Supplementary material for

Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies

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Table S1| Source data of the North Sea well inventory.

|  |  |  |
| --- | --- | --- |
| Country | Data Source (Date) | Link |
| Norway (NOR) | Norwegian Petroleum Directorate (Dec. 2018) | https://www.npd.no/en/about-us/information-services/available-data/map-services/ |
| United Kingdom (UK) | Oil and Gas Authority (Dec. 2018) | https://data-ogauthority.opendata.arcgis.com/datasets/oga-wells-ed50 |
| Germany (GER) | Niedersächsisches Landesamt für Bergbau Energie und Geologie (Dec. 2018) | https://nibis.lbeg.de/cardomap3/?TH=BOHRKW |
| Denmark (DK) | Danish Energy Agency (Dec. 2018) | https://ens.dk/en/our-services/oil-and-gas-related-data/shape-files-maps |
| Netherland (NL) | Netherland Oil and Gas Portal (Dec. 2018) | https://www.nlog.nl/en/boreholes |

Table S2| Well selection for offshore North Sea (NSEA) wells.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Country | Onshore | Offshore | Multilateral | NSEA | NSEA (non-sidetracked) | Decommissioned |
| UK | n/a | 12,040 | 3,071 | 11,672 | 8,655 | 4,048 |
| NOR | n/a | 7,769 | 764 | 6,254 | 5,551 | 1,891 |
| NL | 6,481 | 2,108 | 661 | 2,108 | 1,447 | 750 |
| DK | 102 | 269 | n/a | 269 | 264 | n/a |
| GER | 21,100 | 204 | n/a | 204 | 204 | n/a |
| Total | 27,683 | 22,390 | 4,496 | 20,507 | 16,121 | 6,689 |

Table S3| Investigated wells during POS518 and POS534. The table shows field identification number (FID), well identification number (well ID), latitude (WGS84), longitude (WGS84), flare identification index (1 positive detection), corresponding cruise number, distance to bright spot with polarity reversal from seismic data, the mean root-mean-square (RMS) amplitude for a 300 m circular buffer around the well location, the corresponding RMS amplitude standard deviation (RMS SD), well spud year (start date of drilling) and well intent.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| FID | Well ID | Lat. [°] | Lon. [°] | Cruise | Flare | Distance to polarity reversal [m] | RMS amplitude (300 m buffer mean) | RMS SD (300 m buffer mean) | Spud date [Year] | Well intent |
| 1 | 15/30-1 | 58.081721 | 0.839666 | POS518 | 1 | 240 | 988 | 180 | 1975 | Exploration |
| 2 | 15/30-11Z | 58.110768 | 0.846873 | POS518 | 0 | 780 | 1,111 | 202 | 1995 | Exploration |
| 3 | 15/30-12 | 58.100815 | 0.858856 | POS518 | 1 | 100 | 1,241 | 142 | 2003 | Appraisal |
| 4 | 15/30-2 | 58.102421 | 0.841843 | POS518 | 1 | 400 | 1,029 | 244 | 1977 | Appraisal |
| 5 | 15/30-7 | 58.068499 | 0.839686 | POS518 | 0 | 960 | 975 | 201 | 1990 | Exploration |
| 6 | 16/26-24 | 58.040716 | 1.181016 | POS518 | 0 | 950 | 721 | 147 | 1992 | Exploration |
| 7 | 16/26-3 | 58.061740 | 1.166899 | POS518 | 1 | 570 | 956 | 98 | 1981 | Exploration |
| 8 | 16/27a-6 | 58.053665 | 1.225865 | POS518 | 1 | 250 | 896 | 197 | 1991 | Exploration |
| 9 | 16/27b-5 | 58.045337 | 1.210067 | POS518 | 1 | 570 | 784 | 176 | 1986 | Exploration |
| 10 | 21/03-2 | 57.960323 | 0.594846 | POS518 | 1 | 0 | 1,213 | 288 | 1975 | Appraisal |
| 11 | 21/04b-5 | 57.987966 | 0.648638 | POS518 | 1 | 150 | 1,044 | 316 | 1991 | Exploration |
| 12 | 22/02b-15 | 57.943307 | 1.388942 | POS518 | 1 | 100 | -9999 | -9999 | 2008 | Exploration |
| 13 | 22/02c-10 | 57.950753 | 1.355541 | POS518 | 0 | 300 | -9999 | -9999 | 1994 | Exploration |
| 14 | 22/03a-2 | 57.944971 | 1.439124 | POS518 | 1 | 0 | 717 | 182 | 1988 | Exploration |
| 15 | 22/03a-3 | 57.932767 | 1.426663 | POS518 | 1 | 100 | 637 | 174 | 1991 | Exploration |
| 16 | 23/26a-11 | 57.005108 | 2.164740 | POS518 | 1 | 0 | 973 | 313 | 1988 | Exploration |
| 17 | 29/01c-4 | 56.986807 | 1.128700 | POS518 | 1 | 570 | 693 | 90 | 1990 | Exploration |
| 18 | 29/01c-9z | 56.991495 | 1.094668 | POS518 | 0 | 500 | 840 | 100 | 2012 | Exploration |
| 19 | 30/01a-7 | 56.998989 | 2.165184 | POS518 | 1 | 0 | 985 | 362 | 1988 | Exploration |
| 20 | 30/01f-8 | 56.954942 | 2.049750 | POS518 | 1 | 0 | 1,027 | 183 | 1991 | Exploration |
| 21 | 20/10-2 | 57.668590 | -0.146838 | POS534 | 0 | 1,040 | 1,025 | 156 | 1976 | Appraisal |
| 22 | 20/10b-4 | 57.681923 | -0.145130 | POS534 | 0 | 810 | 879 | 124 | 1997 | Exploration |
| 23 | 20/15-1 | 57.560452 | -0.076122 | POS534 | 1 | 310 | 917 | 217 | 1985 | Exploration |
| 24 | 21/06-1 | 57.826023 | 0.108633 | POS534 | 1 | 35 | 882 | 247 | 1977 | Appraisal |
| 25 | 21/06-2 | 57.804332 | 0.000688 | POS534 | 1 | 0 | 907 | 224 | 1977 | Appraisal |
| 26 | 21/06a-3 | 57.778930 | 0.071013 | POS534 | 1 | 0 | 1,086 | 330 | 1989 | Exploration |
| 27 | 21/06b-6 | 57.768707 | 0.052362 | POS534 | 0 | 620 | 651 | 219 | 2005 | Exploration |
| 28 | 21/08-2 | 57.750513 | 0.405838 | POS534 | 0 | 730 | 747 | 111 | 1987 | Exploration |
| 29 | 21/11-5 | 57.520818 | 0.005042 | POS534 | 1 | 330 | 668 | 177 | 1995 | Exploration |
| 30 | 21/12-1 | 57.559972 | 0.306242 | POS534 | 1 | 0 | 1,313 | 270 | 1973 | Exploration |
| 31 | 21/12-2B | 57.646800 | 0.336925 | POS534 | 1 | 260 | 1,175 | 141 | 1981 | Exploration |
| 32 | 21/12-4 | 57.514748 | 0.335738 | POS534 | 0 | 1,000 | 1,238 | 147 | 2001 | Exploration |
| 33 | 21/13a-3 | 57.544567 | 0.421852 | POS534 | 1 | 1,000 | 1,202 | 187 | 1990 | Appraisal |
| 34 | 21/13b-2 | 57.565747 | 0.585255 | POS534 | 0 | 1,100 | 952 | 127 | 1983 | Exploration |
| 35 | 21/13b-4 | 57.500018 | 0.432610 | POS534 | 0 | 3,300 | 1,307 | 149 | 1992 | Exploration |
| 36 | 21/14b-3 | 57.539863 | 0.668117 | POS534 | 0 | 1,800 | 1,070 | 158 | 1986 | Exploration |
| 37 | 21/15b-5 | 57.659193 | 0.848283 | POS534 | 1 | 200 | 738 | 157 | 1985 | Exploration |
| 38 | 21/16-1 | 57.468655 | 0.148182 | POS534 | 0 | 500 | 696 | 98 | 1993 | Development |
| 39 | 21/16-4 | 57.416752 | 0.131247 | POS534 | 1 | 310 | 762 | 140 | 1995 | Appraisal |
| 40 | 21/16-A1 | 57.464052 | 0.158402 | POS534 | 1 | 180 | 651 | 165 | 1996 | Exploration |
| 41 | 21/17-4 | 57.462742 | 0.264408 | POS534 | 1 | 270 | 1,417 | 190 | 1986 | Exploration |
| 42 | 21/17a-6 | 57.468530 | 0.307422 | POS534 | 0 | 2,400 | 1,482 | 168 | 2011 | Exploration |
| 43 | 21/19-1A | 57.481067 | 0.622222 | POS534 | 1 | 100 | 516 | 118 | 1980 | Appraisal |

1. **Statistical Analysis**

Our analysis indicates that leakage from decommissioned hydrocarbon wells is elevated in areas where seismic amplitude anomalies in the sedimentary succession indicate the presence of shallow gas. We test, if the propensity of a well to leak can be identified by using a logistic regression, which includes regressors such as well activity data and/or derived parameters such as mean RMS amplitude and RMS amplitude standard deviation of that, the distance towards the most proximal bright spot with polarity reversal and age (spud date).

1. **Model selection**

The model selection is done using best subset selection. This method runs all combinations of regressors and the most suited of all models is selected. This is only possible because there are only 31 combinations and fitting the regressions is computationally undemanding. Yet best subset selection bears the pitfalls of overfitting, which is addressed in the final selection.

For the selection the sample of 43 investigated wells is randomly split into training and test data – with 70% of observations being used for training. For all the models the logistic regression is fit, and the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) is recorded. These are selection criterions are based on R2 with a penalty term for the number of regressors. Using the fitted regressions, predictions on the test data is made and the accuracy is recorded. This procedure is repeated 1.000 times and the means of all runs are summarized below:

Table S4| The top ten logistic regression fits averaged from 1,000 runs. Ranked by accuracy.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Rank | Parameters | AIC | BIC | Accuracy |
| 1 | distance, year, intent | 13.96 | 19.43 | 0.90 |
| 2 | distance, year | 13.63 | 17.73 | 0.90 |
| 3 | distance | 16.59 | 19.33 | 0.89 |
| 4 | distance, amplitude, year | 11.06 | 16.53 | 0.87 |
| 5 | distance, STD, year | 14.25 | 19.72 | 0.87 |
| 6 | distance, amplitude, year, intent | 11.34 | 18.18 | 0.87 |
| 7 | distance, intent | 16.06 | 20.17 | 0.87 |
| 8 | distance, STD, year, intent | 13.63 | 20.47 | 0.86 |
| 9 | distance, amplitude, STD, year | 12.77 | 19.61 | 0.86 |
| 10 | distance, amplitude | 15.80 | 19.91 | 0.85 |

The lowest AIC and BIC values are produced by using distance, amplitude and year as regressors. Closely followed by distance, amplitude, year, intent. This already hints at the problem that the information criteria do not penalize too many regressors strong enough and thus lead to overfitting due to the scarcity of data. This can be seen by the fact, that these two models do not produce the best results in predicting the test data.

It shows that we cannot blindly trust the produced ranking. For prediction purposes only distance should be used. There are several reasons for just picking distance as a regressor:

1. Parsimonious models usually increase prediction accuracy as the variance decreases with less predictors. 2. Data is too sparse for a multidimensional model they increase the chance of overfitting. 3. There are correlations between the different regressors, even though weak and with very low variance inflation factor. 4. Despite not being so important for forecasting: All the multi-regressors logistic regression are not statistically significant whilst with just distance it is. We will thus continue to only use distance as a regressors.

1. **Model fit**

The logistic regression is then fitted on the entire sample of 43 investigated wells and yields the following result:

Table S5| Logistic regression fit for distance

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | z value | Pr(>|z|) | Significance |
| Intercept | 4,853.946 | 1,735.128 | 2.797 | 0.00515 | 0.01 |
| Distance | -0.007361 | 0.002700 | -2.726 | 0.00640 | 0.01 |

The odds are a measurement of the likelihood that the event will occur. It can be viewed as the ratio of successes to non-successes. Precisely, odds are the probability of an event occurring divided by the probability that the event will not occur. The log odds of our model are thus:

Thus, we obtain the probability of leakage:

Each additional meter of the drill hole decreases the odds of leakage by so roughly a decrease of 0.7 % per meter.

As it can be seen from Figure 7 the logistic regression using distance fits really well. The classes are distinct but not perfectly separated. There is a steep ascent of the probability of leakage below 1,000 m distance of a shallow gas reservoir. The confidence intervals are not too large. Yet the confidence interval assumes normally distributed regressors.

The Shapiro-Wilk test is used to check normality. The null hypothesis states that the sample comes from a normal distribution. Which can be strongly rejected for the distance parameter in our sample. The test yields a test statistic W = 0.7354 and a A confidence interval assuming normality is thus nonsensical.

Fortunately, it is possible to use strictly monotonic transformations in order to obtain normally distributed regressors. The following transformation is used This transformation leads to the following test statistic: , . Meaning the null hypothesis of normality cannot be rejected at a 5% level, which is good enough for our prediction purposes. For completeness the logistic regression results of the normalized distance follow:

Table S6| Logistic regression fit of the normalized distance

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | z value | Pr(>|z|) | Significance |
| Intercept | 27.161 | 8.840 | 3.072 | 0.00212 | 0.01 |
| Normalized distance | -4.196 | 1.367 | -3.069 | 0.00215 | 0.01 |

1. **Predictions**

The transformed logistic regression model is then used to predict the probabilities of leakage for the other UK boreholes in North Sea. In order to obtain confidence bands this logistic regression is performed subtracting and adding two standard deviation from the calculated probability. The point estimate predicts the leakage of 926 boreholes, where the 95 % confidence interval ranges from 719 to 1058.