From: Matthew Currell
To: fracking inquiry
Subject: Some follow-up references
Date: Monday, 7 August 2017 10:34:16 AM
Attachments: IESC 2014 background-review-bore-integrity.pdf
Davies et al 2014 Well integrity review.pdf
Han Currell & Cao 2016 Deep challenges Env Poll.pdf

Dear Hydraulic Fracturing Inquiry,
Many thanks for the opportunity to speak with you on Friday in Alice Springs.
I have attached a few documents requested by the panel following my presentation, namely:
1. The IESC's bore integrity review from 2014
2. The Davies et al. study looking at well integrity datasets worldwide
3. Paper by my colleagues and I looking at vertical leakage of contaminants due to well-integrity issues in northern China.
I hope these and my submissions are helpful to the inquiry.
Best regards,
Matthew Currell

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Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development

Australian Government

Department of the Environment

Background review

Bore integrity

This background review was commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. The review was prepared by Sinclair Knight Merz Pty Ltd and revised by the Department of the Environment following peer review.

June 2014

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This background review was commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. The review was prepared by Sinclair Knight Merz Pty Ltd. It was revised by the Department of the Environment following peer review by John Henrich (Bergerson Caswell Inc.) and Don Scott (Pennington Scott) and relevant Queensland, New South Wales and South Australian Government departments.

Disclaimer

The views and opinions expressed in this publication are those of the authors and do not necessarily reflect those of the Australian Government or the Minister for the Environment or the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining or the statutory Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC).

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Addendum

Changes to state government departments have occurred since the finalisation of this report by the authors. The Queensland, New South Wales and South Australian Government agencies were contacted and updated information provided in September 2013; however, no guarantees can be made as to the completeness of these updates. Up-to-date information should be sourced from the relevant department.

On 1 January 2013, the Queensland Water Commission (QWC) ceased operations. The Office of Groundwater Impact Assessment (OGIA) retains the same powers as the former QWC under Chapter 3 of the *Water Act 2000* (Qld).

Sinclair Knight Merz Pty Ltd is now Jacobs SKM.

Contents

Summary

This report provides an overview of bore construction, integrity, monitoring, reporting, decommissioning and legacy issues in Australia. It focuses on bore integrity issues as they relate to coal seam gas extraction in Australia and is informed by the international context and relevant experience in other sectors. It refers to bores constructed for water supply, coal mining exploration and coal seam gas exploration and production. With the exception of coal seam gas wells, onshore and offshore petroleum and gas wells are not considered.

In this report the terms ‘well’ and ‘bore’ are used interchangeably, but most often ‘well’ is used when referring to the extraction of coal seam gas and ‘bore’ when referring to the extraction, exploration or monitoring of water and the exploratory sampling of coal where a bore is required.

Key points

- Bore integrity failure can cause adverse changes in groundwater levels, flow rates and flow directions and can also lead to changes in groundwater quality.
- Bore integrity depends on good bore design, appropriate selection of construction materials and a high standard of cementing.
- In Australia, different types of bores are regulated under different legislation. Existing guidelines and regulations provide frameworks to establish bore integrity; driller and operator compliance is essential.
- Opportunities for future research include more detailed assessments of the frequency of, mechanisms for and consequences of bore integrity failure.
- Monitoring and reporting of bore and well integrity across all industries will be important to provide information needed to assess bore integrity and to act if there are issues.

The significance of bore integrity

In the context of this report “bore integrity” means:

> *‘…instantaneous state of a well, irrespective of the purpose, value or age, which ensures the veracity and reliability of the barriers necessary to safely contain and control the flow of all [gases] and fluids within or connected to the well’.*
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A failure of bore integrity is a failure to prevent fluid flow between aquifers and between the surface and the aquifer. Bore integrity is fundamental to protect the target aquifer and surrounding aquifers for the full life cycle of the well.

Hundreds of thousands of bores have been drilled and constructed across Australia and many of these are located in key groundwater resources. Where bore integrity is not maintained, or bores are not decommissioned properly, there is the potential to impact on groundwater resources, which can affect existing and future groundwater users as well as the environment. Bore integrity failure can cause adverse and unintended changes in groundwater levels, flow rates and flow directions and can also lead to changes in groundwater quality. A further impact often associated with bore integrity failure is the contamination of aquifers by leakage of gas or water of a different quality, either through the bore casing, the bore annulus or open (i.e. uncased) bores.

In relation to coal seam gas development, understanding bore integrity is essential to:

- understanding the risk of coal seam gas loss to overlying aquifers, and subsequent risks to groundwater quality and human safety
- predicting the impacts on aquifers from depressurising coal seams, as degraded or inappropriately constructed boreholes may provide sufficiently increased connectivity of aquifers to require factoring into groundwater flow analysis.

Causes and incidence of bore integrity failure

Bore integrity failure is usually due to one or more of the following scenarios.

- Poor construction methods – for example, a poorly sealed annulus that allows contaminated surface water to enter the bore, or the inappropriate placement of bore openings against multiple aquifers that link aquifers of differing water quality.
- Poor monitoring and maintenance – for example, inadequate monitoring or routine maintenance of bore casings and associated headworks results in bore integrity failures not being detected or corrected.
- Failed integrity of bore materials – for example, a corroded bore casing or a failed grout seal allows cross flow of water between aquifers.
- Poor decommissioning – decommissioning refers to work undertaken to properly shut down a bore. All failed or unwanted drill holes, bores and wells should be decommissioned properly, to restore aquifer-isolation and prevent surface water inflow, uncontrolled discharge of gas or fluids and flow between aquifers.

Bore integrity failure is most likely to occur as a result of poor construction techniques. Therefore, good bore design, appropriate selection of construction materials and a high standard of cementing are essential to the integrity of a new bore. Existing guidelines and regulations provide frameworks to establish bore and well integrity; driller and operator compliance is essential.

Bore integrity regulation and management

Coal seam gas wells

The construction and integrity of Australian coal seam gas wells is managed through a combination of state and territory legislation, industry standards and codes of practice. For example, Australia’s petroleum and gas legislation is largely based on international standards such as the American Petroleum Institute (API) and Standards Norway (NORSOK). The Norwegian petroleum industry developed the NORSOK standards to ensure adequate safety, value-adding and cost-effectiveness for petroleum industry developments and operations. The API publishes a range of practice notes that are used by many countries to guide well construction and operations, including Australian codes of practice for coal seam gas. The regulatory regime in Australia for the petroleum and gas industry is regarded to be leading practice.

In Queensland and New South Wales there are specific codes of practice for coal seam gas well integrity. Queensland has a *Code of practice for coal seam gas wellhead emissions detection and reporting*, and New South Wales has a *Code of practice for coal seam gas well fracture simulation activities* and *Code of practice for coal seam gas well integrity*. These codes of practice outline monitoring and reporting requirements to ensure well integrity as specified by each regulator. Standards and the level of compliance within the coal seam gas industry are higher than that of the water and mining industries.

Water bores

The water bore industry is regulated by various acts, standards and guidelines, many of which are based on international standards. The design, drilling, construction, maintenance and decommissioning of water bores in Australia are guided by the *Minimum construction requirements for water bores in Australia* (MCRWBA), which was first published in 1997. However, at a national and state level there are no regulatory requirements for monitoring the integrity of water bores, either upon completion, over their workable life, or upon decommissioning. This is considered to be the responsibility of the bore owner.

Mining and exploration bores

Mining and coal exploration bores are regulated in Australia under the relevant legislation in each jurisdiction. Similar to water bores, there is little published on the adequacy of the mining regulatory framework and the level of compliance. Drillers are not required to be licensed, there is little information about decommissioning of exploration bores in the public domain and there are no regulatory requirements for monitoring the integrity of decommissioned exploration bores.

Integrity monitoring

Monitoring the integrity of a bore through its life cycle is crucial to ensuring the bore is maintained. Bores can deteriorate with age, operation and site-specific conditions, reducing their capacity for the intended use. Bore monitoring and maintenance is required to ensure the bore is preserved and its components are in good condition for the life of the bore. There are a variety of tools and techniques available to assess bore integrity, including technologies available for measuring well integrity in a coal seam gas field. These techniques apply equally to other well types, including coal seam gas wells and water bores. However, the cost of integrity assessment techniques may be a barrier to their use, especially for bores that are shallow and/or of simple construction, and may be replaced at a relatively low cost.

Monitoring and reporting of bore and well integrity across all industries will be important to ensure that there is sufficient information available to assess bore integrity and to act if there are issues. Research to assess the most appropriate and cost-effective techniques to locate legacy bores throughout Australia and to determine the scale of the issue would also be of benefit.

Abbreviations

Abbreviation	Description
ADIA	Australia Drilling Industry Association
ADITC	Australian Drilling Industry Training Committee
API	American Petroleum Institute
APPEA	Australian Petroleum Production and Exploration Association
AQF	Australian qualifications framework
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ASR	Aquifer storage and recovery
ASV	Annulus safety valve
BGL	Below ground level
CBT	Cement bond tools
CCS	Carbon capture and storage
CCTV	Closed circuit television
CMA	Catchment management authority
CO_2	Carbon dioxide
CSG	Coal seam gas
DEEDI	QLD Department of Employment, Economic Development and Innovation
DEHP	QLD Department of Environment and Heritage Protection
DERM	QLD Department of Environment and Resource Management.
DMITRE	SA Department for Manufacturing, Innovation, Trade, Resources and Energy
DNRM	QLD Department of Natural Resources and Mines
DSE	VIC Department of Sustainability and Environment
ECP	Extracellular polymers
FRP	Fiberglass-reinforced polymer
GAB	Great Artesian Basin
GMV	Goulburn Murray Water
G-WMW	Grampians-Wimmera Mallee Water
H_2O	Water molecule
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
ISWD	International School of Well Drilling
MCRWBA	Minimum construction requirements for water bores in Australia
ML	Megalitre (1 million litres)

Abbreviation	Description
MRSD Act	*Mineral Resources (Sustainable Development) Act 1990* (Vic)
NMBSC	National Minimum Bore Specifications Committee
NORSOK	Norsk Sokkels Konkuranseposisjon (Standards Norway)
NSW	New South Wales
NSW T&I	Department of Trade and Investment, Regional Infrastructure and Services (known as NSW Trade & Investment)
NUDLC	National Uniform Drillers Licensing Committee
ODNR	Ohio Department of Natural Resources (US)
OGIA	Office of Groundwater Impact Assessment
PGE Act	*Petroleum and Geothermal Energy Act 2000* (SA)
PGER Act	*Petroleum and Geothermal Energy Resources Act 1967* (WA)
PN	Nominal pressure
PSA	Petroleum Safety Authority, Norway
PVC-U	Polyvinyl chloride
QWC	Queensland Water Commission
REF	Review of environmental factors
RPL	Recognised prior learning
SA	South Australia
SCER	Standing Council on Energy and Resources
SCVF	Surface-casing-vent flow
SEO	Statement of environmental objective
SRW	Southern Rural Water
UK	United Kingdom
US	United States of America
VIT	Vertical interference test
WA	Western Australia

Glossary

Term	Description
Annulus	The space between the bore casing and borehole, or between bore casings, or between casing and tubing, in coal seam gas wells.
Aquifer	Rock or sediment in a formation, group of formations or part of a formation, that is saturated and sufficiently permeable to transmit quantities of water to wells and springs.
Aquitard	A saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.
Artesian	Pertaining to a confined aquifer in which the groundwater is under positive pressure (that is, a bore screened into the aquifer will have its water level above ground).
Bore	A narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole, drill holes or piezometer. This report uses the term 'bore' in reference to the extraction, exploration or monitoring or water.
Bore development	The vigorous agitation of water and air in the borehole to remove fine particles and other material introduced in the drilling process and to provide a good hydraulic connection between the bore and the aquifer.
Bore failure	The condition of a bore once it becomes unserviceable to the point of requiring refurbishment, replacement or decommissioning.
Borehole	Refer to Bore.
Bridge	A solid fixture that is positioned in a drilled hole, to form a base for grout or backfill material, when the drilled hole is to be only partially infilled.
Casing	A tube used as a temporary or permanent lining for a bore. *Surface casing*: The pipe initially inserted into the top of the hole to prevent washouts and the erosion of softer materials during subsequent drilling. Surface casing is usually grouted in and composed of either steel, PVC-U or composite materials. *Production casing*: A continuous string of pipe (casing) that is inserted into or immediately above the chosen aquifer and back to the surface through which water or gas is extracted / injected.
Cement grout	A fluid mixture of Portland Cement and water of a consistency that can be forced through a pipe and placed as required.
Cementing	The process of placing grout into the annulus around the casing to provide a permanent seal. Is also known as grouting.
Clearbore	A biodegradable granular chemical designed to remove the blockage of sludge and hard encrustations that result from dissolved iron and iron-related bacteria. Is manufactured by Clearbore Pty Ltd.
Construction	The entire process of creating a bore from initial drilling and inserting the surface casing and screen, completing the bore and developing it for use.
Confined aquifer	An aquifer which is isolated from the atmosphere by an impermeable layer. Pressure in confined aquifers is generally greater than atmospheric

Term	Description
	pressure.
Contaminant	Biological (e.g. bacterial and viral pathogens) and chemical introductions capable of producing an adverse response (effect) in a biological system, seriously injuring structure or function or producing death.
Corrosion	The act or process of dissolving or wearing away a material.
Decommissioned (abandoned)	A bore for which the purpose and use have been permanently discontinued.
Dewatering	The lowering of static groundwater levels through complete extraction of all readily available groundwater, usually by means of pumping from one or several groundwater bores.
Disinfection	A preventative measure against iron bacteria, potential encrustation and resulting decline in bore efficiency. Disinfection generally involves chemical treatment such as chlorination.
Drilling fluids	A medium used to stabilise the formation, control groundwater flow and remove the drill cutting from the hole as drilling takes place.
Exploration bore	A bore, or hole, drilled with the purpose to collect samples of geology.
Fugitive emissions	The unintentional release of gases or vapours, generally from industrial activities.
Good oilfield practice	A long held industry concept that is defined as 'all those things that are generally accepted as good and safe in carrying out exploration or recovery operations'.
Gravel pack	Granular material introduced into the annulus between the borehole and casing / screen, to prevent or control the movement of finer particles from the aquifer to the bore. Also referred to as a filter pack.
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 there. This does not include water held in underground tanks, pipes or other works.
Groundwater injection bore	A bore installed to facilitate the injection of liquid (e.g. H_20) or gas (e.g. CO_2) into an aquifer. Commonly used in Managed Aquifer Recharge schemes or groundwater remediation.
Groundwater monitoring/ observation bore	A bore installed to determine the nature and properties of subsurface groundwater conditions, provide access to groundwater for measuring level, physical and chemical properties, and permit the collection of groundwater samples and/or conduct aquifer tests.
Groundwater pumping (production) bore	A bore installed primarily to extract groundwater for productive/consumptive purposes from a particular hydrogeological formation by means of a pump.
Headworks	The part of a bore that protrudes at the ground surface. It usually entails a concrete collar and pad around the bore casing raised above the natural surface to prevent surface water entering the borehole.
Hydraulic fracturing	Also known as 'fracking', 'fraccing', or 'fracture stimulation', is the process by which hydrocarbon (oil and gas) bearing geological formations are 'stimulated' to enhance the flow of hydrocarbons and other fluids towards the well. The process involves the injection of fluids, gas, proppant, and other additives under high pressure into a geological formation to create a network of small fractures radiating outwards from the well through which

Term	Description
	the gas, and any associated water, can flow.
Integrity	The instantaneous state of a well, irrespective of the purpose, value or age, which ensures the veracity and reliability of the barriers necessary to safely contain and control the flow of all fluids within or connected to the well. A failure of integrity is a failure to prevent fluid flow between aquifers and between the surface and the aquifer.
Legacy bore	A bore, or well, that is no longer used and has not been decommissioned/abandoned correctly.
Production well	A well drilled to produce oil or gas.
Rehabilitation	The restoration of a bore to its most efficient condition using a variety of chemical or mechanical techniques, which may include replacing the production casing and/or screens.
Screen	The intake portion of a bore, which contains an open area to permit the inflow of groundwater at a particular depth interval, whilst preventing sediment from entering with the water.
Tubing (coiled)	Tubing refers to metal piping, normally 2.5 cm to 8.3 cm in diameter, used for interventions in oil and gas wells and sometimes as production tubing in depleted gas wells.
Unconfined aquifer	An aquifer which has the upper surface connected to the atmosphere.
Vadose zone	The vadose zone, also called the unsaturated zone, extends from the top of the ground surface to the water table. In the vadose zone, the water in the soil's pores is at atmospheric pressure.
Water quality	The physical, chemical, and biological attributes of water that affects its ability to sustain environmental values.
Water table	The upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.
Well	A human made hole in the ground, generally created by drilling, to obtain fluid or gas.
Yield	The rate at which water (or other resources) can be extracted from a pumping well, typically measured in litres per second (L/s) or megalitres per day (ML/d).

1 Introduction

This review is one of a number commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining. These reviews aim to capture knowledge on the water-related impacts of coal seam gas extraction and large coal mining, but do not aim to provide detailed analysis and evaluation of methods for identifying and managing impacts, or to develop such methods.

The focus of this report is bore integrity, which is defined as the:

> *"…instantaneous state of a well, irrespective of the purpose, value or age, which ensure the veracity and reliability of the barriers necessary to safely contain and control the flow of all fluids within or connected to the well."*
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In this report the terms 'well' and 'bore' are used interchangeably, but most often 'well' is used when referring to the extraction of coal seam gas and 'bore' when referring to the extraction, exploration or monitoring of water and the exploratory sampling of coal where a bore is required.

A failure of bore integrity is a failure to prevent fluid flow between aquifers and between the surface and the aquifer. Bore integrity is fundamental to protect the target aquifer and surrounding aquifers for the full life cycle of the bore (or well). Hundreds of thousands of bores have been drilled and constructed across Australia and many of these are located in key groundwater resources. If bore integrity is not maintained, or bores are not decommissioned appropriately, there is the potential to impact on groundwater resources, which can affect existing and future users of groundwater as well as the environment.

This report focuses on bore integrity issues as they relate to coal seam gas extraction in Australia and is informed by the international context and relevant experience in other sectors. It examines issues associated with bore construction, integrity, monitoring and reporting, decommissioning, and legacy issues. Bores constructed for water supply, coal mining exploration and coal seam gas exploration and production are reviewed, whilst other onshore and offshore petroleum, oil and gas wells are not.

This report provides a summary and synthesis of the relevant and available literature without focusing on the results of any specific study or research project. The report was prepared from information available in the public domain and discussions with industry representatives. The major sources of information were:

- scientific journal articles
- conference proceedings
- scientific text books
- government department reports, guidelines and policies
- industry technical reports and standards.

This report begins with a review of the regulations governing bore management in Australia (Chapter 2) and established methods for bore design and construction (Chapter 3).

Chapter 4 explores methods and requirements for bore monitoring and reporting and Chapter 5 reviews aspects of bore decommissioning.

The final section of this report (Chapter 6) identifies the major knowledge gaps that present a risk to the future management of water resource impacts from bores and wells in Australia. These gaps include uncertainties in the understanding of frequency, mechanisms, criteria and consequences of bore integrity failure; and uncertainties in the understanding of cumulative issues associated with multiple incidents of bore integrity failure.

2 Regulations governing bore management

2.1 Overview

In Australia, different types of bores are regulated under different legislation. All water bores, including water supply bores for agriculture, irrigation and stock and domestic use, and dewatering bores are regulated under the relevant state or territory water acts. Mining exploration bores are regulated under the relevant state or territory mining acts. Coal seam gas extraction is generally regulated in the same way as other onshore petroleum upstream activity through the state and territory petroleum and gas acts. As the majority of coal seam gas and coal mining is located in New South Wales and Queensland, this review of legislation is focused largely on these states.

2.2 Drilling licences

2.2.1 Water bores

Australia has a National Water Well Drillers' Licensing System, which requires anyone who drills bores for the purpose of accessing groundwater to be licensed (ADITC 2010) (unless state or territory legislation provides an exemption). The Australian Drilling Industry Training Committee Limited (ADITC) coordinates the licensing program. Drillers' licences are classified according to the type of aquifers and drilling methods:

- class 1 – restricted to drilling operations in single non-flowing aquifer systems, such as water table aquifers
- class 2 – in addition to operating in Class 1 conditions, permits drilling operations in multiple on-flowing aquifer systems, such as confined aquifers
- class 3 – in addition to operating in Class 1 and 2 conditions, permits drilling operations in flowing aquifer systems, such as artesian aquifers.

All jurisdictions use the National Water Well Drillers' Licensing System as a common basis for a national examination so that technical skills at the national level have a benchmark (ADITC 2010). If a driller is licensed in one state they can apply for their licence to be converted to the equivalent class of licence in another state. Each jurisdiction also requires drillers to meet minimum requirements to ensure they are aware of the local legislation and conditions (ADITC 2010).

2.2.2 Mining, petroleum and gas wells

Drillers operating in the mining and petroleum and gas industries are required to be qualified in accordance with the Australian Qualification Framework (AQF), but they are not required to hold a National Water Well Drillers' Licence (ADITC 2011). The AQF is a national qualifications framework that comprises a series of qualifications that are formally named Certificate I, II, III and IV, Diploma and Advanced Diploma (ADITC 2011). The process of assessment is either carried out on-the-job with a qualified industry assessor or through a Recognised Prior Learning (RPL) process involving the preparation of a portfolio outlining the participant's experience in drilling (ADITC 2011).

There is no legal requirement by the Commonwealth or state governments for drillers to comply with the AQF (ADITC 2012, pers. comm., September). For example, in Queensland while it is the tenure holder, rather than the driller, who has primary responsible for ensuring bore construction meets the regulatory requirements, the Queensland Government requires that all drillers be appropriately qualified and drilling inspectors may close a site if drillers are operating without appropriate qualifications. In Victoria, these qualifications are not mandated. In New South Wales, drillers need to be licensed to drill a bore that meets the definition of a 'water bore' under the *Water Management Act 2000* (NSW). This is also the case for CSG activities in New South Wales. This variation in qualifications across industries and jurisdictions reflects the differences in responsibilities of the driller. However, most companies require drillers to hold these qualifications despite it not being a national legal requirement.

This review found no published literature discussing the adequacy of Australia's drilling licensing systems. However, the Australian Drilling Industry Association (ADIA) recommends that all drillers be certified or licensed, which would help ensure aquifers are protected across the different industries (Fitzgerald (ADIA) 2012, pers. comm., September). ADIA's primary concern is with mining exploration bores, particularly ensuring they are decommissioned appropriately.

2.3 Water bores

Water bore construction is now required to meet mandatory construction standards across Australia unless state or territory legislation provides an exemption. For example, in Western Australia, stock and domestic and monitoring bores are not regulated and do not need to be drilled by a licensed driller. Queensland and the Northern Territory do not require bores outside of certain management areas to be licensed (Scott 2013). State governments have implemented bore construction licensing programs at various stages, in alignment with their respective legislative requirements. Bores drilled prior to the introduction of particular regulatory requirements may pose a higher risk for the loss of bore integrity.

2.3.1 Water supply and monitoring bores

Water bores include any bores that have been drilled for water supply, including that for stock and domestic use, irrigation and commercial purposes, groundwater monitoring and dewatering. Table 1 provides a summary of the regulatory context in each state and territory of Australia.

Design, drilling, construction, maintenance and decommissioning of water bores anywhere in Australia is governed by the *Minimum construction requirements for water bores in Australia* (MCRWBA) (NUDLC 2012), first published in 1997. Prior to 1997, there were no national guidelines. The current version of the MCRWBA is referred to extensively by regulators and the drilling industry, as it provides a consistent standard reference across Australia. It focuses on protecting groundwater resources and providing a good water supply. Mandatory requirements are enforceable for the protection of the groundwater resource. It also includes recommendations for 'good industry practice' for some methods and techniques. Legislation and the regulations that follow are managed by water regulators in each state and territory.

Previous versions of the MCRWBA (i.e. NMBSC 2003; ARMCANZ 1997) were reviewed to identify changes in standards relating to bore integrity. On a broad scale, very little change was observed between the 1997 and 2003 revisions of the document. However, a complete re-structure of the document was evident in 2012, with a higher level of requirements and more detailed standards, particularly in the casing and grouting/cementing/bore sealing sections. The mandatory requirements within the report clearly summarise the standards and requirements for each aspect of bore installation.

Table 1 Overview of the regulatory framework for water bores in Australia.

Jurisdiction	Regulatory Framework for Water Bores
Australian Capital Territory	The *Water Resources Act 2007* controls licensing of drillers, construction of bores and groundwater extraction. The ACT government Environment and Sustainable Development Directorate is the body that regulates licensing and a 'requirement' of each driller's licence is to undertake work on bores as per the *Minimum construction requirements for water bores in Australia* (MCRWBA) (NUDLC 2012). The NSW drilling licence is also recognised in ACT (Fitzgerald (ADIA), pers. comm., September).
New South Wales	The Department of Primary Industries (Office of Water) is responsible for the management of and access to groundwater. Approval to construct a bore and extract groundwater is governed by the *Water Management Act 2000,* which 'recommends' that all water bores be constructed to meet MCRWBA (NUDLC 2012).
Northern Territory	The protection and control of groundwater is covered by the *Water Act 1992* and regulated by the Department of Land Resource Management. Water bores in the Northern Territory are required to comply with MCRWBA (NUDLC 2012).
Queensland	All bores are required to comply with the MCRWBA (NUDLC 2012). If a bore is located in the Great Artesian Basin (GAB), it must also comply with *Minimum standards for the construction and reconditioning of water bores that intersect the sediments of artesian basins in Queensland* (DNRM 2013). These standards apply to both artesian and sub-artesian water bores intersecting artesian water beds in the area managed under the *Water Resource (Great Artesian Basin) Plan 2006* (Queensland Government 2006).
South Australia	Groundwater resources are managed under the *Natural Resources Management Act 2004* and regulated by the Department of Environment, Water and Natural Resources. Water bores in South Australia are required to comply with the MCRWBA (NUDLC 2012) and the general specification for well construction modification and abandonment in South Australia pursuant to well construction permits issued under the *Natural Resources Management Act 2004*.
Tasmania	Water bores 'should' be constructed in accordance with the MCRWBA (NUDLC 2012) and groundwater access is regulated by the Department of Primary Industries, Parks, Water and Environment and controlled under the *Water Management Act 1999*. There is a requirement, under Part 7 of the *Water Management Act 1999*, that the occupier of land on which a water bore is situated must ensure that the bore, including the casing, lining, screen and mechanism used to cap the well (if any), is properly maintained. It is also an offence under the Act to introduce any matter into a well that could cause pollution of groundwater.
Victoria	The *Water Act 1989* provides the basis for the rules under which Victoria's water users can access and take and use water. The Department of Sustainability and Environment (DSE) is responsible for coordinating state-wide groundwater management activities and providing groundwater policy direction. There are three water corporations in Victoria that regulate drilling and construction of water bores – Goulburn Murray Water (GMW), Grampians Wimmera Mallee Water (G-WMW) and Southern Rural Water (SRW). All bores in Victoria 'must' be constructed to an 'acceptable' standard and meet the MCRWBA (NUDLC 2012).
Western Australia	The Department for Water administers the *Rights in Water and Irrigation Act 1914* to issue groundwater licences in all proclaimed areas and for all artesian water bores in the state. Water from sub-artesian bores can be taken without a licence in unproclaimed areas. Drillers are required to 'perform all work' under the MCRWBA (NUDLC 2012).

At the time of writing there was no published literature reviewing the adequacy of the MCRWBA but the water industry accepts that the third edition of the MCRWBA (NUDLC 2012) provides a sound framework for the design and construction of water bores (Fitzgerald (ADIA) 2012, pers. comm., September). However, there are no regulations at a national and state level for monitoring the integrity of water bores, either upon completion, during operation or upon decommissioning.

The level of compliance by drillers within the guidelines is largely unknown and/or unpublished. The *National framework for compliance and enforcement systems for water resource management* outlines offences that regulators must endeavour to prevent (DSEWPaC 2012). These include bore construction by an unlicensed water driller and non-compliance by licensed water drillers such as non-lodgement of drilling logs or faulty bore construction (DSEWPaC 2012). Regulators in all jurisdictions have compliance officers to ensure that bores are drilled and constructed in accordance with guidelines (e.g. SRW 2011). The number of bore inspections that are actually undertaken is not published.

2.4 Coal mining exploration bores

Mining exploration bores are regulated under the mining legislation specific to each Australian jurisdiction. A mining exploration licence is granted and exploration holes can be drilled and should also be decommissioned when finished. If a mining lease is located in an area where there are important groundwater resources, the application is referred to the appropriate water department, so that specific conditions can be included in the conditions of the licence to ensure the groundwater resources are protected. However, this referral process does rely on the regulators having the right processes and capacity to deal with these referrals (SKM 2012a). At the time of writing, documentation on how often this actually occurs, or if the regulator has the capacity to assess each case and how it may vary across the jurisdictions was not found.

As part of the conditions on the mining lease permit, annual reports are often required to be submitted to the regulators detailing the exploration activities that have been undertaken. The relevant mining legislation in each jurisdiction is outlined below:

- in New South Wales, mining activities are governed under the *Mining Act 1992*
- in Northern Territory, mining activities are governed under the *Mineral Titles Act 2010*
- in Queensland, mining activities are governed under the *Mineral Resources Act 1989*
- in South Australia, mining activities are governed under the *Mining Act 1971*
- in Tasmania, mining activities are governed under the *Mineral Resources Development Act 1995*
- in Victoria, mining activities are governed under the *Mineral Resources (Sustainable Development) Act 1990* and the *Mineral Resources Development Regulations 2002*
- in Western Australia, mining activities are governed under the *Mining Act 1978*.

2.5 Coal seam gas wells

The practice of drilling and constructing coal seam gas wells in Australia is governed by a number of petroleum and gas international standards, national and state legislation, guidelines and codes of practice. Australia’s petroleum and gas legislation is largely based on international standards such as the American Petroleum Institute (API) and Standards Norway (NORSOK). The Norwegian petroleum industry developed the NORSOK standards to ensure adequate safety, value adding and cost-effectiveness for petroleum industry developments and operations (NORSOK 2004). The API publishes a range of practice notes that are used by many countries as guidance for well construction and operations, including Australian codes of practice for coal seam gas (NSW T&I 2012a; DEEDI 2011a; API 2009). A summary of the relevant legislation, codes and recommendations in these states is provided below. This information is largely based on a stock take report of existing coal seam gas legislation undertaken by Norton Rose (2012).

2.5.1 New South Wales

The Department of Trade and Investment, Regional Infrastructure and Services (known as NSW Trade & Investment) is largely responsible for regulating the coal seam gas industry under the *Petroleum (Onshore) Act 1991 (*Roth 2011), which is supported by the *Petroleum (Onshore) Regulation 2007* and the *Schedule of Onshore Petroleum and Production Safety Requirements 1992*.

The Schedule of Onshore Petroleum and Production Safety Requirements states that all work activities of title holders must comply with ‘good oilfield practice’ and that all materials and equipment employed by title holders must follow good oilfield practice. ‘Good oilfield practice’ is used throughout the Petroleum (Onshore) Act, however there is no definition provided in the Act. In the *Petroleum (Offshore) Act 1982* (NSW), ’good oilfield practice’ is defined as:

> *“…good oilfield practice means all those things that are generally accepted as good and safe in the carrying on of exploration for petroleum, or in operations for the recovery of petroleum, as the case may be.”*
>
> © Copyright, NSW Government (2014)

The concept of ‘good oilfield practice’ is discussed more in the following section.

NSW Trade & Investment has also developed codes of practice for coal seam gas exploration. They include the *Code of practice for coal seam gas well integrity* and *Code of practice for coal seam gas well fracture stimulation activities* (NSW T&I 2012a; NSW T&I 2012b). The code of practice for coal seam gas well integrity aims to provide a practical guide for coal seam gas titleholders on how to comply with a condition of title for coal seam gas exploration, extraction or production under the Petroleum (Onshore) Act and the Petroleum (Onshore) Regulation. The code includes (NSW T&I 2012a):

- mandatory standards for well design and construction to ensure the environmentally sound, safe production of coal seam gas and the protection of groundwater resources
- well monitoring and maintenance requirements
- management of back flow or ‘co-produced’ water from the coal seam gas extraction process
- design of all coal seam gas wells to ensure the safe and environmentally sound production of gas by:
  - preventing any interconnection between coal seams and aquifers
  - ensuring that gas is contained within the well and associated pipework and equipment without leakage
  - ensuring isolation between different aquifers and water bearing zones
  - not introducing substances that may cause environmental harm

- requiring all chemicals used to be disclosed during the approvals process.

2.5.2 Northern Territory

Petroleum activities including coal seam gas are governed by the *Petroleum Act 1984* and the *Petroleum Regulations 1994,* which are administered by the Department of Resources. The Petroleum Act requires that a licensee for exploration, retention or production of petroleum conduct all operations with ‘good oilfield practice’ and ‘approved technical works programme’.

2.5.3 Queensland

The primary legislation that governs petroleum including coal seam gas well drilling, construction and abandonment is the *Petroleum and Gas (Production and Safety) Act 2004* and the *Petroleum and Gas (Production and Safety) Regulation 2004*. The Petroleum and Gas (Production and Safety) Regulation sets out mandatory and recommended codes of practice (Norton Rose 2012). There is also the *Queensland Petroleum Act 1923* and associated *Petroleum Regulation 2004,* which are relevant to the coal seam gas industry.

The *Code of practice for constructing and abandoning coal seam gas wells in Queensland* (DEEDI 2011a) was developed by the Department of Employment, Economic Development and Innovation (DEEDI) and the Department of Environment and Resource Management (DERM) in liaison with the coal seam gas industry and coordinated by the Australian Petroleum Production and Exploration Association (APPEA). The code is a mandatory standard for a prescribed well, proposed well or abandoned wells (Norton Rose 2012). Queensland also has a *Code of practice for coal seam gas well head emissions detection and reporting* (DEEDI 2011b).

2.5.4 South Australia

Unconventional gas including coal seam gas activities are administered by the Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE) under the *Petroleum and Geothermal Energy Act 2000* (PGE Act, onshore) and the *Petroleum and Geothermal Regulations 2010* (DMITRE 2012). Norton Rose (2012) states that well integrity matters are also covered under the fitness for purpose provisions under the PGE Act and Regulations and a licencee is required to demonstrate that the well design and construction methods deployed are fit for the purpose of satisfying the requirements of the Statement of Environmental Objective (SEO).

2.5.5 Tasmania

Coal seam gas development is regulated under the *Mineral Resources Development Act 1995* and overseen by Mineral Resources Tasmania. The approval and regulation of onshore exploration for petroleum, coal seam gas and geothermal energy is governed by Appendix 1 of the *Mineral exploration code of practice* (Bacon & Pemberton 2012), which states that activities must be undertaken in accordance with ‘good oilfield practice’.

2.5.6 Victoria

The *Mineral Resources (Sustainable Development) Act 1990* (MRSD Act) is the primary legislation governing mineral related activity. Unlike other jurisdictions, the MRSD Act defines mineral as:

> *'…any substance which occurs naturally as part of the earth's crust, including oil shale and coal; and hydrocarbons and mineral oils contained in oil shale or coal or extracted from oil shale or coal by chemical or industrial processes; and any substance specified in Schedule 4; [but excludes] water, stone, peat or petroleum…'*
>
> © Copyright, Victorian Government (2010)

This includes coal seam gas. Since 2000, a number of mineral exploration licences have been issued in Victoria for exploration for coal seam gas but no production of coal seam gas has occurred (DPI 2012). There are no specific standards or guidelines relating to coal seam gas well integrity in Victoria.

2.5.7 Western Australia

Western Australia has a high potential for shale and tight gas, which are very different to the coal seam gas resources targeted in Queensland and New South Wales (Hunter 2011). The main difference is that shale and tight gas occur in shale and fine-grained sediments rather than coal seams and are typically found at significantly greater depths, usually beyond 2000 m. Coal seam gas is generally found between 300 to 1000 m. Because the shale and tight gas reserves are a lot deeper and have low permeability, hydraulic fracturing is routinely used.

The unconventional gas industry including shale gas, tight gas and coal seam gas development is governed by the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act). The PGER Act is supported by several other schedules and regulations. However coal seam gas well integrity is regulated solely by the PGER Act (Norton Rose 2012). This Act requires that all petroleum exploration and production be carried out in a proper and workmanlike manner and in accordance with 'good oilfield practice' (Norton Rose 2012).

2.5.8 Summary

The petroleum and gas regulations for well construction are considered adequate to maintain well integrity for coal seam gas wells (SKM 2012a). SKM has completed the *Leading practice framework for coal seam gas development in Australia* (SKM 2012a). This report recommended 22 leading practice strategies. One strategy is the adoption of existing standards and regulations consistent with the principles, mandatory requirements and good practices detailed in the *Code of practice for constructing and abandoning coal seam gas wells in Queensland* (DEEDI 2011a). SKM noted that the legislation and standards within Australia are considered leading practice and are capable of addressing and mitigating the risks associated with well integrity.

The Queensland code of practice is considered to be leading practice in Australia as it is specific to coal seam gas and outlines principles as well as mandatory requirements and good practice. The New South Wales code of practice is consistent with the Queensland code of practice. While SKM (2012a) identified these regulations as leading practice for the construction of coal seam gas wells, this review has not identified any scientific evidence confirming that if bores are constructed to these standards they will not fail.

There are other jurisdictions where the regulatory framework may not be sufficient to ensure the protection of the environment. Hunter (2011) highlights that the regulatory regime for resources and the environment in Western Australia lacks legal enforceability because resource management and environmental regulations are not included in the PGER Act. One of Hunter's (2011) 15 recommendations was that the:

> *'…WA Department of Mines and Petroleum undertake to write environmental regulations to regulate onshore petroleum activities, including the recovery of coal seam gas.'*
>
> © Copyright, Hunter (2011)

SKM (2012a) also highlighted that it is important to ensure that compliance measurement by the regulator occurs and that the results of this are transparently reported, and that the regulators have the skill and capacity to meet their responsibilities.

2.5.8.1 Good oilfield practice

'Good oilfield practice' is a long held industry concept that is generally stated as all those things that are generally accepted as good and safe in carrying out exploration or recovery operations. There is flexibility in the design of the regulatory framework to allow innovation or optimisation (Manifold 2010). This also allows for different interpretation of the regulations and standards, which means the concept of good oilfield practice and the subsequent application and engineering will vary from site to site and between operators. New South Wales has recently stated what it considers is 'good industry practice' through the two codes of practice on coal seam gas well integrity and fracture stimulation activities. This helps to define what is expected of New South Wales coal seam gas operators.

The concept of good oilfield practice also appears to be focussed on safety and minimising gas explosions. However, SKM (2012a) note that the extent to which good oilfield practice protects the surrounding groundwater resources or environment is not well understood. Unlike coal seam gas, conventional oil and gas does not need to depressurise the gas bearing layer. Some depressurisation will occur inevitably, but it is not a prerequisite to release conventional gas. Depressurisation at the scale that is required for coal seam gas extraction can cause significant impacts to groundwater resources and the environment if not managed appropriately and whether good oilfield practice can achieve the right management balance needs to be considered further (SKM 2012a).

2.5.8.2 Wells for hydraulic fracturing

Hydraulic fracturing, also known as 'fracking', 'fraccing' and 'fracture stimulation', is the process by which hydrocarbon (oil and gas) bearing formations are 'stimulated' to enhance the flow of hydrocarbons to the wellhead (NSW T&I 2012b). It involves the injection of fluid (and other materials) under high pressure into a geological formation from which hydrocarbons are intended to be extracted (NSW T&I 2012b).

NSW introduced a moratorium on hydraulic fracturing in April 2011 and this was lifted in September 2012, with the introduction of the NSW Strategic Land Use Policy (Herbert 2012). Victoria is the only jurisdiction with a moratorium on hydraulic fracturing, which was introduced in August 2012 (Wilkinson 2012).

Generally the hydraulic fracturing regulatory framework incorporates a range of regulations and guidelines relating to petroleum and gas, environmental protection, water and safety. Information on the NSW regulatory environment for coal seam gas hydraulic fracturing is provided below, as an example.

As mentioned previously, NSW Trade & Investment have recently published two codes of practice for coal seam gas well integrity and fracture simulation activities (NSW T&I 2012a; NSW T&I 2012b). The *Code of practice for coal seam gas fracture stimulation activities* sets out the different components of the NSW regulatory framework which includes:

- *Petroleum (Onshore) Act 1991*
- *Petroleum (Onshore) Regulation 2007*
- Petroleum title conditions
- NSW *Code of practice for coal seam gas well fracture stimulation activities* (NSW T&I 2012b)
- NSW *Code of practice for coal seam gas well integrity* (NSW T&I 2012a)
- ESG2: Environmental Impact Assessment Guidelines
- Additional Part 5 REF requirements for petroleum prospecting - a supplement to ESG2: Environmental Impact Assessment Guidelines
- *Work Health and Safety Act 2011* and subsidiary regulatory requirements
- *Environmental Planning and Assessment Act 1979* and subsidiary regulatory requirements
- *Water Management Act 2000* and subsidiary regulatory requirements
- *Protection of the Environment Operations Act 1997* and subsidiary regulatory requirements.

New South Wales is the only jurisdiction to have a specific code of practice for hydraulic fracturing. Hydraulic fracturing in other jurisdictions is regulated under the wider regulatory framework.

2.6 Conversion to a water bore

If a mining exploration bore or coal seam gas well is converted to a water bore for production or dewatering, then a special permit is required under the relevant mining or petroleum and gas act (Fitzgerald (ADIA) 2012, pers. comm., September). Also, the bore must be designed, constructed and decommissioned compliant with the MCRWBA (NUDLC 2012). A licensed water driller must also either undertake the drilling, or supervise the drilling and construction.

3 Bore design and construction

3.1 Overview

Bores or wells are physical assets that connect an underground resource to the surface (Manifold 2010). They also connect the surface with a source of energy pressure within the groundwater or gas resource. It is vital to design and install a bore in such a way that it provides sufficient barriers to contain and control the flow of material under pressure from the resource (Manifold 2010).

Leakage can occur through multiple pathways in the 'disturbed zone' surrounding a bore casing (Gasda et al. 2010). The disturbed zone is defined as the annular region along the exterior of the casing that includes Portland cement, the damaged host rock and the casing-cement-rock interfaces (Gasda et al. 2010). Bore integrity is maintained through barriers or controls within the disturbed zone to control well fluids and pressures. These controls are established through (Manifold 2010):

- bore design and construction techniques
- selection of appropriate bore construction materials such as casings, screens and grout materials
- appropriate placement of seals within the bore annulus
- an appropriate bore decommissioning process.

3.2 Bore design and leakage pathways

Bores with poor integrity have the potential to provide a pathway for gases and liquids to migrate into or between aquifers (Nygaard 2010). Nygaard (2010), Gasda et al. (2004) and Watson and Bachu (2009) outline the leakage pathways from a carbon dioxide (CO_2) injection bore, which is indicative for all bores. Watson and Bachu (2009) state that three elements must exist for leakage in a bore to occur:

- leak source
- driving force such as buoyancy or pressure head differential
- leakage pathway.

In cased wells, cement should be placed in the annulus between the formation and the casing. Cementing is done from the bottom of the bore by injecting the cement into the casing and forcing the cement to flow up within the annulus. Once dried, the cement then seals the annulus and protects the outside surface of the casing (Nygaard 2010). Leakage pathways are generally associated with poor cementing in the annulus, casing failure (associated with corrosion) or physical damage and abandonment failure (Watson & Bachu 2009).

Figure 1 highlights the possible leakage pathways from a cased bore or well. These pathways include leakage along the interfaces between different material (such as the casing and cement interface, the cement plug and casing interface or the rock and cement interface), as well as through the cement or fractures in the cement (Gasda et al. 2004). Casing corrosion can also lead to casing failure and leakage (Nygaard 2010; GHD 2010).

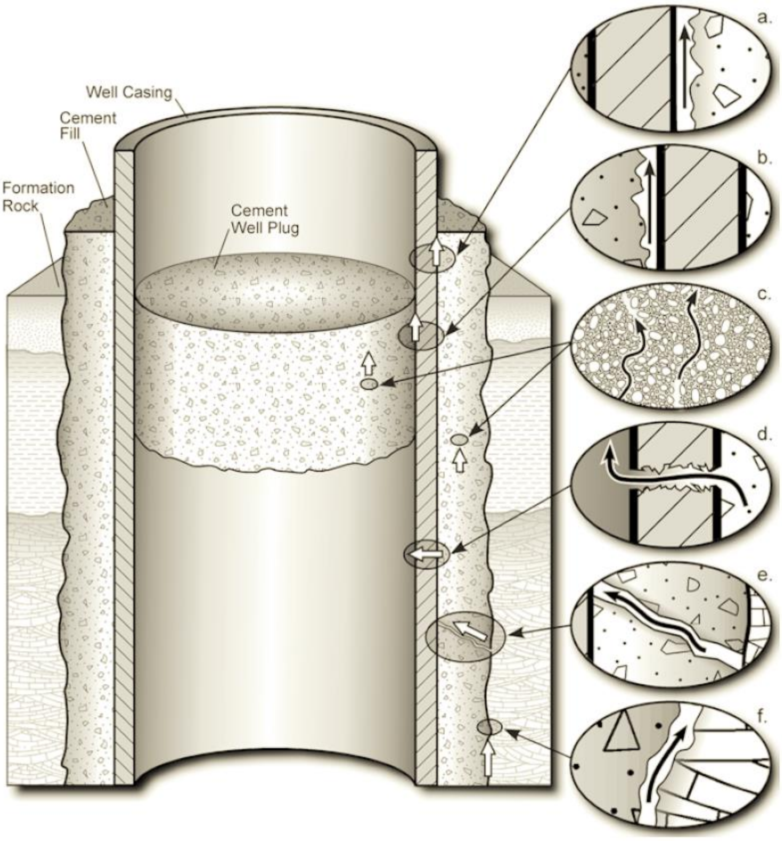


Figure 1 Diagrammatic representation of possible leakage pathways from a cased and abandoned bore or well. (a) Between casing and cement; (b) between cement plug and casing; (c) through the cement pore space as a result of degradation; (d) through casing as a result of corrosion; (e) through fractures in cement; and (f) between cement and rock (© Copyright, Gasda et al. 2004).

Different types of bores and the operational status of a bore also create different leakage scenarios (Nygaard 2010). For example, an exploration bore is drilled but is not cased. After drilling, the exploration bore is decommissioned using cement plugs placed across the porous formations (Nygaard 2010). The main leakage pathways from a decommissioned bore are caused by problems that occur when the cement plugs are set, or if the plugs are missing (Nygaard 2010). The cement plug in a decommissioned bore is much thicker compared to the cement in the annulus of a cased bore. Cased bores can also have casing exposed directly to the formation because the casing is not always cemented all the way up to the surface (Nygaard 2010).

A workshop on well integrity for the long term geological storage of CO_2 was held in Texas in 2005 (Pearce 2005). One of the key findings from the workshop was that it is not possible to promise a leak-free well. State of the art technologies in well construction will reduce risks associated with poor well integrity. Pearce also noted that industry and researchers should be careful not to present well designs and constructions as providing a leak proof solution, but rather that industry is constructing the best wells possible. Pearce suggested that it may not be necessary to demonstrate well integrity for 1000 years and instead provide shorter term integrity (e.g. 100 years). If proven it can then be extrapolated over longer time frame.

Much of the information available on well integrity for CO_2 storage can be extrapolated to other industries. However, there is a key difference between wells used for CO_2 storage and other wells. CO_2 causes degradation to Portland-based cements, which are commonly used in well construction (Pearce 2005). The key reactions involve carbonation of the major cement components resulting in loss of density and strength and an increase in porosity (Pearce 2005). New cements are being developed for wells for CO_2 storage.

3.3 Bore deterioration

There are different processes that cause or accelerate the deterioration of groundwater bores including fouling (such as microbial encrustation (biofouling), mineral scaling and particulate fouling) and corrosion of metal and plastics (GHD 2010).

3.3.1 Fouling

Bore fouling can be attributed to physical, chemical or biological sources. Plugging of the formation around the well screen by fine particles may cause the bore to become physically blocked resulting in reduced yield. The small particles can accumulate in the cracks, fissure, joints, fractures, or cavities that provide most of the water to the well (Driscoll 1986). The images below show examples of bore encrustation (Figure 2) and iron fouling (Figure 3) of submersible pumps.

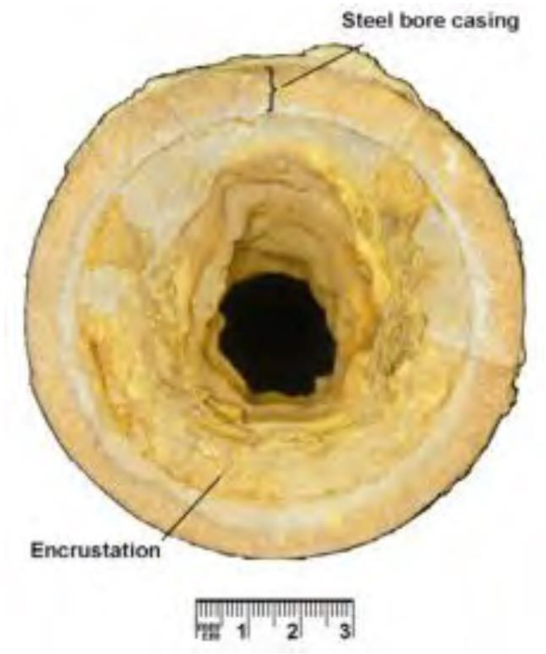


Figure 2 Example of encrustation within a bore (© Copyright, DSE 2004).

Figure 3 Example of iron fouling on a submersible pump (© Copyright, Forward 2008 in GHD 2010).

Biofouling or microbial encrustation is the most common type of bore fouling and is considered to be widespread in Australia and abroad (GHD 2010). This is evident in the data collated from government agencies worldwide on the occurrence of iron bacteria by Cullimore and McCann (1977) and more recently noted by the Department of Sustainability and Environment (DSE) which recorded an increase in reports of iron bacteria in bores throughout Victoria (DSE 2004). Particulate and mineral scale deposits can also lead to bore fouling but these processes are much less common.

Biofouling occurs where bacteria are present in the groundwater and play a key role in numerous chemical reactions that occur in groundwater systems (McLaughlan 2002; McLaughlan 1996). Biofouling deposits are the result of the bacterial production of extracellular polymers (ECP) and the subsequent accumulation of various inorganic compounds and particles (McLaughlan et al. 1993). They create a biological film (biofilm) that forms on solid surfaces such as a bore casing. The rate of biofouling is a function of three processes: bacterial activity within the groundwater system, particle availability and biofilm shear forces (GHD 2010). These processes depend on several factors including nutrient availability, ECP production rate, aquifer characteristics and flow rate, and have been found to vary geographically (GHD 2010; Houben 2008).

Bore design and environmental aspects can also influence the biofouling of groundwater bore casings. For example, biofouling may occur as a result of (GHD 2010; DSE 2004):

- alterations in groundwater biochemistry or hydrogeochemistry over time due to natural processes or anthropogenic activities (e.g. drilling can introduce or stimulate the growth of existing bacteria)
- inadequate or incomplete groundwater bore development resulting in drilling materials and fines remaining in the aquifer and filter pack, and therefore hindrance to good hydraulic connectivity between the bore and the aquifer
- spread of bacteria introduced by the drilling rig or pumping equipment if not properly cleaned
- natural bacteria
- airborne bacteria contaminating unsealed bores
- inappropriate selection of bore casing materials for a particular hydrogeological setting or groundwater biochemistry, which can lead to excessive turbulence and potentially increase biological activity.

Symptoms of biofouling range from decreased flow, and gradual-to-severe decrease in bore performance to a short pump life and high variability in water quality. There is often a decrease in water quality in terms of taste, colour, staining and odour (GHD 2010).

There are several treatments for biofouling but they provide only short-term rehabilitation solutions (GHD 2010; SAMDBNRM 2006). Some involve non-chemical products but the majority involve chemical treatment or acid dosing with chlorine (Cl), sulphamic acid (NH_3SO_3) or Clearbore (a biodegradable granular chemical). Preventative maintenance measures of biofouling in saline water bores includes electrolytic chlorination. This involves disinfection of the bore materials with chlorine that is produced by electrolysis of the saline water.

Fouling by mineral scale deposits occurs due to the mixing of incompatible waters and/or changes in groundwater temperature or pressure during pumping (GHD 2010; McLaughlan 1996). Mixing of groundwater from different aquifers with unique characteristics and/or water chemistry signatures can occur if the bore is screened over multiple aquifers or if the casing deteriorates/corrodes allowing water from different aquifers to mix within the bore. If the waters are incompatible then a rapid accumulation of mineral scale can occur, such as when carbonate rich water mixes with highly saline water that is high in calcium. Mineral scaling can also result from degassing of carbon dioxide (CO_2) in groundwater when it is pumped to the surface (GHD 2010). Precipitation can occur in response to changes in groundwater CO_2 or temperature due to the resultant chemical reactions (GHD 2010).

Particulate fouling occurs when there is a build-up of fines close to the bore, which enter the bore causing particulate deposits and/or pump corrosion. This type of fouling generally results from poor bore design, inadequate bore development or operational factors (McLaughlan 1996). It is typically more prevalent in injection bores than extraction bores and where the quality of injected water is also an important factor in particulate fouling occurrence (GHD 2010).

3.3.2 Corrosion

Casing or well screen corrosion is a major source of well failure and can occur on both plastic and metal bore components (GHD 2010; Driscoll 1986). The corrosiveness of various metals reflects their different tendencies to form ions and dissolve in water (McLaughlan 1996). Corrosion can also occur through erosion resulting from the physical removal of protective layers of iron oxides and carbonate films by particles. This type of corrosion often occurs above a critical flow rate, particularly where there is a restriction of flow or change in flow direction of extraction and injection (McLaughlan 1996). Figure 4 shows examples of corrosion on steel casing and Figure 5 shows corroded casings in regional Victoria.

Figure 4 Examples of corrosion of bore casing (© Copyright, McLauchlan 2002).

Figure 5 Examples of corroded casing (© Copyright, Mallee CMA 2005).

Biofouling can lead to corrosive effects where microorganisms within biofilm help to sustain a chemical environment, different to that of the surrounding groundwater, which favours electrochemical corrosive processes (GHD 2010). Several physical/physiochemical properties of groundwater also influence corrosive processes in groundwater bores. For example, CO_2 can form a weak, corrosive acid in water. These low pH conditions accelerate the corrosion of most metals and as salinity increases, the corrosion rate increases (GHD 2010). Previous research in the north of the Great Artesian Basin measured in situ borehole corrosion rates over three years and found pH to be the principal rate-controlling factor on the corrosion of mild steel casing, with CO_2 concentrations a contributing factor (GABCC 1998).

PVC casing can also be susceptible to structural degradation where organic compounds are present in the groundwater. The degradation processes can be oxidative, mechanical, microbial and chemical (McLaughlan 1996). McLaughlan (1996) describes that plastics are degraded where chemicals penetrate the plastics causing swelling and softening, which leads to structural failure. Bore screens are typically more susceptible as they are often in contact with the highest contaminant concentrations in the aquifer (GHD 2010).

3.3.3 Extent of bore casing deterioration

GHD (2010) assessed the extent of bore casing deterioration in water bores in a project commissioned by the National Water Commission. They highlighted that there was very limited information in the public domain on existing bore condition assessment and limited access to groundwater databases, so they relied heavily on sourcing information from stakeholders. However there was a similar scarcity of information or reports on bore condition assessment from stakeholders (GHD 2010). From the information available to GHD (2010) the following conclusions were drawn:

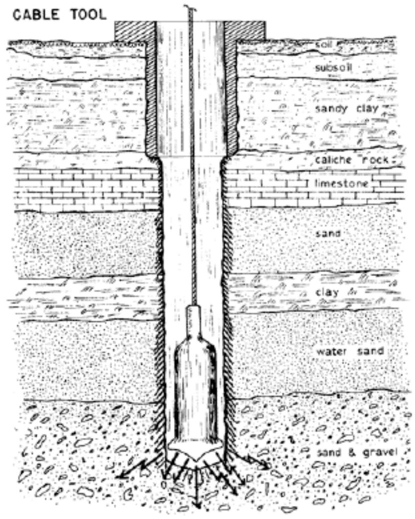
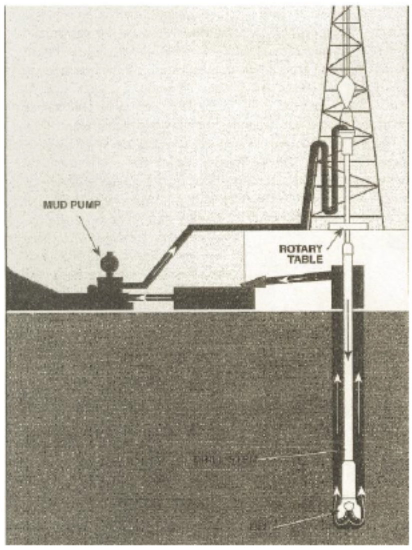
- iron biofouling of groundwater bores was the most dominant bore failure process. In most cases the reason for bore casing deterioration was not documented and presumably unknown
- a range of different rehabilitative and preventative measures have been used to manage bore casing deterioration due to iron biofouling. The most successful rehabilitation and prevention method identified in managing iron biofouling is chemical treatment such as acid dosing
- the corrosion of steel cased bores was very common, particularly in ageing groundwater bores. The frequency of such failures is expected to decrease as groundwater bore assets are replaced with inert casing materials
- rehabilitation measures have generally been introduced once bore deterioration processes have been identified. In most of the case studies assessed for this project, preventative measures were not introduced prior to identification of bore deterioration
- casing studies of fouling and corrosion have been documented in the Carnarvon Basin (Western Australia), South Australia, Mallee (Victoria) and the Great Artesian Basin (Queensland) (GABCC 2011; SKM 2009; Mallee CMA et al. 2005; Astill 2002).

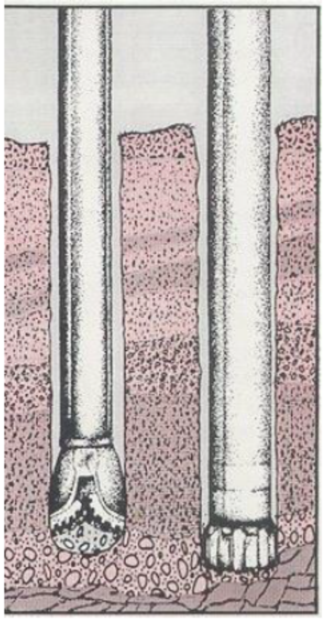
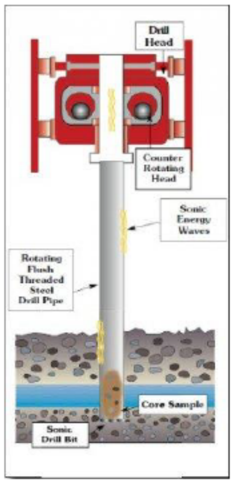
3.4 Drilling methods

3.4.1 Water bores

Drilling methods will vary depending on the anticipated geology, groundwater pressures, bore diameters and depths encountered during the drilling operations. The MCRWBA guidelines (NUDLC 2012), the Australian Drilling Manual (ADITC 1992) and the International School of Well Drilling (ISWD 2012) provide a detailed description of the methods used to drill water bores. A brief summary of typical drilling methods is provided in Table 2.

Table 2 Summary of drilling methods (© Copyright, ISWD 2012; NUDLC 2012; ADITC 1992).

Drilling method	Description	Image
Cable tool	This method of drilling is the oldest drilling method in Australia and was used for all bores drilled in the early 1900s. Drilling involves lifting and dropping a string of solid steel drilling tools suspended from a wire rope to hit the bottom of the hole, a process that drives the cutting bit to fracture or pulverise the formation. Cable tool method is well suited to remote settings due to its low fuel and water consumption. It is also very cost-effective in terms of capital cost, operation and maintenance and only requires one driller to operate. Key disadvantages of the method are the slow drilling rates, in particular through hard rock.	
Rotary drilling techniques	Rotary drilling uses a sharp rotating drill bit to drill into the formation, much like a common hand held drill.	
Mud rotary	Rotary mud drilling is a method commonly used for water bores. Drilling mud is pumped down the drill string to provide wall support for the bore prior to the bore casing being inserted and drill cuttings removed from the borehole. The fluid serves to cool and lubricate the bit. The mud slurry then flows upwards in the annular space around the drill pipe to the surface, carrying the cuttings with it in suspension.	
Rotary air	The rotary air method is used to drill holes in consolidated or semi-hard formations such as sandstone or shales that are self-supporting. This process produces cuttings that are cleared by circulating air, which is derived from a compressor and fed down the drill pipe to emerge through a bit. The up-hole annular air velocity must be maintained to remove cuttings effectively.	

Drilling method	Description	Image
Down-hole hammer	The down-hole hammer method involves a pneumatically operated drill bit that effectively combines a percussion action with a turning action. The image to the right shows a rotary drill bit on the left and a down hole hammer drill bit on the right. A pneumatic drill bit can be used on a standard rotary rig with a high pressure air compressor of sufficient capacity. Down-hole hammers are used for hard rock drilling and enable water bores to be established from fractured hard rock aquifers. Down-hole hammer is generally the fastest method of penetrating hard rock. Foaming additives are occasionally used to increase the volume of cuttings that can be removed by the air returning to the surface. The method is not used for loose unconsolidated materials.	
Reverse circulation drilling - air and mud	Reverse circulation drilling was developed to allow for larger borehole drilling without being limited by drilling fluid pump capacities. Drill rigs are much larger and the drilling method requires a lot of water and sediment handling. The bore is kept filled to the surface during drilling to provide water pressure support to the sides of the hole until the permanent production casing is installed. It is not a common method for water bores; however, it is sometimes used for water sampling programs.	
Sonic drilling	Sonic drilling, also known as a rotary vibratory drill, is a relatively new technique that uses a high-frequency vibration in combination with rotation to drill. It is capable of high speeds and continuous coring and can collect undisturbed samples without the use of drilling fluids.	

3.4.2 Coal exploration bores

Exploratory drilling can be undertaken to recover core samples of coal and non-coal strata for detailed geological description, analytical studies and geotechnical testing, or to recover broken fragments or 'cuttings' of the material penetrated (Kang 2009). The aim is to provide information on the depth, thickness and quality of the coal and it is only the core or cuttings that are of interest. Consequently, bore construction with casings and screens is not used for coal exploration bores. As with water bores, drilling methods will vary depending on the anticipated geology, groundwater pressures, bore diameters and depths encountered during drilling.

Rotary drilling is the most widely used method of non-core drilling in coal exploration and is described above in Table 2 (Kang 2009; Ward 2009). Reverse circulation is also used for mineral sampling to obtain an uncontaminated geological sample because sampling is less precise with rotary drilling techniques.

The most effective method of core drilling is diamond drilling. A hollow cylindrical drill bit impregnated with industrial diamonds is attached to a series of metal drill rods and rotated under controlled downward pressure. A circle of rock is ground away and the cutting removed by water flushing. A cylindrical core remains in the centre of the drill string. A triple tube core barrel is preferential for coal seams and other soft or friable strata, recovering core in a split metal tube that allows it to be exposed for inspection with minimal disturbance (Ward 2009).

Cores of between 45 mm and 85 mm diameter are typically taken for coal exploration programs. Large diameter cores (e.g. 150 mm to 200 mm) may be taken for bulk sampling and pilot-scale coal preparation tests. Keyhole samplers, where a large diameter hole is scooped out by an expanding head at the bottom of a relatively narrow hole, may also be used to gather bulk samples (Ward 2009).

3.4.3 Coal seam gas wells

Coal seam gas wells are generally drilled using rotary or percussion techniques, which require the use of drilling fluids or mud during the drilling process to lubricate the drill bit and remove the cuttings. The drilling fluids in Australia are typically water based, comprising fresh water and organic polymers or clay additives such as bentonite, which are added to increase viscosity, inhibit clay and shale swelling and sticking, and flocculate drilled solids (Zvomuya et al. 2008).

3.5 Construction materials

The materials used in the drilling and construction of bores vary with the drilling method and construction design and can have a large impact on the overall integrity of the bore. Bore design and the materials used are commensurate with the value and purpose of the bore. Every constructed bore should include the following components:

- casing to ensure the bore stays open and sealed
- screened interval over the target aquifer/zone to allow water/gas to flow into the bore
- a seal to isolate and protect the target aquifer/coal measure.

The most common types of materials used for bore casing construction are mild steel, stainless steel, galvanised iron and plastics (SKM 2012b). Steel is the main material used as well casing in the petroleum and gas industry (API 2009).

Statistical studies to determine the effective life of bores based on construction material and installation environments have not yet been undertaken. Information on the reason for a bore coming to the end of its useful life does not appear to have been collected in Australia. Modern non-metallic well materials have not been in the ground long enough to determine deterioration rates or to reach their expected maximum life to confirm predictions of integrity behaviour (SKM 2012b).

3.5.1 Water bores

The third, and current, edition of the *Minimum construction requirements for water bores in Australia* (MCRWBA) (NUDLC 2012) provides a sound framework for the design and construction of water bores (NUDLC 2012). Most jurisdictions require the construction of water bores to comply with MCRWBA. However, issues with bore integrity can arise as a result of different interpretations of construction requirements and the subsequent design and construction variation that follows (Manifold 2010).

The following figures show typical designs of a monitoring bore (Figure 6) and a production bore (Figure 7). A monitoring bore is typically constructed with PVC casing, a bentonite plug to isolate the target aquifer and a cement grout seal at the surface. A production bore is often larger in diameter, constructed using steel or PVC, with a stainless steel screened interval over the target aquifer, a gravel pack and a longer cement grout seal.

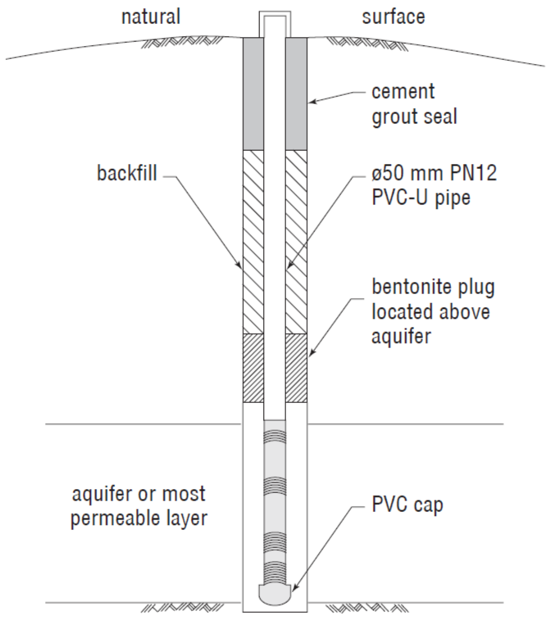


Figure 6 Typical design of a monitoring bore with a bentonite seal (© Copyright, NUDLC 2012).

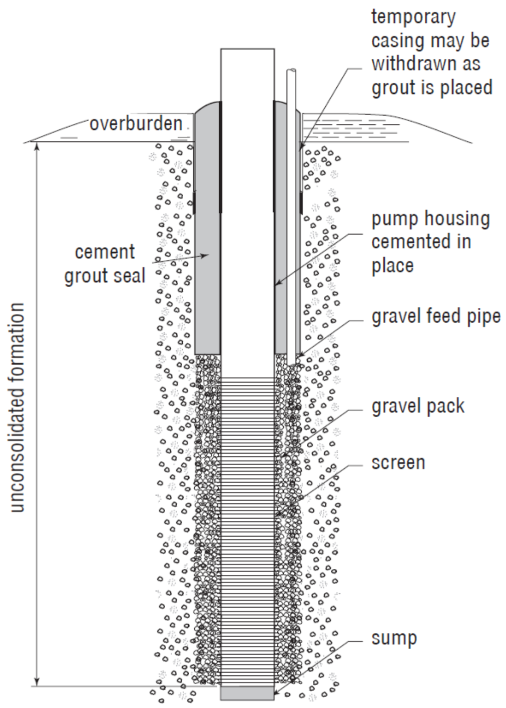


Figure 7 Typical design of a production bore with gravel pack and casing cemented in place (© Copyright, NUDLC 2012).

The key to maintaining bore integrity is the reliability of the cement around the casing to prevent migration paths and effectively isolate the targeted zone from other hydrogeological layers (SKM 2012b). Bore integrity issues mostly develop from poor design and construction techniques. For example, ensuring the cement has had sufficient time to cure is imperative to maintaining good bore integrity (DEEDI 2011a; Dunnivant et al. 1997). Drillers may be under time constraints and may not allow sufficient time for the cement to cure. Therefore, the professional integrity of the engineers and technicians engaged by the operator to design and construct the bores is also a key consideration in ensuring bore integrity (Manifold 2010).

Prior to 1940, bores were typically constructed with mild steel casing because of its strength and ability to withstand high groundwater temperatures (GHD 2010). However, steel casing is particularly vulnerable to corrosion from corrosive soils and water resulting in a service life of only five to 10 years in some locations (GHD 2010).

Polyvinyl Chloride (PVC) casing replaced mild steel as the preferred construction material between the 1970s and 1980s as it is a low cost, light weight and corrosion resistant alternative to steel (Driscoll 1986). However, PVC is less resistant than steel to pressure and temperature, so is rarely used in bores deeper than 200 meters. PVC is available in different nominal pressure (PN) ratings, with the correct rating to be used depending on the depth of the bore. The MCRWBA (NUDLC 2012) states that PN9 can be used with care for shallow bores, but PN12 piping is the recommended casing for most bores to avoid problems associated with inappropriate rating selection. For example, temperatures greater than 20 °C can reduce the pressure rating of the casing, whether it is from groundwater or by cement grouting of the annulus. In these instances, strength de-rating needs to be considered. PVC is not recommended to service temperatures greater than 60 °C (NUDLC 2012).

Fibreglass-reinforced polyester (FRP) casing is typically used for deep and large diameter production bores due to its strength, corrosion resistance and ability to withstand temperatures between 60 °C and + 80 °C. It was popular in the early 1980s as it was used by the South Australian Department of Mines and Energy for the construction of deep bores into the Great Artesian Basin for high temperature and corrosive environments (GHD 2010). The availability of FRP casing significantly extended the service life of groundwater bores and it continues to be used in bores ranging from 50 m to more than 500 m deep. FRP has good ultraviolet resistance and is inert in most environments but must be made-to-order because it cannot be cut in the field.

The screen material is generally perforated steel or PVC (Figure 8), although some bores may be constructed with stainless steel wire-wound screens (Figure 9) or even left with an open hole if the formation is stable enough. Stainless steel wedge wire design screens were first used in 1964, where they gained popularity due to the improved corrosion resistance over mild steel and the efficient inflow of water due to a larger percentage of open area (GHD 2010). From 1980 onwards, the use of stainless steel wire wound screens became prevalent throughout the drilling industry due to increased availability, reductions in cost and an increase in the open area and corrosion resistance (GHD 2010).

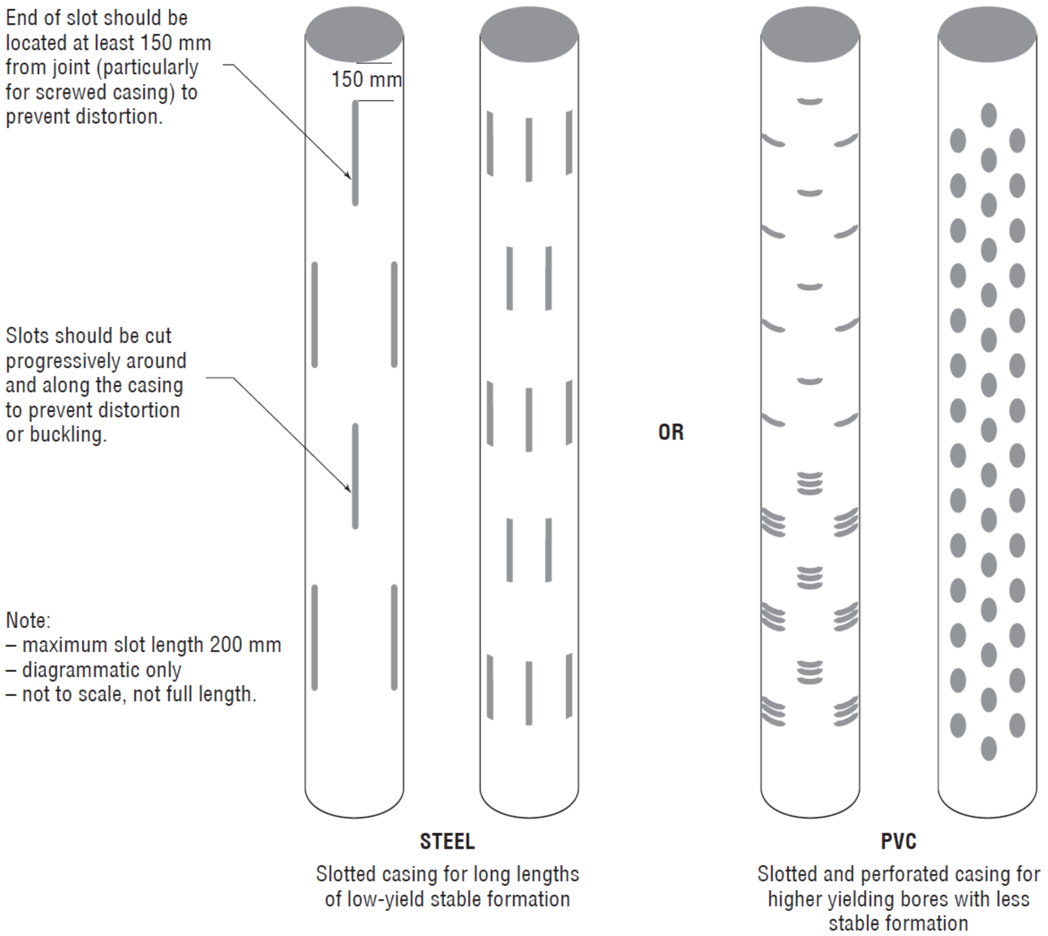


Figure 8 Examples of perforated and slotted casing (© Copyright, NUDLC 2012).

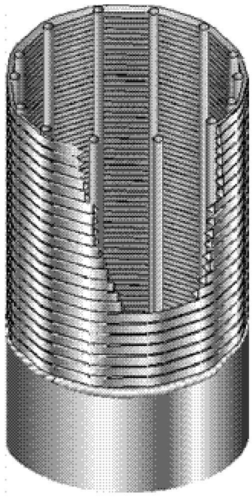


Figure 9 Example of stainless steel wire wound screen (© Copyright, NUDLC 2012).

Slots and screens alone may not be sufficient in allowing water to flow into the bore without bringing surrounding material with it, particularly in relatively fine, loose formations. In these instances, placing a suitably graded, well-rounded (not crushed) gravel pack in the annulus surrounding the casing and hole will effectively filter water coming into the bore from the surrounding strata (NUDLC 2012). Filter material should only be placed adjacent to the target aquifer and not across overlying/underlying units, which could promote inter-aquifer leakage.

3.5.2 Injection bores

Injection bores can be divided into two general categories:

- those used for injection only
- those used for injection, storage and subsequent recovery out of the same bore in a process known as Aquifer Storage and Recovery (ASR).

The drilling method, design and construction of an injection bore is fundamentally the same as a water production bore, but additional testing for geological parameters and mechanical integrity is usually conducted. Pyne (2005) and Maliva and Missimer (2010) provide a guide for the design, construction and operation of an ASR scheme and highlight that the following key issues should be considered:

- maximising bore efficiency
- bore development
- bidirectional flow through gravel pack
- preventing cascading water flow and associated entrainment, or development of bubbles, during injection
- removal of all drilling fluids
- corrosion of casing, pumps and other downhole equipment
- access to bore for rehabilitation activities
- regulatory requirements for construction and operation.

3.5.3 Coal exploration bores

Coal exploration bores are generally not cased, and are decommissioned after the drilling is complete. If an exploration bore was cased, it would be constructed in accordance with the Minimum Construction Requirements for Water Bores in Australia (NUDLC 2012) either by a licensed water driller or supervised by a licensed water driller.

3.5.4 Coal seam gas wells

Coal seam gas is typically extracted from coal seams between 300 m and 1000 m depth in Australia, although some deeper prospects are being explored. Unlike conventional natural gas reserves, coal seam gas is held in the coal seams by water pressure. The water and gas is accessed by drilling a well into the coal seam. The water is then pumped from the coal seams to lower the pressure and release the gas.

New South Wales and Queensland are the only jurisdictions with specific codes of practice on coal seam gas well construction (NSW T&I 2012a; DEEDI 2011a). While SKM (2012) identified these regulations as leading practice, this review has not identified any scientific evidence confirming that if bores are constructed to these standards failure will not occur. Well integrity is therefore monitored throughout the life of a well as a preventative measure to ensure that integrity is maintained. This is discussed further in Section 4.

Wells are designed to ensure the environmentally sound and safe production of gas and other fluids. This includes sealing the well appropriately to contain gases and fluids, protecting the groundwater resources, isolating the targeted formations from surrounding water bearing formations, and by proper execution of treatment, stimulation and completion operations (DEEDI 2011a). Well design must also consider whether hydraulic fracturing will be required and any implications this may have on the design.

A coal seam gas well is designed to provide multiple barriers that prevent fluids moving between aquifers or migrating to the surface. The primary barriers are the casing and cement, where the cement isolates formation fluids from moving behind the casing or from coming to the surface. The well head also provides another barrier at the surface and often contains a blowout preventer, which consists of a series of large valves which can be closed to control the well in the event formation fluids enter the well.

Coal seam gas wells are constructed using steel casing manufactured to American Petroleum Institute (API) standards and designed to withstand the various compressive, tensile and bending forces that are exerted during drilling and construction. A well is constructed using a number of steel casing sections in the upper parts and each casing section is cemented in place, ensuring aquifers above the coal seam are protected. The number of casings reduces with depth, along with the diameter, so there is a single production casing in the production area. The production casing is run to the bottom of the drill hole and perforated, or a slotted liner is installed to allow gas to enter the well. A schematic diagram of a typical Australian coal seam gas well is shown in Figure 10.

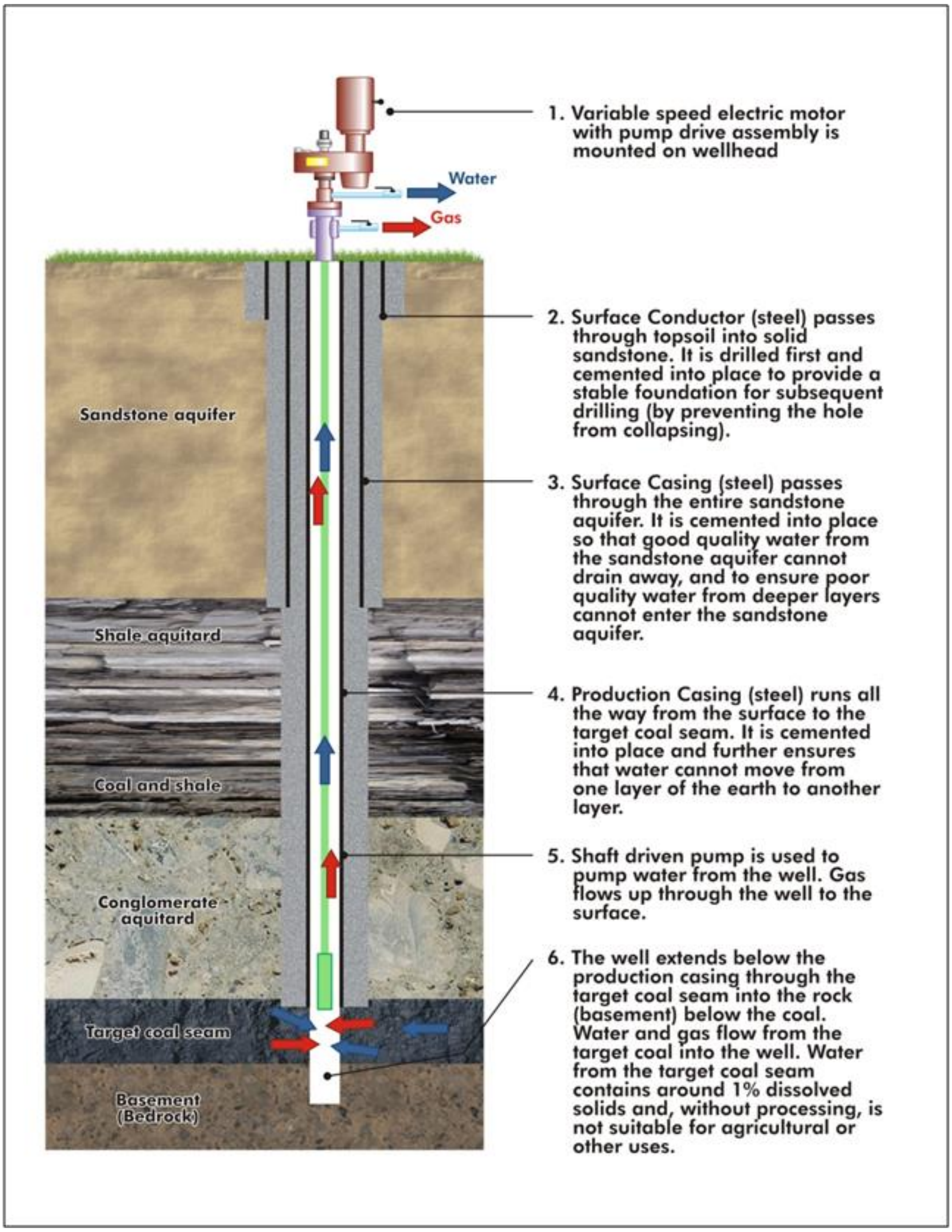


Figure 10 Schematic of a coal seam gas well (© Copyright, SKM 2012a).

3.6 Seals and cement

3.6.1 Water bores

The annular space between the casing and the formation must be properly sealed to minimise the potential for vertical migration of water (Pearce 2005; Dunnivant et al. 1997). The seal protects against infiltration from the surface and provides a discrete sampling zone and minimises the potential for vertical leakage (Dunnivant et al. 1997). The cement around the well casing will isolate the targeted zone from other aquifers to prevent migration pathways, protect surrounding aquifers from contamination and depressurization and protect the casing from corrosion. Materials recommended for backfilling and sealing the annulus include bentonite, cement grouts and mixtures of bentonite and cement (NUDLC 2011; Aller et al. 1989).

Ross (2010) highlights that grouting in water bores has advanced significantly since the late 1980s as a result of education and changes in regulations in the US, and this has generated change in the industry worldwide. Bentonite has been used for sealing and decommissioning since the 1980s because it provides a low permeability seal, is easy to use and does not affect the quality of the groundwater (Dunnivant et al. 1997). Cement grout is also commonly used worldwide. Although cement grouts can shrink during the curing process and separate from the well casing or the formation interfaces, this can be mitigated with the addition of bentonite (Ross 2010; Dunnivant et al. 1997). The most common hydraulic cements in use today are either Portland cements or similar-use cements called 'blended' or 'composite' cements that are made of a Portland cement base plus additives (van Oss & Padovani 2003). NUDLC (2011) provides guidance on cement-water and cement-bentonite-water ratios for mixtures for both Portland general purpose cement and blended builders' cement.

3.6.2 Coal exploration bores

Coal exploration bores are generally not cased, nor decommissioned after drilling is complete. Decommissioning of bores is discussed in Section 5. If an exploration bore is cased, it would be sealed and grouted consistent with the Minimum construction requirements for water bores in Australia (NUDLC 2012).

3.6.3 Coal seam gas wells

Cementing the casing in coal seam gas wells is a key component in ensuring well integrity. The American Petroleum Institute (API 2009) states that although the selection of materials for cementing and casing is important, it is secondary to cement placement. The key to good cementing is good operational practices (Nygaard 2010; Corneliussen et al. 2007; Bourgoyne et al. 1999). Primarily cement failures are due to poor cementation practices including the failure of the cement soon after it has cured (Nygaard 2010). Cement for petroleum and gas wells are engineered products that are governed by the American Petroleum Institute technical standards. The recommended practices for cementing operations are well documented and available to all drilling companies (API 2009). DEEDI (2011) also references the American Petroleum Institute technical standards in recommending benchmarks for cementing wells. The petroleum industry uses Portland cement with several additives such as density reduction materials, viscosifiers, accelerators and retarders to refine the cement slurry (Nygaard 2010).

Cement is forced under pressure down the centre of the casing and allowed to flow within the annulus back to the surface or to an appropriate safety overlap distance of at least 50 m back inside the previous casing shoe. Once the cement has cured, pressure tests are performed and recorded to verify aquifer or zonal isolation (DEEDI 2011a). More information on the testing performed is outlined in Section 4.

Australia has comprehensive standards, codes and legislation to international standards which regulate the design, material, construction, maintenance, decommissioning and rehabilitation of wells (SCER 2013). Successful application of standards, codes and legislation governing well integrity depends on consistent compliance and continual improvement by industry and thorough and effective enforcement by qualified regulators

(SCER 2013). As stated by Nygaard (2010), good cementing relies on good operation practices. Drillers must ensure that bores and wells are cemented appropriately and that there is the appropriate level of compliance to ensure that this is done. Unlike the water industry, the petroleum and gas industries require monitoring of the integrity of coal seam gas wells upon completion, over its workable life, or upon decommissioning. There are a variety of techniques used to monitor the integrity of a well and these are discussed in Section 5.

3.7 Headworks

The headwork on a water bore, or wellhead on a coal seam gas well, is required to ensure bore integrity at the surface by effectively sealing and capping the bore to protect the aquifer and control the flow of water or gas from the bore (DEEDI 2011; NUDLC 2010).

3.7.1 Water bores

A framework for headwork requirements for a water bore to ensure controlled flow is provided by NUDLC (2012). Ensuring that all bores are appropriately sealed at the surface has been an issue in the past. Declining groundwater levels in both the Carnarvon Artesian Basin of Western Australia and the Great Artesian Basin (GAB) have occurred as a result of bores that do not have appropriate headworks to control the flow of water (GABCC 2011; Astill et al. 2002). Bores were permitted to flow uncontrolled for many decades and this has impacted the pressures and flows in the Great Artesian Basin aquifers. The figures below show examples of appropriate headworks for a flowing bore (Figure 11) and a flowing bore that has not been capped appropriately (Figure 12).

Figure 11 Example of a headwork for a flowing bore, where water supply is under control (© Copyright, NDULC 2012).

Figure 12 Example of a headwork for a flowing bore, where water supply is out of control (© Copyright, NDULC 2012).

3.7.2 Coal seam gas wells

A coal seam gas well is completed with a wellhead designed to contain various protection equipment, such as blow out preventers, valves and flanges for control and connection of gas and water to pipelines, and pressure monitoring ports and pumping. Coal seam gas wellheads in New South Wales and Queensland are required to facilitate the installation of a blow-out preventer (NSW T&I 2012; DEEDI 2011). An example of a typical Australian coal seam gas wellhead is shown in Figure 13.

Figure 13 Typical coal seam gas wellhead in Queensland (© Copyright, DSEWPaC 2013; courtesy B. Gray and Origin Energy).

4 Monitoring and reporting

4.1 Introduction

Monitoring the integrity of a bore through its life cycle is crucial to ensuring the bore is maintained. Bores can deteriorate with age, operation and site-specific conditions reducing their capacity for the intended use (DEEDI 2011a). Bore monitoring and maintenance is required to ensure the bore is preserved and its components are in good condition for the life of the bore (NUDLC 2012).

There are a variety of tools and techniques available to assess bore integrity. Duguid et al. (2007) outlined technologies available for measuring well integrity in a carbon capture and sequestration field. These techniques apply equally to other well types, including coal seam gas wells and water bores. However, the cost of integrity assessment techniques may be a barrier to their use, especially for bores that are shallow and/or of simple construction, and may be replaced at a relatively low cost.

There are two primary strategies for monitoring bore integrity described by GHD (2010):

- Failure-based strategies: usually takes place after bore integrity has already been compromised and, subsequently, represents a high risk approach.
- Performance-based strategies: represent a lower risk approach to maintaining bore integrity as they can identify the potential effects of potential bore integrity issues at an early stage and can be managed appropriately.

A failure-based approach may be appropriate where there is little risk to the resource or the environment. A performance-based approach is more likely to be undertaken when resources are available for this more expensive approach, or where it is required through legislation.

Oil and gas wells, including coal seam gas wells, are typically a series of nested casings and well cement and a variety of measurements are necessary to assess their integrity (Duguid & Tombari 2007). There is no one tool or method that can assess all of the leakage criteria at once. A suite of measurements must be run to fully analyse well integrity.

4.2 Simple performance-based tests

Simple performance-based indicators are most appropriate for a water bore, but can also be used for other well types. They are a cheaper alternative to other more expensive ways to measure bore integrity, such as geophysical logging, and include:

- visual inspections of the structural integrity of the bore casing, pumps and wellhead
- changes in power consumption
- analysis of bore performance through review of:
  - water quantity: declining water levels, flow rates or daily pumped volumes can indicate a decrease in bore efficiency
  - water quality data: the most common water quality indicators are sand content, salinity, iron and manganese concentrations.

In addition to direct investigation methods, long-term water level and water quality testing can be used to infer compromised bore integrity and leakage. Trend analysis of long-term monitoring data allows changes to be identified that can trigger further investigation. Data of this type should be collected as part of a bore monitoring and management strategy. However, it requires that the data is sufficiently interrogated on a regular basis.

GHD (2010) found that groundwater bore casing deterioration is generally managed when a problem has been identified. In some cases, this is too late to successfully manage the deterioration and failure occurs. GHD (2010) and Forward (2008) suggested some preventative measures, including:

- development of a performance-based monitoring and maintenance strategy that commences when the bore is commissioned
- analysis of bore performance through reviews of hydrographs showing water levels over time, pump operation, flows rates and water quality
- use of preventative chemical treatments to control bore and pipeline fouling.

These preventative measures and maintenance will assist in reducing the frequency and magnitude of bore casing deterioration and failure, increase the operational life of the bore and reduce the need for costly rehabilitation or replacement. GHD (2010) also recommended that groundwater bore licensing organisations develop methods and procedures for bore owners to monitor bore integrity and report on compliance with construction standards.

4.3 Logging tools

Logging tools are used to examine the condition of the casing and cement and the interfaces between casing, cement and formation in bore water and coal seam gas wells (Duguid & Tombari 2007). Logging tools do not physically change the well in any manner. They include downhole camera, packer tests, multi-finger calliper tools, sonic bond tools and ultrasonic bond tools (Duguid & Tombari 2007).

4.3.1 CCTV down hole camera

A simple and cost-effective method for investigating the internal condition of a bore is to undertake a visual inspection using a CCTV camera logging tool. This will identify problems such as corrosion pits and cracks and poor casing joins.

4.3.2 Packer tests

Packer tests involve isolating a section within a bore with inflatable packers or bladders to test the aquifer or collect water quality data (Driscoll 1986). A series of tests can provide a definition of the vertical distribution of water quality and hydraulic conductivity, which can indicate pathways for water and contaminant movement. Monitoring water levels in nearby bores can also identify permeable intervals in the aquifer beyond the bore. At the time of writing, there was no information found in the public domain of this method being used as a key assessment tool of bore integrity.

4.3.3 Multi-finger caliper tools

Multi-finger caliper tools have fingers protruding radially from the body of the tool (Figure 14), which measure the internal radius of the bore in 360 degrees. Any changes in the internal radius of the bore casing can indicate a bore integrity issues, such as corrosion or other damage (Figure 15). These tools can only give information on the condition of the inside of the casing, and do not provide information on the outside condition or the casing thickness.

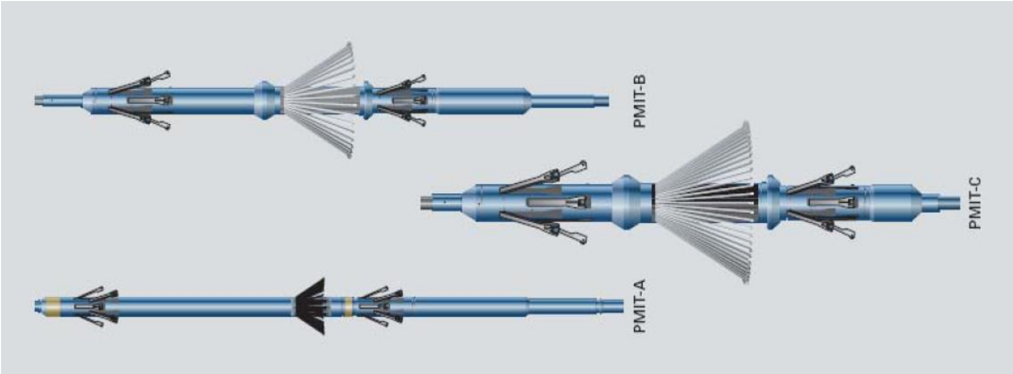


Figure 14 Multi-finger caliper tools (© Copyright, Schlumberger 2008).

Figure 15 A 3D presentation of calliper data showing a damaged casing (dark blue) (© Copyright, Duguid & Tombari 2007 (modified); image courtesy of Schlumberger Limited).

4.3.4 Sonic bond tools

Sonic bond tools or cement bond tools (CBT) transmit a signal through the bore to the casing, cement and formation array. The magnitude and transit time of the refracted signal is then measured to provide information about the bond between the casing and the cement, the density of the cement and the bond between the cement and the formation (Duguid & Tombari 2007). Duguid and Tombari (2007) state that in a bore with a good bond between the cement and casing, the transmitted sound waves will be attenuated when the signal returns from the well to the receiver. In a bore with a poor cement-casing bond, the returning signal will show little attenuation.

CBT are generally effective in most fluids encountered in a bore and not affected by the roughness of the casing (Duguid & Tombari 2007). However, while CBT measurements provide information on the average bond integrity between the cement and the casing, they do not identify specific pathways or locations where the bond may be poor (Duguid & Tombari 2007). This means that where there is little attenuation (indicating a poor cement bond) a CBT will not provide information on the cause (Duguid & Tombari 2007). Furthermore, CBT are less accurate in the unsaturated zone and can falsely indicate good cement bonds.

4.3.5 Ultrasonic bond tools

Like the CBT tools, ultrasonic tools also use acoustic waves to investigate the integrity of a bore (Duguid & Tombari 2007). Sound waves are used to measure multiple criteria, including the internal condition of the casing, the internal radius of the casing, the thickness of the casing and the acoustic impedance of the material outside the casing. Ultrasonic measurements also provide information on the interface between the cement and casing. More modern ultrasonic tools can provide information on the next interface moving outwards from the bore. In many cases this is the cement-formation interface but could also be another cement-casing interface depending on the bore construction. A schematic of ultrasonic wave reflections in a bore is shown in Figure 16.

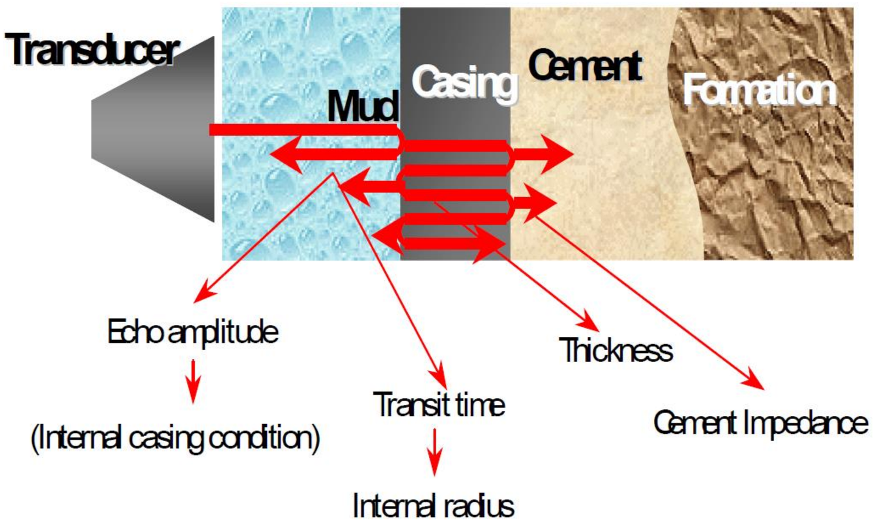


Figure 16 Schematic diagram of the reflections of ultrasonic waves (© Copyright, Duguid & Tombari 2007; image courtesy of Schlumberger Limited).

The acoustic impedance of a material is a product of the acoustic velocity and density of the material. From the acoustic impedance signature, the material outside the casing can be classified. Unlike the sonic tools, ultrasonic tools can image the bore in 360 degrees and specific pathways or de-bonded areas can be identified (Duguid & Tombari 2007).

Although this is a more costly technique than sonic tools, the advantage of using ultrasonic tools is that they can provide information on the condition of the casing and the surrounding cement on the same logging pass (Duguid & Tombari 2007). They provide a detailed image of the bore and can differentiate different types of materials behind the casing.

Duguid and Tombaris (2007) showed that each of the logging tools provide different information about the integrity of a bore and that the best overall view of integrity is achieved using a combination of tools. If an initial caliper tool investigation shows a heavily damaged casing pipe, the integrity assessment program can be halted and the bore can be repaired or decommissioned. If caliper measurements indicate good casing integrity then subsequent sonic and ultrasonic logs can confirm this. For deep injection or production wells Duguid and Tombaris (2007) recommended a minimum combination of multi-finger caliper, sonic and ultrasonic logging tools. In addition to the non-destructive logs, physical testing and sampling techniques provide a good opportunity to correlate the physical and laboratory measurements with the logging results.

4.4 Sampling and testing

Sampling and testing tools can include in situ tests and sample recovery for laboratory testing, including pressure testing, fluid analysis and side wall coring.

4.4.1 Pressure testing

Measurements of the cement and formation permeability can be performed in situ using tools that drill through the casing, draw down the pressure on the exposed material and measure the response. The drawdown test is sometimes also referred to as a ‘pre-test’ or vertical interference test (VIT). From the pre-test, the mobility and permeability of the tested material can be calculated. There are a variety of analytical solutions available to assess the test data depending on the type of pressure test used and the bore construction.

Gasda et al. (2010) proposed a simple pressure test to determine the effective permeability of existing wells. The test involves perforating the casing and inducing a pressure below an aquitard formation and measuring the response above it. The test can also be conducted within an aquitard formation (Gasda et al. 2010).

Arnold (1991) successfully modelled variations in annular pressure due to fluid injection as part of a study of liquid waste injection wells. The pressures inside the well casing and the hydraulic pressure applied to the liquid-filled annular volume were monitored. If the temperature of the system is stabilised and the system is not subjected to changes in injection pressure, a constant annular pressure demonstrates mechanical integrity (Arnold 1991). Arnold (1991) was able to account for pressure and temperature changes caused by injection via numerical modelling techniques and broaden the integrity monitoring to non-steady state conditions.

Chesnaux et al. (2006) developed a method to detect and quantify leakage through faulty seals using non-reactive chemical tracers. For an aquifer-aquitard-aquifer system, a constant rate pumping test can be initiated in the lower aquifer and a tracer injected via a piezometer in the upper aquifer. If a defect is present in the intervening seal, the tracer will be detected in the pumped water. Knowledge of tracer concentration, tracer injection rate and pumping rate allows numerical analysis and quantification of leakage rate and, hence, effective permeability.

4.4.2 Fluid analysis

Fluid analysis tools take fluid samples through a hole in the casing, using a fluid sampling module, to analyse the formation fluid in situ and to collect and retrieve a fluid sample for further laboratory analysis (Duguid & Tombari 2007). Results can indicate bore leakage and mixing of waters.

4.4.3 Sidewall coring

Sidewall coring tools have a coring bit capable of cutting through the casing, the cement and the formation and retrieving a composite sample - a core containing each material (Duguid & Tombari 2007). The retrieval of sidewall cores allows the detailed inspection of wellbore materials for damage at a small scale. However, it is important to run a temperature and pressure module, in conjunction with the integrity logging and sampling tools, to record these conditions so they can be factored into interpretation and modelling work (Duguid & Tombari 2007).

4.5 Integrity assessment

In order to gain a better understanding of well integrity status on the Norwegian Continental Shelf, the Petroleum Safety Authority (PSA) in Norway initiated a well integrity survey to investigate instances of integrity failure (Birgit & Aadnoy 2008). The survey found that most of the integrity problems were within barrier elements such as tubing, annulus safety valve (ASV), casing, cement and wellhead (Figure 17).

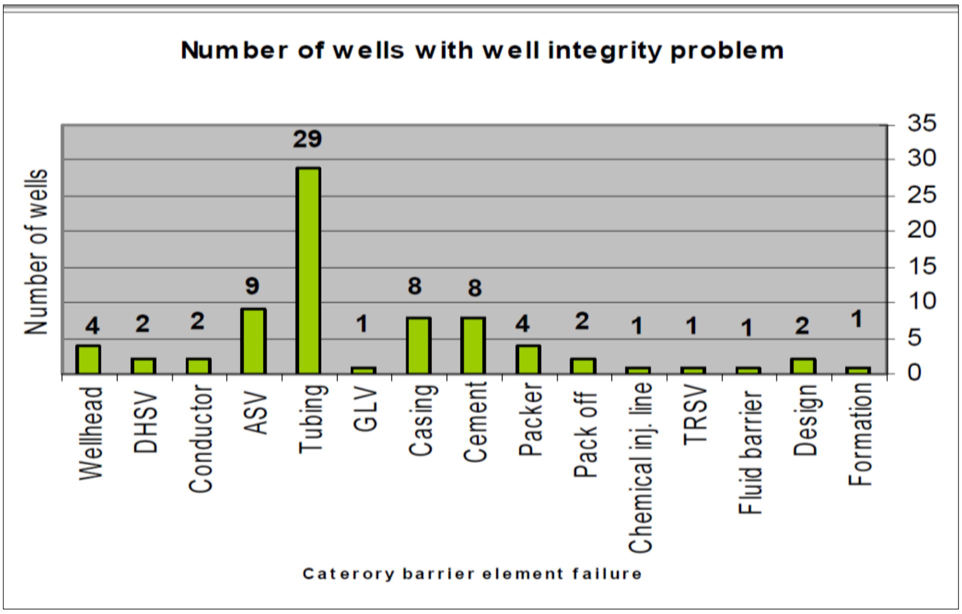


Figure 17 Categories of barrier element failure (© Copyright, Birgit & Aadnoy 2008).

While a direct comparison cannot be made between coal seam gas wells and the offshore wells in this survey, the results from the survey are useful in gaining an understanding of the possible failure mechanisms of coal seam gas wells. Offshore wells are drilled in a very different, difficult environment and therefore the failure rates would be expected to be much higher than that for onshore wells.

The Birgit and Aadnoy (2008) survey concluded that the majority of well integrity problems occurred within the tubing in wells constructed during the early 1990s and that the tubing leaks were likely to be through the telescopic expansion joints, possibly from damage occurred when the production tubing was lowered into the well. The survey also found that:

- eighteen per cent of wells had either integrity failure, issues or uncertainties and seven per cent of them were decommissioned as a result of well integrity issues
- the key factors in well failure related to:
  - operational decisions made during abnormal situations
  - design issues where the long-term effects were not considered
  - an inability to account for rare events that may lead to major incidents.

Gasda et al. (2010) assessed the applicability of the vertical interference test (VIT) by analysing test results with different numerical techniques to estimate the effective permeability of a given well. It was found that field VIT testing was an effective well integrity testing technique and that automated parameter estimation can be useful in reducing uncertainty in identifying key parameters associated with well integrity.

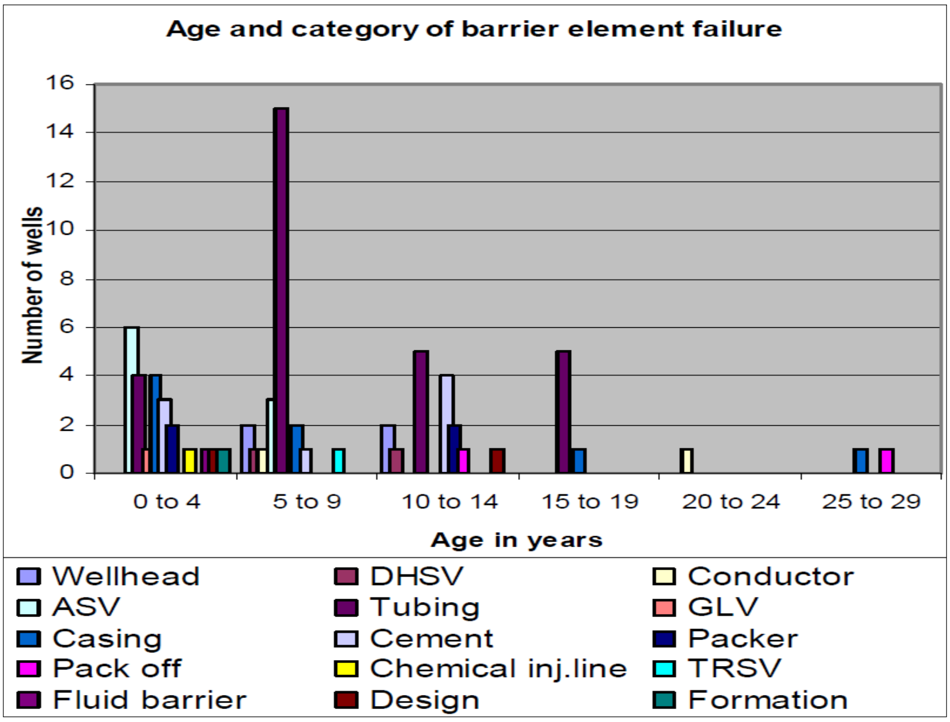


Figure 18 Age and category barrier element failure (© Copyright, Birgit & Aadnoy 2008).

Watson and Bachu (2009) studied records from industry of well leakage at the surface as surface-casing-vent flow (SCVF) through well annuli and gas migration outside the casing, for Alberta, Canada. They found that leakage occurs in 4.5 per cent of wells within the region.

Crow et al. (2009) undertook a well integrity study of a 30 year old production well installed in a high CO_2-bearing formation. A range of monitoring tests were used including sidewall cores that were taken to recover casing, cement and formation samples for laboratory analysis, down-hole ultrasonic imaging, multi-finger caliper logs and a vertical interference test (VIT) that was conducted to measure the response of an applied pressure across a cemented shale section. A simulated numerical analysis was undertaken using the VIT data. It was found that there was discrepancy between simulated and measured results, with increased permeability using the VIT data. This was considered to be due to a scaling issue whereby core sample testing did not include communication along material interfaces and that the most likely leakage path would be along interfaces. Crow et al. (2009) concluded that current technologies are suitable to determine well barrier condition. The logging results were found to correlate well with the VIT results and the side wall core sampling results.

A review of hydraulic fracturing activity in the UK was commissioned by the UK Government to evaluate risks associated with shale gas extraction and develop best practice (Royal Society 2012). The bore integrity aspects addressed in the review are applicable to other wells, in addition to those used for hydraulic fracturing, and focuses on design and construction as the most important issues to ensure integrity. The report reviewed current assessment techniques and recommended that during drilling and installation operations bore casing integrity be assessed by pressure testing of mechanical strength. Formation pressure tests (as discussed in Section 4.4.1) were also recommended to be carried out to understand local stress regimes in the surrounding rocks, which will inform changes to the well design, as required.

Confidence in cement emplacement and integrity (as well as casing integrity) can also be gained by pressure tests and acoustic techniques. Royal Society noted that:

> *'…despite the quality of the initial cementation, some wells can still leak over time'.*
>
> © Copyright, Royal Society (2012)

An explanation for this was given as cement shrinkage. Shrinkage can lead to circumferential cracks that can grow due to changes in pressure gradients and cause leakage, although modern cement formulations are resistant to shrinkage. To mitigate leakage the report suggested that best practice is to cement casings all the way back to surface (Royal Society 2012).

In the UK the *Offshore Installations and Wells Regulations 1996* requires an independent and competent person to examine well design and construction information. The Royal Society (2012) review recommended that the existing well examiner scheme should be widened to include environmental perspectives in addition to health and safety. In terms of post-construction monitoring of coal seam gas wells, there is no legislative requirement in the UK for pressure tests or geophysical analysis. However, emphasis is placed on operators continuing to monitor and verify well integrity during operations. This monitoring should include:

> *'…regular sampling of near surface aquifers'* and *'…continuous monitoring of ground gas emissions.'*
>
> © Copyright, Royal Society (2012)

The Nebraska Grout Study (Ross 2010) demonstrated that bentonite grout issues can occur in water bores. The Nebraska Grout Task Force was established in 2001 and used clear PVC casing to monitor bore integrity and increase the awareness of regulatory personnel on well design and construction. The bores were inspected 16 months after construction and video footage showed that there were large voids and cracks in the grout column. The study highlighted that all of the grouts tested performed as expected in the saturated zone below the water table. However, in the unsaturated zone above the water table, all grouts developed cracks and voids within the first month after construction. Bentonite chip grout was found to perform the best out of all the grout recipes even in the unsaturated zone. While the study provided useful information on how bentonite grout may fail, care must be taken in extrapolating these findings to the failure of the cement grouting used in Australian bores.

Bourgoyne et al. (1999) reported that a large number of producing wells on the outer continental shelf of the US developed undesirable and sometimes potentially dangerous sustained casing pressure in one or more of the casings. The study highlighted that many well integrity problems were the result of poor primary cement jobs and that the most significant cause was a poor cement bond. Gas flow or water flow through unset cement was identified as a major cause of sustained casing pressure in the outer casing. About one-third of the casings exhibited sustained casing pressure in wells that were active.

The Bourgoyne et al. (1999) study recommended that implementing best cementing practices when designing and completing a well may prevent sustained casing pressure in many instances. Best cementing practices would include consideration of cement quality and weight, waiting time, hole size, mud properties, pipe centralisation and pre-cementing circulation procedures.

The results of desk-based studies of potential leakage (across a given area) as a result of poor bore integrity can be useful to inform risk assessments and the prioritisation of remedial works. However, good data sets are required and models also require calibration using field-based investigations. One of the key input parameters is a reliable estimate of well effective permeability/leakage. This can be obtained by direct measurement of a subset of wells followed by application of statistical analysis to include other wells. Field methods, such as those discussed in previous sections, are used to determine the well integrity and effective permeability of a small number of wells. This information is then extrapolated using an analytical or numerical model to determine if there are any spatial correlations. Another approach is to indirectly estimate effective permeability using data such as well age and depth etc. Some recent studies to develop basin-scale predictive models for carbon capture and storage (CCS) wells are summarised below.

Gasda et al. (2004) used a combined spatial and statistical analysis to characterise the CO_2 leakage potential of abandoned oil and gas wells in the mature Alberta Basin. Two sets of parameters were identified as key inputs: the spatial location of wells and the effective permeability of each well. This required a high-quality database of well information and quantification of hydraulic properties using techniques discussed previously. The study presented possible leakage pathways of CO_2 through an abandoned well (refer to Figure 1). These leakage pathways apply to fresh water, brine and natural gas movement, given allowances for the specific physical properties of the particular fluid of interest.

An analytical solution was developed by Cihan et al. (2012) to assess pressure build up and leakage rates in a multi-layered aquifer system. Pressure build up was studied in the context of gas (CO_2) injection and storage in saturated aquifers, although the solution used single-phase fluid flow parameters instead of more complex two-phase gas and water attributes. Leakage via wells and faults was described as ‘focused’ leakage in contrast to the ‘diffuse’ leakage across aquitard layers. They note that induced pressure changes can extend across thousands of square kilometres in the horizontal direction and many local wells and bores may need to be considered.

Localised gas leakage, or fugitive gas emissions, associated with the coal seam gas industry can be a significant issue. In Ohio, US the Clinton sandstone is an oil and gas bearing reservoir with over 79 000 wells (ODNR 2008). An explosion occurred in December 2007, which damaged a house in the Bainbridge township as a result of a leaking gas producing well (ODNR 2008). The high pressures in the annulus of the production well caused gas to migrate into the natural fractures in the formation and into the overlying aquifers, where it discharged through local water wells (ODNR 2008). The primary factors thought to have caused the leakage included poor cementing during construction and the hydraulic fracturing program. The hydraulic fracturing program allowed a long time lag (31 days) between the completion of the hydraulic fracturing and recovery of the fracturing fluids and subsequent pressure released from the formation (ODNR 2008). Experience in hydraulic fracturing in Australia and the US has demonstrated that minimising the time between completing the hydraulic fracturing process and the recovery of fracturing fluids will minimise the likelihood of the fracturing fluids migrating out of the gas-bearing layer (Green et al. 2012).

4.6 Reporting requirements in Australia

4.6.1 Water bores

Australian state and territory governments regulate drilling contractors and consultants to ensure compliance with construction licences, and meet minimum standards for bore construction (i.e. MCRWBA) (NUDLC 2012). Most jurisdictions require a bore to be registered and this involves submitting a bore completion report detailing the location, geology, construction, water quality, bore yield and other details as required.

In many states and territories, there are also dedicated drilling inspectors that will inspect a drilling site to ensure compliance. However there is no regulatory requirement to monitor the integrity of the bore. Some jurisdictions may also undertake bore condition assessment reports on a periodic basis.

4.6.2 Coal exploration bores

In Australia, reporting requirements for coal and mineral exploration bores vary between jurisdictions. A mining exploration licence generally entitles drill exploration holes, among other activities. The exploration holes may have special requirements for drilling or construction techniques to ensure that groundwater resources are protected. In most jurisdictions mining exploration activity reports must be submitted to the regulator on a regular basis showing the type of work that has been undertaken in the mine lease exploration area, including exploration holes that have been drilled, constructed and decommissioned.

It is the responsibility of the mining company to ensure that exploration holes meet the appropriate legislative requirements, are decommissioned appropriately and that relevant reports are submitted to the regulators. Some regulators will undertake audits to ensure that mining companies are compliant with regulations and the conditions of the mining lease. However, only a small proportion of exploration sites are audited and the extent of compliance of most exploration activities is unknown.

4.6.3 Coal seam gas wells

Similar to mineral and coal exploration bores, reporting requirements will vary from jurisdiction to jurisdiction in Australia. Coal seam gas exploration and production activities are governed under the relevant petroleum and gas act, which clearly specify the design and construction requirements for a coal seam gas well. A post-completion report is required to be submitted to the regulator, which details the actual construction of the well and any deviations from the design. If hydraulic fracturing has been undertaken on a well, a report detailing the hydraulic fracturing process, including volumes and chemicals used, is also required to be submitted to the regulator.

The integrity of a coal seam gas well is monitored using the methods discussed in Section 4.3 and 4.4 on a regular basis (i.e. bi-annually or annually) to ensure well integrity is maintained and these reports are submitted to the regulator on an annual basis.

5 Bore decommissioning

5.1 Introduction

Bores have a finite life. Bores are typically designed for a particular productive purpose and when this is no longer being fulfilled they should be decommissioned (or abandoned). The terms ‘decommission’ and ‘abandon’ are used interchangeably in this report. However, the terms mean different things in different industries and in different jurisdictions. For example, the term ‘decommission’ generally refers to work undertaken to properly shut down a bore or well, except in Queensland where the term ‘abandon’ is used for shutting down coal seam gas wells. This can be confusing as in New South Wales the term ‘abandon’ infers that the owner of a bore has ceased using the bore indefinitely but has not properly shut down the bore.

All failed or unwanted drill holes, bores or wells should be decommissioned to restore, as far as possible, the previous aquifer isolation (NUDLC 2012). Decommissioning aims to protect the aquifers intersected by the bore from contamination, either by migration of surface water into the bore or mixing of water from different aquifers. Decommissioning may also be necessary to prevent uncontrolled discharge of fluids or gas. The complexity of the decommissioning procedure depends primarily on the hydrogeology, well construction and groundwater quality.

In Australia, jurisdictional regulations provide a framework to ensure that water bores and exploration bores are decommissioned appropriately and this work reported to the appropriate regulator. However, the level of compliance and enforcement could be expected to vary between jurisdictions and at the time of writing, information on decommissioning was not readily accessible by the public.

5.2 Water bores

A list of mandatory requirements to be met when decommissioning water bores is set out in the MCRWBA. Decommissioning requirements include (NULDC 2012):

- elimination of any physical hazards such as filling in holes
- prevention of groundwater contamination
- prevention of water intermixing
- conservation of yield and maintenance of hydrostatic head of the aquifers.

Bores may be decommissioned for a number of reasons and the preferred method of decommissioning is full grouting from the base to the surface of the hole (NUDLC 2012). Where it can be justified economically and environmentally, an alternative is to install a grout seal in the screened zone, followed by earth fill and then another grout seal at the surface. Similar methods may be used for multiple aquifer bores and flowing bores although each aquifer must be isolated. Regardless of the decommissioning methods used, a concrete or grout surface seal to a minimum depth of 5 m must be installed. It is also recommended to perforate the casing to allow grout to fill any voids between the casing and the formation, to prevent water migrating outside of the casing.

The industry mandatory requirements for decommissioning water bores are also applicable to all test bores that have not been cased. The MCRWBA sets out mandatory requirements for reporting the decommissioning of water bores (NULDC 2012). Various state legislation also have requirements to report decommissioning of water bores including the *Water Act 2000* in Queensland. It needs not only to be mandatory and enforceable to ensure that water bores are decommissioned appropriately but regulators also need to have the capacity to ensure compliance.

5.3 Coal mining exploration bores

Mining exploration bores must be decommissioned or abandoned under the relevant Australian mining legislation. Some jurisdictions have produced specific guidelines outlining decommissioning requirements for exploration (DoR 2011; DMP 2002; DPI 2002). For example, in Queensland, the *Code of environmental compliance for exploration and mineral development projects* (DEHP 2013) sets out the following requirements for exploration drill holes:

> *'The holder of the environmental authority must decommission all non-artesian drill holes, apart from those still required for monitoring purposes as soon as practical, but no later than 6 months after the hole was drilled by undertaking the following actions:*
>
> - *where practical dispose of all unused drill chips to the hole or to a sump pit*
> - *cap the hole at a depth that is appropriate for the previous land use of the area (unless the land owner stipulates a future use which requires the cap to be placed deeper)*
> - *backfill the hole above the cap with soil or material similar to the surrounding soil or material'.*
>
> © Copyright, DEHP (2013)

In addition to the above, non-artesian aquifers must be isolated from each other:

> *'…where a drill hole intersects more than one water bearing strata by casing or plugging the hole as soon as practical after the hole is no longer required, but no later than 2 months after the hole was drilled, apart from those holes that are still required for monitoring purposes if:*
>
> - *the flow difference between aquifers exceeds 500 L/hour*
> - *the difference in electrical conductivity of water is greater than 10% of the lower value'.*
>
> © Copyright, DEHP (2013)

Bridges are sometimes used where it is not possible to grout a bore fully. A bridge is a solid fixture that is positioned in a drilled hole to form a base for grout or backfill material, when the drilled hole is to be only partially in-filled (DPI 2002). Bridges can be made from wooden plugs or metal plates, cementing baskets, formation packers and, in some cases, hessian bags (DPI 2002).

Although there are regulations that specify the decommissioning process, it is difficult to determine the level of compliance in remote areas. For example, mining companies may require that the hole remain open so that they can return to collect further data. Where and if decommissioning actually occurs is not well documented. The level of compliance is not measured by regulators and at the time of writing information on completed bore decommissioning was not in the public domain.

5.4 Coal seam gas wells

Coal seam gas well abandonment is undertaken in a way to ensure the environmentally sound and safe isolation of the well to protect ground water sources, to isolate the productive formations from the surrounding formations and to prevent migration of gas and fluids from the productive formation to the surface. This involves sealing the hole completely from the base to the surface using a series of cement plugs to provide a seal preventing any cross flow of water and gas (APPEA 2012). The wellhead is then removed and the steel casing filled with cement is cut off at least 1.5 m below ground level, sealed with a metal identification plate and buried (APPEA 2012). The cement used in well construction and abandonment is designed to have a life span in excess of 100 years.

DEEDI (2011a) describes in detail the mandatory requirements and good industry practice relating to well abandonment in Queensland and provides a framework for ensuring all Queensland coal seam gas wells are abandoned appropriately.

The level of compliance with abandoning wells in the coal seam gas industry is expected, by the author, to be higher than other industries, although there is no information on the compliance rates available in the public domain. The health and safety risks associated with not abandoning a coal seam gas well appropriately are greater than that of a water bore, or mineral exploration bore. Consequently, appropriately decommissioning a petroleum or gas well has both mandatory and best practice requirements (see, for example, DNRM 2013).

5.5 Legacy bores

Bores that are not decommissioned appropriately are often referred to as ‘legacy bores’ and their number in Australia is not known but likely to be substantial. Legacy bores can be any type of bore, although the most common types are:

- oil and gas wells
- water supply bores
- coal exploration wells
- state government owned bores
- government exploration bores.

There are several significant implications of legacy bores, including:

- localised connectivity of aquifers, which can have further detrimental implications on local groundwater quality
- potential direct access between the ground surface and the aquifer, which is therefore a potential source of aquifer contamination
- potential to release fugitive gas emissions as potential coal seam gas bearing layers are depressurised and release gas, which can ignite.

At the time of writing there was little or no information available in the public domain on legacy bores. However, discussions with representatives at the Queensland government Department of Natural Resources and Mines (DNRM) highlighted that this information may be available in company reports and paper-based bore log records (Free 2013, pers. comm., 28 February).

In Queensland, legacy bores are likely to exist from all types of bores; however, coal exploration wells are the most significant legacy type for Queensland, largely due to their abundance and possible lack of appropriate decommissioning, both of which is at this stage unquantified. It has been estimated some 30 000 coal exploration wells have been drilled in the Surat Basin, with a further 100 000 in the Bowen Basin (Free 2013, pers. comm., 28 February). It is unknown however how many of the bores were decommissioned or, if they were decommissioned, the standard of the decommissioning work.

Many states in the US require that all unused wells be decommissioned, as per state regulation, by a licensed well contractor, and a report be filed with the state agency overseeing the industry. In Minnesota, when a property is sold there is a requirement for disclosure on the transaction document of any 'legacy' bores on the property (Minnesota Statues 2013). Minnesota has sealed over 250 000 legacy wells and it is considered that approximately three-quarters of these well were identified via property transfer disclosures.

The Queensland government *Code of environmental compliance for exploration and mineral development projects* (DEHP 2013) is described in Section 5.3 and allows for capping of non-artesian exploration holes at an appropriate depth for future land use, and backfilling above the cap. Coal exploration bores decommissioned under these specifications may therefore lack an adequate cement plug (appropriate seal) and could be considered as legacy bores.

An example of a coal mining exploration bore that was not decommissioned appropriately was reported in the media in August 2012 (Kennedy 2012). The media report stated that the exploration bore was found after it caught on fire and started a local bushfire (Figure 15). The exploration bore, located 25 km west of Dalby in Queensland within Arrow Energy's Daandine gas field but not installed or used by Arrow Energy, was at least 1 km from any coal seam gas activity and leaking gas, which caught fire (Kennedy 2012). The fire was reported to have been 1 to 2 m high in a depressed section of earth about 50 cm deep and wide (Kennedy 2012). The well was presumed to have been drilled at least 20 years ago. The fire was extinguished by filling the hole with water and the site was then monitored for 24 hours while it was allowed to cool. Following cooling, the bore and surrounding area was filled with concrete (Rowling 2012).

Figure 19 Photo of coal mining bore burning 25 km west of Dalby, Queensland (© Copyright, Kennedy 2012).

Jordan and Hare (2002) outline several methods that can be used to locate abandoned wells such as:

- remote sensing or geophysical methods - the thermal band in remote sensing data, such as Landsat images, can be used to detect temperature changes between the cool land surface and a warmer leaking abandoned well
- a range of geophysical methods such as magnetic, ground penetrating radar and some electromagnetic techniques have been used successfully to detect buried or abandoned wells
- methods such as resistivity, self-potential and transient electromagnetic sounding techniques can detect subsurface plumes of brine or other borehole leakages, which may be the only remaining evidence of a leaking bore.

The type or range of methods employed will depend on the available data, size of the area to be searched and the construction material of the abandoned bore.

6 Summary and knowledge gaps

6.1 What does the science tell us?

Bores with poor integrity have the potential to provide pathways for gases and liquids to migrate into and between aquifers, causing contamination of the groundwater. The Petroleum Safety Authority (PSA) in Norway completed a bore integrity survey to investigate instances of integrity failure and found that 18 per cent of the wells had either failure of, issues with or uncertainties in integrity, and seven per cent of these were decommissioned as a result of integrity issues (Birgit & Aadnoy 2008). Similarly, Watson and Bachu (2009) noted that 4.5 per cent of Alberta's bores leak.

There are many factors that can impact on the integrity of a bore, some of which involve the breakdown of the physical barriers, while others involve the professional integrity of the engineers and technicians engaged to design, drill and construct the bore, or the regulatory regime, which depends on the intended purpose of the bore (Manifold 2010). Birgit and Aadnoy (2008) suggested that the key factors in instances of bore failure in Norway related to operational decisions made during abnormal situations, design issues where the long-term effects were not considered, and the inability to account for rare events that may lead to major incidents.

The bulk of recent international research on bore integrity relates to wells for long-term storage of CO_2; however, much of this information can be extrapolated to other industries in different countries. A key difference between wells used for CO_2 storage and other wells is that CO_2 causes degradation to Portland-based cements, which are commonly used in well construction (Pearce 2005).

One of the key findings from a well integrity workshop for long term storage of CO_2 suggested that it is not possible to promise a leak-free well. However, state-of-the-art technologies in well construction will reduce risks associated with poor well integrity (Pearce 2005). Minimising leakage pathways in the annulus of the bore requires good cementing practices (Nygaard 2010; GHD 2010). These include appropriate cement quality and weight, waiting time, hole size, mud properties, pipe centralisation and pre-cementing circulation procedures (Bourgoyne et al. 1999). However, the Royal Society (2012) noted that despite the quality of the initial cementation, some wells can still leak over time, due to factors like cement shrinkage. In recent years there has been increased awareness of the importance of good cementing practices and more research is required to improve this understanding (Pearce 2005).

6.2 What is current practice?

The water bore industry operates within a complex regulatory framework that includes various acts, standards and guidelines, many of which are based on international standards. The design, drilling, construction, maintenance and decommissioning of water bores in Australia is guided by the *Minimum Construction Requirements for Water Bores in Australia* (MCRWBA) (NUDLC 2012). The MCRWBA was first published in 1997 and prior to this there were no national guidelines. The current edition of the MCRWBA provides a framework to address bore integrity issues during drilling and construction. However, there is no regulatory requirement to monitor the integrity of a water bore, neither upon completion, over the workable life, or upon decommissioning, as this is considered to be the responsibility of the bore owner.

Mining bores, including those for coal exploration, are regulated under the relevant jurisdictional mining acts. The level of compliance is uncertain as there was little information available on this in the public domain at the time of writing. Drillers of coal exploration bores are not required to be licensed and there is no regulatory requirement to monitor the integrity of decommissioned exploration bores.

The broader regulatory regime covering the petroleum and gas industry in Australia is considered to be leading practice (SKM 2012a). It is based on international standards such as the American Petroleum Institute (API) and Standards Norway (NORSOK). The API publishes a range of practice notes that are used by Australian regulators as guidance for well construction and operations, including Australian cods of practice for coal seam gas (NSW T&I 2012a; DEEDI 2011; API 2009).

In Queensland and New South Wales there is significant coal seam gas exploration and production and there are specific codes of practice for coal seam gas well integrity and hydraulic fracturing (NSW T&I 2012a; NSW T&I 2012b; DEEDI 2011a). These codes of practice outline monitoring requirements to ensure well integrity and the reporting requirements specified by each regulator.

From this review, it appears that compliance with regulatory requirements within the coal seam gas industry is generally better than that of the water and mining industries, and is helped by the monitoring of well integrity and reporting requirements for coal seam gas operators. However, whilst drillers operating in the mining and petroleum and gas industries are required to be qualified in accordance with the Australian Qualification Framework (AQF), they are not required to hold a water well drillers’ licence (ADITC 2011). This reflects the responsibilities in different industries and jurisdictions. In Queensland, it is the tenure holder, rather than the driller, who has primary responsible for ensuring bore construction meets the regulatory requirements.

Bore integrity issues mostly develop as a result of poor construction techniques. Key elements to ensure bore integrity include good bore design, selection of appropriate construction materials to withstand pressures and deterioration processes and a good cement job (DEEDI 2011a; Dunnivant et al. 1997). Existing guidelines and regulations provide frameworks to establish bore integrity, and it remains up to the driller and tenure holder to use best practices and regulators to ensure compliance.

6.3 Knowledge gaps

Information on well integrity is documented for the petroleum and gas industry. However, at the time of writing there was very limited information in the public domain on bore integrity for the water and mining industries. GHD (2010) highlighted the lack of information in the public domain on existing bore condition assessment and, with limited access to existing groundwater databases, relied heavily on sourcing information from stakeholders. However, GHD reported a similar scarcity of information or reports on bore condition assessment from stakeholders. Some jurisdictions do have reporting requirements when decommissioning bores; for example, in South Australia a well construction permit is required for the decommissioning of a well and a well construction report is to be submitted on completion of the works. However, this is not the case in all jurisdictions and information on bore integrity is not readily available.

In the oil and gas industry, broad areas for future research opportunities have been identified (Pearce 2005):

- frequency of failure: there is insufficient information available from regulators or oil and gas operators, water bore owners, or the coal industry to enable the frequency of failures to be estimated, either within bores or between bores of a similar or different type. A key contributing factor to this is the commercial sensitivity and inconsistent definitions of failure classes
- mechanisms for failure: there are many mechanisms that can result in bore failure. However, little is known about how these failure mechanisms should be classified, or the detailed processes that ultimately lead to failure
- criteria for failure: there is a need to clearly define criteria against which failure can be judged
- consequences of failure: the consequences of bore integrity failure for water resources, both in terms of quantity and quality, are dependent on a variety of factors including the location of the bores, their depth, the surrounding groundwater resources, the purpose of the bore, its age and construction materials, and the rigour of its monitoring and maintenance program. However, detailed consequence assessments for water resources could not be readily identified in the literature.

In addition, in the context of coal seam gas extraction and coal mining, investigations of cumulative issues associated with multiple incidents of bore failure could not be readily identified in the literature.

6.4 Options to address knowledge gaps

Monitoring and reporting of bore integrity needs to improve for wells and bores across all industries to ensure that there is sufficient information available to assess bore integrity and inform research needs. Research is also required to assess the most appropriate and cost-effective techniques to locate legacy bores throughout Australia, to determine the scale of the issue.

Many states in the US require that all unused wells be decommissioned, as per state regulation, by a licensed contractor, and a report be filed with the state agency overseeing the industry. In Minnesota, when a property is sold there is a requirement for disclosure on the transaction document of any ‘legacy’ bores on the property (Minnesota Statues 2013). Such a policy may have value in Australia to address the issue of legacy bores that are left without being appropriately decommissioned.

The level of compliance by bore owners in maintaining the integrity of their bores through rehabilitation and appropriate decommissioning varies nationally. In several cases, such as in the Great Artesian Basin, the Commonwealth and state governments have provided funding to ensure that bores are rehabilitated and decommissioned to ensure the groundwater resources are protected. However, existing legislation outlines that it is the bore owner’s responsibility to maintain their bores and increased awareness is required to ensure compliance.

Water bore condition monitoring and reporting requirements could be integrated with groundwater bore licencing conditions to improve accountability (GHD 2010). GHD (2010) also recommended developing guidelines for bore casing condition assessments that include:

- a diagnosis program based on bore performance indicators
- specified minimum monitoring and data review requirements
- a matrix array of physical and geophysical testing methods for casing condition integrity assessment.

The Australian Drilling Industry Association (ADIA) believe it should be mandated that all drillers be certified/licensed, not just water drillers, and that this would go some way to ensuring aquifers are protected across the different industries. However, requiring all drillers to be licenced may not be effective if the driller is not the one responsible for ensuring proper bore construction, such as in the Queensland coal seam gas industry. Underpinning many of these options is the need for regulators to have the capacity and processes to deal with increased regulatory requirements.

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Review article

Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation

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ABSTRACT

Data from around the world (Australia, Austria, Bahrain, Brazil, Canada, the Netherlands, Poland, the UK and the USA) show that more than four million onshore hydrocarbon wells have been drilled globally. Here we assess all the reliable datasets (25) on well barrier and integrity failure in the published liter ature and online. These datasets include production, injection, idle and abandoned wells, both onshore and offshore, exploiting both conventional and unconventional reservoirs. The datasets vary considerably in terms of the number of wells examined, their age and their designs. Therefore the percentage of wells that have had some form of well barrier or integrity failure is highly variable (1.9% 75%). Of the 8030 wells targeting the Marcellus shale inspected in Pennsylvania between 2005 and 2013, 6.3% of these have been reported to the authorities for infringements related to well barrier or integrity failure. In a separate study of 3533 Pennsylvanian wells monitored between 2008 and 2011, there were 85 examples of cement or casing failures, 4 blowouts and 2 examples of gas venting. In the UK, 2152 hydrocarbon wells were drilled onshore between 1902 and 2013 mainly targeting conventional reservoirs. UK regulations, like those of other jurisdictions, include reclamation of the well site after well abandonment. As such, there is no visible evidence of 65.2% of these well sites on the land surface today and monitoring is not carried out. The ownership of up to 53% of wells in the UK is unclear; we estimate that between 50 and 100 are orphaned. Of 143 active UK wells that were producing at the end of 2000, one has evidence of a well integrity failure.

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1. Introduction

The rapid expansion of shale gas and shale oil exploration and exploitation using hydraulic fracturing techniques has created an energy boom in the USA but raised questions regarding the possible environmental risks, such as the potential for groundwater contamination (e.g. Jackson et al., 2013; Vidic et al., 2013) and fugitive emissions of hydrocarbons into the atmosphere (e.g. Miller et al., 2013).

Boreholes drilled to explore for and extract hydrocarbons must penetrate shallower strata before reaching the target horizons. Some of the shallower strata may contain groundwater used for human consumption or which supports surface water flows and wetland ecosystems. Although it has been routine practice to seal wells passing through such layers, they remain a potential source of fluid mixing in the subsurface and potential contamination (King and King, 2013). This can occur for many reasons, including poor well completion practices, the corrosion of steel casing, and the deterioration of cement during production or after well abandon ment. Boreholes can then become high permeability potential conduits for both natural and man made fluids (e.g. Watson and Bachu, 2009), and vertical pressure gradients in the subsurface can drive movement of fluids along these flow paths. The potential importance of wellbore integrity to the protection of shallow groundwater has recently been highlighted in research papers and reports (e.g. Osborn et al., 2011; The Royal Society & The Royal

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Glossary

BCF	Billion Cubic Feet
BCM	Billion Cubic Metres
BRGM	Bureau de Recherches Géologiques et Minières, France
BDEP	Brazilian Database of Exploration and Production
CA	California
CO_2	Carbon Dioxide
CCTV	Closed Circuit Television
DECC	Department of Energy and Climate Change, UK
DEFRA	Department of Environment, Food and Rural Affairs, UK
DEP	Department of Environmental Protection, USA
EIA	Energy Information Administration, USA
ERCB	Energy Resources Conservation Board, Canada
EUR	Estimated Ultimate Recovery
GM	Gas Migration
GoM	Gulf of Mexico
IPCC	Intergovernmental Panel on Climate Change
km^2	Square Kilometres
M	Metres
m^3	Cubic Metres
mD	Milli Darcies
NOCS	Norwegian Offshore Continental Shelf
NY	New York
PA	Pennsylvania
PSA	Petroleum Safety Authority, Norway
RRC	Railroad Commission, Texas
SCVF	Surface Casing Vent Flow
SINTEF	Norwegian Foundation for Scientific and Industrial Research
TCF	Trillion Cubic Feet
TCM	Trillion Cubic Metres
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
UKOGL	United Kingdom Onshore Geophysical Library
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
WFD	Water Framework Directive, Europe
WV	West Virginia

Academy of Engineering Report (2012); Jackson et al., 2013; King and King, 2013). In addition to protecting ground and surface waters, effective well sealing prevents leakage of methane and other gases into the atmosphere. This is important as methane is 86 times more effective than CO_2 at trapping heat in the atmosphere over a 20 year period and 34 times more effective over a century (IPCC, 2013). Well barrier and integrity failures can occur during drilling, production, or after abandonment; in rare examples, including in the USA, well leakage has led to explosions at the Earth's surface (e.g. Miyazaki, 2009).

This paper has four aims: 1) to estimate the number of onshore hydrocarbon wells globally; 2) to explain how onshore wells are categorised (e.g. producing, abandoned, idle, orphaned) and what statistical data are available on the numbers of wells in these groups; 3) to document the number of wells that are known to have had some form of well barrier and/or integrity failure, placing these numbers in the context of other extractive industries; and 4) to analyse how many onshore wells in the UK can be easily accessed to assess for barrier and integrity failure. For well barrier and integrity failure our approach has been to include all the reliable datasets that are available, rather than de select any data. This inclusive approach has the draw back that the data we present include wells of different age, of different designs and drilled into different geology. Unsurprisingly there is a significant spread in the statistics on the percentage of wells that have well barrier or integrity failure.

The review is largely focused on North America, as it has a long history of onshore hydrocarbon drilling (including wells drilled for shale gas and shale oil) and the UK, which contrasts in having a mature offshore drilling industry, but relatively little onshore drilling. It mainly, but not exclusively, covers static well failure (i.e. after drilling operations are completed), and summarises currently available data for regulators, non government organisations, the public, and the oil and gas industry.

1.1. Barrier systems

Barriers are containment mechanisms within a well or at the well head that are designed to withstand the corrosion, pressures, temperatures and exposure times associated with the phases of drilling, production and well abandonment. The types of barriers used to prevent contamination of groundwater, surface water, soils, rock layers and the atmosphere depend on whether the well is for exploration or production, but generally include cement, casing, valves and seals (Fig. 1). Barriers can be nested, so that a well has several in place. They can be dynamic (e.g. a valve) or static (e.g. cement), and may or may not be easily accessible for assessment or monitoring (see King and King, 2013).

Drilling a well for exploration or production is a multistage process during which the upper parts of a borehole, once drilled, are sealed with steel casing and cemented into place. Cement was introduced to the petroleum industry as early as 1903, when Frank Hill of Union Oil Co. poured 50 sacks of Portland cement into a well to seal off water bearing strata (Smith, 1976). Cementing is now typically carried out by pumping water cement slurries down the casing to the bottom of the hole, displacing drilling fluids from the casing rock and other annuli, leaving a sheath of cement to set and harden (Fig. 1). The integrity of these seals is pressure tested before the next stage of drilling occurs. Only if the well passes these pressure tests will drilling continue. If the well fails the test, the casing is re cemented before drilling continues. The sizes and lengths of casing, and the depths at which different casings are used depend upon the geology, the importance or sensitivity of the groundwater that the well penetrates, and the purpose of the well (Fig. 1). Well completion should follow statutory regulations and/or industry best practice. When a well is abandoned, cement is normally pumped into the production tubing to form a cement plug to seal it. Commonly (e.g. in the UK), the top of the well is welded shut.

1.2. Terminology

The terms 'well barrier failure' and 'well integrity failure' were differentiated by King and King (2013). They used 'well integrity failure' for cases where all well barriers fail, establishing a pathway that enables leakage into the surrounding environment (e.g. groundwater, surface water, underground rock layers, soil, atmosphere). 'Well barrier failure' was used to refer to the failure of individual or multiple well barriers (e.g. production tubing, casing, cement) that has not resulted in a detectable leak into the surrounding environment. The same terminology is used in this paper:

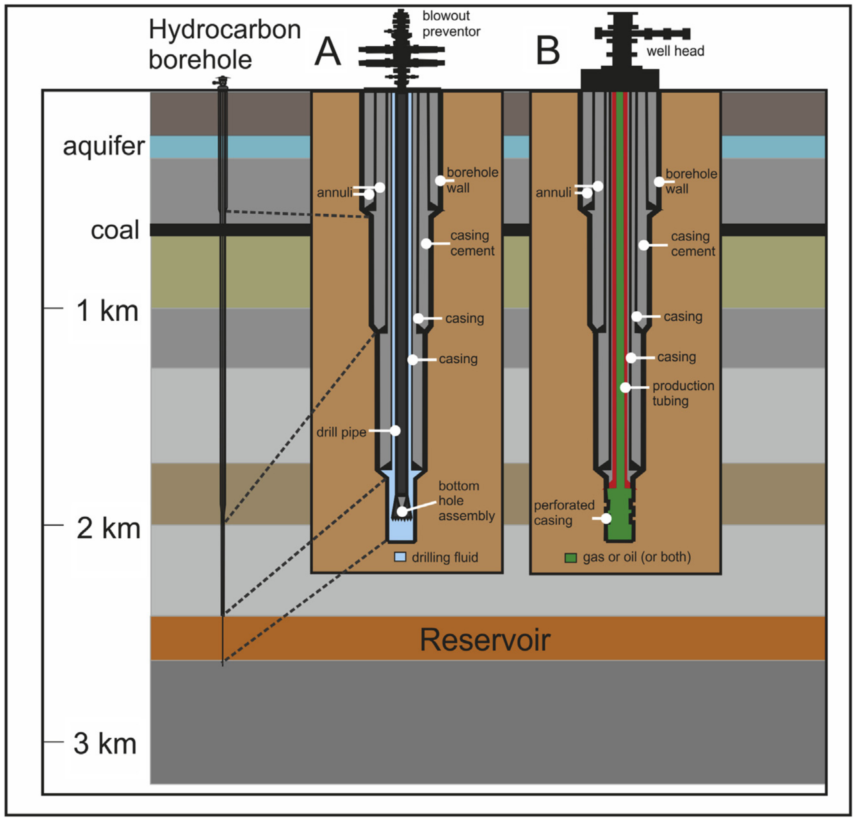

Figure 1. Schematic diagram of typical well design, showing (A): structure of an exploration well; and (B): a production well. Depths to which different casings are used vary according to geology and pressure regime of drill site. Well diameter exaggerated to show sections more clearly.

'well integrity failure' includes cases when gas or fluids are re ported to have leaked into soils, rock strata or the atmosphere, and 'well barrier failure' includes cases where a barrier failure has occurred but there is no information that indicates that fluids have leaked out of the well.

1.3. Routes and driving mechanisms

For a well to leak, there must be a source of fluid (Fig. 2), a breakdown of one or more well barriers, and a driving force for fluid movement, which could be fluid buoyancy or excess pore pressure due to subsurface geology (e.g. Watson and Bachu, 2009). There are seven subsurface pathways by which leakage typically occurs (Figs. 3, 4). These pathways include the development of channels in the cement, poor removal of the mud cake that forms during drilling, shrinkage of cement, and the potential for relatively high cement permeability (e.g. Dusseault et al., 2000). There are other mechanisms that can operate in specific geological settings. Reservoir compaction during production, for example, can cause shear failure in the rocks and casing above the producing reservoir (Marshall and Strahan, 2012; route 7 marked on Fig. 3). Leaking wells can also connect with pre existing geological faults, enabling leakage to reach the surface (Chillingar and Endres, 2005). A range of fluids can leak, for instance formation fluids, water, oil and gas, and they can move through or out of the well bore by advective or diffusive processes (e.g. Dusseault et al., 2000). Overpressure may be the driving force for fluid flow (e.g. the Hatfield blow out near Doncaster, UK; Ward et al., 2003), but hydrostatically pressured successions can also feed leaking wells, with fluids migrating due to buoyancy and diffusion.

A leak can be catastrophic, as seen in cases such as the recent blowout of a Whiting Petroleum Corp oil well (Cherry State 31 16H) in North Dakota (North Dakota Department of Health (2014)) and rare examples of explosions in urban areas (Chillingar and Endres, 2005), or be at sufficiently low rates to be barely detectable. The fluid sources can be hydrocarbon reservoirs (e.g. Macondo, Gulf of Mexico); non producing permeable formations (e.g. Marshall and Strahan, 2012); coal seams (e.g. Beckstrom and Boyer, 1993; Cheung et al., 2010); and biogenic or thermogenic gases from shallow rock formations (e.g. Traynor and Sladen, 1997; Jackson et al., 2013). Oil or gas emissions can seep to the surface, though leaking methane can be oxidised by processes such as bacterial sulphate reduction (e.g. Van Stempvoort et al., 2005). Well failures can potentially occur in any type of hydrocarbon borehole, whether it is being drilled, producing hydrocarbons, injecting fluid into a reservoir, or has been abandoned.

Wells can be tested at the surface for well barrier failure and well integrity failure by determining whether or not there is pressure in the casing at the surface. This is referred to as sustained casing pressure (e.g. Watson and Bachu, 2009), but does not necessarily prove which barrier has failed or its location. Channels in cement, which are potential leakage pathways, can be detected by running detection equipment down the borehole. Migration of fluids outside the well is established by inserting a probe into the soil immediately surrounding the well bore, or by sampling groundwater nearby, hydraulically down gradient of the well. Poor cement barriers can be identified by a number of methods (e.g. ultrasonic frequency detection; Johns et al., 2011) and can be repaired in some cases, using cement or pressure activated sealants (e.g. Chivvis et al., 2009).

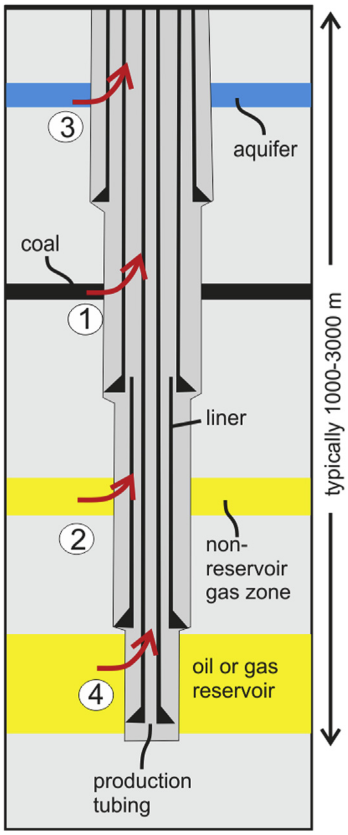

Figure 2. Schematic diagram of typical sources of fluid that can leak through a hydrocarbon well. 1 gas-rich formation such as coal; 2 non-producing, gas- or oil-bearing permeable formation; 3 biogenic or thermogenic gas in shallow aquifer; and 4 oil or gas from an oil or gas reservoir.

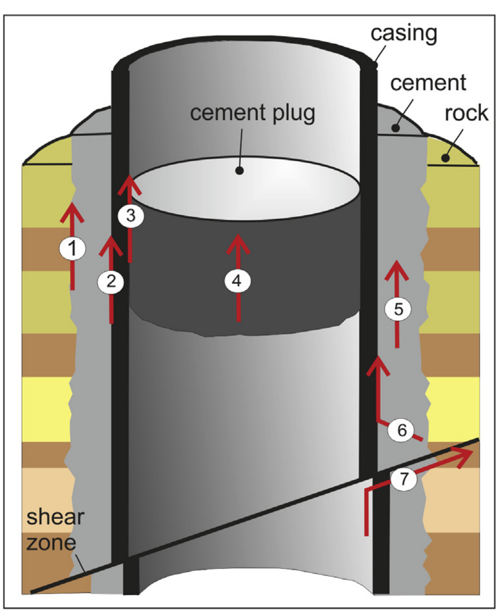

Figure 3. Routes for fluid leak in a cemented wellbore. 1 between cement and surrounding rock formations, 2 between casing and surrounding cement, 3 between cement plug and casing or production tubing, 4 through cement plug, 5 through the cement between casing and rock formation, 6 across the cement outside the casing and then between this cement and the casing, 7 along a sheared wellbore. After Celia et al. (2005) and this paper.

2. Datasets

This paper draws on a variety of datasets, mostly published, but in some instances sourced from online repositories or national databases, and follows the approach of Davies et al. (2013). In that study, the risk of induced seismicity due to hydraulic fracturing was reviewed, and intentionally included all datasets in the public domain that were considered to be reliable, rather than de selecting any data (Davies et al., 2013). This inclusive approach has a drawback because well barrier and well integrity failure fre quencies are probably specific to the geology, age of wells, and era of well construction (King and King, 2013). A wide range of failure statistics is therefore reported, and although they are presented on a single graph to show the spread of results (Fig. 9), this is not intended to imply that direct comparisons between very different datasets (i.e. size, age of wells, geology) can be made.

The sources we used do not report their findings consistently and it is unclear in some cases whether well barrier failures have led to leaks into groundwater, rock layers, soil or the atmosphere,

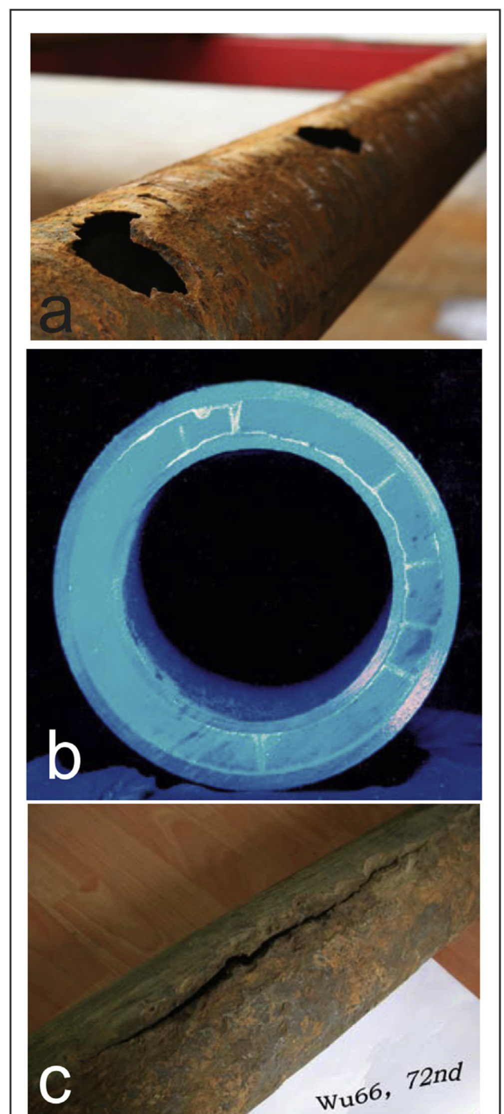

Figure 4. Photographic examples of leak pathways: (a) Corrosion of tubing (Torbergsen et al., 2012); (b) Cracks in cement (Crook et al., 2003); (c) Corrosion of casing (Xu et al., 2006).

producing a true well integrity failure. To be as clear as possible, well barrier and well integrity failure are distinguished in Table 3, quoting directly from the sources used and, where possible, providing additional information on the age of the well and when the monitoring was carried out.

To locate hydrocarbon wells drilled onshore in the UK since 1902 (the age of the earliest well recorded by DECC), the United Kingdom Onshore Geophysical Library (UKOGL) map of well loca tions was used (UKOGL, 2013), coupled with satellite imagery from Google Earth. A visual inspection and categorisation of the locations was carried out to assess whether the wells have a physical pres ence at the surface. Pollution incident data were provided by the Environment Agency (England); these data were used to identify incidents that occurred in close proximity to known well sites.

3. Global well inventory

As shale gas and oil exploitation has been carried out primarily onshore to date, the global well inventory in this study reports only the number of hydrocarbon wells drilled onshore, as this provides a more relevant historical context. Data in the public domain were used, sourced either from published reports or from online datasets populated by regulatory authorities. Several comprehensive review papers were also utilised, particularly those addressing the potential of CO_2 to leak upwards through wells (e.g. Watson and Bachu, 2009).

A graph of wells drilled per year since the 1930s in Australia, Brazil,the Netherlands, Poland, the UK, and the USA shows that some countries, such as the UK, have very modest onshore drilling activity compared to others such as the USA (Fig. 5). Historical data are sparse, so it is difficult to estimate the total number of onshore hydrocarbon wells drilled globally, but in the USA alone, at least 2.6 million wells have been drilled since 1949 (EIA database). Former Soviet countries such as Azerbaijan, where many thousands of wells have been drilled, are not included in this study due to a lack of access to adequate data. Nonetheless, taking into consideration those drilled only in Australia, Austria, Bahrain, Brazil, Canada, the Netherlands, Poland, the UK and the USA, we estimate there are at least 4 million onshore hydrocarbon wells (Table 1).

Table 1
Number of hydrocarbon boreholes drilled onshore in selected nation states.

Country	Number of wells	Source
UK	2152	DECC, 2013
Canada Alberta	316,439	Watson and Bachu (2009)
Bahrain	750	Sivakumar and Janahi (2004)
USA	2,581,782	EIA Database
Austria	1200	Veron (2005)
Netherlands	3231	Geological Survey of the Netherlands
Brazil	21,301	Brazil Database of Exploration and Production (BDEP)
Australia	9903	Geoscience Australia
Poland	7052	Polish Geological Institute

4. Well integrity

4.1. Pennsylvania, USA

The online database collated by the Department of Environ mental Protection (DEP) in the US state of Pennsylvania allows oil and gas well records to be searched by various criteria, such as well status, operator and drilling date. The unconventional hydrocarbon wells included in that database are those that were drilled to target the Marcellus Shale Formation. From these data, Vidic et al. (2013) derived a figure of 3.4% well barrier leakage for shale gas produc tion sites in Pennsylvania (219 violations for 6466 wells) between 2008 and 2013. Using the same database, Ingraffea (2012) argued that 211 (6.2%) of 3391 shale gas wells drilled in Pennsylvania in 2011 and 2012 had failed. More recently, Considine et al. (2013) identified 2.58% of 3533 individual wells as having some form of barrier or integrity failure. This consisted of 0.17% of wells having experienced blowouts (4 wells), venting or gas migration (2), and 2.41% having experienced casing or cementing failures. Measurable concentrations of gas were present at the surface for most wells with casing or cementing violations. Figure 6 shows a breakdown of the 1144 environmental violations issues for the 3533 wells.

In this study, the search criteria used to categorise leakage in cidents in Pennsylvania followed the approach described by Ingraffea (2012) and are based on code violations reported during site inspections. Code violations that would constitute a well failure are those likely to result in a significantly increased risk of con taminants reaching either the surface or potable water sources. They include: (a) failure to case and cement the well properly; (b) excessive casing seat pressure; (c) failure to case and cement suf ficiently to prevent migrations into fresh groundwater; and (d) insufficient cement and steel casings between the wellbore and the near surface aquifer to prevent seepage of fluids. Using the Penn sylvania state database, a well barrier or integrity failure rate of 6.3% is identified for the years 2005–2013. This includes failures noted in inspection reports that were not recorded as a violation, following the methodology of Ingraffea (2012). Without including these reports, the failure rate would be 5%. This is higher than the 3.4% well leakage figure reported by Vidic et al. (2013) for the period 2008–2013, and close to the well failure rate of 6.2% re ported by Ingraffea (2012).

4.2. Gulf of Mexico, USA

Data from the US Minerals Management Service show that, of 15,500 producing, shut in and temporarily abandoned wells in the

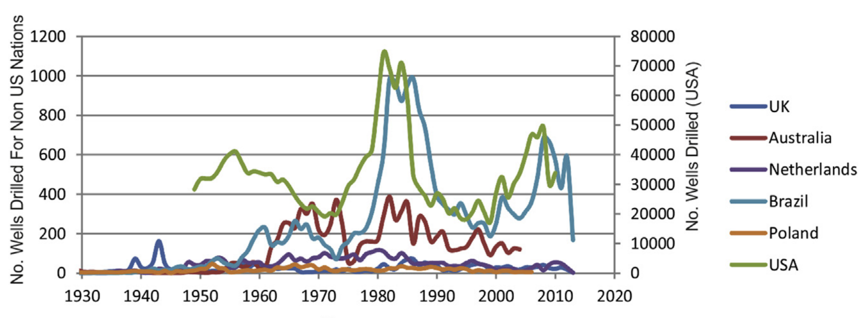

Figure 5. Number of wells drilled annually since the 1930s in Australia, Brazil, Netherlands, Poland, the UK and the USA. Sources: DECC, 2013; Geoscience Australia; Geological Survey of the Netherlands; Brazil Database of Exploration and Production (BDEP); EIA, Polish Geological Institute.

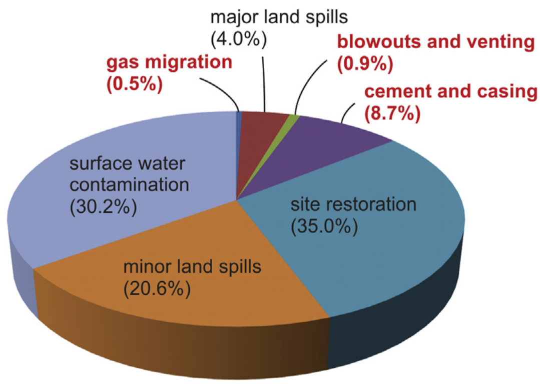

Figure 6. Breakdown of 1144 notices of violations from 3533 wells in Pennsylvania from 2008 to 2011 (after Considine et al., 2013). Red font indicates those related to well barrier and integrity failure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

outer continental shelf of the Gulf of Mexico, 6692 (43%) have sustained casing pressure on at least one casing annulus (Brufatto et al., 2003). Of these incidents, 47.1% occurred in the production strings, 26.2% in the surface casing, 16.3% in the intermediate casing, and 10.4% in the conductor pipe.

4.3. Offshore Norway

Vignes and Aadnøy (2010) examined 406 wells at 12 Norwegian offshore facilities operated by 7 companies. Their dataset included producing and injection wells, but not plugged and abandoned wells. Of the 406 wells they examined, 75 (18%) had well barrier issues. There were 15 different types of barrier that failed, many of them mechanical (Fig. 7), including the annulus safety valve, casing, cement and wellhead. Issues with cement accounted for 11% of the failures, whilst issues with tubing accounted for 39% of failures.

The PSA has also performed analyses of barrier failures and well integrity on the Norwegian continental shelf. Its analysis showed that, in 2008, 24% of 1677 wells were reported to have well barrier failures; in 2009, 24% of 1712 wells had well barrier failures; and in 2010, 26% of 1741 wells had well barrier failures. It is unclear whether the same wells were tested in successive years or whether surveys targeted different wells (Vignes, 2011). A study of 217 wells in 8 offshore fields was also carried out by SINTEF (see Vignes, 2011). Between 11% and 73% of wells had some form of barrier failure, with injectors 2 to 3 times more likely to fail than producers (Vignes, 2011).

At the 20th Drilling Conference in Kristiansand, Norway, in 2007, Statoil presented an internal company survey of offshore well integrity (Vignes, 2011). This analysis showed that 20% of 711 wells had integrity failures, issues, or uncertainties (Vignes, 2011). When subdivided into production and injection wells, the survey concluded that 17% of 526 production wells and 29% of 185 injection wells had well barrier failures.

4.4. Onshore Netherlands

The results of an inspection project carried out by the State Supervision of Mines Netherlands were also reported by Vignes (2011). Their inspections, carried out in 2008, included only 31 wells from a total of 1349 development wells from 10 operating companies. Of those wells, 13% (4 of 31) had well barrier problems; by well type, problems were identified in 4% of the production wells (1 of 26) and 60% of the injection wells (3 of 5).

4.5. Offshore and onshore UK

For offshore wells on the UKCS, Burton (2005) found that 10% of 6137 wells (operated by 18 companies) had been shut in (valves at the well head closed) during the last five years as a result of ‘structural integrity issues’. The total number of wells drilled on the UKCS is 9196; exploration boreholes that did not make commercial discoveries were not included in the Burton (2005) study.

Onshore, 2152 hydrocarbon wells have been drilled in the UK between 1902 and 2013. Although the onshore sedimentary succession is not thought to be overpressured, hydrocarbons could still migrate upwards because of their buoyancy relative to pore water or the fluid in a borehole (e.g. the Hatfield blow out near Doncaster, UK; Ward et al., 2003). Pollution incident data were reviewed for all incidents reported within 1 km of wells in England between 2001 and 2013 (the only time period for which data are available). These data were filtered for those indicating a release of crude oil to the environment. These incidents were described as pipe failures above or below ground and could be related to the well or pipelines connected to the wells. To act as a control to this data, pollution incidents within a 5 km radius of the well were also examined to assess whether there was a broader issue of hydrocarbon pollution incidents that should be considered and taken into account.

The number of wells active prior to the period covered by the pollution records was also calculated. Based on data provided by DECC, 143 onshore oil and gas wells were producing at the start of the year 2000. Between 2000 and 2013, the Environment Agency records nine pollution incidents involving the release of crude oil within 1 km of an oil or gas well (Table 7, Fig. 8). The records are not clear as to whether the incidents were due to well integrity failure, problems with pipework linked to the well, or other non well related issues. In February 2014, therefore, the present day operators of the wells at which the nine events occurred were contacted (Perenco, IGas, and Humbly Grove Energy Ltd.). The two pollution incidents at the Singleton Oil Field (now operated by IGas but operated by a different company when the incidents occurred) occurred in the early 1990s, and were caused by failure of cement

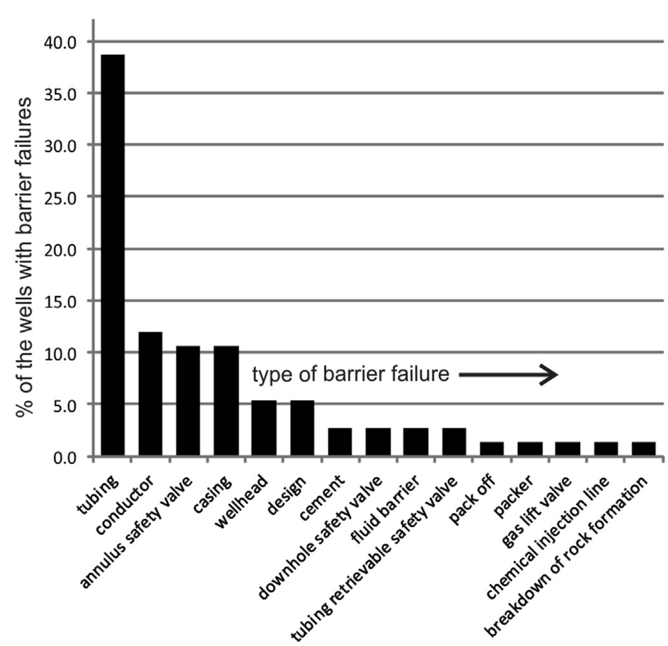

Figure 7. Causes of barrier failures for the 75 (of 406) production and injection wells surveyed in offshore Norway that showed evidence for such failures (from Vignes, 2011).

Table 2
Sources of data reporting well barrier and well integrity failures.

Country	Region	Well location	Status	Completion date	Well type	Well numbers	Failure statistics	Organisation
USA	PA	X	X	X	X	X	X	Department of Environmental Protection
	Texas	X	X	X	X	X		RRC
	Alabama	X	X	X	X	X		Geological Survey of Alabama
	New York	X	X	X	X	X		New York Department of Environmental Conservation
	Florida	X	X	X	X	X		Florida Department of Environmental Protection
	North Dakota	X	X	X	X	X	X	North Dakota Oil and Gas Division & North Dakota Department of Environmental Health
	W. Virginia	X	X	X	X	X	X	West Viginia Department of Environmental Protection
UK	National	X		X	X	X		DECC
Canada	Alberta	X	X	X	X	X	X	Energy Resources Conservation Board (ERCB)
Australia	National	X	X	X	X	X		Geoscience Australia
France	National	X	X	X	X			BRGM
Netherlands	National	X	X	X	X	X		Geological Survey of the Netherlands
Brazil	National	X		X	X	X		BDEP
Norway (offshore)	National		X	X		X		Norway Offshore Continental Shelf Data Access Portal
Poland	National	X		X	X	X		Polish Geological Institute

behind the conductor and the 9 5/8 inch casing. This was identified as a result of five groundwater monitoring boreholes installed at the Singleton Oil Field in 1993. The leak was from the well cellar (cement lined cavity in which the well head sits) via the pre installed conductor and the 9 5/8 inch casing, both of which appear not to have been adequately cemented in situ in at least one well. A thorough investigation commenced in 1997, including the drilling of a number (>11) of additional boreholes, and the carrying out of tracer tests and CCTV examination under the auspices of, and in consultation with, the UK Environment Agency. The leak paths, once identified and verified, were remediated. Monitoring has continued since that time and the observed pollution levels have remained below those set by the Environment Agency as requiring further action.

The other seven pollution incidents recorded by the Environ ment Agency between 2000 and 2013 were not caused by well integrity failure, but due to leaks from pipework linked to the well. No incidents were reported at the other well sites in the UK that were inactive or abandoned.

For context, it should be noted that there are natural, high permeability geological pathways for the migration of buoyant fluids, which are typically associated with structural features such as faults and folds (Selley, 1992). Gas and oil are naturally mobile in the UK subsurface: around 200 natural hydrocarbon seeps, mainly of oil, are known from the onshore UK and some have been used to initiate localised exploitation (Selley, 1992, 2012). A small number of natural gas seeps from shales were recorded by Selley (2012), with notable occurrences in the Weald Basin of south east England (Selley, 2012, Fig. 5).

4.6. Summary of well barrier and integrity failure

For the countries listed (Table 1), publicly available data were tabulated on well type, well location, completion date, well status, number of wells drilled and whether well barriers and integrity failures had occurred (Table 2). Tabulation of all published and online data on well barrier and integrity failure (Table 3, Fig. 9) shows substantial variability in the number of wells that have experienced both categories of failure. This probably relates to the fact that the sizes of the datasets are variable; the included wells were drilled over a period of more than a century, using different well designs and technology; were targeting unconventional and conventional hydrocarbons; and were drilled in diverse geological settings. The most recent dataset from the Marcellus Shale (Penn sylvania, USA), which includes several thousand wells, has some of the lowest well barrier and failure rates (Fig. 9). In Table 3 we have been careful to provide the exact wording from the published source as to the nature of the failure, and to discriminate between well barrier and well integrity failures.

5. Orphaned, abandoned or idle wells

5.1. Definitions

The terms 'abandoned', 'idle' and 'orphaned' are used to describe the state of a well that did not locate economic hydro carbons or a well at the end of its production lifecycle. The USA has the most established and comprehensive definitions of such terms, although their meaning can vary at state and federal levels.

A review of the various state regulatory practices regarding idle wells in the USA was conducted by Thomas (2001) and defined idle wells as those not currently being used for production or injection, but which have not yet been plugged and abandoned. In California, Hesson and Glinzak (2000) and Evans et al. (2003) defined idle wells as those that have been non producing and non injecting for six consecutive months.

In the USA, the definition of an orphaned well depends largely on the state regulatory body. Thomas (2001) defined orphaned wells as those in which the operator has gone out of business or is insolvent, such that the company that operated the well is no longer responsible for it. Based on Californian practices, Hesson (2013) defined orphaned wells as those where the operator is defunct, or where the state regulatory body has determined, based on certain criteria, that a well is orphaned. Such criteria include a well having been idle for 25 years or more, without being in compliance with idle well requirements. In Texas, the oil and gas regulatory body – the RRC – defines orphaned wells as those which have, without permit, been inactive for a year or more. In Penn sylvania, a 1992 amendment to the 1984 Oil and Gas Act defined an orphaned well as one which was abandoned prior to April 1985, which has not been operated by the present owner, and for which the present owner has received no economic benefit. For the UK data in this study, we follow the definition of Thomas (2001) and use 'orphaned' to describe wells where the operator is no longer solvent.

6. USA

Thirty two US states have reported data on orphaned oil and gas wells (IOGCC, 2013). Fifteen of these states account for around 320,000 orphaned wells in total, with ~53,000 of these wells targeted for plugging (Table 4). The states vary greatly in how they

Table 3
Compilation of published statistics on well barrier and well integrity failure, including information on well age, number of wells included in study, well location, and terminology used to describe nature of well barrier or integrity failures.

Country	Location	No. Wells studied	% Wells with barrier failure or well integrity failure	Additional information	Published source
USA	ONSHORE Operational wells in the Santa Fe Springs Oilfield (discovered ~1921), California, USA	>50	75	Well Integrity failures. Leakage based on the 'observation of gas bubbles seeping to the surface along well casing'.	Chillingar and Endres (2005)
USA	ONSHORE Ann Mag Field, South Texas, USA (wells drilled 1998 2011)	18	61	Wells drilled 1998 2011. Well barrier failures mainly in shale zones.	Yuan et al. (2013)
USA	OFFSHORE Gulf of Mexico (wells drilled ~1973 2003)	15,500	43	Wells drilled ~1973 2003. Barrier failure. 26.2% in surface casing.	Brufato et al. (2003)
Offshore Norway	OFFSHORE Norway, 8 Companies, Abandoned Wells (wells drilled 1970 2011)	193	38	Wells drilled 1970 2011. Well integrity and barrier failure. 2 wells with likely leak to surface.	Vignes (2011)
China	ONSHORE Kenxi Resevoir, China (dates unknown)	160	31.3	Well barrier failure	Peng et al. (2007)
China	ONSHORE Gudao Resevoir, China (wells drilled 1978 1999)	3461	30.4	Wells drilled 1978 1999. Barrier failure in oil-bearing layer.	Peng et al. (2007)
Offshore Norway	OFFSHORE Norway, 8 Fields (dates unknown)	217	25	Wells monitored 1998 2007. Well integrity and barrier failure. 32% leaks occurred at well head.	Randhol and Carlsen (2007)
Canada	ONSHORE Saskatchewan, Canada (dates unknown)	435	22	Wells monitored 1987 1993. Well integrity failure: SCVF and GM	Erno and Schmitz (1996)
Offshore Norway	OFFSHORE Internal Audit, Location Unknown (dates unknown)	711	20	Barrier failure	Nilsen (2007)
Offshore Norway	OFFSHORE Norway, 12 Offshore Facilities (wells drilled 1977 2006)	406	18	Wells drilled 1977 2006. Well integrity and barrier failure. 1% had well head failure.	Vignes and Aadnøy (2010)
China	ONSHORE Daqing Field, China (wells drilled ~1980 1999)	6860	16.3	Wells drilled ~1980 1999. Barrier failure	Zhongxiao et al. (2000)
Bahrain	ONSHORE Bahrain (wells drilled 1932 2004)	750	13.1	Wells drilled 1932 2004. Failure of surface casing with some leaks to surface	Sivakumar and Janahi (2004)
Netherlands	ONSHORE Netherlands (dates unknown)	31	13	Barrier failure	Vignes (2011)
UK	OFFSHORE UK Continental Shelf (dates unknown)	6137	10	Well integrity and barrier failure.	Burton (2005)
USA	ONSHORE Marcellus Shale, Pennsylvania, USA (wells drilled 1958 2013)	8030	6.26	Well reports 2005 2013. Well integrity and barrier failure. 1.27% leak to surface.	This study
China	ONSHORE Gunan Reservoir, China (dates unknown)	132	6.1	Barrier failure	Peng et al. (2007)
USA	ONSHORE Nationwide Gas Storage Facilities (<1965 1988)	6953	6.1	Wells drilled <1965 1988. Well integrity and barrier failure.	Marlow, 1989
China	ONSHORE Hetan Reservoir, China (dates unknown)	128	5.5	Barrier failure	Peng et al. (2007)
USA	ONSHORE Marcellus Shale, Pennsylvania, USA (wells drilled 2010 2012)	4602	4.8	Wells drilled 2010 2012. Well barrier and integrity failure.	Ingraffea (2012)
Canada	ONSHORE Alberta, Canada (wells drilled 1910 2004)	316,439	4.6	Wells drilled 1910 2004. Monitored 1970 2004. Well integrity failure: SCVF and GM	Watson and Bachu (2009)
Indonesia	ON/OFFSHORE Malacca Strait (wells drilled ~1980 2004)	164	4.3	Wells drilled ~1980 2010. Both well integrity and barrier failures. Further 41.4% of wells identified as high risk of failure.	Calosa and Sadarta (2010)
USA	ONSHORE Pennsylvania, USA (wells drilled 2008 2013)	6466	3.4	Wells drilled 2005 2012. Well integrity and barrier issues. Leak to surface in 0.24% wells.	Vidic et al. (2013)
China	ONSHORE Kenli Resevoir, China (dates unknown)	173	2.9	Barrier failure	Peng et al. (2007)
USA	ONSHORE Marcellus Shale, Pennsylvania, USA (wells drilled 2008 2011)	3533	2.58	Wells drilled 2008 2011. Well integrity and barrier failure	Considine et al. (2013)
USA	ONSHORE Nationwide CCS/Natural Gas Storage Facilities (dates unknown)	470	1.9	Well integrity failure. Described as significant gas loss.	IPCC (2005)

treat wells for which they have no data. Two decades ago, the US EPA estimated that there were at least 1.2 million abandoned oil and gas wells in the United States (EPA, 1987); more than 200,000 of these wells appear to be unplugged (EPA, 1987).

As the first state to produce oil commercially in the USA, Pennsylvania illustrates the difficulty in characterizing abandoned and orphaned wells. The state has seen around 325,000 to 400,000 oil and gas wells drilled since 1859. As of 2010, the Pennsylvania Department of Environmental Protection (DEP) reported 8823 oil and gas wells targeted for plugging (IOGCC 2013). The PA DEP also reported more than 100,000 orphaned wells, but the precise location and depth of most of these was unidentified. The number of orphaned wells in Pennsylvania is probably closer to 180,000, being the difference between the conservative estimate of ~325,000 wells drilled in the state and the ~140,000 wells listed in the PA DEP database. These wells are mostly a legacy of the first 75–100 years of oil and gas drilling, before record keeping was commonplace. In fact, the earliest regulations on well plugging were designed to stop water entering hydrocarbon wells, particularly during floods, rather than to isolate oil and gas from the environment.

Lost wells represent a different classification to abandoned or orphaned wells. States in the USA report that somewhere between 828,000 and 1,060,000 oil and gas wells were drilled prior to a formal regulatory system, most of which have no information available in state databases (IOGCC, 2008). A New York state report in 1994 estimated that, of the 61,000 oil and gas wells drilled to that date, no records existed for 30,000 of them; Bishop (2013) referred to these as 'forgotten' rather than abandoned or orphaned wells.

The growing number of unplugged wells in New York State illustrates the difficulty of keeping remediation levels commensurate with the number of wells being drilled and abandoned (Bishop, 2013). Up to 2010, a total of ~75,000 oil and gas wells had been drilled in the state. Eleven thousand wells were still active at that time, leaving 64,000 'abandoned' wells (after Bishop, 2013). Of these, 15,900 had been plugged but 48,000 remained unplugged; thus only 25% of the abandoned wells in 2010 had been plugged, down from 27% in 1994. More importantly, the number of unplugged wells had grown by 13,000 since 1994, when 35,000 such wells existed (Bishop, 2013). This demonstrates that, in at least some regions, the plugging of abandoned wells is not keeping pace with the rate at which wells are being abandoned.

Some states have aggressive programmes for plugging abandoned oil and gas wells. Texas has one of the most ambitious, having plugged 41,000 wells between 1991 and 2009 at a cost of ~$80 million (IOGCC, 2008). Overall, US states spent ~$319 million in recent decades to plug and remediate ~72,000 oil and gas wells, at an average cost of ~$4500 per well. Based on that unit cost, plugging 150,000 more wells would require $668 million, and plugging all 320,000 wells estimated in Table 4 would cost $1.43 billion. In 2009, the combined balance available in all US state funds for plugging wells was ~$2.8 million, many orders of magnitude less than that required to finish the job (IOGCC, 2008).

7. UK

In the UK a total of 2152 hydrocarbon wells were drilled onshore between 1902 and 2013, with a peak in drilling activity during World War II (Fig. 10). Approximately 1000 were drilled by companies that still exist. Approximately 1050 were drilled by companies that were subject to takeovers or mergers. For example, 543 wells were drilled by the D'Arcy company, mainly between 1941 and 1961 and D'Arcy is no longer operating.

We estimate that between 50 and 100 of the 2152 wells were drilled by companies that no longer exist and were not bought or merged. In the USA such wells are termed orphaned wells. Where the company that drilled the well no longer exists, or has been taken over or merged (up to 53% of UK wells), liability for any well integrity failures that lead to pollution is unclear; in some cases it may be that of the landowner. Even if a chain of ownership through acquisition of prior licensees can be identified, the position is likely to be more complex as the legal mechanism used for the acquisition may not be known. In some instances, it is possible that a company was purchased for its assets and the liabilities were left with the original entity.

As a case study, one of the 2152 wells listed by DECC was examined (Fig. 11). Drilled in Sunderland in 2002, the well targeted coal mine gas. In February 2014 the company that drilled the well was contacted to confirm the status of the well as either abandoned or temporarily abandoned (suspended). No gas had been produced due to elevated water levels and the well was temporarily abandoned (suspended) in 2002, pending transfer of ownership to the Coal Authority, for water level monitoring or abandonment. The surrounding land has since been acquired by developers and is currently (February 2014) the site of a new residential housing estate. As of February 2014, the well is now being abandoned (DECC, pers. comm.).

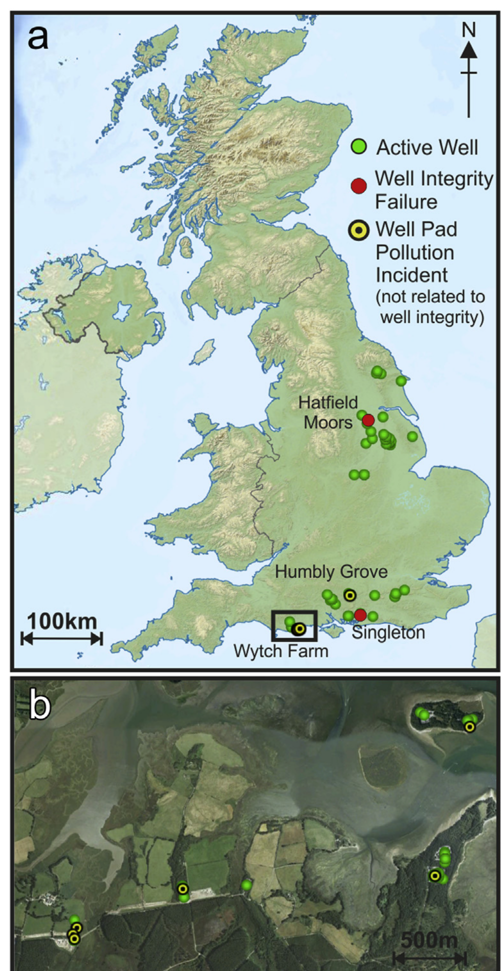

Figure 8. (a) UK map showing locations of wells active in 1999 and crude oil discharges (b) Coincidence of pollution reports with well pads in the Wytch Farm area, southern England.

Many wells have been drilled in areas where there are highly productive aquifers (Fig. 12a) and there is a good spatial correspondence between potential shale reservoirs and highly productive aquifers (Fig. 12b). In the USA, many shale gas wells have also been drilled where there are active aquifers (King and King, 2013).

7.1. Surface identification of wells in the UK

A surface identification study of the 2152 UK onshore hydrocarbon wells was carried out. 128 wells were not included because: (a) the wells were younger than the available satellite imagery and so could not be located using this method (114 wells); (b) the wells were listed in the onshore well database (DECC, 2013) but were not present on the UKOGL map (5 wells); or (c) the wells were listed as 'offshore' in the DECC onshore well database (9 wells).

The remaining 2024 wells were categorised as follows:

a. Cleared area of land present, consistent with site being used as well pad; machinery present and site apparently in use;
b. Indications that well had once been present on site, but clearly not active.
c. No well pad or machinery visible; no indication that well had ever been present on site;

Of the well sites included in our study (Table 5), 33.7% were clearly visible (i.e. the well pad and associated equipment could be

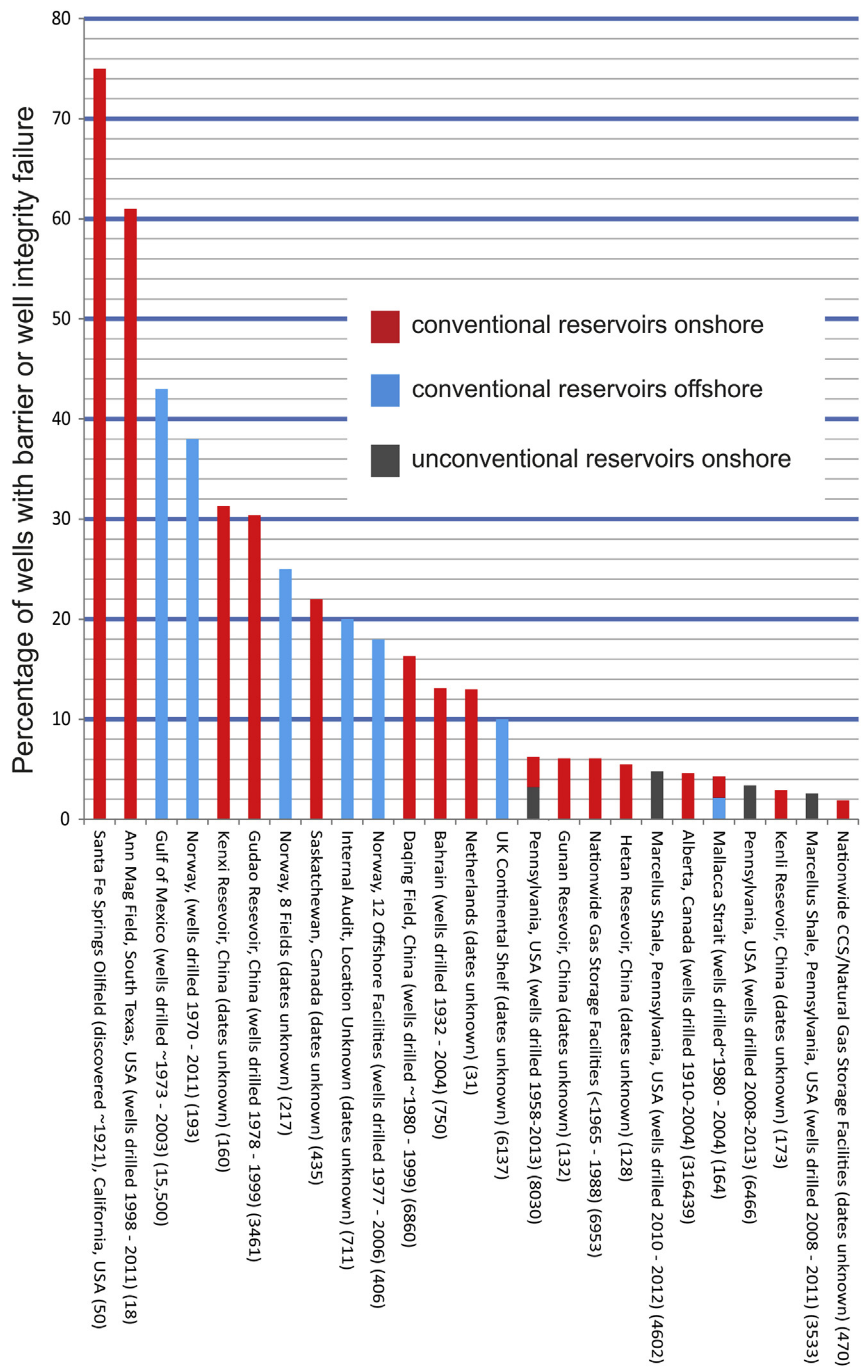

Figure 9. Graph of percentage of well barrier and integrity failures reported in 25 different studies around the world, with drilling dates and number of wells in each study.

Table 4
Estimated numbers of orphaned oil and gas wells for each U.S. state reporting at least 1000 orphaned wells (IOGCC, 2008). Thirty-two of 50 states reported data on orphaned wells.

State	Orphaned oil or gas wells	Orphaned wells targeted by state for plugging
Pennsylvania	180,000	8823
New York	44,600	4600
Kansas	30,000	6500
Kentucky	14,880	12,800
Oklahoma	12,000	1685
Ohio	9500	524
Texas	7323	7323
Tennessee	4053	53
West Virginia	3999	1385
Illinois	3766	3766
Indiana	3000	756
Louisiana	2793	2793
Missouri	2000	2000
South Dakota	1288	NA
California	1000	181
Total	320,202	53,189

seen; Fig. 13a), 5.5% showed evidence of prior on site drilling ac tivity without the current presence of drilling production, drilling equipment or a well head (Fig. 13b), and 65.2% were not visible (Fig. 13c). For 1.1% of sites it was unclear as to whether a well pad existed. These sites mainly comprise industrial locations where it could not be determined visually whether the infrastructure pre sent was related to a well site. It is likely that the reason that 65.2% of wells are not visible is that UK regulations state that, after abandonment, the well should be sealed and cut and the land reclaimed.

8. Discussion

To provide context for the statistics on well barrier failure reviewed above, comparative data are reported from other indus trial processes, primarily mining in the UK and geothermal energy abstraction. The number of wells that may be required to produce shale gas is also considered.

8.1. Coal mining

There are estimated to be ~250,000 lost mining shafts in the UK (Chambers et al., 2007) and many coal exploration boreholes. During mine operation, the potential for cross contamination be tween mined coal horizons and overlying potable aquifers is rela tively low due to the fact that mine workings are dewatered (often at a regional scale, comprising several interconnected pits) to facilitate access by the workforce. However, following mine abandonment and the cessation of dewatering, groundwater rebound occurs over 10–20 years and has the potential to contaminate overlying aquifers. This process is driven by the hy draulic head in the coal workings exceeding that of the overlying aquifer (Younger et al., 2002). In northern England, cessation of pumping for mine dewatering in part of the Durham Coalfield led to pollution of the overlying Magnesian Limestone aquifer, used for public water supply. As a consequence, this led to the aquifer failing an EU Water Framework Directive (WFD) environmental objective for groundwater quality (Neymeyer et al., 2007). More broadly, the 2009 River Basin Management Plans, required as part of the implementation of the EU WFD, reported that 34 out of 304 groundwater bodies in England and Wales had failed 'good' status environmental objectives due to groundwater pollution by rising waters following mine abandonment (including coal and metal mines). In some areas, abandoned mine workings also liberate methane, and emissions from abandoned UK coal mines were estimated to be ~14 million m^3 of methane in 2008 (UNFCCC, 2010).

8.2. Geothermal energy

Environmental concerns linked to the exploitation of geothermal energy include the mobilisation of contaminants from the surrounding rock that could lead to the contamination of aquifers by geothermal fluids. In the Balcova Geothermal Field in Turkey, there has been thermal and chemical contamination of the overlying aquifer by elements such as arsenic, antimony and boron. Aksoy et al. (2009) recommended that regular inspection and maintenance of geothermal wells should be carried out.

Summers et al. (1980) characterised geothermal fluids and investigated the possible sources of well barrier and integrity fail ure and the potential for contamination. Based on their analysis, they proposed a methodological framework for identifying groundwater contamination from geothermal energy de velopments. Possible sources of well barrier and integrity failure of geothermal wells include loading from the surrounding rock for mation, mechanical damage during well development, corrosion and scaling from geothermal fluids, thermal stress, metal fatigue and failure, and expansion of entrapped fluids (Southon, 2005).

The mixing of deep geothermal fluids with shallow groundwa ters can occur via natural mechanisms, such as natural upward fluid convection along fault lines (e.g. within the Larderello geothermal field, Italy; Bellani et al., 2004), and by anthropogenic activities, including uncontrolled discharges to surface waters, faulty injec tion procedures (e.g. Los Azufres, Mexico: Birkle and Merkel, 2000), and accelerated upward seepage from failed casings within wells and boreholes. Casing failures related to inconsistencies in casing cementation have been cited as one common cause of failure (Snyder, 1979). The major failures of several geothermal wells on

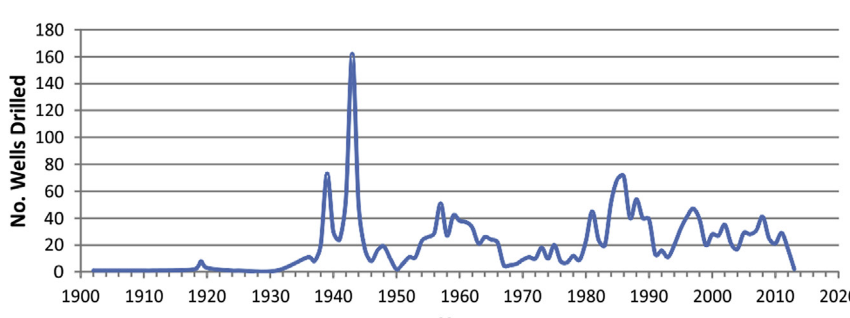

Figure 10. Graph showing number of hydrocarbon wells drilled in UK per year.

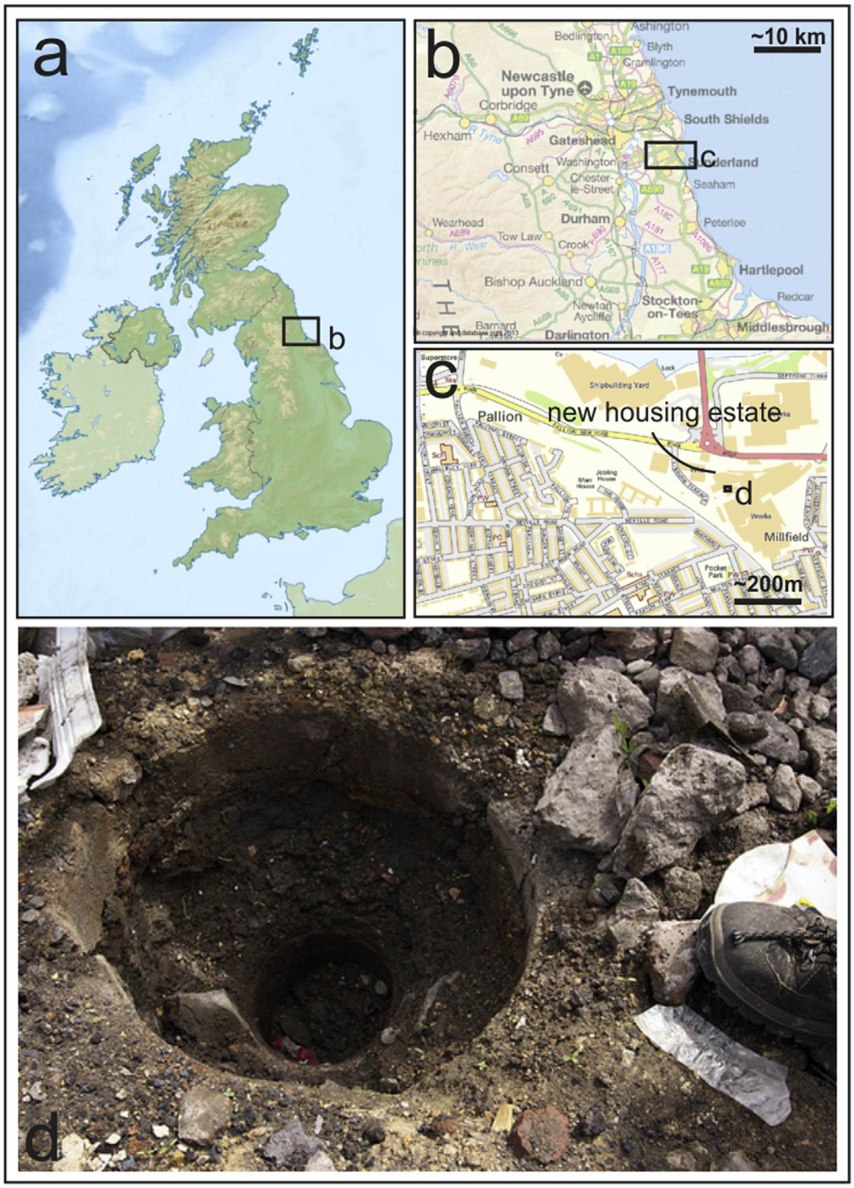

Figure 11. Case study of gas exploration well abandonment in Sunderland, UK: (a) Map of the UK; (b) location of Sunderland; (c) location of new housing estate; (d) photograph of temporarily abandoned (suspended) mine gas exploration borehole on building site of new housing estate (Grid Ref. 438260 557420). Well was completed in 2002 to a depth of 465 m.

the island of Milos, Greece, were attributed to thermal stresses on the well casing that were exacerbated by poor cementation (Chiotis and Vrellis, 1995). There is little published literature on failure rates of geothermal wells, and failure rates are expected to vary due to the wide range of geological settings from which geothermal energy can be exploited, with volcanically active regions carrying higher levels of risk than more tectonically quiescent regions.

8.3. Number of wells for shale gas exploitation

The number of wells that could be drilled to exploit shale gas in Europe depends on various factors, including geological conditions, social acceptance and economics. Based on data from shale gas plays in the USA, the estimated ultimate recovery (EUR) of a shale gas well varies from 1.4 BCF (0.0392 BCM) to 5.9 BCF (0.165 BCM) (Table 6; Baihly et al., 2010). If similar recoveries are assumed for wells in European shale plays, between 169 and 714 wells would be required for every 1 TCF (0.028 TCM) of total production. In comparison, it has been calculated (Gluyas et al., unpublished data) that conventional gas wells in the Rotliegend, which is a gas bearing sandstone reservoir in the Southern North Sea, have EURs of between 1 and 100 times more gas per well.

8.4. Shale exploitation and water contamination

As shale reservoirs have very low permeability compared to conventional sandstone or carbonate reservoirs (typically between 3.9×10^{-6} and 9.63×10^{-4} mD: Yang and Aplin, 2007), fluid movement through and from shales is likely to be extremely slow. Therefore the potential for shales at depth to be the source of pollutants in the near surface environment under natural conditions is low. Geological timescales would be required for significant quantities of hydrocarbons to migrate from a shale reservoir that has not been artificially hydraulically fractured.

The drilling of wells to access gas bearing shales requires the penetration of geological formations close to the surface that will

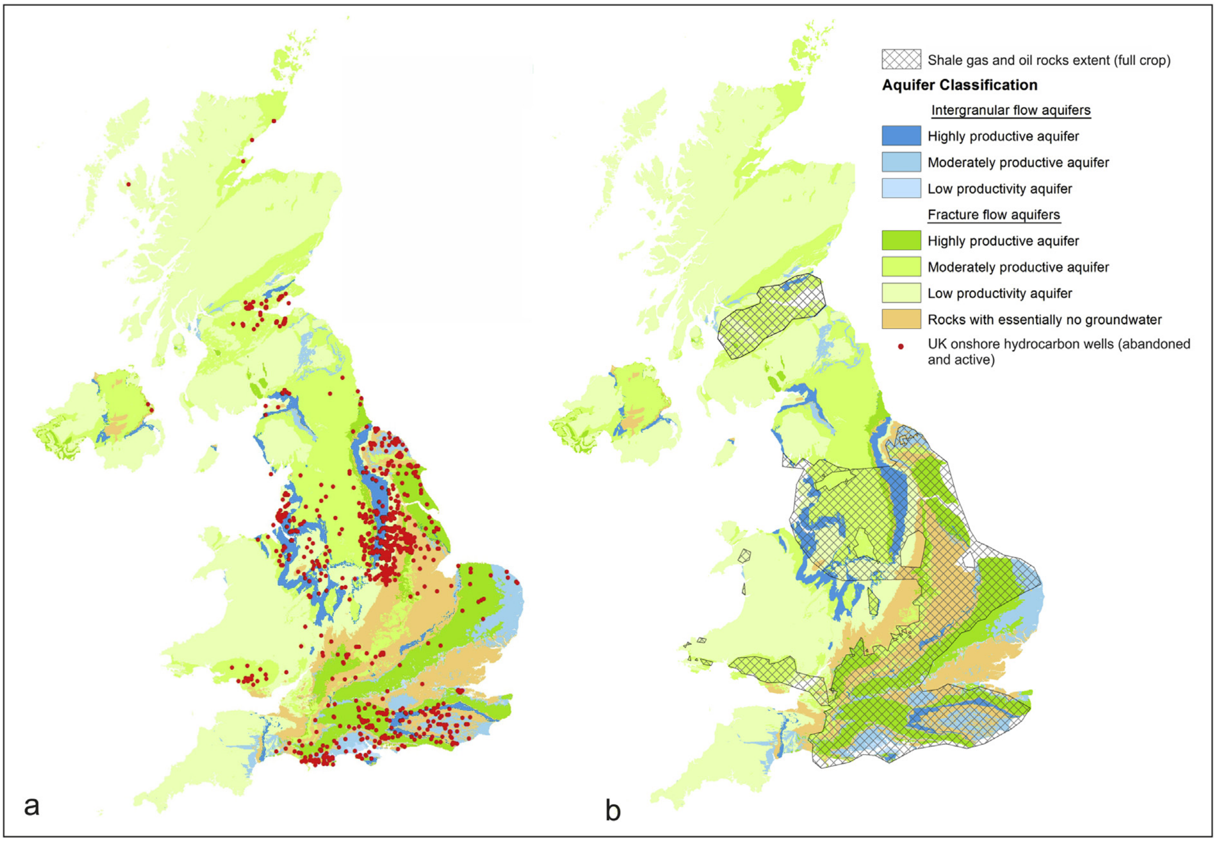

Figure 12. (a) Map of UK showing location of onshore wells drilled for exploration or production and productive aquifers. (b) Map of UK showing location of potential shale gas and oil reservoirs and productive aquifers. Aquifer base map reproduced with the permission of the British Geological Survey. ©NERC. All rights Reserved.

often contain freshwater. Where there is sufficient permeability and storage capacity, these formations will form aquifers (Fig. 12) that may be exploited for drinking water or industrial uses, such as agriculture. Even where aquifers are not currently utilised, they have the potential to be, and therefore require protection. Consideration also needs to be given to protecting groundwater that supports base flow to rivers and wetland ecosystems. Protection is achieved through preventing hazardous pollutants or limiting non hazardous pollutants entering groundwater (European Commission, 2000). Of the 2152 hydrocarbon wells drilled in the UK, the well heads of 428 (20%) of these are located above highly productive aquifers (likely to be exploited for public water supply) and a further 535 (25%) are above moderately productive aquifers, likely to be exploited for both public and private drinking water supplies (Fig. 12a).

Table 5
Statistics on visibility and accessibility of UK onshore wells.

	Number of wells (out of total of 2024 included in study)	Percentage
Visible	682	33.70
Not visible	1319	65.17
Unclear	23	1.14
	Number of Wells on Visible Sites	Percentage
On active sites	626	30.93
Non-active/former/ derelict sites	112	5.53
Urban	159	7.86
Urban/built over	182	8.99

Evidence from conventional hydrocarbon fields shows that hydraulic fracturing due to the injection of fluids can, in very exceptional circumstances, lead to fracture propagation to the surface or near surface, if it takes place at relatively shallow depths. In the Tordis Field of offshore Norway, for example, the average rate of water injection was 7000 m^3 day^{-1} for 5.5 months (total volume ~1,115,000 m^3). Hydraulic fractures propagated from a depth of ~900 m to the surface through Cenozoic (Tertiary) strata. The volume of fluid used in these operations, however, was more than 120 times greater than that typically used for hydraulic fracture stages in shale gas reservoirs and took place over a time period hundreds of times longer. There are several factors in shale fracking operations, including the relatively low volumes of fluid and the short pumping times that make the upward propagation of very tall fractures unlikely (Davies et al., 2012). To date, water contamination caused directly by the upward propagation of hydraulic fractures remains unproven (Davies, 2011), although the possibility cannot be totally ruled out.

As argued by Davies (2011) and Jackson et al. (2013), poor well integrity is a far more likely cause of elevated concentrations of thermogenic methane in shallow groundwater and water supplies than pathways induced solely by hydraulic fracturing. Examples of leaks in shale gas wells have been reported and fines imposed (Roberts, 2010).

8.5. Implications and recommendations

As with our study, King and King (2013) addressed statistics on well barrier and integrity failure. They compared the data with that of other polluting activities in the USA, such as storage tanks, septic

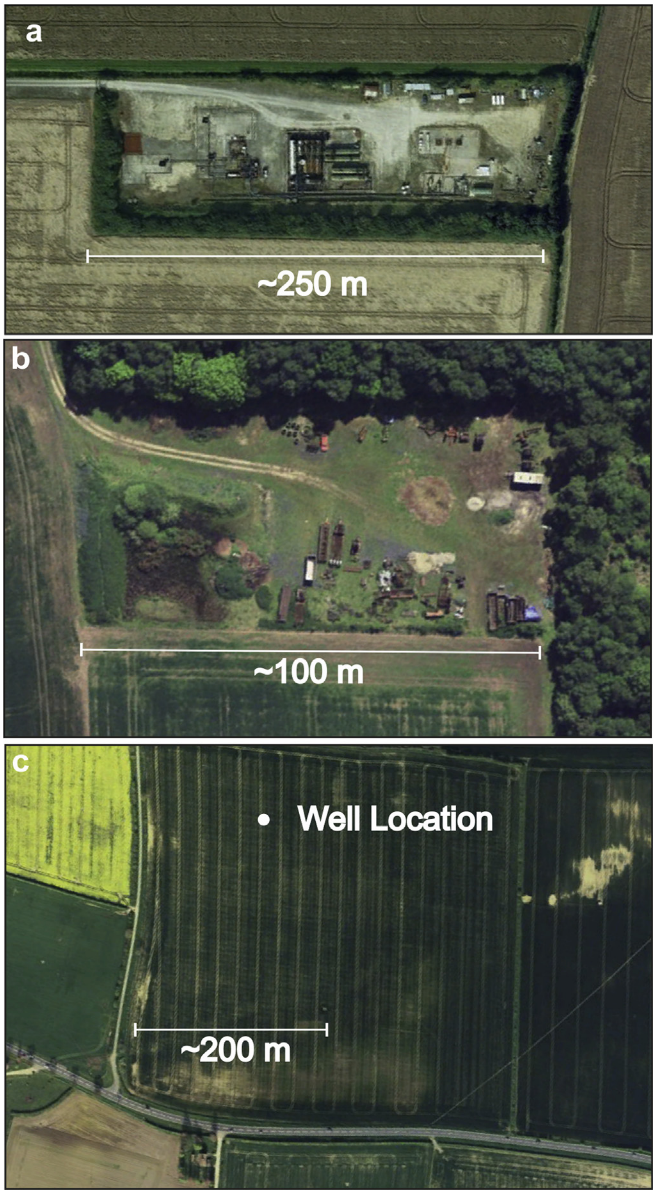

Figure 13. Examples of wells locations taken from UKOGL imaged with Google Earth, illustrating range of surface manifestations of UK onshore wells: (a) cleared area of land with appearance of being a maintained well pad; (b) cleared area of land with appearance of poorly maintained and potentially disused well pad. (c) Location of well drilling in which no well pad or machinery is visible.

tanks and landfills, and made the point that the number of reports of pollution from oil and gas wells was insignificant in comparison. Nevertheless, for the more than 4 million wells drilled in Australia, Austria, Bahrain, Brazil, Canada, Netherlands, Poland, UK and USA alone, there is scarce published or online data on well integrity or

Table 6
Estimated Ultimate Recovery (EUR) for 5 shale gas provinces in the USA (from Baihly et al., 2010).

Shale play	EUR after 30 years (BCF-0.028 BCM)
Barnett	3.0
Fayetteville	1.4
Woodford	1.7
Haynesville	5.9
Eagle Ford	3.8

barrier failure. Improved monitoring is crucial for a better understanding of chances of hydrocarbon well barrier and integrity failure and the impact of this. There are examples of good practice. The DEP database for Pennsylvania, USA, was used by Considine et al. (2013) to carry out a detailed breakdown of the types of well infringements and their severity. The Alberta Energy Resources Board (ERCB) database of well integrity failure for 316,439 wells reported by industry dating back to 1910 is not in the public domain, but the data summary is available (Watson and Bachu, 2009). In Alberta wells are checked for well integrity and barrier failure within 60 days of the drill rig being removed (Watson and Bachu, 2009).

In the UK there have been a small number of reported pollution incidents associated with active wells and none with inactive abandoned wells. This could therefore indicate that pollution is not a common event, but one should bear in mind that monitoring of abandoned wells does not take place in the UK (or any other jurisdiction that we know of) and less visible pollutants such as methane leaks are unlikely to be reported. It is possible that well integrity failure may be more widespread than the presently limited data show. Surveying the soils above abandoned well sites would help establish if this is the case. In terms of monitoring, abandoned wells could be checked 2–3 months after cement plugging for sustained casing pressure and gas migration. If the well has no evidence for barrier or integrity failure, it could be cut and buried as per regulations. Soils above well sites could be monitored every 5 years for emissions that are above a predetermined statutory level. As there are 2152 wells in UK at present, only 430 would need to be checked each year. Monitoring could be intensified or scaled down based upon the results of the first complete survey. Monitoring a proportion of future abandoned shale gas and oil wells should also be feasible. A mechanism may need to be established in the UK and/or Europe to fund repairs on orphaned wells, and an ownership or liability survey of existing wells would be timely.

9. Conclusions

Well barrier and integrity failure is a reasonably well documented problem for conventional hydrocarbon extraction and the data we report show that it is an important issue for unconventional gas wells as well. It is apparent, however, that few data exist in the public domain for the failure rates of onshore wells in Europe. It is also unclear which of the datasets used in this study will be the most appropriate analogues for well barrier and integrity failure rates at shale gas production sites in the UK and Europe. Only 2 wells in the UK have recorded well integrity failure (Hatfield Blowout and Singleton Oil Field) but this figure is based only on data that were publicly available or accessible through UK Environment Agency and only out of the minority of UK wells which were active. To the best of our knowledge and in line with other jurisdictions (e.g. Alberta, Canada) abandoned wells in the UK are sealed with cement, cut below the surface and buried, but are not subsequently monitored. This number is therefore likely to be an underestimate of the actual number of wells that have experienced integrity failure. A much tighter constraint on the risks and impacts would be obtainable if systematic, long term monitoring data for both active and abandoned well sites were in the public domain. It is likely that well barrier failure will occur in a small number of wells and this could in some instances lead to some form of environmental contamination. Furthermore, it is likely that, in the future, some wells in the UK and Europe will become orphaned. It is important therefore that the appropriate financial and monitoring processes are in place, particularly after well abandonment, so that legacy issues associated with the drilling of wells for shale gas and oil are minimised.

Table 7
Crude oil pollution incidents within 1 km of 143 well pads active in UK at start of year 2000.

Event no.	Date reported	Lat.	Lon.	Cause	Due to well integrity failure (Y/N)	Environmental impact		
						Air	Land	Water
981998	18/04/2012	51.19415	−1.009848	Pipe Failure above ground	N	No Impact	Minor	No Impact
639443	08/12/2008	50.93129	−0.74344026	Other	Y	No Impact	No Impact	Minor
685648	08/06/2009	50.92439	−0.73782083	Other	Y	No Impact	No Impact	Minor
137932	19/02/2003	50.66674	−2.0292232	Accidental spillage	N	No Impact	No Impact	No Impact
838199	14/11/2010	50.66655	−2.0290391	Pipe failure below ground	N	Minor	Minor	No Impact
157014	09/05/2003	50.66737	−2.0287566	Control system failure	N	No Impact	No Impact	Minor
138317	21/02/2003	50.67028	−2.0162917	Pipe failure above ground	N	No Impact	No Impact	No Impact
428461	18/08/2006	50.67125	−1.9866881	Pipe failure above ground	N	No Impact	No Impact	No Impact
8177	07/06/2001	50.68239	−1.9825378	Pipe failure below ground	N	No Impact	Minor	Minor

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Review

Deep challenges for China's war on water pollution☆

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ABSTRACT

China's Central government has released an ambitious plan to tackle the nation's water pollution crisis. However, this is inhibited by a lack of data, particularly for groundwater. We compiled and analyzed water quality classification data from publicly available government sources, further revealing the scale and extent of the crisis. We also compiled nitrate data in shallow and deep groundwater from a range of literature sources, covering 52 of China's groundwater systems; the most comprehensive national scale assessment yet. Nitrate pollution at levels exceeding the US EPA's maximum contaminant level (10 mg/L NO_3 N) occurs at the 90th percentile in 25 of 36 shallow aquifers and 10 out of 37 deep or karst aquifers. Isotopic compositions of groundwater nitrate ($\delta^{15}N$ and $\delta^{18}O_{NO3}$ values ranging from 14.9‰ to 35.5‰ and 8.1‰ to 51.0‰, respectively) indicate many nitrate sources including soil nitrogen, agricultural fertilizers, untreated wastewater and/or manure, and locally show evidence of de nitrification. From these data, it is clear that contaminated groundwater is ubiquitous in deep aquifers as well as shallow groundwater (and surface water). Deep aquifers contain water recharged tens of thousands of years before present, long before widespread anthropogenic nitrate contamination. This groundwater has therefore likely been contaminated due to rapid bypass flow along wells or other conduits. Addressing the issue of well condition is urgently needed to stop further pollution of China's deep aquifers, which are some of China's most important drinking water sources. China's new 10 point Water Pollution Plan addresses previous shortcomings, however, control and remediation of deep groundwater pollution will take decades of sustained effort.

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1. Introduction: China's ‘war on pollution’ and the new 10-point plan

In 2014, Chinese Premier Li Keqiang publicly declared ‘war on pollution’ and the Chinese Central Government has since announced major policies in the area of pollution control and remediation (Branigan, 2014; Zheng, 2015). The Water Pollution Prevention and Control Action Plan (“10 Point Water Plan”) was released in April 2015 (Central People's Government of the People's Republic of China, 2015). This is arguably the most comprehensive policy yet aimed at tackling pollution of groundwater and surface water, which are recognized as being among the most severely degraded natural resources in China, and among the most heavily polluted water sources in the world (Ma, 2004; Gleick, 2009; Shapiro, 2012). Despite recent improvements in the provision of clean drinking water (Liu, 2015), it is estimated that more than 200 million people in China are still using unsafe water sources (Tao and Xin, 2014; Liu, 2015). Since 1995, it is estimated that 11,000 water quality related emergencies have occurred – a recent example being the contamination and temporary shutdown of the city water supply (sourced from groundwater) in Lanzhou, because of contamination by benzene from a nearby petrochemical facility (Yan, 2015). It is also estimated that each year thousands of in cidents of civil unrest related to water pollution take place in China, predominantly in rural areas (Gilbert, 2012).

The new water pollution action plan breaks from previous ap proaches to China's water crisis that focused on large scale engi neering solutions for the provision of clean water (e.g. Liu and Yang, 2012). The plan includes ambitious targets for improvement of

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groundwater and surface water quality over coming decades. The promulgation of this and the analogous 10 point plan for air pollution (Central People's Government of the People's Republic of China, 2013) signifies that China's new generation of leaders recognize that pollution poses a risk to China's ongoing develop ment and social stability, and are serious about improving the prospects for all Chinese people to have access to clean and secure water.

Control and remediation of water pollution requires accurate data to diagnose the nature and extent of the problem. While data collection and transparency has improved in China recently, there remain major gaps which hamper accurate assessment at the range of scales required, e.g., major river catchment or groundwater basin to sub catchment or sub basin (Liu, 2015). This is particularly true for groundwater, where data is sparse apart from aggregated regional or national statistics (Ministry of Land and Resources, 2014). In this review we address these gaps to the extent currently possible by: 1) compiling and visualizing the most up to date public data on water quality classes in China's rivers and aquifers from government statistics at national and regional scales; 2) compiling water quality analyses from published and unpub lished research sources, focusing on nitrate − a ubiquitous indicator of anthropogenic groundwater contamination; 3) compiling and analyzing data on the isotopic composition of nitrate, providing insight into major sources of pollution.

In doing so, we help to better illustrate the scale of China's water pollution challenges and uncover key processes driving ground water quality degradation. These data indicate that contamination of deep groundwater, which is generally thought to be a relatively safe source of drinking water, is occurring on a large scale, a phe nomenon which is poorly documented and may not yet be well understood by the relevant authorities. We argue that protection of this high quality groundwater should be a key focus in China's ongoing war against water pollution.

2. Materials & Methods

Data for the water pollution maps presented below (Fig. 1) were compiled from three major sources: China's Ministry of Land and Resources, Ministry of Environmental Protection and State Oceanic Administration bulletins (Ministry of Land and Resources, 2010; Ministry of Land and Resources, 2014; Ministry of Environmental Protection, 2014; State Oceanic Administration, 2015). The data in these bulletins do not include Hong Kong, Macao and Taiwan. Surface and seawater quality class data were aggregated onto a single map (Fig. 1a), color coded for the water quality classes set out in China's national standards. Groundwater data was converted into charts showing the percentage of water quality occupying the 5 different classes for shallow and deep groundwater, respectively, within six sub regions of China − the highest resolution data currently available (Fig. 1b). On top of these maps the locations of 351 ‘cancer villages’, as reported in Gong and Zhang (2013), were overlaid for reference and compiled by region (Table 1). Ground water nitrate data from 52 of China's major groundwater basins, including shallow and deep aquifers (Fig. 2), was compiled and extracted from 71 sources as either NO_3 or $NO_3{-}N$ (Supplementary Fig. S1). All raw NO_3 concentrations were converted to $NO_3{-}N$, and the data was again divided into ‘shallow’ and ‘deep’ groundwater according to the classification in the original source, or if this was not specified, a cut off depth of 100 m. Summary statistics, including median, 10th and 90th percentiles and inter quartile ranges were calculated for each dataset and aggregated as a set of box plots (Fig. 2). Nitrate isotope data ($\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$) were collected from 31 literature sources, covering ten groundwater systems across China (see Supplementary Table S1). These data were compiled and plotted on a bivariate plot showing typical ni trate source isotopic compositions (after Kendall and McDonnell, 1998) and a series of box plots showing ranges of isotopic values for different regions of China (Figs. 4 and 5).

3. Results: China's water pollution crisis − scale, extent and distribution

3.1. Overall water quality classification

China faces one of the most serious water shortage and pollu tion crises ever documented (Gleick, 2009; Tao and Xin, 2014). Based on data released by the Ministry of Environmental Protection (MEP), the State Oceanic Administration (SOA), and the Ministry of Land and Resources (MLR), we constructed pollution maps of the surface water and groundwater environments at the national scale (Fig. 1). Water quality in China is assessed according to a five or six class ranking system under the Environmental Quality Standards GB383 2002, GB3097 1997 and GB/T 14848 93 for surface, marine, and groundwater, respectively (Table 2). These classifications are universally recognized indicators of water quality in China. The water quality class is determined by monitored levels of ~30 indi cator pollutants and chemical indices, with the pollutant or index recorded at the highest concentration relative to guideline levels used to attribute water into one of the classes (Ministry of Environmental Protection, 2002). In general the indicators which most frequently exceed guideline levels by the highest amounts (and therefore determine water quality class) are ammonia N, ni trate, nitrite, biological oxygen demand (BOD) and chemical oxygen demand (COD) (World Bank, 2006).

Fig. 1a shows water quality data from major river basins and near shore coastal waters. Currently, out of 208,000 km of moni tored river reaches in China, water quality in 31.4% reaches falls into class IV or worse, and thus is unfit for potable use or human contact. Water quality in 14.9% of river reaches is inferior to class V, indi cating complete loss of potential for all consumptive uses or human contact. Of ten major watershed areas, only in the southwest and northwest is water quality in the majority of rivers rated as high to moderate (Classes I to III), while the major northern river systems − the Yellow, Liaohe, and Huaihe Rivers are rated as class IV or V, and the Haihe River as class VI (Fig. 1a). Water in six of nine major coastal bays in China is characterized as ‘poor’ or ‘very poor’ (Classes IV or V). In autumn 2014, the combined coastal area with water quality in class IV or V (unfit for human contact) covered 57,000 km^2. These areas are at the discharges of river systems that drain China's major industrial and agricultural regions, integrating numerous upstream pollution sources.

The quality of water in small tributaries feeding China's main river systems is generally recognized as being poorer than the main water courses themselves (Ebenstein, 2012; Yang and Zhuang, 2014). This is due to reduced dilution capacity of small streams compared to major rivers, and in some cases, poorer regulation of industrial wastewater discharge to small streams, which are typi cally in rural areas with poor environmental oversight. This means that surface water quality estimated at the national scale based on an assessment of water quality classes in major rivers (Fig. 1a) probably under estimates the severity of surface water pollution, as smaller tributaries are excluded.

Fig. 1b shows the most detailed nation wide data for ground water pollution currently available in government statistics, using China's 5 class groundwater quality rating standard. Groundwater accounts for one third of total water usage across the domestic, agricultural and industrial sectors in China, and approximately two thirds of cities utilize groundwater as a major water supply. According to the latest Bulletin of Land and Resources of China

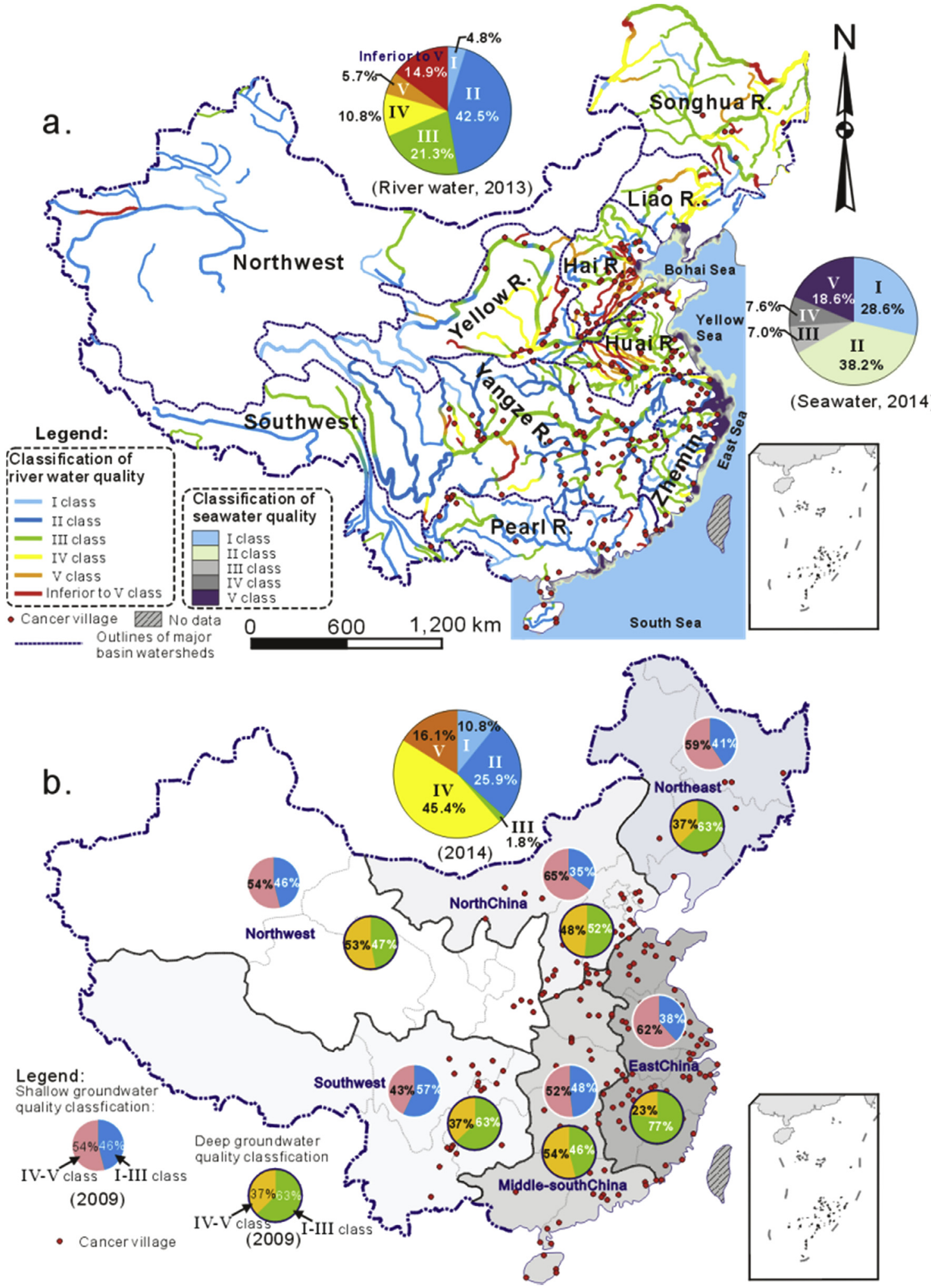

Fig. 1. Status of water pollution in China based on recent government statistics A) Surface water (major rivers and seawater) ranked according to the 6-class water quality classification (GB 3838-2002 see Table 1) and seawater quality of offshore areas ranked according to the 5-class classification (GB3097-1997); B) Groundwater ranked using the 5-class system (GB/T 14848-93) in 6 sub-areas of China, including shallow and deep groundwater. Overall percentages in each class for each water source in China are shown as the large pie-charts. Percentages shown in yellow and red on the smaller pie-charts on Fig. 1b indicate the proportion of samples in the lowest two classes (IV & V) for shallow and deep groundwater, respectively. Both maps (a & b) have been overlain with the locations of known 'cancer villages' (Gong and Zhang, 2013). For further detail on data sources and data processing see *Materials & Methods*.

Table 1
Cancer village distribution in China at provincial level, along with groundwater and river water quality classifications. CVN cancer village number; CVD cancer village density; CVN-r number of cancer villages distributed in areas with river water quality inferior to grade III. The percentages of groundwater in grades IV & V is the ratio of wells with these grades to the total monitoring wells of the province. For river water quality, the percentage refers to the ratio of control sections monitored to the total control sections of the province in a given water quality grade. Data on cancer village distribution are from Gong and Zhang (2013).

Province	CVN	CVD	Groundwater	River water classification (%)				CVN-r
			IV V class (%)	I III	IV V	Interior to V	Interior to III	
HeiLongJiang	6	0.13	57.5	56.7	37.7	5.6	43.3	5
JiLin	1	0.05	27	67.5	24.4	8.1	32.5	0
LiaoNing	8	0.57	62	42.1	27.6	30.3	57.9	5
HeBei	40	2.21	63	48.6	21.4	30	51.4	34
BeiJing	1	0.63	43	52	7	41	48	1
TianJin	3	2.67	48.5	3.8	22	74.2	96.2	3
ShanDong	30	2.03	60	39.2	30.9	29.9	60.8	26
JiangSu	24	2.46	23	37.2	42.1	20.7	62.8	14
ShangHai	1	1.65	19	12.5	30.8	56.7	87.5	0
ZheJiang	20	2.01	30	66.2	18.9	14.9	33.8	2
FuJian	12	0.99	41	82.2	10.5	7.3	17.8	1
GuangDong	25	1.4	69	76	14	10	24	0
HaiNan	9	2.54	15	93.1	6.9	0	6.9	0
Inner Mongolia	9	0.08	55.4	40.4	40.5	19.1	59.6	1
ShanXi	15	0.99	51	48.5	24.2	27.3	51.5	13
HeNan	31	1.94	60	37.9	28	34.1	62.1	29
HuBei	17	0.94	46	77.4	11.1	11.5	22.6	1
HuNan	15	0.72	29	95.5	4.5	0	4.5	0
AnHui	19	1.4	90	70.5	17.8	11.7	29.5	16
JiangXi	18	1.09	66	91.2	4.2	4.6	8.8	0
GuangXi	2	0.08	35	92.5	7.3	0.2	7.5	0
ChongQing	11	1.37	69	74.7	25.3	0	25.3	1
Sichuan	6	0.13	57	83.2	12.7	4.1	16.8	2
ShaanXi	5	0.25	54	36.4	38.9	24.7	63.6	4
GuiZhou	3	0.17	48	74.4	3.9	21.7	25.6	1
YunNan	20	0.52	44	82.5	8.3	9.2	17.5	0
GanSu	0	0	50	63	12.3	24.7	37	0
NingXia	0	0	57	60	40	0	40	0
XinJiang	0	0	37	91.3	8.5	0.2	8.7	0
QingHai	0	0		100	0	0	0	0
Tibet	0	0	43	100	0	0	0	0

(2014), groundwater from 61.5% of 4896 monitoring wells in 202 cities across China was characterized as poor (IV class) or very poor (V class) (Fig. 1b) (Ministry of Land and Resources, 2014). Addi tionally, according to a recently published monthly groundwater status report of the Ministry of Water Resources, 80% of ground water samples taken from more than 2000 shallow groundwater monitoring wells in China's northern basins falls into classes IV and V (Ministry of Water Resources, 2016). According to the national groundwater quality standard (GB/T 14848 93), water at or below Class IV is unfit for domestic or agricultural uses. The main pol lutants above safe levels in these assessments, and which therefore determine the water quality classes, are the three types of nitrogen (NO_3—N, NO_2—N, NH_4—N), phenol, heavy metals and COD.

These data, maps and comparisons with previous surveys con ducted by the Ministry of Land and Resources (Fig. 3) reveal two trends. One is a gradual expansion of the scale of groundwater pollution. The percentage of IV—V class water increased from 55.1% in 2011 to 61.5% in 2014; while an earlier assessment between 2000 and 2002 using fewer monitoring stations found the proportion in the lowest two classes was 37% (Shen, 2015). The second trend is increasing numbers of contaminants detected, signifying more complex pollution mixtures. However, as yet, individual data points and chemical concentrations are not disclosed in government data; the data is aggregated and reported as region wide percentages (Fig. 1b), or numbers of monitoring stations falling into the various classes.

A key concern arising from these data is extensive pollution of deep groundwater, contained in semi confined and confined aquifers, generally at depths greater than 100 m. This poses a challenge for future groundwater remediation efforts, as these aquifers (unlike shallow unconfined aquifers) are typically isolated from the rapid, surficial water cycle and require extremely long time periods — on the order of thousands of years — for natural flushing (Alley et al., 1999). Another concern is that while groundwater pollution does affect particular regions more or less seriously than others, both deep and shallow groundwater pollu tion is ubiquitous nation wide in China. The most seriously affected regions are the densely populated North China Plain, where drinkable groundwater (I—III class) was found to occupy only 22.1% of shallow groundwater and 26.4% of deep groundwater (Duan and Gao, 2013); similar to the data in the more recent Ministry of Water Resources survey (Ministry of Water Resources, 2016). However, the more sparsely populated areas of northwest China are also not immune from serious groundwater pollution in both shallow and deep aquifers (Fig. 1b).

3.2. Nitrate concentrations and isotopic data across China

In addition to the government statistics reporting water quality classes at the national level, we compiled data from 71 studies of groundwater quality from the research literature, documenting concentration ranges of nitrate N in 52 groundwater systems, including shallow (unconfined) and deep (confined) aquifers. We also compiled data for karst aquifers, where there is rapid vertical connectivity between different depths (Fig. 2). These data reveal a more detailed picture of the distribution of groundwater pollution by location and depth, basin by basin across China. Nitrate was selected for this purpose as it is an ideal 'gross' indicator of anthropogenic impact on groundwater, for the following reasons:

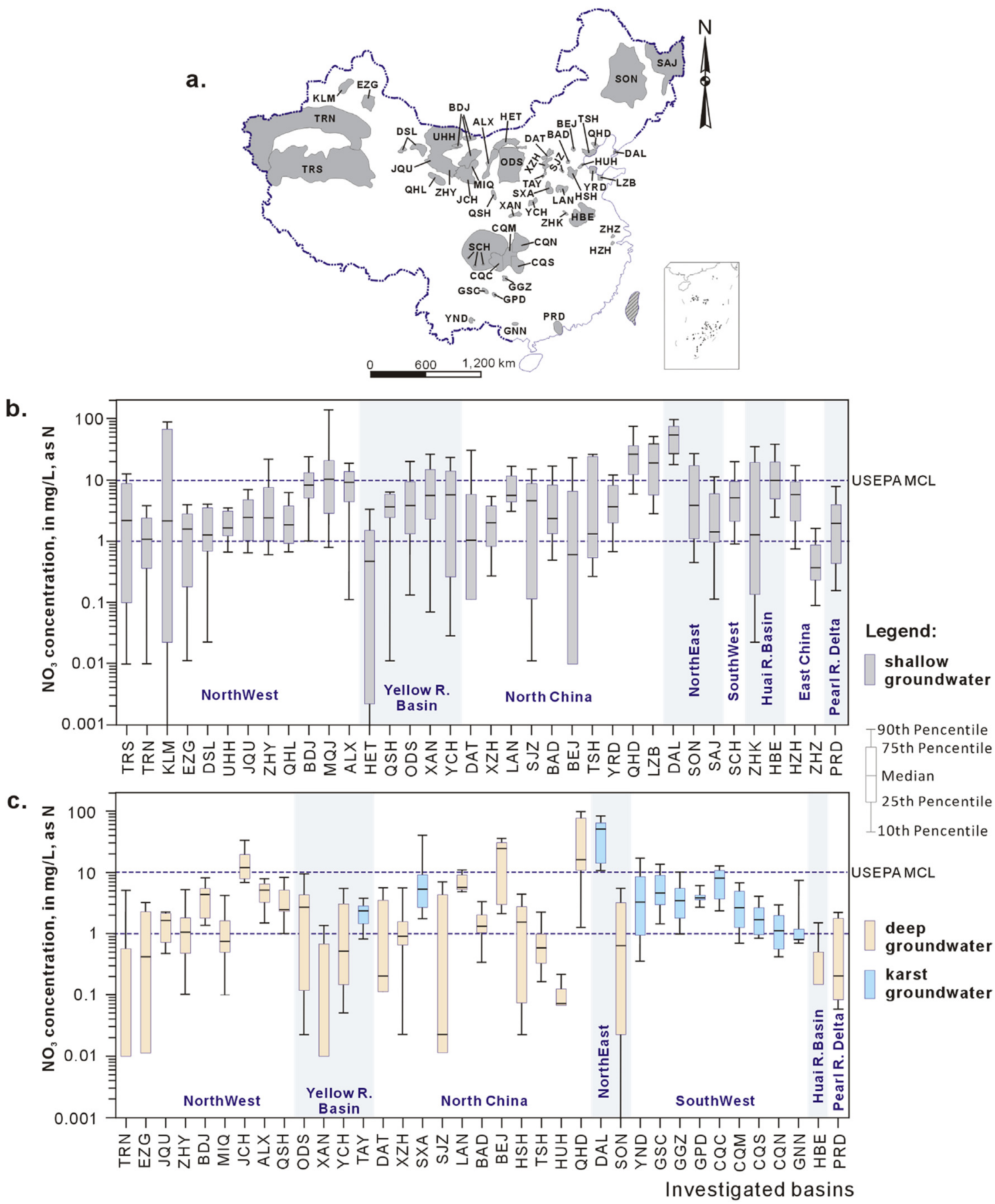

Fig. 2. Nitrate concentrations in groundwater from major groundwater systems in China: a) Location map of the 52 total study areas from which data were compiled; Boxplot distributions of nitrate concentrations (as N) in shallow groundwater (b) and deep or karst groundwater (c) throughout China. Boxplots show median, inter-quartile range and 10th and 90th percentile values. Data is compared to the United States Environmental Protection Agency maximum contaminant level (10 mg/L) and a background concentration of 1 mg/L, according to Burow et al. (2010). The data reveal endemic nitrate pollution in deep and shallow groundwater throughout China. For the full key to the location map and all data sources, refer to Supplementary fig. S1 and accompanying references.

1. Unlike many inorganic contaminants (e.g. arsenic or fluoride), nitrate rarely occurs as a natural constituent in groundwater from geo genic sources (although naturally elevated levels can occur in desert areas, due to fixation by arid zone plants) (Heaton, 1986).
2. It is one of the most readily analyzed contaminants and a large amount of data is available.
3. Nitrate has a range of agricultural, urban and industrial sources (e.g. fertilizers, sewage & animal waste, municipal, domestic and industrial wastewater discharge), and it is highly soluble. Therefore, it is likely to be one of the most common (if not the most common) contaminants, serving as an index pollutant for many different pollution sources, mechanisms and processes.

Nitrate is also an important contaminant from a human health perspective, as it has been linked to chronic illness of the digestive system and increased incidence of digestive cancers, which are widespread in parts of China with severe water pollution (World

Table 2
Surface water quality standard 6-class rating system.

Grade	Classification/applicable uses
I	Pristine water sources (e.g. river headwaters and protected natural catchment areas)
II	Class A water source protection areas for centralized drinking supply
III	Class B water source protection areas for drinking supply and recreation
IV	Industrial water supply and recreational water with no direct human contact
V	Limited agricultural water supply
VI	Essentially useless

Source: Ministry of Environmental Protection (2002).

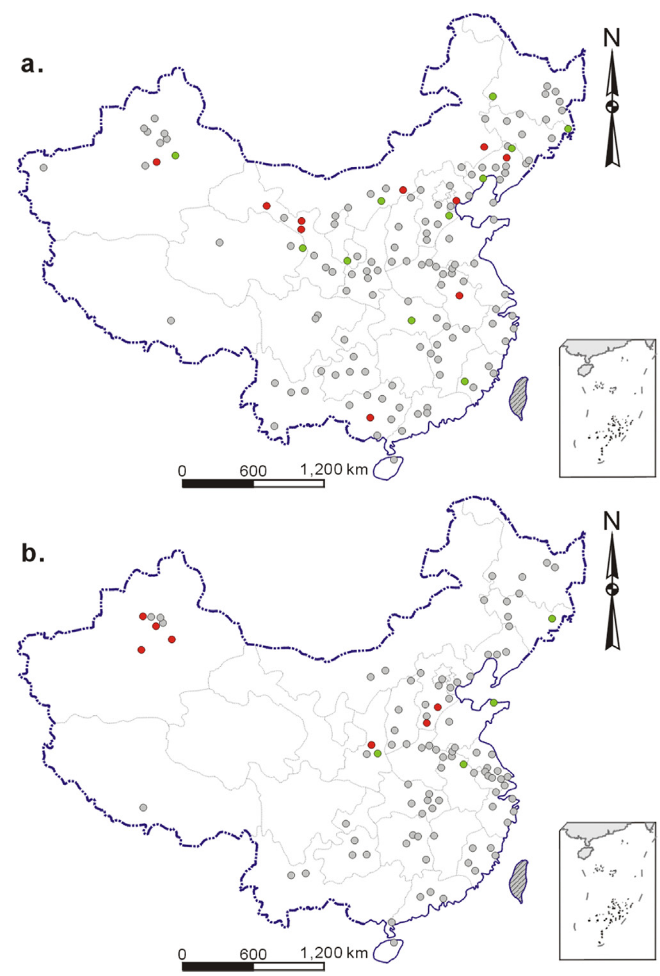

Fig. 3. Distribution of monitored sites where changes in water quality grade occurred between 2008 and 2009 for a) shallow groundwater and b) deep groundwater. Green grade improved; grey grade stable; red grade deteriorated. Modified from Ministry of Land and Resources (2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Bank and State Environmental Protection Administration, 2007; Ebenstein, 2012).

Boxplots of NO_3−N data from the groundwater basins across China are shown in Fig. 2 along with the US EPA maximum contaminant level (MCL) of 10 mg/L, which is approximately equivalent to the World Health Organization standard of 50 mg/L nitrate as NO_3. According to the data, nitrate contamination is ubiquitous in China's groundwater. The MCL level is exceeded by the 90th percentile NO_3−N value observed in the majority of China's shallow groundwater basins (25 out of 36 study areas) as well as many deep and karst aquifers (10 out of 37 study areas). The MCL is also exceeded by the median nitrate N concentration in five shallow groundwater systems and four deep groundwater systems (all in northern China). The worst affected region is the coastal area adjoining the Bohai Sea, including Dalian (DAL); Laizhou Bay (LZB) and Qinhuangdao (QHD) (Fig. 2). All of these sub areas showed median nitrate concentrations above the MCL, with the highest median being 55 mg/L NO_3−N at Dalian (5.5 times the MCL). This area is where a number of northern China's rivers drain to the ocean, and where regional groundwater flows converge and discharge at the coast. Areas of karst groundwater are highlighted in blue on Fig. 2c. In these aquifers, it is known that circulation times are relatively short (due to many preferential flow pathways) and thus shallow and deep groundwater systems are typically in rapid connection. Most of the karst systems show nitrate levels with median values below the MCL (Fig. 2c).

As is typically expected where nitrate is derived from surface sources such as agriculture, sewage or wastewater discharge, ni trate pollution is more serious in shallow groundwater (NO_3−N concentration ranges from 0.1 to 1819.5 mg/L, n 627, median value 8.0) compared to deep groundwater (NO_3−N concentration ranges from 0.1 to 90.3 mg/L, n 118, median value 2.6) (Table S1). However, numerous samples from deep aquifers also show levels of nitrate that indicate anthropogenic contamination, including many samples above the MCL (Fig. 2c).

Figs. 4 and 5 show compiled isotopic compositions of nitrate, including $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$, for groundwater in ten major basins for which data were available (the raw data are contained in Table S1). Overall, the values range from 14.9 to 35.5‰ (n 595, mean 9.5‰, median 8.6‰) for $\delta^{15}N_{NO3}$ and 8.1−51.0‰ (n 255, mean 10.2‰, median 8.2‰) for $\delta^{18}O_{NO3}$ in shallow groundwater. In deep groundwater, the isotopic values range from 8.0 to 14.4‰ (n 89, mean 6.7‰, median 6.8‰) for $\delta^{15}N_{NO3}$ and 2.3−39.6‰ (n 67, mean 10.1‰, median 7.5‰) for $\delta^{18}O_{NO3}$. As shown in Fig. 5 the $\delta^{15}N_{NO3}$ values are generally lower in samples from the northwest of China and lower Yangtze River basin, while $\delta^{18}O_{NO3}$ values show similar ranges (with me dians between 6.2 and 9.0‰) in the majority of basins, except for the northwest, which showed a higher median value (25.9‰). The wide ranges in observed isotopic values of nitrate indicate that nitrate in China's groundwater derives from multiple sources as opposed to one single, dominant source.

4. Discussion

4.1. Major sources of contamination and mechanisms of contaminant spread

Major sources of surface water and groundwater contamination in China include un regulated sewage and municipal wastewater discharge, industrial wastewater discharge and agricultural fertil izers and pesticides (World Bank and State Environment Protection Agency, 2007; Liu and Yang, 2012; Tao and Xin, 2014). Comparisons of pollution load by source indicate that on aggregate, agricultural sector pollution outweighs urban and industrial sources in terms of major water quality indicators such as nitrogen (as nitrate, nitrite and ammonia) and phosphorus (Watts, 2010). However, both sec tors are significant contributors to water pollution, and regional variation in the dominant source depends on the intensity of each sector and the degree of local pollutant discharge regulation. The widespread nitrate contamination documented in Fig. 2 is in large part related to agricultural non point source pollution, as has been documented in previous studies (e.g. Chen et al., 2005; Ju et al., 2007). Areas such as the northwest of China and North China Plain are intensively cultivated, and nitrate contamination from

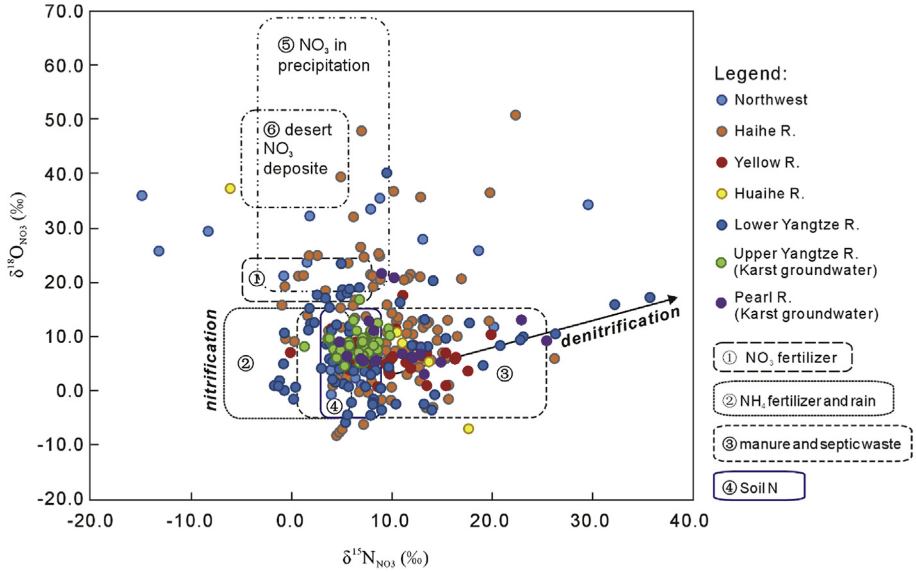

Fig. 4. $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$ values of NO_3 in groundwater samples from different watersheds.

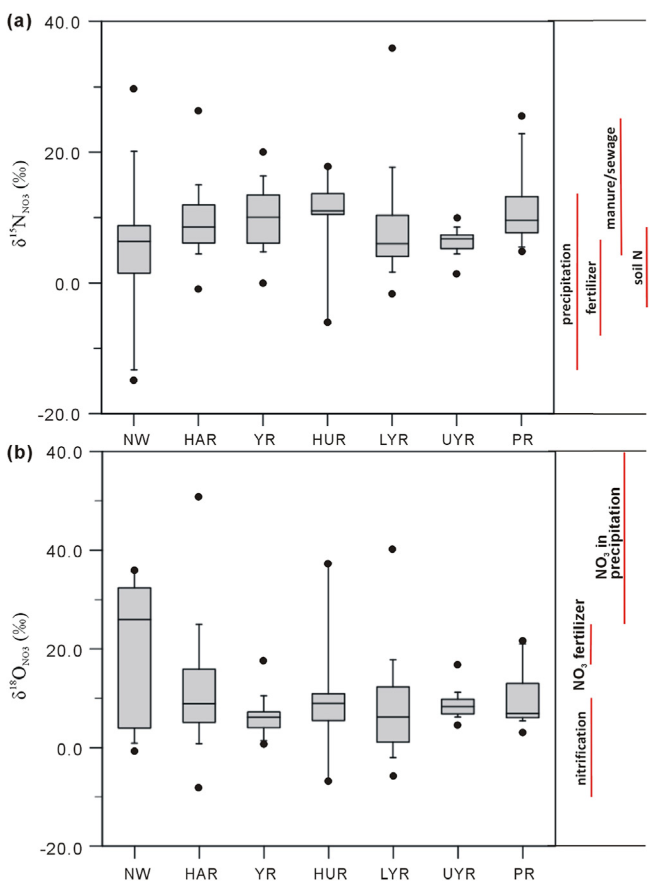

Fig. 5. Compositions of nitrogen and oxygen isotopes of nitrate in groundwater from different basins in China. The lower and upper edges of the box represent 25 and 75 percentiles of all data; the lower and upper bars represent 10 and 90 percentiles of all data; the dots outside of the box and bars represent the maximum and minimum values. NW- northwest basins (numbers of water samples: n 17); HAR- Haihe River basin (n 120); YR- Yellow River basin (n 38); HUR- Huaihe River basin (n 5); LYR- lower reach of Yangtze River basin (n 80); UYR-upper reach of Yangtze River basin (Southwest karst groundwater) (n 44); PR- Pearl River (Southeast karst groundwater) (n 16). Datasets are included in Table S1. The range in isotopic values attributed to different sources are derived from Jin et al. (2015) and references therein.

excess fertilizer appears to be one of the dominant sources in these areas. For example, in northwest China, the $\delta^{15}N_{NO3}$ values group near 0‰, and $\delta^{18}O_{NO3}$ values are between 0 and 25‰ (e.g. Fig. 5 and Supplementary Fig. S2). Nitrate in agricultural regions with higher $\delta^{15}N_{NO3}$ values (e.g. up to 10 or 15‰) may also be derived from excess fertilizer, with subsequent fractionation during de nitrification having enriched the residual ^{15}N in the pool (Fig. 4; Mayer et al., 2002; Kendall et al., 2007). Over usage of fertilizer and pesticide in China is well known, with average per unit area ap plications on farmland 2.8 times and 3 times the world average, respectively (Ministry of Environmental Protection, 2011). Miner alization of organic nitrate due to soil cultivation is also a well documented process (e.g. Heaton, 1986), and many of the sam ples compiled show isotopic values consistent with this source (Fig. 4). This is likely a result of the intensive cultivation practices which have emerged in China over recent decades.

It also appears that septic or other sewage waste and/or animal manure are important sources of nitrate in the groundwater in many regions. Areas such as the Haihe River basin, Huaihe River basin and Pearl River Delta are heavily urbanized, and wastewater discharge to surface water is a well documented problem (World Bank and State Environment Protection Agency, 2007; Yang and Zhuang, 2014). The nitrate isotope data in these three areas (me dian $\delta^{15}N_{NO3}$ values of 8.6, 8.4 and 9.6‰, respectively) and possibly the Yellow River Basin near the city of Xi'an (median of 10.1‰) are all consistent with wastewater being a primary source (Fig. 5; Table S1).

Nitrate contamination shows a predictable trend of decreasing concentration with increasing sample depth, consistent with sur face sources being attenuated during downward transport (by dilution and/or de nitrification). Nitrate concentrations have also been shown in some studies to correlate with tritium contents in groundwater – an indicator of recent recharge (Liu and Chen, 2009; Han et al., 2011). These trends indicate that shallow aquifers are particularly vulnerable to be polluted by surface activities. A basin scale process impacting groundwater quality in China has been the recent switch in the predominant recharge source from natural infiltration of rainfall and surface water to return flow from agri cultural irrigation (O'Dochartaigh et al., 2010; Currell et al., 2012). The process is due to a combination of extensive dam building in mountainous areas, which has prevented natural flooding over the most productive groundwater recharge areas, along with intensive over irrigation in agriculture. Irrigation return flow is generally high in salts, nitrate and agricultural chemicals, and so this switch in recharge mechanism has resulted in major diffuse groundwater pollution (Ju et al., 2007). This is a global problem in semi arid regions (Scanlon et al., 2007), but it is particularly serious in China (Currell et al., 2012); the nitrate data in this study provide further evidence that the process is widespread. Our data also show that wastewater discharge is an important source of nitrate pollu tion in groundwater. Due to intensive pumping of groundwater, many surface water systems in northern China have become 'losing' (Cao et al., 2016) and thus waterways impacted by wastewater discharge can readily act as pollution sources to the underlying aquifers.

The data in Fig. 2 also reveal extensive contamination of deep groundwater by nitrate, particularly in the northern basins (Fig. 2c). This indicates that a pathway must exist which allows contami nants from the surface to reach deep aquifers (including those that are confined by low permeability aquitards). Groundwater age dating studies carried out in the North China Plain and other ba sins indicate that much of the deep groundwater in confined sys tems was recharged 10s of thousands of years before the present, indicating circulation and replenishment on geological time scales (Kreuzer et al., 2009; Currell et al., 2010, 2012). Therefore, the contamination of these deep aquifers by anthropogenic nitrate must be taking place due to 'short circuit' or 'bypass flow', such as rapid transport down faulty or abandoned wells, or those which are constructed with long open screened intervals, providing inter connection between shallow and deep groundwater bodies.

The boom in groundwater development in China over the past 3 4 decades has seen drilling of millions of wells across the nation – it is estimated that over 4.5 million wells have been drilled in northern China alone (Shen, 2015). Many of these wells are known to be screened across multiple aquifers (Wang et al., 2007). These wells create a large number of potential conduits between shallow and deeper aquifers (Fig. 6). This opens the possibility that deeper aquifers containing high quality water, which would naturally have much lower vulnerability to pollution from surface activities, may not be isolated from polluting surface activities (Fig. 6). Due to the general absence of well licensing and maintenance systems, the condition and integrity of all deep wells can't be guaranteed, and cross contamination is in some regards inevitable (Shen, 2015). This type of short circuiting is the only way to explain the observed high nitrate concentrations at hundreds of meters depth in some cases. Currell et al. (2010) documented groundwater samples confined groundwater in the Yuncheng Basin as deep as 180 m, with nitrate N concentrations of more than 45 mg/L. The observation of tritium (an indicator of modern recharge) in selected samples of deep, ni trate contaminated water (Han et al., 2014) is further evidence of this 'short circuiting' mechanism.

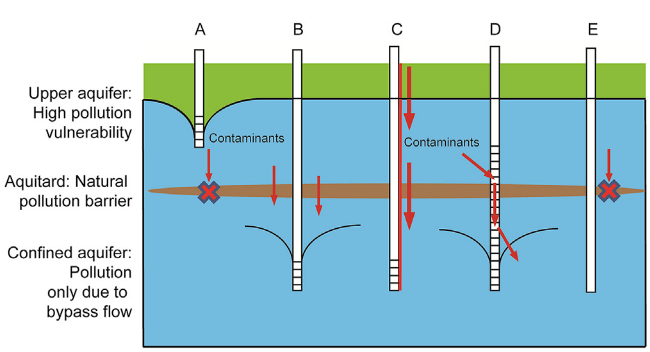

Fig. 6. Schematic diagram showing potential mechanisms of bypass flow leading to contamination of deep groundwater. Red arrows indicate transport of pollutants towards deep aquifer. A) Groundwater pumping only in shallow unconfined aquifer; low risk of pollution crossing aquitard; B) Intensive pumping of deep groundwater (from intact wells) results in slow leakage of shallow groundwater across aquitard; C) Faulty well annular sealing creates conduit for contaminants to bypass aquitard and pollute deep groundwater; D) Long-screened well allows contaminants to cross aquitard through the well; E) Cemented deep well prevents contamination crossing aquitard. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

While the nitrate data do tend to confirm findings from previous assessments that water pollution from agriculture is widespread, urban sources are also significant drivers of water quality degra dation in China. The Bulletin of the Ministry of Land and Resources data (Fig. 1b) are mostly sourced from wells in urban areas, and these generally show relatively high levels of ammonia, COD and organic contaminants, indicating predominantly industrial pollu tion sources. Unfortunately, detailed results of surveys of organic water pollutants and heavy metals in aquifers in China are rare; meaning detailed attribution of sources and mechanisms is more difficult than for agricultural pollution. However, a 2013 investi gation revealed a large discrepancy (over 1×10^{11} tons) in the amount of water supplied to China's industries and the amounts of reported industrial wastewater discharge, leaving a large volume of potentially polluted water unaccounted for. This has led to the conclusion that industries have been engaging in illegal discharge of wastes to surface water through unmonitored discharge points, and groundwater, through secret disposal wells (Ministry of Environmental Protection, 2011). Further publication of site specific data on pollutant concentrations in urban areas in future would greatly assist future pollution control and clean up efforts.

The rapid urbanization currently occurring in China also should not be ignored in the discussion of pollution sources and mecha nisms. Rapid urbanization is creating many new pollution chal lenges, such as the need to collect and treat increasing volumes of urban sewage, and the loss of arable land through urban expansion and soil pollution (Chen, 2007).

4.2. Implications and consequences of water pollution

The datasets compiled in this study, including government data on water quality classes at the river basin/regional level, ground water nitrate data at the basin scale and nitrate isotopic data, show that groundwater pollution is ubiquitous throughout China, with no region unaffected. On the whole, the most serious contamina tion occurs in the north of China, where surface water pollution is also most severe (e.g. Fig. 1). It is widely recognized that the North China Plain, a focal point for both intensive agriculture and inten sive heavy industry, is the location of China's biggest water and other environmental challenges (Shapiro, 2012). This is also the area where 'cancer villages' are most densely distributed in China (Table 1). Cancer villages are population centers where the inci dence of cancer morbidity or mortality is significantly higher than national averages (Liu, 2010; Wan et al., 2011; Gong and Zhang, 2013; Yang and Zhuang, 2014). The first Chinese cancer village was documented in 1954, however by the end of 2011 this number had reached 351, including 186 arising between 2000 and 2009, causing some to call this China's 'decade of cancer' (Gong and Zhang, 2013). A seven year study led by the former deputy direc tor of China's Center for Disease Control and Prevention showed that residents of tributary areas of the Huaihe River basin died in significantly higher proportions due to digestive tract tumors than more distant control areas, and that rates of cancer morbidity rose from below national averages in 1973 74, to significantly higher than China's national average in the 2000s for liver, gastric and esophagal cancers (Yang and Zhuang, 2014). This agrees with pre vious epidemiological studies which have linked these cancer types to chronic exposure to water pollution (Ebenstein, 2012).

Perhaps the most significant issue illustrated by the data is the widespread pollution of groundwater in deep semi confined and confined aquifers (Fig. 2). Contamination of these groundwater bodies is arguably more concerning than widespread shallow groundwater contamination, as the timescales of recharge and residence in deep aquifers are on the order of tens of thousands of years (for a compilation of groundwater ages determined using radiogenic isotope dating throughout major basins of northern China, see Currell et al., 2012). This means that there is limited capacity for natural flushing and dilution of contaminated groundwater on timescales of relevance to current human societies (e.g. Gleeson et al., 2016). Any future efforts to remediate these deep systems will therefore be costly, technically challenging and possibly of limited effectiveness. The Chinese government has also recently responded to concerns about high levels of shallow groundwater pollution in northern China by assuring the public that most drinking water supplies are derived from deep wells, which are naturally less vulnerable to contamination (Buckley and Piao, 2016). This indicates that 1) many people depend on deep groundwater for drinking water, and thus protection of its quality is critically important; 2) there is a belief that pollution pathways to these deep aquifers are limited. However, the data in this study indicate that this is not necessarily the case and that widespread pollution of deep aquifers is already underway. Given the evidence for bypass flow in the form of elevated nitrate in deep groundwater samples, it is likely that many other contaminants, including more recalcitrant and hazardous organic substances may have also been transported to deep levels, but that the available data is not yet detailed enough to document all such impacts. This is a major concern that should be addressed through targeted sampling of deep aquifers and analysis of a range of representative pollutants.

4.3. The 10 point water pollution action plan: the beginning of new era for China?

The *10 point Water Pollution Prevention and Control Action Plan of the Government of the People's Republic of China* was released in April of 2015 (Central People's Government of the People's Republic of China, 2015; Zheng, 2015). The major action points of the plan are:

1. Take control of and reduce pollutant discharge
2. Promote transformation of the economic structure (to lower pollution intensity)
3. Focus on protection of water resources through water saving
4. Strengthen support for science and technology
5. Allow market mechanisms to impact water and pollution levies
6. Strict environmental law enforcement & supervision
7. Strengthen the management of the overall hydrological cycle
8. Ensure security of water for ecological and environmental purposes
9. Confirm and implement the responsibilities for all parties involved
10. Strengthen public participation and social supervision

Major goals of this ten point water plan are that by 2020, 70% of surface water quality in the seven major river basins will be of classes I – III, while no more than 15% of groundwater monitoring points will be of the lowest class (V). The plan has a focus on drinking water safety, and will ensure management and supervi sion of the water supply process ‘from source to tap’. The national and regional water security situation for drinking water will be reported annually from 2016 onwards.

The plan introduces new incentives and penalties for water polluting industries, promising to periodically announce lists of poor performing enterprises, and giving out ‘yellow cards’ and ‘red cards’ based on annual performance. League tables of the worst and best performing 10 cities in each year will also be reported based on pollution control and water quality class improvements. A lack of positive or negative incentives for government officials to address water pollution has in the past been identified as a major barrier to the effective control of water pollution in China (Liu and Yang, 2012; Tao and Xin, 2014).

Several other aspects of the plan differ from previous approaches:

1. It lays stress on the philosophy of total water cycle health including groundwater, surface water and marine water, acknowledging their connections. It directly addresses seaport pollution control, which has been given less attention in past environmental policies.
2. It aims to give rise to the development of an extensive envi ronmental protection industry and environmental protection services sector, creating a new area to boost sustainable eco nomic growth. The implementation of the plan is expected to contribute to service sector growth as a share of GDP by 2.3%, including a cumulative increase in non agricultural employ ment of 3.9 million people.
3. It clearly assigns monitoring and compliance responsibilities to particular agencies and responsible persons. This has been a major hurdle to successful water management policy in China in the past, as institutional overlap and lack of clarity on ac countabilities have left many issues un resolved (Liu and Yang, 2012; Liu, 2015; Shen, 2015). Under the new plan, agencies are being charged with particular responsibilities (Table 3) and will be held accountable through performance assessments.

The success of the plan will heavily depend on inter agency co operation and coordinated implementation at regional and local scales. The issue of non cooperation between different agencies or levels of government and/or lack of clearly defined roles and re sponsibilities has hindered many previous attempts at improving environmental governance in China and it is still a major hurdle to effective groundwater management (Cai, 2008; Shen, 2015). This has caused cynicism among some Chinese citizens, who have coined sayings such as “The Ministry of Environmental Protection won't step into the water and the Ministry of Water Resources won't step ashore”. Laws and regulations related to water resources have thus been characterized by weak enforcement and inconse quential penalties for non compliance (Ma, 2004; Cai, 2008). On the other side, for many enterprises, costs of sewage treatment and pollution control technology have been prohibitive, and in combi nation with the weak regulatory regime, have fostered a culture which has long tolerated un regulated discharge of pollution.

The 10 point plan does address these key issues to an extent, through setting new incentives and penalties for officials and in dustries and ‘naming and shaming’ through the league tables. However the detailed workings of the incentive and deterrence measures, and the relationship between these and existing and/or conflicting incentives and performance targets are complicated. It is therefore difficult to predict how implementation of the plan will unfold in the coming years. One certainty is that without clear, accurate and transparent data on the scale and extent of pollution and its sources, the co ordination between agencies and control and clean up efforts will prove difficult (Qin, 2016). While our data compilation is a preliminary attempt to synthesize disparate datasets on water pollution, there are still many data gaps.

One area of particular importance which we have identified and

Table 3
Government agencies primarily involved in water management in China and their roles under the 10-point water pollution action plan (Central People's Government of the People's Republic of China, 2015).

Agency name	Primary responsibilities	Leading role(s) under the 10-point water plan
Ministry of Housing and Urban-Rural Development	Municipal water supply, drainage, construction of sewage treatment plants	*Points 1 and 3 of the plan.* Strengthen urban pollution control, strengthen the construction of supporting pipe networks, promote sludge disposal and recycled water use, strengthen urban water saving
Ministry of Agriculture	Management of agricultural pollution (non-point source); fisheries & wildlife conservation	*Points 1, 3 and 8 of the plan.* Promote agricultural rural pollution prevention, control agricultural non-point source pollution, adjust the planting structure and layout, promote the ecological health of aquaculture, develop agricultural water-saving
Ministry of Water Resources	Protection of water resources; flood control and drought relief; water withdrawal licences; *trans*-boundary water conflicts	*Point 3 of the plan.* Monitor and oversee the total quantity of water, improve water use efficiency, protect water resources scientifically, strengthen the management of rivers and lakes, determine ecological flow limits, strict control on groundwater exploitation, pay special attention to industrial water-saving, develop water-saving agriculture
Ministry of Land and Resources	Monitoring and protection of groundwater resources	*Point 3 of the plan.* Actively protect ecological space, strict control of groundwater exploitation
Ministry of Environment Protection	Pollution control, water quality monitoring; wastewater discharge monitoring; environmental impact assessment	*Points 1, 2, 6, 7, 8, 9 and 10 of the plan.* Vigorously promote the prevention and control of industrial pollution, carry out a special program to control pollution from ten key industry types, centralized management of industrial agglomeration, speed up comprehensive improvement of the rural environment, strict environmental law enforcement, ensure the eco-hydrological environmental security, confirm and implement the responsibilities for all parties, strengthen public participation and social supervision.
National Development and Reform Commission	Governance of major river basins	*Points 2, 4 and 5 of the plan.* Promote sustainable seawater desalination, develop the environmental protection industry, set the price of taxes and fees, establish incentive mechanisms, speed up the development of environmental services, improve levy policies, examination of results of water pollution prevention and control for relevant capital allocation, promote pluralistic financing of improvement projects, lead optimization of land-use and water network layout
State Oceanic Administration	Supervision, monitoring and control of marine pollution	*Point 8 of the plan.* Strengthen the near-shore environmental protection, protect marine ecological health
Ministry of Transport	Marine pollution control (shipping)	*Point 1 of the plan.* Strengthen port pollution control and prevention
Ministry of Industry and Information Technology	Prevention and control of industrial water pollution	*Point 2 of the plan.* Adjust the industrial structure, promote exit of polluting enterprises, pay special attention to the industrial water-saving, lead optimizing land-use zoning & urban growth layout

which is currently not addressed in the 10 point plan is ensuring the integrity of water (and other) wells, so that these do not act as pollution pathways between shallow and deep aquifers. A well licensing, maintenance and decommissioning program at the appropriate jurisdictional level(s) should thus be an urgent priority. As noted above, statements from the Ministry of Water Resources suggest that this agency believes that sourcing drinking water supplies from deep aquifers ensures that these water supplies are isolated from surface pollution impacts; yet the data we have compiled indicate that this is not always the case, and that urgent action to cut pollution pathways is needed.

5. Conclusions and recommendations

A review and compilation of data on the water quality classes in groundwater and surface water at the regional and national scale shows that China faces a huge water pollution challenge in all parts of the country. As yet, the publicly available government data on water quality consists of aggregated regional indices, as opposed to detailed data on individual pollutants at the catchment or basin scale. Our compilation of groundwater nitrate data from the research literature for the first time enables a more detailed na tional assessment of the degree of water pollution. In particular, it highlights the issue of pollution of deep aquifers that are generally thought to be relatively isolated from the surficial hydrological cycle.

China's new 10 point Water Plan offers hope that China has reached a turning point with respect to water pollution. Based on our analysis of the groundwater and surface water pollution data, and a reading of the 10 point plan in this context, we offer the following recommendations:

1. Apart from controlling pollution sources and reducing discharge of wastewater to streams and shallow aquifers (a focus of the plan), effort needs to be concentrated on the problem of groundwater well integrity, to protect deep groundwater aqui fers from further pollution. Our analysis indicates by pass flow from poorly constructed wells has caused widespread contam ination of deep groundwater with nitrate, and therefore prob ably other contaminants. A program of well cementing and decommissioning aimed at cutting these pathways, and new standards for well licensing and construction are vital, as deep aquifers contain particularly high quality water and are almost impossible to remediate once contaminated.
2. Our analysis confirms that non point source pollution (with nitrate and related compounds) due to agriculture is a major issue affecting groundwater quality nation wide (as well as wastewater discharge). There still exists no quantifiable stan dard in China to control non point source pollution from fer tilizers. A further step should thus be to establish standards for improving farming practices to effectively control application of chemical fertilizers and pesticides.
3. Water quality monitoring and data disclosure, particularly for groundwater, should be improved. To date, government agencies have only reported spatially aggregated data (rather than specific monitoring points or even catchments/sub

catchments). This hampers efforts to encourage public participation in local pollution control and remediation action.

4.Due to increasingly complex arrays of pollutants being detected in recent years, the standards for surface and ground water quality should be updated. The quality standard for groundwater (GB/T 14848 93) is more than 20 years old and should be amended to include additional contaminants of potential concern such as persistent organic pollutants known to pose significant health and ecological risks (e.g., polycyclic aromatic hydrocarbons, polychlorinated biphenyls and organochlorine pesticides) as well as 'emerging' groundwater contaminants which are particularly important in urban and industrial areas – such as pharmaceuticals and their residues (e.g. Lapworth et al., 2012; Lapworth et al., 2015).

China's war on water pollution has just begun, and it will be fight that will take decades. If China can learn from international experiences, and build on the current momentum and political will, we believe great progress can be made under the new 10 point plan.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2016.08.078.

The typical ranges of isotopic values for various sources are from Kendall and McDonnell (1998).

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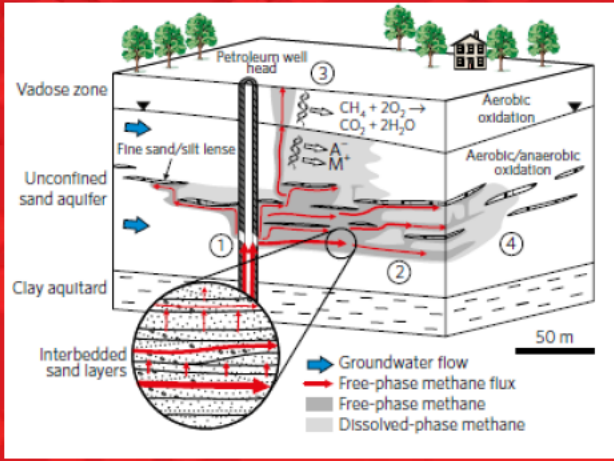
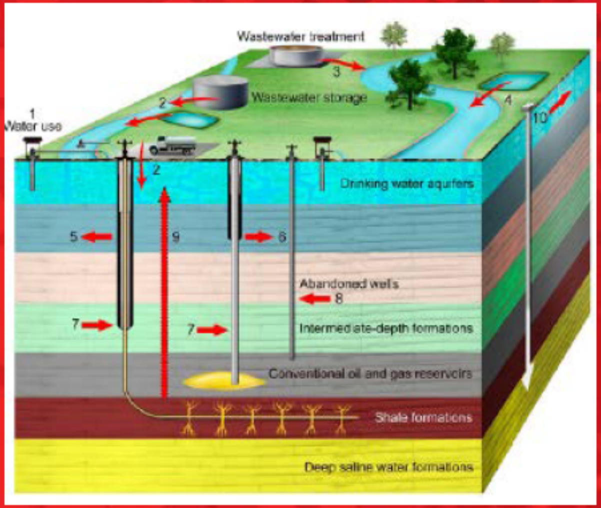
Hydraulic fracturing and groundwater protection in the Northern Territory





Dr Matthew Currell
Senior Lecturer, Environmental Engineering
School of Engineering
RMIT University

1. The need for baseline data: What type of data are required?

- What is a ***baseline*** for unconventional gas development?

1. Pre-existing datasets: e.g. historic time-series of groundwater levels and groundwater quality data in aquifers above/adjacent to gas deposits

plus

2. Understanding of the groundwater system(s) in question, which allows an observed change in water quality or quantity to be

a) Clearly detected

b) Explained e.g. what mechanism/activity caused the change and how?

➢ *All of these requirements must be met if a baseline monitoring program is to do its job properly, and provide unequivocal evidence of whether an unconventional gas-related impact has occurred or not*

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Why is baseline data important?

- Without it, impossible to detect or resolve the cause(s) of changes in groundwater quality or quantity due to gas development
- Likely that should there be an impact and/or a dispute (e.g. between a bore owner and a gas company), it will end in costly litigation, with the parties unable to conclusively resolve the matter.

➢ Bad for communities and bad for gas companies


ABC NEWS
LOCATION: Melbourne, Vic Change
Just In Australia World Business Sport Science Arts Analysis

CSG could increase methane emissions near 'bubbling' Condamine River, report finds

Exclusive by the National Reporting Team's Dominique Schwartz, Alexandra Blucher and Mark Willacy
Updated 18 Apr 2017, 5:56pm

PHOTO: Australia could fail to meet its Paris climate commitments due to unmeasured methane leaks. (ABC News: Scott Kyle)


The Courier Mail
BRISBANE 10-26°C
Condamine River erupting in flames
QLD News

Condamine River bubbling unlikely to be caused by coal seam gas, CSIRO says

John McCarthy, The Courier-Mail
July 27, 2017 12:00am
Subscriber only

- Condamine River set on fire

What baseline data should be collected in areas of unconventional gas?

Type of baseline data required depends on the types of activities being conducted and potential associated impacts. Some key data based on international experience with shale gas (e.g. US):

Water quality (contaminants that may impact aquifers due to gas development):

- Dissolved and/or free phase methane (CH_4) and other hydrocarbons;
- Saline wastewater (e.g. due to surface spills and leaks of wastewater);
- Heavy metals, radionuclides (radium), chemicals used in hydraulic fracturing
- Foreign bacterial communities (e.g. SRB) which catalyse other biogeochemical changes
- Refs: Van Stempvoort et al., 2005, Jackson et al., 2013, Vidic et al., 2013; Warner et al., 2013; Darrah et al., 2014;

➢ ***Baseline datasets need to include these analytes and capture natural existing levels and variability***

Monitoring for fugitive gas impacts

Stray gas contamination has been documented in the US as a contaminant that has impacted shallow aquifers. Generally accepted that this is due to well-integrity failures (see next section):

PNAS

Increased stray gas a
water wells near Mar

Robert B. Jackson[a,b,1], Avner Vengosh[a], Thomas
Stephen G. Osborn[d], Kaiguang Zhao[a,b], and Jor

[a]Division of Earth and Ocean Sciences, Nicholas School of the
of Earth and Environmental Sciences, University of Rochester
University, Pomona, CA 91768

Edited by Susan E. Trumbore, Max Planck Institute for Biogeo

PNAS

CrossMark
click for updates

Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales

Thomas H. Darrah[a,b,1], Avner Vengosh[a], Robert B. Jackson[a,c], Nathaniel R. Warner[a,d], and Robert J. Poreda[e]

[a]Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, NC 27708; [b]Divisions of Solid Earth Dynamics and Water, Climate and the Environment, School of Earth Sciences, The Ohio State University, Columbus, OH 43210; [c]Department of Environmental Earth System Science, School of Earth Sciences, Woods Institute for the Environment, and Precourt Institute for Energy, Stanford University, Stanford, CA 94305; [d]Department of Earth Sciences, Dartmouth College, Hanover, NH 03755; and [e]Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY 14627

-Thus, need a comprehensive baseline dataset of groundwater methane (and other hydrocarbons) prior to gas development;

-Also need to understand *sources* and *behaviour* of methane in aquifers.

- ➢ Can be achieved by analysing isotopes of methane (as well as inorganic carbon and water) in groundwater and gas deposits. Allows for 'fingerprinting' of methane sources

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Sources of methane in groundwater & methane isotopes

Carbonate reduction: $CO_2 + 4H_2 \longrightarrow CH_4 + H_2O$
Acetate fermentation: $CH_3COOH \longrightarrow CH_4 + CO_2$
} 'biogenic' / bacterial

Themogenic methane (Primary and secondary) } Methane in gas deposits

- Biogenic/bacterial pathways produce CH_4 with more depleted isotopes (compared to thermogenic)
- Isotopes of hydrogen in CH_4 relate to mechanism + isotopic composition of source water (δ^2H_{H2O})

Methane type	Pathway/mechanism	Typical isotopic values $\delta^{13}C_{CH4}$ & δ^2H_{CH4}
Biogenic	Acetate fermentation	$\delta^{13}C_{CH4}$: -50 to -65‰ δ^2H_{CH4} : -250 to -350‰
	Carbonate reduction	$\delta^{13}C_{CH4}$: -65 to -90‰ δ^2H_{CH4} : -150 to -300‰
Thermogenic	Primary (thermo-catalytic breakdown of organic matter)	$\delta^{13}C_{CH4}$: -30 to -40‰ (Gippsland basin mean = -35.3‰) δ^2H_{CH4} : -150 to -250‰
	Secondary (bacterial destruction of oil deposits)	$\delta^{13}C_{CH4}$: -35 to -45‰ (Gippsland basin mean = -38.6)

Data sources Typical values: Whiticar, 1999. Chemical Geology 161: 291-314.
Gippsland Basin values: Pallasser, 2000. Organic Geochemistry 31: 1363-1373

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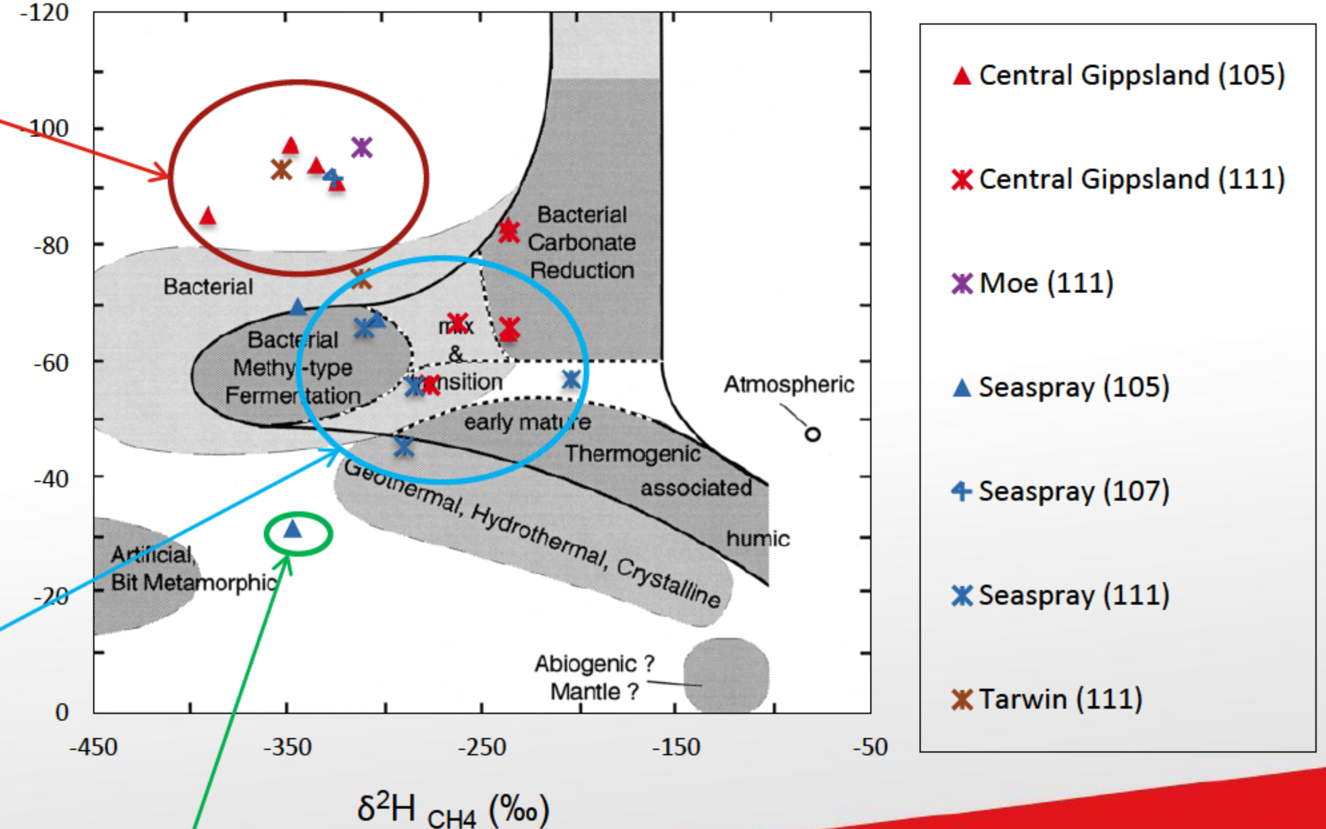
Isotopes of methane

- Isotopes of methane ($\delta^{13}C_{CH4}$ & $\delta^{2}H_{CH4}$) indicate different sources of methane in groundwater from different regions of Gippsland Basin:

Region 1: very depleted isotopes of C & H (inland)



Region 2: less depleted isotopes; more 'classic' biogenic methane (coastal)

Outlier: stray gas? Local (minor) surface leak?

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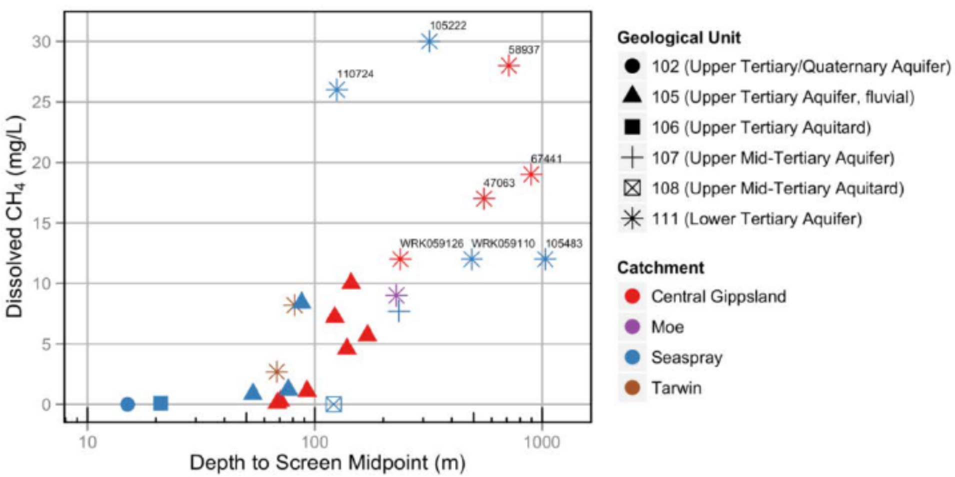
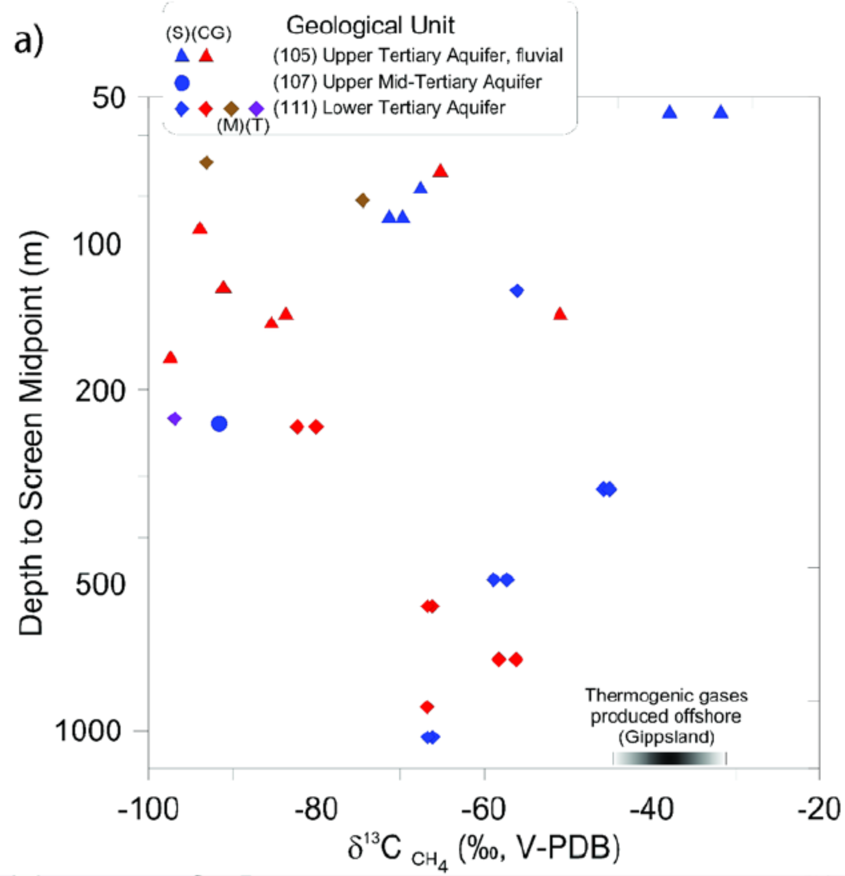
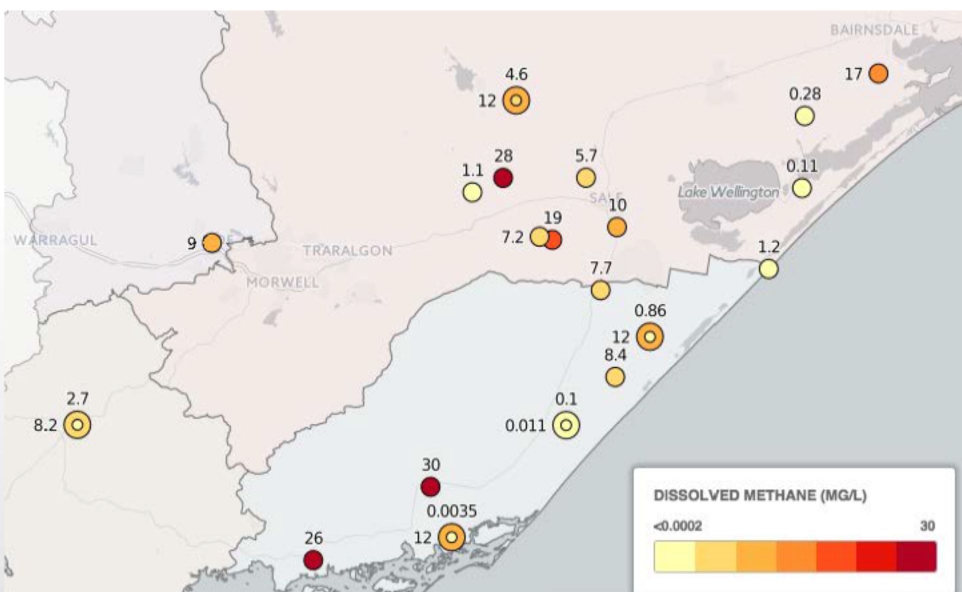
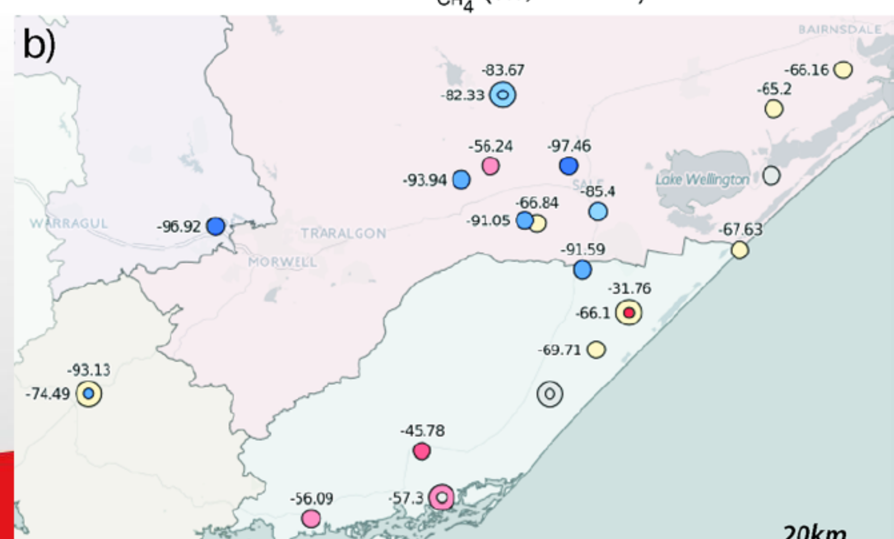
Currell et al., 2017. *Environmental Science and Pollution Research* **24**(15): 13168-13183

Baseline data: example









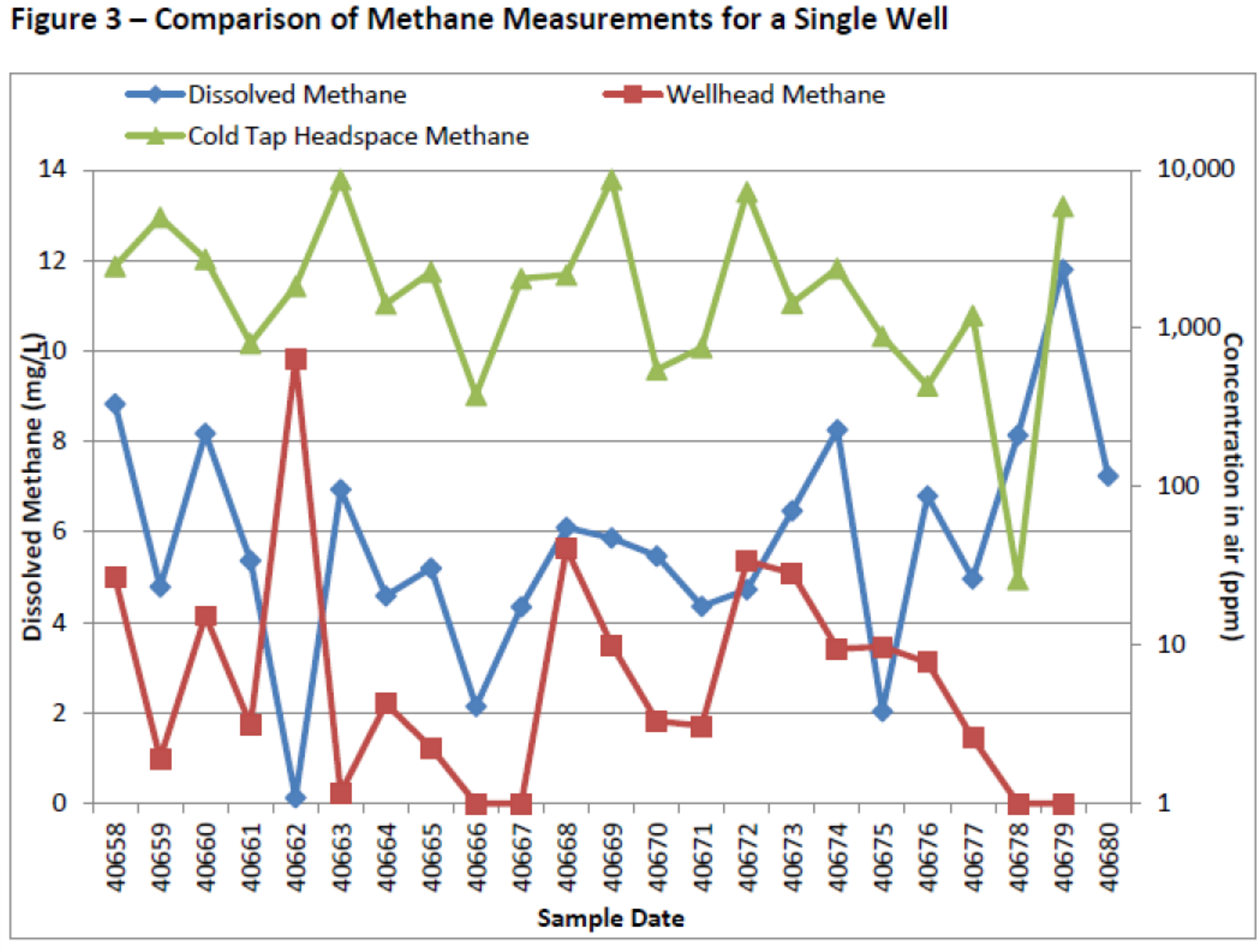
Currell et al., 2017. *Environmental Science and Pollution Research* **24**(15): 13168-13183

Why is isotopic and other geochemical data important?

- Time series of methane in groundwater alone may be inconclusive.
- CH_4 levels tend to vary naturally in groundwater regardless of mechanism/source
- Methods of sampling and measuring CH_4 in groundwater **not straightforward** and can be hard to cross-compare and validate results from multiple sampling events

Hence, need additional data (such as isotopes) and a sound understanding of the different sources of CH_4 (e.g. Biogenic vs. Thermogenic) in geological units in the vicinity of unconventional gas

Baseline data: not just a concentration time-series:



Source: **Ground Water Protection Council (2012) White paper on GWPC's Stray Gas Forum. 48pp**

Examples: Baseline data in areas of gas development

This *can be done*, e.g.

Atkins et al., 2015 (Northern Rivers in NSW baseline CSG study)

Jacobs, 2015 (Victorian Water Science studies)

Bioregional assessment program

- Does cost money and take time (upfront)

But

- Will save significant time and money in the event of a dispute, and will provide people and communities with confidence that impacts are being taken seriously and there is a proper effort to monitor and document any impacts that do occur

2. Well integrity failures: Reconciling vastly different failure rates from the industry and academic literature

- APPEA argue in their submission to this inquiry that well failures resulting in gas or fluid migration from unconventional gas reservoirs are rare (e.g. 0.1 to 0.2% or as low as 0.004% of wells).
- This is largely based on a paper by King and King (2013), who define ‘Single barrier failure’ as distinct from ‘total well failure’
- Davies et al (2014) considered this difference in definition (‘barrier’ vs. ‘integrity failure’), and reviewed >25 databases of wells from around the world (more than 1 million wells).
- Found that for unconventional gas (Marcellus) failure rate involving detected leakage of gas at surface has been on the order of 1 to 5% of wells
- These rates are typical of most onshore oil and gas operations

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Well integrity – different definitions

- Key issue: whether a well failure leads to leakage of gas or other fluids between aquifers or the surface.

- Davies et al 2014 data (most comprehensive international review to date) indicates most reported well failures in unconventional shale gas reported in the US involved detectable leaks of gas at the surface:

> *"From these data, Vidic et al. (2013) derived a figure of 3.4% well barrier leakage for shale gas production sites in Pennsylvania (219 violations for 6466 wells) between 2008 and 2013. Using the same database, Ingraffea (2012) argued that 211 (6.2%) of 3391 shale gas wells drilled in Pennsylvania in 2011 and 2012 had failed. More recently, Considine et al. (2013) identified 2.58% of 3533 individual wells as having some form of barrier or integrity failure. This consisted of 0.17% of wells having experienced blowouts (4 wells), venting or gas migration (2), and 2.41% having experienced casing or cementing failures.* ***Measurable concentrations of gas were present at the surface for most wells with casing or cementing violations.****"*

Marine and Petroleum Geology 56 (2014) 239–254

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ELSEVIER

Review article

Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation

CrossMark

Richard J. Davies [a,*], Sam Almond [a], Robert S. Ward [b], Robert B. Jackson [c,d], Charlotte Adams [a], Fred Worrall [a], Liam G. Herringshaw [a], Jon G. Gluyas [a], Mark A. Whitehead [e]

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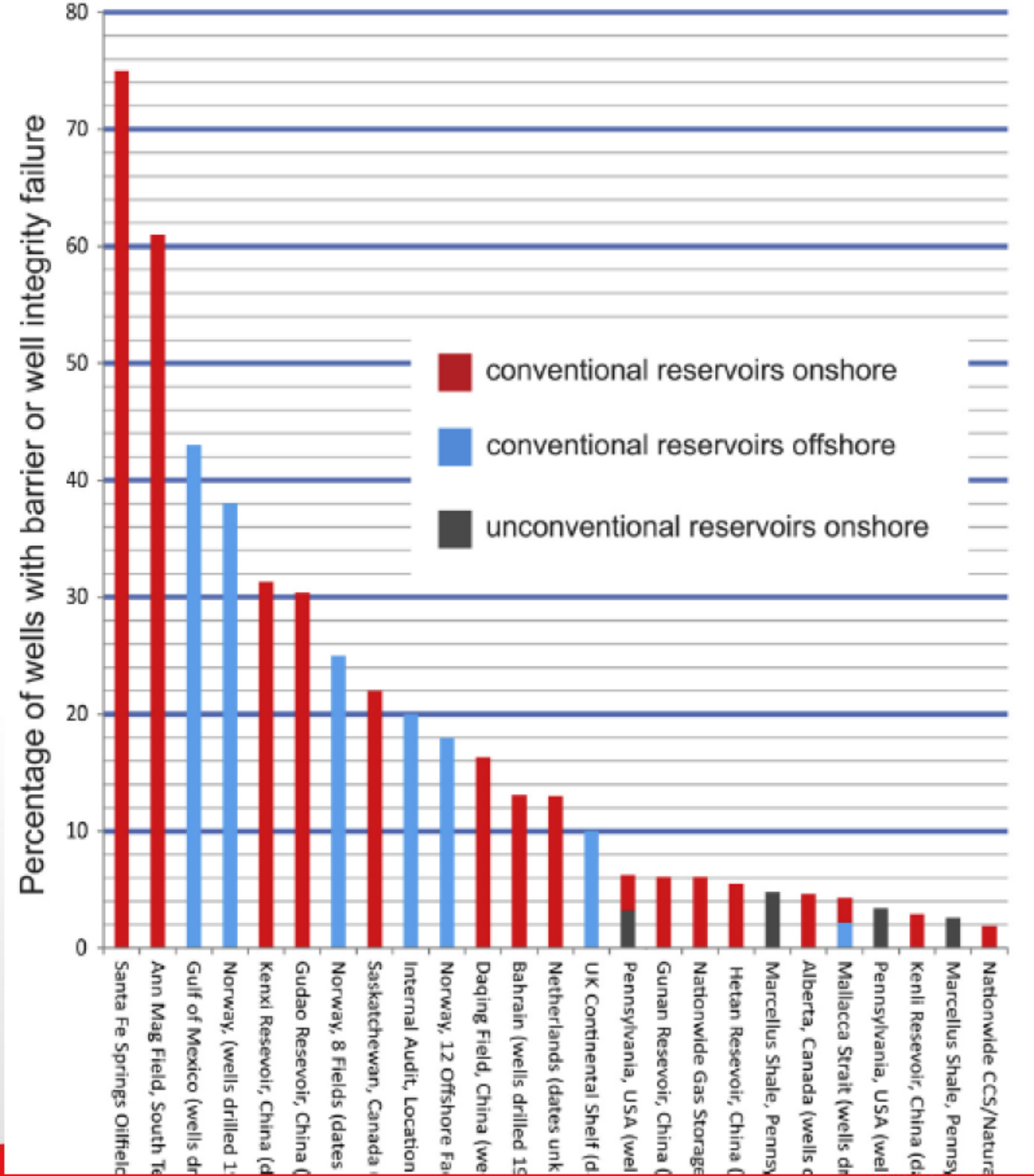
Davies et al 2014 Inventory

- Rates of failure vary widely, however, range from ~2% up to 10s of %
- Depends on well age & type, source of data, monitoring regime etc.
- Argument that age of wells has no impact on failure rate/integrity contradicted by these data
- Issues with abandoned/legacy wells and long-term monitoring and 'life-cycle care' of wells important



Implications

Quoting from Chapter 7 of the Inquiry's interim report (page 58):

"It is possible for fluid (liquid or gas) to move into an aquifer through defects or deficiencies in the production well casing and/or the cement. ***However, as discussed in Chapter 5, the likelihood of this occurring is low*** *assuming wells are constructed to current best or leading practice standards"*

Suggests that the inquiry has relied heavily on the APPEA submission, and has not considered the evidence of significant well failure rates worldwide reported in the Davies et al (2014) global review, or other academic literature sources, which are all broadly consistent in their findings (e.g. Vidic et al 2013; Ingraffea et al, 2012; Kiran et a., 2017).

- Fugitive gas contamination due to well integrity failures is not listed as one of the primary risks to water quality in chapter 7.4.2 of this Inquiry's interim report, on the basis of the assumption that the risk of well integrity failures is 'low' (relying largely on APPEA's submission).
- Empirical data are required to illustrate what impact 'leading practice standards' might have on well failures covering a long enough time period and large enough number of wells to make meaningful comparison with the existing historical data.

Implications

Down-playing the risk/incidence of well-integrity issues could be a major oversight, given that stray gas impacts have been documented in areas of shale gas development in the US (Bair, 2010; Jackson et al 2013a; Darrah et al., 2014)

- More rigorous assessment of this risk, and a comprehensive baseline data program (such as described above) to guard against well-integrity issues and associated fugitive methane (and other hydrocarbon) contamination of groundwater needed.
- Not easy to detect stray gas contamination incidents and conclusively link this to a source/mechanism (e.g. shale gas). ***Impossible*** without a robust monitoring program and baseline datasets.

Database of environmental violations – Marcellus Shale Gas wells

- For shale gas, best available data on frequency and type of environmental incidents from Pennsylvania (Marcellus Shale)
- Davies et al (2014) (citing Considine et al., 2013) shows that **1144** environmental violations (845 incidents) detected/reported from 3533 wells 2008 to 2011 (~20% of wells)
- Mostly 'minor' in environmental impact
- Approx 10% related to well integrity failure; most others to do with spills & contamination of surface water or land

➢ *Underscores how common environmental contamination incidents are in areas of shale gas development*

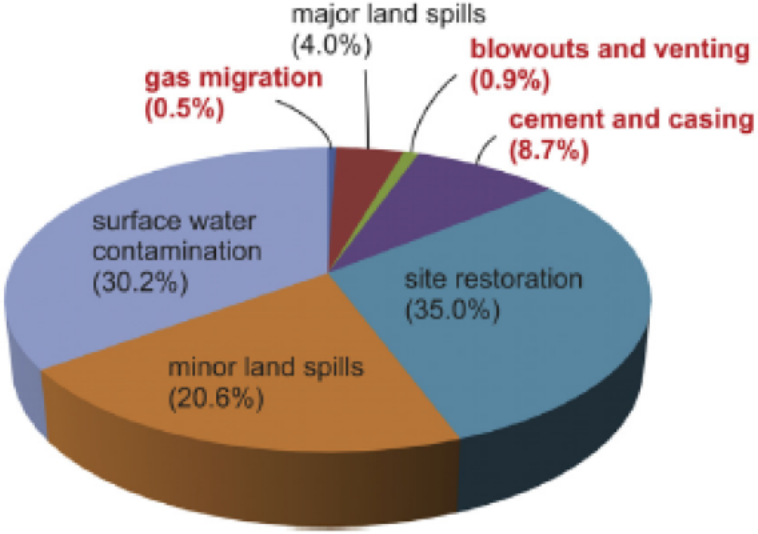


Figure 6. Breakdown of 1144 notices of violations from 3533 wells in Pennsylvania from 2008 to 2011 (after Considine et al., 2013). Red font indicates those related to well barrier and integrity failure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Davies et al., 2014 (data from Considine et al., 2013)

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3. Behaviour of methane in groundwater: new insights

- Methane can cause explosions, pump failure, cause associated geochemical/microbiological changes to water and is a potent greenhouse gas

- Understanding methane occurrence, transport and cycling in sedimentary basins that contain groundwater is an important topic, regardless of unconventional gas activity

- Cahill et al., 2017 recently published findings from a controlled experiment at Borden site, CAN

➢ Best insight yet into methane behaviour in groundwater due to natural gas-related leaks.

nature geoscience

ARTICLES

PUBLISHED ONLINE: 27 MARCH 2017 | DOI: 10.1038/NGEO2919

Mobility and persistence of methane in groundwater in a controlled-release field experiment

Aaron G. Cahill[1,2], Colby M. Steelman[1], Olenka Forde[2], Olukayode Kuloyo[3], S. Emil Ruff[3], Bernhard Mayer[3], K. Ulrich Mayer[2], Marc Strous[3], M. Cathryn Ryan[3], John A. Cherry[1] and Beth L. Parker[1]*

Cahill *et al.* 2017. *Nature Geoscience* **10**: 289-297.

NATURE GEOSCIENCE DOI: 10.1038/NGEO2919

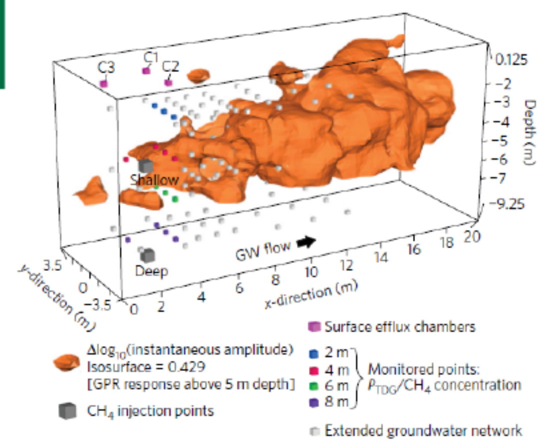

Figure 4 | GPR response associated with gas-phase methane accumulation extending downgradient from the injection points. The iso-surface boundary (orange zone) demarcates a laterally extensive volume of high-amplitude reflection events on day 65 (Methods and Supplementary Fig. 6), in the direction of groundwater flow impacted by methane gas accumulation beneath and along distinct sedimentary interfaces to a maximum sensing depth of 5 m below ground surface. Methane gas migrated >17 m downgradient, which is significantly greater than an estimate of ~6 m based on aquifer hydraulic properties and gradients[22].

Behaviour of methane in groundwater

Experimental set-up

Methane injected under carefully controlled experimental conditions (72-day experiment); designed to replicate reported (low range) surface casing vent flows reported from gas wells with casing problems

Monitoring took place in one of the most heavily instrumented and well-characterised hydrogeological settings in the world (Borden site, where most understanding of contaminant transport in GW comes from)

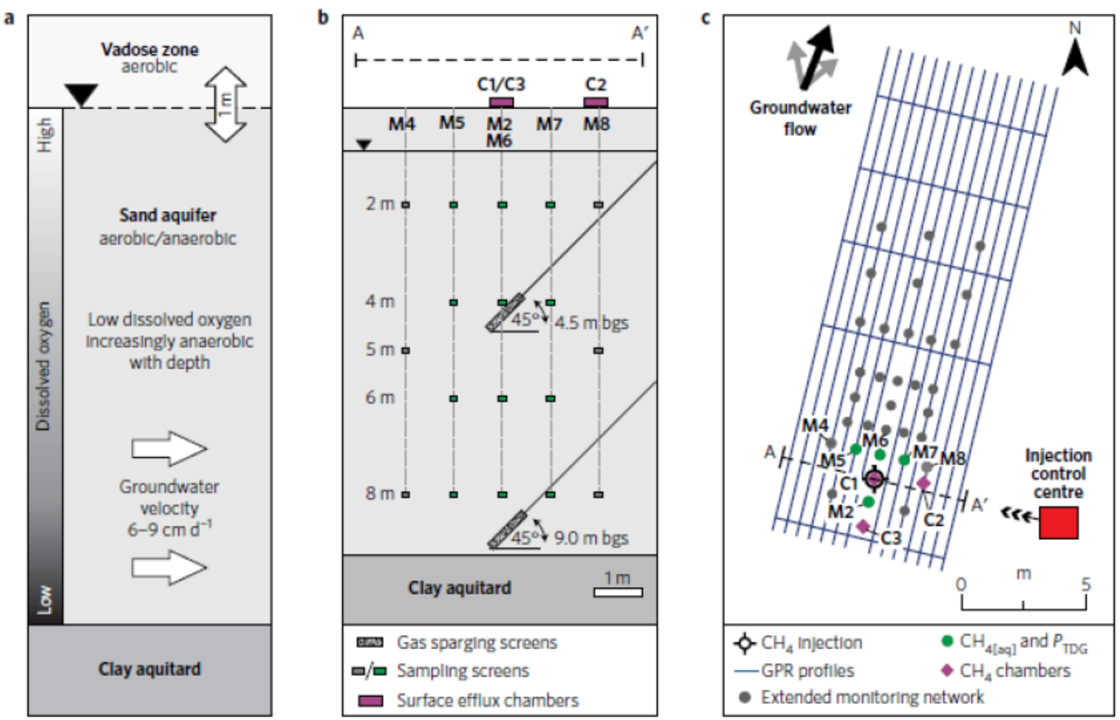

Figure 1 | Hydrologic setting and experimental set-up of the methane injection experiment. a, Borden aquifer consisting of a thin vadose zone

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Borden site methane injection experiment

Key findings:

- Even in these well-constrained settings, methane behaved in un-predictable and un-expected ways in the aquifer
- Methane switches between 'free phase' gas and dissolved methane in groundwater periodically; difficult to predict why/when this will occur
- Highest concentrations and extent of dissolved methane reported many days after gas injection ceased (>100d); significant concentrations remained after 245 days
- Presence of methane in the groundwater led to a range of indirect water quality changes, including increases in trace metal concentrations and other cations near the injection zone.

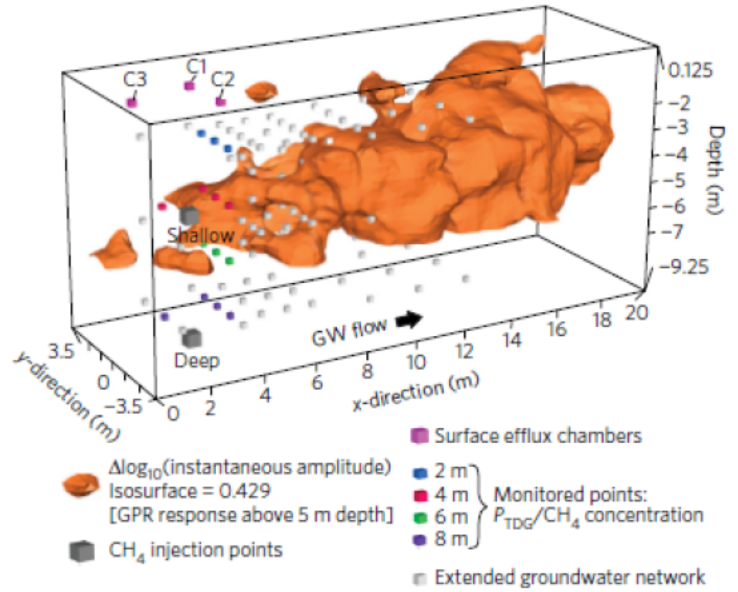

Figure 4 | GPR response associated with gas-phase methane

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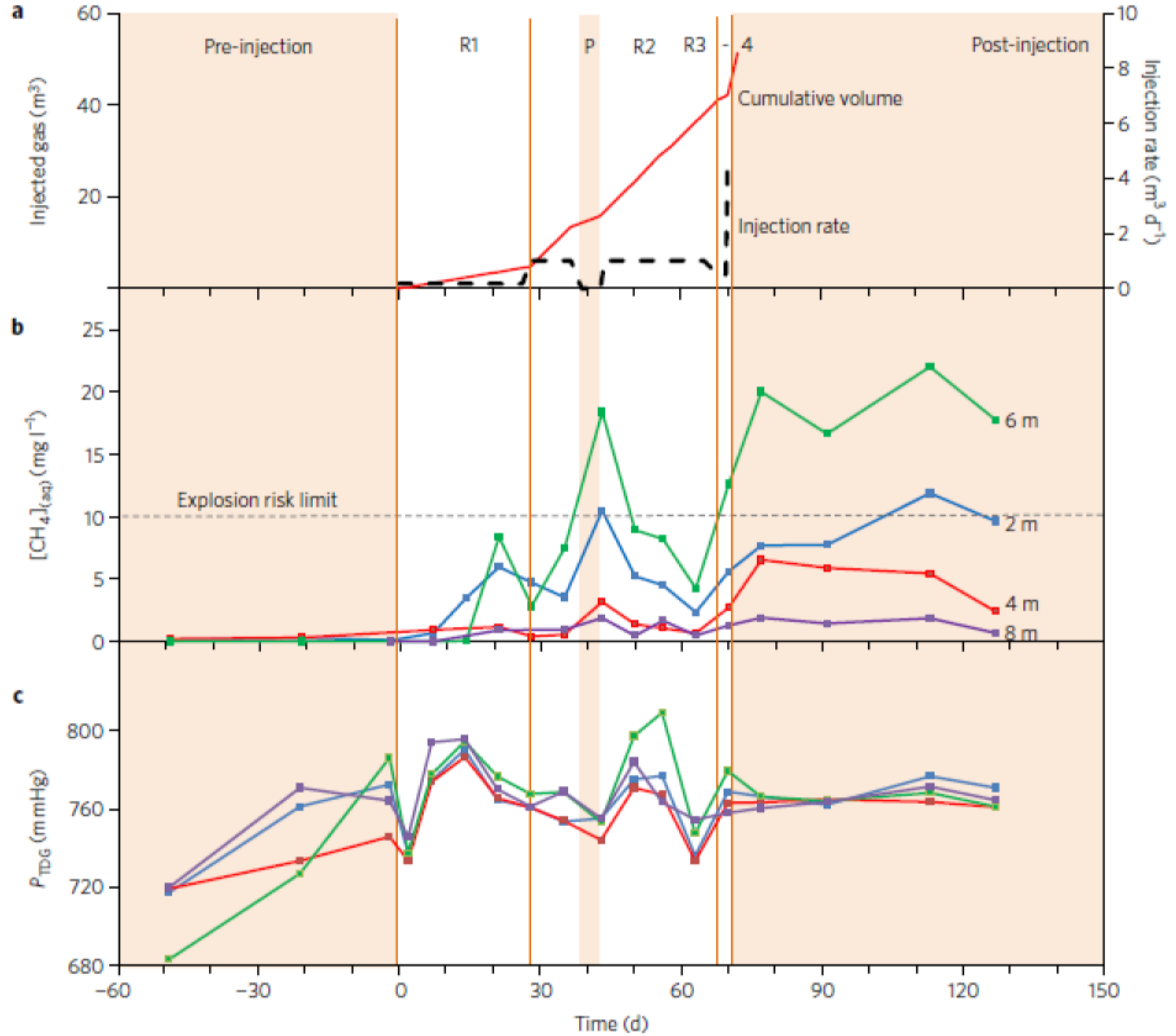

Figure 2 | Aqueous methane $[CH_4]_{(aq)}$ concentrations and total dissolved gas pressure (P_{TDG}) of the groundwater during methane injection

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Flux to atmosphere

- Flux of methane to the atmosphere out of the aquifer also measured, again, the timing/rate of this was not easily predictable – ‘episodic’ releases of gas to the atmosphere.
- Significant microbial community changes also detected during the experiment

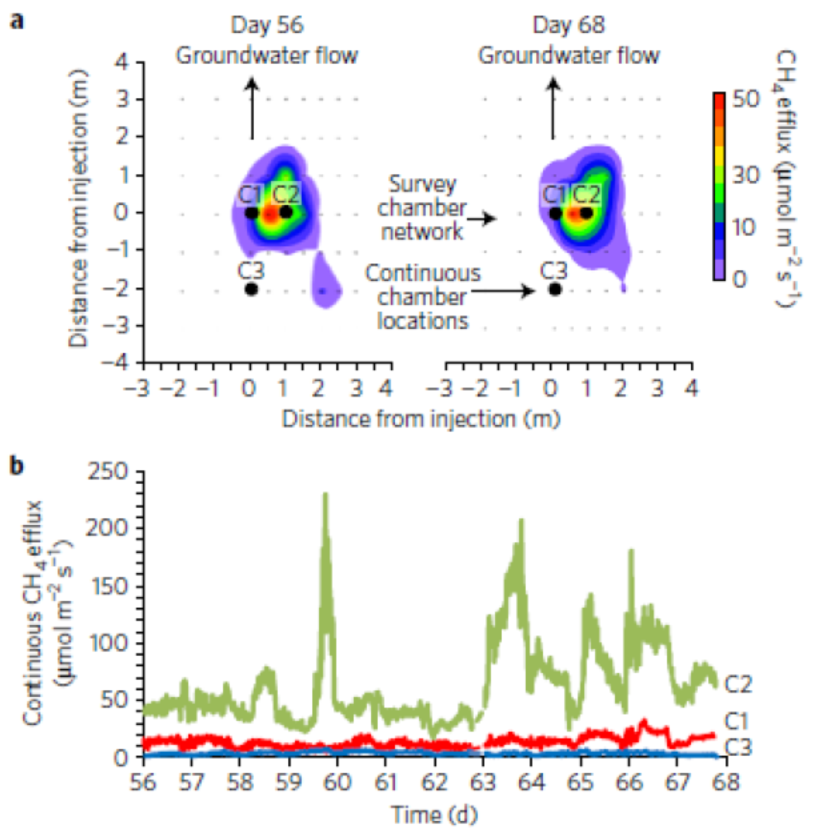

Figure 3 | Measured methane efflux to atmosphere during injection.

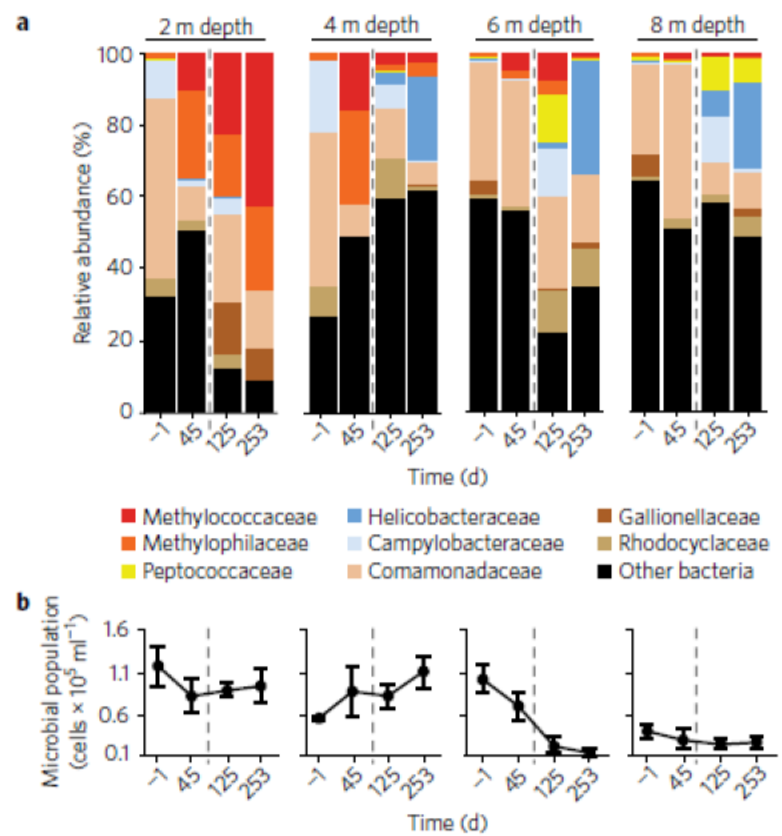

Figure 5 | Microbial response to injected methane gas in groundwater

Implications

- Release of methane into an aquifer (e.g. due to a casing leak) can have significant impacts on water quality and bio-geochemistry of groundwater;
- Impacts of an ‘episode’ of methane leakage can have significant residual effects after the fact
- Characterisation of these changes requires extensive monitoring networks and a range of complimentary monitoring parameters (e.g. multiple lines of evidence)

➢ Rigorous baseline monitoring and comprehensive monitoring programs must be carried out in areas of potential gas development in case of such impacts materialising (requiring the cause/mechanism to be resolved).

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