International Journal of Greenhouse Gas Control 114 (2022) 103560

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Prioritizing stewardship of decommissioned onshore oil and gas wells in the United Kingdom based on risk factors associated with potential long-term integrity

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ARTICLE INFO

Keywords:
Oil and gas wells
Abandoned wells
Well integrity failure
Fugitive gas

ABSTRACT

A portion of decommissioned oil and gas wells develop integrity failure resulting in release of methane, a potent greenhouse gas, into the surrounding soils and atmosphere. As the number of decommissioned wells grows during our transition to NetZero and technologies such as carbon capture and geological storage are implemented, it is essential that strategies for stewardship of this legacy subsurface infrastructure are developed. To formulate an abductive heuristic strategy for ongoing stewardship of onshore legacy wells in the United Kingdom (UK), we reviewed readily available data and identified five risk factors including regulatory frameworks, technologic aspects and construction characteristics, likely to influence long-term integrity. Subsequently we developed a prioritization methodology to segregate wells by ascending Tiers of decreasing potential long-term integrity. The prioritization method, which is supported by independent field observations, identifies 4% (n = 84), 23% (n = 501), 40% (n = 867), 23% (n = 497) and 9% (n = 200) of decommissioned wells in the UK as Tiers 1 (i.e., greatest relative integrity) to 5 respectively, while none were assigned as Tier 6 (i.e., lowest relative integrity). Tier 5 wells, which are generally characterized as production wells completed before 1953 and either deviated or completed during a year of intense drilling activity, are found clustered in several locations in England. Overall, we infer that not all decommissioned onshore wells in the UK are equally likely to suffer integrity failure. Consequently, they can be differentiated into groups of varying potential risk in an abductive heuristic manner using basic well data, thereby facilitating effective and efficient stewardship.

1. Introduction

Wellbore integrity failure poses a poorly constrained environmental risk associated with petroleum resource development (Trudel et al., 2019) having been suggested to occur in 0.1 – 75% of oil and gas wells (Davies et al., 2014). It results in petroleum fluid migration within and/or outside a wellbore structure into the environment (Cahill et al., 2019). Migrating petroleum fluids can impact groundwater (Cahill et al., 2018; Steelman et al., 2017; Hammond et al., 2020), pose an explosion hazard (Dusseault et al., 2014) and contribute to greenhouse gas emissions upon reaching the atmosphere (Forde et al., 2018; Forde et al., 2019; Kang et al., 2014; Riddick et al., 2020). Once released, methane (CH_4) has a global warming potential 86 times greater than carbon dioxide (CO_2) over 20 years, and 25 times greater over 100 years (Shindell et al., 2009; Frankenberg et al., 2011). Consequently, CH_4 emissions can be a significant contributor to short term global warming and their role in climate change is becoming increasingly recognized as scientists observe atmospheric concentrations of CH_4 continually rising (Hmiel et al., 2020; Wuebbles et al., 2002). Leakage of CH_4 from legacy wells, particularly those that are unplugged, is of particular interest (Kang et al., 2021) as its magnitude is highly uncertain (Agency, 2020), likely underestimated (Williams et al., 2021; Miller et al., 2013) and counteracts or directly compromises efforts to control greenhouse gases through subsurface energy activities such as geological carbon storage (Böttner et al., 2020; Postma et al., 2019).

Oil and gas wellbore integrity is a general concept which includes a series of activities, processes and physical barriers implemented by industry to reduce the risk of uncontrolled release of fugitive gas during an oil and gas well's life cycle (Fig. 1). Integrity failure, which involves breakdown in one or more of the physical barriers, is a complex and multifaceted phenomenon (Jackson, 2014; King et al., 2013; Benedictus, 2009; Bachu, 2017), whereby a combination of environmental (e.

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https://doi.org/10.1016/j.ijggc.2021.103560
Received 17 May 2021; Received in revised form 10 December 2021; Accepted 20 December 2021
Available online 7 January 2022

g. geographic/geologic) and anthropogenic (e.g. engineering or regulatory) factors have been suggested to play a role in development (Sandl et al., 2021; Milton-Thompson et al., 2021). Integrity failure can occur in any "demographic" of oil and gas well (e.g., whether an oil and gas well is shallow, deep, producing, abandoned, conventional, unconventional etc.). However, it is of particular concern with respect to decommissioned wells (which have ceased production, been sealed and the area returned to pre-lease conditions), for which plug and abandonment (P&A; the installation of cement plugs in a wellbore to seal the reservoir, potential flow zones and other fluid-bearing formations) has sought to seal and prevent the migration of fluids within or outside of them in perpetuity (Herndon and Smith, 1976; Vrålstad et al., 2019). After decommissioning there is a benefit to monitor, measure and verify well integrity in order to ensure wells are sealed effectively, safely and that no environmental impacts are occurring (Schout et al., 2019). There are currently few such stewardship programs for decommissioned wells (DW's). Consequently, DW integrity status or the presence and nature of actual or potential environmental impacts remains uncertain and a point of debate.

While the UK does not have an extensive onshore oil and gas industry (i.e. compared to some regions such as North America), approximately 2149 onshore oil and gas wells exist; the majority of which (i.e. 1700) are decommissioned (Davies et al., 2014). Recently, field investigations were undertaken to assess the integrity of a subset of 102 DW's across the UK, and specifically to identify if leakage of petroleum fluids might be occurring (Boothroyd et al., 2016). It was reported that approximately 30 of the DW's investigated exhibited potentially elevated levels of methane at the soil surface around the abandoned well location (compared to a paired control site), indicative of well integrity failure. Associated emissions of CH_4 from these wells was estimated, suggesting they may potentially reach up to 3256 kg CO_2 eq/well/year (a modest magnitude when compared to a typical dairy cow, which emits approximately ~2000 kg CO_2 eq /year of CH_4 of which there are 1.8 million in the UK).

Since then, no other research has sought to further understand the status of DW's in the UK, or assess factors that may determine their long-term integrity. For example, it is not currently clear which regulatory standards were in place during construction or decommissioning of the UK's onshore DW population, or how such standards have changed with time despite such information having a strong influence on the likely long-term integrity of a given DW. Similarly, it is unclear what data is readily available on the DW population (e.g., construction or P&A configuration) and from this, what factors could be important and used to assess or appraise potential long-term well integrity. While efforts to identify legacy wells that may be at greater risk of developing integrity failure have been made in the US and Canada (Duguid et al., 2019; Haagsma et al., 2017; Lackey et al., 2019), there has been no attempt to develop a methodology to prioritize stewardship of the UK's onshore DW's, such that stewardship efforts can be optimized and the legacy of DW's efficiently managed with a risk-based approach. Even in the UK, with a relatively small population of DW's (i.e., currently ~1700, to eventually reach 2149), it would be arduous and economically infeasible to monitor or investigate all DW's to assess and confirm integrity status. Thus, any form of stewardship will be challenging without methods to segregate or prioritize DW's according to their propensity for long-term integrity. This is even more relevant for regions with much larger populations of DW's such as those present in the Canadian provinces of Alberta and British Columbia, which host ~170,000 and ~7000 DW's respectively (eventually expected to reach a total DW population of ~500,000). Consequently, the development of prioritization methods to identify DW's which may be at greater potential risk for integrity failure is highly desirable, especially in the context of future decarbonization alongside continued use of the subsurface for geoenergy applications (e.g. geological carbon storage).

To contribute towards development of methods to prioritize stewardship of DW's, we review and assess readily available data on DW's in the UK and identify factors likely to exert control on long-term integrity, i.e. increasing risk of fugitive emissions due to loss of containment. Subsequently we use the identified DW integrity risk factors to form an abductive heuristic methodology to prioritize stewardship by segregating the existing well stock into ascending Tiers (i.e., 1 to 6) of decreasing potential long-term integrity. Following segregation of the UK well stock, tier assignments are assessed by cluster analyses and compared against previously reported field investigations on DW integrity. Finally, recommendations are made for potential next steps to increase understanding on onshore DW integrity and for further development of optimal management and stewardship strategies.

2. Readily available data concerning onshore decommissioned wells in the UK

Basic data on all onshore wells in the UK is available from the main regulatory authority's online data centre (the UK Oil and Gas Authority, https://data-ogauthority.opendata.arcgis.com/). These data include key basic attributes associated with each well as shown in Table 1. Unfortunately, key information potentially relevant to integrity status of

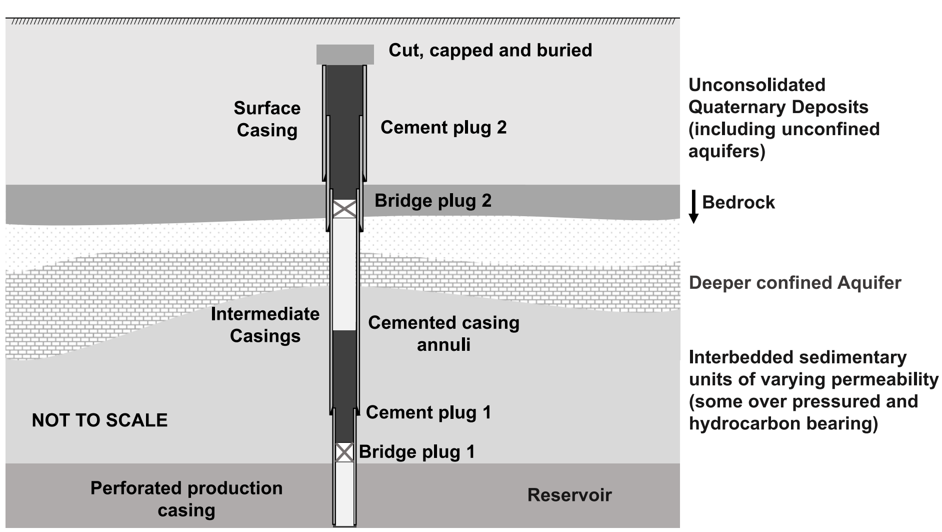

Fig. 1. Generic example of a UK specific decommissioned onshore well showing a typical subsurface environment (of varying sedimentary geology; including groundwater systems) intersected by the well and various well barriers (i.e., casings, annular cement, bridge and cement plugs) which confer overall well integrity.

Table 1
Readily available data on basic oil and gas well attributes for UK onshore wells from the UK Oil and Gas Authority online Data Centre.

Well Data Attribute	Definition
NAME	Well site name identifier
OPERATOR	Company who designed, installed and operated the well
TYPE	Fluid target and/or produced: conventional oil and gas (COG), coal bed methane (CBM), shale gas (SG), mine gas (MG) or gas storage (GS).
RELEASED	Date that well information and results were released
East	Easting coordinate
North	Northing coordinate
DEV	If well was deviated from vertical (yes or vertical)
COUNTY	County of location within UK
SPUD	Date drilling of the well began
COMPLETED	Date well was completed (i.e. prepared for production)
INTENT	Intended purpose of the well (Exploration, Appraisal or Development)

onshore oil and gas wells such as detailed well construction information (cement tops, casing depths etc.), P&A date, P&A configuration (i.e. number and nature of plugs), cement types used, intersected geology or other information is not readily available in a condensed or collated format for the whole well population. However, uncollated well data for select (typically more modern), individual onshore oil and gas wells in the UK is potentially available upon request (subject to availability). As the focus of this study was to develop an abductive heuristic stewardship prioritization method using readily available data; we focus only on available collated data as attained and demonstrated in table 1.

3. General overview of onshore oil and gas wells in the UK

Data from the UK oil and gas development regulatory authority's onshore repository (The Oil and Gas Authority, attained January 2020) shows there are 2149 onshore oil and gas wells in the UK (Fig. 2); most of which (i.e. ~1700) have been decommissioned with the remainder to be decommissioned in the coming decades. The oldest well was completed in 1902 (118 years old), the most recent in 2013 while the average well completion age is approximately 50 years old. Data shows the onshore well stock is comprised of 834 exploration, 249 appraisal and 1066 production wells. Most wells are associated with conventional oil and gas (a total of 1994) with much lower numbers of coal bed methane, mine gas, shale gas and gas storage wells (99, 48, 5 and 3 respectively). In terms of well orientation, 1434 are specified as vertical while some 715 are identified as deviated. Meanwhile, there are >100 operators listed for all onshore wells in the UK with one single company and its subsidiaries accounting for more than half of all wells (i.e. BP, formally known as D'arcy). Other companies typically operate a total of <50 wells in the UK with an average of 5 wells per operator. More than 50 companies operated only 1 well, many of which are presumed to be very small and are likely no longer in existence. Thus, although the UK has a relatively small overall population of onshore DW's; the industry has spanned many decades and the population of DW's includes a broad demographic of well types and operators.

3. Factors likely to influence long term well integrity of UK wells

3.1. Drilling activity

Readily available onshore well data attained as described shows that onshore petroleum resource development in the UK began with the discovery of oil in Scotland in 1851, then gas in England in 1896. After this, a slow but consistent advancement of onshore drilling activity, mainly in England, proceeded with 3 noticeable upturns (Fig. 3). These upturns are attributable to geopolitical or economic events which necessitated or increased the desirability for domestic petroleum production, including; World War 2; a period following the Suez Crisis; and the 1979 Iranian Oil Crisis together with the Gulf War. Upturns in drilling were interspersed with steady, sustained and ongoing low levels of development to the present day. Overall, an average of approximately 23 oil and gas wells were completed per year from 1902 to 2013 with a maximum of 141 wells completed in 1943.

Periodic, regional upturns in drilling activity induced by economic (e.g., higher oil or gas prices driving increases in drilling activity) and/or geopolitical factors (e.g., instability in global petroleum resource supply) have previously been linked to increases in oil and gas well integrity failure. For example, Watson and Bachu (Watson et al., 2009) showed a direct positive correlation between oil price and incidence rate of integrity failure (manifesting as surface casing vent flow or gas migration) in Alberta, Canada between 1973 and 1999. Ingraffea et al. (Ingraffea et al., 2014) also identified a link between sudden and rapid upturns in drilling activity (related to unconventional shale development in Pennsylvania from 2006 to 2012) and an increase in the likelihood of integrity failure. The causes of these relationships likely relate to attempting to satisfy high demand with limited equipment resources in "boom times" or a general decrease in quality of well construction or P&A (or conversely an increase in rates of structural integrity loss) due to "rushed" development. This may be related to economics (as with oil prices, as previously described) or urgency in attaining petroleum resources (e.g., importance of maintaining petroleum supplies during a war effort) which results in an elevated risk of integrity failure. Consequently, we identify upturns in drilling activity in the UK as a potentially key risk factor in development of integrity failure for onshore wells. For the purposes of this study we propose that years during which the number of wells completed was more than 2 standard deviations ($\sigma = 21$) greater than the mean ($\mu = 24$) (i.e. years where 66 or more wells were completed) were likely constructed under duress, such that overall long term integrity of these wells may be reduced compared to the rest of the well population. Fig. 2 shows wells completed by year and years identified as having intensive drilling activity (i.e. 1939, 1943 and 1986 during which more than 66 wells were completed).

3.2. Well age

As seen in table 1, data on age or vintage of onshore wells in the UK are readily available. While no direct, simple linear correlation with age and wellbore integrity has previously been proven (Boothroyd et al., 2016), the year in which a well was constructed and abandoned will have influence on its long term integrity. It is logical to assume the prevailing regulatory framework and technologies available at the time of a well's completion and P&A will ultimately have a strong influence on long-term well integrity. Consequently, here we review the evolution of regulatory and technological frameworks for well construction and P&A in the UK and identify key dates before and after which wells will potentially have a greater or lesser risk of having reduced integrity.

3.2.1. UK regulatory framework for oil and gas well construction and P&A

With a history running greater than 150 years, regulation of global petroleum resource development has evolved significantly with time and by region. In the UK, general legislation concerning petroleum resource development was introduced in 1918 with the Petroleum Production Act, which sought to encourage (as well as control) exploration and production. This was replaced by a new Act in 1934 after which various other pieces of general legislation were then combined to form the 1998 Petroleum Act which encompasses rules relating to decommissioning of both on- and off-shore oil and gas wells. Currently all petroleum resource development in the UK is overseen by the Oil and Gas Authority which was founded in 2015 and is: "*Responsible for maximizing field life and economic revenues as well as ensuring that decommissioning is executed in a safe, environmentally sound and cost-effective manner*".

Specific regulations concerning well construction, P&A and

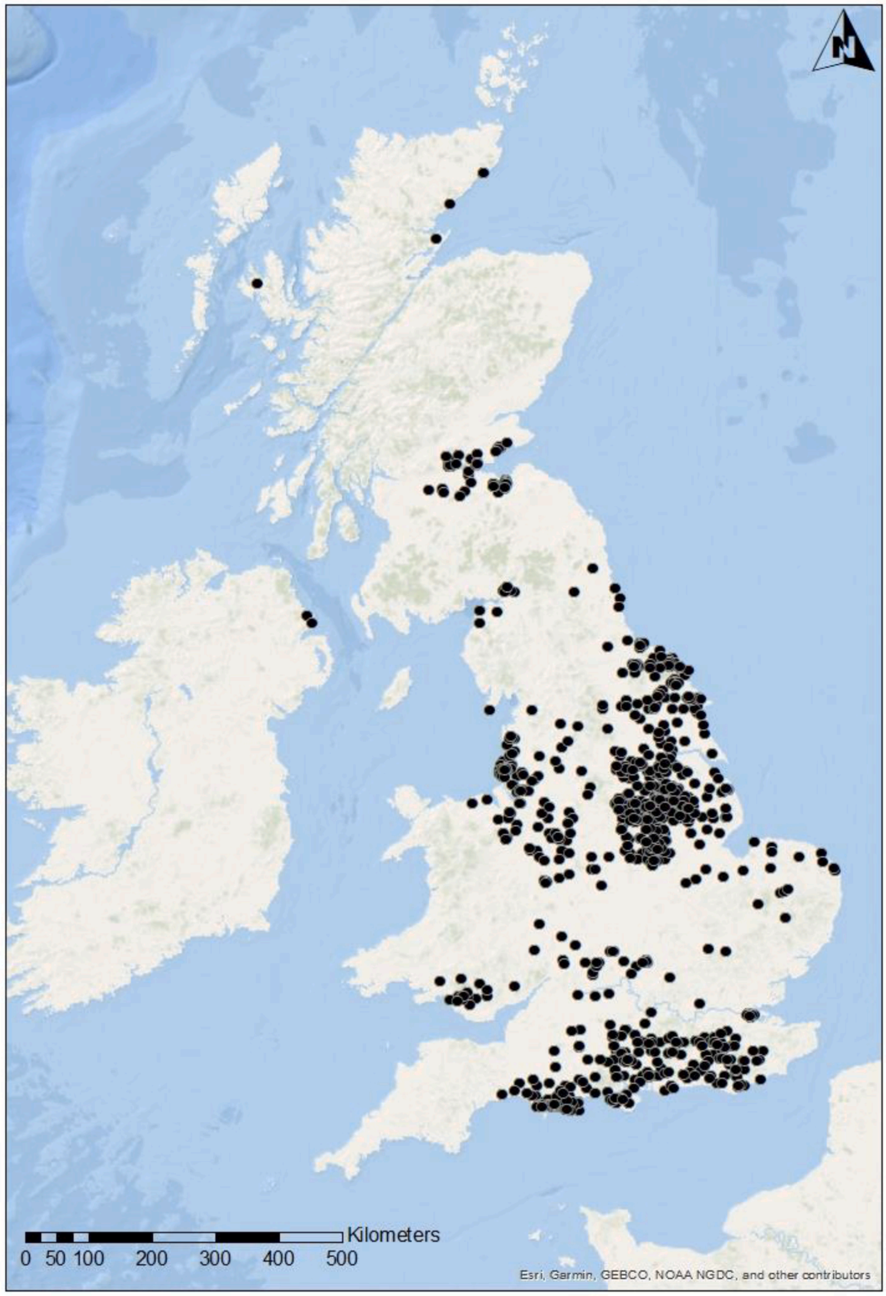

Fig. 2. Map showing location of 2149 UK onshore oil and gas wells. The average UK well is 50 years old and typically a vertical, conventional oil and gas production well.

decommissioning appear to have evolved in several distinct phases in the UK. The first references to construction and P&A of wells appears in the Offshore Installations (Operational Safety, Health and Welfare) Regulations 1976 (SI 1976/1019). This was followed by the Offshore Installations (Well Control) Regulations 1980 (SI 1980/1759) before being superseded by the Offshore Installations (Well Control) (Amendment) Regulations 1991 (SI 1991/308). However, these regulations are for the most part high level and do not provide any specific detail on how wells should be constructed, abandoned or managed (other than they should be "adequately constructed and sealed"). Consequently, no firm conclusions can be drawn on construction, P&A configuration or propensity for long-term integrity based on the development of regulations up to and including 1991. Modern day regulations were achieved through the Wells Design and Construction Regulations (1996), commonly referred to as the DCR. These regulations were, in part, developed as a result of the explosion and fire on the offshore platform Piper Alpha (Crawley, 1999). Following this incident, it was recognized that a more robust construction and P&A process was needed and that in the coming decades many more oil and gas wells would reach the end of their economic life and need to be abandoned safely and effectively. It should be noted that the DCR were primarily developed for the offshore industry, however, are stated as applicable to onshore wells. Aside from the DCR, another key piece of regulation relating to integrity of onshore oil and gas wells is the Borehole Sites and Operations Regulations introduced in 1995 (BSOR). BSOR primarily concerns the management of the Borehole Site and the operational aspects of well decommissioning, while the DCR outlines the actual downhole requirements for the decommissioning of wells. Key regulations relevant to well construction

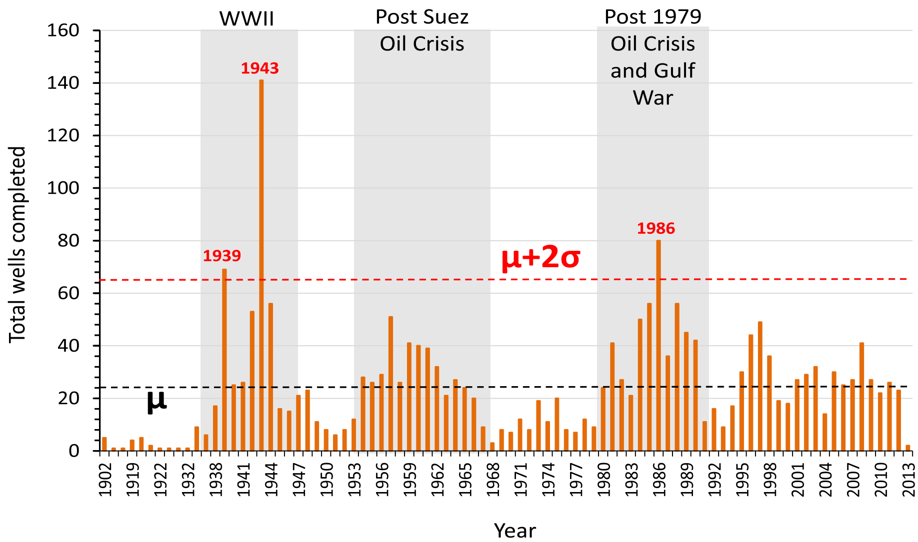

Fig. 3. Timeline showing wells completed by year onshore in the UK with upturns in activity initiated by various geopolitical events evident. The black line indicates the mean (μ) number of wells completed per year while the red dashed line indicates extraordinary years of intensive drilling and completion (defined as μ+2σ).

and P&A in the DCR and BSOR are described in more detail in Supplementary Information.

Together the DCR, BSOR and related guidance led to a much more robust framework for how onshore wells should be constructed and abandoned in the UK. This led to a significant increase in general well integrity and therefore after their introduction in 1996, more certainty can be assigned to how robustly a well will have been constructed and abandoned. Consequently, we conclude that 1996 is a watershed moment in terms of UK oil and gas well construction, P&A and therefore integrity. An oil and gas well constructed post-1996 can be assumed as "modern" and likely of greatest possible relative integrity. Wells constructed before 1996 potentially have lower relative long-term integrity. It should be noted this assumption does not infer pre-1996 wells are or will definitely suffer integrity failure nor that wells constructed after 1996 cannot under any circumstances suffer integrity failure. Nonetheless, we propose that overall there will be some difference in potential long-term integrity for wells constructed either before or after this date.

3.2.2. Development of cementing technologies

While legislative and regulatory frameworks set standards for well construction and P&A, available technology will ultimately determine a well's integrity and how effective construction and P&A will be. Consequently, we consider the evolution of well cementing technologies (cement being the major component of well integrity barriers and the dominant component of both construction and P&A) in order to assess how effective construction and P&A in the UK might be based on age.

Various key developments in cementing procedures have occurred over the past century, driven mostly by the US petroleum industry (Trudel et al., 2019; Benedictus, 2009, Oil-well et al., 1959). Beginning early in the 20th century (i.e., 1903), Portland cement was first employed as a robust seal for oil and gas well casings and well plugs. By 1917 more oil field cements were being developed and used. By 1919 the American Petroleum Institute (API) was established and began a more systematic and rigorous approach to the development of well cementing techniques for completing and abandoning wells. By 1928 more new cement types and additives for different subsurface conditions had been developed; as well as the introduction of centralizers to ensure correct placement of cement within a well (Benedictus, 2009). In 1937 the API formed a subcommittee on cementing and cement quality, which through to 1947 developed various cement testing procedures, types and standards. Overall, this led to the release of API Code 32 in 1948 and API Std 10A in 1953 which sought to standardize cementing types and methodologies. Development of plugging materials continued after 1953 to the present day with other key updates including API Spec 10A in 1972 followed by ISO 10,426 in 2000. A summary of cement types developed as part of API Std. 10A is shown in Table 2.

The history of well completion and cement engineering is long and complex (Benedictus, 2009), a detailed review of which is beyond the scope of the current study. Over time, cementing techniques and materials have continually improved, however, many factors will contribute to the overall integrity of a specific cementing job. Nonetheless, we conclude that 1953 was a key year after which API Std 10A and different cement types were available to operators constructing and abandoning oil and gas wells. It is reasonable therefore to propose this will have significantly increased general wellbore and P&A integrity (King et al., 2013; Benedictus, 2009). Consequently, we include this time event as a risk factor in assessing likely long-term well integrity (i.e. greater likely long term well integrity for wells completed after 1953 and relatively lower before).

It should be noted that in many parts of the world API well cement was (or still is) difficult if not impossible to obtain. Consequently other less effective cements may have been used after 1953 and even up to the present day in certain regions (Rogers et al., 2006). Therefore, whilst completion pre- and post-1953 serves as a potential key indicator of

Table 2
Overview of cement types available for use after API Std 10A was introduced in 1953.

Cement Class	Intended Depth Use	Special Properties
A	Surface to 6000 ft (∼1830 m)	None
B	Surface to 6000 ft (∼1830 m)	Moderate to high sulphate resistance
C	Surface to 6000 ft (∼1830 m)	High early strength and sulphate resistance
D	6000 to 10,000 ft (1830 - 3050 m)	High temperature and pressure and sulphate resistance
E	10,000 to 14,000 ft (3050 - 4270 m)	High temperature and pressure and sulphate resistance
F	10,000 to 16,000 ft (3050 - 4880 m)	Extremely high temperature and pressure and sulphate resistance
G/H	Surface to 8000 ft (∼2440 m)	General cement: can be augmented for different depth, pressure, temperature ranges and sulphate resistance

likely long term well integrity, it is not certain that any given well-constructed or abandoned after 1953 will have utilized these cements (use of which would need to be confirmed in individual records). For the purpose of this report when considering oil and gas wells drilled in the UK after 1953, we will assume API cement standards were used, but acknowledge that this may not have been the case.

Fig. 4 shows cumulative wells completed with time onshore in the UK in the context of identified well age factors that will influence long term integrity (i.e., regulatory and technological frameworks). Data show that some 568 wells were drilled before introduction of the API cementing standards (delineated by section period labelled A), 1706 before the introduction of modern regulatory framework (delineated by section period labelled B) and 442 after (delineated by section period labelled C).

3.3. Well orientation

Deviation of an oil and gas well from vertical occurs for various reasons; most recently with respect to horizontal drilling in thin layered, low permeability reservoirs such as shales to ensure production is economically viable. Deviation, which typically leads to greater productivity, is generally accepted to make well completion (i.e. the preparation for production including installation of all necessary pipework) more challenging and therefore has been suggested to influence long-term well integrity (Watson et al., 2009; Lackey et al., 2017; Montague et al., 2018). For example, during analysis of information held by the Alberta Energy Regulator on 315,000 oil and gas wells in the province of Alberta, it was observed that deviated wells were 4 – 5 times more likely to exhibit integrity failure than vertical wells (15% vertical well integrity failure rate compared to 65% for deviated wells) (Watson et al., 2009). Similarly, others have shown deviated wells are more likely to exhibit integrity failure than their vertical counterparts in the Wattenberg field, Colorado (Lackey et al., 2017). The cause of decreased overall well integrity in such cases is likely associated with poor cementing because of mechanical/physical factors such as poorly centralized casing or poor mud removal (both a direct result of a deviated orientation). These deficiencies in turn have been suggested to result in cement slumping, bridging, shrinkage and de-bonding; all phenomena known to reduce integrity (Jakobsen et al., 1991). While such issues are ubiquitous challenges associated with cementing in oil and gas wells, published data suggests they are seemingly exacerbated in deviated wells, leading to development of more leakage pathways (such as voids, fractures or micro-annuli) that allow migration of fluids along or outside the wellbore (i.e. well integrity failure).

Consequently, we propose to use available data on orientation (i.e. deviated or not) for onshore DW's in the UK as stated to infer potential long-term well integrity. Where a well is identified as being vertical (i.e. not deviated), it is deemed to have greatest relative integrity. Where deviation is identified, a well is assumed to have relatively less long-term integrity.

3.4. Well intent

Well intent (i.e. why a well was drilled or what its ultimate purpose was) has previously been suggested as a key factor that may strongly influence long-term integrity (Duguid et al., 2019; Watson et al., 2009). Here, whether or not an oil and gas well produced hydrocarbon fluids (i.e., through production or appraisal) and therefore if it was cased or completed has been suggested to influence the likelihood that it ultimately suffers integrity failure. In the case of production or appraisal wells (where hydrocarbon fluids were present), the intricacies of cementing with casings in a well (including typical risks associated with cementing as previously described in section 4.3), the presence of perforations in casings and the presence of a potential fugitive hydrocarbon fluid source have been hypothesized to infer greater risk for integrity failure and fluid release (King et al., 2013; Benedictus, 2009; King et al., 2014). In contrast, exploratory wells drilled and then abandoned immediately due to little or no hydrocarbon fluids being encountered (and therefore with no casings being present) are inferred to present less relative risk for long-term integrity failure and fugitive fluid release.

Consequently, we propose well intent as an indicator for long-term well integrity and potential for fugitive fluid leakage from DW's. Here, exploration wells are assumed to be more likely to have greater long-term well integrity (i.e. with no fugitive fluid source encountered and less chance of cementing issues) while appraisal and development wells (i.e. where a fugitive fluid source is present and there is greater chance for cementing issues to occur) relatively less. It should be noted that to the author's knowledge little to no work has specifically examined exploratory wells and their integrity as a key subset of legacy well types in detail. Consequently, their integrity over the longer term is uncertain and should be constrained in future work.

4. Methodology

4.1. Prioritization of stewardship

Based on the five key risk factors identified (summarized in Section 4), for which data is readily available in the UK, an abductive heuristic

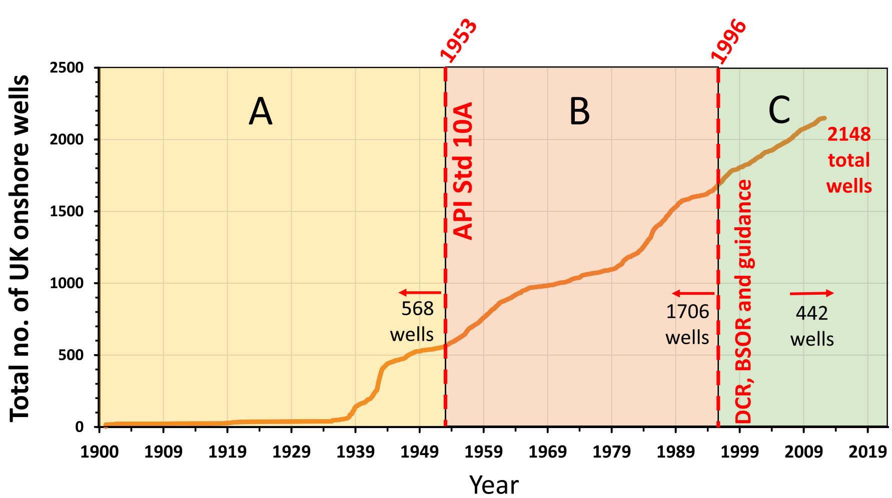

Fig. 4. Timeline showing cumulative total number of wells completed onshore in the UK and factors associated with vintage that will influence long-term well integrity. These include introduction of the DCR and BSOR including associated guidance in 1996 and advances in cementing practices due to the introduction of API std. 10A in 1953.

methodology for prioritization of stewardship for onshore decommissioned wells is proposed. The method identifies oil and gas wells that potentially have the lowest overall relative long-term integrity in the well population and should therefore be prioritized for monitoring and stewardship moving forwards. The proposed method uses the five key risk factors to segregate wells into ascending Tiers, according to their decreasing potential long-term integrity. The method considers whether each well was/is: 1) Completed in periods of intense drilling activity in which the number of wells drilled was significantly greater than normal (defined here as 2 standard deviations greater than the mean number of completions per year); 2) Completed before or after the introduction of a robust regulatory and guidance framework for how wells should be constructed and abandoned in 1996 (The Well Design and Construction Regulations and Borehole Site Operations Regulations and associated guidance); 3) Completed before or after the evolution of cementing standards for oil and gas wells post 1953 (API Std. 10A); 4) Deviated from vertical; and/or, 5) Intended for exploration, appraisal or production. All wells are initially classed as Tier 1 (i.e., of greatest relative long-term integrity). The Tier score is then increased depending on vintage, orientation and intent; assigning up to a potential maximum of Tier 6 status (i.e., likely to have the lowest relative long-term integrity) as shown in Table 3. A Tier assignment decision tree is shown in Fig. 5.

4.2. Clustering and cluster analyses

In order to assess spatial distribution and clustering of DW's by assigned Tiers, Moran's *I* analyses were conducted on the DW population. Moran's *I* is an inferential statistical method that allows assessment of spatial auto-correlation of features and their attributes (Moran, 1950; Li et al., 2007). More simply put, the analyses assess how similar an object is to ones surrounding it (including determination of statistical significance) and is commonly used in spatial assessment during various geographic investigations (Bone et al., 2013; Gholizadeh et al., 2017). Analyses were conducted using ArcMap's Spatial Autocorrelation (Moran's *I*) and Cluster and Outlier Analysis (Anselin Local Moran's *I*) tools in conjunction with DW coordinates and assigned Tier. First, Global Moran's *I* was determined for all DW's and assigned Tiers to assess overall DW population wide clustering and significance. Next Local Anselin Moran's *I* (Anselin, 1995) was determined to identify statistically significant hotspots or clusters of Tier 5 DW's (or high-high clusters). More information on how spatial analyses were performed is provided in Supplementary Information.

Table 3
Criteria for Tier assignment based on temporal evolution of geopolitical, regulatory and technological framework in which wells were constructed and or abandoned. All wells start as Tier 1 assuming maximum potential integrity and Tier factors are added depending on identified factors for which data is readily available as shown.

Attribute	Tier Factor	Rationale
Drilled post-1996	No change (remains tier 1)	Modern regulatory framework with highly prescriptive guidance on construction and P&A
Drilled pre-1996, post-1953	+1	Weaker regulatory framework and less guidance on construction and P&A; however, cementing practices were developed
Drilled pre-1953	+1	Cementing practices poorly developed making effective construction and P&A less likely
Drilled during intense drilling activity	+1	Pressure on supply chains and urgency leading to chance of lower quality well completion
Wellbore deviated from vertical	+1	Other studies have shown that there is a statistically significant association between deviated wells and integrity failure
Well Intent	+1	Production and appraisal wells have been shown to suffer poorer integrity in the long term due to the presence of casing/tubing leading to complexities with construction and P&A compared to exploration wells.

5. Results

5.1. Tier assignment and spatial distribution

Following the methodology described in Section 5, all 2149 UK onshore wells were assigned a Tier from 1 to 6 with examples of each Tier assignment shown in Table 4. Areas of interest (AOI's), i.e. local areas of civil parish scale where more than a total of 5 Tier 5 wells are found in close proximity to each other (i.e. heuristically identified), are shown in Table 5. The spatial distribution across England (where 97% of onshore wells are hosted) of wells according to assigned Tiers (including key regions delineated A to D) are shown in Fig. 6a.

Results show Tier 4 and 5 wells are found in 4 main regions (delineated by rectangles A to D in Fig. 6a and b): the East Midlands, the South, the Northwest and Yorkshire and the Humber. Here, Tier 5 wells tend to be found in higher density AOI's associated with a specific petroleum development play and/or geopolitical events (as shown in Table 5). For example, the East Midlands, which has by far the largest number of Tier 4 and 5 wells, hosts a series of decommissioned Tier 5 wells (i.e., AOI's 1, 3 comprising a total of 120/200 Tier 5 wells) which were drilled as part of the war effort to secure petroleum fuels. These wells are assigned Tier 5 due to their status as production wells drilled pre-1953, in a year of intense drilling activity. Similarly, a number of Tier 5 wells are hosted in the Northwest (i.e., AOI's 2 and 5 in the Northwest and North Yorkshire and the Humber with a total of 31 and 9 Tier 5 wells respectively) also relating to increased drilling activity during WWII. Again, these DW AOI's are assigned Tier 5 due to their status as production wells drilled pre-1953, in a year of intense drilling activity. Meanwhile 2 smaller AOI's of Tier 5 wells are found in the South (AOI's 6 and 7 in the South with 8 and 6 Tier 5 wells respectively). These Tier 5 wells differ from those in other areas being more recently constructed, characterized as deviated production wells completed pre-1996 during a year of intense drilling activity.

5.2. DW tier clustering and cluster analyses

Global Moran's *I* (determined to be 0.45 with a concurrent z-score of 38.4) shows statistically significant clustering of like Tier DW's occurs throughout the UK. Meanwhile, the Anselin Local Moran's *I* assessment shows a series of statistically significant high-high Tier 5 hotspots or clusters of Tier 5 DW's (Fig. 6b) are present across the UK, generally concurring with the heuristically defined AOI's of Tier 5 DW's as identified and described in Section 6.1 and Table 5.

6. Discussion

6.1. Higher risk wells present in clusters and by permutation

Here we reviewed basic, readily available data on the UK onshore well population and identified factors associated with geopolitical, regulatory and technological frameworks in which wells were constructed and/or abandoned, and that are likely to influence their long-term integrity. The identified factors were integrated into an abductive heuristic methodology to prioritize stewardship of decommissioned wells in the UK according to potential long-term integrity, and in doing so wells were segregated into Tier levels 1 to 6 (with Tier 1 as potentially of greatest integrity and 6 of relatively lowest). Through this abductive heuristic methodology we identified that approximately 23% (497 wells) of wells could be considered Tier 4 and 9% (200 wells) as Tier 5, while no wells were assigned as Tier 6. Tier 4 and 5 wells are seen to be constrained to several key regions in England including the East

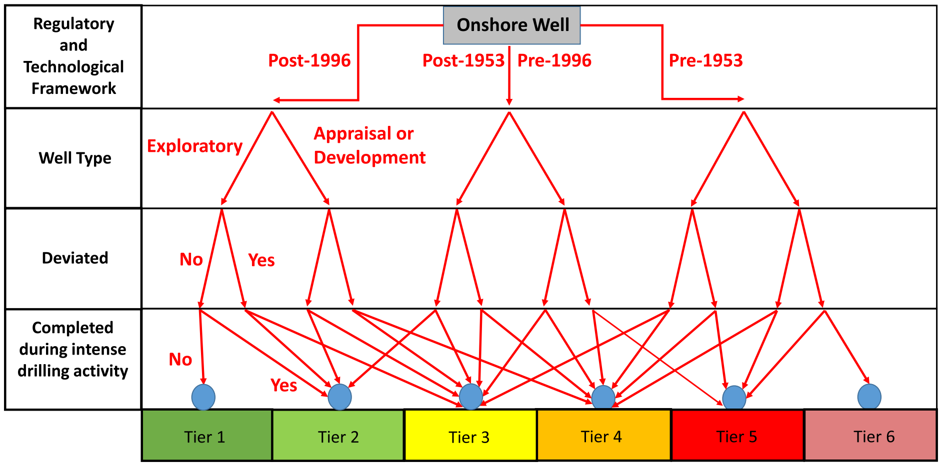

Fig. 5. Tier Assignment Decision Tree showing how identified factors compound to assign an increasing Tier based on factors known to induce potentially lower overall long term well integrity.

Table 4
Example of prioritization assignment for identified criteria showing range and inferred potential long-term integrity (i.e. Tier 1 to 6).

UK DW Tier Example by County Location (Well Completion Date)	Tier Factors Summary	Tier Assignment	Relative Potential Long Term Well Integrity
South Yorkshire (October 2004)	Vertical exploration well completed post-1996	1	Greatest
Cheshire (January 1994)	Vertical exploration well completed pre-1996, post-1953	2	Very good
Lincolnshire (January 2011)	Deviated development well, completed post-1996	3	Good
Leicestershire (December 1943)	Vertical exploration well completed pre-1996, pre-1953 in year of intense drilling activity	4	Moderate
Nottinghamshire (November 1986)	Deviated development well completed pre-1996, post-1953 in year of intense drilling activity	5	Low
No wells In the UK met these conditions	Deviated development well completed pre-1996, pre-1953 in year of intense drilling activity,	6	Lowest

Table 5
Key Areas of Interest (AOI) heuristically identified where more than five Tier 5 wells are found within close proximity of each other (i.e. approximately UK civil parish scale); including rationale for Tier 5 Status.

AOI	Name	Number of Tier 5 Wells	Region	Completion Date	Tier 5 Rationale
1	Eakring	79	East Midlands	1943	Vertical ex-production well that was completed before 1996, in a year of intense drilling activity and that was cemented before 1953.
2	Formby	31	Northwest	1943	
3	Kelham	31	East Midlands	1943	
4	Caunton	10	East Midlands	1943	
5	Kirby	9	Yorkshire and the Humber	1939	
6	Stockbridge	8	The South	1986	Deviated ex-production well that was completed before 1996, in a year of intense drilling activity and that was cemented after 1953.
7	Humbly	6	The South	1986	

Midlands (total of 134), the South (a total of 19), the Northwest (total of 32) and Yorkshire and the Humber region (total of 9). Although no Tier 6 wells were identified in the UK, such wells (i.e., deviated production wells, constructed prior to 1953 in a year of intense drilling activity according to the current methodology) may exist in other jurisdictions (e.g. North America); where they should be strongly considered in any stewardship or monitoring programs.

Moran's *I* analyses show there is statistically significant clustering of like Tiers throughout the population and clear clustering of wells delineated as higher relative risk for integrity failure (i.e. assigned as Tier 5). This clustering observation is simple and intuitive but important with respect to prioritization of stewardship. Real cases of well integrity failure clustering have been observed in other regions whereby a series of common factors manifest which are hypothesized to induce challenges with attaining good well integrity for all wells constructed and decommissioned in that area. For example, the Jean Marie region in NE British Columbia, Canada, exhibits a high rate of well integrity failure; whereby 62 out of a total of 145 cases of gas migration for the province have been found (Cahill et al., 2019). The causes for failure have been explored and suggested to be the result of a complex interaction of factors including; the presence of intermediate sources of fugitive gas (i.e. in paleovalleys), the type of drilling methods used in the area at the primary time of development (i.e. prevalence of underbalanced drilling methods), the occurrence of over pressurized gas bearing formations intersected by oil and gas wells in the area (e.g. the Lower Debolt Formation) and other well construction attributes (Sandl et al., 2021). Acknowledgement of the propensity for well integrity failure clustering in a proactive DW risk prioritization exercise is important as DW's of greater relative risk may be clustered in groups, which can be easily identified and incorporated, into stewardship programs for increasing efficiency and effectiveness. For example, in this case we reduce 2149 DW's across the domain to approximately 6 high risk cluster areas, which could be more easily and effectively monitored and assessed

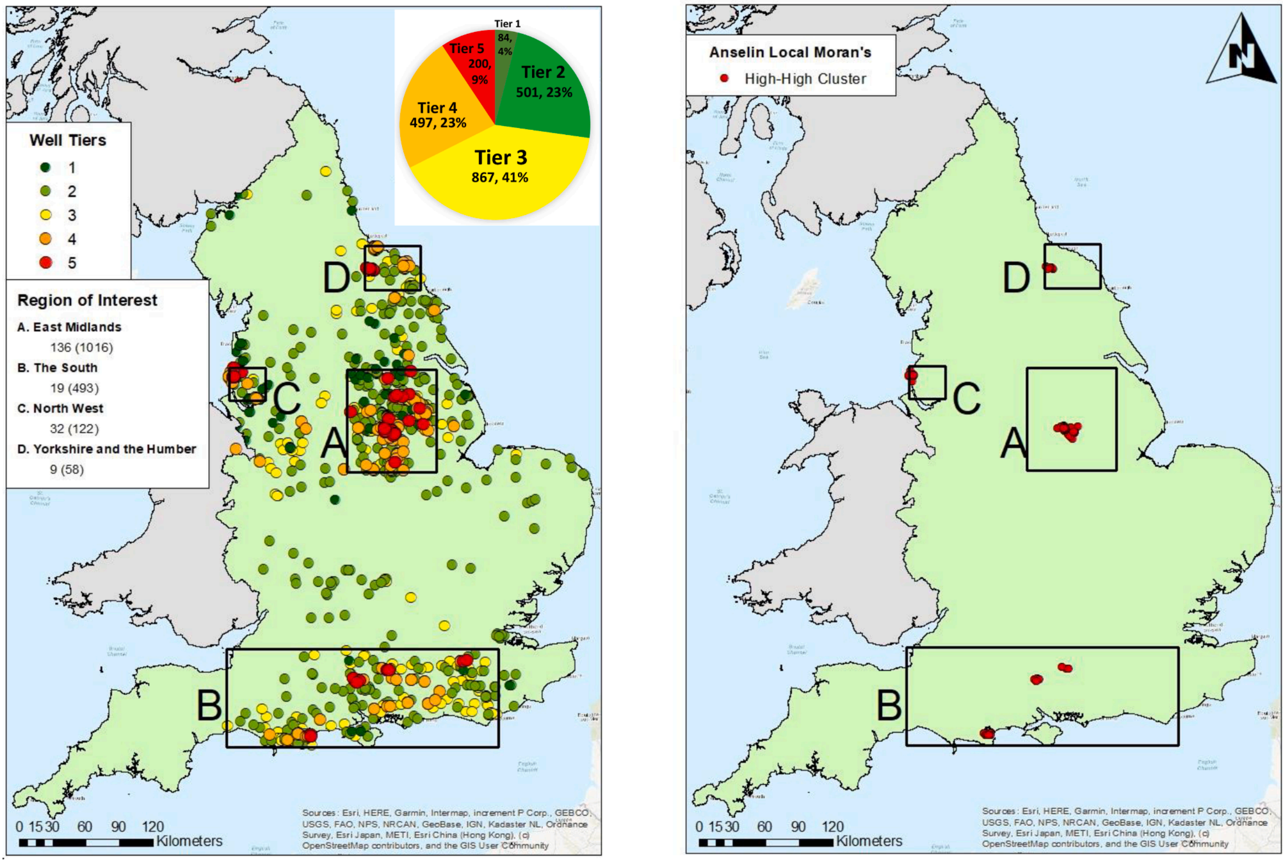

Fig. 6. **a)** Map, with inset pie chart, showing distribution of onshore wells in England according to assigned Tier by key regions. The legend shows the 4 key regions total number of Tier 5 wells (and total number of wells in brackets) including: A) the East Midlands (136 Tier 5 wells out of a total of 1016), B) the South (19 Tier 5 wells out of a total of 493), C) the Northwest (32 Tier 5 wells out of a total of 122) and D) Yorkshire and the Humber region (9 Tier 5 wells out of a total of 58). **b)** Map showing Anselin Local Moran's *I* high-high (Tier 5) clusters whereby the whole population of 2149 DW's has been reduced to approximately 6 higher risk clusters of Tier 5 wells.

during future stewardship activities.

Interestingly our observed results also highlight and reinforce how multiple risk factors conspire to reduce potential overall well integrity, and that no single cause, oil and gas well type or area will uniquely experience risk for high rates of well integrity failure. For example, there are 2 main "types" of Tier 5 clusters identified in the UK using the current methodology. The first are present in a few discrete areas in the East Midlands of England typically associated with WWII. These clusters are assigned Tier 5 status as they are comprised of production wells completed before 1953 in a year of intense drilling activity associated with the war effort (whereby there was urgent need to attain petroleum fuels). Such a combination of attributes infers these wells are likely to have potential for relatively lower long-term integrity; having been constructed under duress (i.e. during intense drilling activity), at a time when cementing practices were in their infancy and regulations and guidance on construction and P&A was less detailed or rigorous. In addition, as production wells (with various casing and tubing infrastructure down hole) these wells would have been generally more challenging to cement during completion and P&A and would have a potential fugitive hydrocarbon source present.

The second DW cluster type is found in the South of England (i.e. Hampshire), also ranked as Tier 5. The attributes that led to this assignment are distinct from those in the northern regions; with wells being much younger (i.e. completed in 1986), deviated production wells. These wells were completed prior to the Wells Design and Construction Regulations (i.e. DCR) introduced in 1996 or the Borehole Sites and Operations Regulations (i.e. BSOR) introduced in 1995 meaning there is less certainty in the robustness of their construction or P&A; and in addition they are deviated production wells. Their deviation from vertical and the presence of casing and tubing paraphernalia mean that accurate and effective cementing during construction and P&A may have been challenging. These observations highlight how multiple factors may conspire in a complex manner to determine a given DW's overall relative potential long term integrity and that there may be several types of DW's of concern identified in an area or jurisdiction that need to be incorporated into a stewardship strategies for varying reasons.

6.2. Implications for legacy well stewardship strategies and geoenergy activities

Although our method is relatively simple, it offers an abductive heuristic strategy to take the UK's whole onshore well population, which would be challenging if not impossible to steward in the long term, and reduce the number of DW's and locations that may need to be considered in a stewardship program to a more manageable subset. Consequently, the proposed method can aid optimization of stewardship and inform the efficient and effective use of resources. As Tier 5 wells are almost exclusively located in high-density clusters in discrete areas, they will potentially be easier to manage, monitor and assess in any ongoing stewardship program. For example, the largest clusters of Tier 5 wells are located in the East Midlands of England, i.e. Nottinghamshire, which contain 120 of the 200 Tier 5 wells in the UK. In particular, AOI 1 as identified in Table 5 contains 79 Tier 5 wells all within a 2 km (Davies et al., 2014) area. Consequently, many Tier 4 and 5 wells could be monitored or assessed in a short period for minimized costs during multi-well, on the ground field investigations. These areas could also be targeted for deployment of longer-term remote monitoring stations. Furthermore, top down approaches (e.g. aerial or satellite monitoring) in particular might form effective integrity monitoring strategies, which can cover many Tier 4 or 5 wells in clusters in a short time for minimized costs. In order to monitor and verify ongoing well integrity it is recommended that clusters of Tier 4 and 5 type wells, i.e. DW's with a combination of characteristics known to influence long term integrity in a negative manner (e.g. such as those identified here) are targeted for stewardship. This should be advanced through ongoing periodic field assessment; including monitoring of surficial and shallow subsurface conditions. This is particularly important for areas where ongoing and future geoenergy applications (e.g. CCS and other subsurface fluid or heat storage activities) may take place. In that case, a legacy well prioritization exercise, followed by field investigations to constrain DW integrity should precede any new geoenergy development and continue concurrently to ensure sustainability.

6.3. Validation against past DW field investigations

Validation is a key challenge associated with any risk assessment or prioritization method as field measurements at scale are rare and difficult to attain; but necessary to prove a method is fit for purpose. Indeed, in other studies that explore the risks posed by legacy wells on subsurface activities, few have field data for validation to support their overall structure and particular combination and weighting of factors (Duguid et al., 2019; Haagsma et al., 2017; Lackey et al., 2019). Unfortunately, during the current study it was not possible to attain new field measurements to assess integrity at DW's in the UK with a view to validation. However, as described in the introduction, a previous field study did examine integrity at 102 DW's in England (Boothroyd et al., 2016); results from which offer an opportunity for comparison and validation of the current prioritization Tier assignments. Consequently, we reviewed data on apparent DW integrity in England as reported by Boothroyd et al. in the context of DW Tier assignment. Here we might expect to see a relationship between inferred integrity (i.e. surficial CH_4 concentrations) and increasing Tier status if the proposed abductive heuristic method is reasonable. Initial descriptive statistical review of published DW CH_4 anomaly data suggests a normal distribution with one outlier (identified by a Z-score of ~6.8, where >3 is generally accepted as an outlier). After removing the outlier, the average CH_4 anomaly for each Tier level (i.e. Tiers 1 to 5 as individual groups where $n = 1, 47, 30, 10$ and 8 for each tier respectively) was calculated and the relationship between assigned Tier and CH_4 anomaly assessed by linear regression. The regression (shown in Fig. 7) appears to show a strong, positive relationship between increasing Tier level and average relative CH_4 anomaly observed in the field, offering support for the prioritization methodology.

However, further assessment by Kruskal-Wallis Test (a non-parametric one-way ANOVA on ranks), which checks a null hypothesis (H_0) that for each DW Tier group there is an equal probability of any containing the highest relative CH_4 anomaly, we see that H_0 cannot be rejected (i.e. p-value $> \alpha$). Consequently, the difference between the mean ranks of all Tier groups, and therefore the observed trend, is not big enough to be statistically significant. However, it should be noted that in a Kruskal-Wallis test, a non-significance result cannot prove that H_0 is correct, only that it cannot be rejected. It should also be noted that if the proposed outlier is not removed, linear regression shows no strong positive relationship between increasing Tier level and average relative CH_4 anomaly from field investigations. So overall, assessment of past field results against current Tier assignments is inconclusive, however somewhat promising. Consequently, it will be necessary to attain new field measurements (particularly a greater number of measurements at all Tier levels) in order to validate the prioritization method more definitively. Such field investigations are beyond the scope of the current study but should be carefully designed to ensure they are able to effectively and accurately assess integrity at DW's, taking into account soil types and conditions, prevailing meteorological factors and include the use of continuous monitoring methods (Forde et al., 2019; Chao et al., 2020).

6.4. Method simplicity, potential development and transferability

As dictated by the availability of data on UK DW's, the prioritization methodology described is relatively simple and will not capture all the complexities of well integrity and its failure. Consequently, the suggested method forms an abductive heuristic that is not perfect but is sufficient to form a starting point for prioritization of DW stewardship in the UK. This is a reasonable initial approach according to the principle of parsimony; at least until robust field validation can guide further

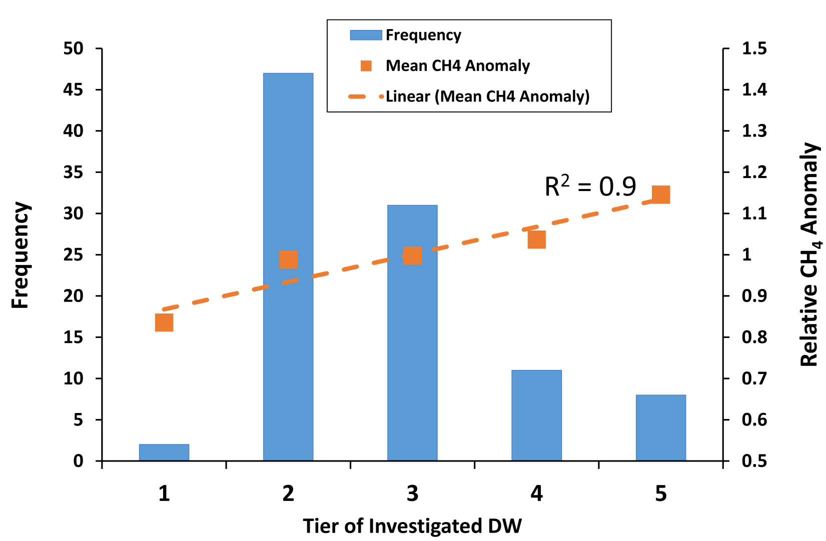

Fig. 7. Histogram showing Tier Assignment of DW's previously assessed for integrity in field investigations (by frequency) and average reported relative CH_4 anomaly (CH_4 measured at surface normalized to an adjacent background) by Tier (orange squares). Comparison of field and prioritization results reveals a strong (R^2 of 0.9), positive relationship (orange dashed line) between increasing average CH_4 anomaly and increasing Tier.

development and justify addition of more factors and complexity as needed. Beneficially, the prioritization methods simplicity makes it potentially adaptable, whereby it could easily be expanded or tailored to include other factors known or suspected to influence wellbore integrity failure (e.g. local geology, well construction details including casing and P&A configurations, more detail on P&A practices and their evolution, remedial treatments etc.) or parameter weighting as necessary. Integration of data on geology intersected by a DW in particular should be prioritized during any future method development as intersected strata have been shown to be a critical factor in determining long-term well integrity and the propensity for fugitive fluids to be released and migrate at a given site (Sandl et al., 2021; Chao et al., 2020). Expansion of the method and inclusion of more factors or well attributes related to integrity would allow for a more detailed dissection of the DW population into groups according to potential long-term integrity. Priority groups could then be targeted for further desk study and/or field monitoring.

While we used the UK onshore DW population as a case study, the method described and insights made may be transferable to other regions of extensive onshore oil and gas development where the same data is readily available. For example, the same data as used here (i.e. attributes in Table 1) is also available in regulatory data repositories for Alberta and British Columbia in Canada and the Netherlands (which collectively host >400,000 energy wells, all of which will ultimately be decommissioned). Thus, these regions have the basis for a similar abductive heuristic prioritization method to delineate wells by relative potential long-term integrity. Although details and history of petroleum development will be unique in each region there is usually a clear evolution of regulatory and technological advancements in oil and gas well construction and P&A practices, as we describe here, such that watershed moments or key timelines can be identified and delineated in a similar manner. Moreover, environmental and engineering factors associated with long-term integrity discussed here will be relevant to all DW's, regardless of region and/or varying regulatory frameworks. For example, introduction of the API cementing standards and its impact on overall well integrity have formed best practice for most global development (including in Canada and the Netherlands). Similarly, an oil and gas wells intent and deviation will have the same overall potential implications on integrity regardless of where a well is located globally. It should be acknowledged that the method described here would not be applicable to all regions of significance with respect to petroleum resource development. In particular, the method will not be transferable to jurisdictions where oil and gas well attribute data (as used here) is not readily available (e.g., information on intent of wells such as in the US). In such regions significant effort would be needed to compile a useable database, inferring the method would not be easily transferable.

7. Conclusion

Well integrity is a complex issue associated with all petroleum wells. It is of particular concern with respect to abandoned or decommissioned wells which are required (and assumed) to be sealed in perpetuity. A complex combination of environmental, engineering, regulatory and geopolitical factors can interact and compound to determine if a well suffers integrity failure in the long-term. Globally, many millions of DW's will exist, even after full decarbonization of energy systems is achieved, so it will be important that strategies to prioritize stewardship of this legacy infrastructure are developed. Such strategies can help assess how likely it is that DW's are effectively sealed or releasing greenhouse gases into the atmosphere; hampering efforts to achieve NetZero or posing a direct risk to the sustainability of new geoenergy activities. The UK has a modest, but significant, onshore population of decommissioned oil and gas wells; stewardship of which could be challenging if all wells were considered equally likely to suffer integrity failure. Here we show how basic, readily available data held by regulatory authorities can be integrated into an abductive heuristic methodology to segregate onshore DW's in the UK according to their likely long-term integrity. Even though a relatively simple method, the rationale for Tier assignments is supported in the literature and somewhat supported by review of previously published field data on DW integrity in the UK (albeit inconclusively in terms of statistical significance with currently available data). The proposed method therefore appears to offer a reasonable, abductive heuristic approach to identify a subset of DW's in a larger population for prioritized stewardship. It is recommended that DW's identified as being of higher relative risk for integrity failure (e.g. Tiers 4, 5 or 6 in the current method) should be prioritized for further investigation by desk and/or field study. It will be necessary in the future for new field data to be collected, both to constrain integrity of DW's more generally (recognizing DW integrity is generally poorly constrained) and in order to develop, validate and calibrate prioritization methods such as this. Such methods will be increasingly necessary to steward the large number of legacy wells that will eventually exist amongst ongoing use of the subsurface for geoenergy applications in a NetZero future.

It should be noted that the assignment of Tiers in this study is relevant to the UK context. Inference of potential long-term relative well integrity does not suggest identified wells in the UK currently lack or will definitely lose integrity at any point, nor will other similar wells elsewhere. The Tier assignment suggests only that these UK based wells should be prioritized in any ongoing or future stewardship scheme as they possess characteristics or attributes known to influence integrity.

CRediT authorship contribution statement

Aaron Graham Cahill: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Paula Sofia Gonzalez Samano:** Formal analysis, Visualization, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was jointly funded by Heriot Watt University and the Environment Agency of England. The authors are grateful for valuable and useful input to the study provided by Dr. Sian Loveless, Dr. Doug Boddy, Prof. Roger Timmis and Dr. Alwyn Hart of the Environment Agency of England. In addition, the authors acknowledge valuable input from Toni Harvey and Alan Poole (the UK Oil and Gas Authority) and Trevor Sexty (the UK Health and Safety Executive), as well as comments from anonymous reviewers which all greatly improved the study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2021.103560.

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