Government of Western Australia
Department of Health

Hydraulic fracturing for shale and tight gas in Western Australian drinking water supply areas

Human Health Risk Assessment

Hydraulic Fracturing for Shale and Tight Gas in Western Australian Drinking Water Supply Areas: Human Health Risk Assessment.

June 2015

Delivering a **Healthy WA**

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Foreword

The Western Australian Department of Health continues to be a strong advocate for adoption of a risk management approach to all proposals for new industries, developments or technologies where people live or work close to public water resources, to ensure the protection of public health. The established framework for Health Risk Assessment (HRA) in Western Australia incorporates the interaction of risk communication, community consultation, risk assessment and management. Effective risk management strategies can be developed through this process when public health and community concerns are addressed at an early stage in planning and proposal stages of developments.

Hydraulic fracturing, also known as fraccing or fracking, has been presented in the media as a particular threat to public health. This HRA was established to address community concerns about the introduction of hydraulic fracturing to assist extraction of natural gas reserves in Western Australian shale and tight rock. It is only one part of the whole of government approach to assess the potential impacts of this new technology and to ensure associated risks are effectively managed through best practice approval and regulatory activities. In addition to preparation of this document, the Department of Health has actively participated within the whole of government "Interagency Working Group into Shale and Tight Gas" and "Interagency Science Needs Working Group". This HRA should be used as part of the State's regulatory framework for hydraulic fracturing. I note that some of the recommendations from this HRA have already been addressed by the framework.

This document introduces and reviews many of the recent investigations into hydraulic fracturing and its potential to impact public health, from experiences in the coal seam gas industry in eastern Australia and international experience in shale and tight rocks. It specifically focuses on potential impacts to drinking water supplies, with reference to similarities and differences between the geological and environmental conditions within Western Australia compared to elsewhere in the world.

In October 2013, the Department of Health provided a written submission to the *Inquiry into the Implications for Western Australia of Hydraulic Fracturing for Unconventional Gas* and made reference to a preliminary draft of this final document. At the time, the regulatory framework and associated legislation was either in draft, or awaiting stakeholder consultation for adoption by state legislators. Similarly, very little information specific to Western Australian proposals was available to accurately assess local risks. However, many jurisdictions around the world, with many years of experience with hydraulic fracturing, had also initiated similar studies to this one with imminent completion dates. In order to provide the most informed review incorporating current and relevant information, latter drafts were delayed to accommodate the additional research.

We trust that this document provides readers with a better understanding of assessment and management of potential health risks associated with hydraulic fracturing.

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Contents

List of Figures

List of Tables

Abbreviations

%	per cent
ABC	Australian Broadcasting Corporation
ACOLA	Australian Council of Learned Academics
ADWG	Australian Drinking Water Guidelines
APPEA	Australian Petroleum Production and Exploration Association
ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	benzene, ethylbenzene, toluene and xylene
CAS	chemical abstract service
COC	Chemicals of Concern
CoNTC	Concentration of No Toxicological Concern
CSG	coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSM	Conceptual Site Model
DART	Developmental and Reproductive Toxicology Database
DEC	Department of Environment and Conservation
DMP	Department of Mines and Petroleum
DOH	Department of Health
DOHA	Department of Health Australia
DOW	Department of Water
EARS2	Environmental Assessment and Regulatory System
EEA	European Environmental Agency
ERA	Environmental Risk Assessment
ESIS	European (Chemical) Substance Information System
EU	European Union
HHRA	Human Health Risk Assessment
HQ	Hazard Quotient
HRA	Health Risk Assessment
HVHF	high volume hydraulic fracturing
IARC	International Agency for Research on Cancer
IEA	International Energy Agency
IRIS	Integrated Risk Information System
MOU	Memorandum of Understanding
NHMRC	National Health and Medical Research Council
NICNAS	National Industrial Chemicals Notification and Assessment Scheme
NORMS	Naturally occurring radioactive materials
NSW	New South Wales
NTP	National Toxicology Program
NYS	New York State
NYS DeptHealth	New York State Department of Health
PDWSAs	pubic drinking water source areas
RIVM	National Institute for Public Health and the Environment
RS&RAE	Royal Society and Royal Academy of Engineering
tcf	trillion cubic feet
TTC	threshold of toxicological concern
UGWD	unconventional gas well development
UK	United Kingdom
US EIA	United States Environmental Impact Assessment
USA	United States of America
USEPA	United States Environmental Protection Authority
WA	Western Australia
WA EPA	WA Environmental Protection Authority
WHO	World Health Organisation

Executive Summary

- Western Australia is well placed to learn from the experience of hydraulic fracturing in the northern hemisphere and from coal seam gas activities within Australia, in order to establish a hydraulic fracturing industry, whilst ensuring minimal adverse impacts.
- In Western Australia (WA) shale gas is the only commercially viable form of unconventional gas reserves. Unlike coal seam gas, shale gas always requires hydraulic fracturing to release the natural gas.
- It is important that public health is considered where relevant in the approvals process for hydraulic fracturing.
- This health risk assessment (HRA) has focused on the potential for hydraulic fracturing to affect drinking water sources.
- The HRA has found that, under the right conditions, hydraulic fracturing of shale gas reserves in WA can be successfully undertaken without compromising drinking water sources.
    - Firstly, in WA, shale and tight gas reserves have been identified at depths of between two and four kilometres below ground level which are a considerable distance below potable ground water sources.
    - Secondly, the risks to drinking water sources associated with hydraulic fracturing can be well managed through agreed industry and engineering standards, best practice regulation, appropriate site selection (including consideration of Public Drinking Water Source Areas) and monitoring of the drinking water source.
- The DOH initially undertook a Preliminary Health Risk Assessment of hydraulic fracturing for unconventional gas (PHRA) which has been superseded by this HRA. As part of the PHRA certain recommendations were made in relation to the protection of PDWSAs, some of which were included in the recommendations the DOH made to the WA Legislative Council's Inquiry into the implications for Western Australia of hydraulic fracturing for unconventional gas in 2013. Those recommendations which are supported by this HRA have been addressed by regulatory agencies in WA, including the Department of Mines and Petroleum, the WA Environmental Protection Authority and the Department of Water.
- Further recommendations to aid in the protection of drinking water sources are:
    - The application of the Australian Drinking Water Guidelines for chemicals found in drinking water, or the conduct of more detailed human health risk assessment where no regulatory guidelines have been established.
    - A communication plan for notification of incidents with potential to impact public health and drinking water sources to be incorporated into ongoing stakeholder engagement.

    - Ongoing consultation and collaboration between all Government agencies with responsibilities related to potential impacts of hydraulic fracturing.
- The HRA should be used as part of the State’s regulatory framework for hydraulic fracturing.

Background

Hydraulic Fracturing in Western Australia

Hydraulic fracturing or hydraulic fracture stimulation is also colloquially known as fraccing or fracking. It has been employed in Western Australia (WA) to stimulate release and flow of oil and gas for approximately 65 years from both off-shore and on-shore reserves. However, until 2005, hydraulic fracturing had only been used in WA in association with conventional drilling methods (DMP, 2014a).

As the momentum to find new energy resources for domestic and export supply have increased around the world, improved drilling technologies were developed to exploit the extensive natural gas resources identified in the deep shale and tight rock formations that were previously too difficult to access with conventional methods (Royal Society and Royal Academy of Engineering (RS&RAE), 2012). In WA shale and tight rock formations that are potentially rich in natural gas have been identified in the Perth, Carnarvon and Canning Basins, representing approximately 73% of recoverable shale gas in Australia (US EIA, 2011a; RS&RAE, 2012; Geoscience Australia, 2012; Cook et al., 2013). Locations of Australian basins with potential shale gas reserves are shown in Figure 1 and estimated technically recoverable shale gas volumes in each country are shown in Table 1.

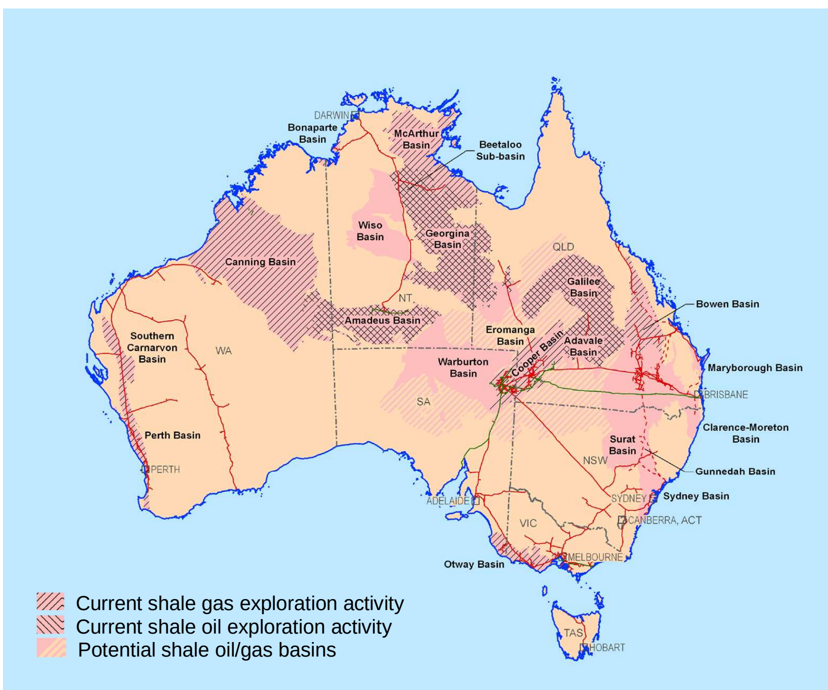

Figure 1: Australian basins with shale gas potential

Source: CSIRO, 2013 Australia's Shale and Gas Resources. More detail on reserves in WA is provided in DMP 2014a.

Conventional drilling for natural gas involves drilling many multiple vertical wells into a single well field, in contrast to unconventional drilling that converts a single vertical drill hole that articulates into several horizontal wells within the otherwise impermeable rock formation (Gradient, 2013). This is shown schematically in Figure 2. Unconventional resources differ greatly from conventional resources in characteristic porosity, permeability, fluid trapping mechanism of the reservoir or rock formations (Broomfield, 2012).

In WA, shale and tight gas reserves have been identified at depths of between two and four kilometres below ground level. The horizontal wells may extend up to 1000 metres within the shale and tight rock formations (DMP, 2014a).

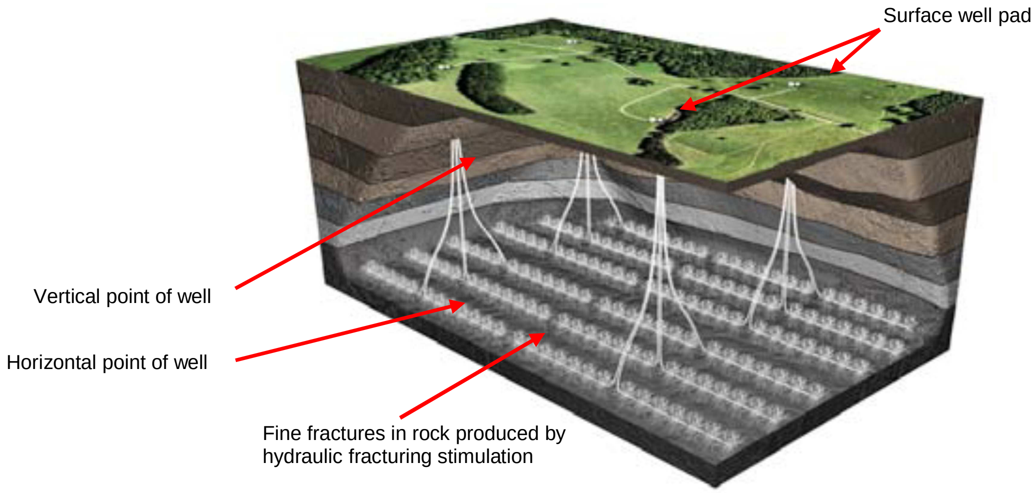

Figure 2. Schematic illustrating unconventional drilling for natural gas.
Source: DMP, 2014a.

Currently hydraulic fracturing is being used to explore how Western Australian shale and tight rock behaves and to test and optimise this technology for local conditions. From this work, it should be possible to determine whether it is economically feasible to invest further to fully exploit these resources in WA (Cook et al., 2013; DMP, 2014a). During this time, rigorous local investigations should provide the necessary information to address the variety of scientific, social, cultural, technological, environmental and economic issues that exist. Hence, if the resource is confirmed production remains five to 10 years into the future and is unlikely to start before 2019 (DMP, 2014a).

Mechanism of Hydraulic Fracturing

Hydraulic fracturing is the process used to stimulate and release the gas resource from low and impermeable rock formations. The hydraulic fracturing process is shown schematically in Figure 3. Large volumes of hydraulic fracturing fluid are pumped into the rock under high, but controlled pressure to create fine fractures that radiate from the well to access the natural gas produced and stored within the rock (APPEA, nd; Broomfield, 2012). Fine sand granules, commonly referred to as proppants, are mixed into the hydraulic fracturing fluid to prop open newly created fractures through which released gas and hydraulic fracturing fluid flow back through the well for collection and storage at the well-head (Howarth & Ingraffea, 2011; Broomfield, 2012). The gas is then piped to the consumer and the flow-back fluids are collected for storage, transport and/or treatment prior to disposal (USEPA, 2012a).

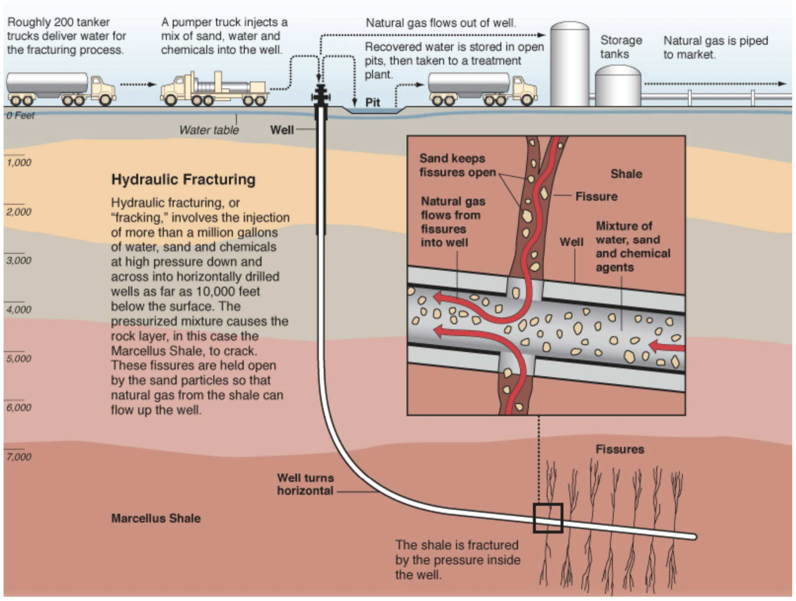

Figure 3. Schematic illustrating the process of hydraulic fracturing *Source: Newell, 2014, via ProPublica.*

The hydraulic fracturing fluid is comprised mainly of water, representing between 75 to 99% of the total volume (APPEA, nd). Water is pumped into "blenders" that mix the proppant sand and chemical additives immediately before being pumped down the well hole with high pressure positive displacement pumps. Proppants usually represent five to 8%, but may contribute to up to 25% of the hydraulic fracturing fluid volume (DMP, 2014b; APPEA, nd). A variety of other substances may be added at very low concentrations which, when combined, are reported to represent approximately one per cent, but no more than five per cent of the volume (Hunter, 2011, APPEA, nd; DMP 2014b & c). These chemical additives carry out a number of different functions that include:

- proppants hold the cracks or fractures open;
- biocides control microbial growth in the fluid;
- corrosion inhibitors and oxygen scavengers assist in maintenance of well integrity;
- scale and iron control chemicals for maintenance of well integrity;
- pH stabilisers and buffers to maintain hydraulic fracturing stability and immobilise clays;
- friction reducers to improve recovery;
- gelling agents to increase the viscosity to allow more sand to be carried into fractures;
- clay stabilisers to minimise clay swelling in the well and rock formation;
- surfactants to reduce the surface tension to improve fluid recovery and
- breakers to break down the gel to enable release of the proppant into the fractures and enhance recovery of the flowback fluid (DMP, 2014c).

Since 2012, all exploration and trial projects seeking approval to undertake hydraulic fracturing in WA, are required to provide an Environmental Plan Summary that is made publicly available from the

Department of Mines and Petroleum (DMP) online Environmental Assessment and Regulatory System (EARS2). Generally, the full lists of chemicals that are commonly used, or may be required as contingency chemicals, are included within the Environmental Plan Summary unless there are post approval amendments. Chemical by-products or chemicals within flowback water do not need to be identified (DMP 2013a). Chemical changes in flow back fluids are required to be submitted to the DMP post approval. The requirements for chemical assessment and disclosure are outlined in the following DMP guidelines:

- Chemical Disclosure Guideline (DMP, 2013a) and
- Environmental Risk Assessment of Chemicals used in WA Petroleum Activities Guideline (DMP, 2013b).

While hydraulic fracturing is somewhat standardised, treatment conditions (volumes, chemical additives, flow-rates, pressures used and treatment frequency) may vary from project to project and between operators based on their experience within the local geology, and water resource quality and availability.

Each well may undergo multiple hydraulic fracture treatments, ranging from five to 30 treatments per well, before optimal production conditions are established. Up to 20 million litres of hydraulic fracturing fluid may be used to treat a single well (Hunter, 2011; DMP, 2014a).

Public Concerns and Social Licence

While use of hydraulic fracturing to exploit natural gas in shale and tight rock remains in its infancy in WA, with the majority of listed wells in early stages of development (DMP, 2013c) community concern is considerable as reflected in media and political commentary (Paddenbug, 2013; Cannon, Kennedy & Barndon, 2013). Fears of negative impacts to community health continue to be raised in the media and in scientific literature related to hydraulic fracturing specifically (Broomfield, 2012, Coram et al 2014, Kovats et al 2014, Shonkoff et al 2014).

The first anti-fracking rally was held in Perth in April 2012 (PerthNow, 2012). More recently, a number of Australian communities have been declaring themselves as ‘Gasfield Free Communities” (communities against unconventional gas mining on their land) but the legal standing of such declarations has been questioned by industry (Hadji and Sweeney 2014). The Shires of Coorow and Greenough in the Mid-West region of WA have voted to suspend hydraulic fracturing pending a public inquiry and also for health and agricultural assessments to be undertaken (Mercer 2014, ABC, 2014).

While the most common public health concern relates to the potential for negative impacts to water resources from over-abstraction and contamination, other objections include:

- Greenhouse impacts from pollution on air quality with associated safety and health impacts;
- increased noise and vibration from the operation and associated increased traffic levels;

- soil and groundwater contamination and land subsidence;
- lack of consultation with the public and local communities;
- destruction of natural ecosystems and spread of dieback;
- perceived preferential support for exploitation of minerals and energy over other conflicting land uses (e.g., forestry and agriculture); and,
- perceived preferential support for energy derived from fossil fuels rather than focusing support and investment into solar, wind and renewable energy resources (Wilderness Society, 2013).

During June 2013 the Department of Mines and Petroleum (DMP) commissioned a survey to measure community support for the use of hydraulic fracturing in WA (DMP, 2014e). A state-wide sample of 402 respondents was telephoned, with approximately half of the respondents living in areas where shale and tight gas could be potentially developed. Approximately 36% of the respondents objected to "fracking", with 26% strongly objecting. Support was registered by 22% of respondents, yet a significant proportion (41%) had never heard of "fracking". With respect to existing knowledge of hydraulic fracturing, 75% of this population sample "felt they did not currently have enough information regarding the emerging shale gas industry and what is currently happening in Western Australia" (DMP, 2014e, p1).

The rapid development of hydraulic fracturing in the United States of America (USA) has also been associated with expressed public concern related to health risks. A suite of inquiries into the impacts of hydraulic fracturing on water sources was commissioned in 2012 (Broomfield, 2012; USEPA, 2012). Moratoria on hydraulic fracturing have also been imposed in numerous states of the USA, Quebec Canada, France, South Africa and Bulgaria (RS&RAE, 2012). Similarly in Australia moratoria have been in place at various times in Victoria, New South Wales (NSW) and local councils in Queensland (Burke, 2011; Duffy, 2012a; Duffy, 2012b).

Risk communication consultant, Peter Sandman, describes the type of public concern that exists with hydraulic fracturing as "outrage". He explains that management of this outrage requires understanding that the public do not recognise risk of the unknown, technically new or complicated as a technical issue, but describes it as a social issue that is "influenced by factors like fairness, trust and who has control" (Sandman, 2013). Hence developing trust requires more than reiteration of technical details that are not well understood by non-technical people. Sandman (2013) also suggests that in fracking risk communication, it is important to sell the valid pluses; rebut invalid minuses; and acknowledge valid minuses. He proposes that the latter is most important (Sandman, 2013). For example, where there is identified potential for contamination through modelling or previous experience, it is important to acknowledge the potential for the risk event and develop appropriate actions to prevent, monitor for and establish mitigation strategies should the worst case scenario occur. Furthermore, these risks, monitoring and mitigation strategies need to be communicated to stakeholders early and often during exploration, feasibility trials, construction, development, production and well closure to provide confidence that all of the risks will be effectively managed without impacting public health of the local community.

WA Government Response to Community Concerns

The WA Legislative Council initiated the Inquiry into the Implications for Western Australia of Hydraulic Fracturing for Unconventional Gas in August 2013 to address the level of public concern as well as gain information on all the potential benefits and negative impacts. This inquiry is scheduled to report to the Legislative Council by August 2015.

Meanwhile, a WA Government Interagency Working Group and Science Needs Committee have been established by the DMP. These groups have been meeting regularly to review all existing processes, provide comment and advice to ensure particular areas of government agency responsibility and concerns are being addressed by DMP, the lead agency and regulator of the shale and tight gas industry. The Department of Health (DOH) does not currently have specific regulatory responsibilities or powers unless drinking water supplies are contaminated which would trigger coordination of an emergency response to protect the health of the public (DOH, 2013). However, DOH is an active participant in both interagency groups promoting consideration of public health issues at every stage of projects employing hydraulic fracturing in shale and tight gas resources in WA. This follows on from a number of lessons that were learned from the Legislative Assembly Inquiry into the cause of lead pollution in the Esperance area that reiterated the importance of consideration of public health in resource project approvals, particularly with projects viewed as contentious (Education and Health Committee, 2007).

As the lead agency and regulator of all mining and energy resources in WA, the DMP have recently updated all legislation and guidance material associated with shale and tight gas. Information regarding updated legislation and public review is available from the DMP homepage entitled “Natural gas from shale and tight rocks” (DMP, 2014f).

National and International Reviews into Impacts of Hydraulic Fracturing

Western Australian regulators and government departments are currently in a unique position to learn from hydraulic fracturing activities in shale reserves in the USA and from the significantly shallower coal seam gas (CSG) reserves in Queensland and New South Wales. After many years of natural gas production from these reserves, several significant independent reviews were recently initiated starting from 2011. Table 2 lists the most recent, large scale investigations into exploration and production of natural gas using hydraulic fracturing in Australia and the USA since the WA Government announced interest in exploring similar reserves in WA.

In 2011 the USA House of Representatives commenced an investigation into substances being used in hydraulic fracturing (Waxman, Markey & DeGette, 2011). Fourteen US companies provided lists of chemicals used in hydraulic fracturing between 2005 and 2009. While this list was the most complete at the time, not all substances were divulged due to trade secrets. Attempts were made to contact suppliers of these products to determine the precise constituents but with little success.

Hydraulic fracturing in the United Kingdom (UK) was reviewed by the RS&RAE in 2012. This report concluded that hydraulic fracturing to extract shale gas could be managed effectively in the UK if operational best practices are implemented and enforced through strong regulation (RS&RAE, 2012). Existing UK regulations require full disclosure of hydraulic fracturing fluids; open ponds for wastewater are not allowed and there are specific requirements for well integrity and blow out prevention already in place. It described the most likely cause of possible environmental contamination to be associated with surface activities where hydraulic fracturing and flowback fluid may be released from faulty wells, leaks and spills and that these events pose a greater contamination risk than the underground fracturing process itself (RS&RAE, 2012). Ensuring well integrity was the highest priority, however it also recommended use of non-hazardous chemical additives, wherever possible, to mitigate the impact of any leak or spill (RS&RAE, 2012). Robust monitoring before, during and after shale gas operations to detect methane and other contaminants in groundwater and in the atmosphere were also recommended to assess local and cumulative impacts. Authors recommended that monitoring information, along with site-based characterisation of the geology and identification of faults should be provided to the regulators to assist with managing potential hazards, informing local planning and to address wider concerns. Mandatory Environmental Risk Assessment (ERA) to assess risks across the lifecycle of the operations (including seismicity, water use through to disposal of wastes and well abandonment) and involving participation of local communities at the earliest possible opportunity, was a priority recommendation of this UK review (RS&RAE, 2012).

Concurrently a separate report was prepared for the Director General of the European Commission-Environment to explore the risks associated with hydraulic fracturing with a view to exploit unconventional gas reserves in the European Union (EU) (Broomfield, 2012). It assessed risks associated with each stage of well-pad development focusing on the hydraulic fracturing experience in the US, including:

- well pad site identification and preparation
- well design, drilling, casing and cementing
- technical hydraulic fracturing stage
- well completion
- well production and
- well closure/site abandonment (Broomfield, 2012).

Broomfield (2012) described the risks to be high for both surface and groundwater contamination during hydraulic fracturing processes and highlighted that a number of similar, or cumulative, developments within a single area could further increase this risk. Yet, the risk of hydraulic fracture fluid migrating through fractures to groundwater was considered to be remote as long as the drinking water source was separated from the zone of hydraulic fracturing by a distance of 600 metres or more. The report also described some uncertainty with respect to the possibility of human made or geological faults that could aid this process and the effects of repeated hydraulic fracturing in the same area (Broomfield, 2012).

From the US experience, Broomfield (2012) acknowledged limitations in their risk screening study due to the lack of systematic baseline monitoring and the absence of a comprehensive, centralised data of well-failure and incident rates. A centralised database that includes all incidents and monitoring results related to operations employing hydraulic fracturing was therefore recommended for implementation in the EU (Broomfield, 2012).

Meanwhile, the Australian Council of Learned Academics (ACOLA) reviewed issues related to extraction of shale gas in Australian reserves (Cook et al., 2013). The ACOLA report reiterated the need for operators to carry-out site specific monitoring for methane and other contaminants in groundwater before, during and after shale gas operations commence to accumulate information on groundwater chemistry, ecological systems, and seismic activity. Gaining and retaining a social licence to operate was also considered crucial. The authors emphasised that early and frequent stakeholder engagement that demonstrates respectful transparency is essential for all communications with acknowledgement that there is no single communication plan that works for all situations. The ACOLA review also highlighted the need for site specific health risk assessments (HRA) where shale gas production wells are proposed in populated areas. The HRA should not only ensure all risk is identified but communication plans implemented outlining how the risks will be managed effectively to reduce public concerns (Cook et al., 2013).

Horizontal (also referred to as directional) drilling and hydraulic fracturing have been used since 1996 in Queensland and later in New South Wales (NSW) to extract CSG (Department of Climate Change and Energy Efficiency, 2012). While there are many similarities in the extraction methods, it is important to recognise significant distinctions between CSG and the prospective shale and tight gas reserves that occur in WA. Coal seam gas is significantly shallower, trapped within larger pores and fractures in underground coal deposits located within 300 metres to one kilometre below ground, and frequently located near communities and their associated infrastructure in the form of roads, power, water and pipework systems (Department of Climate Change and Energy Efficiency, 2012). In contrast, shale and tight gas formations are usually less porous, are usually located in remote areas with limited infrastructure, at depths greater than one kilometre to as deep as five kilometres below ground (Department of Climate Change and Energy Efficiency, 2012; CSIRO, 2012; DMP, 2014a & b). Hydraulic fracture stimulation is always necessary to release less permeable shale and tight gas but is not always necessary to release CSG (Department of Climate Change and Energy Efficiency, 2012).

An independent review into CSG activities in NSW commenced in February 2013 was overseen by the NSW Chief Scientist and Engineer (O'Kane, 2013). The final report described the concerns related to CSG as a "complex and multi-layered issue which has proven divisive chiefly because of the emotive nature of community concerns, the competing interests of the players, and a lack of publicly-available factual information" (O'Kane, 2013, p iv).

A separate report focusing on the management of environmental and human health risks from CSG activities was also released with the final report (O'Kane, 2014b). The report assessed the risks from CSG activities to water catchments and impacts to surface water, groundwater, soil and air quality were all considered in relation to different aspects of the CSG activities, including:

- drilling, well integrity and fracture stimulation;
- spills and leaks;
- seam depressurization (*N.b. not relevant to shale and tight gas*) and
- produced water and solids.

Health risks were considered through potential exposure pathways that are shown schematically in Figures 4 to 6 and include pathways from the operation to humans via water, soil, air and indirectly within food (O'Kane, 2014b). The final dose taken up by the human receptors (people living nearby or drinking water supplies) is critical to identify possible health effects and predict their likelihood. The expert opinion was that all chemicals would be diluted resulting in decreased exposures for people who may be in contact. To predict these final concentrations, mathematical modelling of water, air movement, or ecological webs could be applied, however such modelling requires detailed knowledge of the local environment (geology, hydrogeology, geochemistry etcetera) (O'Kane, 2014b).

The NSW Chief Scientist and Engineer (O'Kane, 2014b) also stated that management of potential risks requires effective control and regulation, that includes incorporation of emerging engineering technologies and solutions; monitoring and modelling, conducted with high levels of expertise, that is made available for independent, transparent and rigorous peer review to gain an understanding of all processes occurring below ground, including interactions with groundwater and geological responses, so that any deviations from modelled results will trigger prompt termination of activities and implementation of remediation management plans prepared following comprehensive risk assessment (O'Kane, 2014b).

The final NSW CSG report (O'Kane, 2014a) concluded that the technical challenges and risks posed by the CSG industry can in general be managed through:

- careful designation of areas appropriate in geological and land-use terms for CSG extraction,
- high standards of engineering and professionalism in CSG companies,

- creation of a State Whole-of-Environment Data Repository so that data from CSG industry operations can be interrogated as needed and in the context of the wider environment,
- comprehensive monitoring of CSG operations with ongoing automatic scrutiny of the resulting data,
- a well-trained and certified workforce, and
- new technological developments as they become available.

Although not routinely undertaken at site level, a site-based environmental health risk assessment incorporating early and ongoing stakeholder engagement, has been recommended by several of the recent reviews into gas extraction activities where hydraulic fracture stimulation is employed (RS&RAE, 2012; Broomfield, 2012; Cook et al., 2013; O'Kane, 2014a & b). In 2013, an environmental health risk assessment investigated air quality, groundwater, surface water, noise, vibration, hazards and subsidence impacts during construction and production of the Camden Gas Project for the Camden Northern Expansion Project (Wright, 2013a). It was undertaken in consultation with the NSW Health Department and local community and addressed all of the concerns highlighted by stakeholders (Wright, 2013b). The review systematically assessed the risk of worst-case exposure scenarios and historic monitoring data and found the health risk to be low and acceptable, and protective of the health of the community (Wright, 2013a & b).

The United States Environmental Protection Authority (USEPA) has also initiated a number of independent research projects into the potential impacts of hydraulic fracturing for oil and gas on drinking water resources. It is anticipated that the final papers for this study will be published in peer reviewed journals by the middle of 2015, with the final report expected by the end of 2016 (USEPA, 2014; New York DEC, 2014). This study takes each stage of the hydraulic fracturing water cycle into consideration.

The stages and potential impacts include:

- Water acquisition
    - Changes in quantity and of water available and change in drinking water quality
- Chemical mixing
    - Potential for release to surface and groundwater through on-site spills / leaks
- Well injection
    - Potential release of hydraulic fracturing fluids due to inadequate well construction or operation
    - Movement of hydraulic fracturing fluids from the target formation to drinking water aquifers through local man-made or natural features, such as abandoned wells and existing faults.
    - Movement of natural substances found underground, such as metals or radioactive material that have been mobilized during the hydraulic fracturing activities.

- Flowback and Produced Water (wastewaters)
- Release to surface or ground water through spills or leakage from on-site storage
- Wastewater Treatment and Waste Disposal
    - Potential for contaminants reading drinking water due to surface water discharge and inadequate treatment of wastewater.
    - Byproducts formed at drinking water treatment facilities from reactions of hydraulic fracturing contaminants with disinfectants.

During 2012, National Industrial Chemicals Notification and Assessment Scheme (NICNAS) initiated the National CSG Chemicals Assessment project to investigate and report on human health and environmental risks from chemicals used in drilling and hydraulic fracturing for CSG extraction in Australia (NICNAS, 2012). Given the similarity in the chemical process of hydraulic fracturing in CSG and shale and tight gas, this study, due to be reported on shortly, will inform the Australian Government, industry, and the public about the use and potential risks of these chemicals. Through collaborative projects, environmental and human health risk assessments have been undertaken focusing on risks associated with release to surface and near surface water environments (Swirepick, A., personal communication, 11 July, 2014). Finalisation of this review was anticipated at the end of 2014. It had not yet been published by the final draft of this document.

An expert panel of the Council of Canadian Academies reviewed the state of knowledge about environmental impacts of shale gas exploration, extraction and development in Canada. The report authors noted challenges due to "the number of issues involved, the lack of evidence on some of the issues, and rapidly evolving industry practices" (Council of Canadian Academies, 2014, p vii).

In summary, the Council of Canadian Academies (2014) reported;

- accidental surface releases of chemicals and wastewater, and changes in hydrology and water infiltration from new infrastructure may impact shallow groundwater and surface water supplies.
- upward migration of natural gas and saline water from leaky well casings, possibly though naturally fractured rock, old abandoned wells and permeable faults present possible risks to potable groundwater.
- there is insufficient information on the fate of flowback chemicals from existing operations and further analysis and monitoring is required to better understand fate and transport because this fluid often contains aromatic hydrocarbons, such as benzene, in addition to the hydraulic fracturing additives.

The main reasons for the information shortfall are due to the youth of the industry which is approximately 20 years old, the proprietary nature of much of the industry information historically, confidentiality of settlements associated with damage claims and the absence of systematic regulations requiring disclosure of chemical additives in the USA. Full chemical disclosure and assessment of chemical composition of flowback water is seen as necessary. In December 2014, New York State (NYS) declared that high volume hydraulic fracturing (HVHF) was prohibited in that state in which the Marcellus Shale has been the primary target for shale gas (NYS DEC, 2014). This decision was in response to findings of a public health review undertaken by the NYS Department of Health (NYS DH) (2014). The report concluded that:

- "the overall weight of the evidence from the cumulative body of information contained in this Public Health Review demonstrates that there are significant uncertainties about the kinds of adverse health outcomes that may be associated with HVHF, the likelihood of the occurrence of adverse health outcomes, and the effectiveness of some of the mitigation measures in reducing or preventing environmental impacts which could adversely affect public health. Until the science provides sufficient information to determine the level of risk to public health from HVHF to all New Yorkers and whether the risks can be adequately managed, DOH recommends that HVHF should not proceed in NYS" (p2).

In particular, the report described significant information gaps associated with potential environmental impacts and health outcomes relating to drinking water;

- drinking water impacts from underground migration of methane and/or fracking chemicals associated with faulty well construction;
- surface spills potentially resulting in soil and water contamination; and
- surface-water contamination from inadequate wastewater treatment.

Two additional reviews of public health risk assessment related to unconventional gas well development (UGWD) were published by the University of Maryland (2014) and the Maryland Departments of Natural Resources and Environment (2014 & 2015). More detail of these studies is provided in the Risk Categorisation section of this document.

At the end of March 2015, the USEPA published their analysis of hydraulic fracturing fluid data that was provided to the first version of the FracFocus Chemical Disclosure Registry (referred to as FracFocus 1.0) during the period of January 2011 and March 2013 (US EPA, 2015). Approximately 39,000 FracFocus disclosures were evaluated to address the following research questions:

- What are the identities and quantities of chemicals used in hydraulic fracturing fluids, and how might this composition vary at a given site and across the country?
- How much water is used in hydraulic fracturing operations, and what are the sources of this water?

The analysis confirmed the distribution of chemicals used in hydraulic fracturing fluids that has been widely published elsewhere. It reported that generally water represented 88% (by mass), 10% was quartz and chemical additives were less than one per cent. The most common additives disclosed to FracFocus 1.0 were:

- Hydrochloric acid
- Methanol
- Hydro-treated light petroleum distillates
- Isopropanol
- Propargyl alcohol
- Ethanol
- Ethylene glycol
- Glutaraldehyde
- Citric acid
- Sodium hydroxide
- Peroxydisulfuric acid, diammonium salt
- Water (as a component of additives)

No attempt was made to assess the toxicity or potential for health impacts by this study.

Drinking Water for all Western Australians

Approximately 90% of Western Australians receive drinking water from licensed and regulated public drinking water supply systems, or scheme providers. The remaining 10% include:

- Remote Indigenous communities
- Local government: Small community drinking water scheme suppliers
- Minesites and exploration camps
- Private small system operators that supply to public (for example roadhouses, caravan parks and water carriers).
- Domestic households in remote or regional areas that are not connected to any other reticulated scheme manage their own drinking water systems (DOH, 2014).

Due to its vast area, geological and hydrogeological heterogeneity, WA's natural groundwater and surface water resources are diverse, complex, and not evenly distributed across the state (Department of Water (DOW), 2014). Fresh water is collected via a number of different mechanisms for supply of a variety of competing demands that include drinking and residential water, agricultural/ irrigation and industrial uses. It is collected either by damming rivers and shorter, freshwater streams which flow in response to seasonal rainfall or by abstracting groundwater that also contributes to the base-flow of some rivers (DOW, 2014). Important groundwater resources occur in sedimentary basins (Perth, Carnarvon and Canning Basins), sedimentary alluvial aquifers (along major rivers in the Pilbara and Gascoyne) and in ancient bedrock in fractures, joints, bedding planes and cavities in an otherwise solid rock mass (in semi-arid central parts) (DOW, 2014).

Protection and careful management of abstraction rates is vital to enable a continual supply for all of the competing demands for water currently and into the future, concomitant with the drying climate of WA (DOW, 2014). However, this HRA focuses on the potential for health impacts of chemicals from hydraulic fracturing to contaminate drinking water supplies.

The following section on health risk assessment will focus on human toxicity of hydraulic fracturing chemicals. This analysis uses hypothetical scenarios for chemicals that could contaminate drinking water via potential pathways highlighted in Figures 4 to 6.

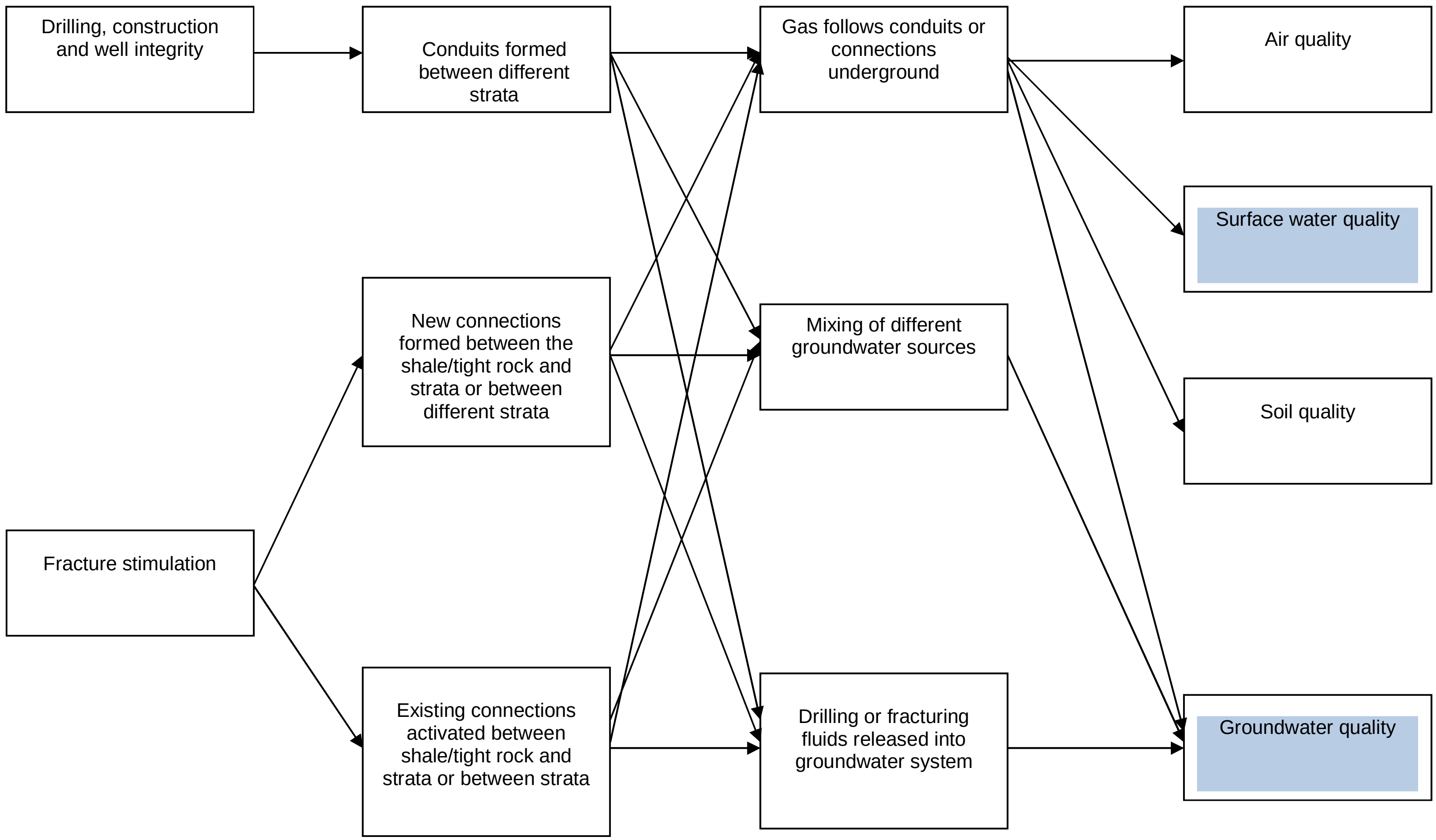

Figure 4. Risks for drilling, well integrity and hydraulic fracture stimulation.
Modified from: O'Kane (2014b) Managing environmental and human health risks from CSG activities.

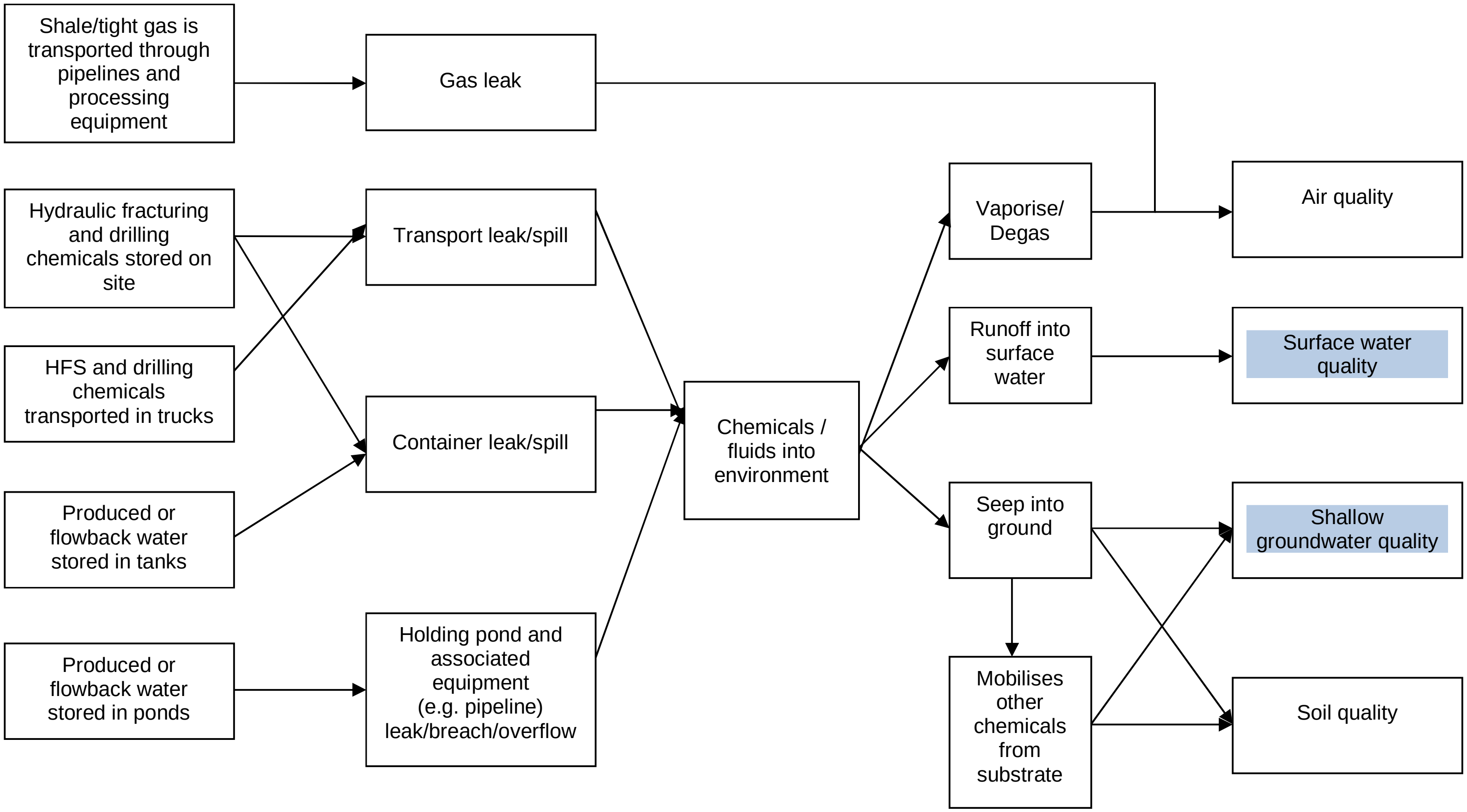

Figure 5. Risk for spills and leaks.
Modified from: O'Kane (2014b) Managing environmental and human health risks from CSG activities.

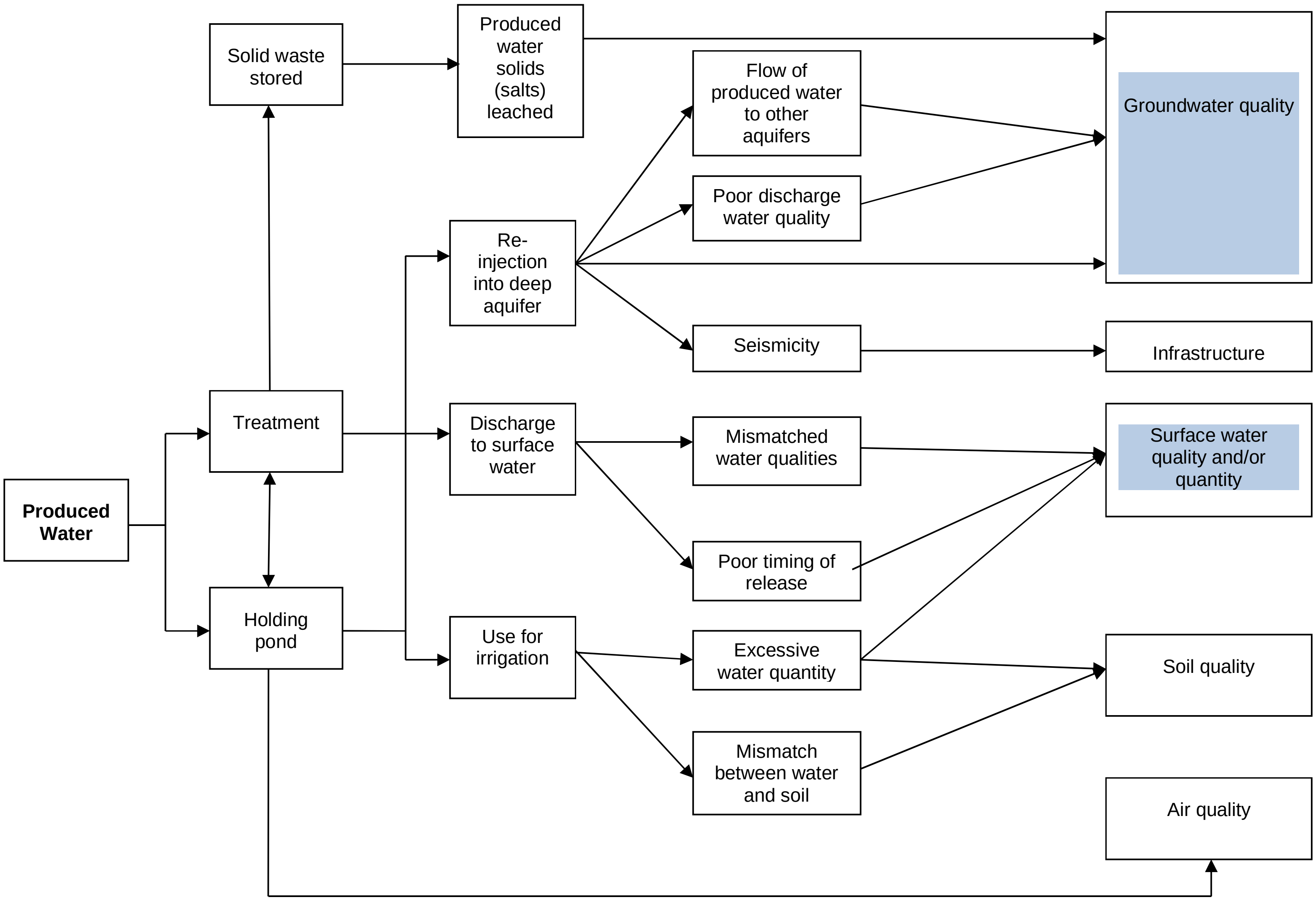

Figure 6. Risks associated with produced water and solids.
Source: O'Kane (2014b) Managing environmental and human health risks from CSG activities.

Human Health Risk Assessment Framework

This framework is based on the model of human health risk assessment (HHRA) set out in the 'Guidelines for assessing human health risks from environmental hazards' (enHealth, 2012). This HHRA focuses on the potential adverse health effects related to contamination of drinking water supplies. The HHRA framework is shown in Figure 7:

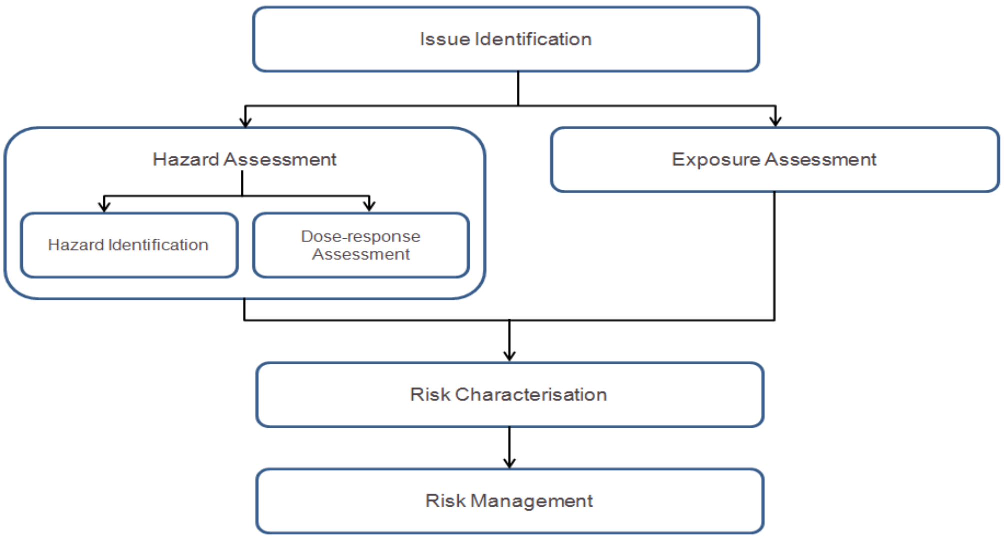

Figure 7. Human Health Risk Assessment Framework. (enHealth, 2012)

- **Issue Identification**
  Issue identification is the identification of key issues that are amenable to risk assessment. It also establishes a context for the risk assessment by specifying the problems the risk assessment will address.
- **Hazard Assessment**
  Hazard assessment looks at the capacity of agents to produce adverse health effects and where possible compares known concentrations to safe guideline values to identify which chemicals represent the greatest concern. This includes the collection and analysis of relevant data, where they exist.
- **Exposure Assessment**
  Exposure assessment investigates the character of the exposure; the population exposed and estimates the exposure concentration for all exposure pathways to the relevant population.
- **Risk Characterisation**
  Risk characterisation combines the information from the above stages. It characterises the potential for adverse effects to occur. Risk characterisation information is used define and evaluate options in the risk management process.

Issue Identification

In 2012 The Commonwealth Scientific and Industrial Research Organisation (CSIRO) conducted a series of community meetings and a workshop concerning shale gas development in the Midwest of WA (Taylor & Stone, 2012). These workshops were attended by stakeholders including community members, government representatives, industry and scientists. The goals were to identify concerns, identify information gaps and foster a fact-based discussion. A report was produced by the CSIRO that summarised the main points that were discussed. While a broad range of concerns were discussed, some of the concerns did relate specifically to drinking water supply and were amenable to risk assessment. They included:

- Protection of water security.
- Impacts of hydraulic fracturing on human health, especially through introduction of chemicals into surface and ground water
- Short and long term well integrity and potential impacts on groundwater quality and quantity.
- Disposal of waste water from wells and hydraulic fracturing: risks of contamination of surface and groundwater.
- Review of existing information on impacts of gas extraction on groundwater quality and quantity, from overseas if required, and interpreted as far as possible to the local conditions.

The report summarised concerns related to risks to the water supply from hydraulic fracturing such as:

- Contamination of groundwater with hydraulic fracturing or flowback fluids through the initial drilling process, well malfunction, gaseous seepage post fracturing, communication with the fractured area and from poorly stored or managed flowback fluids at the surface.
- Contamination of surface water with hydraulic fracturing or flowback fluids through surface spill of hydraulic fracturing fluids, uncontrolled release of fluids in a blow-out, flood or extreme weather causing overflow of waste water and poor treatment of waste water prior to disposal into water ways.
- Stressing water sources through sourcing large quantities of water for hydraulic fracturing.

Community concerns and issues raised in the literature can be synthesised into two areas;

- What are the potential adverse health effects of hydraulic fracturing substances if they were to contaminate the water supply? and
- What are the potential risks to water supply volume from the practice of hydraulic fracturing?

This HHRA focuses on:

The risk of drinking water supply contamination from the result of hydraulic fracturing processes, particularly from well drilling, hydraulic fracturing fluid and flowback of fluid in wells.

Hazard Assessment

A priority list of substances related to hydraulic fracturing was created for this HHRA based on substances meeting any one of the following criteria:

- Listed as being present in more than one per cent of products used in fraccing examined by the US House of Representatives Committee (Waxman, Markey & DeGette, 2011)
- Listed as a common hydraulic fracturing fluid by Fracfocus, a USA based hydraulic fracturing industry group (Fracfocus, 2013a)
- Listed as a constituent of flowback fluid by the US EPA (2012a)
- A substance used in the process of drilling a hydraulic fracturing well following a well malfunction in Clark County Wyoming (Terracon, 2008)
- Listed as a constituent of drilling or hydraulic fracturing fluid from selected Environmental Plan Summaries for DMP approved projects listed in EARS2.

The following sources were examined to determine the toxicological characteristics including a guideline level for oral intake, carcinogenicity, developmental and reproductive toxicity for each substance:

- The Australian Drinking Water Guidelines 6 - 2011 (National Health and Medical Research Council [NHMRC], 2014).
- Acceptable Daily Intakes for Agricultural and Veterinary Chemicals (DOHA, 2005a).
- Nutrient Reference Values for Australia and New Zealand (DOHA, 2005b).
- Hazardous Substance Information System (Safework Australia, 2013).
- Guidelines for Drinking-water Quality: fourth edition (WHO, 2011).
- Integrated Risk Information System (IRIS) database (US EPA, 2013a).
- US Centre for Disease Control, Agency for Toxic Substances and Disease Registry (ATSDR, 2013).
- European Chemical Substance Information System: ESIS (European Commission, 2013).
- National Institute for Public Health and the Environment (RIVM) Holland (RIVM, 2013)
- Australian and New Zealand Food Standards Code (DOHA, 2013)
- International Agency for Research on Cancer (IARC) Monographs (WHO, 2012).
- US National Toxicology Program Report (NTP) on Carcinogens 12th Edition (US Department of Health and Human Services, 2011).
- Developmental and Reproductive Toxicology Database (DART, 2013)

Australian guidelines have been used preferentially for this assessment and are considered most applicable from a regulatory perspective, which is a significant driver for best practice environmental management. Where an Australian guideline has not been established, guidelines generated from WHO sources are adopted. Standards from other regulatory agencies have been applied where there is no Australian or WHO guideline value available.

Substances were classified as known, suspected or possible carcinogens based on the highest rating received from one of the information sources mentioned above. Substances that received the highest rating for carcinogenicity are referred to as known human carcinogens whilst substances that received a lower rating, as specified in Table 3, were referred to as suspected or possible carcinogens.

Using the above sources a list of 195 substances of concern was produced. These substances can be further grouped based on whether they are used in the initial drilling process, as an additive in hydraulic fracturing but not detected in flowback fluid, an additive in hydraulic fracturing fluid and found in flowback fluid or if they were an additional substance detected in flowback fluid.

Substances used in the drilling process

Table 4 lists 22 substances known to be used in the drilling process. A guideline value was not found for any substance. However, barium sulphate is used in groundwater machinery and four other substances are approved as drinking water treatment chemicals (NHMRC, 2011). A further five were found to be approved as food additives.

Silica or crystalline quartz, bentonite clay and cristobalite are the only chemicals in this group that are known to be carcinogenic. The primary malignancy associated with exposure to these chemicals is through inhalation and the susceptible population would be employees handling proppant (IARC, 2012a).

None of the substances were reported to be developmental or reproductive toxins by regulatory agencies.

Substances used as additives to hydraulic fracturing fluid but not detected in flowback fluid

Forty-seven substances commonly used as additives in hydraulic fracturing fluid but were not detected in the analysis of flowback fluids are listed in Table 5. Only three of these substances have established guidelines. Silica was listed by the Australian Drinking Water Guidelines as having no known adverse health effect when consumed in drinking water but that it does alter taste; therefore an aesthetic guideline was given only. Sodium chloride currently has no established guideline but does affect taste at greater than 200mg per litre (WHO, 2011). Sodium hydroxide is approved as a drinking water chemical (NHMRC, 2011). A further nine substances are approved food additives (DOHA, 2013).

Three of these substances are known or suspected carcinogens with Quartz being discussed in the previous section. Ethanol is classified as a class 1 carcinogen by IARC (IARC, 2012b). This is however specific to the oral intake of alcoholic beverages and IARC also considers the acetaldehyde in combination with ethanol as the most likely cause of carcinogenicity from alcoholic beverages (IARC, 2012b).

Safework Australia, IRIS and ESIS state that Borax can cause both developmental and reproductive toxicity (Safework Australia, 2013; European Commission, 2013; US EPA, 2013a).

Substances used as additives to hydraulic fracturing fluid and detected in flowback fluid

Thirty five substances used as additives in hydraulic fracturing fluid and also detected in flowback fluid are listed in Table 6. Of these substances, 23 have guidelines for safe levels of oral intake. A further three have aesthetic guidelines due to disturbances in taste and three are approved food additives. Aluminium currently has an aesthetic guideline only in the Australian Drinking Water Guidelines (NHMRC, 2011). However there are concerns about neurotoxicity from this substance and the guideline suggests the need to review when further research is available (NHMRC, 2011). Ammonia has an aesthetic guideline due to taste. The Australian Drinking Water Guidelines state that health effects may be experienced at levels greater than 1000 mg/litre of water but this level was thought to be unlikely and therefore no guideline was set (NHMRC, 2011).

Benzene, a known human carcinogen should not exceed 0.001 milligrams per litre in drinking water based on the carcinogenic potential to induce leukaemia, usually following inhalation of this volatile compound (NHMRC, 2014; IARC 2012aj; US Department of Health and Human Services, 2011; European Commission, 2013; US EPA, 2013a). Arsenic is classified as a Class 1 carcinogen by IARC, owing to evidence of increased risk of malignancy from ingesting it through drinking water (IARC, 2012c). Safework Australia and the National Toxicology Program also give arsenic their highest rating (Safework Australia, 2013; US Department of Health and Human Services, 2011). Chromium VI is also classified as a class 1 carcinogen by IARC but the evidence is primarily based on exposure by inhalation causing lung cancer (IARC 2012d).

Of the six substances suspected of being carcinogens two of them, naphthalene and ethylbenzene, had evidence from inhalational studies in animals of an association with malignancies (IARC, 2000a; IARC, 2002). The other four (1,4 dioxane, bis(2-chloroethyl) ether, di (2-ethylhexyl) phthalate and lead) have some evidence of an association with malignancies from animal studies that administered the substance through the oral route (IARC, 1999a; IARC, 1999b; IARC, 2012e; IARC, 1987a). The evidence for the carcinogenicity of these substances is however poor given a general lack of evidence from human studies. Some evidence of possible developmental or reproductive toxicity was reported by regulatory agencies for seven of the substances.

Substances that were not used as additives in hydraulic fracturing fluid but were detected in flowback fluid

An additional 96 substances were found in the flowback fluids that were not used in hydraulic fracturing fluid (see Table 7). Of these substances 60 have guidelines for safe levels of oral intake. Sodium has an aesthetic guideline owing to the disturbance in taste it can produce. Two substances, Benzyl Alcohol and propionic acid, are approved food additives. Potassium is mentioned in the Nutrient Reference Values for Australia and New Zealand but an upper limit guideline is not given (DOHA, 2005b). The authors cite no evidence of toxicity from oral ingestion of food containing potassium in healthy people. Similarly tin was assessed for the ADWG but a guideline value was not established as it was thought that concentrations in water are likely to be considerably lower than the level that can cause ill effects and that there is no evidence of adverse effects in humans from long term exposure.

Of these 96 substances, 28 were found to be listed by regulatory agencies as known or suspected carcinogens. Of the six known carcinogens only radium 226 and 228 are carcinogenic via oral exposure (IARC, 2001). Cadmium and benzo(a)pyrene have some evidence of carcinogenicity via the oral route but most evidence is from inhalational studies (IARC, 2012i; IARC, 2010). Beryllium and nickel are carcinogenic via inhalation only (IARC, 2012g; IARC, 2012f). Of the suspected carcinogens aldrin, dieldrin, benzo(b)fluoranthene, benzo(k)fluoranthene, bromodichloromethane, dibenz(a,h)anthracene, heptachlor, heptachlor epoxide, lindane, n-nitrosodiphenylamine, tribromomethane, p,p'DDE, safrole, tetrachloroethylene and trichloromethane have only been shown to be carcinogenic in animal studies by the oral route (IARC, 1987a; IARC, 2010; IARC, 1999g; IARC, 2001; US Department of Health and Human Services, 2011; IARC, 1976; IARC, 1995; IARC, 1999e) and acrylonitrile, antimony, chloromethane, cobalt, dibutyl phthalate, dichloromethane and indeno(1,2,3-cd) pyrene have some evidence of carcinogenicity but predominantly by other routes of exposure such as inhalation, (IARC, 1999f; IARC, 1989; IARC, 1999c; IARC, 1999d; Safework Australia, 2013; IARC, 1973).

Methane contamination

Methane seepage is considered to be a natural phenomenon from sedimentary basins containing coal (Day, Dell'Amico, Etheridge, Ong, Rodger Sherman and Barrett, 2013). It occurs by movement of methane through naturally occurring rock fractures. During 2013, CSIRO completed a remote sensing survey in an attempt to characterise regional fluxes in background emissions from methane to the atmosphere in the Queensland Surat Basin. This pilot study reported that the distribution and flux is highly uncertain and difficult to measure due to rapid dispersion that is affected by normal meteorological conditions (Day et al., 2013).

A separate CSIRO study looked in methodologies that may be employed to measure methane in water bores in the Surat and Bowen basins to assess concerns associated with ignition and asphyxiation risks (Walker and Mallants, 2014). It found that methane concentrations are highly variable in space and time and that much more investigation is necessary. It reiterates that methane occurs naturally in groundwater and in the vapour phase of the unsaturated zone, especially in areas where there is coal seam gas (Walker and Mallants, 2014). While these Australian studies are informative, they are not directly applicable to methane seeping from deeper tight or shale deposits due to the increased depths of variable geological features acting as barriers.

In their recent review “Environmental Impact of Shale Gas Extraction in Canada”, the Council of Canadian Academies (2014) describe fugitive emissions of methane and their impacts on health through climate change as a primary concern. Elevated levels of methane have been reported in groundwater from multiple sites surrounding hydraulic fracturing wells (Council of Canadian Academies, 2014; Jackson, Vengosh, Darrah, Warner, Down, Poreda and Karr, 2013). However, as most of these sites did not undertake adequate baseline testing for methane prior to performing hydraulic fracture stimulation, the origin of the methane remains uncertain.

There is evidence that methane can exist in water supplies without hydraulic fracturing occurring (Darling and Gooddy, 2006; Walker and Mallet, 2014). An analysis of groundwater in New York State, where hydraulic fracturing wells have not yet been established, showed that two per cent had methane at levels greater than 28 mg/L and nine per cent had methane exceeding 10 mg/L (Kappel and Nystrom, 2012). Darling and Gooddy (2006) assert that methane is almost always detectable in groundwater, including non-contaminated aquifers with aerobic conditions from biogenic (produced from bacteria) and thermogenic (thermal decomposition of organic matter at depth, under high pressure) sources. Higher concentrations of dissolved methane were routinely measured in thermal waters under anaerobic conditions from Cretaceous, Jurassic and Triassic carbonated and sandstone aquifers in the UK (Darling and Gooddy, 2006). Detailed background investigations into natural baseline levels of methane in UK groundwater, were initiated prior to widespread shale gas extraction based upon the recommendation of the Royal Society and Royal Academy of Engineers in 2012 (British Geological Society, 2015).

Evidence has been presented that hydraulic fracturing has contributed to the methane concentrations in some groundwater supplies. A study by Osborn et al., (2011) found concentrations in groundwater up to 64 mg/L with concentrations increasing based on proximity to the nearest hydraulic fracturing well. Furthermore, a study in Bradford County Pennsylvania found that the concentrations of methane in a well supplying drinking water increased 10 times from baseline to a level of 6.2 mg/L post hydraulic fracturing (ATSDR (2011). Duke University researchers reported that the average concentration of methane in groundwater within one kilometre of hydraulically fractured wells was on average six times higher than in wells further away (Jackson et al., 2013). However, the source of the methane was disputed by Molofsky et al. (2013) who concluded that the gas concentrations correlated best with topography and groundwater geochemistry as opposed to hydraulic fracturing activity. In order to confirm the origin of contamination and to ensure protection of sensitive water supplies, it is pertinent to ensure that baseline characterisation is well designed and there is ongoing appropriate surveillance in the vicinity of sensitive receptors such as those near drinking water abstraction wells.

Summary

Chemical mixtures employed in drilling and hydraulic fracturing are highly variable between companies, regional and local geographical areas and consecutive hydraulic fracture treatments (Atherton, 2014). They are not standardised and can be complex and Atherton (2014) asserts “that there is no direct evidence of harm, or lack of it, from any specific mixture being deployed” (Atherton, 2014, p 129).

Tables 4, 5, 6 and 7 show that 78 (40%) of the 195 priority chemicals do not have a guideline or relevant approval by a regulatory agency, 13 are known human carcinogens but only five via oral exposure. Twenty eight chemicals have only been considered as carcinogenic in animal studies only. Thirty five are listed by DART as animal developmental and reproductive toxicants but 28 are only via oral exposure.

These findings were reflected in a similar review undertaken by the University of Michigan School of Public Health (Basu, 2013) that prepared a list on “notable chemicals intentionally used in hydraulic fracturing” accounted frequency of use based on the lists compiled by Waxman, Markey and DeGette (2011), and Colborn and colleagues (2011). From that list, the most common chemical components included:

- Hydrochloric acid
- Methanol
- Hydro-treated light petroleum distillates
- Isopropanol
- Ethylene glycol
- 2-Butoxyethanol
- Hydrogen sulphide,
- Quartz
- Diesel
- Methane

Exposure Assessment

According to enHealth (2012), exposure assessment in HHRA involves the determination of magnitude, frequency, extent, character and duration of exposures of a susceptible or vulnerable population in the past, currently and into the future. It also includes the identification of exposed populations and their potential exposure pathways.

Oral ingestion is the most significant exposure route when considering public exposure to drinking water potentially contaminated with chemicals from hydraulic fracturing. Therefore human toxicity by oral intake is the focus of this HHRA.

Exposure assessment is done in two stages;

1. Identifying and evaluating potential pathways to reach and contaminate drinking water supplies and

2. Comparing water monitoring results to existing drinking water guidelines. In the absence of reliable monitoring data, fate and transport modelling that estimates the final concentrations at various locations from the source of the contamination and at the drinking water supply is necessary.

Potential pathways to drinking water supplies

A Conceptual Site Model (CSM) is a tool used to list potential sources of environmental contaminants and identify all potential pathways that chemicals could travel to reach sensitive environmental receptors. The CSM may be presented as flow diagrams (refer to Figures 4 to 6), pictorially (see Figure 8) or in written or tabulated form (see Tables 8 and 9).

Table 8 lists activities from which chemicals may be released from the drilling and fluid systems employed in hydraulic fracturing operations. At this stage of the assessment, all potential pathways are included assuming the worst case scenario is possible and all existing controls and mitigation mechanisms have failed. The next step is to determine the feasibility of each pathway. Open pathways require further investigation by reviewing monitoring data and/or preparation of realistic fate and transport models to estimate the environmental distribution of released chemicals. Such modelling provides likely ranges in the concentrations that may reach the drinking water supply or source area.

This HHRA is focused on exposures to the public from potentially contaminated drinking water from environmental release of chemicals present in drilling, hydraulic fracturing or flow-back fluids that may be released into the environment during the specific operations of preparation and actual drilling, performing hydraulic fracturing treatments and handling and storing of flowback fluids. Release to the environment may occur on the surface during any of the operations; from leaks in waste water storage pond liners or overflowing chemical bunds or from leaks or faulty well casings (Table 8).

There are a number of risk factors that influence the fate and transport of chemicals (enHealth, 2012) that must be taken into consideration in assessing the likelihood and consequence of a water supply being contaminated sufficiently to cause aesthetic or health impacts. These include:

- Chemical properties of the constituent mix of the spill (or release into the environmental medium) that influence whether chemicals adhere or adsorb to solid substrates (local rocks, soil particles or biological material), volatilise or become water soluble or are transported within the groundwater flow.
- Biological degradation and/or chemical reactions within the soil and/or local groundwater is known as natural bioremediation. Persistent chemicals are those that are not degraded and remain in the environment. Thus persistent chemicals may be more likely to reach water supplies.

- The concentration of chemicals, volume and area that is affected by the release before it is identified and rectified will influence the extent of the impact. If the volume released and/or final chemical concentration is very low or insignificant when it is diluted within local groundwater, the risks of toxic concentrations occurring at the water supply are reduced.
- Hydraulic conductivity of soils is a measure of the soil's ability to transmit water under a hydraulic gradient and is influenced by local soil characteristics such as granule size and porosity. It varies significantly in sandy, clayey and silty soils. Hydraulic conductivity may also vary significantly within a regional catchment area, horizontally and vertically, therefore a good understanding of the local and regional hydrogeological characteristics are essential to assess the risk for local releases to reach drinking water supplies.
- Distance from and direction to the nearest surface water, abstraction well or groundwater used for drinking purposes will affect the travel time for the released chemicals to reach the receptor. Travel time is determined from knowledge of porosity and the rate of groundwater flowing towards the drinking water source area or well (Schubert, 1999). If local and/or regional groundwater flow is away from the water supply, the risk of contamination is remote.
- Local geological features, may include:
  - Impermeable rock formations between local groundwater and HF wells, sealed natural faults and fracture zones that provide additional barriers preventing contaminants reaching groundwater. However, the risk for interconnectivity between aquifers and wells will increase if the shallower rock formations are fractured.
  - Coexistence of natural faults and fractures in direct contact with the fracture zone could provide pathways for upward migration against gravity, when hydraulic fracturing is being pumped into the rock formation during treatment. However, following the brief hydraulic fracturing stage, this pathway is unlikely to exist when pumps are used to extract flowback fluids and gas during the well's production life. Also, in some geologic regimes, natural faults acts as hydraulic barriers.

Reliability or certainty of conclusions generated from fate and transport models is dependent on the proportion of adopted assumptions, compared with use of current scientific evidence collected from monitoring programs to characterise the local geological and hydrogeological features and conditions (enHealth, 2012). Where decisions involve assumptions that local characteristics are similar to other areas rather than based on confirmed local investigations, there will be additional uncertainty in the conclusions. Similarly, uncertainty may arise if data is not current, was not collected using current best practice methods or there is insufficient spatial or temporal distribution of measurements to adequately characterise the local conditions that influence fluid movement. To manage the level of uncertainty with the severity of the outcomes, there is a case for assigning a relatively higher risk rating when the uncertainty is high. When comparing results to safety guidelines and the potential outcome is severe and significant, or there is potential accumulation of risk factors within a regional area, the application of a larger safety factor is appropriate (USEPA, 2002; enHealth, 2012).

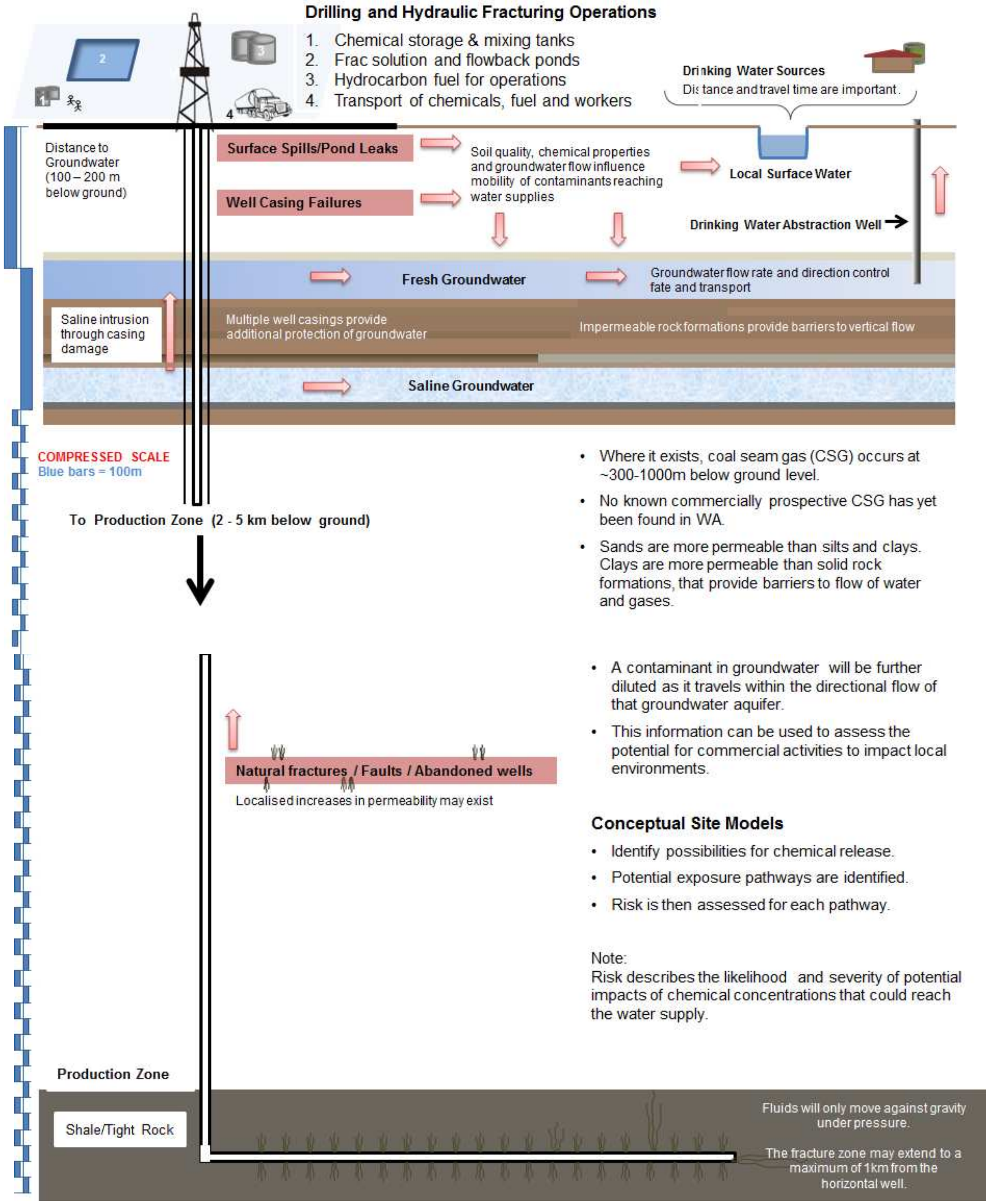

Figure 8. Conceptual Site Model. Potential pathways for hydraulic fracturing chemicals to impact drinking water supplies.

Water monitoring and drinking water guidelines

Exposure assessment is undertaken by comparing measured chemical concentrations at representative monitoring locations and comparing these to accepted health and aesthetic guidelines (ADWG, 2014). At this stage in the WA experience, there is no publicly available monitoring data to identify or evaluate concentrations of chemical additives or flowback/production constituents that may exist naturally in the environment prior to the operations, or after activities undertaken during exploration, trial or production wells where hydraulic fracturing has been used (irrespective of the type of drilling methods). Hence, this prospective HHRA is reliant on the North American experience where extraction of shale gas using hydraulic fracturing has been underway for approximately 20 years (Broomfield, 2012; RSRAE, 2012; Council of Canadian Academies, 2014; NYS DEC, 2014).

Unfortunately, despite the large number of wells that have undergone hydraulic fracturing, there has been little systematic or robust scientific investigation to confirm the origin of chemicals detected in contaminated drinking water near hydraulic fracture operations (Broomfield, 2012; Basu, 2013; Chen et al., 2014; Council of Canadian Academies, 2014; NYS DeptHealth, 2014). There has been no systematic collection or reporting of natural background environmental concentrations, sporadic regulation for disclosure of chemicals used, and little to no information regarding the concentrations used at each operational stage in the US shale gas industry to date. Hence insufficient scientific evidence is available to make satisfactory conclusions or prospective judgements regarding possible exposures of local public communities to chemicals detected in drinking water supplies, despite hydraulic fracturing activities being undertaken nearby (NYS DeptHealth, 2014; Council of Canadian Academies, 2014).

Elevated concentrations of some chemicals used in hydraulic fracturing that are also known to exist normally in some regions had been detected in drinking water at concentrations above health guidelines near sites where hydraulic fracturing had been employed (Hayes, 2009; Terracon, 2007; NYS DEC, 2012; West Virginia Department of Health via New York Times, 2012; USEPA, 2012b). Although the association of proximity was implied, it was not possible to confirm that these concentrations resulted from hydraulic fracturing as there were no natural background measurements available and the evidence was circumstantial. This was a common finding and limitation of all of the public health reviews and risk assessments completed to the end of 2014 (Basu, 2013; Canadian Council of Academies, 2014; University of Maryland, 2014; NYS DeptHealth, 2014, Adgate, 2014; Levy, 2014).

Risk Characterisation

Possible consequences of a contamination event

Contamination of both surface and underground drinking water supplies could occur via a variety of mechanisms, discussed above, that would render them unusable for human consumption. Once a drinking water supply is contaminated, it is difficult to remediate it to its initial quality. In some circumstances however it may be possible to bioremediate *in situ* or pump and treat the water using existing water purification systems such as reverse osmosis technology (Maryland Department of Natural Resources and Maryland Department of Environment, 2014). Notwithstanding, application of the precautionary approach to prevent contamination and maintain the unpolluted water reserve for access by future generations takes precedence.

Table 9 describes worst-case hypothesised outcomes assuming the drinking water supply is significantly contaminated and the exposed population receives sufficient dose to exert the described responses. The health effects described in Table 9 are possible and have been reported following significant exposures or from testing in laboratory animals, therefore every effort to minimise these exposures is warranted. However, although possible, there is no certainty that any or all of the people exposed will experience any or all of these health impacts (NYS DEC, 2011). For example, cancer would only be a possible outcome if an individual was to consume drinking water containing a carcinogen over a lifetime. Exposure concentration, duration and frequency, influence the likelihood and severity for adverse outcomes to develop among susceptible populations (enHealth, 2012). As an example, individuals working or living closest to the operations will have a greater chance of being exposed to significant concentrations of chemicals with the potential to impact their comfort and amenity which may also lead to developing more serious symptoms. The risks will reduce as distance increases from the operations (Basu, 2013; University of Maryland, 2014; NYS DeptHealth, 2014).

At the end of 2014, several public health impact and/or risk assessment investigations into potential public health risks associated with hydraulic fracturing in Shale rock formations finalised their reports (Basu, 2013; Canadian Council of Academies, 2014; University of Maryland, 2014; NYS DeptHealth, 2014). Each of these state and national reviews concluded that despite the substantial experience in hydraulic fracturing to date, there is a distinct lack of substantive research to address the main public health concerns (Cook et al., 2013; Canadian Council of Academies, 2014; University of Maryland, 2014; NYS DeptHealth, 2014, Adgate, 2014; Levy, 2014).

Study design of the existing epidemiological or public health studies has been described as exploratory in nature and criticised as often inadequate to confirm suggested associations between hydraulic fracturing activities and the described adverse health outcomes. The general consensus was that bias and confounding issues had not been adequately addressed (Canadian Council of Academies, 2014; University of Maryland, 2014; NYS DeptHealth, 2014, Adgate, 2014; Levy, 2014).

In Australia, the only relevant health study investigating health outcomes, in any way related to hydraulic fracturing, is an occupational health study, entitled *Health Watch,* that has been tracking the health of over 20,000 past and present petroleum industry employees since 1980 (Monash University, 2013). However, while employees will receive the greatest exposures to any chemicals used during hydraulic fracturing, they are not representative of the general population, and the study, like most occupational health studies, will not be directly applicable to a broader public health assessment.

Likelihood of a contamination event occurring

Surface spills (at each stage of operations, including transport accidents, broken gauges, pipes and connections) and sub-surface leaks (from faulty or damaged well casings and wastewater storage ponds) are not uncommon in most types of industrial and resource projects (Waxman, Markey and DeGrette, 2011; O'Kane, 2014a). For example, there are common regulatory requirements for all resource companies to develop chemical and hydrocarbon spill management and recovery plans that include reporting of any significant chemical or hydrocarbon release into the environment to environment and resource regulators. The likelihood for release of chemical additives from hydraulic fracturing during transport and operational activities is unlikely to differ significantly to other resource activities using large volumes of process chemicals and water (O'Kane, 2014a). While the frequency will vary a probable spill frequency of between 3.3 and 6.6 per cent was considered reasonable for an industry funded health risk assessment (Gradient, 2013).

Maryland Department of Natural Resources and Maryland Department of Environment (2015) compiled a number of expert teams to assess risks related to identified public health and amenity issues associated with natural gas projects employing hydraulic fracturing, that they refer as unconventional gas well development (UGWD) projects. A "moderate" consequence and "low" likelihood rating with an overall "low" risk rating was assigned to all surface spills associated with transport, mixing and use of drilling and hydraulic fracturing fluids. This risk rating related to potential contamination of both surface and groundwater (Maryland Department of Natural Resources and Maryland Department of Environment, 2015). However an overall risk of "moderate" was assigned to risks associated with absorbed methane in groundwater sources within one kilometre of the limit of the nearest fracture zone to the groundwater supply (Maryland Department of Natural Resources and Maryland Department of Environment, 2015).

A similar review entitled "National Human Health Risk Evaluation for Hydraulic Fracturing Fluid Additives" (Gradient, 2013) determined a Hazard Quotient (HQ) by comparing a derived distribution of possible exposure concentrations of drilling and hydraulic fracturing chemical additives, using standardised health risk assessment methodology. For HQ less than one, the potential outcome is not expected as the likely exposure concentration is below the safe guideline value. This study reported that spills of typical hydraulic fracturing and flowback fluids are expected to be “insignificant” (Gradient, 2013).

Investigations of potential contamination events from hydraulic fracturing operations in the USA have not provided any evidence of contamination from release of fluids into the fracture zone and the risk of this occurring is considered remote, if not implausible, due to the considerable distances between the shale and the closest freshwater aquifers and because considerable pressure is necessary to force fluids upwards against gravity, even if existing faults were present within fracture zones (RS&RAE, 2012; Gradient, 2013; Maryland Department of Natural Resources and Department of Environment, 2015).

The likelihood of any contamination event occurring will be influenced by the attention given to effective risk management in conjunction with:

- Implementation of best practice methodology at each stage of the process of the shale and tight gas project, from exploration to proof of concept, production and decommissioning.
- Highest quality equipment and infrastructure design and construction.
- Regular and routine testing, maintenance and surveillance monitoring to detect deviations from best practice for prompt implementation of effective mitigation strategies.
- Effective and practiced incident and emergency management plans to minimize the extent of impact of unavoidable accidents and incidents.

Risk Management

In the context of minimising or eliminating the impacts of contaminated drinking water to the Western Australian public, appropriate risk management will incorporate:

- Gas companies employing best practice technologies and procedures to prevent significant chemical release into the environment.
- Stringent regulatory review and auditing of gas extraction activities to ensure best practice is employed continuously and all legislative requirements have been met.

- Regular and routine review of surveillance monitoring of sentinel water bores to evaluate whether identified chemicals of concern are being detected at levels greater than what is known to occur naturally as background.
- Regular and timely notification of local stakeholders, regulators and the DOH of any significant changes in chemical concentrations, along with mitigation strategies and plans to prevent further impacts.

If mitigation strategies are not effective, the Executive Director of Public Health may direct the closure of any water supply that has been significantly impacted to prevent contaminated water supplies impacting the health of the public, in accordance with the *Health Act, 1911*. Under these circumstances, the DMP and DOW will ensure the provision of alternative water supplies through their combined authorities and provisions established with the gas companies at approval (DMP, 2015).

Findings

A priority list of 195 substances of concern was created that included chemicals that represent either more than one per cent of products used in hydraulic fracturing identified by the USA House of Representatives Committee, were listed as a common component of hydraulic fracturing fluid, a constituent of flowback fluid or used in the process of drilling hydraulic fracture wells. Toxicological characteristics and guideline levels for oral intake, carcinogenicity, developmental and reproductive toxicity were assessed against Australian and then other relevant international sources of toxicology standards, as appropriate.

The following HHRA framework was employed.

Issue identification

- Drilling processes
- Hydraulic fracturing stimulation treatments
- Flowback/produced water

Hazard assessment

- Comparison of measured concentrations and/or water monitoring results to health screening guidelines for oral intake.
- Worst-case scenario exposures assessed using maximum concentrations.

Exposure assessment

- Identification of potential pathways to sources of drinking water.
- Review monitoring data or fate and transport modelling for potential pathways.

Risk Categorisation

- Likelihood of a contamination event
- Possible consequences of a contamination event

Of the 195 priority chemicals identified and investigated in the Hazard Assessment:

- 78 (40%) do not have an assigned health guideline value for safe drinking (oral intake);
- 13 chemicals are known human carcinogens – but only five of these are known to cause cancer following oral exposure;
- 28 chemicals have been classified as carcinogens from animal studies, without support from epidemiology;
- 35 have been listed as animal developmental/reproductive toxins, but only 28 via oral exposure.
- Many have been approved as drinking water treatments, approved food additives or for use in groundwater machinery.
- Along with release of natural gas from the shale and tight gas reserves, many other organic hydrocarbons may be released into the flowback fluids (and produced waters). For example

benzene, ethylbenzene, toluene and xylene (BTEX), and naphthalene are commonly (thermogenically) produced as organic matter within the rock formation decomposes over time. Naturally occurring radioactive materials (NORMs) within the shale may also be released into the flowback and produced water. The composition and concentration of flowback materials will vary between locations based on the geology and history of the reserve formation.

Exposure risk from contamination of drinking water is dependent on the local environmental conditions, geology, hydrogeology and geographical placement with respect to usable water reserves in general, and more specifically on designated drinking water supplies. Likelihood of a contamination event is largely dependent on failure to follow industry best practice design, construction, maintenance and closure with full implementation of effective management plans and monitoring impacts of any environmental release of chemicals above natural background levels. The overall risk of such an event is categorised by determining the number of people who are likely to be impacted and the severity of these impacts. This determination is best made with sufficient relevant and current scientific evidence that allows a certain and reliable conclusion to be made. The balance between adopting a precautionary yet practicable approach to background and ongoing surveillance monitoring is essential so that where risks are determined to be significant, appropriate levels of risk management are applied to minimize, if not eliminate these risks and potential impacts.

Discussion

Hydraulic fracturing within drinking water source areas has the potential to affect water quality, yet the level of risk is dependent on the chemicals used or produced, operational practices employed and location of wells and extent of fracture zones relative to the drinking water supply or source area. Where hydraulic fracture stimulation is proposed within pubic drinking water source areas (PDWSAs) the perceived risk of any chemicals released into the environment reaching the water source is increased.

The DOH initially undertook a Preliminary Health Risk Assessment of hydraulic fracturing for unconventional gas (PHRA) which has been superseded by this HRA. As part of the PHRA certain recommendations were made in relation to the protection of PDWSAs and included:

- *Consideration of exclusion zones near drinking water sources and abstraction well heads*
- *Transparent risk management that takes public health into consideration*
- *Characterisation of local geological and hydrogeological conditions*
- *Reporting of chemicals used in hydraulic fracturing, including chemical identity and human toxicological profile*
- *Industry best practice should be standard for all hydraulic fracturing operations that are likely to impinge upon drinking water supplies*
- *Background and ongoing surveillance monitoring*

The majority of these recommendations, after consultation, have been addressed by regulatory agencies, including the Department of Mines and Petroleum, the Environmental Protection Authority and the Department of Water, and are addressed below.

Exclusion zones

The issue of setbacks, separation distances and exclusion or prohibition zones around water assets has been widely supported. The NSW Chief Scientist and Engineer published an information paper on managing the interface between coal seam gas (CSG) activities and other land uses (O'Kane, 2014c). It discussed how the risks are assessed and understood is fundamental to the management of perceived risk, which is significantly influenced by proximity of the industry to communities. It also describes how setbacks, or separation distances, assist regulators to protect "entities that have been judged to merit additional protection, like human and animal inhabited spaces – including residences, urban areas, schools, hospitals – and surface and subsurface water resources" (O'Kane, 2014c, p. iii).

Exclusion zones can be:

- prescriptive and defined by legislation or by industry codes; or
- outcomes-based where specific risks and impacts of an individual project and/or site are assessed and setback distances applied with consideration of the research evidence; or
- a combination of both approaches (O'Kane, 2014c).

Within public drinking water source areas (PDWSAs) in WA, setback distances in the form of prioritized protection zones are prescribed for specific land use compatibilities (Department of Water, 2014a). Priority 1, 2 and 3 protection areas are based on proximity to a PDWSA reservoir (Reservoir Protection Zone) or within 500 metres of an existing or proposed drinking water source bore (Wellhead Protection Zone) (Department of Water, 2014a). However, extraction industries are conditionally compatible and may operate within these zones with specific restrictions imposed. Restrictions regarding storage of fuels and chemicals are imposed, often with strict guidelines for rehabilitation or other conditions placed on the operation lease (Department of Water, 2014a).

Hydraulic fracturing directional drilling allows for the movement of vertical wells and well heads away from sensitive areas with the establishment of horizontal or high angle wells into the shale gas reserves several kilometres below the ground surface (R. Wilkinson, APPEA Technical Briefing, 11 December 2014). Hence it is realistic for proposed surface activities to be relocated beyond water protection zones. In highly sensitive or contentious areas, movement of the surface equipment and vertical well could reduce associated risks of any potential surface spills contaminating sensitive shallow groundwater or local surface waters.

Buffer distances are documented in a Memorandum of Understanding (MOU) between the WA Environmental Protection Authority (WA EPA) and DMP that trigger liaison between the departments with possible referral of projects for further environmental review (WA EPA, 2009). For example, where a proposed activity is within two kilometres of a town site, the coastline or within a public drinking water source area (including a water reserve, water catchment and groundwater protection area and declared or proposed water supply catchment area) or an area used for other water supply purposes, the DMP will liaise with WA EPA regarding requirements for further environmental assessment (WA EPA, 2009).

Public health

Following interagency collaboration and consultation, the WA EPA (2014) recently published a bulletin outlining circumstances under which proposals using hydraulic fracturing for onshore natural gas in shale and tight rocks will be assessed. It also describes expectations for environmental impact assessment and details what is considered to be sufficient information to undertake a thorough assessment of impacts and risks to the environment, including human health (WA EPA, 2014). The EPA advocates a precautionary approach and best practice management, especially where there is uncertainty about the potential risks and impacts to the environment (WA EPA, 2014, p1).

The DMP will liaise with the EPA if proposed hydraulic fracturing activity is likely to impact a water resource area, including a water reserve, water catchment and groundwater protection area and declared or proposed water supply catchment area (WA EPA 2009).

In addition to effective risk management and communication, it is imperative that WA regulators and stakeholder agencies continue to consult and collaborate to ensure public health is considered in all approval and regulatory activities undertaken related to hydraulic fracturing of shale and tight gas reserves in WA.

Characterisation of local geology and hydrogeology

The WA EPA Bulletin (WA EPA, 2014) reiterates that building community confidence in the regulation of hydraulic fracturing requires a sound knowledge based on the hydrogeology in the target area, the receiving environment and the chemicals and techniques involved. Where the project is likely to impact an environmentally sensitive area or drinking water source area or any other water supplies, additional information on the local geological and hydrogeological is conditions required to assess the risk of all potential impacts, including to local water resources information (WA EPA, 2014).

Detailed environmental impact assessment is indicated based on a number of factors including the scale of the proposal, uncertainty related to limited knowledge of the local geological and hydrogeological characteristics and sensitivity of local receptors (WA EPA, 2014). Knowledge of the aquifer systems in the Perth Basin is generally well understood' therefore assessment of potential impacts from hydraulic fracturing is generally well-informed by science. However in the Canning, Carnarvon and Officer Basins the aquifer systems are less well understood, and as a greater level of scientific uncertainty exists, more detailed investigations will be required (WA EPA, 2014).

Background and surveillance monitoring

Relevant baseline (or background) investigations and ongoing surveillance monitoring, from the exploration stage through to closure and rehabilitation of the project, will build a cumulative dataset related to:

- Groundwater and surface water characteristics
- Propagation of fractures
- Water use
- Well design and integrity
- Hydraulic fracture fluids and produced waters

The WA EPA Bulletin 22 *Hydraulic fracturing for onshore natural gas from and tight rocks* (WA EPA, 2014) provides further detail on information requirements under each of the headings listed above. Specifically with respect to **"**fracking fluids and produced water" the following are listed:

- Identify chemicals and likely concentrations in fracking fluids and produced water.
- Provide ecotoxicity and biodegradability information on all chemicals used.
- Demonstrate a best-practice approach to the choice and use of fracking fluids.
- Identify expected final concentrations of fracking chemicals, released formation chemicals (e.g. metals, hydrocarbons) and radioactive elements in flowback and produced formation fluid.
- Provide information about expected volumes of fracking, flowback and produced formation fluids.

- Detail arrangements for storage and management of wastewater (i.e. drilling fluids, flowback water and produced formation water), including choice of tanks or ponds, liners, risk of leakage and monitoring, and reporting arrangements for leakage.
- Using relevant climate data, model pond water balance to demonstrate adequacy of storage volume and identify risk and frequency of any overflows.
- Model the likely extent and distribution of spills, leakages and overflows of flowback fluid and produced water.
- Outline response measure to be implemented in the event of a spill.
- Describe measures for disposal of contaminated waste from ponds or other sources.
- Provide a description of the design, location and extent of discharges of the proposed waste facilities.
- Provide information on any proposed reinjection of wastewater, particularly in relation to potential impacts on aquifers.

Chemical disclosure

It is important to have an accurate and transparent public record of all products and chemicals used in regulated petroleum and geothermal activities. Guidance is provided by DMP's Chemical Disclosure Guideline and Environmental Risk Assessment of Chemicals used in WA Petroleum Activities Guideline (DMP, 2013a & b).

All chemicals used down a well are approved, based on an assessment of their toxicity, by the DMP and the information is made public (DMP 2014f). Companies must demonstrate that the use of chemicals does not pose an unacceptable risk to human health, the environment or groundwater resources. The chemicals are assessed under environment and safety regulations and include: toxicity to humans (including acute toxicity, carcinogenicity, mutagenicity and reproductive toxicity [DMP 2013a]); toxicity to the environment; biodegradability; potential chemical routes of exposure; and health and environment standards (DMP 2014d).

In circumstances where modelling or monitoring of local water resources indicates a significant potential for hydraulic fracture solutions to reach and/or contaminate drinking water supplies, a more detailed HHRA is necessary to adequately consider public health impacts. *Health Risk Assessment in Western Australia* (Spickett et al., 2006) and *Environmental Health Risk Assessment: Guidelines for assessing human health risks from environmental hazards* (enHealth Council, Department of Health and Aging, 2012) provide detail on the framework and process of HHRA, respectively. Both of these documents also emphasise the importance of effective risk management and appropriate risk communication.

Ecotoxicology screening levels are used to assess impacts to a variety of species with consideration of total impact on the species' population (Persoone and Gillet, 1990). In contrast, when considering public health impacts, the focus is on individuals. Complaints of public health impacts range from experiencing unpleasant tastes, noise disturbances, irritated skin and eyes and headaches to the development of acute, chronic and latent diseases. Focus is usually on protection of the most susceptible individuals in the population (babies, children and the frail-aged). Acceptability of health risk is determined objectively by comparing the estimated risk of the health impact (or disease) occurring under the modelled exposure conditions against what is predicted for the event to occur randomly. Experience from toxicological and epidemiological studies is assessed to determine predicted rates (enHealth Council, Department of Health and Aging, 2012).

Several potentially toxic chemicals have been identified within hydraulic fracturing fluids and flowback fluids and produced waters. However it is important to acknowledge that human toxicity is dependent on the concentration taken into the body, or dose. If the potentially toxic chemicals are present in hydraulic fracture fluids or in drinking water supplies at a concentration below an identified threshold of toxicological concern (TTC) it is unlikely that this exposure will lead to any aesthetic or health impact. The ADWG (NHMRC, 2014) provides maximum concentrations of potential drinking water contaminants that are known to be safe and do not adversely affect health. However, the ADWG does not provide safe levels for all of the chemicals used in hydraulic fracturing, therefore alternative human health screening levels should be consulted that evaluate oral intake.

The TTC concept is widely used by food and water supply industries in the European Union and USA to screen chemicals identified in foods at concentrations that were not previously able to be measured, and had not yet been fully assessed (Health and Environment, 2012). It is used to prioritise toxicological review of any chemicals that have not been assessed by standard toxicity-based risk assessment. If a chemical exists at very low concentrations, below the calculated TTC, it is unlikely to cause significant systemic health impacts following chronic lifelong exposures, and a more detailed health risk assessment is not considered necessary. However, if a higher exposure is measured or predicted from modelling, further appropriate health risk assessment and toxicity testing is required.

Application of TTC involves screening chemicals by grouping them into one of four categories based on their structural and physiochemical or carcinogenic properties. In 2010, the DOH coordinated the development of the Concentration of No Toxicological Concern (CoNTC) to screen detected air toxics without an adopted air guideline value (DOH, 2010). For chemicals without any existing health guideline values, development of CoNTC for a registered list of common chemicals additives for drilling hydraulic fractures and in flowback fluids would assist both the industry and regulators to undertake toxicity pre-screening. For example, if exposure assessments indicate that the chemical will exist at such low and insignificant concentrations below the CoNTC; this would provide sufficient confidence that the chemicals are not likely to cause any significant health impacts. How such a process could work is shown schematically in Figure 8.

Best practice

Shale and tight gas operators are required by DMP to meet international standards for well construction so activity does not contaminate any water sources. The wells must have several layers of cement and steel casing where they pass through underground water resources. Also before any activity can take place the wells must be tested to pressures above those required for hydraulic fracturing to ensure that there are no leaks (DMP 2014f).

The DMP initiated and chaired inter-agency working group is focused on ensuring all projects adopt industry best practice methodologies, particularly related to equipment design, drilling methods, multiple well casings, ongoing surveillance and maintenance of well integrity (testing and verification). Potential impacts to all drinking water resources will be monitored, from exploration and feasibility trials through to well closure, to demonstrate that risks have been managed and that appropriate mitigation strategies exist.

The International Energy Agency (2012) provides specific guidance to industry best practice through the “Golden Rules for a Golden Age of Gas” which is endorsed by APPEA (APPEA, nd). An abstract of the Golden Rules is provided in Appendix A. It is presented to reiterate that recommendations presented within this document are also supported by the International Energy Agency and APPEA.

The recommendations provided are also in line with the report from The Council of Canadian Academies (2014), who concluded their report with the following statement:

> *The lessons provided by the history of science and technology concerning all major energy sources and many other industrial initiatives show that substantial environmental impacts were typically not anticipated. What is perhaps more alarming is that where substantial adverse impacts were anticipated, these concerns were dismissed or ignored by those who embraced the expected positive benefits of the economic activities that produced those impacts (European Environmental Agency (EEA), 2001, 2013). Many of these adverse impacts could have been lessened, if not entirely avoided, if appropriate management measures, including monitoring programs, had been put in place from the beginning.*

Western Australia is currently in an ideal position to learn these lessons from previous experience of hydraulic fracturing in the northern hemisphere and from CSG activities within Australia, in order to establish this new industry, whilst ensuring minimal adverse impacts.

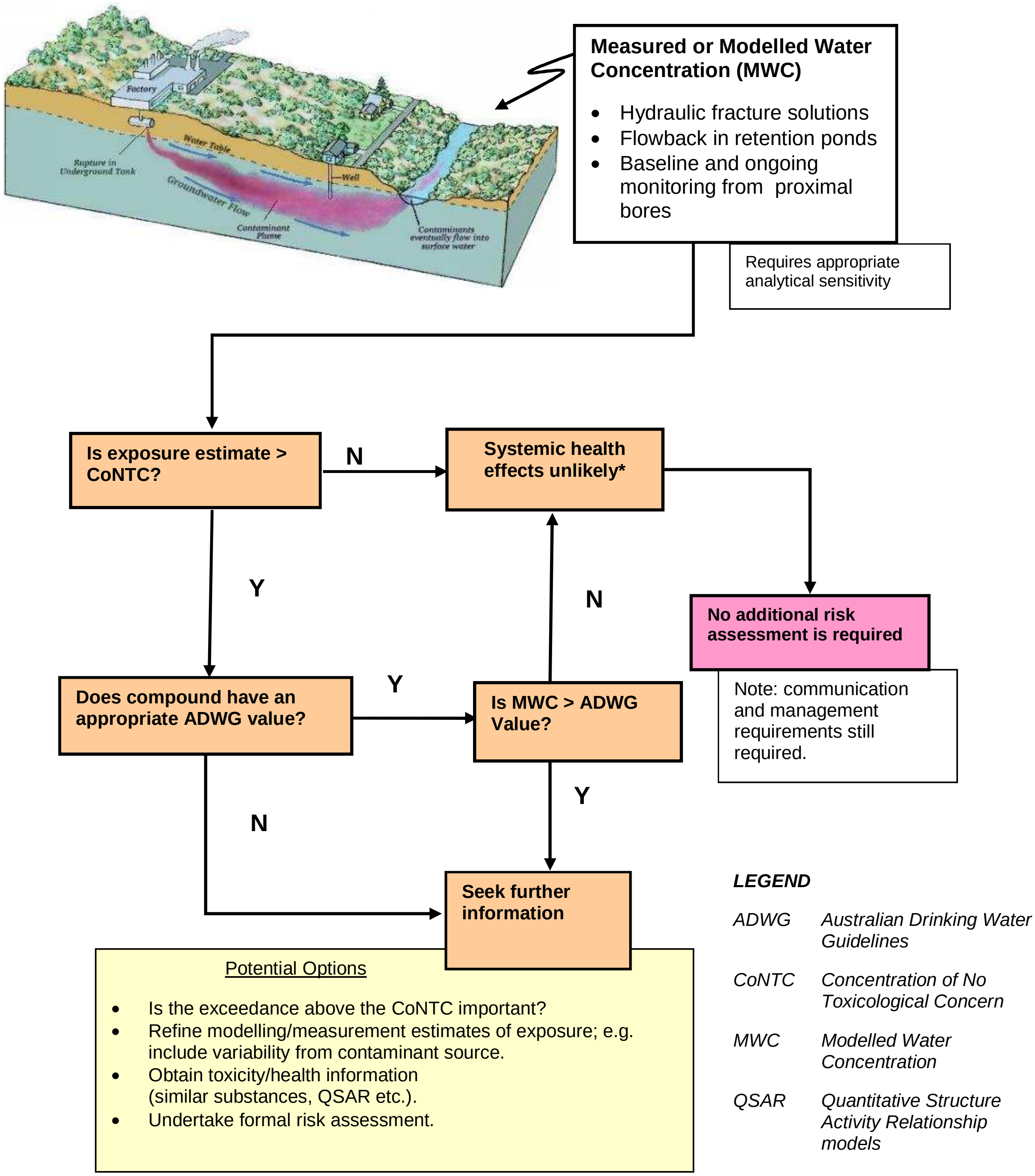

Figure 9. Schematic of application of CoNTC in screening risk assessments.

Recommendations

The DOH initially undertook a Preliminary Health Risk Assessment of hydraulic fracturing for unconventional gas (PHRA) which has been superseded by this HRA. As part of the PHRA certain recommendations were made in relation to the protection of PDWSAs some of which were included in the recommendations the DOH made to the WA Legislative Council's Inquiry into the implications for Western Australia of hydraulic fracturing for unconventional gas in 2013. Those recommendations which are supported by this HRA have been addressed by regulatory agencies in WA. See discussion for details.

To further protect drinking water sources the following recommendations are made:

1. The application of the Australian Drinking Water Guidelines for chemicals found in drinking water, or more detailed human health risk assessment where no regulatory guidelines have been established.
2. A communication plan for notification of incidents with potential to impact public health and drinking water sources is incorporated into ongoing stakeholder engagement.
3. Ongoing consultation and collaboration between all Government agencies with responsibilities related to potential impacts of hydraulic fracturing.

Tables

Table 1. Estimated recoverable shale gas by country (US EIA, 2011a).

Country	Estimated technically recoverable shale gas - trillion cubic feet (tcf)	Country	Estimated technically recoverable shale gas - trillion cubic feet (tcf)
1. China	1275	17. Pakistan	51
2. USA	862	18. Bolivia	48
3. Argentina	774	19. Ukraine	42
4. Mexico	681	20. Sweden	41
5. South Africa	485	21. Denmark	23
6. Australia	396	22. Uruguay	21
Western Australia	288	23. UK	20
7. Canada	388	24. Colombia	19
8. Libya	290	25. Tunisia	18
9. Algeria	231	26. Netherlands	17
10. Brazil	226	27. Turkey	15
11. Poland	187	28. Morocco	11
12. France	180	28. Venezuela	11
13. Norway	83	30. Germany	8
14. Chile	64	31. Western Sahara	7
15. India	63	32. Lithuania	4
16. Paraguay	62	33. Mauritania	0

Table 2. Recent reviews into impacts of hydraulic fracturing in shale, tight gas and coal seam gas \continued.

Date	Agency	Review /Report Name	Areas of Review
April 2011	US House of Representatives Committee on Energy and Commerce Minority Staff (Waxman, Markey and DeGette, 2011)	Chemicals used in hydraulic fracturing	Review of chemicals used between 2005 - 2009 supplied by 14 companies using hydraulic fracturing in US.
September 2011	Colborn, Kwiatkowski , Schultz & Bachran, 2011	Natural gas operations from a public health perspective	List of 944 products with 632 chemicals used in HF assessed: >75% could affect skin, eyes & sense, respiratory and GI organs; 40-50% could affect brain/nerves, immune, cardiovascular & kidneys; 37% could affect hormones, 25% could cause cancer/mutations. Discusses difficulty to develop effective water quality monitoring programs.
2012	Geoscience Australia	Australian Gas Resources 2012	Nature and extent of Australian gas reserves; Domestic and overseas markets
June 2012	Royal Society and Royal Academy of Engineering (RS& RAE, 2012)	Shale gas extraction in the UK: a review of hydraulic fracturing.	Terms of reference explored major risks associated with hydraulic fracturing to extract shale gas in the UK and whether they could be managed.
August 2012	Director General of the European Commission-Environment (Broomfield, 2012)	Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe.	Sets out key environmental and health risk issues associated with potential employment of high volume hydraulic fracturing in Europe; based on North American experience of hydraulic fracturing against existing EU legislative structures.
December 2012	United States Environmental Protection Authority (USEPA) (USEPA, 2012a; USEPA, 2014)	Study of the Potential Impact of Hydraulic Fracturing on Drinking Water – Progress Report. *(Outline of all 18 research projects)* Further investigations pending – anticipated to publish in May 2015.	Description of analysis of existing data; scenario evaluations; laboratory studies; toxicity assessment of chemicals reportedly used in hydraulic fracturing fluids or found in hydraulic fracturing wastewater; case studies of retrospective water impacts and prospective studies from sites before, during, and after well pad construction and hydraulic fracturing.
September 2013	Graham Sustainability Institute Integrated Assessment Report Series (Volume II, Report 5). University of Michigan. (Basu, 2013)	Hydraulic Fracturing in the State of Michigan. Public Health and Hydraulic Fracturing in Michigan.	Identified public health issues but did not attempt to undertake health risk assessment. Advocates pre-fracturing baseline environmental and public health review with ongoing surveillance; disclosure of all chemicals, increased understanding for policy makers and regulators re exact volumes, recoveries at each stage; public health education.
May 2013	Gradient Prepared for Halliburton Energy Services Inc.	National Human Health Risk Evaluation for Hydraulic Fracturing Fluid Additives.	HHRA related to drinking water from use of hydraulic fracturing with unconventional drilling in the broad range of shale plays and other tight formation across the US. Considers spills to surface and groundwater, connectivity from fractures to groundwater, including flowback fluids.

Table 2. Recent reviews into impacts of hydraulic fracturing in shale, tight gas and coal seam gas \continued.

Date	Agency	Review /Report Name	Areas of Review
May 2013	Australian Council of Learned Academies (ACOLA) (Cook et al., 2013)	Engineering Energy: Unconventional Gas Production. A study of shale gas in Australia.	Review of shale gas resources and markets; Identification of major issues requiring further investigation.
July 2013	NSW Chief Scientist and Engineer (O'Kane, 2013)	Initial report on the Independent Review of Coal Seam Gas Activities in NSW	Summary of information gathering, stakeholder meetings, interviews, community consultations, site visits, and technical paper preparation.
December 2013	Parliament of Victoria (Ross & Darby, 2013)	Unconventional Gas: Coal Seam Gas, Shale Gas and Tight Gas. An introduction and overview of issues relevant to the development of unconventional gas in Victoria	Overview of Australian gas reserves with a focus on relevance to Victoria.
2014	Council of Canadian Academies	Environmental Impacts of Shale Gas Extraction in Canada. The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction.	Focused on groundwater and surface water quality; greenhouse gases and anthropogenic climate change; disruptive effects on communities and land, adverse effects on human health (including psychosocial impacts); radioactive and chemical contaminants; local and regional impacts of increased fractured rock and impacts of minor seismic activity around existing faults.
July 2014	University of Maryland	Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland	Prepared to assist State policymakers and regulators in determining whether and how gas production from the Marcellus shale in Maryland can be accomplished without unacceptable risks of adverse impacts to public health, safety, the environment and natural resources.
September 2014	NSW Chief Scientist and Engineer (O'Kane, 2014a)	Final report - Independent Review of Coal Seam Gas Activities in NSW	Accompanied by a series of individual reports overviews a variety of environment and health impacts from CSG. Concludes that risks are similar to majority of resource projects and management are also comparable.
September 2014	NSW Chief Scientist and Engineer (O'Kane, 2014b)	Managing environmental and human health risks from CSG activities.	Identified all potential sources of exposure that may impact human health from CSG activities.
September 2014	NSW Chief Scientist and Engineer (O'Kane, 2014c)	Independent Review of Coal Seam Gas Activities in NSW Information paper: On managing the interface between coal seam gas activities and other land uses (Setbacks).	Setback distances for management of the interface of CSG activities, other land uses and public concern.
December 2014	New York State Department of Health	A Public Health Review of High Volume Hydraulic Fracturing for Gas Development.	Concludes significant uncertainty and lack of scientific evidence re: potential public health impacts. Recommends hydraulic fracturing should not proceed until a number of health outcome studies currently underway have been completed and reported on.
March 2015	US EPA Analysis of Hydraulic Fracturing Fluid Data from FracFocus Chemical Disclosure Registry 1.0 (Burden, et al., 2015)	Analysis of frequency and types of chemicals used in hydraulic fracturing in the US between January 2011 and March 2013.	Of 39,000 disclosures, across 20 US states, found that generally HF fluids comprise 88% water (by mass), 10%quartz and <1% additives.

Table 3. Approximate equivalents of regulatory authorities' carcinogenicity rating and the description used in this HHRA.

This HRA	IARC	IRIS	NTP	ESIS	Safework Australia
Known	1	A	Known	1a	1
Suspected	2A, 2B	B1, B2	Reasonably suspected	1b, 2	2
Possible	3,4	C	-	-	3

Table 4. Substances used in the drilling process, guideline values and hazards.

CASN	Chemical Name	Guideline value	NOEL toxic effect	Carcinogen	DART
637-12-7	Aluminium tristearate				
7727-43-7	Barium sulphate	Medical investigation Aesthetic 250 mg/L	-		
1302-78-9	Bentonite (Aluminium silicate clay)	Food additive	-	Known (respirable)	
1317-65-3	Calcium carbonate (chalk)	Water treatment Aesthetic 75mg/L (hardness)	-		
1305-62-0	Calcium hydroxide	Water treatment	-		
50815-10-6	Coal				
77-92-9	Citric Acid	Food additive			
14464-46-1	Cristobalite			Known (respirable)	
111-42-2	Diethanolamine				
533-74-4	Dazomet				
34590-94-8	Dipropylene glycol monomethyl ether				
64742-47-8	Distillates, petroleum, hydrotreated light				
110-17-8	Fumaric acid	Food additive	-		
111-30-8	Glutaraldehyde				
67-63-0	Isopropyl alcohol	Food additive	-		
8008-20-6	Kerosene				
12001-26-2	Mica				
14808-60-7	Quartz , (Crystalline Silica)			Known (respirable)	
7758-16-9	Sodium acid pyrophosphate	Food additive	-		
7447-40-7	Potassium chloride	Aesthetic 250 mg/L	-		
25987-30-8	PHPA-2-Propenoic acid, polymer with 2-propenamide, sodium salt				
144-55-8	Sodium Bicarbonate	Water treatment	-		
497-19-8	Sodium carbonate		-		
9004-32-4	Sodium carboxymethylcellulose				
1310-73-2	Sodium hydroxide	Water treatment	-		
8061-51-6	Sodium ligninsulfonate				
7757-83-7	Sodium sulphite	Water treatment	-		
11138-66-2	Xanthan gum	Food additive	-		
Legend	(shaded)	No available health or aesthetic guideline values.			

N.b. ADWG is a review of previously identified drinking water contaminants, or potential contaminants. If there is no guideline, additional chemical health risk investigations are indicated. This may involve a more detailed review of reported toxicological studies, computing modelling to identify an appropriate concentration of no toxicological concern (CONTC) or further toxicity testing.

Table 5. Substances used for hydraulic fracturing but not detected in flowback fluid, guideline values and hazards.

CASN	Chemical Name	Guideline value	NOEL toxic effect	Carcinogen	DART
10222-01-2	2,2-Dibromo-3-nitrilopropionamide				
111-76-2	2-Butoxyethanol	0.4mg/L	Hepatotoxicity rats		
25987-30-8	2-Propenoic acid, polymer with 2-propenamide, sodium salt				
75-07-0	Acetaldehyde			Suspected	
12125-02-9	Ammonium chloride				
1303-96-4	Borax	4mg/L	Developmental toxicity rats		Yes
10043-52-4	Calcium chloride	Food additive	-		
67-48-1	Choline chloride				
77-92-9	Citric acid	Food additive	-		
1302-74-5	Corundum				
14464-46-1	Cristobalite				
7727-54-0	Diammonium peroxodisulphate				
64742-47-8	Distillates (petroleum) hydrotreated light				
64-17-5	Ethanol	Food additive	-	Known	
68476-34-6	Fuels, diesel, no. 2			Possible	
111-30-8	Glutaraldehyde				
9000-30-0	Guar gum	Food additive	-		
68130-15-4	Guar gum, carboxymethyl 2-hydroxypropyl ether, sodium salt				
7647-01-0	Hydrochloric acid	Food additive	-		
1302-76-7	Kyanite				
1309-48-4	Magnesium oxide	Food additive	-		
14452-57-4	Magnesium peroxide				
100-97-0	Methenamine				
1302-93-8	Mullite				
9003-35-4	Phenol-formaldehyde resin				
9016-45-9	Poly(oxy-1,2-ethanediyl), alpha-(nonylphenyl)-omega-hydroxy-				
584-08-7	Potassium carbonate				
7447-40-7	Potassium chloride	Food additive	-		
1310-58-3	Potassium hydroxide				
13709-94-9	Potassium metaborate				
107-19-7	Propargyl alcohol	0.007mg/L	Organomegaly rats		
14808-60-7	Quartz			Known	
61789-71-1	Quaternary ammonium				
64741-85-1	Raffinates (petroleum), sorption process				
112945-52-5	Silica, amorphous, fumed, cryst-free	80mg/L aesthetic	Scale		
1333-73-9	Sodium borate				
497-19-8	Sodium carbonate	Food additive	-		
7647-14-5	Sodium chloride	200mg/L aesthetic	Taste		
151-21-3	Sodium dodecyl sulphate	4mg/L	No specific		
6381-77-7	Sodium erythorbate (1:1)	Food additive	-		
1310-73-2	Sodium hydroxide	Water treatment	-		
64742-94-5	Solvent naphtha (petroleum), heavy aromatics.				
55566-30-8	Tetrakis(hydroxymethyl) phosphonium sulphate				
75-57-0	Tetramethylammonium chloride				
68-11-1	Thioglycolic acid				
113184-20-6	Zirconium, hydroxylactate sodium complexes				
101033-44-7	Zirconium, tetrakis(2-(bis(2-hydroxyethyl)amino-kappa N)ethanolato-kappa O)				
Legend	(shaded)	No available health or aesthetic guideline values.			

Table 6. Substances used for hydraulic fracturing and detected in flowback fluid, guideline values and hazards.

CASN	Chemical Name	Guideline value	NOEL toxic effect	Carcinogen	DART
95-63-6	1,2,4-Trimethylbenzene				
57-55-6	1,2-Propanediol				
108-67-8	1,3,5-Trimethylbenzene				
123-91-1	1,4-Dioxane	0.05mg/L	Hepatocellular tumours rats	Suspected	
64-19-7	Acetic acid	Food additive	-		
67-64-1	Acetone	3mg/L	Nephropathy rats		Yes
98-86-2	Acetophenone	0.4mg/L	No specific		
107-02-8	Acrolein	0.002mg/L	Increased mortality rats		
7429-90-5	Aluminium	0.1mg/L aesthetic	Taste		
7664-41-7	Ammonia	0.5mg/L aesthetic	Taste		
7440-38-2	Arsenic	0.01mg/L	Carcinogenicity humans	Known	
71-43-2	Benzene	0.001mg/L	Carcinogenicity humans	Known	
111-44-4	Bis(2-chloroethyl)ether			Suspected	
124-38-9	Carbon dioxide	Food additive	-		
16887-00-6	Chloride	250mg/L aesthetic	Taste		
7782-50-5	Chlorine	5mg/L	No specific		
16065-83-1	Chromium (III)	5mg/L	No specific		
18540-29-9	Chromium (VI)	0.05mg/L	Historical level	Known	Yes
7440-50-8	Copper	2mg/L	Gastric irritation humans		
117-81-7	Di(2-ethylhexyl)phthalate	0.07mg/L	Hepatomegaly guinea pigs	Suspected	Yes
100-41-4	Ethylbenzene	0.3mg/L	Organomegaly	Suspected	
107-21-1	Ethylene glycol	7mg/L	Renal toxicity rats		Yes
64-18-6	Formic acid		Skin & mucosal irritant		
7439-89-6	Iron	3mg/L	No specific		
67-63-0	Isopropanol	Food additive	-		
7439-92-1	Lead	0.01mg/L	Lead retention infants	Suspected	Yes
67-56-1	Methanol	2mg/L	Neurotoxicity rats		
91-20-3	Naphthalene	0.07mg/L	Decreased weight rats	Suspected	
85-01-8	Phenanthrene	0.1mg/L	No specific		
108-95-2	Phenol	1mg/L	Low maternal weight rats		
7631-86-9	Silica				
14808-79-8	Sulphate	500mg/L	Purging humans		
108-88-3	Toluene	0.8mg/L	Hepatomegaly rats		Yes
1330-20-7	Xylenes	0.6mg/L	Decreased growth rats		
7440-66-6	Zinc	1mg/L	Erythrocyte changes humans		
Legend		No available health or aesthetic guideline values.			

Table 7. Additional substances detected in flowback fluid, guideline values and hazards. (continued)

CASN	Chemical Name	Guideline value	NOEL toxic effect	Carcinogenicity	DART
87-61-6	1,2,3-Trichlorobenzene	0.03mg/L	Hepatic/Thyroid changes rat		
120-82-1	1,2,4-Trichlorobenzene	0.03mg/L			Yes
105-67-9	2,4-Dimethylphenol	0.07mg/L	Behaviour change mice		
87-65-0	2,6-Dichlorophenol				
91-57-6	2-Methylnaphthalene	0.1mg/L	Alveolar proteinosis mice		
95-48-7	2-Methylphenol	0.2mg/L	Neurotoxicity rats	Possible	
79-31-2	2-Methylpropanoic acid				
109-06-8	2-Methylpyridine				
503-74-2	3-Methylbutanoic acid				
108-39-4	3-Methylphenol	0.2mg/L	Neurotoxicity rats		
106-44-5	4-Methylphenol	0.2mg/L	Neurological effects rats	Possible	
57-97-6	7,12 Dimethylbenz(a)antracene				
107-13-1	Acrylonitrile	0.1mg/L	Blood abnormalities rats	Suspected	Yes
309-00-2	Aldrin	0.0003mg/L	Hepatomegaly rats/dogs	Suspected	Yes
7440-36-0	Antimony	0.003mg/L	Decreased lifespan rats	Suspected	Yes
12672-29-6	Aroclor 1248				Yes
7440-39-3	Barium	2mg/L	Renal toxicity mice		
50-32-8	Benzo(a)pyrene	0.00001mg/L	Carcinogenicity mice	Known	Yes
205-99-2	Benzo(b)fluoranthene	0.0001mg/L	Carcinogenicity mice	Suspected	
191-24-2	Benzo(g,h,i)perylene	0.001mg/L	Carcinogenicity mice		
207-08-9	Benzo(k)fluoranthene	0.0001mg/L	Carcinogenicity mice	Suspected	
100-51-6	Benzyl alcohol	Food additive	-		
7440-41-7	Beryllium	0.06mg/L	Intestinal lesions dogs	Known	
319-85-7	beta-Hexachlorocyclocylohexane	0.00007mg/L	Infertility rats	Possible	Yes
7440-42-8	Boron	4mg/L	Foetal weight rats		Yes
24959-67-9	Bromide	4mg/L	No specific		
75-27-4	Bromodichloromethane	0.25mg/L	Carcinogenicity rats	Suspected	Yes
107-92-6	Butanoic acid				
104-51-8	Butylbenzene				
7440-43-9	Cadmium	0.002mg/L	Renal toxicity humans	Known	Yes
10045-97-3	Caesium 137				
7440-70-2	Calcium	125mg/L	Renal calculi humans		
75-15-0	Carbon disulphide	0.4mg/L	Foetotoxicity rabbits		Yes
74-87-3	Chloromethane			Suspected	Yes
7440-47-3	Chromium	0.05mg/L	(further testing required)		
7440-48-4	Cobalt	0.005mg/L	Cardiomyopathy humans	Suspected	Yes
57-12-5	Cyanide, free	0.08mg/L	Ambivalence pigs		
319-86-8	delta-Hexachlorocyclohexane				
53-70-3	Dibenz(a,h)anthracene	0.00001mg/L	Carcinogenicity mice	Suspected	
124-48-1	Dibromochloromethane	0.3mg/L	Carcinogenicity rats	Possible	Yes
84-74-2	Dibutyl phthalate	0.4mg/L	Increased mortality rats	Suspected	Yes
75-09-2	Dichloromethane	0.004mg/L	Hepatic changes rats	Suspected	
60-57-1	Dieldrin	0.0003mg/L	Hepatomegaly rats/dogs	Suspected	Yes
84-66-2	Diethyl phthalate	3mg/L	Decreased growth rats		Yes
117-84-0	Dioctyl phthalate	1mg/L	Hepatic changes rats		
122-39-4	Diphenylamine	0.07mg/L	No specific		Yes
959-98-8	Endosulfan	0.02 mg/L	neurotoxicity		
7421-93-4	Eldrin aldehyde				
206-44-0	Fluoranthene	0.1mg/L	Nephropathy mice		Yes
86-73-7	Fluorene	0.1mg/L	Erythrocyte changes mice		
16984-48-8	Fluoride	1.5mg/L	Mottling dentition humans		
76-44-8	Heptachlor	0.0003mg/L	Hepatic changes dogs	Suspected	Yes
1024-57-3	Heptachlor epoxide	0.0003mg/L	Hepatic changes dogs	Suspected	Yes
111-14-8	Heptanoic acid				
142-62-1	Hexanoic acid				
193-39-5	Indeno(1,2,3-cd)pyrene	0.0001mg/L	Carcinogenicity mice	Suspected	
58-89-9	Lindane	0.01mg/L	Nephropathy rats	Suspected	

Table 7. Additional substances detected in flowback fluid, guideline values and hazards. (continued)

CASN	Chemical Name	Guideline value	NOEL toxic effect	Carcinogenicity	DART
7439-93-2	Lithium				
7439-95-4	Magnesium	17.5mg/L	Diarrhoea humans		
7439-96-5	Manganese	0.5mg/L	No specific		
7439-97-6	Mercury	0.001mg/L	Neurotoxicity humans	Possible	Yes
74-83-9	Methyl bromide	0.001mg/L	Stomach hyperplasia rats		Yes
78-93-3	Methyl ethyl ketone	2mg/L	Decreased weight rats		Yes
7439-98-7	Molybdenum	0.05mg/L	No specific		
7440-02-0	Nickel	0.02mg/L	Organomegaly rats	Known	Yes
86-30-6	N-Nitrosodiphenylamine			Suspected	
72-55-9	p,p'-DDE	0.002mg/L	No specific	Suspected	
99-87-6	p-Cymene				
109-52-4	Pentanoic acid				
298-02-2	Phorate	0.002mg/L	No specific		
7723-14-0	Phosphorus	0.0002mg/L	Parturition rats		
7440-09-7	Potassium	High	-		
79-09-4	Propionic acid	Food additive	-		
103-65-1	Propylbenzene				
129-00-0	Pyrene	0.1mg/L	Nephrotoxicity mice.		
110-86-1	Pyridine	0.004mg/L	Hepatomegaly rats		
13982-63-3	Radium 226			Known	
7440-14-4	Radium 226,228				
15262-20-1	Radium 228			Known	
94-59-7	Safrole			Suspected	
135-98-8	sec-Butylbenzene				
7782-49-2	Selenium	0.01mg/L	No specific		Yes
7440-21-3	Silicon (elemental)				
7440-22-4	Silver	0.1mg/L	No specific		
7440-23-5	Sodium	180mg/L aesthetic	Taste		
7440-24-6	Strontium	2mg/L	Bone changes rats		
14265-45-3	Sulphite				
127-18-4	Tetrachloroethylene	0.05mg/L	CNS depression	Suspected	
7440-28-0	Thallium				
7440-31-5	Tin	high	Gastric irritation		
7440-32-6	Titanium				
75-25-2	Tribromomethane	0.25mg/L	Hepatic pathology rats	Suspected	Yes
67-66-3	Trichloromethane	0.25mg/L	Hepatic pathology dogs	Suspected	Yes
7440-62-2	Vanadium	0.04mg/L	Foetal abnormalities dogs		
7440-67-7	Zirconium				
Legend		No available health or aesthetic guideline values.			

Table 8. Exposure Assessment – Identification of potential contamination events and associated exposure pathways.

<table>
<tr><th>Source of Chemicals of Concern (COC)</th><th>Activity</th><th>Release to Environment</th><th>Receptor</th><th>Chemical Mobility Risk Factors</th></tr>
<tr><td rowspan="3">Drilling Chemicals

(Refer to Table 4 for examples of COC)</td><td>Transportation</td><td>Surface spill</td><td rowspan="10">Soil

Surface water
• Private Residence
• Small community

Groundwater
• Private Residence
• Small community
• PDSWA</td><td rowspan="10">Location, volume and concentration of spill (environmental release)
• Location of spill relative to transfer media (surface or groundwater) the chemical will travel to reach human receptors
• Volume and concentration of spill / environmental release
• Chemical and physical properties
    • Volatility – liquid to vapour
    • Viscosity - adherence to soils
    • Solubility – likelihood to dissolve in water
• Relative human toxicity when ingested from water

Soil and groundwater properties affecting transport (mobility) of chemicals of concern
• Porosity of surface (sealed - granular soil) at spill
• Potential for biodegradation by endemic microbes in soil, surface or groundwater
• Vertical distance from spill to aquifer
• Horizontal distance from spill to drinking water source area / abstraction well
• Confined / unconfined aquifer – porosity and nature of highly impermeable aquitards
• Hydraulic conductivity within aquifer – regionally and locally
• Modelled travel times indicate how long before released chemicals reach a drinking water supply
• Direction of groundwater flow (towards or away from receptor)</td></tr>
<tr><td>Preparation</td><td>Surface spill</td></tr>
<tr><td>Drilling & well production</td><td>Loss of well integrity/ well malfunction</td></tr>
<tr><td rowspan="3">Hydraulic Fracturing Chemicals
(Refer to Tables 5 & 6 for examples of COC)</td><td>Transportation</td><td>Surface spill</td></tr>
<tr><td>Preparation</td><td>Surface spill</td></tr>
<tr><td>Treatment</td><td>Loss of well integrity/ well malfunction</td></tr>
<tr><td rowspan="2">Flowback / Produced Water
(Refer to Table 7 for examples of COC)</td><td>Leak from pipework to storage pond</td><td>Surface spill</td></tr>
<tr><td>Leak from storage pond</td><td>Loss of dam integrity</td></tr>
<tr><td rowspan="2">Fuel Stores for Operational Power
(Not in scope)</td><td rowspan="2">Fuelling and tank refilling</td><td>Surface spill</td></tr>
<tr><td>Loss of well/pipe integrity</td></tr>
<tr><td>Off-Gases
(Not in scope)</td><td>Seepage</td><td>Ground seeps
Loss of well/pipework integrity</td><td>Air</td><td>• Dilution, fate and transport based on environmental dispersion and proximity of receptors to source of emission.</td></tr>
</table>

Table 9. Possible outcomes from potential exposures.

Sources - Potential Contaminated / Impacted Media	Human Receptors	Exposure Route	Possible Consequences of Contamination Event	Comments
Soil	• Workers *(Not in the scope of this report.)*	• Inhalation of soil vapours • Skin contact (dermal)	• Aesthetic discomfort from odours • Respiratory irritants • Skin irritants	Contaminated soils may act as a source for ongoing groundwater contamination if the spill is not satisfactorily remediated, or degraded in situ.
Local surface water – onsite dams	• Workers *(Not in the scope of this report.)*	• Skin contact (dermal)	• Aesthetic discomfort from taste and odour • Respiratory irritation • Skin irritation	Workers handling dam water are most likely to be exposed. Potential for off-site contamination during severe rainfall events.
Local surface water – streams/rivers/creeks	• Workers at downstream industries may be exposed. *(Not in the scope of this report.)* • Public – swimming users • Private – drinking water	• Skin contact (dermal) • Inhalation of mists • Ingestion	• Aesthetic discomfort from odours • Respiratory irritation • Skin irritation • Gastrointestinal irritation • Reproductive effects • Liver or kidney effects • Neurological effects • Cancer	Downstream uses may include industrial or agricultural businesses or small communities requiring residential water supplies. Extent of health impacts is dependent on dose and duration of exposure and susceptibility of exposed individuals.
Local groundwater Including: • Remote Aboriginal community drinking wells • Private residential wells and • PDWSAs	• Workers at downstream industries. *(Not in the scope of this report.)* • Public – swimming users • Private – drinking users	• Ingestion • Skin contact (dermal) • Inhalation of mists	• Aesthetic discomfort from odours • Respiratory irritation • Skin irritation • Gastrointestinal irritation • Reproductive effects • Liver or kidney effects • Neurological effects • Cancer	Downstream uses may include industrial or agricultural businesses or small communities requiring residential water supplies. Extent of health impacts is dependent on dose and duration of exposure and susceptibility of exposed individuals.

Bibliography

Adgate, J. (2014) *Letter to Director Environmental Health Bureau. Re: Review of Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland.* Accessed online http://phpa.dhmh.maryland.gov/OEHFP/EH/Shared%20Documents/Reports/Adgate%20comments%20on%20final%20report%202014.pdf

Atherton, F. (2014) *Chapter 4: The protection of public health.* Report of the Nova Scotia Independent Panel on Hydraulic Fracturing. Accessed online http://energy.novascotia.ca/sites/default/files/Report%20of%20the%20Nova%20Scotia%20Independent%20Panel%20on%20Hydraulic%20Fracturing.pdf?bcsi_scan_313cddce030931be=0&bcsi_scan_filename=Report%20of%20the%20Nova%20Scotia%20Independent%20Panel%20on%20Hydraulic%20Fracturing.pdf

Australian Broadcasting Corporation (ABC) (2014) *Central Greenough locks the gate on fracking*. Accessed online http://www.abc.net.au/local/stories/2014/08/19/4070205.htm

Australian Petroleum Production & Exploration Association (APPEA) (no date) *Hydraulic fracturing (fraccing)*. Accessed online http://www.appea.com.au/oil-gas-explained/operation/hydraulic-fracturing-fraccing/

ATSDR (2011). *Health Consultation: Chesapeak ATGAS 2H well site- Leroy Hill Road, Leroy- Leroy Township, Bradford County, PA*. ATSDR. Accessed online http://www.atsdr.cdc.gov/hac/pha/ChesapeakeATGASWellSite/ChesapeakeATGASWellSiteHC110411Final.pdf

ATSDR (2013). *United States Centre for Disease Control, Agency for Toxic Substances and Disease Registry*. Accessed online http://www.atsdr.cdc.gov/

Basu, N. (2013). *Public Health Technical Report. Hydraulic Fracturing in the State of Michigan.* University of Michigan, School of Public Health. Accessed online http://graham.umich.edu/media/files/HF-05-Public-Health.pdf

British Geological Society (2015) *National Methane Baseline Survey of UK groundwaters*. Accessed online http://www.bgs.ac.uk/research/groundwater/shaleGas/methaneBaseline/home.html

Broomfield, M. (2012). *Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe*. European Commission DG Environment, Didcot.

Burke, J. (2011). *Moratorium extended on fracking in NSW.* Australian Mining. Accessed online http://www.miningaustralia.com.au/news/moratorium-extended-on-fracking-in-nsw

Cannon, G., Kennedy, J. & Barndon, G. (2013). *Election candidates clarify their position on gas fracking. ABC Perth*. Accessed online http://www.abc.net.au/local/stories/2013/02/19/3693588.htm?site=perth

Chen, J., Al-Wadei, M., Kennedy, R. & Terry, P. (2014) *Hydraulic fracturing: Paving the way for a sustainable future?* Journal of Environmental and Public Health. 2014: 1-10.

Colborn, T., Kwiatkowski, C., Schultz, K. & Bachran M. (2011). *Natural gas operations from a public health perspective. Human and Ecological Risk Assessment. 17(5): 1039-1056.* Accessed online http://cce.cornell.edu/EnergyClimateChange/NaturalGasDev/Documents/PDFs/fracking%20chemicals%20from%20a%20public%20health%20perspective.pdf

Cook, P., Beck, V., Brereton, D., Clark, R., Fisher, B., Kentish, S., Toomey, J. and Williams, J. (2013). *Engineering energy: unconventional gas production. Report for the Australian Council of Learned Academies*. Accessed online www.acola.org.au

Coram, A., Moss, J. & Blashki, G. (2014). Harms Unknown: Health Uncertainties Cast Doubt on the Role of Unconventional Gas in Australia's Energy Future. *Medical Journal of Australia 200 (4): 210-213*.

Council of Canadian Academies (2014) *Environmental Impacts of Shale Gas Extraction in Canada. Ottawa: The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction.* Accessed online http://www.scienceadvice.ca/uploads/eng/assessments%20and%20publications%20and%20news%20releases/

shale%20gas/shalegas_fullreporten.pdf?bcsi_scan_313cddce030931be=0&bcsi_scan_filename=shalegas_fullreporten.pdf

CSIRO (2013) Australia's shale gas resources. CESREfs017-12. Accessed online at: www.csiro.au/Outcomes/Energy/...oil...gas/Shale-gas-potential.aspx

Darling, WG and Gooddy, DC (2006). *The hydrogeochemistry of methane: Evidence from English groundwaters.* Chemical Geology: 229 (4): 293-312

DART (2013) *Developmental and Reproductive Toxicology Database*. National Library of Medicine, Bethesda MD. Accessed online at: http://toxnet.nlm.nih.gov

Day, S., Dell'Amico, M., Etheridge, D., Ong, C., Rodger, A., Sherman, B., and Barrett, D. (2013) *Characterisation of regional fluxes of methane in the Surat Basin, Queensland.* Published by CSIRO Energy Flagship. Accessed online at: http://www.gisera.org.au/publications/tech_reports_papers/ghg-emission-proj-1-lit-review.pdf

Deeley G. (2011) *Fate and transport evaluation of potential release scenarios during hydraulic fracturing operations.* Presentation to Hydraulic Fracturing Technical Workshop 3 – Contaminant Identification, Transformation and Transport Theme. March 28-29 2011. Accessed online: http://www2.epa.gov/sites/production/files/documents/fateandtrasportevaluationofpotentialreleasescenariosduringhfoperations.pdf

Dekant, W., Melching-Kollmuss S & Kalberlah F (2010). *Toxicity assessment strategies, data requirements, and risk assessment approaches to derive health based guidance values for non-relevant metabolites of plant protection products.* Regulatory Toxicology and Pharmacology 56, 135-142.

Department of Climate Change and Energy Efficiency (2012) *Australian National Greenhouse Accounts. Coal Seam Gas: Estimation and Reporting of Greenhouse Gas Emissions.* Accessed online http://www.environment.gov.au/system/files/pages/63b569ff-ae63-4d7b-be54-16f2e79900e0/files/nga-factsheet7.pdf

Department of Health (DOH) (2010) *Guidance on Using the Threshold of Toxicological Concern to Screening Evaluation of Air Toxics*, Accessed online http://www.public.health.wa.gov.au/cproot/3281/2/11830%20GUIDANCE%20OF%20AIR%20TOXINS%20(Summary)pdf.pdf

DOH (2013) *WA Department of Health Submission to Standing Committee on Environment and Public Affairs. Inquiry into the Implications for Western Australia of Hydraulic fracturing for Unconventional Gas*. Accessed online http://www.parliament.wa.gov.au/parliament/commit.nsf/(Evidence+Lookup+by+Com+ID)/9D7EF06DA3B8A9C348257C40000FA2F2/$file/ev.fra.131004.sub.107.+wa+department+of+health.pdf

DOH (2014) *Drinking Water in WA*. Accessed online http://www.public.health.wa.gov.au/2/640/2/drinking_water.pm

DOH Australia (2005a). *Acceptable Daily Intakes for Agricultural and Veterinary Chemicals*. Accessed online http://www.health.gov.au/internet/main/publishing.nsf/content/ocs-adi-list.htm

DOH Australia (2005b). *Nutrient Reference Values for Australia and New Zealand Including Recommended Dietary Intakes*. Department of Health, Canberra.

DOH Australia (2013). *Australian and New Zealand Food Standards Code*. Australian Government Accessed http://www.comlaw.gov.au/Search/food%20standards%20code

Departments of Industry and Resources & Radiological Council (2005) *Memorandum of Understanding between the Department of Industry and Resources and the Radiological Council in relation to the regulation of Naturally Occurring Radioactive Materials associated with Petroleum Exploration and Production.* Accessed online http://www.dmp.wa.gov.au/documents/RadiologicalCouncil_MOU.pdf

DMP (2013a). *Chemical Disclosure Guideline*. Version 2: August2013.

Accessed online http://www.dmp.wa.gov.au/documents/ENV-PEB-178.pdf

DMP (2013b). *Environmental Risk Assessment of Chemicals used in WA Petroleum Activities Guideline*. WA Department of Mines and Petroleum, Perth. Accessed online http://www.dmp.wa.gov.au/documents/ENV-PEB-165.pdf

DMP (2013c). *WA Hydraulic Fracture Stimulation Well List*. WA Department of Mines and Petroleum, Perth. Accessed online http://www.dmp.wa.gov.au/documents/WA_Hydraulic_Fracture_Stimulation_Well_List.pdf

DMP (2014a). *Natural Gas from Shale and Tight Rocks. An overview of Western Australia's Regulatory Framework*. DMPFEB14_2960. Department of Mines and Petroleum, Perth. Accessed online http://www.dmp.wa.gov.au/documents/Natural_Gas_from_Shale_and_Tight_Rocks_-_An_overview_of_Western_Australia_regulatory_framework.pdf

DMP (2014b). *Natural Gas from Shale and Tight Rocks Fact Sheet. Chemicals used in hydraulic fracturing.* DMPSEP14_3288. Department of Mines and Petroleum, Perth. Accessed online http://www.dmp.wa.gov.au/documents/Chemicals_used_in_hydraulic_fracturing.pdf

DMP (2014c). Natural Gas from Shale and Tight Rocks Fact Sheet. Water use and management. DMPSEP14_3281. Department of Mines and Petroleum, Perth. Accessed online http://www.dmp.wa.gov.au/documents/Petroleum_Water_Use_and_Management_Fact_Sheet(1).pdf

DMP (2014d). *Natural Gas from Shale and Tight Rocks Fact Sheet. What is shale and tight Gas?* DMPSEP14_3282. Department of Mines and Petroleum, Perth. Accessed online http://www.dmp.wa.gov.au/documents/Petroleum_What_is_Shale_Gas_Fact_Sheet.pdf

DMP (2014e). *Survey: Community attitudes toward shale and tight gas.* DMPJUN14_3175. Department of Mines and Petroleum, Perth. Accessed online http://www.dmp.wa.gov.au/documents/Shale_Gas_Community_Survey_Information_Sheet.pdf

DMP (2014f). *Natural Gas from Shale and Tight Rocks*. Accessed online http://www.dmp.wa.gov.au/15136.aspx

DMP (2015). *Draft. Statutory Framework for Shale and Tight Gas Projects in Western Australia V2. March 2015.*

Department of Water (2013). *Drinking Water*. Government of Western Australia. Accessed online http://www.water.wa.gov.au/Managing+water/Drinking+water/default.aspx

Department of Water (2014a) *Water resources inventory 2014. Water availability, quality and trends*. Accessed online http://www.water.wa.gov.au/PublicationStore/first/107262.pdf

Department of Water (2014b) *Land use compatibility in PDWSAs. WQPN 25.* Accessed online http://www.water.wa.gov.au/PublicationStore/first/12441.pdf

Duffy, A. (2012a). Victoria bans fracking. *Australian Mining*. Accessed online http://www.miningaustralia.com.au/news/victoria-bans-fracking.

Duffy, A. (2012b). Confusion reigns on mining bans. *Australian Mining.* Accessed online http://www.miningaustralia.com.au/features/confusion-reigns-on-mining-bans.

Education and Health Committee (2007). Legislative Assembly Inquiry into the cause of lead pollution in the Esperance area. Accessed online http://www.parliament.wa.gov.au/parliament/commit.nsf/all/28F900665F5C386048257831003E970C?opendocument

EEA (2001). *Late Lessons from Early Warnings: The Precautionary Principle 1896–2000*. Copenhagen, Denmark: EEA. Accessed online http://www.eea.europa.eu/publications/environmental_issue_report_2001_22

EEA (2013). *Late Lessons from Early Warnings: Science, Precaution, Innovation*. Copenhagen, Denmark: EEA. Accessed online http://www.eea.europa.eu/publications/late-lessons-2

enHealth Council, Department of Health and Aging (2012). *Environmental health risk assessment: Guidelines for assessing human health risk from environmental hazards*. Commonwealth of Australia, Canberra. Accessed online https://www.health.gov.au/internet/main/publishing.nsf/Content/A12B57E41EC9F326CA257BF0001F9E7D/$File/DoHA-EHRA-120910.pdf

European Commission (2012). *Opinion on Use of the Threshold of Toxicological Concern (TTC) Approach for Human Safety Assessment of Chemical Substances with focus on Cosmetics and Consumer Products.* Accessed online http://ec.europa.eu/health/scientific_committees/consumer_safety/docs/sccs_o_092.pdf

Four corners (2011). Questions posed by Four Corners. *Australian Broadcasting Commission*. Accessed online http://www.abc.net.au/4corners/special_eds/20110221/gas/docs/QGC_Response.pdf

Fox, J. (2010). *GasLand*. Palace Films, Melbourne.

Fracfocus (2013a). *What Chemicals are used*? Accessed online http://fracfocus.org/chemical-use/what-chemicals-are-used

Fracfocus (2013b). *Fracfocus, find a well*. Accessed online http://www.fracfocusdata.org/fracfocusfind/

General Purpose Standing Committee (2012). *NSW Legislative council inquiry into coal seam gas*. New South Wales Parliament, Sydney.

Geoscience Australia (2012) *Australian Gas Resource Assessment 2012*. Accessed online http://www.ga.gov.au/webtemp/image_cache/GA21116.pdf

Gradient (2013) *National Human Health Risk Evaluation for Hydraulic Fracturing Fluid Additives.* Prepared for Halliburton Energy Services Inc. Accessed online http://www.appea.com.au/wp-content/uploads/2013/08/Gradient-Report_2.pdf

Hadji, R. and Sweeney, P. (2014). *Greenough says no to fracking*. Geraldton Guardian 15 August 2014.

Haluszcak, A., Rose, W. & Kump, L. (2013). *Geochemical evaluation of flowback brine from Marcellus gas wells in Pennsylvania, USA*. Applied Geochemistry, vol. 28, pp. 55-61.

Hayes, T. 2009. *Sampling and analysis of water streams associated with the development of Marcellus Shale Gas*. Gas Technology Institute for Marcellus Shale Coalition. Accessed online http://eidmarcellus.org/wp-content/uploads/2012/11/MSCommission-Report.pdf.

Helman, C. (2011) *Questions emerge on Wyoming fracking study*. *Forbes*, December 9, 2011. Accessed online http://www.forbes.com/sites/christopherhelman/2011/12/09/questions-emerge-on-epas-wyoming-fracking-study/

Howarth, R. & Ingraffea, A. (2011). Should fracking stop? *Nature*, vol. 477, pp271-273.

Hunter, T. (2011). *Regulation of Shale, Coal Seam and Tight gas activities in Western Australia: Final.* Accessed online http://www.dmp.wa.gov.au/documents/000041.jason.medd(1).pdf

IARC (1973). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 3 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol3/volume3.pdf

IARC (1976) *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 10 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol10/volume10.pdf

IARC (1987a). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 23 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol87/volume87.pdf

IARC (1987b). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 5 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol5/volume5.pdf

IARC (1989). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 47 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol47/mono47-16.pdf

IARC (1995). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 63 Accessed online http://monographs.iarc.fr/ENG/Publications/techrep42/TR42-15.pdf

IARC (1999a). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 71 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol71/mono71-25.pdf

IARC (1999b). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 71 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol71/mono71-66.pdf

IARC (1999c). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 71 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol71/mono71-32.pdf

IARC (1999d). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 74 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol86/mono86.pdf?bcsi_scan_2F83426B613409AB=0&bcsi_scan_filename=mono86.pdf

IARC (1999e). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 73 Accessed online http://monographs.iarc.fr/ENG/Publications/techrep42/TR42-16.pdf

IARC (1999f). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 71 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol71/mono71-7.pdf

IARC (1999g). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 71 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol71/mono71-73.pdf

IARC (2000). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 77 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol77/mono77-10.pdf

IARC (2000b). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 78 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol78/mono78.pdf

IARC (2001). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 79 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol79/mono79-17.pdf

IARC (2002). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans,* vol 82 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol82/mono82-8.pdf

IARC (2010). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans,* vol 32 Accessed online http://monographs.iarc.fr/ENG/Monographs/vol32/volume32.pdf

IARC (2012a). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100c Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-14.pdf.

IARC (2012b). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 96 pp1278-9. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol96/mono96-6F.pdf.

IARC (2012c). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100c pp41-93. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-6.pdf

IARC (2012d). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100c pp147-68. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-9.pdf

IARC (2012e). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100c Accessed online http://monographs.iarc.fr/ENG/Monographs/vol101/mono101-006.pdf.

IARC (2012f). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100c. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-10.pdf

IARC (2012g). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100c. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-7.pdf.

IARC (2012h). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100f. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100F/mono100F-14.pdf

IARC (2012i). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100c. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-8.pdf

IARC (2012j). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol 100f. Accessed online http://monographs.iarc.fr/ENG/Monographs/vol100F/mono100F-24.pdf

International Energy Agency (2012) *Golden rules for a golden age of gas: World energy outlook. Special report on unconventional gas*. Accessed online: http://www.appea.com.au/wp-content/uploads/2013/05/WEO2012_GoldenRulesReport.pdf

Jackson, R., Vengosh, A., Darrah, T., Warner, N., Down, A., Poreda, R., Karr, J. D. (2013). *Increased stray gas abundance in a subset of drinking water wells near Marcellus Shale gas extraction*. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 110(8),11250-11255.

Kappel & Nystrom (2012). *Dissolved Methane in New York Groundwater.* USGS, New York. Accessed online http://pubs.usgs.gov/of/2012/1162/pdf/ofr2012-1162_508_09072012.pdf

Kovats, S., Depledge, M., Haines, A. & Fleming, L.E. (2014). *The health implications of fracking*. The Lancet 383 (March 1): 757-758.

Lapenna, S. and Worth, A. (2011) *Analysis of the Cramer classification scheme for oral systemic toxicity - implications for its implementation in Toxtree*. doi:10.2788/39716 Accessed online: http://ihcp.jrc.ec.europa.eu/our_labs/predictive_toxicology/doc/EUR_24898_EN.pdf

Levy, J. (2014) *Letter to Director Environmental Health Bureau Review of Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland*. Accessed online http://phpa.dhmh.maryland.gov/OEHFP/EH/Shared%20Documents/Reports/Levy%20comments%20on%20final%20HIA%20report%208-14.pdf

Maryland Department of Natural Resources and Maryland Department of Environment (2014) *Marcellus Shale Safe Drilling Initiative Study. Part III. Final Report. Findings and Recommendations*. Accessed online http://www.mde.state.md.us/programs/Land/mining/marcellus/Documents/Final_Marcellus_Shale_Report.pdf

Maryland Department of Natural Resources and Maryland Department of Environment (2015) *Assessment of Risks from Unconventional Gas Well Development in the Marcellus Shale of Western Maryland.* Accessed online http://www.mde.state.md.us/programs/Land/mining/marcellus/Documents/A_Final_Draft_Cover_Ex_Sum_and_RA.pdf

Melching-Kollmuss S, Dekant W & Kalberlah F (2010). *Application of the "threshold of toxicological concern" to derive tolerable concentrations of "non-relevant metabolites" formed from plant protection products in ground and drinking water.* Regulatory Toxicology and Pharmacology 56, 126-134.

Mercer, D. (2014) *Coorow calls for stop to fracking*. *West Australian 22 August 2014*.

Middleton, H., Moore, M.R., Chapman, H., Leusch, F., Tan, B., Drew, R., Frangos, J., Khan, S., Leslie, G. & Shaw, G. (2008) *Recycled Water Quality. A guide to determining, monitoring and achieving safe concentrations of chemicals in recycled water*. Accessed online http://www.ephc.gov.au/sites/default/files/WQ_AGWR_RPT_Uniquest_Recycled_Water_Quality_Final_200806.pdf.

Molofsky, L., Connor, J., Wylie, A., Wagner, T., & Farhat, S.(2013) *Evaluation of methane sources in groundwater in northeastern Pennsylvania.* Groundwater, 51(3), 333-349.

Monash University and Deakin University (2001) *Occupational Health in the Oil Industry: Health Watch: Lympho-haemopoetitic cancer and exposure to benzene in the Australian Petroleum Industry. Technical Reprot and Appendices.* Accessed online http://www.aip.com.au/pdf/health/case_study.pdf

Monash University (2013) *Occupational Health in the Oil Industry: Health Watch: November 2013 A continuing study of the health of people in the Australian Petroleum Industry*. Accessed online http://www.aip.com.au/pdf/health/Healthwatch13%20-%20InfoSheet.pdf

Munro, I., Ford, R., Kennepohl, E. & Sprenger, J. (1996) *Correlation of structural class with no-observed effect levels: a proposal for establishing a threshold of concern*. Food Chem. Toxicol. 34 (9): 829–867.

NHMRC (2014) *The Australian Drinking Water Guidelines 6 - 2011*. Version 3.0 Updated December 2014. Australian Government, Canberra. Accessed online: https://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh52_australian_drinking_water_guidelines_150108.pdf

NICNAS (2012) *National Assessment of Chemicals Associated with Coal Seam Gas Extraction in Australia – fact sheet*. Accessed online: http://www.nicnas.gov.au/communications/issues/fracking-hydraulic-fracturing-coal-seam-gas-extraction/information-sheet

Newell, S (2014) *Zoning as a response to hydraulic fracturing: A comparison of New York and Pennsylvania (Thesis)*.

New South Wales Trade and Investment (2014) *NSW regulatory framework for coal seam gas*. Available at: http://www.resourcesandenergy.nsw.gov.au/landholders-and-community/coal-seam-gas/features/nsw-regulatory-framework

New York State DEC (2011) *Revised Draft Supplemental Generic Environmental Impact Statement on The Oil, Gas and Solution Mining Regulatory Program: Well permit issuance for horizontal drilling and hydraulic fracturing in the Marcellus shale and other low-permeability gas reservoirs.* Accessed online http://www.dec.ny.gov/energy/75370.html

New York State DEC (2014) Press Release: New York State Department of Health Completes Review of High-volume Hydraulic Fracturing. DEC Commissioner Martens Will Issue a Findings Statement Early Next Year to Prohibit High-Volume Hydraulic Fracturing. Accessed online http://www.dec.ny.gov/press/100055.html

New York Times (2012) *A case of fracking related contamination- source documents.* New York Times. Accessed online http://www.nytimes.com/interactive/us/drilling-down-documents-7.html#document/p1/a27935

O'Kane (2013) *Initial report on the Independent Review of Coal Seam Gas Activities in NSW.* Accessed online http://www.chiefscientist.nsw.gov.au/coal-seam-gas-review/initial-report-july-2013

O'Kane (2014a) *Final report - Independent Review of Coal Seam Gas Activities in NSW.* Accessed online http://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0005/56912/140930-CSG-Final-Report.pdf

O'Kane (2014b) *Managing environmental and human health risks from CSG activities.* Accessed online http://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0006/56922/140930-Final-Managing-Environmental-and-Human-Health-Risks.pdf

O'Kane (2014c) *Independent Review of Coal Seam Gas Activities in NSW Information paper: On managing the interface between coal seam gas activities and other land uses (Setbacks).* Accessed online http://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0007/56923/140930-Final-Setbacks-info-paper.pdf

Osborn, S., Vengosh, A., Warner, N. & Jackson, R. (2011) *Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. PNAS early edition*, accessed online http://www.pnas.org/content/108/20/8172.abstract

Paddenbug, T. (2013) *Fracking fury over Ningaloo coast as new conservation council WA campaign launches. Perth Now*, February 9, 2013. Accessed online http://www.perthnow.com.au/news/western-australia/fracking-fury-over-ningaloo-coast/story-e6frg13u-1226574620219.

Palmer C. & Mattson E. (2011) *A Simple approach to identifying contaminants of most concern to underground drinking water supplies from hydraulic fracturing operations.* Presentation to Hydraulic Fracturing Technical Workshop 3 – Contaminant Identification, Transformation and Transport Theme. March 28-29 2011. Accessed online: http://www2.epa.gov/hfstudy/simple-approach-identifying-contaminants-most-concern-underground-drinking-water-supplies

Persoone, G. & Gillet, J. (1990) *Toxicological versus Ecotoxicological Testing.* In Short-term Toxicity Tests for Non-genotoxic Effects. Edited by Bourdeau et al., SCOPE. John Wiley & Sons Ltd. Accessed online http://dge.stanford.edu/SCOPE/SCOPE_41/SCOPE_41_2.12_Chapter_17_287-300.pdf

ProPublica (2013) *What is Hydraulic Fracturing*? Accessed online: http://www.propublica.org/special/hydraulic-fracturing-national

Rego, F. (2012) Claim CSG river leak caught on video. *ABC News*. Accessed online http://www.abc.net.au/news/2012-05-30/claim-csg-river-leak-caught-on-video/4041298

RIVM (2013) *National Institute for Public Health and the Environment (RIVM) Holland*. Accessed online http://www.rivm.nl/en

Ross, C and Darby, P (2013) Parliament of Victoria. *Unconventional Gas: Coal Seam Gas, Shale Gas and Tight Gas.* Accessed online http://www.parliament.vic.gov.au/publications/research-papers/8927-unconventional-gas-coal-seam-gas-shale-gas-and-tight-gas

Royal Society and Royal Academy of Engineering (RS&RAE) (2012) *Shale gas extraction in the UK: a review of hydraulic fracturing.* Accessed online https://royalsociety.org/policy/projects/shale-gas-extraction/report/

Rowling, T. (2012) *QGC should spill details, not just gas. Queensland Country Life*, 20/7/12. Accessed online http://www.queenslandcountrylife.com.au/news/state/agribusiness/general-news/qgc-should-spill-details-not-just-gas/2614696.aspx

SAIC & GES (2011) *ATGAS investigation initial site characterization and response. April 19, 2011 to May 2, 2011 ATGAS 2H well pad permit no. 37-015-21237 LeRoy Township, Bradford County, PA*. SAIC Energy, Environment & Infrastructure, Norman. Accessed online http://www.chk.com/news/articles/documents/atgas_initial_site_characterization_report_final_08292011.pdfSafe Work Australia (2013) *Hazardous Substance Information System*. Accessed online http://hsis.safeworkaustralia.gov.au/

Sandman, P (2013) *Fracking Risk Communication*. Accessed online http://www.psandman.com/col/fracking.htm#activist

Sapien, J. (2009) *With natural gas drilling boom, Pennsylvania faces an onslaught of wastewater.* ProPublica, October 2009. Accessed online http://www.citizenscampaign.org/PDFs/fracking-news/With%20Natural%20Gas%20Drilling%20Boom,%20Pennsylvania%20Faces%20an%20Onslaught%20of%20Wastewater%20-%20ProPublica.pdf

Senate Stating Committee on Rural Affairs and Transport (2011) *Interim report: the impact of coal seam gas on the management of the Murray Darling Basin*. Commonwealth of Australia, Canberra.

Schubert,C. (1999) *Growndwater flow paths and traveltime to three small embayments within the Peconic Estuary, Eastern Suffolk County, New York.* US Geological Survey Water-Resources Investigations Report 98-4181. Accessed online http://ny.water.usgs.gov/pubs/wri/wri984181/WRIR98-4181.pdf?bcsi_scan_313cddce030931be=0&bcsi_scan_filename=WRIR98-4181.pdf

Shonkoff, S., Hayes, J., & Finkel, M. (2014) Environmental Public Health Dimensions if Shale and Tight Gas Development. *Environmental Health Perspectives 122 (8)*: 787-795.

Spickett, J.,Brown, H., Matisons, M. & Katscherian, D. (2006) *Health Risk Assessment in Western Australia*. Department of Health WA, Perth.

Taylor, B. & Stone, P. (2012) *Dongara Mid-West onshore gas community workshop – 24 October 2012*. CSIRO. Accessed online http://www.dmp.wa.gov.au/documents/Report_Onshore_gas_workshop.pdf

Terracon (2007) *Monitoring report April 2007 Crosby 25-3 Natural gas well release road 1AB Clark, Park County Wyoming*. Accessed online http://deq.state.wy.us/volremedi/downloads/Web%20Notices/Windsor%20Well_Clark/April%202007%20Monitoring%20Report%20-%20Report%20Text%20and%20Tables.pdf?bcsi_scan_2F83426B613409AB=0&bcsi_scan_filename=April%202007%20Monitoring%20Report%20-%20Report%20Text%20and%20Tables.pdf

Terracon (2008) *Remedial investigation work plan- final Crosby 25-3 natural gas well release road 1AB Clark, Park County Wyoming.* Accessed online http://deq.state.wy.us/volremedi/downloads/Web%20Notices/Windsor%20Well_Clark/Work%20Plan%20FINAL%20020108.pdf

Tracy, Y. (2012) *New EPA findings test fracking site*. The Wall Street Journal, October 10, 2012. Accessed online http://online.wsj.com/article/SB10000872396390443294904578049210534771442.html

University of Maryland (2014) *Review of Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland.* Accessed online: http://phpa.dhmh.maryland.gov/OEHFP/EH/SitePages/MarcellusShale.aspx

US Department of Health and Human Services (2011) *US National Toxicology Program Report on Carcinogens 12th Edition*. US Department of Health and Human Services.

US EIA (2011a) *World Shale Gas Resources: An Initial Assessment of 14 Regions Outside the United States.* US Department of Energy, Washington.

US EIA (2011b) *Review of emerging resources: US shale gas and shale oil plays*. US Department of Energy, Washington.

US EPA (2002). *Consideration of the FQPA safety factor and other uncertainty factors in cumulative risk assessment of chemicals sharing a common mechanism of toxicity.* United States Environmental Protection Agency, Washington.

US EPA (2004). Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coalbed Methane Reservoirs. United States Environmental Protection Agency, Washington.

US EPA (2011) *Priority PBT profiles. Persistent Bioaccumulative and Toxic Chemical Program*. United States Environmental Protection Agency. Accessed online http://www.epa.gov/pbt/pubs/cheminfo.htm

US EPA (2012a) *Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report*. US Environmental Protection Agency Office of Research and Development, Washington. Accessed online http://www2.epa.gov/sites/production/files/documents/hf-report20121214.pdf

US EPA (2012b) *Draft report- Pavillion Groundwater investigation*. Accessed online http://www.epa.gov/region8/superfund/wy/pavillion/

USEPA (2013) *Chemical Assessment Tools: Toxicity Estimation Software Tool (TEST)* Accessed online http://www.epa.gov/nrmrl/std/chemicals.html

US EPA (2013a) *Integrated Risk Information System database*. Accessed online http://www.epa.gov/IRIS/

US EPA (2013b). *Natural gas star program*. United States Environmental Protection Agency. Accessed online at http://www.epa.gov/gasstar/basic-information/index.html

US EPA (2014) *EPA's Study of Hydraulic Fracturing for Oil and Gas and Its Potential Impact on Drinking Water Resources*. Accessed online http://www2.epa.gov/hfstudy

US EPA (2015) *Analysis of Hydraulic Fracturing Fluid Data from the FracFocus Chemical Disclosure Registry 1.0.* Office of Research and Development, Washington, DC. EPA/601/R-14/003. Accessed online at: http://www2.epa.gov/sites/production/files/2015-03/documents/fracfocus_analysis_report_and_appendices_final_032015_508_0.pdf

Waxman H, Markey E, DeGette D. (2011) *Chemicals used in hydraulic fracturing.* United States House of Representative Committee on Energy and Commerce Minority Staff, Washington. Accessed online http://democrats.energycommerce.house.gov/sites/default/files/documents/Hydraulic-Fracturing-Chemicals-2011-4-18.pdf

WA EPA (2009) *Memorandum of Understanding between the Department of Mines and Petroleum and the Environmental Protection Authority in relation to the referral of Mineral and Petroleum (Onshore and Offshore) and Geothermal Proposals*. Accessed online http://edit.epa.wa.gov.au/EPADocLib/EPA-DMP-MOU.pdf

WA EPA (2014) *Environmental Protection Bulletin No. 22. Hydraulic fracturing for onshore natural gas from shale and tight rocks.* (December 2014).

Walker, G., and Mallants, D (2014) *Methodologies for investigating gas in water bores and links to coal seam gas development.* CSIRO, Australia. Accessed online at: http://people.csiro.au/~/media/People%20Finder/M/D/Dirk-Mallants/Methane%20gas%20in%20water%20bores_Final_Report_281014.ashx

Warner, N.R., Christie, C.A., Jackson, R.B. & Vengosh, A. (2014) *Impacts of Shale Gas Wastewater Disposal on Water Quality in Western Pennsylvania. Environmental Science & Technology* (submitted in press).

Water and Rivers Commission (2002) *Allanooka and Dongara-Denison water reserves water source protection plan: Geraldton and Dongara-Port Denison Town Water Supplies*. Water and Rivers Commission, East Perth

Waxman H, Markey E & DeGette D. (2011) *Chemicals used in hydraulic fracturing.* United States House of Representative Committee on Energy and Commerce Minority Staff, Washington. Accessed online http://democrats.energycommerce.house.gov/sites/default/files/documents/Hydraulic-Fracturing-Chemicals-2011-4-18.pdf

WHO (2011) *Guidelines for Drinking-water Quality fourth edition*. World Health Organisation, Geneva.

WHO (2012) *International Agency for Research on Cancer Monographs*. World Health Organisation, Lyon. Accessed online http://www.iarc.fr/en/publications/list/index.php

Wilderness Society (2013) Don't *destroy the Fitzroy: No place for dams, coal mining and gas fracking!* Accessed online https://www.wilderness.org.au/articles/don%E2%80%99t-destroy-fitzroy-no-place-dams-coal-mining-and-gas-fracking

Wright, J. (2013a) *Environmental Health Impact Assessment – Camden Northern Expansion Project.* (EnRiskS) Accessed online http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Camden/Assessments%20and%20Reports/2013/October/Environmental%20Health%20Impact%20Assessment%20Revised%20Final%2030%20October%20Report.pdf?bcsi_scan_313cddce030931be=lE5zHCzKwUMeJkxUia7F9dNlPcMrAAAAlUivpQ==&bcsi_scan_filename=Environmental%20Health%20Impact%20Assessment%20Revised%20Final%2030%20October%20Report.pdf

Wright, J. (2013b) *Environmental Health Impact Assessment – Camden Northern Expansion Project*. Presentation (EnRiskS) Accessed online http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Camden%20Document%20Repository/CCC%20Meetings/20131121CCC%20Meeting%2038%20%20EnRiskS%20Environmental%20Health%20Impact%20Assessment%20%20Camden%20Northern%20Expansion%20Project.pdf

Appendix A - IEA Golden rules to manage environmental impacts.

The IEA recommends the following rules to manage environmental impacts associated with the use of hydraulic fracturing:

Measure, disclose and engage

- *Integrate engagement with local communities, residents and other stakeholders into each phase of a development.*
- *Establish baselines for key environmental indicators, such as groundwater quality, prior to commencing activity, and continue monitoring during operations.*
- *Measure and disclose operational data on water use, on the volumes and characteristics of waste water and on methane and other air emissions, alongside full, mandatory disclosure of fracturing fluid additives and volumes.*
- *Minimise disruption during operations, taking a broad view of social and environmental responsibilities, and ensure economic benefits are felt by local communities.*

Watch where you drill

- *Choose well sites to minimize impacts on the local community, heritage, existing land use, individual livelihoods and ecology.*
- *Properly survey the geology of the area to make smart decisions about where to drill and where to hydraulically fracture: assess the risk that deep faults or other geological features could generate earthquakes or permit fluids to pass between geological strata.*
- *Monitor to ensure that hydraulic fractures do not extend beyond the gas-producing formations.*

Isolate wells and prevent leaks

- *Put in place robust rules on well design, construction, cementing and integrity testing as part of a general performance standard that gas bearing formations must be completely isolated from other strata penetrated by the well, in particular freshwater aquifers.*
- *Consider appropriate minimum-depth limitations on hydraulic fracturing to underpin public confidence that this operation takes place only well away from the water table.*
- *Take action to prevent and contain surface spills and leaks from wells, and to ensure that any waste fluids and solids are disposed of properly.*

Treat water responsibly

- *Reduce freshwater use by improving operational efficiency; reuse or recycle, wherever practicable, to reduce the burden on local water resources.*
- *Store and dispose of produced and waste water safely.*
- *Minimise use of chemical additives and promote the development and use of more environmentally benign alternatives.*

Eliminate venting, minimise flaring and other emissions

- *Target zero venting and minimal flaring of natural gas during well completion and seek to reduce fugitive and vented greenhouse-gas emissions during the entire productive life of a well.*
- *Minimise air pollution from vehicles, drilling rig engines, pump engines and compressors.*

Be ready to think big

- *Seek opportunities for realising the economies of scale and co-ordinated development of local infrastructure that can reduce environmental impacts.*
- *Take into account the cumulative and regional effects of multiple drilling, production and delivery activities on the environment, notably on water use and disposal, land use, air quality, traffic and noise.*

Ensure a consistently high level of environmental performance

- *Ensure that anticipated levels of unconventional gas output are matched by commensurate resources and political backing for robust regulatory regimes at the appropriate level, sufficient permitting and compliance staff, and reliable public information.*
- *Find an appropriate balance in policy-making between prescriptive regulation and performance-based regulation in order to guarantee high operational standards while also promoting innovation and technological improvement.*
- *Ensure that emergency response plans are robust and match the scale of risk.*
- *Pursue continuous improvement of regulations and operating practices.*
- *Recognise the case for independent evaluation and verification of environmental performance. (IEA,2012,p42-49).*

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