

Environmental issues associated with coal seam gas recovery: managing the fracking boom

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Environmental context. Coal seam gas reserves are likely to make a major contribution to future energy needs. However, the new technology for exploiting these reserves, termed hydraulic fracturing, raises several environmental issues. We discuss the research required to assess the ecological risks from gas recovery.

Abstract. Coal seam gas reserves represent a major contribution to energy needs, however, gas recovery by hydraulic fracturing (fracking or fraccing), requires management to minimise any environmental effects. Although the industry is adapting where possible to more benign fracking chemicals, there is still a lack of information on exposure to natural and added chemicals, and their fate and ecotoxicity in both the discharged produced and flow-back waters. Geogenic contaminants mobilised from the coal seams during fracking may add to the mixture of chemicals with the potential to affect both ground and surface water quality. The research needs to better assess the ecological risks from gas recovery are discussed.

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Introduction

Coal seam gas and coal bed methane are synonyms for the reserves of natural gas, predominantly methane, in coal formations. Exploration over the last 20 years has revealed massive natural gas reserves worldwide, especially in Russia, China, the Middle East and the US,^[1] with new reserves still being discovered. Shale formations are also an important source of natural gas. Shale gas appears to represent the larger source, with coal seam gas reserves estimated to exceed $30 \times 10^{12} \text{ m}^3$ in the US, Russia, China and Australia,^[2] making a significant contribution to the world's energy needs. Not surprisingly, the industry has experienced exponential growth over the last decade, both in exploration and in resource recovery. Industrial activities have looked to technologies that offer efficiencies in gas recovery that minimise costs and increase yields.

The methane, formed both by biogenic processes as well as the thermal decomposition of organics, becomes trapped within the high surface area pore networks within the coal. The recovery process involves drilling typically up to 1000 m (and deeper, e.g. 2000 m for shale gas) to locate naturally occurring fractures within the formation and increasing the porosity within the formation to provide conduits for gas migration.

Hydraulic fracturing (fracking)

Recovery is not always that simple and the rapid growth in coal seam gas exploration has been facilitated by the development of sophisticated engineering technologies that enhance gas mobilisation by fracturing the seams.^[3,4] This process, termed hydraulic fracturing or more commonly fracking (or fraccing), involves the injection of fluids (generally water, sand and small amounts of chemicals) under high pressure into the coal seams.

This causes cracking of the seams for distances typically up to 30 m. Sand is commonly used as a proppant that can wedge open the seams permitting gas to escape. Other materials such as ceramic particles are also used for this purpose.^[5] The proppant used depends on the geology, depth and formation characteristics. The efficiency of this process is enhanced by the addition of a mixture of chemicals to the fracking fluid whose functions comprise:

- (i) dissolving minerals and aiding in crack formation,
- (ii) reducing bacterial growth,
- (iii) restricting fluid loss,
- (iv) reducing friction in the fissures to allow proppant delivery and the flow back of water to the surface,
- (v) minimising corrosion of metal components (drill casings etc), and
- (vi) assisting in post fracture fluid recovery by reducing viscosity.

Water and salt management are major issues associated with coal seam gas production.^[4] The water pumped into wells (0.2–0.6 ML per well) for hydraulic fracturing returns to the surface as the pressure is reduced.^[3] The chemistry of this water is altered as it interacts with the coal seam minerals. In addition, there is water associated with the coal deposits that becomes mobilised as part of the drilling operation. This is generally termed produced water or formation water. It is typically quite saline as well as containing other constituents, both inorganic and organic, of the minerals and coal with which it has been associated in the deposits. The water used in fracking mixes with produced water during the fracking process, with the composition gradually becoming more characteristic of the produced

Table 1. Typical fracking chemicals and their function

Additive type	Chemicals used	Action
Proppant	Sand, silica, ceramic particles	To wedge seams open
Viscosity modifiers	Guar gum, hydroxypropyl guar, hydroxyethyl cellulose, gelatine	Gelling agents (including food additives) to increase viscosity
Gel crosslinkers	Borate salts, monoethanolamine, ethylene glycol	To maintain gel stability
Gel breakers	Sodium persulfate, hemicellulase enzyme, <i>t</i> -butylhydroperoxide	To break down gel for return to surface
Mineral dissolution	Hydrochloric acid	To dissolve clay minerals
Iron complexation	Citric acid	To prevent iron precipitation
Biocides	Sodium hypochlorite, tetrakis(hydroxymethyl) phosphonium sulfate, glutaraldehyde	To eliminate bacteria in the water
Corrosion inhibitors	<i>N,N</i> -dimethylformamide, gelatine, methanol	To prevent pipe corrosion
Scale inhibitors	Ethylene glycol	To prevent scale formation
Friction reducers	2-Butoxyethanol, isopropyl alcohol, terpenes and terpenoids, sweet orange oil, polyacrylamides, anionic surfactants and petroleum products	To reduce surface tension

water. The industry typically refers to ‘flow-back water’ as the water produced within a few days of the fracking, and ‘produced water’ after that, even though it may still have characteristics of both types of water.

Volumes of produced water can be up to 100 kL day⁻¹ per well, but this typically diminishes over the lifetime of a well which may be as long as 10 years.^[3] Depending on the operation, and the water quality, these produced waters may be reinjected, treated, stored in dams, used for livestock watering, irrigation or dust control or tankered off the site.^[3,4]

In the US, most of the produced water is reinjected, 40 % being disposed into non-producing formations, whereas the remainder is used in active formations to maintain formation pressure and increase gas output.^[6] The effect on groundwater quality is a potential issue here. Where treatment is used, it generally involves reverse osmosis to reduce the high salinity.^[6,7] Storage in dams is a short-term solution, now abandoned at least in Queensland, Australia, largely because of seepage into soils.^[3]

As with any large mining or industrial operation, consideration needs to be given to the environmental effects of fracking.^[8] Depending on the jurisdiction, this may involve an environmental impact assessment (EIC). Operational regulation is highly desirable given the thousands of wells being sunk by a range of operators in relatively small areas. This regulation may involve obtaining approval to use certain chemicals in the process, and once production is underway, ensuring the quality of any releases to the environment, both controlled releases and spillage. To date there have been relatively few publications in the open scientific literature dealing with the environmental impacts of coal seam gas production and especially of fracking as well as geogenic contaminants, with most information contained in confidential reports to the service companies.

The number of hydraulic fracturing products is not trivial. It has been suggested that in the US, between 2005 and 2009, oil and gas service companies used more than 2500 products containing some 750 chemicals.^[9] The number used in coal-seam gas fracking is considerably less, and in Australia, the Australian Petroleum Production and Exploration Association Limited recently released a list of 45 chemicals that supposedly comprised for that time, ‘all chemicals used in Australian coal seam gas fracking fluids’.^[10] The FracFocus website (<http://fracfocus.org>) lists chemicals used in the fracking process in the US. There are, however, drawbacks because of the uncertainty of full disclosure of chemicals used and many are listed as proprietary.

In the US, regulation of fracking chemicals is a state responsibility and rules regarding disclosure of chemicals vary from state to state. In Australia, regulatory agencies can require companies to provide details of proprietary chemicals used in fracking, and as a consequence many coal seam gas companies have proactively listed such chemicals (and Material Safety Data Sheets (MSDSs) in some cases) on their websites. Data are also available in publically available EICs. A listing of commonly used fracking chemicals from these sources is provided in Table 1, however their use is rapidly changing with a view to choosing more environmentally friendly chemicals.

The quality of produced and flow-back water must be such that it protects certain environmental values. These include livestock drinking water, water for human consumption and aquatic ecosystem protection. Livestock exposure can also occur through designated water impoundments or water spillage. The potential for fracking chemicals to contaminate aquifers or catchments that are a source of drinking water is viewed as a priority,^[8] and the United States Environmental Protection Agency (US EPA) is in the process of a major study investigating the possible environmental impacts.^[11]

Few of the chemicals used in fracking have listed drinking water guidelines either in the US or Australia. MSDSs are typically vague on the descriptions of both toxicological and ecotoxicological effects. Nevertheless, for many of the chemicals it was possible to find at least some ecotoxicological data although typically the data referred to acute toxicity and rarely to more than one test species. Such limited data would result in overly conservative guidelines that would be protective of aquatic ecosystems, and additional testing is likely to be required by regulatory agencies to allow realistic guidelines to be developed. Little information is also available on the fate and transport of the chemicals.

The need for ecotoxicological studies

Because chemical analysis of coal seam fracking fluids and discharge waters will be a complex exercise that may not be able to detect all of the chemicals in the mixture being analysed, ecotoxicity testing of whole effluents offers the possibility to gauge the collective impacts from all chemicals present in the mixture. The toxicity of metabolites or reaction products of fracking chemicals should also be considered. Such ecotoxicological testing will require the use of a range of aquatic species, so will not be a trivial undertaking. Animal testing for drinking water quality is an equally costly exercise. Terrestrial ecosystems are also important and may be affected by spills.^[12]

Such is the pace of development that the current suite of fracking chemicals is likely to have altered considerably in the three or more years required to initiate and complete ecotoxicological studies. Already it is noticeable that service companies have been abandoning those chemicals that are known toxicants in favour of those that have low toxicity and preferably natural products already in common use. Often this comes with a cost saving, provided they have an equivalent performance for their required use.

Assessing the ecological risk

A hazard assessment of what goes into the wells is relatively straightforward, in that the chemicals are in high concentrations. What comes out of the wells is more problematic. Concentrations will be more dilute as a consequence of the additional produced water. Furthermore, information is required on their chemical fate. Ideally an additive with a short half-life is preferable. For example, the half-lives for biodegradation of additives such as monoethanolamine, 2-butoxyethanol and fumaric acid are as low as 5 days, but the addition of biocides may prolong this time.

The larger unknown relates to produced water and the geogenic contribution to flow-back waters. Published data typically focus on the major ion composition, the dominant ecosystem stressor being high salinity. The total dissolved solids content of produced water is typically $\sim 5000 \text{ mg L}^{-1}$ (mainly NaCl) compared to $10\,000 \text{ mg L}^{-1}$ in flow-back water ($\sim 10\%$ salinity).^[13]

Orem et al.^[14] identified phenols, biphenyls, heterocyclic compounds, aromatic amines and aliphatic compounds in produced waters. Polycyclic aromatic hydrocarbons (PAHs) present were typically the lower-molecular-weight, more soluble species (individual PAHs identified ranged from <0.01 to $3.2 \mu\text{g L}^{-1}$, with naphthalene from 0.26 to $0.66 \mu\text{g L}^{-1}$, c.f. naphthalene Australian water quality guideline of $2.5 \mu\text{g L}^{-1}$). The maximum concentration of total PAHs detected in this study was $23 \mu\text{g L}^{-1}$. Volk et al.^[15] reported a similar suite together with data for total petroleum hydrocarbons (TPHs) from 0.2 to 6.8 mg L^{-1} in the C_{15-28} and C_{29-36} fractions in waters associated with some Australian Permian coal seams.

Contaminant concentrations in produced water generally decreased to background in as little as a week after fracturing. Flow-back waters have sometimes been found to have higher concentrations of TPHs and phenols than formation waters.^[13] The detection of benzene in discharge waters has led to bans on the use of BTEX compounds (benzene, toluene, ethylbenzene and xylenes) in fracking fluids.

Other geogenic contaminants include metals and radionuclides.^[16,17] Although these chemicals may be natural constituents of produced water, there are potential transformation and release processes associated with the introduction of oxidic waters and their associated chemicals. Oxidation of reduced iron may lead to iron oxyhydroxide precipitation and a lowering of water pH (chelating agents are added to solubilise iron). Elevated iron and manganese concentrations have been observed in flow-back waters.^[13] Acids in the fracking fluids will cause metal dissolution, aided by chelating agents. Surfactants and solvents may assist solubilisation of organic compounds.

Clearly there is a multitude of research questions to be addressed with respect to the introduction of large volumes of chemical mixtures into coal and shale formations. These questions concern the fate of these compounds, their interactions

with geogenic materials and the extent to which they represent a risk to key receptors, be they birds, livestock, humans or aquatic organisms. Currently there is very little understanding of the concentrations and especially the temporal variability of the potential contaminants that may be present in the produced water. Such data will provide the scientific evidence to address the uninformed concerns of opponents of coal seam gas extraction, and to ensure that the industry can be appropriately managed.

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