 to over 9 million barrels per day in 2015, and the US Energy Information Administration projects that US oil production will reach 10 million barrels per day by 2018 [3].

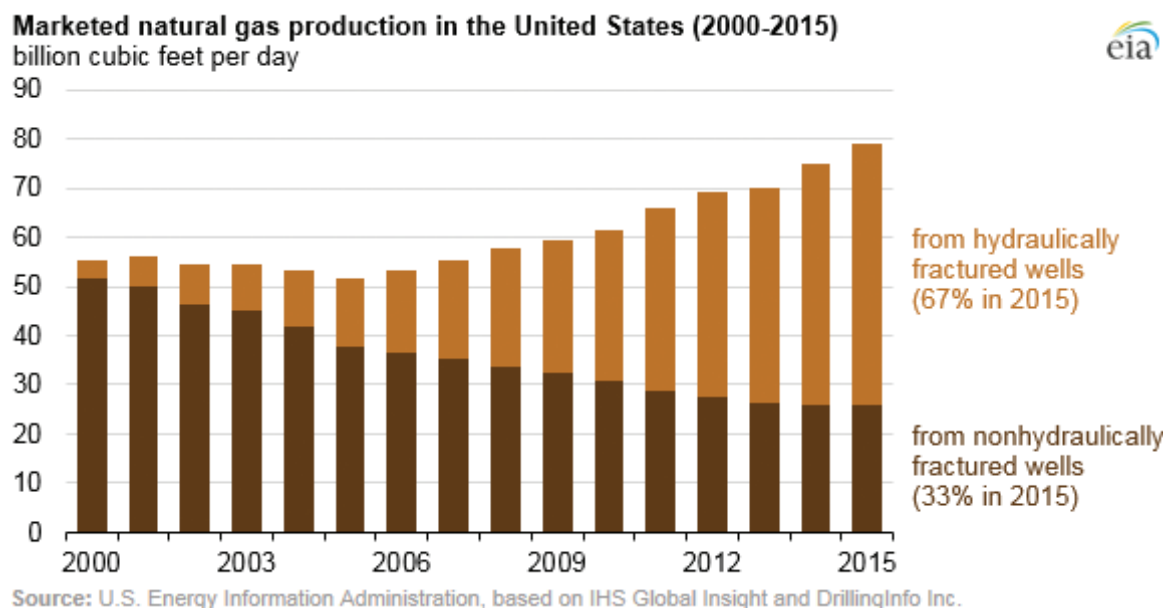


Figure 1. Natural gas production in the USA in billion cubic feet per day (2000–2015) [5]. Conventional gas shown in dark shading and shale gas shown in light shading.

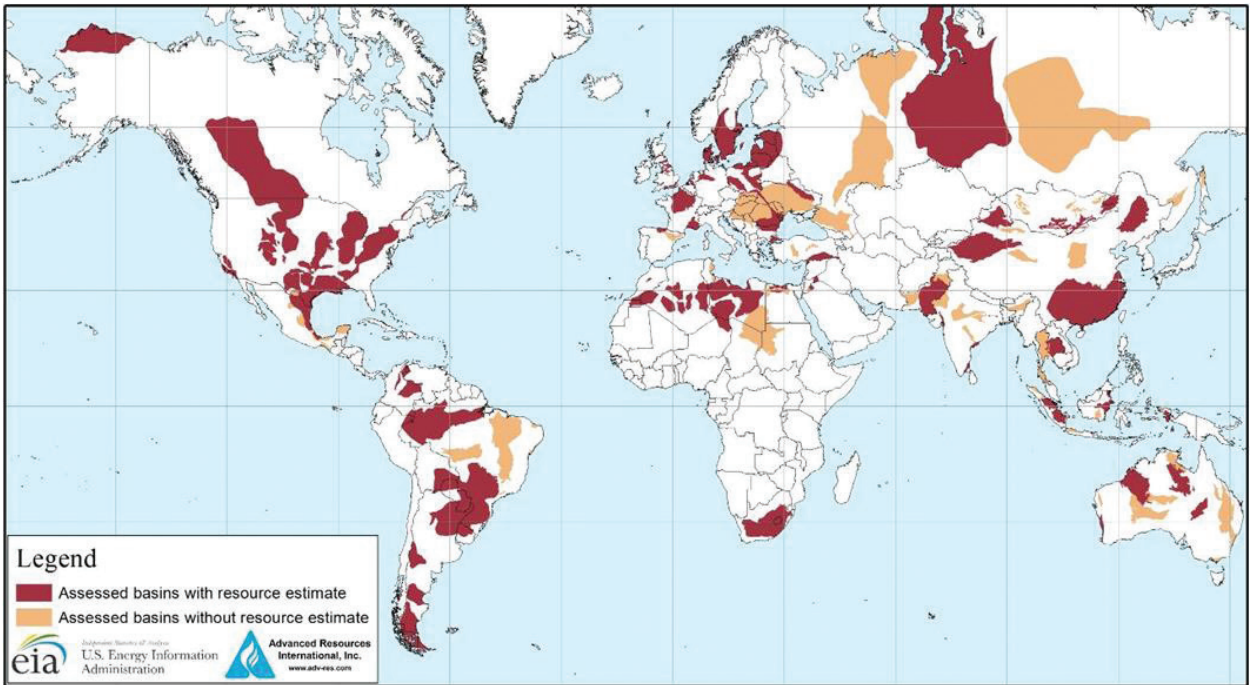


Figure 2. Basins with assessed shale oil and shale gas formations [6].

The technological revolution that has transformed the oil and gas proven reserve and production story in the USA is beginning to affect production worldwide. The US Energy Information Administration has found that tight shale gas and tight shale oil resources are distributed around the world (**Figure 2**).

Shale oil			Shale gas		
Rank	Country	(billion barrels)	Rank	Country	(trillion cubic feet)
1	Russia	75	1	China	1,115
2	U.S. ¹	58 (48)	2	Argentina	802
3	China	32	3	Algeria	707
4	Argentina	27	4	U.S. ¹	665 (1,161)
5	Libya	26	5	Canada	573
6	Australia	18	6	Mexico	545
7	Venezuela	13	7	Australia	437
8	Mexico	13	8	South Africa	390
9	Pakistan	9	9	Russia	285
10	Canada	9	10	Brazil	245
World Total		345 (335)	World Total		7,299 (7,795)

¹EIA (Energy Information Administration) estimates used for ranking order. ARI (Advanced Resources International) estimates in parentheses.

Table 1. Top 10 countries with technically recoverable shale oil and shale gas resources [6].

Countries with the highest technically recoverable tight shale oil and shale gas, as shown in **Table 1**, are found on every inhabited continent. The US Geological Survey has estimated that the technically recoverable shale gas represents a 47% increase in the world's total technically recoverable natural gas and that the technically recoverable shale oil represents an 11% increase [4]. The capital and know-how intensive hydrofracking revolution has only begun in a handful of countries, most notably China, Argentina, Mexico, and Algeria.

5. Aquifers and water resources: hydrofracking's threat to water quantity and water resources

In terms of aquifers, hydrofracking presents two threats: it uses too much water, and the water it uses becomes polluted and unfit for any other use. This section will address the threat hydrofracking poses to water resources due to imposing a new demand on already stretched water resources. Hydraulic fracturing as a technology is well known as a water hog. The volume of water used per well depends on the length of the horizontal borehole and the formation, but it is not unheard of for a single well to use 20 million liters. This is a consumptive use of water, in that once the hydrofracking chemicals are added and the water is injected into the subsurface, it cannot be reused. For perspective, consider that 20 million liters of sufficient water to meet the basic needs and few health concerns arise for approximately 200,000–400,000 people, according to the World Health Organization [7]. And, that is just the water used for a single well!

As with the most water resource problems, the geographic distribution of available water resource and water need may not align. A look at the hydrofracking experience in the USA is illustrative. Some shale gas formations underlie areas of abundant water, such as the Marcellus shale and Utica shale in the Northeastern USA. This area is well supplied with rivers, lakes, and abundant groundwater. The area is humid and receives on the order of 100 cm of precipitation annually. In contrast the Uinta-Piceance Province in Colorado, located in the Western USA,

is located mainly in an area of high desert. The waters of the Colorado River are already over allocated, yet energy companies have secured over a million acre-feet (1.25 billion cubic meters) of water rights. Many of the shale gas formations poised to make a significant contribution to the world’s natural gas production are also found in areas already experiencing water stress.

The World Resources Institute reports that China, India, Pakistan, Mexico, and South Africa are among the top 20 countries in the world in terms of shale gas potential, but each may have insufficient unallocated water to develop this resource [8]. Currently, farmers in China, India, and Pakistan use tube wells and electric pumps to pull 400 billion cubic meters of groundwater out of aquifers annually. This volume exceeds recharge by an estimated 170 billion cubic meters per year [9]. The three countries combined are responsible for more than half of the world’s agricultural use of groundwater. Water is in such short supply near major cities in parts of Asia that untreated sewage is used to irrigate crops. It is estimated that a quarter of all of Pakistan’s vegetables are irrigated with sewage. These are not countries with excess water waiting to be used for hydrofracking! **Table 2** lists 20 countries with the largest technically recoverable shale gas resources by average exposure to baseline water stress over shale play area.

If a significant shale gas resource exists in a water short area, the problem is likely not that there will be insufficient water to develop the lucrative natural gas resource. The problem is more likely that the water for hydrofracking will be diverted from some of the use. There will be winners and losers.

One country to consider is China. It is estimated that China has twice the shale gas resource of the USA, over 1100 trillion cubic feet. This is enough to be a significant factor in China’s transition toward a cleaner energy future. China currently uses coal to provide 62% of its total energy output [10]. It has been said that shale gas on its worst day is better than coal on its best day; so to any extent possibility, a transition from coal to shale gas could be a positive development. Shale gas, photovoltaics, and wind power will likely all be part of the mix used to wean China away from coal as it strives to meet its obligations under the Paris agreement.

China is the world’s most populous country. In his book *When the Rivers Run Dry*, Fred Pearce states that “If northern China were a separate country it would be one of the most water-stressed in the world.” The World Bank estimates that China has already lost 14 billion dollars in industrial production due to water shortages. More than a quarter of China’s landmass is already a desert. The Gobi, the fastest-expanding desert on earth, grows toward Beijing at a rate of 2 miles per year. It has been estimated that the country lost more than 6% of its farmland to desertification between 1997 and 2008 [11].

Extremely high	High	Medium to high	Medium to low	Low
Pakistan (105)	China (1115)	USA (567)	Argentina (802)	Australia (437)
	Mexico (545)	Paraguay (75)	Canada (573)	Russia (287)
	S. Africa (390)		Poland (148)	Brazil (245)
	India (96)		France (137)	Venezuela (167)
			Ukraine (128)	Columbia (55)

Estimated shale gas in trillion cubic feet in brackets. Data source: [8].

Table 2. Baseline water stress over shale play area.

Some of China's potential shale gas fields underlie areas already experiencing water stress. The statement of [12] indicates that fracking in the Sichuan Basin will compete with domestic water needs in an area that is already water stressed, but the specter of additional desertification and diversion of water for hydrofracking has not deterred multinational oil and gas companies. Chinese energy companies Sinochem, Sinopec, and CNOOC have invested in US shale gas operations such as Chesapeake Energy partly to gain access to hydrofracking experience. Major western energy companies including ExxonMobil and Chevron have initiated joint ventures in Chinese shale gas. The US shale gas boom in formations such as the Bakken in Texas and the Marcellus in Pennsylvania has taken place in nearly horizontal, relatively shallow formations. Many of China's most promising formations are deeper and in more complex geology, indicating that it will take even more water per well to successfully frack the formations [13].

Figures 3 and 4 show current water scarcity in China and shale gas plays in China, respectively. Development of shale gas basins in the northern area in particular will compete with other uses for scarce water. Both the Bohai Bay Basin and the Ordos Basin are found in areas already classified as under extreme water scarcity. Population will grow, industry will expand, and agriculture will struggle to keep up with growing food demand; each of these areas will continue to be at least as water short as they are presently.

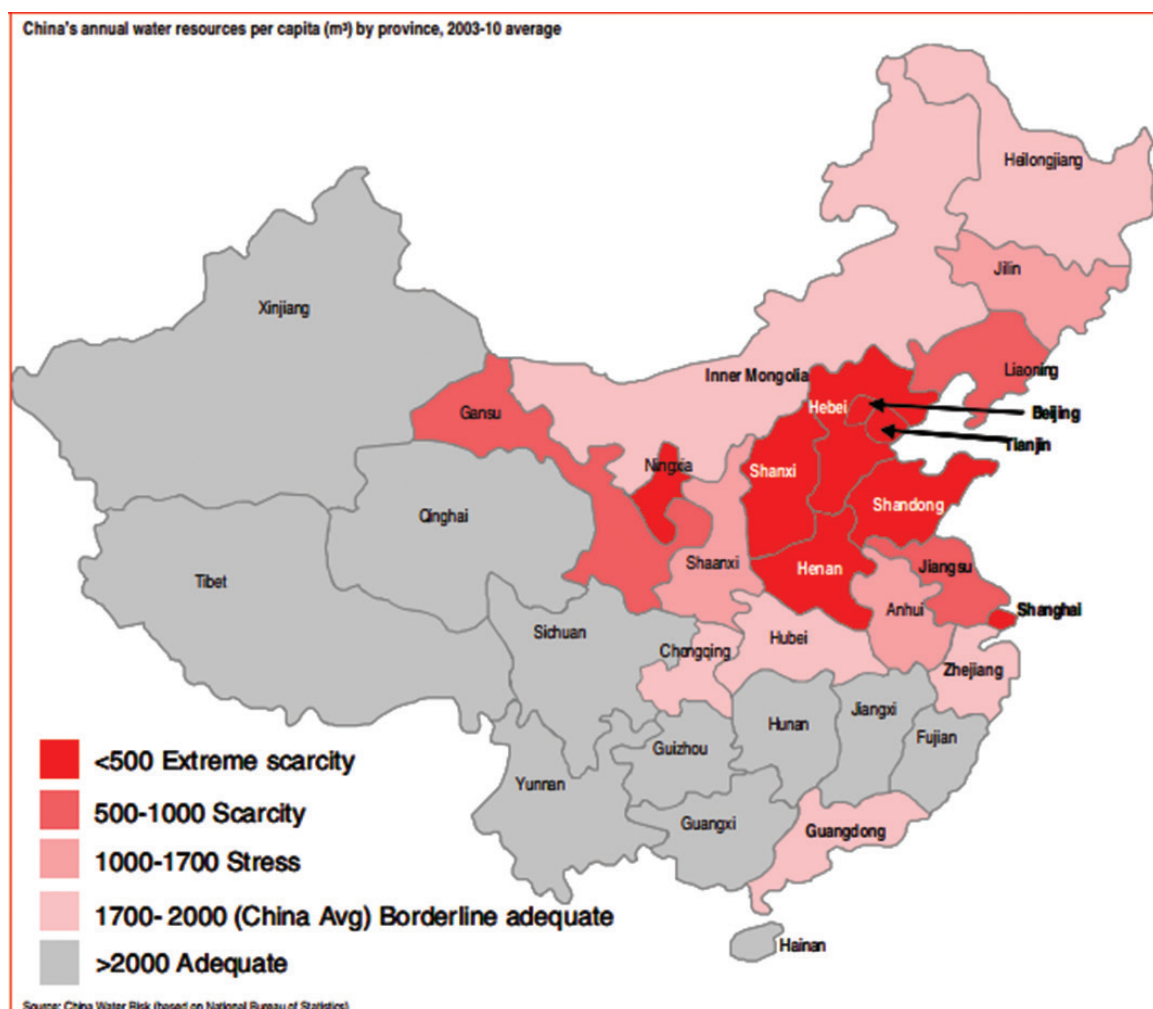


Figure 3. China's annual water resources per capita (m³) by province (2003–2010 average) [15].

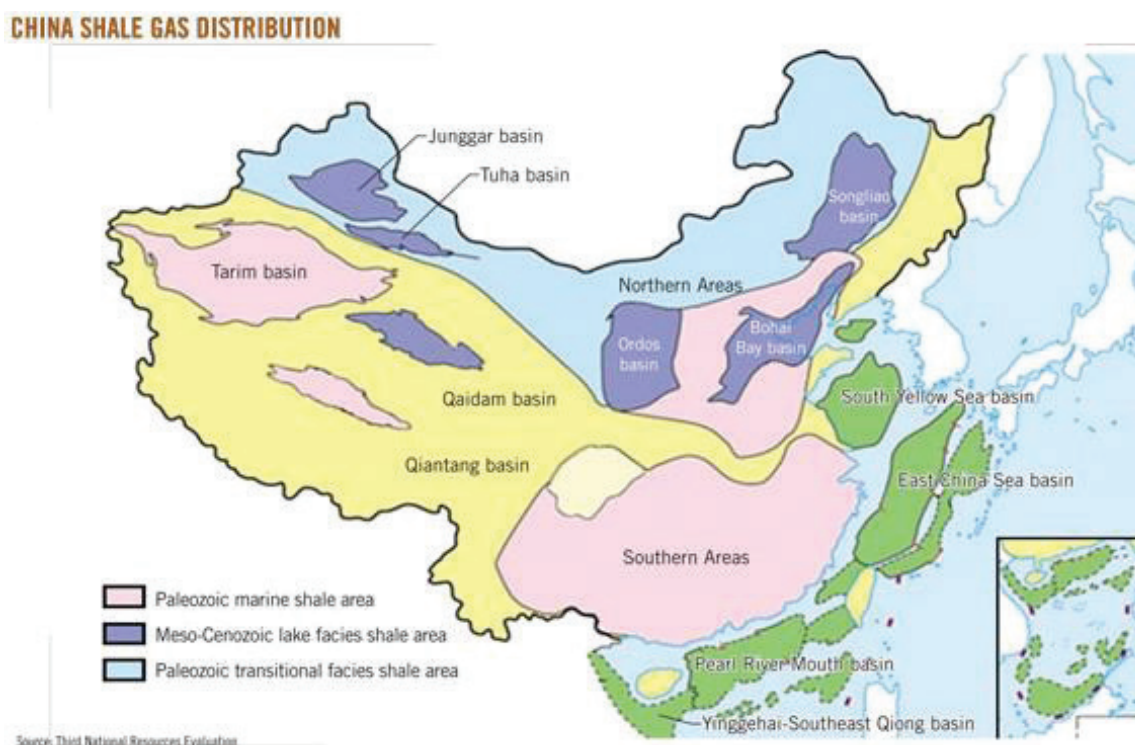


Figure 4. China's shale gas distribution [16].

A rather extreme case of competition between current water demand and the coming demand from hydrofracking is illustrated by Algeria. Algeria is estimated to have the third largest reserve of technically recoverable shale gas in the world, after China and Argentina. Its two significant shale gas formations are the Frasnian Shale and the Tanezuft Shale. These are found in multiple basins throughout the southern portion of the country [14]. Algeria is dependent on domestic gas production for energy. More than 60% of Algeria's energy needs are currently met with domestic production of conventional gas, but the output has been declining. Algeria will not be able to leave the shale gas in the ground.

Few countries on earth are as dry as Algeria. Over 80% of the country is located within the Sahara desert. Only the northern coastal portion of the country is temperate, but it becomes hotter and dryer away from the coast and the coastal mountains. The majority of the country located above the shale gas formations receives little to no rainfall. Annual precipitation is less than 10 cm per year for the majority of the country. Except for the coastal area, all surface water is ephemeral, with wadis draining to sebkas—closed internal basins with high evaporation [17].

Figure 5 shows annual precipitation in Algeria. Figure 6, showing the location of shale gas basins in Algeria, indicates that all of the resource exists in areas of the country that receive less than 10 cm of precipitation annually. The population away from the coastal areas is entirely dependent on water pumped from deep aquifers. In that there is no recharge, they are essentially mining their non-renewable groundwater from aquifers below the Sahara. The aquifers used for water supply include moderate to high permeability unconsolidated material, sedimentary rock layers, and karst rock layers.

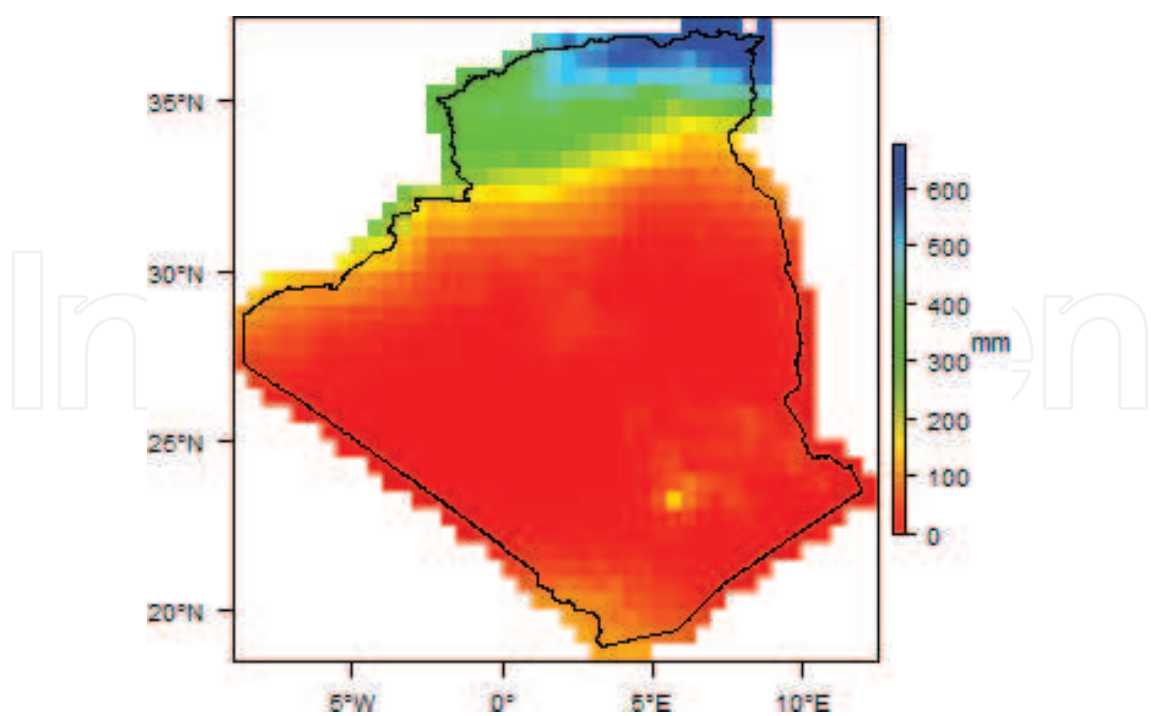


Figure 5. Annual precipitation in Algeria [17].

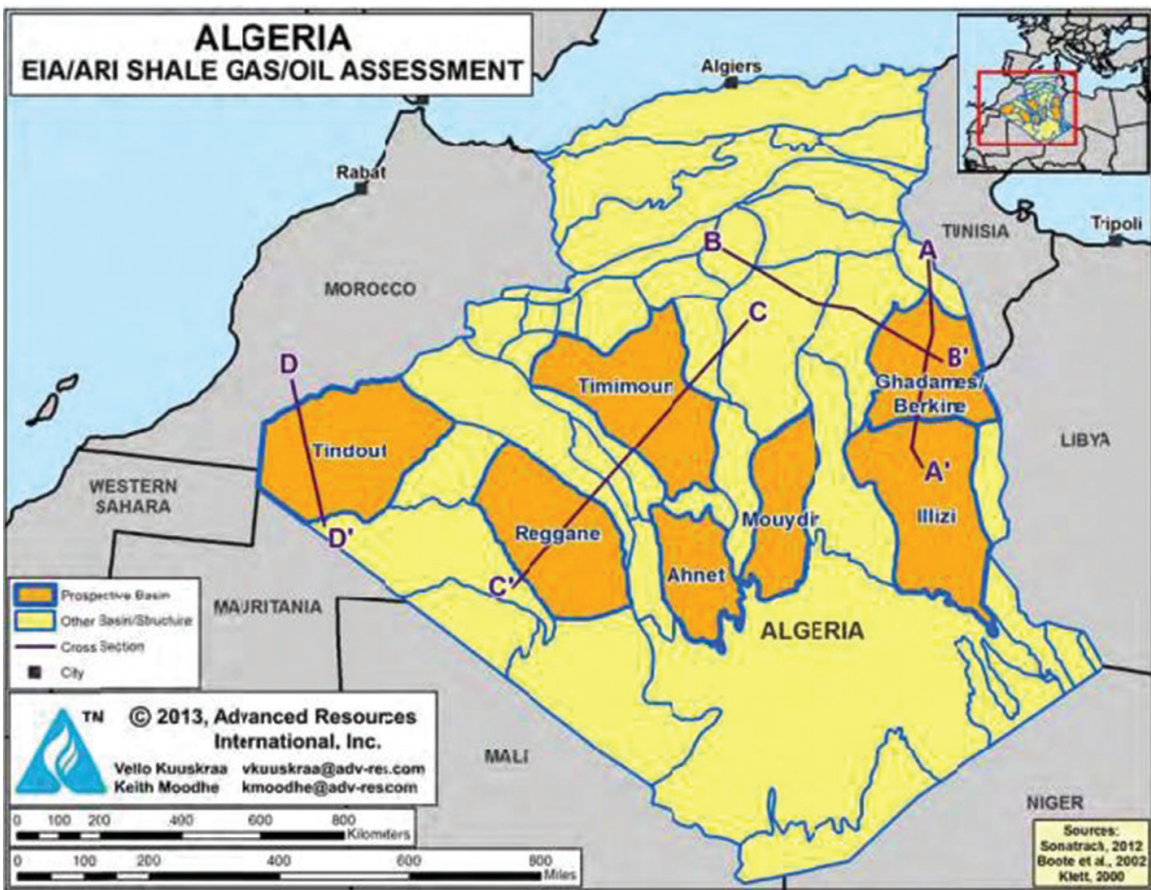


Figure 6. Location of shale gas basins in Algeria [14].

Algerians concerned for their water resources have already staged demonstrations and sit-ins. Their concerns range from water availability to pollution from fracking. Algerians living in areas above shale gas reserves rely on sole source aquifers, that is, aquifers that are their only source of drinking water, so their fears are well justified.

Another country where concerns over water availability (**Figure 7**) for hydrofracking are real and justified is Mexico. Mexico is the eleventh most populous country on earth, with over nearly 125 million people. Mexico has the second largest economy in Latin America after Argentina. Petroleum was discovered in Mexico in the nineteenth century, and production and export began in the 1890s. Petroleum has played a major part in the economy since at least 1980 and currently contributes about 35% of the country's GDP (CIA). It is estimated that Mexico has nearly 600 trillion cubic feet of shale gas, the sixth largest in the world.

Mexico is an arid country with large and growing water shortage issues. The Sonoran Desert and the Chihuahuan Desert are both found in the northern part of the country. The water shortage in 2012 led to failure of pasture land and the starvation of some 350,000 heads of cattle in the northern state of Chihuahua [18].

In some areas development of Mexico's shale gas resource (**Figure 8**) could be limited by water availability, or water already allocated to irrigation and human needs could be in danger of being diverted. Mexico's shale gas is found in the Burgos Basin and Sabinas Basin in the relatively dry north and in the Tampico and Veracruz basins along the Gulf of Mexico (shaded in orange) (**Figure 8**). The Burgos is an extension of the Eagle Ford Formation that has been so successfully developed in Texas (**Figure 8**). The western portion is the La Casita area shown on straddles the Chihuahuan desert.

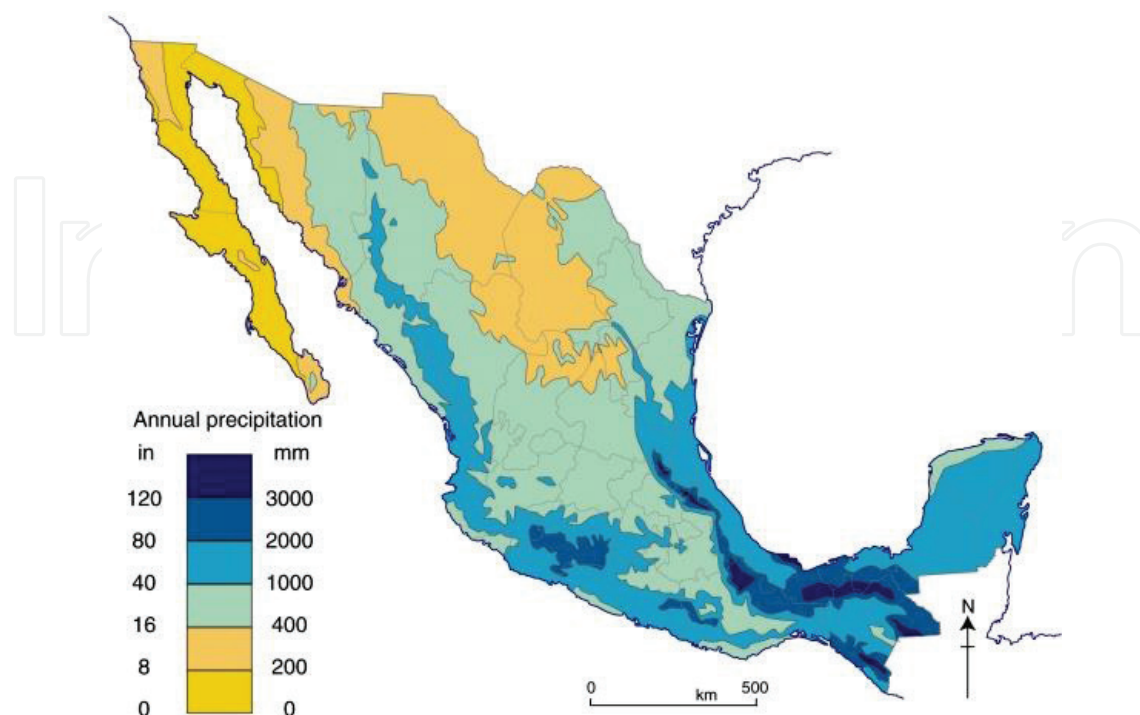


Figure 7. Annual precipitation in Mexico [19].

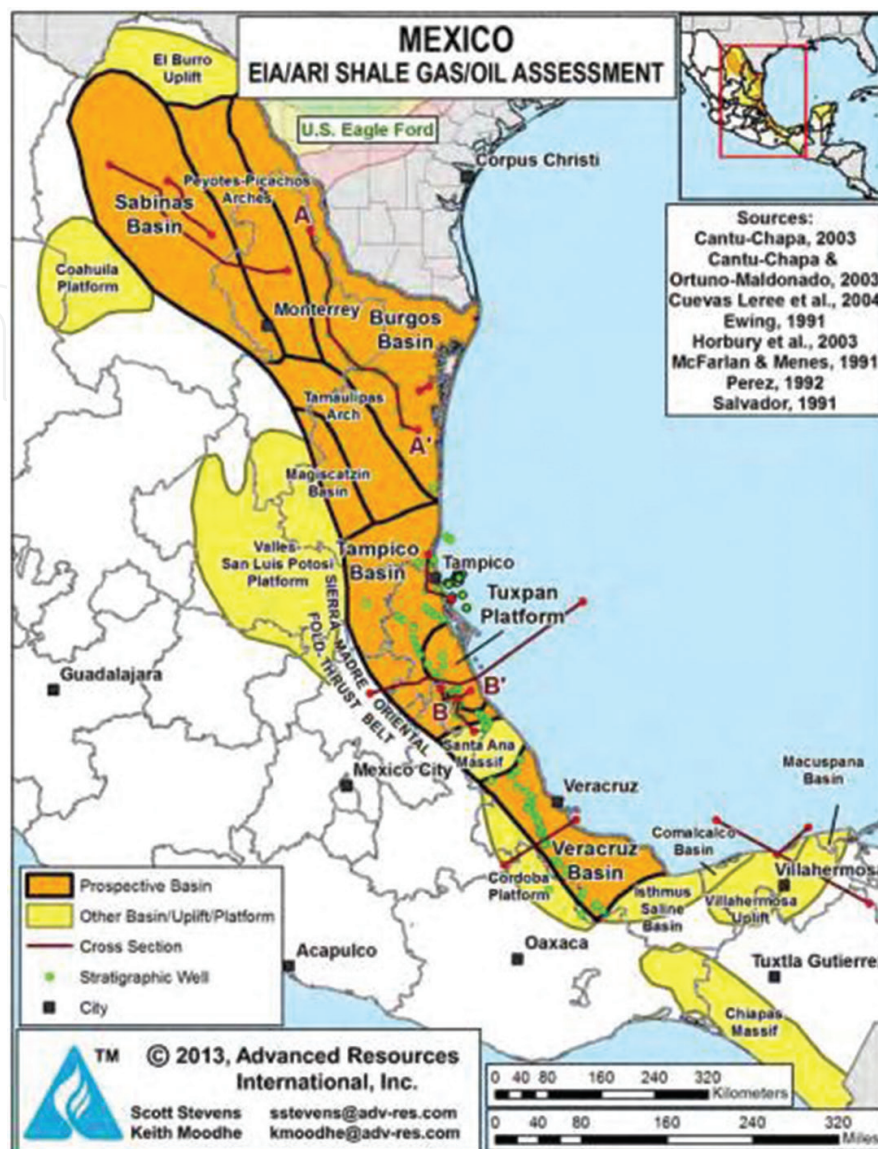


Figure 8. Location of shale gas basins in Mexico [14].

The Burgos and Sabinas lie below the watershed of the Rio Grande, a river system that drains one-tenth of the US territory and 40% of Mexico. The flow of the Rio Grande is used entirely for irrigation and dries entirely during the summer months [9]. Agriculture in the area is increasingly dependent on groundwater pumping, and fields are being abandoned due to salt buildup. Less than 500 cubic meters of water per person per year is available in the Rio Grande watershed. Clearly, supplying millions of liters of water for each hydrofracked well will have dire water resource consequences.

South Africa, located on the southern tip of the continent, is the 26th largest country in the world and the 25th most populous one. It is a developing country, with a GDP per capita near the world median [20]. Petroleum production has played little to no role in the country's economy to date. It has been estimated that the Karoo Basin hold as much as 13 trillion cubic feet of shale gas [21].

South Africa is a relatively dry country, with more than half of the country classified as hot desert, cold desert, hot semiarid, or cold semiarid. Demand exceeds reliable yield in 11 of

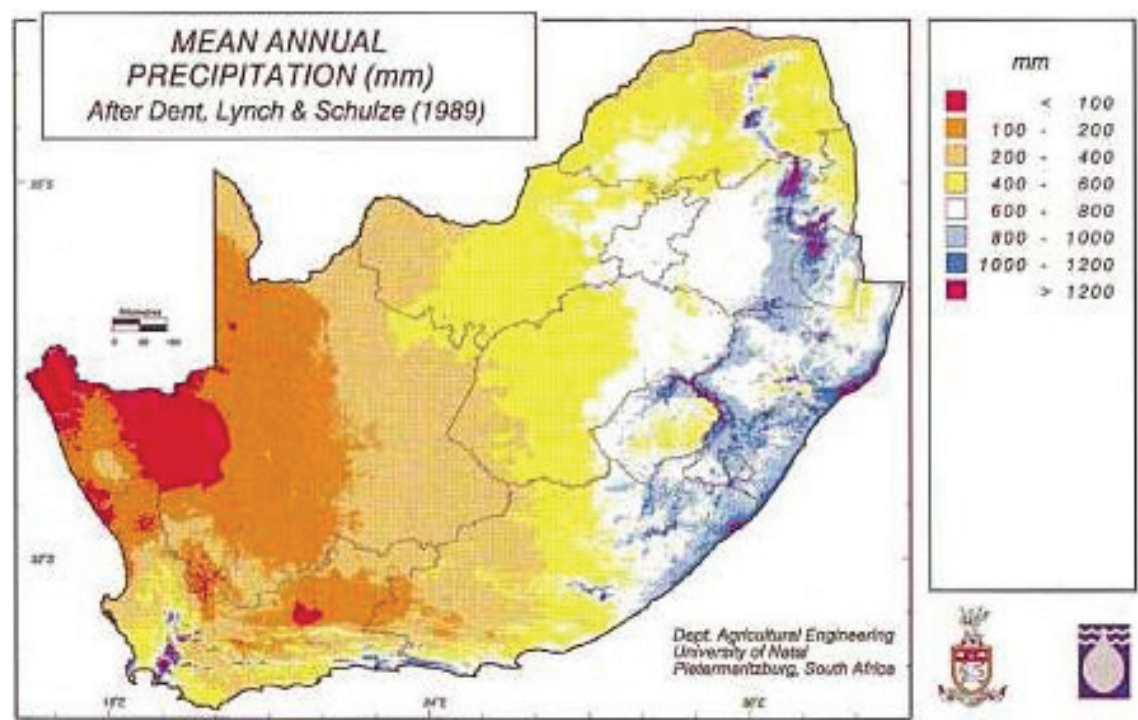


Figure 9. Annual precipitation in South Africa [22].

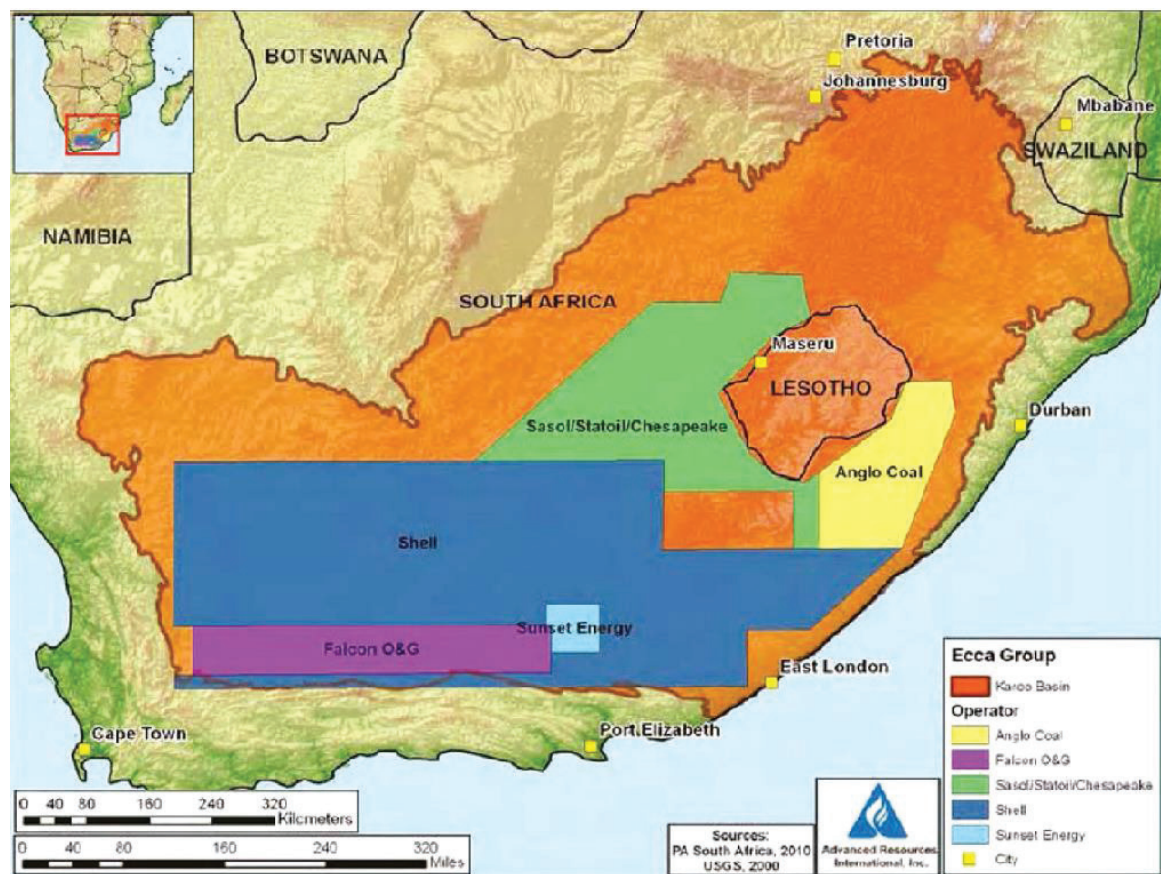


Figure 10. Location of shale gas basins in South Africa [14].

the country's 19 water management areas. The Orange and Limpopo watersheds cover the areas of potentially recoverable shale gas. These watersheds can supply only 500 to 1000 cubic meters of water per person on an annual basis. Nearly all groundwater in the shale gas areas is already under license for use. The proximity of the shale gas areas to low precipitation regions of South Africa can be seen in **Figures 9 and 10**.

South Africa already struggles to supply water to agriculture, domestic use, and industry. Growing population and an increase in standard of living will continue to increase the growth in demand. Much of the population in areas overlying South Africa's shale gas resources is fully dependent on groundwater.

6. Aquifers and water resources: hydrofracking's threat to water quality

Hydraulic fracturing may seem like a simple and straightforward process until one becomes aware of the complex chemistry of the fracking fluid and the necessary complexity based on the number of problems that must be overcome. One way to understand the chemical additives is to consider the problems that must be overcome to fracture thousands of feet of source rock located thousands of feet underground.

6.1. Problem 1: fracturing the rock

The main challenge of hydraulic fracturing is to create deep fractures in solid rock that is confined by the pressure associated with great depth. To accomplish this water is forced at high pressure through perforations in the well pipe. Pressures can be as high as 15,000 psi. In a horizontal well that is thousands of meters long, the fracking process is accomplished in multiple shorter sections.

This process uses vast quantities of water. In the USA it has been found that some wells use as little as 10,000 liters, but more typically wells are using in the range of 1 to 10 million liters, with some wells using more than 35 million liters. More important than the water use itself is the fact that the water use is consumptive, in that most of the water used to hydrofrack a well is lost within the fracked formation. The water that does return to the surface through the production well is too contaminated to be reused.

The water is only able to fracture rock if it is delivered at extremely high pressures. Pumps at the surface must not only pressurize the water but also deliver that pressure vertically and then horizontally through thousands of feet of pipe to the portion of the formation being fractured. This involves overcoming the frictional resistance to flow. This could not be accomplished without chemical friction reducers. Currently, organic polymers are most often used, but historically petroleum distillates were the friction reducer of choice.

6.2. Problem 2: keeping the fractures open

Hydrofracking generally is used on deep targets, usually at least a kilometer below the ground surface. If hydrofracking was done with water alone, the newly created fractures would

collapse as soon as the applied pressure decreased due to the weight of the overlying rock. Hydrofrackers use proppants to prop the fractures open. Proppants need to be strong enough not to fracture or be crushed during the fracking process or during the producing life of the well. By far the most common proppant used in the USA to date is so called “white” sand. White sand is high-purity silica sand with few other minerals. This gives the sand its light color and relatively uniform chemical and physical properties. Prior to use the sand is washed and sieved to produce a more uniform size distribution. Multiple sizes are used, with smaller particles injected first to infiltrate farthest into the newly fractured bedrock and larger sand particles used near the end of the process to better match the larger aperture near the well. The volume of sand used in the hydrofracking industry is considerable. The US Geological Survey reports that sand and gravel production in the USA more than doubled between 2010 and 2014, with more than 70% of the total 2014 sand production being used by the hydrofracking industry! [23].

Sand is not the only proppant. Ceramic proppants of various formulations allow for a more uniform manufactured proppant with specific beneficial properties. Ceramic proppant can be manufactured with properties that make them better than sand, such as higher sphericity, more uniformity of size, and more crush resistant. Formations hydrofracked with ceramic proppants have higher conductivity than those propped with sand. Many other materials have been used as proppants including resin-coated sand, resin-impregnated crushed walnut shell, and thermoplastics.

Proppants by their nature are inert and nonpolluting, but not without environmental impact. The landscape of rural Wisconsin is being transformed by mines that provide roughly 9000 truckloads of fracking sand per day [24].

6.3. Problem 3: keeping everything in solution

Sand or ceramic proppants are more than twice as dense as water. Gelling agents and cross-linking polymers are added to the fracking fluid to increase the water’s density and help keep the proppants suspended. Various guar formulations are the typical gelling agents. This is the same plant-based material seen as an emollient on processed food. Other plant-based gelling agents are used as well.

6.4. Problem 4: keeping the propped fractures open for flow

The polymers and organic material described in Sections 6.1 and 6.3 keep proppants in solution, adjust the water’s density, and decrease friction, making fracking possible. These same chemicals can then restrict the flow of natural gas out of the formation by clogging the newly created fractures and lowering the conductivity of the fractured rock. Therefore, an additional additive breaks these chemicals up into smaller molecules that will not clog the fractures. These “breakers” are usually enzymes that cut the organic chemicals into smaller pieces.

6.5. Problem 5: preventing corrosion, scale, etc.

Additional chemical additives include pH adjusters, corrosion inhibitors, clay stabilizers, scale inhibitors, and metal precipitation inhibitors that are added to the hydrofracking fluid. In general these prevent mineral precipitates and particulates from clogging fractures and inhibiting flow in the well.

6.6. Problem 6: preventing bacterial proliferation

Many of the additives in hydrofracking solution, including the breaker, surfactant, gelling agent, cross-linkers, surfactants, and friction reducers, are organic chemicals. All of these are substrates for microorganisms to feed on. Proliferation of microorganisms creates biomass. The biofilm on surfaces made up of living and dead microbes can lower porosity and gas permeability by lowering the fracture aperture. This is the same effect seen in bioremediation of aquifers where the stimulation of the native flora choke off conductivity. Biocide is added to fracking fluid to prevent this counterproductive effect.

Among all the chemicals used to formulate hydrofracking fluid, it is the biocides that are of most concern for water quality. Fewer than 20 biocides have been identified as more or less commonly used in the hydrofracking industry. Among the most common are glutaraldehyde, dibromonitrilopropionamide (DBNPA), tetrakis(hydroxymethyl)phosphonium sulfate, and chlorine dioxide [25]. These biocides are toxic to microorganism, and some are quite toxic to aquatic fauna. They have low toxicity for mammals. Although they are not acutely toxic to mammals, some are toxic during long-term exposure or possess carcinogenicity or mutagenicity.

How do these hydrofracking chemicals get into the hydrosphere, and how do they become a threat to water resource quality? Chemicals must be transported to the site by rail or truck so accidents are of course a threat to surface water quality. Hydrofracking fluids are generally mixed on site and stored in railroad tank cars or in lined storage lagoons. It is not uncommon for lagoons lined with geotextile to leak at the geotextile seams or from punctures, so this could be a threat to shallow aquifers.

Once fully mixed hydrofracking fluid is injected into the target formation. Fluids travel first down through the vertical well and then into the horizontal portion being hydrofracked. Improperly cased and grouted wells could leak into shallow aquifers during high-pressure injection of the fracking fluid. Hydrofracking opponents in the USA have claimed that hydrofracking of shale gas formations can cause fractures to extend upward from the target shale formation, allowing fracking fluid to reach freshwater aquifers above. This is likely not a realistic fear. Freshwater aquifers are generally found within a few hundreds of meters of the ground surface. Shale gas formations that could be subject to hydrofracking are generally found thousands of meters below the ground, and the pressures used to hydrofrack are incapable of creating fractures of the length that would be required to reach a freshwater aquifer. It is possible however for hydrofracking fluid to flow upward through existing faults or abandoned wells.

There have been wide ranges reported, but between a quarter and half of the hydrofracking fluid injected to break the shale returns to the surface as flow-back subsequent to the frack. This hydrofracking fluid wastewater returns to the surface to the wellhead where it is collected. Wastewater can be treated onsite, treated offsite, treated and reused as hydrofracking fluid, or disposed of in a deep brine aquifer. This presents a number of additional opportunities for pollution of surface water or aquifers.

Hydrofracking wastewater that is treated offsite or treated and reused as hydrofracking fluid must be transported and so again poses the threats associated with transporting chemical-laden water. Wastewater treated onsite and then disposed of to a surface water body may not be sufficiently treated and could still contain some chemicals not removed by the

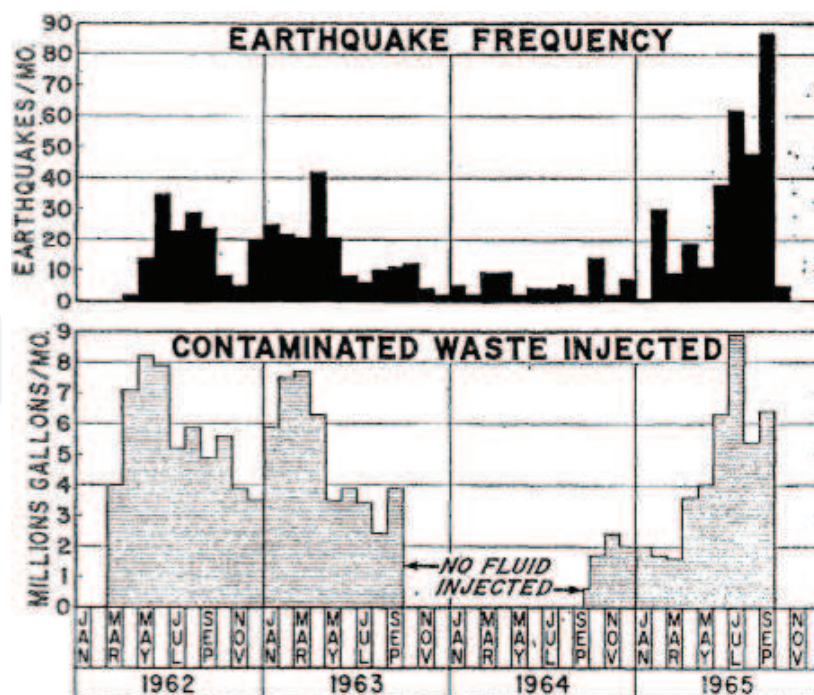


Figure 11. Correlation between the number of earthquakes and the volume of fluid injected [26].

treatment process. Injecting wastewater into a deep brine aquifer again presents the hazard of leakage from improperly cased or grouted wells.

Hydraulic fracturing operations cause earthquakes. The USGS has reported a sharp increase in the number of potentially damaging earthquakes, those with a magnitude of three or larger in the Central and Eastern USA due to hydrofracking operation. There has been a 50-fold increase in M3+ quakes from an average of roughly 20 per year to over a thousand in 2015.

The realization that high-pressure injection of fluids into the deep subsurface can cause earthquakes is not new. In 1967 David Evans, a consulting geologist in Colorado, noted a correlation between injection volumes at a US Army hazardous waste injection well located at the Rocky Mountain Arsenal and earthquake frequency. His figure showing the correlation (Figure 11) became a staple of college-level geology textbooks. It was determined that the injection of wastes into the nearly 4000 feet deep well decreased frictional resistance to faulting. "The mechanism by which the fluid injection triggered the earthquakes is the reduction of frictional resistance to faulting, a reduction which occurs with increase in pore pressure" [26]. Disposal of waste fluids by injection into a deep well has triggered earthquakes near Denver, Colorado [26].

It should be obvious to all readers that the injection of millions of gallons of highly pressurized hydrofracking fluid into each well contributes to the notable increase in induced seismicity reported by the US Geological Survey. Less obvious is the reinjection of brine wastewater that is produced from the formation along with the hydrocarbons after hydrofracking.

7. Conclusion

So, should we hydrofrack? On the positive side of the ledger, we need resources for an energy-hungry world. Although the Paris accords require countries to limit greenhouse gas emissions worldwide, fossil fuel consumption will continue to increase for decades. Also, on the positive side is that as we increase shale gas usage we have the opportunity to decrease the usage of coal for electricity production. Also, on the positive side of the ledger is the fact that shale gas production and export provide hard currency for exporting countries, some of which are in the developing world.

There are also significant considerations on the negative side of the ledger. It is an unassailable fact that hydrofracking will consumptively use vast volumes of freshwater, and a great deal of that usage will occur in regions already short on water resources. Pollution of water resources both in surface water and in aquifers due to hydrofracking is a reality. If we could hydrofrack the world's shale gas resource without human error, without equipment failure, and without any shortcuts taken to increase profits, then our freshwater resources would likely be safe from chemical pollution due to fracking!

Also, on the negative side of the ledger is the fact that methane is a significantly more potent greenhouse gas than carbon dioxide. Methane leaks during drilling, production, transportation, processing, distribution, and usage, and the effect these will have on the environment should be considered. Climate change caused by methane leaks will affect precipitation, surface water availability, and ultimately the recharge of our aquifers.

We will develop our shale gas resource through the marriage of horizontal drilling and high-volume hydrofracking. The shale gas is simply too valuable and too tempting to leave in the ground. It is reasonable to accept that hydrofracking will have a negative effect on water availability and water quality.

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