

National assessment of chemicals associated with coal seam gas extraction in Australia

Technical report number 13

Human health risks associated with surface handling of chemicals used in coal seam gas extraction in Australia

This report was prepared by the National Industrial Chemicals Notification and Assessment Scheme (NICNAS)



Australian Government

Department of the Environment and Energy

Department of Health

National Industrial Chemicals
Notification and Assessment Scheme

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Reports in this series

The full set of technical reports in this series and the partner agency responsible for each is listed below.

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<i>Reviewing existing literature</i>		
1	Literature review: Summary report	NICNAS
2	Literature review: Human health implications	NICNAS
3	Literature review: Environmental risks posed by chemicals used coal seam gas operations	Department of the Environment and Energy
4	Literature review: Hydraulic fracture growth and well integrity	CSIRO
5	Literature review: Geogenic contaminants associated with coal seam gas operations	CSIRO
6	Literature review: Identification of potential pathways to shallow groundwater of fluids associated with hydraulic fracturing	CSIRO
<i>Identifying chemicals used in coal seam gas extraction</i>		
7	Identification of chemicals associated with coal seam gas extraction in Australia	NICNAS
<i>Modelling how people and the environment could come into contact with chemicals during coal seam gas extraction</i>		
8	Human and environmental exposure conceptualisation: Soil to shallow groundwater pathways	CSIRO
9	Environmental exposure conceptualisation: Surface to surface water pathways	Department of the Environment and Energy
10	Human and environmental exposure assessment: Soil to shallow groundwater pathways – A study of predicted environmental concentrations	CSIRO
<i>Assessing risks to workers and the public</i>		

Technical report number	Title	Authoring agency
11	Chemicals of low concern for human health based on an initial assessment of hazards	NICNAS
12	Human health hazards of chemicals associated with coal seam gas extraction in Australia	NICNAS
13	Human health risks associated with surface handling of chemicals used in coal seam gas extraction in Australia	NICNAS
<i>Assessing risks to the environment</i>		
14	Environmental risks associated with surface handling of chemicals used in coal seam gas extraction in Australia	Department of the Environment and Energy

Foreword

Purpose of the Assessment

This report is one in a series of technical reports that make up the *National Assessment of Chemicals Associated with Coal Seam Gas Extraction in Australia* (the Assessment).

Many chemicals used in the extraction of coal seam gas are also used in other industries. The Assessment was commissioned by the Australian Government in June 2012 in recognition of increased scientific and community interest in understanding the risks of chemical use in this industry. The Assessment aimed to develop an improved understanding of the occupational, public health and environmental risks associated with chemicals used in drilling and hydraulic fracturing for coal seam gas in an Australian context.

This research assessed and characterised the risks to human health and the environment from surface handling of chemicals used in coal seam gas extraction during the period 2010 to 2012. This included the transport, storage and mixing of chemicals, and the storage and handling of water pumped out of coal seam gas wells (flowback or produced water) that can contain chemicals. International evidence¹ showed the risks of chemical use were likely to be greatest during surface handling because the chemicals were undiluted and in the largest volumes. The Assessment did not consider the effects of chemical mixtures that are used in coal seam gas extraction, geogenic chemicals, or potential risks to deeper groundwater.

The Assessment findings significantly strengthen the evidence base and increase the level of knowledge about chemicals used in coal seam gas extraction in Australia. This information directly informs our understanding of which chemicals can continue to be used safely, and which chemicals are likely to require extra monitoring, industry management and regulatory consideration.

Australia's regulatory framework

Australia has a strong framework of regulations and industrial practices which protects people and the environment from adverse effects of industrial chemical use. For coal seam gas extraction, there is existing legislation, regulations, standards and industry codes of practice that cover chemical use, including workplace and public health and safety, environmental protection, and the transport, handling, storage and disposal of chemicals. Coal seam gas projects must be assessed and approved under relevant Commonwealth, state and territory environmental laws, and are subject to conditions including how the companies manage chemical risk.

Approach

Technical experts from the National Industrial Chemicals Notification and Assessment Scheme (NICNAS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Department of the Environment and Energy conducted the Assessment. The Assessment drew on technical expertise in chemistry, hydrogeology, hydrology, geology, toxicology, ecotoxicology, natural resource management and risk assessment. The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining

¹ See Mallants et al. 2017a; Jeffrey et al. 2017; Adgate et al. 2014; Flewelling and Sharma 2014; DEHP 2014; Stringfellow et al. 2014; Groat and Grimshaw 2012; Vidic et al. 2013; Myers 2012; Rozell and Reaven 2012; The Royal Society and The Royal Academy of Engineering 2012; Rutovitz et al. 2011.

Development (IESC) provided advice on the Assessment. Experts from the United States Environmental Protection Authority, Health Canada and Australia reviewed the Assessment and found the Assessment and its methods to be robust and fit-for-purpose.

The Assessment was a very large and complex scientific undertaking. No comparable studies had been done in Australia or overseas and new models and methodologies were developed and tested in order to complete the Assessment. The Assessment was conducted in a number of iterative steps and inter-related processes, many of which needed to be done in sequence (Figure F.1). There were two separate streams of analysis – one for human health and one for the environment. The steps included for each were: literature reviews; identifying chemicals used in drilling and hydraulic fracturing for coal seam gas extraction; developing conceptual models of exposure pathways; models to predict soil, surface and shallow groundwater concentrations of identified chemicals; reviewing information on human health hazards; and identifying existing Australian work practices, to assess risks to human health and the environment.

The risk assessments did not take into account the full range of safety and handling precautions that are designed to protect people and the environment from the use of chemicals in coal seam gas extraction. This approach is standard practice for this type of assessment. In practice, safety and handling precautions are required, which means the likelihood of a risk occurring would actually be reduced for those chemicals that were identified as a potential risk to humans or the environment.

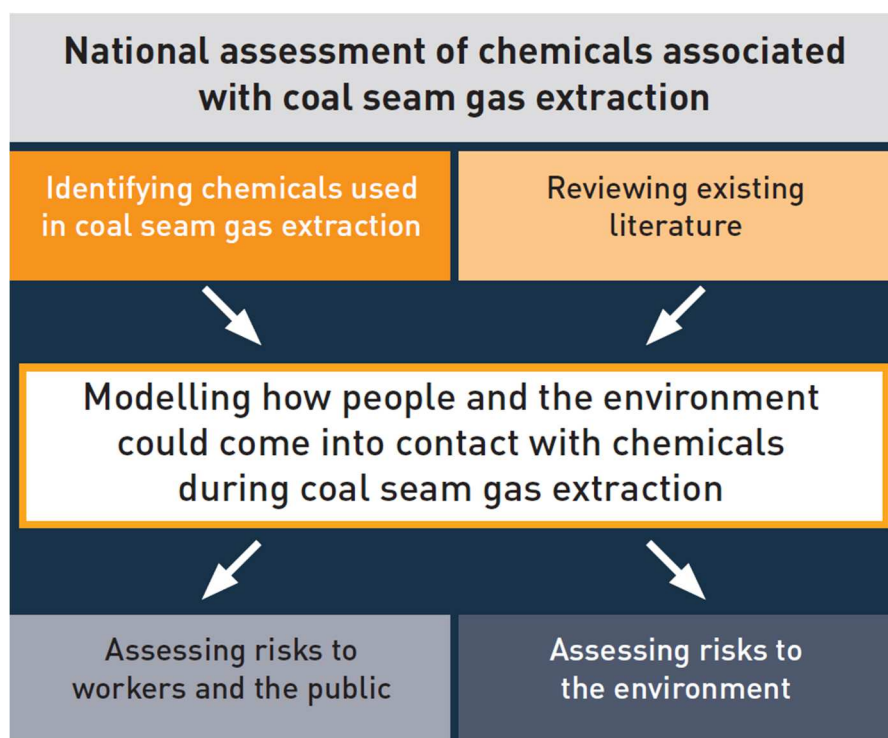


Figure F.1 Steps in the assessment

Collaborators

The Australian Government Department of the Environment and Energy designs and implements policies and programs, and administers national laws, to protect and conserve the environment and heritage, promote action on climate change, advance Australia's interests in the Antarctic, and improve our water use efficiency and the health of Australia's river systems.

Within the Department, the Office of Water Science is leading the Australian Government's efforts to improve understanding of the water-related impacts of coal seam gas and large coal mining. This includes managing the Australian Government's program of bioregional assessments and other priority research, and providing support to the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC). The IESC provides independent, expert scientific advice on coal seam gas and large coal mining proposals as requested by the Australian Government and state government regulators, and advice to the Australian Government on bioregional assessments and research priorities and projects.

The National Industrial Chemicals Notification and Assessment Scheme (NICNAS) is a statutory scheme administered by the Australian Government Department of Health. NICNAS aids in the protection of the Australian people and the environment by assessing the risks of industrial chemicals and providing information to promote their safe use.

CSIRO, the Commonwealth Scientific and Industrial Research Organisation, is Australia's national science agency and one of the largest and most diverse research agencies in the world. The agency's research is focused on building prosperity, growth, health and sustainability for Australia and the world. CSIRO delivers solutions for agribusiness, energy and transport, environment and natural resources, health, information technology, telecommunications, manufacturing and mineral resources.

This report: Human health risks associated with surface handling of chemicals used in coal seam gas extraction

This report, together with the reports *Chemicals of low concern for human health based on an initial assessment of hazards* (NICNAS 2017a) and *Human health hazards of chemicals associated with coal seam gas extraction in Australia* (NICNAS 2017b), describes the 'assessing risks to workers and the public' stage of the Assessment.

The 'assessing risk to workers and the public' stage of the assessment began with an initial screening to identify which of these 113 chemicals were of low human health hazard and therefore of low concern for human health. This initial screening identified 44 chemicals as being of low concern for human health (NICNAS 2017a). These chemicals were excluded from further human health assessment given their low concern for human health.

Human health risk is a product of the hazard (toxicity) of a chemical and the level of exposure of a person to the chemical. Hazard (toxicity) assessments were conducted for each chemical for use in these risk assessments (NICNAS 2017b).

This report considers the 69 chemicals that were not identified as of low concern for human health in the initial screening and:

- Assesses the potential exposure of workers and the public to chemicals used for drilling or hydraulic fracturing in coal seam gas extraction
- Uses information about hazards and potential exposure to characterise the risks to workers and the public from chemicals used for drilling or hydraulic fracturing in coal seam gas extraction.
- Notes risk mitigation measures that can be used to manage the identified risks. Note that this report does not consider whether these risk mitigation measures are in place in particular coal seam gas operations. Therefore, the discussion of risk mitigation measures should not be read as suggesting that risk mitigation measures are not in place or that existing risk mitigation measures are inadequate.

This report uses predictive contaminant transport modelling with conservative assumptions to develop exposure estimates. Such a conservative approach is used in the absence of site-specific parameters and environmental fate information for each chemical with the consequence of a likely overestimation of risk. Such 'realistically conservative' risk assessments, which overestimate, rather than underestimate risk are an effective strategy for dealing with unknown or uncertain risks. The results of such assessments will be deliberately conservative to provide confidence that risk mitigation measures implemented to reduce this risk to an acceptable level will be protective for the maximum number of affected individuals.

For workers, the risk of adverse health effects from single, short duration (acute) exposures to chemicals is likely to vary with work practices, but is highest for handling chemicals in their most concentrated form as delivered to operational sites. Forty-four of the 69 chemicals were of potential concern for the health of workers through acute inadvertent exposure to the chemicals as delivered to the site. Chemicals in diluted form in formulated drilling and hydraulic fracturing fluids, or in highly diluted form as a component of produced water, represent a lower acute health risk.

Long-term repeated exposure to most chemicals was of low concern for workers. However, 4 of the 21 chemicals used for drilling, and 10 of the 58 chemicals used for hydraulic fracturing, had risk estimates suggestive of a potential concern from repeated exposures during these activities if not managed appropriately. Consistent with international practice in risk assessment to account for variability in risk mitigation measures implemented in workplaces, risks were estimated assuming no engineering controls or use of personal protective equipment (PPE).

Acute exposure to chemicals used for drilling and hydraulic fracturing was of low concern for the public because these chemicals are not available to the public in the forms, quantities, packaging or handling situations typical of coal seam gas operations.

Using conservative exposure modelling and high-end exposure estimates:

- 11 of 21 chemicals used for drilling and 30 of 58 chemicals used for hydraulic fracturing were of a potential concern for public health following a bulk spill during transport. This exposure scenario assumes a spill of high volume (i.e. the entire contents of a truck) and relatively high concentration to surface water which is then used for drinking, bathing and swimming.
- 14 of 58 chemicals used for hydraulic fracturing were of potential concern for public health from long-term exposures from a subsurface leak from a storage pond holding flowback and / or produced water containing hydraulic fracturing chemicals. This exposure scenario assumes drinking and bathing in shallow groundwater and swimming in surface water.
- only 2 hydraulic fracturing chemicals were of potential concern for public health assuming drinking, bathing and swimming in surface water only. These two chemicals were considered to be of potential concern on the basis of a conservative qualitative risk analysis in the absence of quantitative toxicity data.

Because of their greater daily consumption of water relative to body weight, risk estimates showed that children were generally at greater risk than adults from consumption of contaminated water.

Sensitivity analyses were conducted of the effects of key assumptions in the conservative (Tier 1) exposure modelling for the bulk transport spill scenario and the leaking flowback and / or produced water storage pond scenario. These revealed far fewer chemicals with

quantitative risk estimates (MOEs) of potential concern when less conservative assumptions were made.

The sensitivity analyses highlight the conservative nature of the Tier 1 risk assessments. These assessments provide a relative measure of human health risk across the range of chemicals used for drilling and hydraulic fracturing. They also reliably identify chemicals of low concern. However, for individual chemicals with risk estimates suggestive of a potential concern, more refined risk estimates are needed to better determine the actual level of human health risk. Such a subsequent analysis by risk managers, based, for example, on site-specific data, may find some of these chemicals to be of low concern.

Abbreviations

General abbreviations	Description
BAuA	German Federal Institute for Occupational Safety and Health
BW	Body weight
CAS	Chemical Abstract Service
CBI	Confidential business information
CSG	Coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DoEE	Department of the Environment and Energy
EASE	Estimation and Assessment of Substance Exposure
ECETOC	European Centre for Ecotoxicology and Toxicology of Chemicals
ECHA	European Chemicals Agency
EHD	Estimated human dose
EMKG	Einfaches Maßnahmenkonzept für Gefahrstoffe
GISERA	Gas Industry Social and Environmental Research Alliance
HSE	United Kingdom Health and Safety Executive
HSIS	Hazardous Substances Information System
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
IPCS	International Programme on Chemical Safety
LOAEL	Lowest-observed-adverse-effect level
MOE	Margin of Exposure
NCM	Namoi Catchment Model
NICNAS	National Industrial Chemicals Notification and Assessment Scheme
NOAEL	No-observed-adverse-effect level
NOHSC	National Occupational Health and Safety Commission
OECD	Organisation for Economic Cooperation and Development
PCBU	Persons conducting a business or undertaking
PEC	Predicted environmental concentration
PPE	Personal protective equipment
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RQ	Risk quotient

General abbreviations	Description
UK	United Kingdom
UNECE	United Nations Economic Commission for Europe
US EPA	United States Environmental Protection Agency
WHO	World Health Organisation

Units, chemicals and symbols	Description
cm ²	Square centimetre
cm ³	Cubic centimetre
g	Gram
kg	Kilogram
kg BW	Kilograms body weight
kPa	Kilopascal
km	Kilometre
km ²	Square kilometre
L	Litre
mg	Milligrams
m	Metre
m ²	Square metre
m ³	Cubic metre
ML	Megalitre
µm	Micrometre
mm	Millimetre
%	Per cent
E _{derm}	Internal dermal dose of a chemical, mg/kg bw/day
E _{inh}	Internal inhalation dose of the chemical, mg/kg bw/day
E _{oral}	Internal dose of the chemical from ingestion, mg/kg bw/day
f _{resp}	Respirable/inhalable fraction of the chemical, dimensionless
C	Concentration of the chemical
D _{EASE}	External dose estimated by EASE model, mg/cm ² /day
SA _{derm}	Surface area of exposed skin, cm ²
B _{derm}	Dermal bioavailability, %

Units, chemicals and symbols	Description
BW	Body weight, kg bw
D_{EMKG}	External dose estimated by EMKG-EXPO-TOOL, mg/m ³
V_{air}	Worker ventilation rate, m ³ /day
B_{inh}	Inhalation bioavailability, %
t	Duration of exposure (h/day)
DF	Dilution factor
DF_L	Ratio of the chemical concentration at the source (C_s) to the concentration at the water table (C_{WT}) at the base of the unsaturated soil column
DF_{GW}	Ratio of chemical's concentration at the water table (C_{WT}) at the base of the unsaturated soil column to the chemical's concentration in the groundwater (C_{GW}).
C_{WT}	Concentration of a chemical at the water table at the base of the unsaturated soil column
C_{GW}	Concentration of a chemical in the groundwater
$C_{ingested}$	Concentration of the chemical in groundwater or surface water derived from PECs, mg/L
$V_{ingested}$	Volume of water ingested per day, L/day
B_{oral}	Oral bioavailability, %
n	Mean number of events per day
th	Layer of water in contact with the skin, cm

Equation	Formulae	Description
1	$E_{derm} = \frac{C \times D_{EASE} \times SA_{derm} \times B_{derm}}{BW}$	Used to calculate the internal dermal dose of a chemical from dermal exposure, mg/kg bw/day
2	$E_{inh} = \frac{f_{resp} \times C \times D_{EMKG} \times V_{air} \times B_{inh} \times t}{BW}$	Describes an internal dose of a chemical via inhalational exposure, mg/kg bw/day
3	$DF = DF_L \times DF_{GW}$	Describes the combined dilution factor for movement of contaminants through both soil and groundwater
4	$E_{oral} = \frac{C_{ingested} \times V_{ingested} \times B_{oral}}{BW}$	Used to calculate internal dose of the chemical from ingestion, mg/kg bw/day
5	$E_{derm} = \frac{n \times C \times SA_{derm} \times th \times B_{derm}}{1000 \times BW}$	Describes an internal dose of a chemical arising from skin contact with water during bathing or recreation (swimming)

Glossary

Term	Description
Adverse effect	Change in the morphology, physiology, growth, development, reproduction, life span of an organism, system, or (sub)population that results in an impairment of functional capacity, an impairment of the capacity to compensate for additional stress, or an increase in susceptibility to other influences
Adsorption	The binding of molecules to a particle surface. This process can bind methane and carbon dioxide, for example, to coal particles
Alluvial	A type of sediment deposited from flowing water into floodplains
Aquifer	Rock or sediment in a formation, group of formations, or part of a formation, which is saturated and sufficiently permeable to transmit quantities of water to wells and springs
Bioregion	A geographic land area within which coal seam gas and / or coal mining developments are, or could, take place, which will be subject of a bioregional assessment
Bounding estimate	A bounding estimate captures the highest possible exposure, or theoretical upper bound, for a given exposure pathway
Coal seam	Coal seams or coal deposits are layers containing coal (sedimentary rock). Coal seams store both water and gas. Coal seams generally contain more salty groundwater than aquifers that are used for drinking water or agriculture
Coal seam gas	A form of natural gas (generally 95 to 97% pure methane, CH ₄) typically extracted from permeable coal seams at depths of 300 to 1 000 m. Also called coal seam methane (CSM) or coalbed methane (CBM)
Concentration	Amount of a material or agent dissolved or contained in unit quantity in a given medium or system
Conceptual model	A conceptual model is a set of qualitative assumptions to describe a system, or part thereof. The assumptions would normally cover, as a minimum, the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical, chemical and biological processes and phenomena
Contaminant	Biological (e.g. bacterial and viral pathogens) and chemical (see toxicants) introductions capable of producing an adverse response (effect) in a biological system, seriously injuring structure or function or causing death
Conservative	An assessment aimed at deliberately overestimating the potential risks to humans and the environment (after US EPA 1992)
Critical (health) effect	Health effect(s) observed in the hazard assessment that show the most sensitive dose-response relationship i.e. observed at the lowest doses
Dermal	Relating to, or affecting the skin
Dilution factor	Defines how many times a contaminant source concentration becomes diluted for a particular receiving environment. Calculated as ratio of source concentration to concentration in the receiving environment. The

Term	Description
	dilution factor is always > 1 , and often much larger > 1
Dose	Total amount of an agent administered to, taken up by, or absorbed by an organism, system or (sub)population
Dose-response	Relationship between the amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub)population and the change developed in that organism, system, or (sub)population in reaction to the agent
Drilling fluids	Fluids that are pumped down the wellbore to lubricate the drill bit, carry rock cuttings back up to the surface, control pressure and for other specific purposes. Also known as drilling muds
Drilling / Fracturing products	Proprietary mixtures of chemicals – often with a trade name – used by companies to assist in the drilling and / or hydraulic fracturing processes
Effect	Change in the state or dynamics of an organism, system, or (sub)population caused by the exposure to an agent
Endpoint	A category of health effects
Exposure	Concentration or amount of a particular agent that reaches a target organism, system, or (sub)population in a specific frequency for a defined duration
Exposure assessment	Evaluation of the exposure of an organism, system, or (sub)population to an agent (and its derivatives)
Exposure scenario	A set of conditions or assumptions about sources, exposure pathways, amounts or concentrations of agent(s) involved, and exposed organism, system, or (sub)population (i.e., numbers, characteristics, habits) used to aid in the evaluation and quantification of exposure(s) in a given situation
Flowback water	The initial flow of water returned to a well after fracture stimulation and prior to production
Gaining river	A river which gains water from an aquifer. When the water table is above the river, the river acts as a drain and water is removed from the aquifer proportionally to the difference in elevation between the water table and the river
Groundwater	Water occurring naturally below ground level (whether in an aquifer or other low permeability material), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage. This does not include water held in underground tanks, pipes or other works
Hazard	Inherent property of an agent or situation having the potential to cause adverse effects when an organism, system, or sub(population) is exposed to that agent
Hazard assessment	A process designed to determine the possible adverse effects when an organism, system, or sub(population) could be exposed. The process includes hazard identification and hazard characterisation. The process focuses on hazard, in contrast to risk assessment, where exposure assessment is a distinct additional step
Hazard characterisation	The qualitative and, wherever possible, quantitative description of the inherent property of an agent or situation having the potential to cause adverse effects

Term	Description
Hazard identification	The identification of the type and nature of adverse effects that an agent has an inherent capacity to cause in an organism, system, or (sub)population
High-end estimate	A high-end exposure estimate is a plausible estimate of the individual exposure for those persons at the upper end of an exposure distribution. Conceptually, the high end of the distribution means above the 90th percentile of the population distribution, but not higher than the individual in the population who has the highest exposure.
Hydraulic fracturing	Also known as 'fracking', 'fracing' or 'fracture stimulation', is one process by which hydrocarbon (oil and gas) bearing geological formations are 'stimulated' to enhance the flow of hydrocarbons and other fluids towards the well. In most cases is only undertaken where the permeability of the formation is initially insufficient to support sustained flow of gas. The hydraulic fracturing process involves the injection of fluids, gas, proppant and other additives under high pressure into a geological formation to create a conductive fracture. The fracture extends from the well into the coal reservoir, creating a large surface area through which gas and water are produced and then transported to the well via the conductive propped fracture channel
Hydraulic fracturing fluid	A fluid injected into a well under pressure to create or expand fractures in a target geological formation (to enhance production of natural gas and / or oil). It consists of a primary carrier fluid (usually water or gel based), a proppant and one or more additional chemicals to modify the fluid properties
LOAEL	Lowest-observed-adverse-effect level
Margin of exposure (MOE)	Ratio of the no-observed-adverse-effect level (NOAEL) for the critical (most sensitive) effect to the theoretical, predicted, or estimated exposure dose or concentration
NOAEL	No-observed-adverse-effect level
Predicted environmental concentration (PEC)	Chemical concentration in a given environmental component (soil water, groundwater, surface water) that has been calculated by means of exposure models for a given exposure scenario
Physico-chemical	Relating to both the physical and chemical properties of chemicals
Polymer	A substance which has a molecular structure built up mainly or completely from a large number of similar units covalently bonded together
Produced water	Water that is pumped out of the coal seams to release the natural gas during the production phase. Some of this water is returned fracturing fluid and some is natural 'formation water' (often salty water that is naturally present in the coal seam). This produced water moves back through the coal formation to the well along with the gas, and is pumped out via the wellhead
Proppant	A component of the hydraulic fracturing fluid comprised of sand, ceramics or other granular material that 'prop' open fractures to prevent them from closing when the injection pressure is stopped
Risk	The probability of an adverse effect in an organism, system, or (sub)population caused under specified circumstances by exposure to an agent

Term	Description
Risk assessment	A process intended to calculate or estimate the risk to a given target organism, system, or (sub)population, including the identification of attendant uncertainties, following exposure to a particular agent, taking into account the inherent characteristics of the agent of concern as well as the characteristics of the specific target organism.
Risk characterisation	The qualitative and, wherever possible, quantitative description of the likelihood of an agent or situation having the potential to cause adverse effects
Risk quotient	Risk quotients (RQs) are calculated by dividing exposure estimates (i.e. predicted environmental concentrations or PECs) by the acute and chronic ecotoxicity values (i.e. $RQ = PEC/Toxicity\ value$)
Runoff	The proportion of precipitation that is not immediately absorbed by the soil and thus flows across the surface
Shallow groundwater	Groundwater that occurs in the shallowest aquifer, bounded by a water table and an unsaturated zone of variable thickness (sometimes absent) above, and by deeper aquifer or aquitard systems below. Also generally referred to as the water table aquifer
Shale gas	Shale gas is natural gas generally extracted from a clay-rich sedimentary rock which has naturally low permeability
Solute	The substance present in a solution in the smaller amount. For convenience, water is generally considered the solvent even in concentrated solutions with water molecules in the minority
Subregion	A subdivision of a bioregion which contains distinctive geomorphic units that closely aligns with land capability and development potential
Surface water	Water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs
Tote	A reusable industrial container, also known as an intermediate bulk container (IBC)
Toxicity	Inherent property of an agent to cause an adverse biological effect
Toxicokinetics	The study of the adsorption, distribution and elimination of toxic compounds in the living organism
Uncertainty factor	Reductive factor by which an observed or estimated no-observed-adverse effect level (NOAEL) is divided to arrive at a criterion or standard that is considered safe or without appreciable risk. Related term: Safety factor
Unsaturated zone	The unsaturated zone, also called the vadose zone, extends from the top of the ground surface to the water table. In the unsaturated zone, the water in the soil pores has a pressure less than atmospheric
Validation rules	Criteria used to determine if a chemical is of low concern for human health, or not
Water table	The surface between the unsaturated zone and the saturated zone. The groundwater table can also be defined as the surface at which groundwater pressure is equal to atmospheric pressure.
Well	As used in this report: a completed wellbore, typically including casing and tubing strings and possibly a pump. A well is intended for injection or production of fluids

Term	Description
Workplace Hazardous Substances (Chemicals)	Any substance or mixture that satisfies the criteria for a hazard class in the Safe Work Australia Approved Criteria For Classifying Hazardous Substances or the United Nations Globally Harmonised System of Classification and Labelling of Chemicals
Xenobiotic metabolism	Chemical reactions an organism uses to alter and eliminate substances that are foreign to the organism

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1 Hazard assessment

Hazard assessment (consisting of hazard identification and dose-response assessment) is a necessary step for assessing the risks to human health associated with chemicals.

The World Health Organisation (WHO) International Programme on Chemical Safety [IPCS (1999)] notes that the purpose of hazard assessment is to review and evaluate data pertinent to two questions:

- whether an agent may pose a hazard to human health
- under what circumstances an identified hazard may be expressed.

The WHO IPCS defines hazard as the inherent property of an agent or situation having the potential to cause adverse effects when an organism, system or (sub) population is exposed to that agent (IPCS 2004). For a chemical, hazard identification establishes its toxicity and identifies the set of inherent properties that makes it capable of causing adverse effects.

The WHO IPCS defines dose-response assessment as an analysis of the relationship between the total amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub) population, and the changes developed in that organism, system, or (sub) population in reaction to that agent (IPCS 2004). In other words, for chemicals, a dose-response assessment involves examining how the dose of an administered chemical relates to the incidence or severity of an adverse, toxic effect (a response).

From an industry survey seeking information about chemicals used in drilling and hydraulic fracturing, and a review of publicly available lists of chemicals reportedly used in coal seam gas extraction, 113² chemicals were reported as being used in drilling and hydraulic fracturing between 2010-2012 (NICNAS 2017c). These 113 chemicals were then screened to identify chemicals of low human health hazard and therefore inherently of low concern for human health. The screening approach, validated by national experts, compared these chemicals with lists of chemicals considered of low concern and then used separate validation rules for discrete chemicals and polymers based on chemical structural features to further identify low concern chemicals. Using this screening approach, 44 chemicals were identified as chemicals of low concern. Sixty-nine chemicals were determined to require further assessment (NICNAS 2017a), and hazard assessments were then conducted on these chemicals.

For each chemical, the critical adverse health effects were characterised and quantitative values were identified for relevant human health endpoints for use in human health risk assessments.

The results from the hazard assessments were also utilised to confirm current workplace hazard classification/s and / or to identify new hazard classification/s for the protection of workers. Of the 69 chemicals, 27 were found to be currently listed on the Safe Work Australia Hazardous Substances Information System (HSIS) as workplace hazardous chemicals (Safe Work Australia 2013). Four of these 27 chemicals currently listed on the HSIS required their existing listings to be modified.

² Initially, 114 chemicals were identified from the industry survey as being used for coal seam gas extraction. However, industry later confirmed that one chemical had been erroneously reported. This chemical was therefore removed from the assessment.

In addition to the 27 chemicals currently listed on HSIS as workplace hazardous chemicals, NICNAS has recommended to Safe Work Australia that 30 chemicals be classified and listed on HSIS based on the Approved Criteria for Classifying Hazardous Substances (NOHSC 2004) and the Globally Harmonised System of Classification and Labelling of Chemicals (UNECE 2009). The remaining 12 of the 69 assessed chemicals were not classified as hazardous. For four chemicals, the toxicity information was insufficient to consider classification and for eight chemicals, the toxicity information was sufficient but indicated the chemical did not warrant classification.

The human health hazard assessments for all 69 chemicals are available both in summary form and as individual hazard assessments for each chemical (NICNAS 2017b).

2 Exposure assessment

2.1 Introduction

Assessment of human health risks associated with chemicals used in coal seam gas extraction requires a consideration of the inherent hazards or toxicity of the chemicals (the subject of the previous Section), and also how, to what extent, and over what period, exposure to these chemicals may occur.

The assessment of exposure of workers and the general public is the subject of Section 2. Section 3 describes how information on hazards and exposure are integrated to characterise the health risk.

For workers, there is potential for direct exposure to chemicals used in coal seam gas extraction during chemical transport, storage and use. The public may be exposed to these chemicals indirectly through environmental contamination extending beyond the footprint of the coal seam gas extraction operation. Exposure scenarios and routes of exposure for the public are discussed in Section 2.5.

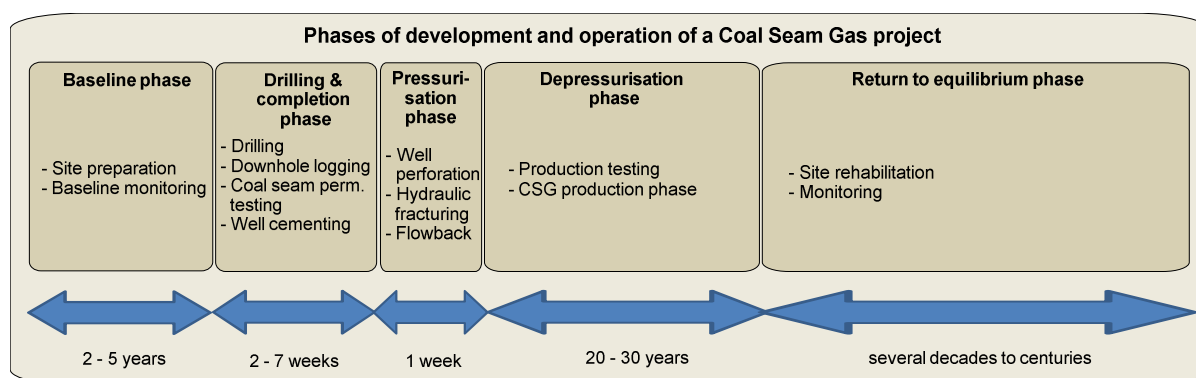
2.2 Worker exposure

Worker exposure to chemicals during coal seam gas operations is possible during occupational handling of the chemicals, handling of formulated drilling and hydraulic fracturing fluids, and contact with flowback and / or produced water containing the chemicals. Worker exposure could occur either through breathing chemical vapours, gases or dusts, or by absorption following skin contact. Ingestion through oral exposure is also possible, but is not considered in this report for workers as it is assumed that exposures via this route are negligible due to effective, easily implemented, occupational hygiene practices.

Accordingly, for human health risk assessment, worker exposures are considered for dermal and inhalational routes only.

Coal seam gas extraction involves drilling and, if required to increase gas production, hydraulic fracturing. It is important to understand these processes to identify the stages at which potential exposures to workers may occur.

Drilling and hydraulic fracturing (if required) occur at defined times within the lifetime of an individual coal seam gas well or entire well field (Figure 2.1). Although not depicted in Figure 2.1, there may be a number of hydraulic fracturing events within the lifetime of a well.



Note. Duration of each phase is indicative (length of arrows is not to scale).

Figure 2.1 Phases of development and operation of a coal seam gas project with typical activities

2.2.1 Drilling operation description

Drilling fluids (also called drilling muds) are used in drilling operations and serve various functions including to cool and lubricate the drill bit, prevent the borehole from collapsing, and to remove cuttings.

During drilling, a circulating system pumps drilling fluids down the drill hole, out of the nozzles in the drill bit and returns drilling fluids to the surface via the annulus (space between the drill string and the hole wall). At the surface, the larger debris in the returning fluid are separated from the fluid using a shaker and discarded. Smaller solids are separated by pumping the remaining fluid to a mud pit to allow settling. Separated fluids are then recirculated from the mud pit to the hole. This process occurs continuously as drilling progresses. During drilling, a mud engineer periodically monitors the mud by measuring its viscosity, density and other properties to ensure optimal performance.

Drilling operations are normally conducted by sub-contracted service providers 24 hours per day on rotating shifts over a continuous period. Operations take approximately five days for a vertical well typically 900 m deep, to approximately five weeks for a horizontal well 700 m deep and 2 000 m long. Estimates of the total volume of drilling muds typically required per operation range from approximately 159 000 L to 318 000 L (NICNAS 2017c).

2.2.2 Chemicals handling: drilling fluids

Most of the chemicals used in drilling fluids are imported as finished end-use products. These products are handled as solids or liquids, packaged in two to 25 kg containers (for solids) or 20 L containers (for liquids) or for large introduction quantities, in bulk bags of up to 10 000 kg (for solids) and 206 L drums or 500 to 1 000 L totes (for liquids) (NICNAS 2017c). Products are transported and stored at holding warehouses prior to transport to the drilling sites.

Drilling fluids are typically formulated at the drilling site. Small containers of solid or liquid chemicals are opened and loaded manually to a mixing unit. Liquids from larger containers are loaded using transfer pumps and pipes which are connected and disconnected manually. The formulated drilling fluid is then pumped to an open, plastic-lined mud pit for storage prior to, during and after drilling. In some cases, formulations are mixed at the holding warehouses and then transported to drilling sites for final mixing or transfer to the mud pit.

After drilling is completed, the site is remediated. The mud pit lining is removed and drilling solids (cuttings) are buried in the mud pit. Empty bags or sacks are compressed, wrapped,

and placed in half-tonne bins manually. Residual materials are returned to the drilling service providers.

Workers may be exposed to chemicals during formulation of the drilling fluids at storage warehouses or at the drill site. Worker exposures (dermal and inhalational) may occur during manual handling of the chemicals in preparation for mixing. Mixing could result in a combination of vapours, aerosols and / or dusts at the mixing unit and mud pit. Levels of airborne chemicals at the mud pit may be exacerbated by the elevated temperatures of drilling fluids returning to the mud pit from the drill string. Workers at these locations may then be exposed to chemicals via inhalation. However, inhalational exposures will be mitigated by natural ventilation provided from operations conducted in the open and by personal protective equipment (PPE) used by workers.

Worker exposures (mainly dermal) may also occur from liquid spills during manipulation of transfer pumps and pipes containing residual chemicals.

Exposure (both dermal and inhalational) could also occur during site remediation and disposal of empty containers/liners containing residual chemicals.

2.2.3 *Hydraulic fracturing operation description*

Hydraulic fracturing is a well stimulation technique in which fluid is injected into the well at high pressure to create or enhance fractures in the target coal seam. If required, hydraulic fracturing is conducted after a well has been drilled and completed. Fracturing fluid consists of a base fluid (commonly water), proppant (commonly sand) and chemical additives.

A fracturing operation for a single coal seam typically takes between two and eight days. For each well, the total number of operations varies according to the number of coal seams accessed by the well. After one coal seam has been hydraulically fractured, a plug is placed in the well to allow fracturing of the next coal seam. For a single well, and depending on the number of coal seams, up to nine operations can be conducted over the life of the well (NICNAS 2017c). Fluid volumes, pressures and flow rates vary depending on the fluid system being used and the properties of the target coal seam. A typical hydraulic fracturing fluid volume, per operation, is 150 000 to 200 000 L (NICNAS 2017d).

2.2.4 *Chemicals handling: hydraulic fracturing fluids*

Most of the chemicals in hydraulic fracturing fluids are imported as finished end-use products. These products are handled as solids or liquids, packaged in 25 kg (for solids) or 20 L (for liquids) containers. Large quantities are introduced in bulk bags of up to 1 000 kg (for solids) and 206 L drums or 500 to 1 000 L totes (for liquids) (NICNAS 2017c). Products are transported and stored at holding storage sites prior to transport to the well sites.

Hydraulic fracturing fluids are typically formulated at the well site. However, in some cases, preliminary mixing is done at holding sites with mixed fluid then delivered to the well site for final mixing and injection. Fluids are blended using one of two methods:

- batch mixing, where chemicals are pumped from individual on-site storage containers into tanks or above ground lined pits using a mixing hopper and fluid transfer pumps
- continuous mixing, where chemicals are pumped from individual on-site storage containers to the main hydraulic fracturing fluid 'on-the-fly' by utilising specialised liquid additive system pumps and mixers.

High pressure pumps then draw and pressurise the hydraulic fracturing fluid for injection into the well. The flow rates of each injected component and the flow rates and pressures of the formulated hydraulic fracturing fluid are monitored from an on-site control centre.

At the completion of the operation, unused fracturing fluid is transported back to the holding storage site, or in the case of small amounts of unused fluid, occasionally disposed of at the site in accordance with site-specific plans. Empty bags / sacks previously containing solid chemicals are disposed of manually. Bags or sacks are compressed, wrapped and placed in half-tonne bins. Residual materials are returned to the service providers.

Water from coal seam gas wells potentially containing residual fracturing fluid chemicals is commonly transported via underground pipes to water management facilities (e.g. storage ponds) for treatment prior to other uses. However, in some cases, flowback water may be stored and transported via separate holding tanks.

Workers may be exposed to chemicals during formulation of the hydraulic fracturing fluids at storage warehouses or at the well site. Worker exposures (dermal and inhalational) may occur during manual handling of chemicals in preparation for mixing. Inhalation exposures generally are most likely for volatile chemicals but may also occur from generation of dusts such as from high volume transfer of particulate chemicals (e.g. proppant) from storage to the mixer. However, inhalational exposures will be mitigated by the natural ventilation provided from operations conducted in the open.

Exposures (dermal and inhalation) may also occur from spills during manipulation of transfer pumps and pipes containing residual chemicals and also during disposal of empty containers containing residual chemicals.

2.3 Worker exposure assessment

2.3.1 Scenarios and routes of exposure

Exposure assessments for drilling and hydraulic fracturing chemicals consider the following specific coal seam gas activities with potential for worker exposures:

- transport and storage of chemicals
- mixing / blending of drilling and / or hydraulic fracturing chemicals to produce formulations
- injection of drilling and / or hydraulic fracturing fluid formulations
- cleaning and maintenance
- transport and storage of produced water
- accidents / incidents from any of the activities above.

2.3.2 Methodology

Worker exposures to chemicals can be measured by personal monitoring of workers or estimated from exposure modelling. For exposure assessments, actual monitoring data are preferred over modelling data. No Australian monitoring data are available for the coal seam gas workplace scenarios being considered in this assessment, and so worker exposures have been estimated using exposure modelling.

For these activities, the exposure routes considered are dermal and inhalational. Worker exposure via the oral route is possible, but it is assumed that exposures via this route are negligible due to effective, and easily implemented, occupational hygiene practices.

The Estimation and Assessment of Substance Exposure (EASE) model (UK HSE 1997; Cherrie et al. 2003) and the EMKG-EXPO-TOOL (REACH 2008; BauA 2011) were used to model dermal and inhalational workplace exposures respectively. Consistent with accepted

international practice in human health risk assessment to account for variability in the use of PPE, all exposures were estimated for workers in the absence of PPE.

The EASE model, developed by the United Kingdom (UK) Health and Safety Executive (HSE), predicts workplace dermal (and inhalational) exposure ranges (lower and upper limits) for substances based on a standard eight-hour working day.

The EASE model uses a decision tree-based approach based upon the following inputs:

- process properties
- substance properties
- use pattern
- pattern of control.

Dermal exposures are assumed to occur only to the hands and forearms of the worker.

The EMKG-EXPO-TOOL, developed by the German Federal Institute for Occupational Safety and Health (BAuA), is a generic tool to estimate workplace inhalational exposure values within the breathing zone of workers. The model is based on a banding approach originally developed by the UK HSE for the EASE model and predicts a range (lower and upper limits) of concentrations of chemicals (as solids or liquids) in the workplace.

The EMKG-EXPO-TOOL requires the following inputs:

- for solids – dustiness, quantity of chemical used per batch, and control strategy
- for liquids – boiling point, quantity of chemical used per batch, short- / long-term use per eight-hour shift, surface application or not, and control strategy.

Both the EASE model and EMKG-EXPO-TOOL are general predictive models for the estimation of exposures to multiple types of chemicals in the workplace. With minimal inputs, the outputs of these models are conservative and likely to overestimate actual workplace exposures. Other exposure models exist but are either complex in nature, applicable only to specific types of chemicals, or require numerous inputs for which the data are not available from the limited exposure information obtained from the coal seam gas industry survey or supplementary data requests (NICNAS 2017c).

2.3.3 Exposure during transport and storage of chemicals

Worker exposure to chemicals during transport and storage is regarded as minimal. Exposures are likely only in the event of accidental release, such as leaks and spills from inadvertent breaching of containers or packaging.

2.3.4 Exposure during mixing / blending of chemicals

Although some formulation may occur at holding sites, drilling fluids are formulated typically at the drilling site. During formulation, containers of solid or liquid chemicals are opened and loaded manually to a mixing unit. Worker exposures via the dermal and inhalational routes may occur during these manual handling activities through liquid spills and the generation of dusts. During mixing, inhalational exposure may also occur from vapours, aerosols and / or dusts generated at the mixing unit and mud pit.

Similarly, hydraulic fracturing chemicals are formulated typically at the well site, although preliminary mixing may be conducted at holding sites that service a region. Formulation is conducted either by batch mixing or continuous mixing at well sites. Mixing is predominantly an automated process. Worker exposures by the dermal and inhalational routes may occur

during manual handling of chemical containers. Inhalational exposures may also occur from dusts generated during high volume transfer of particulate chemicals (e.g. proppant).

For both drilling and hydraulic fracturing chemicals, internal doses via dermal and inhalational exposures were estimated for workers for mixing / blending activities.

2.3.4.1 Dermal exposure

The internal dose via dermal exposure was estimated using Equation 1:

$$E_{\text{derm}} = \frac{C \times D_{\text{EASE}} \times SA_{\text{derm}} \times B_{\text{derm}}}{BW} \quad [\text{Equation 1}]$$

Where:

E_{derm} = Internal dermal dose of the chemical, mg/kg bw/day

C = concentration of the chemical, %

D_{EASE} = external dose estimated by EASE model, mg/cm²/day

SA_{derm} = surface area of exposed skin, cm²

B_{derm} = dermal bioavailability, %

BW = body weight, kg bw.

The sources of information for the parameters used in Equation 1 are:

- C – obtained from data provided in the coal seam gas industry survey or from supplementary data requests³ (i.e. the concentration of chemical *as delivered to site*). Concentrations provided to NICNAS as confidential business information (CBI) were included in the estimations. In the absence of information from the industry survey, values for individual chemicals were obtained from a public literature search. In the absence of information from the industry survey or a literature search, a default concentration of 1 000 g/L (100%) is used (and assumes the chemical is in its pure form and not diluted with other chemicals).
- D_{EASE} – for both solids and liquids, the inputs to the EASE model used to calculate D_{EASE} were: pattern of use is ‘non-dispersive’, pattern of control is ‘direct handling’, and contact level is ‘incidental’. These inputs generated a D_{EASE} range of 0 to 0.1 mg/cm²/day. Assuming no PPE, the upper limit value of D_{EASE} , 0.1 mg/cm²/day, is used.
- SA_{derm} – default value of 840 cm² (hands) (US EPA 2011).
- B_{derm} – identified in the chemical’s hazard assessment. In the absence of data on bioavailability, absorption data were used.
- BW – default value of 70 kg bw (enHealth 2012).
- Since D_{EASE} is based on a standard eight-hour working day, the exposure estimates for mixing / blending were adjusted to reflect the specific duration of this activity (assumed to be four hours).

³ Supplementary data were sought from industry in 2014-2015 to address data gaps for specific chemicals regarding environmental chemistry, points of release and environmental receptors.

2.3.4.2 Inhalational exposure

The internal dose via inhalational exposure was estimated using Equation 2:

$$E_{inh} = \frac{f_{resp} \times C \times D_{EMKG} \times V_{air} \times B_{inh} \times t}{BW} \quad [\text{Equation 2}]$$

Where:

E_{inh} = Internal inhalation dose of the chemical, mg/kg bw/day

f_{resp} = respirable/inhalable fraction of the chemical, dimensionless

C = concentration of the chemical, %

D_{EMKG} = external dose estimated by EMKG-EXPO-TOOL, mg/m³

V_{air} = worker ventilation rate, m³/day

B_{inh} = inhalation bioavailability, %

t = duration of exposure, h/day

BW = body weight, kg bw.

The sources of information for the parameters used in Equation 2 are:

- C – obtained from data provided in the coal seam gas industry survey or from supplementary data requests (i.e. concentration of chemical as *delivered to site*). Concentrations provided to NICNAS as CBI were included in the estimations. In the absence of information available in the industry survey, values for individual chemicals were obtained from a public literature search. In the absence of information in the industry survey or a literature search, a default concentration of 1 000 g/L (100%) is used (and assumes no dilution with other chemicals).
- D_{EMKG} – inputs to the EMKG-EXPO-TOOL model were:
 - For liquids – ‘chemical-specific boiling point’, ‘batch sizes of greater than 1 m³’, and ‘general ventilation’.
 - For solids – ‘crystalline or granular solids where dust is seen but settles out quickly’, batch sizes of ‘between 1 and 1 000 kg’, and ‘general ventilation’.
 - Outputs for D_{EMKG} were in ranges. Assuming no PPE, the upper limit value of the range is used.
- f_{resp} – assumed to be 1.
- V_{air} – assumed to be 22 m³/day (enHealth 2012).
- B_{inh} – identified in the chemical’s hazard assessment. In the absence of data on bioavailability, absorption data were used.
- t – assumed to be four hours, which is an estimate of the duration of manual handling activities that occur during mixing.
- BW – default value of 70 kg bw (enHealth 2012).

Total internal doses for workers associated with mixing / blending activities were then obtained from the sum of the separate internal doses via dermal and inhalational routes.

2.3.5 Exposure during injection of drilling and / or hydraulic fracturing fluid formulations

During drilling, formulated drilling fluids are pumped from a plastic-lined mud pit and injected into the well. A continuous circulating system injects the fluids and returns the fluid, with cuttings, to the surface.

During hydraulic fracturing, formulated fracturing fluids are injected, under high pressure, into the well. Both drilling and hydraulic fracturing injection processes are automated with regular monitoring of parameters such as pressures and flow rates from on-site control centres.

Although there is potential for exposure of workers to recirculated drilling fluids in the vicinity of the open mud pit, worker exposures during injection of formulated drilling and hydraulic fracturing fluids is expected to be negligible in the absence of inadvertent leaks and spills following equipment malfunction or mishandling.

2.3.6 Exposure during cleaning and maintenance

After completion of drilling operations, transfer pumps and pipes are disconnected manually. The site is then remediated through the removal of the mud pit lining and disposal of empty containers. Workers could potentially be exposed to formulations during these operations. Similarly, worker exposure could occur during manual disconnection of pumps and pipes after completion of hydraulic fracturing operations and disposal of residual fracturing chemicals. Exposures to residual chemicals may occur during maintenance activities for both drilling and hydraulic fracturing operations.

Internal doses associated with dermal and inhalational exposures to drilling and hydraulic fracturing chemicals were estimated for workers for cleaning and maintenance activities.

2.3.6.1 Dermal exposure

The internal dose via dermal exposure was estimated using Equation 1. The sources of information for the parameters used in Equation 1 were:

- C – obtained from data provided in the coal seam gas industry survey (i.e. concentration of chemical *in the final formulation prior to injection*). Concentrations provided to NICNAS as CBI were included in the estimations. In the absence of information available in the industry survey, values for individual chemicals were obtained from a public literature search. In the absence of information in the industry survey or a literature search, a default concentration of 10 g/L (1%)⁴ was used.
- D_{EASE} – for both solids and liquids, the inputs to the EASE model used to calculate D_{EASE} are: pattern of use is ‘non-dispersive’, pattern of control is ‘direct handling’, and contact level is ‘incidental’. These inputs generated a D_{EASE} range of 0 to 0.1 mg/cm²/day. Assuming no PPE, the upper limit value of D_{EASE}, 0.1 mg/cm²/day, is used.
- SA_{derm} – default value of 840 cm² (hands) (US EPA 2011).

⁴ Other than for proppants and water, the majority of drilling and hydraulic fracturing chemicals assessed for human health risks were reported in the industry survey as present in formulated fluids at < 1%. Two chemicals were reported at approximately 1%. Six chemicals were reported at greater than approximately 0.5%. Accordingly, in the absence of information from the industry survey or from public literature, a value of 1% (10 g/L) was adopted as a conservative default concentration for chemicals in formulated fluids.

- B_{derm} – identified in the chemical's hazard assessment. In the absence of data on bioavailability, absorption data were used.
- BW – default value of 70 kg bw (enHealth 2012).

The duration of exposure is assumed to be eight hours.

2.3.6.2 Inhalational exposure

The internal dose via inhalational exposure was estimated using Equation 2. The sources of information for the parameters used in Equation 2 were:

- C – obtained from data provided in the coal seam gas industry survey (i.e. concentration of chemical *in the final formulation prior to injection*). Concentrations provided to NICNAS as CBI were included in the estimations. In the absence of information available from the industry survey, values for individual chemicals were obtained from a public literature search. In the absence of information available from the industry survey or a literature search, a default concentration of 10 g/L (1%)⁵ was used.
- D_{EMKG} – inputs to the EMKG-EXPO-TOOL model were:
 - For liquids – ‘chemical-specific boiling point’, ‘batch sizes of greater than 1 m³’ and ‘general ventilation’.
 - For solids – ‘crystalline or granular solids where dust is seen but settles out quickly’, batch sizes of ‘between 1 and 1 000 kg’ and ‘general ventilation’.
 - Outputs for D_{EMKG} were in ranges. Assuming no PPE, the upper limit value is used.
- f_{resp} – assumed to be 1.
- V_{air} – assumed to be 22 m³/day (enHealth 2012).
- B_{inh} – identified in the chemical's hazard assessments. In the absence of data on bioavailability, absorption data were used.
- t is assumed to be eight hours, which is an estimate of the manual handling activities that occur during cleaning and maintenance.
- BW default value of 70 kg bw (enHealth 2012).

Total internal doses for workers associated with cleaning/maintenance activities were then obtained from the sum of the separate internal doses via dermal and inhalational routes.

2.3.7 Exposure during transport and storage of flowback and produced water

Workers may be exposed to hydraulic fracturing chemicals during handling of flowback and produced waters. Flowback and produced waters are typically transported via underground pipes to storage and treatment facilities in which case worker exposures are likely to be negligible. However, transport via road tanker may occur in some cases and in these situations exposures to residual fracturing chemicals may occur via spills and leaks during

⁵ Other than for proppants and water, the majority of drilling and hydraulic fracturing chemicals assessed for human health risks were reported in the industry survey as present in formulated fluids at < 1%. Two chemicals were reported at approximately 1%. Six chemicals were reported at greater than approximately 0.5%. Accordingly, in the absence of information from the industry survey or from public literature, a value of 1% (10 g/L) was adopted as a conservative default concentration for chemicals in formulated fluids.

manual handling of equipment. However, such exposures are unlikely to exceed exposures expected during cleaning and maintenance of equipment containing more concentrated residual hydraulic fracturing fluids.

2.3.8 Exposure during incidents

A total of 10 incidents resulting in unintentional releases were reported in the coal seam gas industry survey (NICNAS 2017c). These included incidents during transport (e.g. truck rollover with drilling mud samples), mixing (e.g. tank overflow during mixing of hydraulic fracturing fluids), well injection (e.g. mechanical failure of valves, pump disc failure), and storage of flowback and / or produced water (e.g. release of fluids following high rainfall event, leaking storage pond from liner failure). The fluids released from the well injection incidents were reportedly handled and contained at the well site. For the other reported incidents, revisions to company operating procedures (e.g. wet weather preparedness, review of engineering design of well lease and ponds, additional inspection activities as part of monitoring) were conducted to minimise further incidents.

Although some information on the containment of inadvertent chemical releases was available in the industry survey, no data were provided on worker exposures during these reported incidents. Because of the difficulty in conducting a contaminant source-pathway-receptor analysis given the range of potential unintentional release scenarios and different levels of engineering controls mitigating worker exposures, worker exposures from incidents are not quantified in the risk assessments.

2.4 Public exposure

A number of chemicals used in drilling and / or hydraulic fracturing for coal seam gas extraction are available to the public for use in the home (e.g. glycerol, ethanol, bleach, etc.). However, the public is unlikely to experience direct contact with, and acute exposures to, these chemicals in the forms, quantities, packaging or handling situations typical of coal seam gas operations. In addition, operational sites have controlled access and signage preventing public access.

However, exposure to these chemicals may occur indirectly via environmental contamination from coal seam gas operations, especially if operations occur in close proximity to residential, farming, or recreational areas.

The assessment of public exposure to chemicals requires an understanding of the sources of contamination, the routes of contaminant flows, the receiving environments affected by contamination and how humans interact with, and absorb, contaminants from these receiving environments.

2.5 Public exposure assessment

2.5.1 Scenarios and routes of exposure

Public exposures from coal seam gas operations are most likely via contamination of ambient air and water used for drinking, bathing and recreational uses (e.g. swimming).

Literature reviews and conceptualisation reports established contaminant sources and flow pathways associated with coal seam gas operations. Modelling frameworks were also developed for calculating predicted environmental concentrations (PECs) for coal seam gas chemicals for various coal seam gas activities and contaminant release scenarios (Mallants et al. 2017b and 2017c; DoEE 2017a and 2017b). From these analyses, distinct points of release of chemical contamination were identified which differ in characteristics, such as the geometry of the chemical contaminant source, chemical release volumes,

durations of release, frequencies of release, chemical composition and concentration. The characteristics of releases associated with coal seam gas activities therefore potentially vary from point source, high volume, high chemical concentration, infrequent, rapid releases such as from a transport accident, to area source, low volume, low chemical concentration, long duration releases such as undetected leaks from a produced water storage pond.

Additionally, distinct transfer pathways for chemical contamination were identified. Chemical flows resulting in water contamination may occur via the surface, via subsurface, or both (Mallants et al. 2017b; DoEE 2017a). In addition, in the case of gases, vapours, aerosols or particulates, contaminant transport may occur via ambient air (NICNAS 2017b and 2017e).

From these analyses, the following coal seam gas related scenarios, representative of different source characteristics and contaminant transfer pathways, are considered for assessing the extent of potential environmental contamination and resultant human exposures from coal seam gas operations:

1. a bulk spill during transport and surface runoff to surface water (e.g. a river) used for drinking, bathing and recreation (swimming)
2. a bulk spill at operational sites from a surface storage tank or pond and migration to soil, to shallow groundwater used for drinking and bathing, and to surface water used for drinking, bathing and swimming
3. a long-term subsurface leak from a coal seam gas flowback and / or produced water storage pond and migration to soil, to shallow groundwater used for drinking and subsequently to surface water used for drinking, bathing and swimming
4. emissions of volatilised chemicals / particulates / aerosols to ambient air in the vicinity of operations.

These exposure scenarios recognise that the predominant environmental media through which humans may be exposed to chemicals used in drilling and hydraulic fracturing are water used for drinking, bathing and recreational purposes (swimming) and ambient air.

Exposure to these chemicals is also possible through the consumption of foods such as meat, milk, vegetables and cereals contaminated via uptake of contaminated water and / or direct airborne deposition of chemical particulates. However, currently no data are available on levels of chemical residues in food which could be linked to contamination by drilling and hydraulic fracturing operations. Therefore, because of the difficulty in establishing likely levels of contamination of foods linked to these operations, public exposure to drilling and hydraulic fracturing chemicals via food is not quantified in the current assessment.

The scenarios outlined above recognise that, depending on source characteristics, contaminant flows to these environmental media can occur predominantly via the surface or subsurface pathways. For these scenarios, human exposures are considered via oral (drinking), dermal (bathing and swimming) and inhalational routes. In order to assess the total human exposures associated with environmental contamination, human exposures are calculated separately for each exposure route and for different environmental media. Internal human doses are then calculated by summing internal doses expected from contact with these different environmental media.

To determine the extent of contamination of different environmental media for these different release scenarios, separate modelling was used to simulate surface contaminant flows to surface water and subsurface contaminant flows through soil, shallow groundwater and then to surface water.

2.5.1.1 Public exposure from chemicals in ambient air

The general population may be exposed to drilling and hydraulic fracturing chemicals by inhalation of these chemicals in ambient air or via deposition to dust / soil and inhalation of dust / soil particles. Inhalational exposures are most likely in cases of:

- volatile chemicals (vapour pressure greater than 0.5 kPa)
- inhalable / respirable particles that can potentially be inhaled (particle diameters below 100 µm)

or

- non-volatile chemicals (vapour pressure less than 0.5 kPa) released to the environment adsorbed to dust and / or deposited to soil.

Inhalational exposure via dust / soil can be estimated if the concentration of the chemicals in dust / soil and the amount of dust in the air are known.

No Australian information is available on the concentrations of drilling and hydraulic fracturing chemicals in the atmosphere and dust / soil in close proximity to coal seam gas extraction activities. Therefore, the inhalational exposures of the public to drilling and hydraulic fracturing chemicals for coal seam gas extraction cannot be determined.

Based on occupational inhalation exposures, it is expected that inhalational exposure of the public to chemicals via ambient air is likely to be low compared to other exposure routes. The following analysis puts the likely extent of atmospheric exposure of the public to chemicals into context. If the estimated internal doses for workers from inhalational exposure to chemicals during mixing / blending (assuming no engineering controls or PPE) are taken as representative of internal doses that the public may experience by inhalation of contaminated ambient air, the values, across all chemicals, are on average more than two orders of magnitude lower than internal doses calculated for the public from combined oral and dermal exposures to surface water contaminated by the same chemicals as a result of a transport accident. If only highly volatile chemicals i.e. chemicals with vapour pressure > 25 kPa (ECHA 2012a), are considered (two chemicals), then the difference between internal doses for these chemicals for workers and the public is still more than two orders of magnitude.

Thus, based on this analysis of potential individual workplace exposures, the atmospheric exposure route is unlikely to represent a major route of exposure for the public. However, it is likely that inhalation exposure would occur on a more regular basis than exposure via contamination of surface or subsurface water. Monitoring data on ambient air emissions from coal seam gas developments would assist the assessment of human health risks from exposures via ambient air.

2.5.2 Methodology for deriving Predicted Environmental Concentrations for environmental media

As with occupational exposures, actual monitoring data for the environmental media relevant for the public exposure scenarios being considered are preferred over exposure modelling data. However, no monitoring data relevant to the exposure scenarios being considered in this report were available. Therefore, in the absence of these data, public exposures were estimated using models.

Predicted environmental concentrations for surface water impacted by a bulk surface spill and surface runoff were provided to NICNAS by the Department of the Environment and Energy (DoEE). These values were based on the conceptualisation of exposure pathways occurring via the surface environment (DoEE 2017a). For contamination scenarios involving

subsurface transport, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) provided dilution factors from which PECs were derived for soil, shallow groundwater and surface water using source concentrations for the chemicals (Mallants et al. 2017c).

The DoEE and CSIRO modelling methodologies used for the human health risk assessment evaluated different pathways for contaminant flows that together contribute to potential human exposures via the environment (surface transport only for the DoEE modelling and subsurface transport only for the CSIRO modelling). In the majority of cases, both methodologies utilised high-end or conservative, but realistic, assumptions for various input parameters for the exposure assessment (DoEE 2017a; Mallants et al. 2017b, 2017c). However, at the Tier 1 level, it is assumed that dilution is the only process that can reduce the concentration of a chemical, with no loss occurring via adsorption to soil or chemical or biological degradation.

Overall, the exposure assessments reflected a 'high-end' estimate approach, rather than a bounding estimate or worst-case approach for calculating exposures. This results in exposure estimates that are higher than average, but still within a realistic, reasonably anticipated range (US EPA 1992). Such a high-end estimate approach seeks to ensure that risks are not underestimated to provide confidence that risk mitigation measures will be sufficiently protective, while ensuring that risk mitigation measures represent an appropriate use of risk mitigation resources.

Predicted environmental concentrations for shallow groundwater and surface water, for each relevant exposure scenario, were then used as input concentrations to calculate the internal human dose of the chemical, based upon uptake of the chemical via consumption and use of these waters.

2.5.2.1 Surface contaminant transport modelling

Impacts on surface water via surface contaminant release and transport were assessed using modelling outputs from DoEE. The DoEE model was used to calculate PECs for surface water via surface runoff for the bulk spill scenario where a transport incident, such as a truck rollover, causes a large volume spill of drilling or hydraulic fracturing chemicals directly to soil. The incident is considered a single event where the release is limited in duration and, in general terms, restricted to the location of the accident. The release is also limited by the carrying capacity of the truck.

This scenario assumes no attenuation of surface runoff, leading to long-term environmental contamination. This is a conservative assumption, given that prompt reporting of any transport incident and site remediation would be expected. However, this assumption is appropriate for a 'high end' Tier 1 exposure estimate which includes the possibility of long-term environmental contamination through delays in reporting and remediation and / or where site remediation is ineffective.

The primary assumption made by the surface transport model at the Tier 1 level of assessment is that the chemicals run off to a surface water body and do not degrade or bind to soil components in transit. Overall, the following conditions were assumed in determining Tier 1 PECs for the surface transport pathway (DoEE 2017a):

- Chemical concentrations used as inputs to calculate PECs are the concentrations reported in the industry survey or from supplementary data requests (NICNAS 2017c) for chemicals as delivered to site. Concentrations reported as confidential business information (CBI) are included in the calculations. In the absence of information in the industry survey, values for individual chemicals were obtained from the publically

available literature, or failing that, a default concentration of 1 000 g/L (100%) was used.

- Contaminants are dissolved in water and, as noted, losses do not occur via adsorption to soil or via degradation. All of the contaminated area is considered to contribute equally to runoff. The amount of suspended chemical is considered to be negligible.
- The chemical quantity is released to soil and a fraction of the volume is transported with runoff water to a surface water body. The runoff fraction is related to the amount of runoff and the total water input (i.e. precipitation).
- The volume of chemical transported is assumed to be equal to the maximum truck capacity (i.e. 10 000 kg for solids or 10 000 L for liquids).
- The quantity spilled is equivalent to the total quantity transported (e.g. concentration (g/L) multiplied by the maximum truck capacity i.e. 10 000 L). However, some chemicals had information from the industry survey on quantities in intermediate storage based on information on products / formulations in intermediate storage which contained the chemical. For these chemicals, the assumption was made that the quantity transported to well sites could not exceed the quantity in intermediate storage and, therefore, the quantity spilled was limited to the quantity calculated for intermediate storage (DoEE 2017a).
- The volume of the receiving surface water body is assumed to be 1 500 m³ (DoEE 2017a).
- The volume of surface runoff is a function of rainfall, retention potential, and the fraction of the chemical in runoff water which is dependent on slope and several other variables. The assumed slope of land over which the spilled quantity runs off is 12.5%. Daily rainfall value is assumed to be 30 mm, discharged to low permeability soils.

The DoEE report (DoEE 2017a) contains further information on the methodology and parameters used in deriving PECs in surface water from surface runoff from a bulk spill.

2.5.2.2 Subsurface contaminant transport modelling

Dilution factors, reflecting dilution during subsurface chemical contaminant transport in soil and shallow groundwater, were derived from the modelling conducted by CSIRO. These dilution factors were applied to source concentrations to derive PECs for receiving environments including shallow groundwater, rivers receiving discharge from shallow groundwater (i.e. gaining rivers), and wetlands that are either connected to, or disconnected from rivers. The PECs for each chemical were estimated from dilution factors derived from the CSIRO modelling and source concentrations from the industry survey or default concentration values.

CSIRO developed models for up to four source-pathway-receptor combinations for which three – the soil, groundwater and river receptors (Figure 2.2) – are utilised in this assessment.

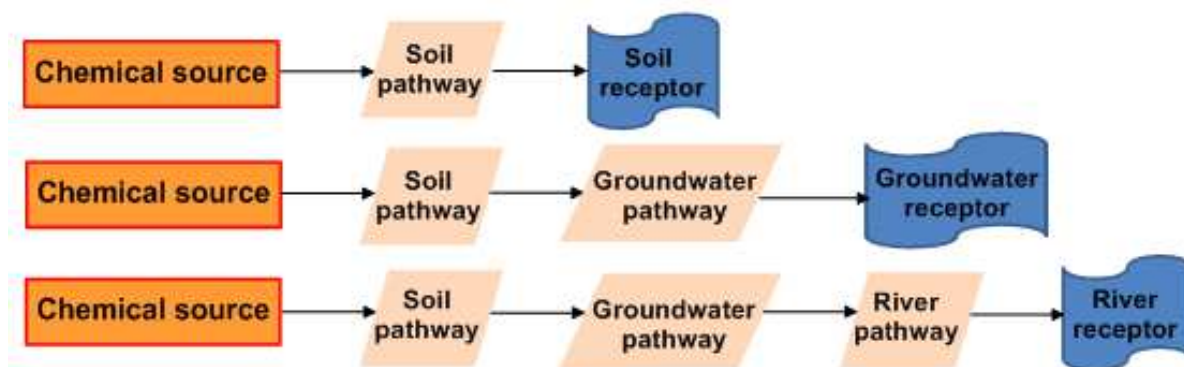


Figure 2.2 Schematic diagram of the CSIRO models used for the soil, groundwater and river receptors

Dilution factors associated with contaminant movement through the unsaturated soil zone (DF_L) and groundwater (DF_{GW}) were determined. The combined dilution factor for movement of contaminants through both soil and groundwater is therefore described in Equation 3.

$$DF = DF_L \times DF_{GW} \quad [\text{Equation 3}]$$

Where:

DF_L = the ratio of the chemical concentration at the source (C_S) to the concentration at the water table (C_{WT}) at the base of the unsaturated soil column.

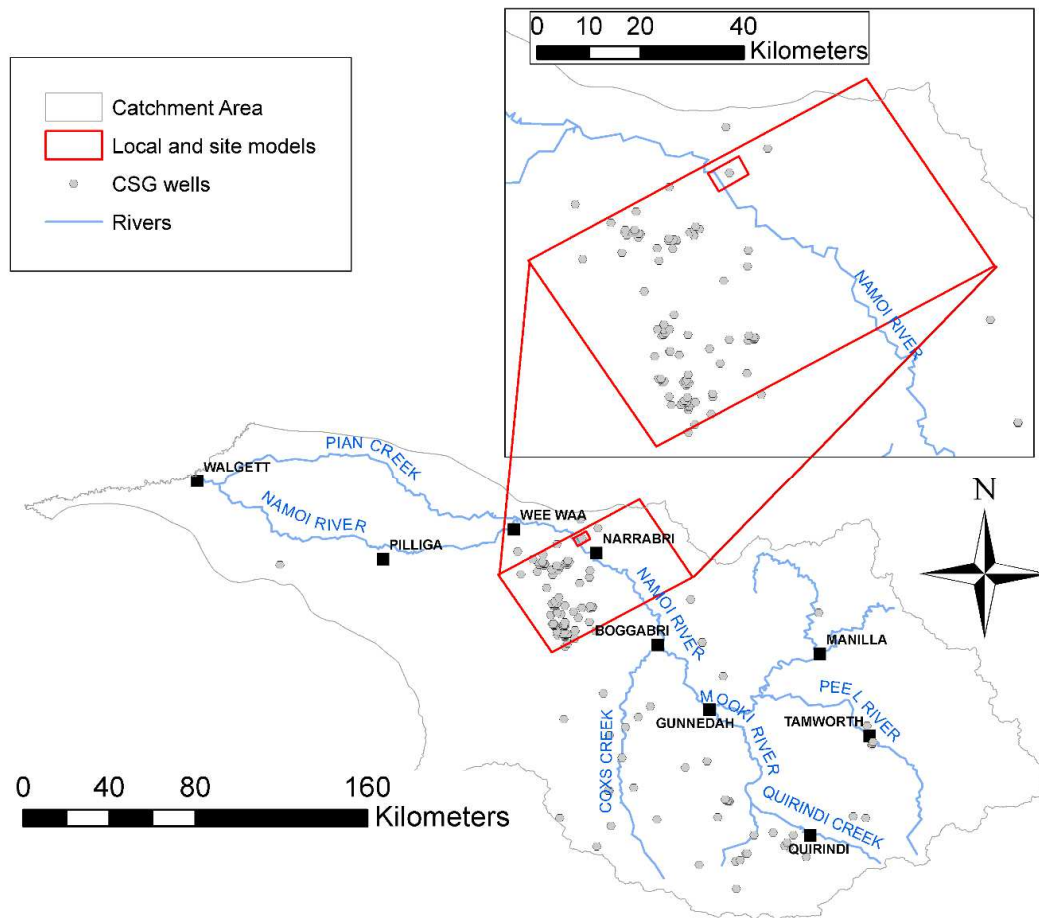
DF_{GW} = the ratio of C_{WT} and the chemical's concentration in the groundwater (C_{GW}).

These dilution factors are conservative since they assume no chemical interactions between contaminants and the solid phases such as mineral and organic matter, and no biogeochemical transformations (e.g. sorption, precipitation, or (micro) biological degradation).

The most conservative approach to derive dilution factors for a surface chemical release is to use the hydrogeological modelling parameter values that would give the lowest dilution factors (i.e. assuming highly permeable soil such as sand, low long-term mean recharge rate, low hydraulic conductivity, and low hydraulic gradient) as inputs for contaminant transport modelling. However, this conjunction of conditions would result in bounding estimates of PECs and is arguably overly conservative, representing a scenario that is unlikely to occur in practice.

An alternative approach, as used in this assessment, is to derive dilution factors using reference values for modelling parameters based on those for a catchment area for which hydrogeological data are available. CSIRO identified an existing groundwater flow model (Namoi Catchment Model) developed by Schlumberger Water Services which is based on a subregion within the Namoi Catchment region.

Using this Namoi Catchment Model (NCM) as the starting point, CSIRO developed a reference groundwater model containing reference values for key hydrogeological parameters based on the best available hydrogeological knowledge for a small defined modelling subdomain of 24 km² (Figure 2.3).



Note. Smallest rectangle depicts the modelling subdomain of 24 km² used to establish a reference groundwater flow model (from Mallants et al. 2017c).

Figure 2.3. Subregions within the Namoi Catchment chosen to provide data for solute transport calculations

To extend the results beyond the boundaries of this small modelling domain, multiple model runs were made spanning realistic ranges in the values of key groundwater flow and solute transport parameters based on typical values observed in other parts of the Namoi region and other priority bioregions. A similar approach was undertaken for the soil pathway where multiple model runs accounted for different depths of soil to shallow groundwater, based on an analysis of soil profiles across the entire alluvial groundwater system within the NCM.

Whilst this ‘regionalised generic approach’ allowed a set of groundwater flow models to be developed reflecting existing hydrogeological conditions for a single catchment area (Namoi Catchment), it also provided for extension of the modelling results to a broader range of catchments with similar bounding hydrogeological parameters. These flow models were then used to derive high-end estimate dilution factors and then PECs, for different environmental media for subsurface contaminant transport from surface releases.

Using this modelling approach, the following specific conditions and parameter combinations have been assumed in determining high-end estimate PECs for shallow groundwater and surface water:

- leak of flowback and / or produced water, defined as equivalent to the manufacturer's specifications for the permeability of the membranes lining the pond (3.5 mm/year/m²). The duration of the leak is 30 years.
- For modelling releases from flowback and / or produced water storage, limited data are available on the recovery of hydraulic fracturing fluids in flowback water. In the coal seam gas industry survey, one company estimated that 40 to 60% of the mass or volume injected in the well during hydraulic fracturing could be recovered. In this assessment, 100% recovery is assumed, with the hydraulic fracturing fluid remaining unchanged and the flowback water untreated. Thus, the chemical concentrations used as inputs to calculate PECs are the concentrations reported in the industry survey (NICNAS 2017c) as those for formulated hydraulic fracturing fluids immediately prior to injection. The derived PECs are considered to be high-end estimates as information on the recovery and the extent of flowback water treatment and / or dilution of the hydraulic fracturing fluids is limited. Concentrations provided to NICNAS as CBI were included in the estimations of PECs. In the absence of information for a specific chemical from the industry survey, values were obtained from a public literature search. In the absence of information in the industry survey or from a literature search, a default concentration of 10 g/L (i.e. 1% of the as-supplied undiluted chemical) was used.
- For the soil pathway, the chemical contaminants are assumed to migrate through loam soil. An unsaturated soil zone depth of 5 m was used. Unsaturated soil zone depths of up to 5 m represent 65.7% of the 108 km² subregional flow model area within the Namoi Catchment.
- For the groundwater pathway, the parameters for the soil pathway (i.e. loam soil and 5 m unsaturated soil zone depth) were combined with the groundwater parameters. The flow of groundwater is assumed to be parallel to the source length. A long-term average recharge rate of 20 mm/year was used to estimate solute flux from the soil into the groundwater. The porosity, used to estimate the pore water velocities from groundwater fluxes, was a spatially uniform reference value of 0.2 cm³/cm³. The hydraulic conductivity used was 5 m/day. CSIRO indicated that these combined soil and groundwater parameters are the set of reference values for the NCM which would give more realistic dilution factors.
- A distance of 100 m between the contaminant source and the nearest groundwater extraction well is assumed.
- For the river pathway, the parameters for the soil and groundwater pathways (i.e. loam soil, 5 m unsaturated soil zone depth, 20 mm/year long-term average recharge rate, 0.2 cm³/cm³ porosity, 5 m/day hydraulic conductivity) were combined with the river parameters. The daily discharge rate used was 150 ML/day (25th percentile value). The model assumed a distance of 2 000 m between the contaminant source and the river based on the groundwater-surface water model developed within the Namoi Catchment.

For further information on the methodology used to produce high-end estimates for dilution factors, as well as the reference values giving more realistic dilution factors, refer to Mallants et al. (2017b, 2017c).

2.5.3 Estimating public exposures from PECs for shallow groundwater and surface water

Predicted environmental concentrations derived from the DoEE and CSIRO modelling were used to estimate long-term public exposure through use of water from shallow groundwater and surface water bodies for the purposes of drinking (oral exposure), bathing (oral and dermal exposures) and recreation, such as swimming (oral and dermal exposures). Total internal doses were calculated as a sum of the separate internal doses arising from exposures during drinking, bathing and swimming.

2.5.3.1 Oral exposure

Oral exposures to chemical contaminants can occur via drinking contaminated and untreated water or via inadvertent ingestion of contaminated and untreated water during bathing or recreation (swimming). In the Namoi Catchment, based on current Namoi data, drinking water is derived from groundwater and surface water in approximately the same proportions (i.e. 50 per cent from each source). Therefore, human exposures are considered for drinking water sourced from both groundwater and from surface water (e.g. rivers).

The internal oral dose following drinking contaminated water was estimated using PECs for groundwater and surface water. Separate calculations were conducted for adults and children. For calculating doses, adults are considered as one group without segregation into sub-groups such as those who are pregnant or elderly. Exposure to children is estimated for infants (< 1 year) since water consumption relative to body weight is the highest at this age.

The internal dose arising from the ingestion of drinking water can be derived using Equation 4.

$$E_{\text{oral}} = \frac{C_{\text{ingested}} \times V_{\text{ingested}} \times B_{\text{oral}}}{BW} \quad [\text{Equation 4}]$$

Where:

E_{oral} = internal dose of the chemical from ingestion of contaminated drinking water, mg/kg bw/day

C_{ingested} = concentration of the chemical in groundwater or surface water derived from PECs, mg/L

V_{ingested} = volume of drinking water ingested per day, L/day

B_{oral} = oral bioavailability, %

BW = body weight, kg

The values used in Equation 4 for V_{ingested} are two and one L/day for adults and children, respectively (enHealth 2012). The BW used for adults and children is 70 and 10 kg, respectively (enHealth 2012).

Internal oral doses were also assessed for inadvertent ingestion of water during bathing and during recreation (swimming).

For bathing, a reasonable assumption can be made that, given the duration of the activity, inadvertent oral ingestion of water is negligible.

For swimming, where ingestion of water is more likely compared to bathing due to the nature and duration of the activity, ingestion is calculated using Equation 4 with an additional

numerator term (n) (such as in Equation 5) to reflect intermittent exposure events. Ingestion during swimming of 25 mL/hour (adults) and 50 mL/hour (children) is assumed (enHealth 2012) with a value for n reflecting one hour swimming per day for 52 days/year (enHealth 2012).

2.5.3.2 Dermal exposure during bathing

Internal doses arising from skin contact with water during bathing can be derived using Equation 5.

$$E_{\text{derm}} = \frac{n \times C \times SA_{\text{derm}} \times th \times B_{\text{derm}}}{1000 \times BW} \quad [\text{Equation 5}]$$

Where:

E_{derm} = internal dose of the chemical via the dermal route, mg/kg bw/day

n = mean number of events per day

C = concentration of the chemical in surface water derived from PECs, mg/L

SA_{derm} = surface area of skin, cm²

th = layer of water in contact with the skin, cm

B_{derm} = dermal bioavailability, %

BW = body weight, kg

The value used in Equation 5 for n reflects bathing activities for eight minutes per day, 365 days per year (enHealth 2012). The values used for SA_{derm} , th, and BW are 20 000 cm² (adult) and 5 300 cm² (child) (US EPA 2008; 2011), 0.01 cm (ECHA 2012b), and 70 kg (adult) and 10 kg (child) (enHealth 2012; US EPA 2008), respectively.

2.5.3.3 Dermal exposure during swimming

Internal doses arising from skin contact with water used for recreation (swimming) can also be derived using Equation 5. For swimming, the same parameters for C, SA_{derm} , th, B_{derm} and BW are used. However, for swimming, the value for n reflects swimming activities for one hour per day for 52 days per year (enHealth 2012).

Both dermal and inadvertent oral exposures were considered during bathing and swimming. However, for volatile chemicals, inhalation exposure is also possible during these activities. For this assessment, inhalation exposure during these activities was not calculated. The majority of drilling and hydraulic fracturing chemicals are of low or negligible volatility. Moreover, based on an analysis of occupational inhalation exposures (Section 3.5.2), it is expected that inhalation exposures during these activities are likely to be very low compared to combined exposures via oral and dermal routes.

2.5.4 Public exposure scenario 1: exposure from a bulk spill during transport and surface runoff

For this scenario, it is assumed that contamination of surface water used for drinking, bathing and recreation (swimming) occurs following a bulk spill and surface runoff.

The assumptions used for this scenario are summarised below:

- The contents of a transport truck containing 10 000 kg (for solid chemicals) or 10 000 L (for liquid chemicals) of a drilling or hydraulic fracturing chemical in the form as delivered to operational sites is spilled to soil.
- The entire quantity of the drilling or hydraulic fracturing chemical spilled is available for surface transport via runoff water to a surface water body with a volume of 1 500 m³.
- Predicted environmental concentrations for the surface water are obtained from DoEE modelling (DoEE 2017a) with parameters previously described.
- Adults and children utilise the surface water body as a source of water for drinking, bathing and recreation (swimming).

Oral exposures of adults and children to the chemical are estimated using Equation 4 with parameters previously described. Dermal exposures from bathing and swimming are estimated using Equation 5 with parameters previously described.

2.5.5 Public exposure scenario 2: exposure from a bulk spill from a surface storage tank or pond at operational sites and downward migration into soil

For this scenario, it is assumed that contamination of shallow groundwater and surface water used for drinking, bathing and recreation (swimming) occurs following a bulk spill and migration downwards into the soil.

The assumptions used for this scenario are summarised below:

- The contents of a surface storage tank or pond containing 15 000 L of a drilling or hydraulic fracturing chemical in the form as delivered to operational sites is spilled or overflows to soil.
- The whole spill quantity migrates within the unsaturated soil zone (depth of 5 m), then to shallow groundwater, and then to surface water. The unsaturated soil zone is assumed to contain loam soil.
- Adults and children utilise the shallow groundwater and surface water as a source of drinking water. The CSIRO models (Mallants et al. 2017b; 2017c) were used with parameters previously described.

CSIRO derived dilution factors at different soil depths for one day, 10 days, and 100 days following the bulk spill. Assuming a 1000 mg/L concentration of chemical in the spilled fluid, and using the dilution factors derived from the CSIRO soil receptor model, the following concentrations at 5 m depth for loam soil are predicted at the following times:

- 1 day after spill = 0
- 10 days after spill = 0
- 100 days after spill = 864 mg/L.

The modelling estimates that the concentration of the chemical in the unsaturated soil zone (depth of 5 m) within 10 days of the spill is zero. Assuming remediation of this operational site occurs within this time, the potential for movement of the chemical to shallow groundwater and surface water within this timeframe is similarly negligible.

Accordingly, public exposure for this scenario involving a bulk release from surface storage, followed by rapid cleanup results in negligible shallow groundwater and surface water contamination.

2.5.6 *Public exposure scenario 3: exposure from a long-term subsurface leak from a coal seam gas flowback and / or produced water storage pond*

The assumptions used for this scenario are summarised below:

- A flowback and / or produced water surface storage pond has a very small subsurface leak⁶ with an assumed uniform water loss across the entire liner in accordance with the liner design specifications. These ponds are typically located nearby the coal seam gas production wells. The duration of the undetected leak is 30 years which is reflective of a typical design life of a storage pond and an entire coal seam gas production phase. The leakage rate is 3.5 mm/year representative of a pond with a composite geomembrane/compacted clay liner.
- The recovery of hydraulic fracturing fluids into flowback and / or produced water is 100%, and the storage pond contains 100% hydraulic fracturing fluid only.
- The leak has migrated to the unsaturated soil zone (depth of 5 m), shallow groundwater, and then to surface water.
- The distance of the groundwater extraction well from the leaking storage pond is 100 m. The distance of the surface water source (e.g. river) to the leaking storage pond is 2 000 m. Adults and children utilise the untreated groundwater for drinking and bathing and the untreated surface water for drinking, bathing and swimming.
- The PECs for groundwater and surface water are obtained from dilution factors from CSIRO modelling (Mallants et al. 2017b; 2017c) with parameters previously described. The concentrations used to derive the PECs from the dilution factors are those reported in the industry survey (NICNAS 2017c) for formulated hydraulic fracturing fluids immediately prior to injection.
- Oral exposures of adults and children to the chemical are estimated using Equation 4 with parameters previously described. Dermal exposures from bathing and swimming are estimated using Equation 5 with parameters previously described.

⁶ While generally low, leakage (the combination of advective and diffusive migration of fluids) from a composite liner (geomembrane combined with either a compacted clay liner or a geosynthetic clay liner) cannot be avoided and is mainly due to the fact that a geomembrane installed as part of a liner system generally may have some holes [2.5 to 5 holes per hectare being most commonly assumed (Rowe et al. 2004; Rowe and Hosney 2010; Rowe 2012)].

3 Risk characterisation

Risk characterisation is the qualitative and, wherever possible, quantitative description of the likelihood of an agent or situation having the potential to cause adverse effects. With respect to chemicals, risk characterisation is conducted by integrating information on hazard (toxicity) with information on exposure.

The risk characterisation estimates the risk to human health under relevant exposure scenarios. A logical consequence of this process of assessment is application of the information to the development of practical measures (risk management) for the protection of human health (IPCS 1999), where such measures are deemed to be warranted. Section 3 sets out the methodology used to characterise the risks for occupational and public health.

3.1 Methodology

Risk characterisation can be conducted qualitatively through qualitative descriptive expressions of risk, or quantitatively through the derivation of numerical risk estimates as expressions of risk.

A Margin of Exposure (MOE) methodology is accepted practice and is used frequently in international chemicals assessments to quantify risks to human health (EC 2003). In this report, the MOE methodology is used to estimate the health risks to workers and the public from long-term (repeated) exposures to chemicals used for coal seam gas extraction. Risks from acute, single exposures are characterised qualitatively.

An MOE for risk characterisation is derived using the following steps:

1. Identification of critical (most sensitive) health effect(s) ie. health effect(s) relevant to the assessed human population seen at the lowest doses.
2. Identification of the most appropriate / reliable no-observed-adverse-effect level (NOAEL) (if available) for the critical effect(s).
3. Where appropriate, comparison of the estimated or measured human dose or exposure (EHD) to provide a MOE.
4. $MOE = NOAEL/EHD$.
5. Characterisation of risk, by evaluating whether the MOE indicates a concern for the human population under consideration.

The MOE provides a measure of the likelihood that a particular adverse health effect will occur under the conditions of exposure. As the MOE increases, the risk of potential adverse effects decreases. This is in contrast to environment risk assessment where, as the equivalent measure – the risk quotient (RQ) – increases, the risk of potential adverse environmental effects increases as well.

In deciding whether the MOE is of sufficient magnitude (i.e. whether the total internal dose calculated in humans from exposures to contaminated environmental media is sufficiently small compared to the dose at which no adverse health effects are expected in humans) expert judgement is required. Such judgements are usually made on a case-by-case basis, and take into account uncertainties arising in the risk assessment process such as the completeness and quality of the database, the nature and severity of effect(s) and intra- / inter-species variability. Uncertainties in the risk characterisation are accounted for through the use of uncertainty factors by which the magnitude of the MOE is assessed.

A qualitative risk assessment of health effects from long-term exposures takes into consideration physicochemical properties, such as if the chemical dissociates in aqueous solutions, as well as the nature of its constituent ions, known reactivities and intended uses of the chemical, to derive a conclusion about the risk.

3.2 Choice of uncertainty factors

Uncertainty factors, representing uncertainties associated with the risk assessment process, are used to assist in determining whether the magnitude of an MOE represents a concern for human health. An MOE of greater than 100 in risk characterisation is commonly regarded as an indication of low concern. This MOE encompasses conservative default uncertainty factors of 10 each for intra-species variability (variability across the human population) and inter-species variability (variability between responses seen in animals and humans) (ECETOC 2003; IPCS 1994).

In essence, using these default uncertainty factors based on intra-species and inter-species variability means that a low concern for human health can be established if the internal human dose of a particular chemical is more than 100 times less than the no-observed-adverse-effect level derived from the toxicological animal test database for the chemical.

Conversely, an MOE of equal to, or less than 100 is commonly regarded as indicating a potential concern for human health.

Uncertainty factors vary with data quality and availability. For example, if adequate human data are available on which to base the risk characterisation, then the uncertainty factor accounting for inter-species variability is not required. In this case, an MOE of greater than 10 (accounting for intra-species variability only) is considered an indication of low concern.

In this report, an additional uncertainty factor of 3 is used in cases where extrapolation from a lowest-observed-adverse-effect level (LOAEL) to a NOAEL is required. Also, an uncertainty factor (sometimes called an adjustment factor) of 3 is used to adjust NOAELs from repeat dose studies of inadequate duration (e.g. 28 days rather than 90 days or longer in the absence of studies of longer duration).

Uncertainty factors are also used to reflect susceptibilities of specific human subpopulations such as the elderly or children. In the current risk assessments, no additional uncertainty factors are applied to account for risks specific for children. The toxicokinetics of xenobiotic metabolism are considered at an age of six to 12 months to be at least the equivalent of those in adults (ECETOC 2003; Renwick 1998) and so similar MOEs for both adults and children are regarded as appropriate indications of low concern for human health.

For the majority of the 69 chemicals assessed for human health risk, an uncertainty factor of 100 was applied. Around 40% of the chemicals warranted an uncertainty factor either above or below 100 (for reasons described in the individual risk assessment report for each chemical).

3.3 Occupational risks

3.3.1 Health risks from acute exposure

Human health hazard assessments were conducted on the 69 chemicals used in drilling and / or hydraulic fracturing. Of these, 57 of the 69 chemicals are considered hazardous based on Safe Work Australia's Approved Criteria for Classifying Hazardous Substances (NICNAS 2017b). This means that contact with these chemicals in pure, concentrated form in

the absence of exposure controls is likely to result in adverse health effects, depending on the toxic properties of the chemical.

However, use information derived from the industry survey (NICNAS 2017c), and as provided in individual risk assessments for these chemicals (Appendix C), indicates that chemicals as delivered to operational sites for drilling and hydraulic fracturing vary in concentration and in physical form. The potential for adverse health effects will depend on how the chemical is presented. For example, adverse health effects are less likely for chemicals delivered and handled in highly diluted forms rather than as concentrates. Forty-four of the 69 chemicals were of potential concern for the health of workers through acute inadvertent exposure to the chemicals as delivered to the site.

In general, acute inadvertent exposure to chemicals in their most concentrated form (i.e. as delivered to operational sites) is most likely during manual handling (if required) and during manual manipulation of equipment containing residual chemicals during operations, cleaning and maintenance and during cleanup of spills. Levels of exposure, and thus the risk of acute adverse health effects from inadvertent exposures during occupational handling, will therefore be highest for handling of concentrated chemicals as delivered to site, but will vary depending on the chemical concentration and the work practices employed.

Given the dilution of these chemicals in formulated drilling and hydraulic fracturing fluids, and in flowback water after fracturing, exposure to chemicals via these fluids generally represents a much lower acute health risk for workers, compared to handling the undiluted chemicals initially delivered to operational sites. Also, in the case of hydraulic fracturing chemicals, given the high degree of dilution of these chemicals in produced water, the risk of acute adverse health effects for workers from contact with produced water containing these chemicals is likely to be negligible.

3.3.2 *Health risks from long-term exposure*

Health risks associated with long-term repeated occupational exposures to chemicals were quantified by calculating separate MOEs for separate occupational activities. The occupational activities for which MOEs were derived are:

- Mixing / blending
- cleaning and maintenance.

Additionally, given the drilling and hydraulic fracturing work routines at coal seam gas well sites, MOEs were also calculated for workers assuming combined exposures from both mixing / blending and cleaning and maintenance.

Conclusions from MOE calculations for different chemicals for these separate occupational activities are detailed in Appendix A. Based on calculated MOEs using conservative assumptions, the numbers of chemicals with risk estimates suggestive of a potential concern from repeated exposures are summarised in Table 3.1. These numbers include chemicals for which the magnitude of the MOE was suggestive of a potential concern, but the MOE was based on a study in which no adverse effects were noted at the highest dose used (see Section 3.5.1). For these chemicals, a potential concern could not therefore be ruled out.

These numbers also include chemicals regarded as a potential concern based on a qualitative risk analysis in the absence of repeated dose toxicity data needed for a quantitative risk assessment. In a qualitative analysis of health effects from long-term exposures, the potential for health effects were assessed by considering physicochemical properties (including the nature of constituent ions if the chemical dissociates in aqueous solution), known reactivities and intended uses of the chemical. Percentages are relative to

the total number of chemicals used for drilling (21) and the total number of chemicals used for hydraulic fracturing (58) that have been assessed for human health risks.

Table 3.1 Summary of risk estimates for drilling and hydraulic fracturing chemicals for different occupational activities

Occupational activity	Number of chemicals with risk estimates suggestive of a potential concern #
Drilling chemicals	
Mixing / blending	4 (19%)
Cleaning and maintenance	1 (5%)
Combined exposure—mixing / blending and cleaning and maintenance	4 (19%)
Hydraulic fracturing chemicals	
Mixing / blending	9 (16%)
Cleaning and maintenance	3 (5%)
Combined exposure—mixing / blending and cleaning and maintenance	10 (17%)

Percentages are relative to the total number of drilling chemicals (21) or total number of hydraulic fracturing chemicals (58).

For mixing / blending activities, a total of four out of 21 drilling chemicals (19%) and nine out of 58 hydraulic fracturing chemicals (16%) have MOEs suggestive of a potential concern.

For cleaning and maintenance activities, only one out of 21 drilling chemicals (5%) and three out of 58 hydraulic fracturing chemicals (5%) have MOEs suggestive of a potential concern.

For combined exposures during both mixing / blending and cleaning and maintenance, assuming that the same workers carry out both these activities, a total of four out of 21 drilling chemicals (19%) and 10 out of 58 hydraulic fracturing chemicals (17%) have MOEs suggestive of a potential concern.

Overall, the occupational health risk characterisation concluded that the majority of chemicals used for drilling and hydraulic fracturing were of low concern for human health from long-term exposures in the workplace. However, the risk characterisation identified up to four of the 21 chemicals used for drilling and up to 10 of the 58 chemicals used for hydraulic fracturing of potential concern for human health from long-term exposures during certain occupational activities, unless these chemicals are managed appropriately.

3.4 Public risks

3.4.1 Health risks from acute exposure

Drilling and hydraulic fracturing are industrial operations and the chemicals used for these operations are not available to the public in the forms, quantities, packaging or handling situations typical of coal seam gas operations. These operational sites also have controlled access and signage preventing public access. Therefore, the public is unlikely to come into contact with these chemicals as delivered to, and handled at, coal seam gas operational sites and so the chemicals in this form are unlikely to pose a potential concern for the public.

3.4.2 Health risks from long-term exposure

Health risks associated with long-term public exposure to drilling and hydraulic fracturing chemicals were quantified by calculating MOEs for public exposure resulting from separate environmental contamination scenarios (see Section 2.5.1).

The environmental contamination and public exposure scenarios for which MOEs were calculated are:

- a bulk spill during transport, with contamination of surface water such as a river
- a long-term subsurface leak from a coal seam gas flowback and / or produced water storage pond, with contamination of shallow groundwater and, subsequently, surface water.

Public exposure from a bulk spill from a storage tank or pond containing drilling and / or hydraulic fracturing chemicals was also considered. However, given the likelihood of site remediation prior to the contaminant plume reaching groundwater, the resulting PECs from this release are regarded as negligible (Section 2.5.5)

For the scenario of a long-term subsurface leak from a flowback and / or produced water storage pond, PECs were not calculated for drilling chemicals, as it is assumed that only negligible levels of drilling chemicals are present in flowback and / or produced water.

For hydraulic fracturing chemicals for this scenario, PECs were calculated for both shallow groundwater and surface water, and MOEs were calculated separately for two patterns of water use. The first use pattern was drinking and bathing in contaminated shallow groundwater plus swimming in contaminated surface water. The second was drinking, bathing and swimming in contaminated surface water. For each exposure scenario, MOEs were calculated for adults and children. Conclusions from MOE calculations for each chemical and exposure scenario are outlined in Appendix B and summarised in Table 3.2 and Table 3.3 for drilling chemicals and hydraulic fracturing chemicals respectively.

Similar to calculations for risks to workers, the numbers in these tables include chemicals for which the magnitude of the MOE was suggestive of a potential concern but the MOE was based on a study in which no adverse effects were noted at the highest dose used (see Section 3.5.1) and therefore a potential concern could not be ruled out. These numbers also include chemicals of potential concern based on a qualitative risk analysis in the absence of repeated dose toxicity data required for a quantitative risk assessment. In a qualitative analysis of health effects from long-term exposures, the potential for health effects was assessed by considering physicochemical properties (including the nature of constituent ions if the chemical dissociates in solution), known reactivities and intended uses of the chemical.

In general, for each chemical, MOEs for children were lower than for adults (Appendix B). This reflects higher internal doses for each chemical calculated for children compared to adults due to higher water consumption and higher skin surface area and dermal absorption relative to body weight (Section 2.5.3). Accordingly, greater numbers of drilling and hydraulic fracturing chemicals were of potential concern for children compared to adults for the exposure scenarios outlined in Table 3.2 and Table 3.3.

Under conservative Tier 1 assumptions, for the scenario of a bulk spill during transport and exposure to contaminated surface water, a small majority of drilling chemicals were assessed as of potential concern for human health. Nine out of 21 drilling chemicals (43%) have risk estimates suggestive of a potential concern for adults and 11 out of 21 (52%) have risk estimates suggestive of a potential concern for children (Table 3.2).

The conservative exposure modelling approach allowed, with confidence, the identification of chemicals of low concern for human health. Although risk estimates derived for some chemicals were suggestive of a potential concern from long-term exposures for these various exposure scenarios, these risk estimates were predicated using conservative modelling assumptions. For example, the exposure modelling did not account for environmental attenuation through adsorption or degradation. Given the potentially slow movement of chemicals within the environment from surface spills and leaks, the influence of such attenuating fate processes over the long-term, for at least some classes of coal seam gas chemicals, could be considerable. For chemicals for which risk estimates indicated a potential concern, the true level of risk is likely to be equal to, or lower than, the level of risk currently derived. The current assessments are adequate to develop risk mitigation strategies but if more accurate estimates of human health risks are required, these could be conducted on a case-by-case basis by risk managers using refined modelling estimates or environmental monitoring data.

Table 3.2 Summary of risk estimates for different public exposure scenarios – drilling chemicals

Drilling chemicals*	Number of chemicals with risk estimates suggestive of a potential concern #	
Public exposure scenario**	ADULT	CHILDREN
Accidental bulk spill during transport and surface runoff		
Combined exposure from bulk spill–surface water use: Drinking, bathing and swimming in contaminated surface water	9 (43%)	11 (52%)

Percentages are relative to the total number of drilling chemicals (21). * Flowback and / or produced water is assumed to contain only negligible levels of drilling chemicals and so PECs and MOEs for drilling chemicals for the subsurface storage pond leak scenario were not calculated. ** MOEs for a bulk spill from a flowback and / or produced water storage pond are not calculated due to negligible PECs and internal human doses.

Table 3.3 Summary of risk estimates for different public exposure scenarios – hydraulic fracturing chemicals

Hydraulic fracturing chemicals*	Number of chemicals with risk estimates suggestive of a potential concern	
Public exposure scenario**	ADULT	CHILDREN
Accidental bulk spill during transport and surface runoff		
Combined exposure from bulk spill–surface water use: Drinking, bathing and swimming in contaminated surface water	26 (45%)	30 (52%)
Long-term subsurface leak from flowback and / or produced water storage pond		
Combined exposure from subsurface leak–groundwater/surface water use: Drinking and bathing in contaminated shallow groundwater plus swimming in contaminated	7 (12%)	14 (24%)

Hydraulic fracturing chemicals*	Number of chemicals with risk estimates suggestive of a potential concern	
Public exposure scenario**	ADULT	CHILDREN
surface water		
Combined exposure from subsurface leak– surface water use: Drinking, bathing and swimming in contaminated surface water	2 (3%) ***	2 (3%) ***

Percentages are relative to the total number of hydraulic fracturing chemicals (58). * Flowback and / or produced water is assumed to contain only negligible levels of drilling chemicals and so PECs and MOEs for drilling chemicals for the subsurface storage pond leak scenario were not calculated. ** MOEs for a bulk spill from a flowback and / or produced water storage pond are not calculated due to negligible PECs and internal human doses. *** These chemicals were regarded as of potential concern on the basis of conservative qualitative risk analyses in the absence of data for a quantitative risk assessment.

For hydraulic fracturing chemicals, a small majority of chemicals were assessed as of potential concern for human health for the scenario of a bulk spill during transport and exposure to contaminated surface water. A total of 26 out of 58 (45%) and 30 out of 58 (52%) chemicals are of potential concern for adults and children, respectively.

For the scenario of a long-term subsurface leak and exposure to both contaminated shallow groundwater and surface water, the majority of hydraulic fracturing chemicals are of low concern for human health. However, a total of seven out of 58 (12%) and 14 out of 58 (24%) hydraulic fracturing chemicals are of potential concern for adults and children, respectively.

For exposure to contaminated surface water alone, all but two hydraulic fracturing chemicals are assessed as being of low concern for adults or children. The two chemicals of potential concern were assessed on the basis of conservative qualitative risk analyses in the absence of repeated dose toxicity data required for a quantitative risk assessment.

Of the modelled environmental contamination and human exposure scenarios, the greatest number of chemicals of potential concern is associated with the scenario of a bulk spill during transport. For this scenario, risk estimates for 45% of drilling chemicals and 52% of hydraulic fracturing chemicals suggest a potential human health concern from the resulting environmental contamination. This is not surprising, as this scenario assumes prolonged exposure from a chemical spill of high volume and high concentration.

Depending on whether surface or shallow groundwater is used for public consumption, up to 24% of chemicals used for hydraulic fracturing had risk estimates suggestive of a potential concern if leakage occurs to shallow groundwater and surface water from flowback and / or produced water storage. For this modelled contamination scenario, the lowest MOEs were seen if contaminated shallow groundwater is used as a source of drinking water. The highest MOEs were seen if water consumption and use is confined to surface water. In this scenario, chemicals undergo sequential dilution during contaminant flows through shallow groundwater and then to surface water and consequently, chemicals are at their highest dilution in surface water. In this scenario, only two chemicals are regarded as a potential concern (on the basis of conservative qualitative risk analyses in the absence of data for a quantitative risk assessment).

The conservative exposure modelling approach allowed, with confidence, the identification of chemicals of low concern for human health. Although risk estimates derived for some chemicals were suggestive of a potential concern from long-term exposures for these various exposure scenarios, these risk estimates were predicated using conservative modelling assumptions. For example, the exposure modelling did not account for environmental

attenuation through adsorption or degradation. Given the potentially slow movement of chemicals within the environment from surface spills and leaks, the influence of such attenuating fate processes over the long-term, for at least some classes of coal seam gas chemicals, could be considerable. For chemicals for which risk estimates indicated a potential concern, the true level of risk is likely to be equal to, or lower than the level of risk currently derived.

The current assessments are adequate to develop risk mitigation strategies but if more accurate estimates of human health risks are required, these could be conducted on a case-by-case basis by risk managers using refined modelling estimates or environmental monitoring data.

3.4.3 *Refinement of risk estimates for the bulk transport spill scenario*

To ensure potential risks are appropriately assessed, the initial Tier 1 high-end estimates of impacts from a bulk transport spill assumed a single, sudden spill of high volume (up to 10 000 L or kg). For the majority of the 23 chemicals for which supplementary industry data were obtained in 2014-15, data on chemical concentrations were similar to those provided in the original industry survey. Where they were dissimilar, the changes were not of a magnitude to significantly increase the human health risks compared to risks calculated based on the original industry survey data⁷.

However, available supplementary data on chemical storage and transport obtained in 2014-2015 suggested that the majority of drilling and hydraulic fracturing chemicals are not transported for use at operational sites (well sites) at such high volumes. Only one chemical of potential concern for human health (hydrochloric acid) was reported as being transported to well sites at a higher volume (14 000 L).

Therefore, as a refinement of the Tier 1 risk assessments, public health risks for this bulk spill scenario were recalculated for all drilling and hydraulic fracturing chemicals for a range of hypothetical spill volumes representative of those reported in the supplementary 2014-2015 data for well site transport. Table 3.4 shows the numbers of drilling chemicals (out of a total of 21) and hydraulic fracturing chemicals (out of a total of 58) with Tier 1 risk estimates (MOEs) suggestive of a potential concern for adults and children (in brackets) from drinking and bathing/swimming in surface water contaminated by transport spills of different volumes.

For the purposes of a sensitivity analysis of risk estimates, these figures only include chemicals for which an MOE could be calculated. They do not include chemicals for which an MOE could not be calculated due to inadequate repeated dose toxicity data and which, therefore, required a qualitative risk assessment to assess the level of concern.

⁷ For one chemical (boric acid), the human health risk assessment was revised to reflect a significant increase in reported transport concentrations in 2015 compared to the original industry survey.

Table 3.4 Effect of varying assumed spill volumes on numbers of chemicals with MOEs suggestive of a potential concern from exposures from a bulk transport spill

Spill volume (L, kg)	Number of chemicals with MOEs suggestive of a potential concern for adults and children (in brackets) Drilling	Number of chemicals with MOEs suggestive of a potential concern for adults and children (in brackets) Hydraulic fracturing
14 000	9 (12)	25 (29)
10 000 (Default)	9 (11)	24 (28)
5 000	4 (9)	23 (25)
1 000	2 (4)	18 (21)
500	1 (3)	12 (19)
100	1 (1)	2 (9)

As expected, the number of chemicals with risk estimates suggestive of a potential concern is directly related to the magnitude (volume) of the spill. Smaller spill volumes mean smaller numbers of chemicals of potential concern, and vice versa.

It is notable that one drilling chemical and nine hydraulic fracturing chemicals (Appendix C) still have Tier 1 risk estimates suggestive of a potential concern with spill volumes as low as 100 L (kg). This analysis highlights the conservative nature of the Tier 1 risk assessments. For example, at this conservative level, the exposure modelling does not consider the range of chemical-specific environmental fate processes such as adsorption to soils, or chemical or biological degradation that, in reality, are likely to significantly attenuate the level of environmental contamination of surface water bodies from such spills.

Also, with the Tier 1 risk assessments, the analysis does not consider additional risk mitigation issues with particular chemicals such as effects on water palatability which may decrease exposures and health risks. Such chemical-specific issues are discussed in the individual risk assessment reports for drilling and hydraulic fracturing chemicals (Appendix D).

These Tier 1 risk assessments for a bulk transport spill provide a relative measure of risk across the spectrum of chemicals used for drilling and hydraulic fracturing. Being conservative, these assessments can reliably identify individual chemicals of low concern. The assessments also identify chemicals of potential concern so that refined risk assessments may be conducted if required by risk managers using appropriate refined modelling estimates or environmental monitoring data for individual chemicals.

Appendix C contains the details of the chemicals for which Tier 1 risk estimates are suggestive of a potential concern and how risk estimates change for these chemicals as a function of spill volume. The chemical identity data are provided for risks to children, as the Tier 1 risk assessments revealed comparatively more chemicals that were a potential concern for children (because of higher internal doses relative to body weight) than for adults.

3.4.4 Refinement of risk estimates for the storage pond leak scenario

To ensure potential risks are appropriately assessed, it is reasonable for an initial Tier 1 high-end estimate of impacts of leakage from long-term surface storage to assume complete recovery of hydraulic fracturing chemicals in flowback water and that the flowback water is

not diluted in the surface pond with additional water such as produced water from the coal seam. In other words, the chemicals in the storage pond are at the same concentration as in the injected hydraulic fracturing fluid. However, as a refinement of the initial Tier 1 human health risk assessments, it is appropriate to recalculate human health risks based on concentrations of hydraulic fracturing chemicals in the storage pond that are less than this Tier 1 assumption of undiluted fracturing fluids. Such a recalculation will reflect more realistic situations of incomplete recovery of hydraulic fracturing chemicals in flowback and dilution of fracturing chemicals with produced water during long-term storage.

Other key assumptions made in the subsurface contaminant modelling for the leaking storage pond scenario are the distances from the leaking storage pond to the groundwater well and to the surface water receptor (river) which were both identified as sources of drinking water. As noted in the human and environmental exposures assessment report (Mallants et al. 2017c), short distances were deliberately considered so as not to underestimate risks. Therefore, an appropriate additional refinement of the Tier 1 assessments is to recalculate human health risks using different assumed distances between the leaking storage pond and groundwater sources of drinking water (groundwater well).

Table 3.5 depicts the impact on the human health risks of varying the concentration of hydraulic fracturing chemicals in the storage pond. Different concentrations can arise from incomplete recovery of chemicals from the well in flowback water and also dilution of recovered chemicals with produced water. The table also depicts the impacts of varying the distances between the storage pond and groundwater well. The compiled values indicate the numbers of hydraulic fracturing chemicals (out of a total of 58) with MOEs suggestive of a potential concern for adults and children (in brackets) from drinking and bathing in shallow groundwater and swimming in surface water (river).

It is noted that, for the purposes of a sensitivity analysis of risk estimates, these figures only include chemicals for which an MOE could be calculated. They do not include chemicals for which an MOE could not be calculated due to inadequate repeated dose toxicity data and which, therefore, required a qualitative risk assessment to assess the level of concern.

Table 3.5 Effect of fracturing fluid dilution and distance to a groundwater well on numbers of chemicals with MOEs suggestive of a potential concern from exposures from leakage (30 years) of a flowback and / or produced water storage pond

Percentage (%) hydraulic fracturing fluid in storage pond	Numbers of chemicals with MOEs suggestive of a potential concern for adults and children (in brackets) with varying distances from a leaking storage pond to a groundwater well used as a source of drinking water (surface water is at 2 000 m)			
	100 m	400 m	800 m	2 000 m
100%	5 (12)	5 (9)	5 (9)	5 (7)
60%	5 (9)	4 (7)	5 (5)	5 (5)
10%	2 (5)	1 (5)	1 (5)	1 (3)
1%	1 (1)	0 (1)	0 (1)	0 (1)
0.1%	0 (0)	0 (0)	0 (0)	0 (0)

Assuming 100% recovery of hydraulic fracturing fluid chemicals and a distance of 100 m to the groundwater well, five chemicals are assessed as being of potential concern for adults from contamination of shallow groundwater, and consequently of surface water, from a leaking storage pond. Twelve chemicals are of potential concern for children. However, assuming the same 100 m to the groundwater well, but decreasing the concentrations of

hydraulic fracturing fluid chemicals in the storage pond by an order of magnitude (to 10%), only two chemicals are of potential concern for adults and only five are of potential concern for children.

Similarly, increasing the distance between the storage pond and groundwater well decreases the numbers of chemicals that are assessed as a potential concern. Assuming 100% recovery of hydraulic fracturing fluid chemicals and increasing the distance to the groundwater well by more than an order of magnitude (to 2 km), five chemicals are of potential concern for adults and only seven for children. Also, there exists combinations of distance to well and hydraulic fracturing fluid concentrations for which risk estimates suggest no potential concerns for any chemical.

The data in Table 3.4 show that the number of chemicals found to be of potential concern is much more sensitive to source concentration than distance, noting that the modelling for the scenarios in Table 3.4 assumes that there is no net loss of a chemical along the transport pathway.

Appendix C contains the full details of the chemicals for which Tier 1 risk estimates are suggestive of a potential concern (for children), and how risk estimates change for these chemicals as a function of concentration in the pond. The chemical identity data are provided for children rather than for adults as the Tier 1 risk assessments revealed comparatively more chemicals that were a potential concern for children than for adults.

A similar analysis was conducted examining the impact of varying the concentration of hydraulic fracturing fluid in the storage pond and varying the distance between the storage pond and surface water receptor (river) (Table 3.6). The analysis was conducted by distinguishing separate dilution factors for soil, groundwater and surface water within the overall soil-groundwater-surface water exposure pathway. For Tier 1 assessments, the assumed distance between the leaking storage pond and surface water was 2 000 m. values in Table 3.6 indicate the numbers of hydraulic fracturing chemicals (out of a total of 58) with risk estimates suggestive of a potential concern for adults and children (in brackets) from drinking, bathing and swimming in surface water (river). As with the other sensitivity analyses, these figures only include chemicals for which an MOE could be calculated. They do not include chemicals for which an MOE could not be calculated due to inadequate repeated dose toxicity data and for which a qualitative risk assessment was conducted to assess the level of potential concern.

Table 3.6 Effect of fracturing fluid dilution and distance to surface water on numbers of chemicals with risk estimates suggestive of a potential concern from leakage (30 years) from a flowback and / or produced water storage pond

Percentage (%) hydraulic fracturing fluid in storage pond	Number of chemicals with MOEs suggestive of a potential concern for adults and children (in brackets) with varying distances from storage pond to surface water used as a source of drinking water	
	2 000 m (default)	100 m
100%	0 (0)	0 (0)
60%	0 (0)	0 (0)
10%	0 (0)	0 (0)
1%	0 (0)	0 (0)
0.1%	0 (0)	0 (0)

For the default scenario of surface water at 2 000 m from the leaking storage pond and assuming 100% hydraulic fracturing fluid in the pond, no chemicals had MOEs suggestive of a potential concern for either adults or children from exposures to contaminated surface water alone i.e drinking, bathing and swimming in surface water (Table 3.3 and Table 3.5 above). Modelling surface water contamination with surface water at 100 m from the leaking storage pond also revealed no chemicals with potential concerns even assuming 100% recovery of chemicals in fracturing fluid within the pond. Because of the relatively low level of dilution in groundwater relative to the level of dilution in surface water (due to river flow), decreasing the influence of groundwater dilution by changing the distance from the source of contamination (storage pond) to the surface water (river) only induces a relatively small decrease in levels of dilution in the overall soil-groundwater-surface water exposure pathway.

The initial Tier 1 modelling and these analyses assume a long-term (30 year) subsurface leak, reflective of the typical design life of the storage ponds and duration of coal seam gas production. However, recent (2014-15) supplementary industry data on chemicals storage and transport indicated that storage of flowback and produced water in surface ponds also occurs for undefined well 'appraisal' periods during which leakage could occur. In such instances, the source duration for modelling a subsurface leakage of hydraulic fracturing chemicals from surface storage could thus be much shorter (around three years) compared to the leak period of 30 years that has been used in the Tier 1 risk assessments.

Another key assumption for the subsurface contaminant modelling was the rate of leakage from the pond. In the absence of actual Australian performance data for surface ponds used for coal seam gas operations, the reference leak rate (3.5 mm/year) used in the Tier 1 risk assessments was reflective of leak rates for ponds with composite geomembrane or compacted clay liners conforming to typical Australian design specifications. However, overseas information for leak rates for ponds used for municipal solid waste suggest that ponds used for coal seam gas water storage could already be constructed to higher performance specifications (e.g. using geomembrane/geosynthetic clay liners) with reduced leak rates compared to the reference leak rate used in the human health risk assessments (Mallants et. al. 2017b).

Any decrease in leak rates and / or leak duration would decrease the extent of potential groundwater and surface water contamination and decrease potential human health impacts associated with consumption and contact with contaminated water. As an example, decreasing the leak rate by an order of magnitude (0.35 mm/year from the reference 3.5 mm/year) or decreasing the leak duration by an order of magnitude (three years from the reference 30 years) would each decrease human exposures and increase risk estimates (MOEs) by approximately an order of magnitude. For the leaking storage pond scenario, this would significantly decrease the number of chemicals of potential concern compared to current risk estimates based on the reference exposure modelling.

With the reference Tier 1 exposure modelling, 12 hydraulic fracturing chemicals have risk estimates (MOEs) suggestive of a potential concern for children from contamination of groundwater. If exposures are decreased and MOEs consequently increased by a single order of magnitude, then only five chemicals are of potential concern. If exposures are decreased by two orders of magnitude (reflecting decreasing both the leak rate and leak duration), then only one hydraulic fracturing chemical is of potential concern.

Similarly to the analysis for the transport spill, these analyses of risk estimates for the leaking storage pond scenario do not consider additional risk mitigation issues with particular chemicals which may also decrease exposures and health risks. Such chemical-specific issues are discussed in the individual risk assessment reports for drilling and hydraulic fracturing chemicals (Appendix D).

3.4.5 Travel times for subsurface contaminant transport

In addition to the calculation of dilution factors used to derive PECs, the CSIRO subsurface contaminant transport modelling also allowed estimation of the 'travel time' required for a chemical contaminant to move from the subsurface contamination source to a shallow groundwater (or surface water) drinking water source. Travel time is defined as the time needed for the concentration of chemical contaminant to reach one half of its predicted maximum concentration at the drinking water source.

Assuming no environmental attenuation other than dispersion, and for the parameter combinations considered in this assessment, the travel time for a chemical to reach a drinking water well 100 m from the source of contamination (a leaking storage pond for flowback and / or produced water) is 62 years. The travel time to a drinking water well 800 m from the leaking storage pond is 180 years (Mallants et al. 2017c). This suggests a potential for chemical contamination from coal seam gas operations, in the absence of adsorption or degradation in the environment, to emerge in the longer term as a risk to human health. The timeframes are so long that this could occur well after the cessation of coal seam gas extraction operations in the region.

3.5 Analysis of assumptions, data gaps and uncertainties for risk estimates

The human health risk assessments were conducted according to accepted international practice and data were adequate to characterise risks to human health at a Tier 1 level for all chemicals except one. Accordingly, an important aspect of risk assessment is an analysis of any data gaps, assumptions and uncertainties in the available information used to conduct the assessment so that the assessment findings can be interpreted appropriately.

3.5.1 Data gaps and uncertainties

Based on conservative exposure modelling, the Tier 1 risk assessments confidently identified chemicals of low concern for human health. The assessments have also confidently identified those chemicals of potential concern for which risk managers may consider further assessments based on refined modelling estimates or site-specific environmental monitoring data. In evaluating the outcomes of the risk assessments, it is important to consider various sources of uncertainty in the assessments so that refined assessments, if required, can be conducted. An analysis of these sources of uncertainty is presented below.

The major source of information on the identity of chemicals and their use in coal seam gas extraction in Australia was an industry survey. Although responses were received from the major providers of drilling and hydraulic fracturing services and from most coal seam gas companies, the amount and quality of information on chemicals and their use varied and this affected the exposure and risk assessments.

In some instances, information was commercially sensitive and not available from some companies. In most instances, information provided was adequate for an assessment of risk at the Tier 1 level but there may be variations in practice across the industry that would need to be taken into account in project-specific assessments (if these were required).

Uncertainty arises from limitations in available data on transport and handling from the industry survey. For example, for calculating PECs for the transport spill scenario, the spill quantity was assumed to be a function of the concentration of the chemical and the maximum volume capacity of the truck (10 000 L or kg). However, for some chemicals, where the calculated spill quantity exceeded the calculated quantity of the chemical in intermediate storage, the spill quantity was assumed to be limited to the quantity of the

chemical in intermediate storage. Furthermore, not all chemicals had information available on intermediate storage provided within the industry survey (or the more recent supplementary industry data). This variability in available data added variability to the calculation of human exposures and health risks for this exposure scenario.

Uncertainty also arises from limitations in the quality and availability of toxicity and environmental fate data for the chemicals used in coal seam gas extraction. The toxicological data for some chemicals are extensive and recent, while for others, data are incomplete. Repeated dose toxicity data were not available for three chemicals. For two of these chemicals (caustic soda and tributyltetradecyl phosphonium chloride), the corrosive nature of the chemicals prevented adequate repeated dose toxicity testing. For the third chemical (polyamine), the identity of the chemical could not be adequately established from the information provided to allow repeated dose toxicity studies to be identified. For these chemicals, a NOAEL / LOAEL could not be derived (see Appendices A and B) and a qualitative analysis was conducted to assess whether (or not) any of these chemicals should be regarded as being of potential concern for human health.

For some chemicals, repeated dose toxicity information was available, but a NOAEL / LOAEL could not be derived because a dose that would induce adverse effects had not been identified. For these chemicals, the highest dose used in a study, in the absence of observed adverse effects, was used to calculate an MOE. In these cases, assuming that the toxicological study was otherwise adequately conducted, the magnitude of the MOE can be used to identify with a high degree of certainty that a chemical is of low concern but should not of itself be used to indicate an actual concern. However, the studies available for these chemicals do not allow a potential concern to be ruled out.

For example, if the internal dose calculated for humans from the exposure modelling is well below even the highest dose in a well-conducted toxicological study in which no adverse effects were seen at any dose, then there is a high degree of certainty that no adverse effects will be seen in humans from exposure to the chemical. However, a MOE produced by this means, and which indicates a potential concern based on the magnitude of the MOE, cannot be used to identify a concern for human health because the MOE is not based on a dose from a study that caused any adverse effects. In these cases, the MOE can confidently indicate a low concern for human health, but should not of itself be used to indicate an actual concern for human health.

For the purposes of the current conservative Tier 1 risk assessments, chemicals for which the magnitude of the MOE could not confirm a low human health concern were subject to a further qualitative risk analysis to determine whether the chemicals were a potential concern. This analysis considered the potential for health effects by considering physicochemical properties (including the nature of constituent ions if the chemical dissociates in aqueous solution), known reactivities and intended uses of the chemical. For those chemicals regarded as of potential concern, further data for these chemicals would resolve whether or not these chemicals are of actual concern.

A particular source of uncertainty relates to availability of information that quantifies chemical exposures. There is a general lack of workplace, public health and environmental monitoring for measuring actual exposures of individuals and the environment to chemicals. There is a paucity of data on the frequency and duration of chemical exposures and, importantly for the assessment of coal seam gas impacts, a lack of baseline environmental, occupational and public health data to facilitate a robust analysis of the health effects of new coal seam gas developments. Without this baseline information, the effectiveness of any strategies to control chemical emissions and mitigate risks from chemical exposures from coal seam gas activities is difficult to measure relative to the current exposure condition.

Because of this lack of information on actual exposures to chemicals, predictive contaminant transport modelling was used to provide estimates of environmental exposures, worker exposures and indirect exposures to the public via environmental contamination. However, model uses are subject to uncertainties related to the availability of data to support the choice of models and overall modelling assumptions. An example of this is provided by the use of separate models for exposure scenarios involving surface and subsurface contaminant transport with each model accompanied by its own set of data inputs and inherent conservative assumptions.

Incomplete input data necessitated a tiered approach to risk assessment whereby initially, conservative assumptions were made for some of the missing data. For example, because of incomplete environmental fate information for each chemical, a key assumption for the Tier 1 risk characterisation is that contaminant transport excludes attenuating environmental processes such as adsorption or degradation.

The extent to which this attenuation may occur is unknown and is likely to vary with each chemical type. It is also dependent on local environmental conditions under which the chemical release occurs. Such a conservative approach to the risk characterisation is therefore justified on the basis of a lack of detailed environmental fate information for each chemical, but it is acknowledged that it will likely lead to an overestimation of exposures. The consequence is additional uncertainty within the risk characterisation process and a likely overestimation of risk.

In the absence of complete information for the risk assessments, data substitutions or assumptions will necessarily be conservative, and the resulting risk assessments will also be conservative. Such 'realistically conservative' risk assessments, which overestimate, rather than underestimate risk are an effective strategy for dealing with unknown risks. The results of such assessments will be deliberately conservative to provide confidence that risk mitigation measures implemented to reduce this risk to an acceptable level will be protective for the maximum number of affected individuals, but they will ideally also be realistic (based on 'high-end' estimates rather than 'bounding' or 'worst-case' estimates) so that risk mitigation measures represent an appropriate use of risk mitigation resources.

3.5.2 *Effects of key assumptions on the human health risk assessments*

Another important aspect of risk assessment is an analysis of the assumptions required to conduct the assessments. This 'reality check' of assumptions ensures that the conclusions from the risk assessment and any consequent risk management decisions are realistic and appropriate.

A series of assumptions was required for assessing exposures of humans to chemicals used in drilling and hydraulic fracturing.

3.5.2.1 Occupational exposure

For workers, the models used for predicting occupational exposures are general predictive models suitable for different types of chemicals and workplace environments. With minimal inputs, the outputs are recognised as being conservative and likely to overestimate actual workplace exposures. However, they do provide guidance for when common effective workplace controls may be required.

The modelling of public exposures to chemicals via environmental contamination also required a set of key assumptions relating to contaminant sources and transport. Because of the potential variability in conditions under which coal seam gas is extracted and proximities

of extractive activities to water sources, an analysis is warranted of the effect of variations in these key assumptions on risk assessment outcomes.

3.5.2.2 Public exposure: transport spill scenario

The transport spill was the scenario for which Tier 1 risk estimates suggested the most number of chemicals as potential concerns for both adults and children. Impacts on surface water were assessed using modelling from DoEE with the primary assumption, at the Tier 1 level, of surface runoff to a surface water body with no environmental attenuation. At the Tier 1 level, the model also requires additional conservative assumptions regarding chemical volumes released, rainfall, slope of land and permeability of soils. An analysis of the effects of spill volumes on Tier 1 risk estimates highlighted the conservative nature of the exposure modelling, and therefore risk estimates, for this scenario.

While transport spills have been reported [e.g. in the industry survey and elsewhere in the literature (Rutovitz et al. 2011)], such events are rare. They are also likely to be rapidly reported and sites of impact quickly remediated. Therefore, a further examination of key assumptions in this modelled scenario is not required to recognise that despite the majority of chemicals not being a potential concern for this scenario, a high concentration, large-scale environmental release without timely site remediation and public exposure controls may represent a human health concern for some chemicals.

3.5.2.3 Public exposure: leaking storage pond scenario

In contrast to the bulk transport spill, a leak from a storage pond has the potential to cause undetected, long-term environmental contamination. Modelling for this scenario, provided by CSIRO, required a set of key assumptions regarding the contaminant source and subsurface transport. Given the potential variability in these parameters reflecting different geographical regions and operational practices, the effect of variations in key assumptions on the risk assessment outputs were assessed for this scenario.

One key assumption was the concentration of hydraulic fracturing chemicals within the storage pond. An analysis of the effects of varying assumed hydraulic fracturing chemical concentrations in the storage pond on risk estimates for this scenario indicated that risk estimates were highly sensitive to the concentration of hydraulic fracturing chemicals in the storage pond. At the time this assessment was started there were no reliable publicly available data on concentrations of hydraulic fracturing fluid chemicals within flowback and / or produced water storage ponds. For a Tier 1 risk assessment, it is assumed that the storage pond contains undiluted hydraulic fracturing fluid i.e. the concentrations of fracturing chemicals in the stored flowback water are the same as the injected fluid. This infers complete recovery of fracturing chemicals from the coal seam after fracturing and that these chemicals are not diluted with other fluids such as produced water. However, recovery is often incomplete and flowback water may be diluted with produced water, hence decreasing the concentration of fracturing chemicals. Also, in some instances, company practice may dictate that flowback water not be placed in surface ponds for long-term storage.

There is no published information regarding practices across the Australian coal seam gas industry on the handling of flowback water. There is also little published information on volumes of flowback water or recovery of hydraulic fracturing chemicals in flowback water. A review of information on volumes of initial flowback water recovered after hydraulic fracturing for shale gas in the US reveal significant variations in volumes compared to volumes of fluids used in the fracturing process (DoEE 2017b). Fewer studies are available on coal seam gas. One study of US coal seam gas wells predicted a total recovery of hydraulic fracturing fluids of up to 80% (Palmer et al. 1991).

Although there are some data on volumes, there are few data on recovery of fracturing chemicals. One study reported a 35% recovery of a polymer after fracturing and no effect of flowback rates on this recovery (Willberg et al. 1997).

An environmental risk assessment for Australian coal seam gas operations commissioned by one respondent to the NICNAS industry survey estimates that 40 to 60% of injected fluids including chemical additives are recovered in flowback water. Unrecovered chemicals are either adsorbed to the coal matrix or react with other chemicals within the matrix or remain trapped within minute fracture networks. However, a large proportion may eventually be recovered over time in produced water (Golder Associates 2010).

In summary, estimates for the recovery of injected chemicals from fractured coal seam gas wells range from 40% to almost an eventual complete recovery over various periods post-fracturing. However, the volumes of flowback water containing the majority of recovered hydraulic fracturing chemicals, the concentrations of these chemicals and the periods over which these chemicals are recovered are not clear.

Concentrations of hydraulic fracturing chemicals in surface storage ponds will also be affected by additional produced water subsequently added to the ponds. Flowback water is commonly pumped from the wells in volumes exceeding the fluid volumes used in hydraulic fracturing (Golder Associates 2010), indicating that dilution of hydraulic fracturing chemicals in surface ponds is likely. In the industry survey, chemical monitoring data were provided for produced water for up to 900% of the fluid volume used for hydraulic fracturing. This suggests that if flowback and produced water are stored in the same pond, the concentration of hydraulic fracturing chemicals may be diluted with produced water to one tenth or less of the original concentration in the fracturing fluid.

From information provided to the industry survey and as noted by GISERA (2014), flow rates and volumes of produced water associated with individual wells are highly variable, in the order of several thousand to several hundred thousand litres per day. In Queensland, the average coal seam gas well has produced approximately 30 000 L per day (GISERA 2014). Assuming fluid volumes for hydraulic fracturing of up to 1.1 ML per well, (NICNAS 2017d), these data suggest that volumes of produced water from coal seam gas wells over the long-term may substantially exceed fluid volumes used for hydraulic fracturing leading to a significant dilution of fracturing chemicals if produced water is stored in the same pond. Additional information was provided in supplementary industry data for 2014-2015 on hydraulic fracturing fluid volumes. This information can be used to estimate potential dilution of hydraulic fracturing chemicals with produced water based on the known capacities of produced water storage dams.

Supplementary industry data on fracturing operations provided by two companies in Queensland indicated that fluid volumes for hydraulic fracturing ranged from approximately 0.008 ML to 2 ML, with a mean volume of approximately 0.9 ML. CSIRO has tabulated data on capacities of current operational and future water management ponds in Queensland. Current produced water storage ponds range in capacities from 22 ML to over 5 000 ML with a mean of approximately 2 ML (Mallants et. al. 2017a).

When the smallest fracturing volume for a single fracturing operation (0.008 ML) is compared with the capacity of each current water storage dam, then the potential dilution across all dams is to < 0.1%. When the maximum volume of a single fracturing operation (2 ML) is similarly compared with the capacity of each current water storage dam, then the potential dilution across all dams is to < 10%. If the mean fracturing volume (approximately 0.9 ML) is compared to the mean produced water storage pond capacity (approximately 200 ML), then the potential dilution is to < 0.45%.

This analysis assumes single fracturing events, 100% recovery of fracturing chemicals from fractured wells and storage ponds at maximum operational capacities. Regardless, the analysis shows the potential for significant dilution of fracturing chemicals with produced water and the highly conservative nature of the assumption of leakage of 100% hydraulic fracturing fluid from the storage pond. In reality, the exact concentrations of fracturing fluid chemicals in storage ponds are likely to be highly site specific.

Other key assumptions for the subsurface contaminant modelling were the rate of leakage and the duration of leakage from the pond. Actual Australian performance data for surface ponds used for coal seam gas operations were not available. The reference leak rate (3.5 mm/year) used in the Tier 1 risk assessments was reflective of leak rates for ponds with compacted clay liners conforming to typical Australian design specifications. The leak duration (30 years) was reflective of the typical design life of the storage pond and the duration of coal seam gas production.

Decreasing leak rates and / or leak duration decreases the extent of potential groundwater and surface water contamination and decreases potential human health impacts associated with consumption and contact with contaminated water.

Other key assumptions were the distances from the leaking storage pond to the groundwater well and to the surface water receptor (river) both used as sources of drinking water. At Tier 1, the distance from the storage pond to the groundwater well used as a source of drinking water is assumed to be 100 m. This distance of 100 m to groundwater wells was based on data from the Namoi Catchment showing small numbers of groundwater wells within this distance from coal seam gas developments (indicated by the presence of coal seam gas wells) (Mallants et al 2017b). For this subsurface contaminant modelling, it was assumed for reasons of simplicity that the coal seam gas well is the location where the leak or spill occurs.

However, a quantitative analysis of the locations of groundwater wells used for different purposes such as irrigation, stock and domestic applications in the Namoi Catchment indicates that only a minority of wells (0.03% ie. 10 out of a total of 34 215 wells) are located at approximately 100 m from coal seam gas wells. Of 17 691 groundwater wells within 10 000 m of coal seam gas wells, the majority (99%) are at distances greater than approximately 600 m from coal seam gas wells (Mallants et al. 2017b). Therefore, although the distance of 100 m for conservative Tier 1 calculations of human health risks from subsurface contamination is based on proximity data for water wells in the Namoi Catchment, the likelihood of finding water wells for human consumption at this distance from potential leakage or spill sites is very small.

Similarly, the modelling assumed a distance between the leaking storage pond and the surface water receptor (river) of 2 km. However, bioregional assessments conducted by DoEE of other areas with coal seam gas developments have noted rivers which gain flow from groundwater within 2 km of these developments. Sometimes these activities are within approximately 100 m (e.g. Gloucester Basin). Therefore, an appropriate refinement of the Tier 1 assessment involved recalculating human health risks using different assumed distances between the storage pond and surface water sources of drinking water (Table 3.5).

4 Risk mitigation measures

Using the conservative modelling approaches described in this report, the risk characterisation was used to identify those chemicals that are unlikely to be of concern to human health. It was also used to identify circumstances in which risk estimates for individual chemicals suggest a potential concern and where more refined modelling estimates or environmental monitoring data are required to determine their true level of risk.

For each chemical (or in some cases, groups of similar chemicals), an individual risk assessment report is available (Appendix D) containing information to support the risk characterisation.

This section provides an overview of key measures available to mitigate risks to human health.

Requirements for formal approvals relating to the use of chemicals in coal seam gas activities may differ between Australian states and territories. The risk mitigation measures described below may be required by workplace health and safety legislation and / or as a condition of approval under state or territory regulations.

4.1 Obligations under workplace health and safety legislation

Some chemicals used in drilling and hydraulic fracturing are workplace hazardous chemicals. For these chemicals, the following information and discussion with respect to obligations under workplace health and safety legislation are included in the risk assessment.

Persons conducting a business or undertaking (PCBU) (such as an employer) have obligations under workplace health and safety legislation as adopted by the relevant state or territory. Information in the risk assessment reports assists such persons in meeting these obligations. These obligations include, but are not limited to:

- ensuring that hazardous chemicals are correctly classified and labelled
- ensuring that (material) safety data sheets contain accurate information about both the health hazards and the physico-chemical (physical) hazards of the chemical
- assessing and managing risks arising from storing, handling and using a hazardous chemical.

Because adoptions of workplace health and safety legislation vary, the relevant work health and safety regulator should be contacted for information on the work health and safety laws in each jurisdiction.

Information on how to prepare (material) safety data sheets and how to label containers of hazardous chemicals is provided in relevant codes of practice available from the Safe Work Australia website.

For some chemicals, the hazard characterisation noted serious chronic health effects and / or serious acute toxic effects via inhalation. For these chemicals, PCBUs should conduct site-specific risk assessment of occupational health risks. If the risk assessment indicates a concern, personal monitoring for workers should be conducted to ensure that exposure control measures are implemented and that these are adequate.

4.2 Control measures available to minimise risks to the worker

Some chemicals were identified, from the risk assessments, as posing a potential concern for workers (Appendix A). Workplace health and safety legislation requires the implementation of control measures to minimise risks associated with such chemicals. Measures to eliminate or minimise risk arising from storing, handling and using the chemical depend on the physical form and the manner in which the chemical is used.

Control measures to minimise the risk include, but are not limited to:

- eliminating use of the hazardous chemical
- substituting, where appropriate, a hazardous chemical with a non-hazardous or less hazardous chemical
- using closed systems or isolating operations, where possible
- engineering controls such as local exhaust ventilation to prevent the chemical entering the breathing zone of any worker
- minimising manual processes and work tasks through automating processes and adopting work procedures that minimise splashes and spills
- using appropriate PPE to ensure that workers do not come into contact with the chemical.

One chemical used in drilling and hydraulic fracturing (crystalline silica) is scheduled by Safe Work Australia as a chemical for which health monitoring may be required.

Information on hazardous chemicals is available from the Safe Work Australia website.

Relying on personal protective equipment alone is not an effective way to control risk. PPE is to be used in conjunction with other reasonably practicable control measures to minimise risk. Guidance in selecting PPE can be obtained from Australian, Australian / New Zealand, or other approved standards.

4.3 Control measures available to minimise risks to the public

The following mitigation strategies are available for chemicals of a potential public health concern.

4.3.1 Atmospheric / Shallow ground water monitoring

For volatile chemicals with vapour pressure ≥ 0.5 kPa at standard test temperatures (ECHA 2012a) and known adverse health hazards, the potential for public exposures via ambient air emissions from coal seam gas developments could be assessed. If site-specific assessments indicate a potential for public exposures, such chemicals could be included in an ambient air monitoring program. Where possible, baseline studies undertaken before, as well as during and after coal seam gas operations would enhance the utility of such a program.

For some of the chemicals used for drilling and hydraulic fracturing, risk estimates from conservative exposure modelling suggest a potential concern from contamination of shallow groundwater. If site-specific assessments confirm a potential public health concern, then these chemicals could be included in a groundwater monitoring program. Where possible,

baseline studies conducted prior to coal seam gas developments would enhance the utility of such a program.

Information on drilling and hydraulic fracturing chemicals with potential concerns from groundwater contamination is available in summarised form in Appendix B and in risk assessment reports for individual chemicals (Appendix D).

4.3.2 Measures available to minimise risks to the public from contamination of water

For chemicals for which risk estimates suggest a potential public health concern, from contamination of water, the following risk mitigation measures are available to decrease the potential for environmental contamination and public health risks.

4.3.2.1 For transport

The Australian Code for the Transport of Dangerous Goods by Road or Rail (ADG Code 2007) provides detailed technical requirements for the transportation of dangerous goods. Measures to eliminate or minimise potential public health risk during transportation are provided below.

- Review transport routes to minimise the potential for environmental impacts from incidents and ensure that relevant transport regulations, including those related to packaging, are adhered to.
- Conduct regular reviews of procedures and protocols for the transport of chemicals, including ensuring all transport workers receive adequate training and maintain expertise in chemicals transport, handling and emergency procedures and that non-essential transport of chemicals is avoided.
- Establish and implement contingency plans (e.g. environmental management plans, spill cleanup kits, procedures for cordoning off incident sites) to mitigate the risks from chemical spills.
- Ensure prompt reporting of incidents to relevant state and territory government authorities and conduct an investigation to identify the likely cause of the incident.

4.3.2.2 For storage of flowback and / or produced water

For some of the chemicals used for drilling and hydraulic fracturing, risk estimates from conservative exposure modelling suggest a potential concern from contamination of shallow groundwater through leakage of flowback/produced water from the storage ponds. For these chemicals, the following mitigation measures are relevant.

- Ensure flowback water is appropriately treated prior to its disposal or recycling and not subject to long-term storage in surface pits/ponds.
- Ensure that appropriate lining of pits / ponds for flowback and / or produced water storage is used to minimise leaks.

Monitor the integrity of the storage pits / ponds (e.g. routine inspection activities) and install monitoring measures (e.g. leak detection technology) to minimise the likelihood of leaks to soil and shallow groundwater which exceed design limits. Information on drilling and hydraulic fracturing chemicals of potential concern for workers and / or the public is available in summarised form in Appendix B and in risk assessment reports for individual chemicals (Appendix D).

5 Conclusions

Occupational and public health risk assessments were conducted for 69 chemicals used within drilling and / or hydraulic fracturing at coal seam gas extraction sites in Australia. Of these, 21 chemicals are used for drilling and 58 chemicals are used for hydraulic fracturing. Nine chemicals are used in both drilling and hydraulic fracturing.

Hazard (toxicity) assessments were conducted for each of these 69 chemicals to provide input to the risk assessments. From the hazard assessments, changes to existing classifications as workplace hazardous substances were recommended for four chemicals. A further 30 chemicals were recommended for new classification and listing as workplace hazardous substances.

Potential pathways for human exposures were conceptualised and assessed for workers and for the public. For workers, several coal seam gas operational activities were identified during which exposure to chemicals used for drilling and hydraulic fracturing may occur. Occupational exposure modelling was then used to quantify worker exposure to chemicals for two common operational activities for which exposures are most likely to occur – mixing / blending of chemicals into drilling and hydraulic fracturing fluid formulations, and cleaning and maintenance. Exposure was also quantified for workers engaged in both these activities. Consistent with international practice to account for variability in risk mitigation measures in workplaces, for both activities, exposures were estimated for workers in the absence of PPE.

The health risk for workers associated with chemical exposures from these activities was then assessed. Human health risk from long-term exposures was quantified for each chemical by calculating an MOE comparing estimated human internal doses derived from exposure assessments to doses associated with critical health effects derived from the hazard assessments. For chemicals with no repeated dose toxicity studies or chemicals with MOEs suggestive of a potential concern but based on studies not showing adverse effects, a qualitative risk assessment was conducted to assess the level of concern.

With regards to health risks for workers from acute exposures, the risks vary with work practices. However, the health risk is highest for handling of chemicals in their most concentrated form as delivered to operational sites. Chemicals in diluted form in formulated drilling and hydraulic fracturing fluids, or in highly diluted form as a component of flowback and / or produced water, represent successively lower acute health risks. Forty-four of the 69 chemicals were of potential concern for the health of workers through acute inadvertent exposure to the chemicals as delivered to the site.

With regards to health risks from long-term exposures, the conservative occupational health risk characterisation concludes that the majority of the chemicals are unlikely to pose a risk of adverse health effects from repeated exposures during these handling activities. However, four of the 21 chemicals used for drilling, and 10 of the 58 chemicals used for hydraulic fracturing, could pose a risk of adverse health effects from repeated exposures during these activities if not managed appropriately.

Public exposure to drilling and hydraulic fracturing chemicals was also conceptualised and assessed. Exposure was assessed based on contact with these chemicals via environmental contamination from surface spills and leaks during coal seam gas operations. Exposure modelling was used to calculate PECs for coal seam gas chemicals in shallow groundwater and surface water for several different environmental contamination scenarios. To ensure health risks were not underestimated, conservative assumptions were made in the exposure modelling to quantify exposures.

The potential health risks for the public, based on consumption and use of contaminated water associated with these scenarios, were then assessed. Similar to the evaluation of occupational risks, long-term public health risks were quantified for each chemical by calculating an MOE and comparing estimated human internal doses derived from exposure assessments to doses associated with critical adverse health effects derived from the hazard assessments. For chemicals with no repeated dose toxicity studies or chemicals with MOEs suggestive of a potential concern but based on studies not showing adverse effects at the highest dose used, a qualitative risk assessment was conducted to assess the level of concern.

With regards to health risks for the public from acute exposures, chemicals are not available to the public in the forms, quantities, packaging or handling situations typically delivered to and within coal seam gas operations and are thus considered unlikely to pose an acute health risk.

With regards to health risks from long-term exposures, of all the modelled environmental contamination and human exposure scenarios, the lowest MOEs and greatest health concerns were associated with a bulk spill during transport, which assumes a chemical spill of high volume and relatively high concentration. For this scenario, the risk characterisation concluded that slightly more than half of the drilling and hydraulic fracturing chemicals are of potential concern for adverse health effects for either adults or children if environmental contamination of water sources occurs from a bulk spill during transport. Risk estimates suggestive of a potential concern from long-term exposures are noted for 11 of the 21 chemicals used for drilling and 30 of the 58 chemicals used for hydraulic fracturing. Because of the conservative nature of the assessment, these chemicals require more refined assessment to estimate the true level of risk.

For the scenario of leakage of hydraulic fracturing chemicals from a flowback and / or produced water storage pond and contamination of shallow groundwater and surface water, the risk characterisation concluded that the majority of chemicals are of low concern for adverse health effects for either adults or children from long-term exposures. The highest risk of adverse health effects was associated with contaminated groundwater used for drinking. Risk estimates suggestive of a potential concern from long-term exposures were noted for 14 of 58 hydraulic fracturing chemicals. For use of surface water for drinking, two chemicals used for hydraulic fracturing had risk estimates suggestive of a potential concern from long-term exposures.

In the case of surface water used for drinking, the findings of only two chemicals of potential concern reflect increasing dilution of the chemicals as they move through shallow groundwater and into surface water.

For all modelled scenarios of public exposures, consistent with international risk assessment guidance, risk estimates were predicated on the basis of high-end estimates and modelling assumptions, including that chemicals do not undergo environmental attenuation through adsorption or degradation. This is highly unrealistic given the length of the residence times of the chemicals within the environment and the likelihood of chemical species such as organics degrading over time. In reality, such environmental fate processes will decrease levels of public exposures and therefore the risk of adverse health effects. However, establishing the true level of risk would require either long-term environmental monitoring data or additional material properties information to enable more refined model estimates to be produced. The true level of risk established with such data is likely to be equal to, or lower than, the levels currently assessed.

Estimated PECs in shallow groundwater decrease with distance from the contaminant source. The contaminant transport modelling showed the concentrations at 800 m and 2 000 m from the leaking storage pond reduced by 46 and 61%, respectively, compared to

the concentrations seen at 100 m. Increased distance between sources of contamination and receiving waters will decrease the numbers of chemicals for which exposures through water consumption represent a human health concern.

A sensitivity analysis was conducted for risk estimates of hydraulic fracturing chemical leakage from a flowback and / or produced water storage pond. With less conservative assumptions for the concentrations of hydraulic fracturing chemicals in the storage ponds and proximities to drinking water sources, fewer chemicals had calculated risk estimates suggestive of a potential concern from long-term exposures. Furthermore, for some combinations of assumptions, no hydraulic fracturing chemicals had risk estimates suggestive of a potential concern.

In addition to the calculation of PECs, the subsurface contaminant transport modelling also allowed estimation of the 'travel time' required for a chemical contaminant to move from the subsurface contamination source to a shallow groundwater (and surface) drinking water source. Assuming no environmental attenuation (other than dispersion), using modelling parameters based on the Namoi Catchment, the travel time for a chemical to reach a drinking water well 100 m from a leaking storage pond for flowback and / or produced water is 62 years. The travel time to a drinking water well 800 m from the leaking storage pond is 180 years. This modelling underlines the potential for chemical contamination from coal seam gas operations to have impacts beyond the expected operational life of coal seam gas developments.

Uncertainty in the risk assessment arises firstly from limitations in the quality and availability of toxicological data relating to potential human health impacts. The toxicological data for some chemicals were lacking or insufficient so predictive tools had to be used to infer toxicology from similar types of chemicals with sufficient data. Another source of uncertainty relates to the exposure assessments. There is a lack of workplace and environmental monitoring data specifically measuring human exposures to these chemicals from the coal seam gas extraction activities. The lack of information consequently requires conservative assessments with a potential overestimation of exposures. There is also a paucity of data on the likely frequency and duration of chemical exposures and, importantly, a lack of baseline occupational and population health data to facilitate a more robust analysis of the health effects of coal seam gas developments.

Given the conservative nature of the exposure assessments, the current risk assessments have identified with a high degree of confidence those chemicals of low concern for human health. For those chemicals which have been assessed as of potential concern, monitoring data on occupational and public exposures to chemicals would assist a more refined characterisation of the health risks associated with these chemicals. The true level of risk established with such data is likely to be equal to, or lower than, the levels currently assessed. More accurate estimates of risk, if required, could be conducted on a case-by-case basis by risk managers using site-specific data.

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Appendix A – Conclusions from margin of exposure (MOE) calculations for long-term occupational exposures

Table A.1 Conclusions from MOE calculations for long-term occupational exposures to drilling chemicals

CAS RN		Common name	Occupational activity		
			Mixing / blending	Cleaning and maintenance	Combined exposure
1	107-22-2	Ethanedial	N: n/d	N: n/d	N: n/d
2	111-30-8	Glutaraldehyde	N: 117	N: n/d	N: n/d
3	1303-96-4	Borax	N: 1.21×10^5 (pregnant workers); N: 2.21×10^5 (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)
4	1305-62-0	Slaked lime	N: 4 **,	N: n/d **,	N: n/d **,
5	1310-73-2	Caustic soda	N **	N **	N **
6	14464-46-1	Cristobalite	Y: 18*	N: 92*	Y: 15*
7	14808-60-7	Quartz	Y: 4*	Y: 6*	Y: 2*
8	15468-32-3	Tridymite	Y: 18*	N: 106*	Y: 16*
9	497-19-8	Soda ash	N: 369**	N: n/d**	N: n/d**
10	55566-30-8	THPS	Y: 5	N: 487	Y: 5
11	64-17-5	Ethanol	N: 7.8×10^4	N: 1.1×10^5	N: 4.6×10^4
12	64742-47-8	Deodorised kerosene	N: 2.06×10^3 (pregnant workers); N: $2.06 \times 10^{3**}$ (non-pregnant workers)	N: n/d (pregnant workers); N: n/d ** (non-pregnant workers)	N: n/d (pregnant workers); N: n/d ** (non-pregnant workers)

Human health risks associated with surface handling of chemicals used in coal seam gas extraction

CAS RN		Common name	Occupational activity		
			Mixing / blending	Cleaning and maintenance	Combined exposure
13	67-56-1	Methanol	N: 4 160	N: n/d	N: n/d
14	67-63-0	Isopropanol	N: 2 770	N: n/d	N: n/d
15	7757-83-7	Sodium sulfite	N: n/d (pregnant workers); N: n/d (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)
16	CBI	2-Ethylhexanol heavies	N: n/d	N: n/d	N: n/d
17	CBI	Fatty acids ester	N: 1 509	N: n/d	N: n/d
18	CBI	Ester alcohol	N: n/d**	N: n/d**	N: n/d**
19	CBI	Organic acid salt	N: n/d	N: n/d	N: n/d
20	CBI	Organic sulphate	N: 3 300**	N: 2.00 x 105**	N: 3 250**
21	CBI	Polymer with substituted alkylacrylamide salt	N: n/d	N: n/d	N: n/d

N–MOEs indicate the chemical is of low concern for adverse health effects. Y–MOEs suggest a potential concern for adverse health effects. * Uncertainty factor differs from 100 for this assessment. ** MOEs calculated based on highest available dose for which no adverse effects were noted or MOEs not calculated as repeat dose toxicity studies are not available. n/d—not disclosed due to commercially sensitive data.

Table A.2 Conclusions from MOE calculations for long-term occupational exposures to hydraulic fracturing chemicals

CAS RN		Common name	Occupational activity		
			Mixing / blending	Cleaning and maintenance	Combined exposure
1	10043-35-3	Boric acid	N: 2.36×10^3 (pregnant workers); N: 4.28×10^3 (non-pregnant workers)	N: 1.55×10^6 (pregnant workers); N: 2.81×10^6 (non-pregnant workers)	N: 2.36×10^3 (pregnant workers); N: 4.28×10^3 (non-pregnant workers)
2	10043-52-4	Calcium chloride	N: n/d **	N: n/d **	N: n/d**
3	102-71-6	Triethanolamine	N: 184	N: 4060	N: 176
4	107-21-1	Ethylene glycol	N: 478* (pregnant workers); N: 398 (non-pregnant workers)	N: 2.49×10^4 * (pregnant workers); N: 2.08×10^4 (non-pregnant workers)	N: 468* (pregnant workers); N: 390 (non-pregnant workers)
5	108-10-1	Methyl pentanone	N: n/d	N: n/d	N: n/d
6	111-76-2	Butoxyethanol	N: 165	N: 2.58×10^4	N: 164
7	111-90-0	Diethylene glycol ethyl ether	N: n/d	N: n/d	N: n/d
8	112926-00-8	Precipitated silica	N: n/d	N: n/d	N: n/d
9	12008-41-2	Sodium borate	N: 1300 (pregnant workers); N: 2.31×10^4 (non-pregnant workers)	N: 2.31×10^4 (pregnant workers); N: 4.19×10^4 (non-pregnant workers)	N: 1230 (pregnant workers); N: 2240 (non-pregnant workers)
10	1303-96-4	Borax	N: 7.83×10^3 (pregnant workers); N: 1.43×10^4 (non-pregnant workers)	N: 1.39×10^6 (pregnant workers); N: 2.53×10^6 (non-pregnant workers)	N: 7.78×10^3 (pregnant workers); N: 1.42×10^4 (non-pregnant workers)
11	1305-78-8	Lime	N: n/d*	N: n/d*	N: n/d*

CAS RN		Common name	Occupational activity		
			Mixing / blending	Cleaning and maintenance	Combined exposure
12	1310-73-2	Caustic soda	N **	N **	N **
13	141-43-5	Ethanolamine	N: 3.37 x 10 ⁴	N: n/d	N: n/d
14	144588-68-1	Sintered bauxite	N: n/d**	N: n/d**	N: n/d**
15	14464-46-1	Cristobalite	N: n/d *	N: n/d*	N: n/d*
16	14808-60-7	Quartz	Y: 0.1*	Y: 0.4*	Y: 0.1*
17	26038-87-9	Monoethanolamine, boric acid salt	N: 180 (pregnant workers); N: 330 (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)
18	26062-79-3	Polydimethyldiallylammonium chloride	N: 3.52 x 10 ^{4**}	N: 4.41 x 10 ^{6**}	N: 3.49 x 10 ^{4**}
19	26172-55-4	Methylchloroisothiazolinone	N: 123**	N: 3.06 x 10 ^{5**}	N: 122**
20	2634-33-5	Benzisothiazolinone	N: n/d	N: n/d	N: n/d
21	2682-20-4	Methylisothiazolone	N: 607	N: 1.43 x 10 ⁶	N: 606
22	497-19-8	Soda ash	N: 145**	N: 9230**	N: 144**
23	52-51-7	Bronopol	Y: 17	N: n/d	Y: n/d
24	55566-30-8	THPS	Y: n/d	N: n/d	Y: n/d
25	584-08-7	Potassium carbonate	N: 1 900**	N: 2.38 x 10 ^{4**}	N: 1 760**
26	64-02-8	Tetrasodium EDTA	N: 4.40 x 10 ⁴	N: 1.65 x 10 ⁸	N: 4.40 x 10 ⁴
27	6410-41-9	Pigment Red 5	N: n/d**	N: n/d**	N: n/d**
28	64-17-5	Ethanol	N: 2.6 x 10 ⁴	N: n/d	N: n/d
29	64-19-7	Acetic acid	N: 1 240	N: 1.72 x 10 ⁵	N: 1 232

CAS RN		Common name	Occupational activity		
			Mixing / blending	Cleaning and maintenance	Combined exposure
30	67-56-1	Methanol	N: 100	N: n/d	Y: n/d
31	67-63-0	Isopropanol	N: 926	N: 7.80×10^4	N: 912
32	68187-17-7	C ₆₋₁₀ linear alkyl sulfate, ammonium salt	N: 6 010	N: 4.5×10^5	N: 5 930
33	68439-45-2	C ₆₋₁₂ ethoxylated alcohols	N: 500	N: 2.57×10^4	N: 490
34	68647-72-3	Sweet orange oil terpenes	N: 2.97×10^3	N: n/d	N: n/d
35	75-57-0	Tetramethylammonium chloride	Y: 18**	N: 436**	Y: 17**
36	7631-86-9	Amorphous silica	N: 3.9×10^4	N: 1.7×10^9	N: 4.0×10^4
37	7647-01-0	Hydrochloric acid	N: n/d	N: n/d	N: n/d
38	7681-52-9	Sodium hypochlorite	Y: 46**	N: 1.34×10^4 **	Y: 45**
39	7722-84-1	Hydrogen peroxide	N: 324	N: 1.04×10^4	N: 314
40	7727-54-0	Ammonium persulfate	Y: 3	N: 384	Y: 3
41	7757-83-7	Sodium sulfite	N: n/d (pregnant workers); N: n/d (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)	N: n/d (pregnant workers); N: n/d (non-pregnant workers)
42	7758-19-2	Sodium chlorite	N: 450	N: 300	N: 180
43	7772-98-7	Sodium thiosulfate	N: 480**	N: 8.50×10^4 **	N: 476**
44	7775-27-1	Sodium persulfate	N: 107	N: 1.22×10^4	N: 105
45	81741-28-8	Tributyltetradecyl phosphonium chloride	Y **	Y **	Y **
46	9012-54-8	Cellulase	N: 7.64×10^5 **	N: 2.86×10^6 **	N: 6.03×10^5 **

CAS RN		Common name	Occupational activity		
			Mixing / blending	Cleaning and maintenance	Combined exposure
47	9025-56-3	Hemicellulase	N: 9.55 x 10 ^{4**}	N: 7.87 x 10 ^{8**}	N: 9.54 x 10 ^{4**}
48	91053-39-3	Calcined silica	Y: 0.2*	N: 1 333*	Y: 0.2*
49	90622-53-0	Alkanes, C ₁₂₋₂₆ branched and linear	N: 1.69 x 10 ^{3**}	N: 2.03 x 10 ^{4**}	N: 1.56 x 10 ^{3**}
50	CBI	Amine salt	N: n/d	N: n/d	N: n/d
51	CBI	Enzyme	N: n/d**	N: n/d**	N: n/d**
52	CBI	Ethoxylated fatty acid I	N: n/d	N: n/d	N: n/d
53	CBI	Ethoxylated fatty acid II	N: n/d **	N: n/d **	N: n/d **
54	CBI	Ethoxylated fatty acid III	N: n/d	N: n/d	N: n/d
55	CBI	Inner salt of alkyl amines	N: n/d **	N: n/d **	N: n/d **
56	CBI	Polyamine	Y **	Y **	Y **
57	CBI	Quaternary amine	N: n/d	N: n/d	N: n/d
58	CBI	Terpenes and terpenoids	N: n/d	N: n/d	N: n/d

N–MOEs indicate the chemical is of low concern for adverse health effects. Y–MOEs suggest a potential concern for adverse health effects. * Uncertainty factor differs from 100 for this assessment. ** MOEs calculated based on highest available dose for which no adverse effects were noted or MOEs not calculated as repeat dose toxicity studies are not available. n/d—not disclosed due to commercially sensitive data.

Appendix B – Conclusions from margin of exposure (MOE) calculations for long-term public exposures

Table B.1 Conclusion from MOE calculations for long-term public exposures to drilling chemicals

DRILLING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak from flowback and / or produced water storage		Bulk spill (transport)	Subsurface leak from flowback and / or produced water storage	
CAS RN	Common name		Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
1	107-22-2	Ethanedial	N: n/d	N/A	N/A	N: n/d	N/A	N/A
2	111-30-8	Glutaraldehyde	Y: 0.4	N/A	N/A	Y: 0.1	N/A	N/A
3	1303-96-4	Borax	N: 2.54×10^4 (pregnant individuals); N: 4.61×10^4 (non-pregnant individuals)	N/A	N/A	N: 1.33×10^4	N/A	N/A
4	1305-62-0	Slaked lime	N: 0.003*,**	N/A	N/A	N: 0.001*,**	N/A	N/A
5	1310-73-2	Caustic soda	N **	N/A	N/A	N **	N/A	N/A
6	14464-46-1	Cristobalite	N: no exposure	N/A	N/A	N: no exposure	N/A	N/A
7	14808-60-7	Quartz	N: no exposure	N/A	N/A	N: no exposure	N/A	N/A
8	15468-32-3	Tridymite	N: no exposure	N/A	N/A	N: no exposure	N/A	N/A

DRILLING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak from flowback and / or produced water storage		Bulk spill (transport)	Subsurface leak from flowback and / or produced water storage	
CAS RN	Common name	Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use	Surface water use
9	497-19-8	Soda ash	N: 0.3**	N/A	N/A	N: 0.1**	N/A	N/A
10	55566-30-8	THPS	Y:5	N/A	N/A	Y:2	N/A	N/A
11	64-17-5	Ethanol	N: 719	N/A	N/A	N: 205	N/A	N/A
12	64742-47-8	Deodorised kerosene	Y: 55 (pregnant individuals); Y: 55** (non-pregnant individuals)	N/A	N/A	Y: 16**	N/A	N/A
13	67-56-1	Methanol	Y: 96	N/A	N/A	Y: 27	N/A	N/A
14	67-63-0	Isopropanol	Y: 76	N/A	N/A	Y: 22	N/A	N/A
15	7757-83-7	Sodium sulfite	Y: n/d (pregnant individuals); Y: n/d (non-pregnant individuals)	N/A	N/A	Y: n/d	N/A	N/A
16	CBI	2-Ethylhexanol heavies	N: n/d	N/A	N/A	Y: n/d	N/A	N/A
17	CBI	Fatty acids ester	Y: 17**	N/A	N/A	Y: 5**	N/A	N/A
18	CBI	Ester alcohol	N: n/d **	N/A	N/A	Y: n/d **	N/A	N/A
19	CBI	Organic acid salt	N: n/d	N/A	N/A	N: n/d	N/A	N/A
20	CBI	Organic sulphate	Y: 25**	N/A	N/A	Y: 7**	N/A	N/A

DRILLING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak from flowback and / or produced water storage		Bulk spill (transport)	Subsurface leak from flowback and / or produced water storage	
CAS RN	Common name		Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
21	CBI	Polymer with substituted alkylacrylamide salt	Y: n/d	N/A	N/A	Y: n/d	N/A	N/A

N–MOEs indicate the chemical is of low concern for adverse health effects. Y–MOEs suggest a potential concern for adverse health effects, (Tier 1 risk assessments).

* Uncertainty factor differs from 100 for this assessment. ** MOEs calculated based on highest available dose for which no adverse effects were noted or MOEs not calculated as repeat dose toxicity studies are not available. n/d—not disclosed due to commercially sensitive data. N/A—not applicable. It is assumed that the concentration of drilling chemicals in flowback and / or produced water is negligible.

Table B.2 Conclusion from MOE calculations for long-term public exposures to hydraulic fracturing chemicals

HYDRAULIC FRACTURING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak (flowback and / or produced water)		Bulk spill (transport)	Subsurface leak (flowback and / or produced water)	
CAS RN	Common name	Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
1	10043-35-3	Boric acid	Y: 2.1 (pregnant individuals); N: 3.7 (non-pregnant individuals)	N: 625 (pregnant individuals); N: 1136 (non-pregnant individuals)	N: 1270 (pregnant individuals); N: 2300 (non-pregnant individuals)	Y: 1.1	N: 325	N: 658
2	10043-52-4	Calcium chloride	N: n/d **	N: n/d **	N: n/d **	N: n/d **	N: n/d **	N: n/d **
3	102-71-6	Triethanolamine	Y: 4	N: 123	N: 6.75×10^5	Y: 1	Y: 35	N: 1.93×10^5
4	107-21-1	Ethylene glycol	N: 41* (pregnant individuals); Y: 49 (non-pregnant individuals)	N: 618* (pregnant individuals); N: 742 (non-pregnant individuals)	N: $3.40 \times 10^{6*}$ (pregnant individuals); N: 4.08×10^6 (non-pregnant individuals)	Y: 14	N: 212	N: 1.17×10^5
5	108-10-1	Methyl pentanone	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d
6	111-76-2	Butoxyethanol	Y: 1	N: 240	N: 1.32×10^6	Y: 0.3	Y: 69	N: 3.78×10^5
7	111-90-0	Diethylene glycol ethyl ether	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d
8	112926-00-8	Precipitated silica	N: no exposure	N: no exposure	N: no	N: no	N: no	N: no

HYDRAULIC FRACTURING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak (flowback and / or produced water)		Bulk spill (transport)	Subsurface leak (flowback and / or produced water)	
CAS RN	Common name		Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
					exposure	exposure	exposure	exposure
9	12008-41-2	Sodium borate	Y: 1 (pregnant individuals); Y: 2 (non-pregnant individuals)	Y: 9 (pregnant individuals); Y: 17 (non-pregnant individuals)	N: 5.13×10^4 (pregnant individuals); N: 9.32×10^4 (non-pregnant individuals)	Y: 1	Y: 5	N: 2.66×10^4
10	1303-96-4	Borax	Y: 37 (pregnant individuals); Y: 68 (non-pregnant individuals)	N: 561 (pregnant individuals); N: 1023 (non-pregnant individuals)	N: 3.09×10^6 (pregnant individuals); N: 5.63×10^6 (non-pregnant individuals)	Y: 19	N: 292	N: 1.61×10^6
11	1305-78-8	Lime	N n/d* **	N n/d* **	N n/d* **	N n/d* **	N n/d* **	N n/d* **
12	1310-73-2	Caustic soda	N **	N **	N **	N **	N **	N **
13	141-43-5	Ethanolamine	N: 9572	N: n/d	N: n/d	N: 2736	N: n/d	N: n/d
14	144588-68-1	Sintered bauxite	N: n/d**	N: n/d**	N: n/d**	N: n/d**	Y: n/d**	N n/d**
15	14464-46-1	Cristobalite	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure
16	14808-60-7	Quartz	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure

HYDRAULIC FRACTURING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak (flowback and / or produced water)		Bulk spill (transport)	Subsurface leak (flowback and / or produced water)	
CAS RN	Common name		Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
17	26038-87-9	Monoethanolamine, boric acid salt	Y: 7 (pregnant individuals); Y: 12 (non-pregnant individuals)	N: n/d (pregnant individuals); N: n/d (non-pregnant individuals)	N: n/d (pregnant individuals); N: n/d (non-pregnant individuals)	Y: 4	N: n/d	N: n/d
18	26062-79-3	Polydimethyldiallylammonium chloride	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure
19	26172-55-4	Methylchloroisothiazolinone	Y:5**	N: 1.14 x 10 ^{4**}	N: 6.27 x 10 ^{7**}	Y:2**	N: 3 259**	N: 1.79 x 10 ^{7**}
20	2634-33-5	Benzisothiazolinone	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d
21	2682-20-4	Methylisothiazolone	Y: 11	N: 4.24 x 10 ⁴	N: 2.33 x 10 ⁸	Y: 3	N: 1.21 x 10 ⁴	N: 6.66 x 10 ⁷
22	497-19-8	Soda ash	N: 2**	N: 2**	N: 1.31 x 10 ^{4**}	N: 0.5**	N: 0.7**	N: 3732**
23	52-51-7	Bronopol	N: 576	N: n/d	N: n/d	N: 165	N: n/d	N: n/d
24	55566-30-8	THPS	Y: 2	Y: n/d	N: n/d	Y: 1	Y: n/d	N: n/d
25	584-08-7	Potassium carbonate	N: 2**	N:6**	N: 3.36 X 10 ^{4**}	N: 0.4**	N: 2**	N: 9611**
26	64-02-8	Tetrasodium EDTA	N: 691	N: 8.49 x 10 ⁵	N: 4.68 x 10 ⁹	N: 197	N: 2.43 x 10 ⁵	N: 1.34 x

HYDRAULIC FRACTURING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak (flowback and / or produced water)		Bulk spill (transport)	Subsurface leak (flowback and / or produced water)	
CAS RN	Common name		Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
								10 ⁹
27	6410-41-9	Pigment Red 5	N: n/d**	N: n/d**	N: n/d**	N: n/d**	N: n/d**	N: n/d**
28	64-17-5	Ethanol	N: 240	N: n/d	N: n/d	Y: 68	N: n/d	N: n/d
29	64-19-7	Acetic acid	Y: 34**	N: 5 607	N: 3.08 x 10 ⁷	Y: 10**	N: 1602	N: 8.82 x 10 ⁶
30	67-56-1	Methanol	Y: 2	N: n/d	N: n/d	Y: 1	Y: n/d	N: n/d
31	67-63-0	Isopropanol	Y: 70	N: 2 606	N: 1.43 x 10 ⁷	Y: 20	N: 745	N: 4.10 x 10 ⁶
32	68187-17-7	C ₆₋₁₀ linear alkyl sulfate, ammonium salt	Y: 23	N: 664	N: 3.66 x 10 ⁶	Y: 7	N: 190	N: 1.04 x 10 ⁶
33	68439-45-2	C ₆₋₁₂ ethoxylated alcohols	Y: 5	N: 144	N: 7.95 x 10 ⁵	Y: 1	Y: 41	N: 2.27 x 10 ⁵
34	68647-72-3	Sweet orange oil terpenes	N: 320	N: n/d	N: n/d	Y: 91	N: n/d	N: n/d
35	75-57-0	Tetramethylammonium chloride	Y: 0.3**	Y: 13**	N: 7.12 x 10 ^{4**}	Y: 0.1**	Y: 4**	N: 2.03 x 10 ^{4**}
36	7631-86-9	Amorphous silica	N: No exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure
37	7647-01-0	Hydrochloric acid	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d
38	7681-52-9	Sodium hypochlorite	Y: 1**	N: 445**	N: 2.45 x 10 ^{6**}	Y: 0.4**	N: 127**	N: 7.00 x

HYDRAULIC FRACTURING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak (flowback and / or produced water)		Bulk spill (transport)	Subsurface leak (flowback and / or produced water)	
CAS RN	Common name		Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
								10 ^{5**}
39	7722-84-1	Hydrogen peroxide	Y: 6	N: 307	N: 1.69 x 10 ⁶	Y: 2	Y: 88	N: 4.82 x 10 ⁵
40	7727-54-0	Ammonium persulfate	Y: 0.1	Y: 11	N: 6.27 x 10 ⁴	Y: 0.02	Y: 3	N: 1.79 x 10 ⁴
41	7757-83-7	Sodium sulfite	N: n/d (pregnant individuals); N: n/d (non-pregnant individuals)	N: n/d (pregnant individuals); N: n/d (non-pregnant individuals)	N: n/d (pregnant individuals); N: n/d (non-pregnant individuals)	N: n/d	N: n/d	N: n/d
42	7758-19-2	Sodium chlorite	Y: 1	Y: 1	N: 5.27 x 10 ³	Y: 0.3	Y: 0.3	N: 1.51 x 10 ³
43	7772-98-7	Sodium thiosulfate	Y: 9**	N: 2523**	N: 1.39 x 10 ^{7**}	Y: 3**	N: 721**	N: 3.97 x 10 ^{6**}
44	7775-27-1	Sodium persulfate	Y: 2	N: 364	N: 2.00 x 10 ⁶	Y: 1	N: 104	N: 5.72 x 10 ⁵
45	81741-28-8	Tributyltetradecyl phosphonium chloride	Y **	Y **	Y **	Y **	Y **	Y **
46	9012-54-8	Cellulase	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure

HYDRAULIC FRACTURING CHEMICALS			ADULTS			CHILDREN		
			Bulk spill (transport)	Subsurface leak (flowback and / or produced water)		Bulk spill (transport)	Subsurface leak (flowback and / or produced water)	
CAS RN	Common name		Surface water use	Groundwater plus surface water use	Surface water use	Surface water use	Groundwater plus surface water use	Surface water use
47	9025-56-3	Hemicellulase	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure
48	91053-39-3	Calcined silica	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure
49	90622-53-0	Alkanes, C ₁₂₋₂₆ branched and linear	N: 133**	N: 629**	N: 3.46 x 10 ⁶ **	Y: 38**	N: 180**	N: 9.89 x 10 ⁵ **
50	CBI	Amine salt	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d
51	CBI	Enzyme	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure	N: no exposure
52	CBI	Ethoxylated fatty acid I	Y: n/d	N: n/d	N: n/d	Y: n/d	N: n/d	N: n/d
53	CBI	Ethoxylated fatty acid II	N: n/d **	N: n/d **	N: n/d **	N: n/d **	N: n/d **	N: n/d **
54	CBI	Ethoxylated fatty acid III	Y: n/d	N: n/d	N: n/d	Y: n/d	N: n/d	N: n/d
55	CBI	Inner salt of alkyl amines	N: n/d **	N: n/d **	N: n/d **	N: n/d **	Y: n/d **	N: n/d **
56	CBI	Polyamine	Y **	Y **	Y **	Y **	Y **	Y **
57	CBI	Quaternary amine	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d	N: n/d
58	CBI	Terpenes and terpenoids	N: n/d	N: n/d	N: n/d	Y: n/d	N: n/d	N: n/d

N–MOEs indicate the chemical is of low concern for adverse health effects. Y–MOEs suggest a potential concern for adverse health effects (Tier 1 risk assessments)

*Uncertainty factor differs from 100 for this assessment. ** MOEs calculated based on highest available dose for which no adverse effects were noted or MOEs not calculated as repeat dose toxicity studies are not available. n/d–not disclosed due to commercially sensitive data.

Appendix C – Effect of varying key assumptions in the Tier 1 exposure modelling for calculating risks to human health

Bulk transport spill – varying the spill volume – drilling chemicals

Table C.1 Effect of different drilling chemical spill volumes on Tier 1 health risk estimates for children for the bulk transport spill scenario

Drilling chemicals for which Tier 1 risk estimates suggest a risk to human health (children)		Transport spill volume					
CAS RN	Common name	14 000	10 000*	5 000	1 000	500	100
111-30-8	Glutaraldehyde	✓	✓	✓	✓	✓	✓
55566-30-8	THPS	✓	✓	✓	✓	✓	-
64742-47-8	Deodorised kerosene	✓	✓	✓	-	-	-
67-56-1	Methanol	✓	✓	✓	-	-	-
67-63-0	Isopropanol	✓	✓	✓	-	-	-
7757-83-7	Sodium sulfite	✓	✓	✓	-	-	-
CBI	(Ester alcohol)	✓	✓	-	-	-	-
CBI	(2-Ethylhexanol heavies)	✓	✓	-	-	-	-
CBI	(Fatty acids ester)	✓	✓	✓	✓	✓	-
CBI	(Organic acid salt)	✓	-	-	-	-	-
CBI	(Organic sulphate)	✓	✓	✓	✓		
CBI	(Polymer with substituted alkylacrylamide salt)	✓	✓	✓	-	-	-

CBI—Confidential business information. ✓ - MOEs suggest a potential concern for adverse health effects for children (Tier 1 risk assessments). * Tier 1 risk estimates assume a bulk transport spill of up to 10 000 L (or kg). The estimates assume drinking and bathing/swimming in contaminated groundwater. Names (in brackets) indicate use of a generic name in place of CBI.

Bulk transport spill – varying the spill volume – hydraulic fracturing chemicals

Table C.2 Effect of different hydraulic fracturing chemical spill volumes on Tier 1 health risk estimates for children for the bulk transport spill scenario

Hydraulic fracturing chemicals for which Tier 1 risk estimates suggest a risk to human health (children)		Transport spill volume					
CAS RN	Common name	14 000	10 000*	5 000	1 000	500	100
10043-35-3	Boric acid	✓	✓	✓	✓	✓	-
102-71-6	Triethanolamine	✓	✓	✓	✓	✓	-
107-21-1	Ethylene glycol	✓	✓	✓	-	-	-
108-10-1	Methyl pentanone	✓	-	-	-	-	-
111-76-2	Butoxyethanol	✓	✓	✓	✓	✓	✓
12008-41-2	Sodium borate	✓	✓	✓	✓	✓	✓
1303-96-4	Borax	✓	✓	✓	-	-	-
26038-87-9	Monoethanolamine, boric acid salt	✓	✓	✓	✓	✓	-
26172-55-4	Methylchloroisothiazolinone	✓	✓	✓	✓	✓	-
2682-20-4	Methylisothiazolone	✓	✓	✓	✓	✓	-
55566-30-8	THPS	✓	✓	✓	✓	✓	✓
CBI	(Ethoxylated fatty acid I)	✓	✓	✓	✓	✓	-
CBI	(Ethoxylated fatty acid III)	✓	✓	✓	✓	✓	-
64-17-5	Ethanol	✓	✓	-	-	-	-
64-19-7	Acetic acid	✓	✓	✓	✓		
67-56-1	Methanol	✓	✓	✓	✓	✓	✓
67-63-0	Isopropanol	✓	✓	✓	-	-	-
68187-17-7	C ₆₋₁₀ linear alkyl sulfate, ammonium salt	✓	✓	✓	✓	-	-
68439-45-2	C ₆₋₁₂ ethoxylated alcohols	✓	✓	✓	✓	✓	-
68647-72-3	Sweet orange oil terpenes	✓	✓	-	-	-	-
CBI	(Terpenes and terpenoids)	✓	✓	-	-	-	-

Hydraulic fracturing chemicals for which Tier 1 risk estimates suggest a risk to human health (children)		Transport spill volume					
75-57-0	Tetramethylammonium chloride	✓	✓	✓	✓	✓	✓
7681-52-9	Sodium hypochlorite	✓	✓	✓	✓	✓	✓
7722-84-1	Hydrogen peroxide	✓	✓	✓	✓	✓	-
7727-54-0	Ammonium persulfate	✓	✓	✓	✓	✓	✓
7758-19-2	Sodium chlorite	✓	✓	✓	✓	✓	✓
7772-98-7	Sodium thiosulfate	✓	✓	✓	✓	✓	-
7775-27-1	Sodium persulfate	✓	✓	✓	✓	✓	✓

CBI—Confidential business information. ✓ - MOEs suggest a potential concern for adverse health effects for children (Tier 1 assessments). * Tier 1 risk estimates assume a bulk transport spill of 10 000 L (or kg). The estimates assume drinking and bathing/swimming in contaminated groundwater. Names (in brackets) indicate use of a generic name in place of CBI.

Leaking storage pond – varying the concentration of hydraulic fracturing chemicals in the pond

Table C.3. Effects of varying concentrations of hydraulic fracturing chemicals on risks to human health (children) from subsurface leakage from a flowback and / or produced water storage pond

Chemicals for which Tier 1 risk estimates suggest a risk to human health (children)*		Hydraulic fracturing chemical concentration in storage pond				
CAS RN	Common name	100%	60%	10%	1%	0.1%
102-71-6	Triethanolamine	✓	✓	-	-	-
111-76-2	Butoxyethanol	✓	-	-	-	-
12008-41-2	Sodium borate	✓	✓	✓	-	-
144588-68-1	Sintered bauxite	✓	✓	-	-	-
55566-30-8	THPS	✓	✓	✓	-	-
67-56-1	Methanol	✓	✓	-	-	-
68439-45-2	C ₆₋₁₂ ethoxylated alcohols	✓	✓	-	-	-
75-57-0	Tetramethylammonium chloride	✓	✓	✓	-	-
7722-84-1	Hydrogen peroxide	✓	-	-	-	-
7727-54-0	Ammonium persulfate	✓	✓	✓	-	-
7758-19-2	Sodium chlorite	✓	✓	✓	✓	-
CBI	Inner salt of alkyl amines	✓	-	-	-	-

CBI—Confidential business information. ✓ - MOEs suggest a potential concern for adverse health effects for children (Tier 1 assessments). * Tier 1 risk estimates assume groundwater well is 100 m and surface water (river) is 2000 m from leaking storage pond. The estimates assume drinking contaminated groundwater and bathing/swimming in contaminated surface water. Names (in brackets) indicate use of a generic name in place of CBI.

Appendix D – Human health risk assessment reports

Human health risk assessments are available in a separate document (NICNAS 2017f).