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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 literature 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.

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 abandonment. 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:

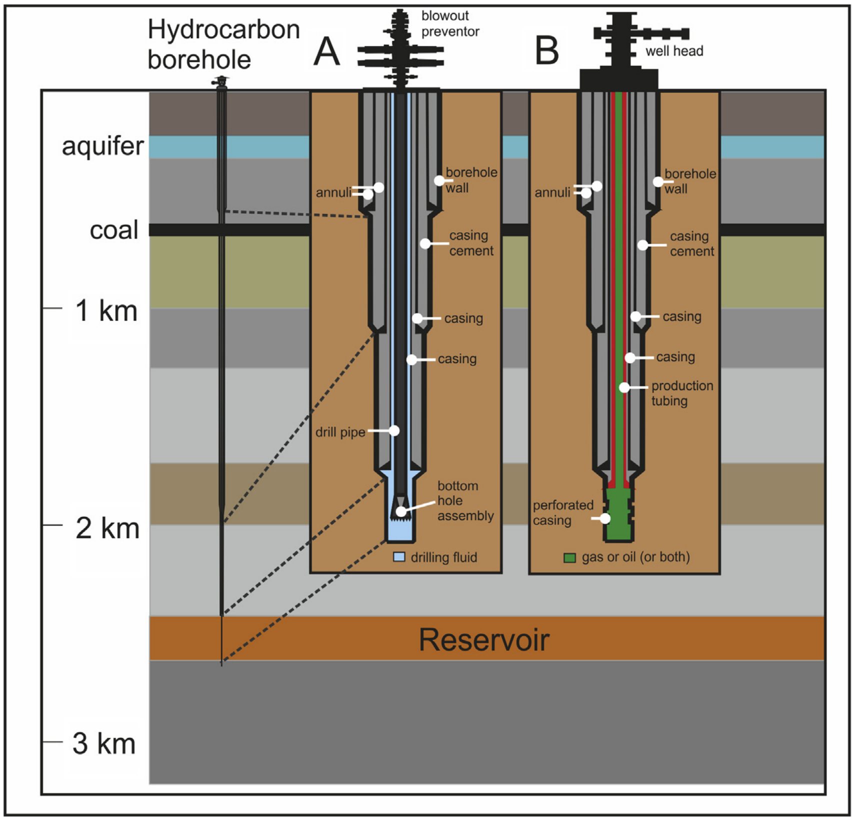

Figure 1. Schematic diagram of typical well design, showing (A): structure of an exploration well; and (B): a production well. Depths to which different casings are used vary according to geology and pressure regime of drill site. Well diameter exaggerated to show sections more clearly.

'well integrity failure' includes cases when gas or fluids are reported 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).

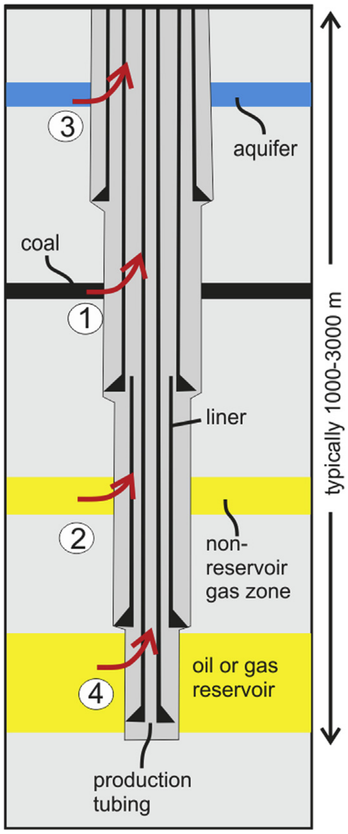

Figure 2. Schematic diagram of typical sources of fluid that can leak through a hydrocarbon well. 1 – gas-rich formation such as coal; 2 – non-producing, gas- or oil-bearing permeable formation; 3 – biogenic or thermogenic gas in shallow aquifer; and 4 – oil or gas from an oil or gas reservoir.

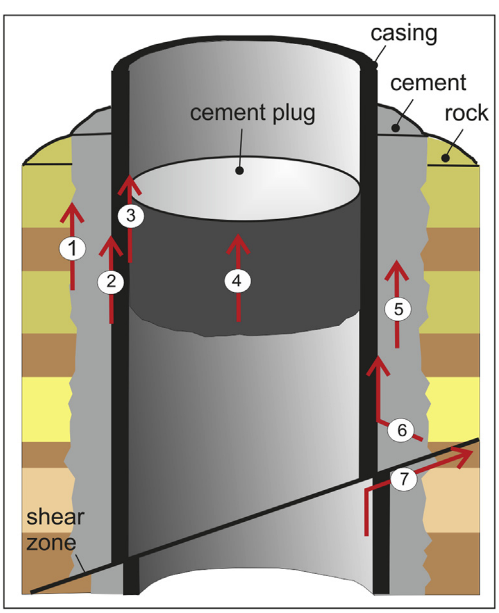

Figure 3. Routes for fluid leak in a cemented wellbore. 1 – between cement and surrounding rock formations, 2 – between casing and surrounding cement, 3 – between cement plug and casing or production tubing, 4 – through cement plug, 5 – through the cement between casing and rock formation, 6 – across 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 frequencies 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,

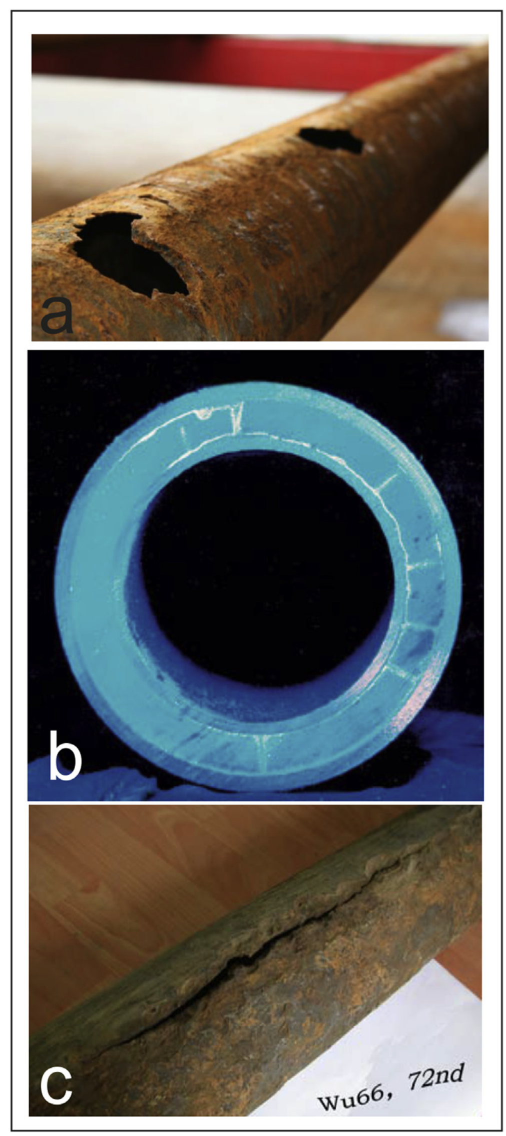

Figure 4. Photographic examples of leak pathways: (a) Corrosion of tubing (Torbergsen et al., 2012); (b) Cracks in cement (Crook et al., 2003); (c) Corrosion of casing (Xu et al., 2006).

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 locations 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 presence 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).

4. Well integrity

4.1. Pennsylvania, USA

The online database collated by the Department of Environmental 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)

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

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. 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 incidents 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 contaminants 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 sufficiently 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 Pennsylvania 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% reported 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

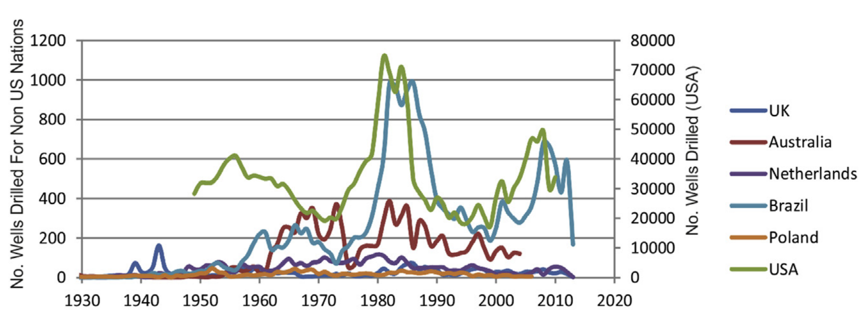

Figure 5. Number of wells drilled annually since the 1930s in Australia, Brazil, Netherlands, Poland, the UK and the USA. Sources: DECC, 2013; Geoscience Australia; Geological Survey of the Netherlands; Brazil Database of Exploration and Production (BDEP); EIA, Polish Geological Institute.

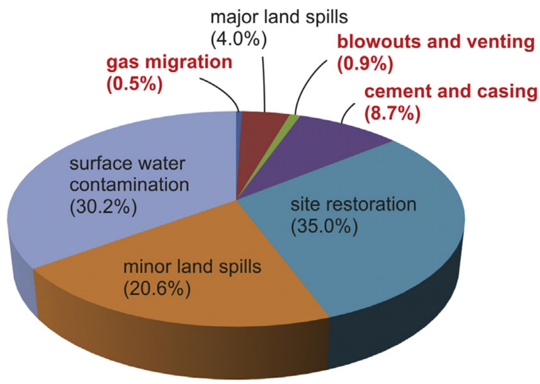

Figure 6. Breakdown of 1144 notices of violations from 3533 wells in Pennsylvania from 2008 to 2011 (after Considine et al., 2013). Red font indicates those related to well barrier and integrity failure. (For interpretation of the references to colour in this figure legend, the reader is referred to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

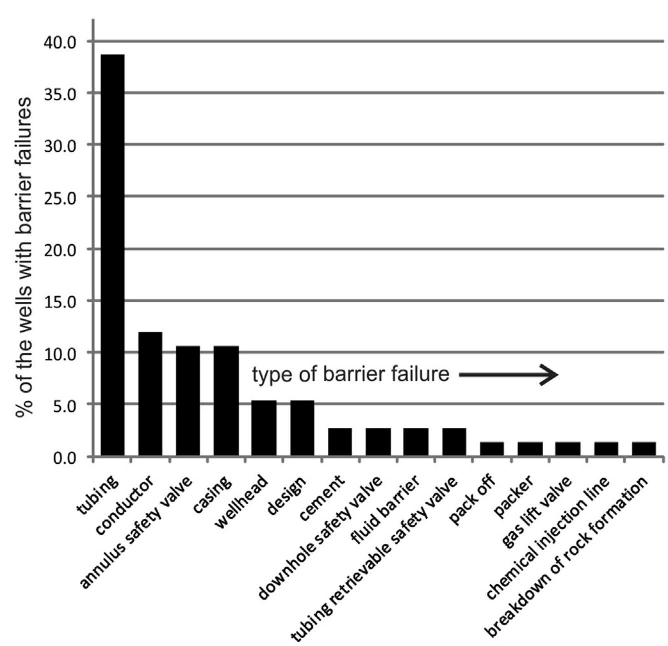

Figure 7. Causes of barrier failures for the 75 (of 406) production and injection wells surveyed in offshore Norway that showed evidence for such failures (from Vignes, 2011).

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 Environment 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 (Pennsylvania, 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 hydrocarbons 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 Pennsylvania, 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.).

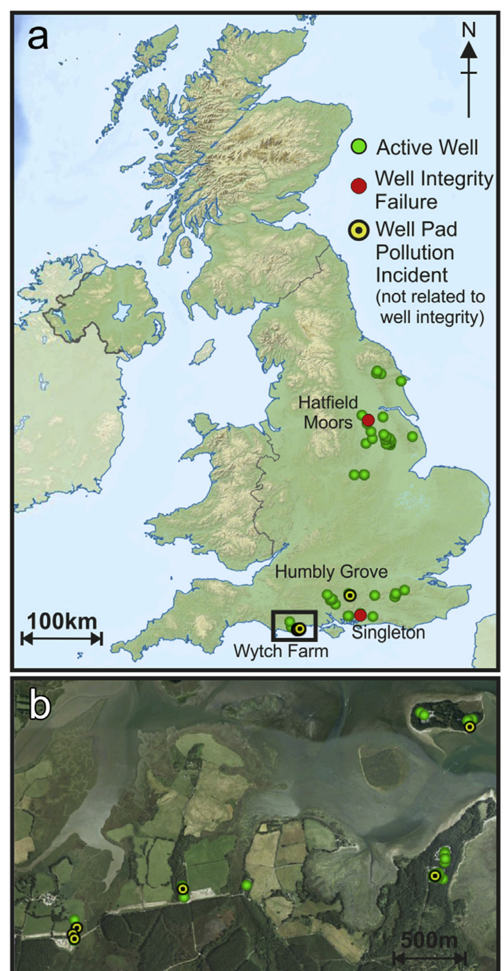

Figure 8. (a) UK map showing locations of wells active in 1999 and crude oil discharges (b) Coincidence of pollution reports with well pads in the Wytch Farm area, southern England.

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

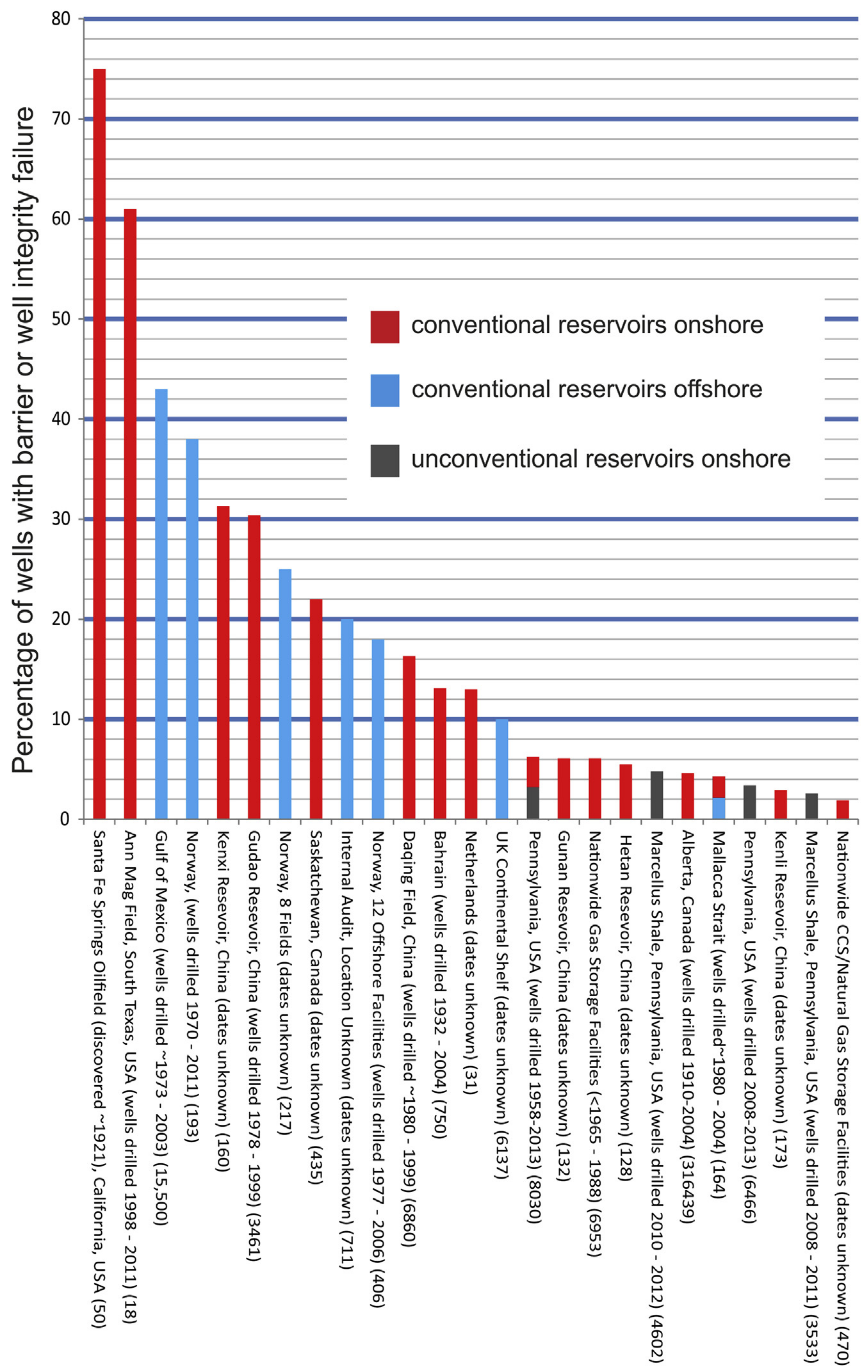

Figure 9. Graph of percentage of well barrier and integrity failures reported in 25 different studies around the world, with drilling dates and number of wells in each study.

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 activity 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 present 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 industrial 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 between mined coal horizons and overlying potable aquifers is relatively 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 hydraulic 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 failure and the potential for contamination. Based on their analysis, they proposed a methodological framework for identifying groundwater contamination from geothermal energy developments. Possible sources of well barrier and integrity failure of geothermal wells include loading from the surrounding rock formation, 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 groundwaters 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 injection 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

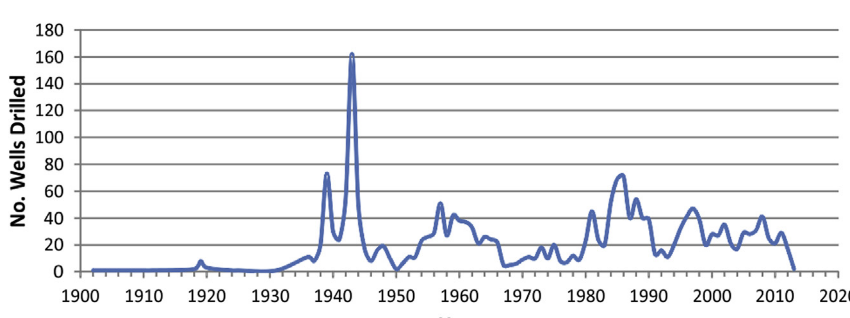

Figure 10. Graph showing number of hydrocarbon wells drilled in UK per year.

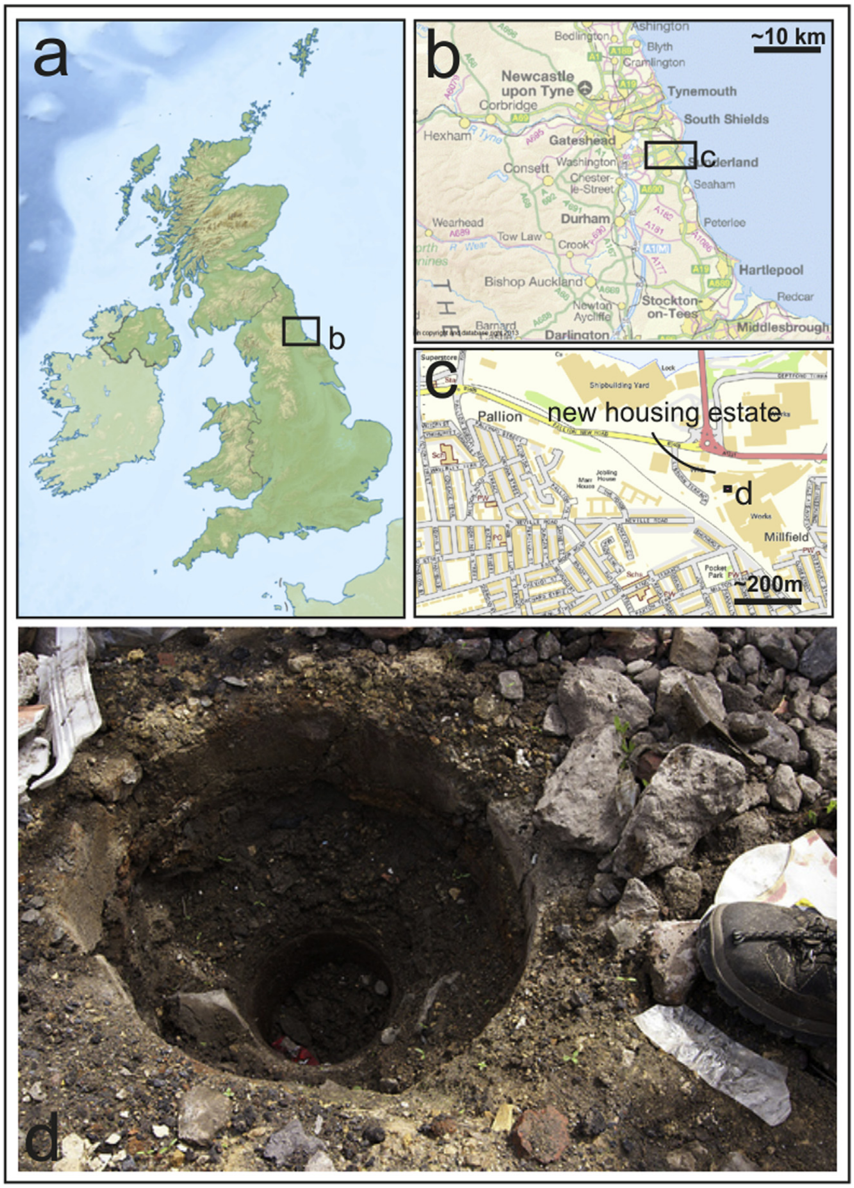

Figure 11. Case study of gas exploration well abandonment in Sunderland, UK: (a) Map of the UK; (b) location of Sunderland; (c) location of new housing estate; (d) photograph of temporarily abandoned (suspended) mine gas exploration borehole on building site of new housing estate (Grid Ref. 438260 557420).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

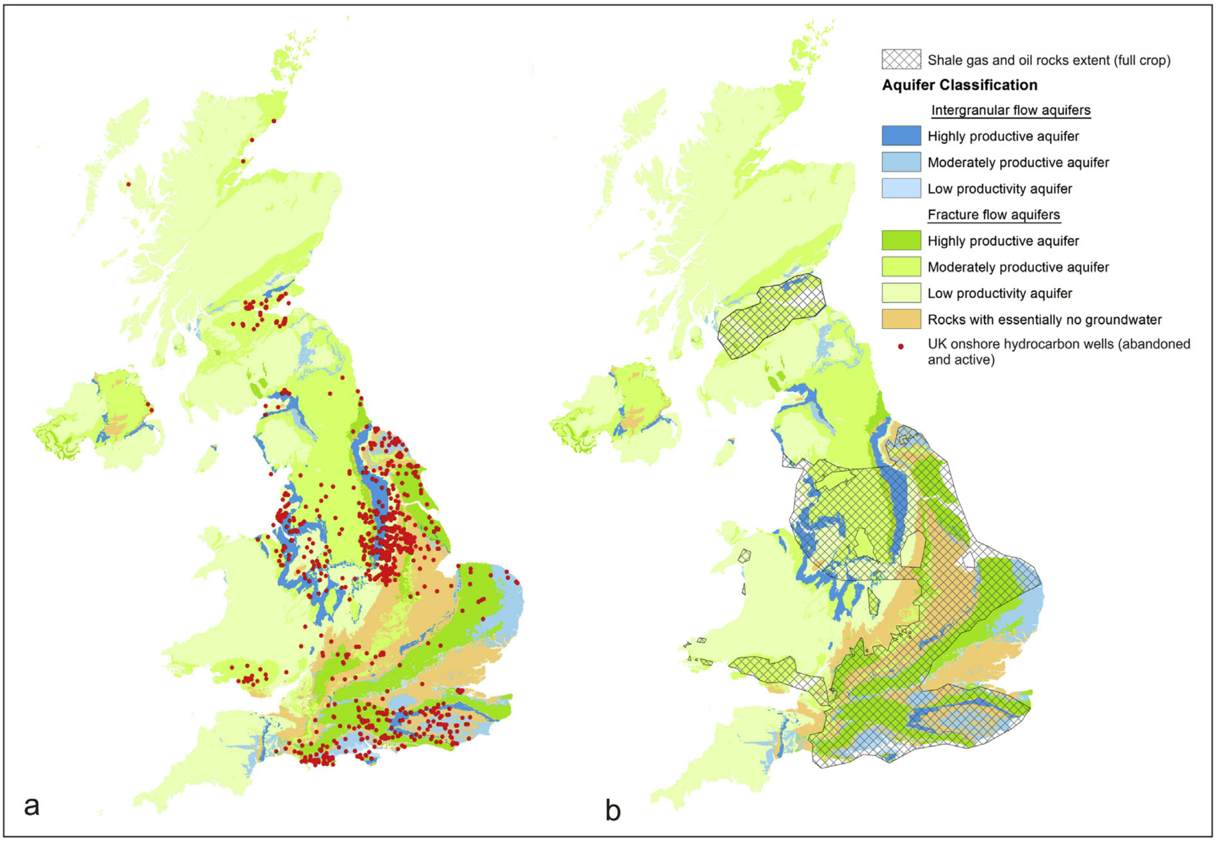

Figure 12. (a) Map of UK showing location of onshore wells drilled for exploration or production and productive aquifers. (b) Map of UK showing location of potential shale gas and oil reservoirs and productive aquifers. Aquifer base map reproduced with the permission of the British Geological Survey.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

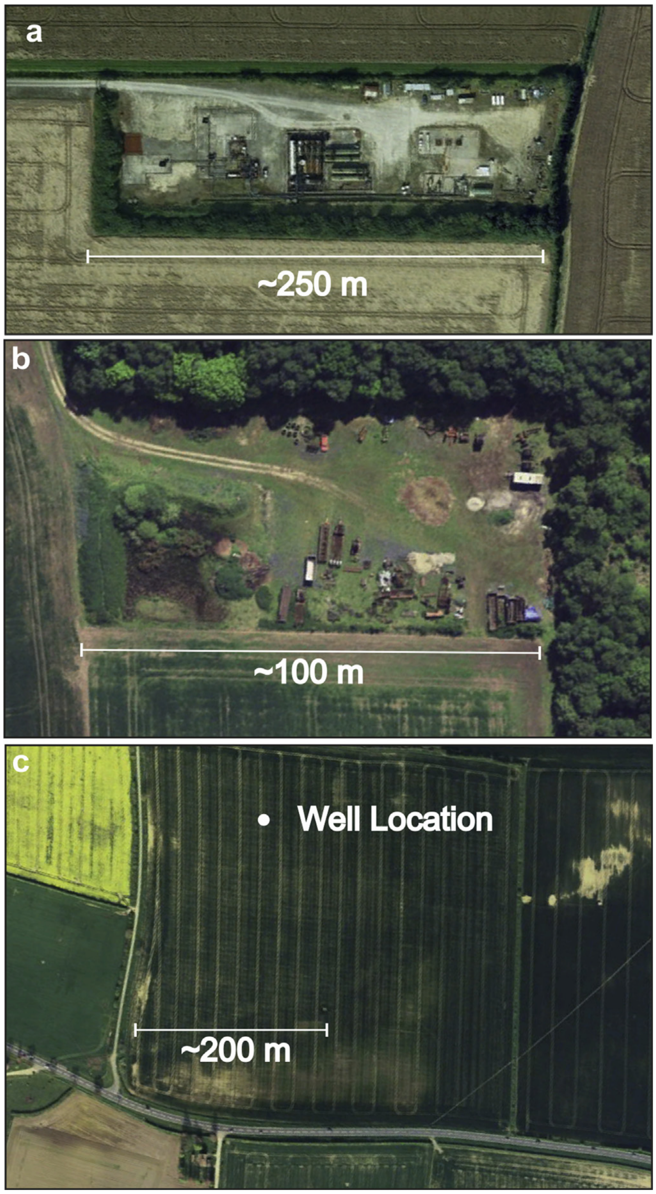

Figure 13. Examples of wells locations taken from UKOGL imaged with Google Earth, illustrating range of surface manifestations of UK onshore wells: (a) cleared area of land with appearance of being a maintained well pad; (b) cleared area of land with appearance of poorly maintained and potentially disused 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 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).

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

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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