Measuring changes in earthquake occurrence rates in Groningen.

Update June 2016.

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by

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Executive Summary

Differences between epochs in earthquake (EQ) occurrence rates were estimated, for each of four different regions within the Groningen gas field. The number of EQ occurrences per unit of time is also referred to as the "activity rate". On the 1^{st} of January 2014, gas production at a number of production clusters in a part of the gas field near the town of Loppersum was greatly reduced. Of particular interest is the question whether there is evidence that EQ occurrence rates have changed following this reduction in gas production rates. The period following the 1^{st} of January 2014 is referred to as the "post shut-in epoch". The period prior to this date is partitioned into a number of epochs such that the numbers of events that occurred within each of these "pre shut-in epochs" are equal to the number of events observed in the post shut-in epoch.

The statistical methodology for estimating EQ occurrence rates for a given epoch, as well as differences in EQ occurrence rates between epochs, has been described in detail in Paleja and Bierman [2016]. The results as presented in Paleja and Bierman [2016] were based on the earthquake catalogue (EC) as downloaded from the website of the Royal Dutch Meteorological Institute (KNMI) which was complete up to and including the event recorded on the 9^{th} of September 2015 near the town of Harkstede, with associated magnitude of M=1.2. In this report, we provide an update of the estimates of differences between epochs in EQ occurrence rates, using an earthquake catalogue which was complete up to and including the event recorded on the 16^{th} of June 2016 near the town of Hellum, with associated magnitude of M=0.5. Thus, in the present report the results are based on a catalogue with approximately 9 months of additional monitored time compared to the results as published in Paleja and Bierman [2016].

The results of the statistical analyses as presented in this report are similar to the results as presented in Paleja and Bierman [2016]. However, given the additional monitored time and recorded event occurrences in the updated catalogue, the weight of evidence has shifted towards a further decrease in the activity rate in the Loppersum region since the 1^{st} of January 2014 (the post shut-in epoch). For example, for events with associated magnitudes $M \geq 1.5$ in the Loppersum region (without removal of potential aftershocks), the difference in the average inter-event time between the post epoch and the most recent pre-epoch (pre_{10}: 7/02/2013 to 15/11/2013; see Table 5.2) was estimated (95% confidence interval) at 44.6 (17.1, 92.6) days. This means that in the epoch following the 1^{st} of January 2014 the average time between two consecutive earthquakes has *increased* by an estimated 44.6 (95% confidence interval: between 17.1 and 92.6) days compared to the time between events in the epoch preceding this date. Further, if the inter-event times in the period following the 1^{st} of January 2014 are compared to the inter-event times in a number of epochs preceding this date, then the 95% confidence intervals of the differences in average inter-event times either just exclude 0 or in some cases (for example following declustering of the catalogue) just include 0. This indicates that, with the current methodology and catalogue, there is an estimated chance of about 5% that the differences in average inter-event times between the post and pre shut-in epochs would have been observed if the underlying true rate of event occurrence was the same between these epochs. Lastly, the average inter event time in Loppersum for $M \geq 1.5$ is 62.9 days in the post epoch. In the most recent pre-epoch, the average time was 20 days (with aftershocks retained) and 32.6 days (with aftershocks removed). There are indications that the average inter-event time has decreased in the years leading up to January 2014. Assuming that the decrease in average inter-event time had continued into the post January 2014 epoch, there would be a more pronounced difference between this expected (given the extrapolation from a trend model) rate and the actual observed decrease in event occurrence rate. We recommend therefore that methodology is developed to estimate the probability that the post January 2014 inter-event times would have occurred given an assumed trend model(s). For events of $M \geq 1.0$ the dif-

ference in the expected inter event time between the post epoch and the two most pre epoch is statistically significant with and without declustering.

For the Zuidwest region, evidence was found that the activity rate was higher in the epoch after the 1^{st} of January 2014 (post shut-in epoch) compared to the epoch preceding this date. We note that due to the relatively small number of event occurrences in this region, it is not possible to determine when a change in activity rate has occurred. It is also possible that a gradual change in activity rate has occurred over the period of several years. It is unclear whether the the timing of changes in activity rate coincides with the changes in gas production rates at the 1^{st} of january 2014.

We recommend that the presented analyses are regularly updated to monitor evidence of changes in event occurrence rates over time.

Amsterdam, June 2016.

Table of Contents

List of Figures

List of Tables

1.Introduction

We estimate differences between epochs in earthquake (EQ) occurrence rates, for each of four different regions within the Groningen gas field. The number of EQ occurrences per unit of time is also referred to as the "activity rate". On the 1^{st} of January 2014, gas production at a number of production clusters in a part of the gas field near the town of Loppersum was greatly reduced. Of particular interest is the question whether EQ occurrence rates have changed following this reduction in gas production rates. The period following the 1^{st} of January 2014 is referred to as the "post shut-in epoch". The period prior to this date is partitioned into a number of epochs such that the numbers of events that occurred within each of these "pre shut-in epochs" are equal to the number of events observed in the post shut-in epoch.

The statistical methodology for estimating EQ occurrence rates for a given epoch, as well as differences in EQ occurrence rates between epochs, has been described in detail in Paleja and Bierman [2016]. The results as presented in Paleja and Bierman [2016] (see also Paleja et al. [2015]) were based on the earthquake catalogue (EC) as downloaded from the website of the Royal Dutch Meteorological Institute (KNMI) which was complete up to and including the event recorded on the 9^{th} of September 2015 near the town of Harkstede, with associated magnitude of M=1.2. **In this report, we provide an update of the estimates of differences between epochs in EQ occurrence rates, using an EC which was complete up to and including the event recorded on the 16^{th} of June 2016 near the town of Hellum, with associated magnitude of M=0.5.**

In Paleja and Bierman [2016] two methods were used for estimating differences between epochs in EQ occurrence rates; 1) A method based on estimating the average inter-event time using the exponential distribution, and; 2) A method based on estimating standardised differences between rates of occurrences between epochs using a normal approximation. Because both methods yield similar results, in this report only the method based on exponentially distributed inter-event times is used. Analyses are done both with a clustered and declustered catalogue to account for the potential presence of aftershocks. The assumption that inter-arrival times may reasonably be assumed to be exponentially distributed, with and without declustering of the catalogue, has been investigated in Paleja and Bierman [2016]. For some epoch by region combinations, evidence was found that the variability in event occurrences per unit of time was greater than expected given the assumed exponentially distributed inter-arrival times. However, any deviations from the assumed exponential distribution appeared to be small, especially following declustering of the catalogue. In this report, we therefore only apply the method based on exponentially distributed inter-event times to assess evidence of changes in rates of EQ occurrences. However, in future analyses we recommend that alternative distributions are used to model inter-event times to assess the sensitivity of the inferences to the potential presence of larger variability in inter-event times than expected given the exponential distribution (over-dispersion).

2.Notation and Terminology

Here, a brief overview of notation is given. A full description of the methodology is given in Paleja and Bierman [2016].

- The period from the 1^{st} of January 2014 up to and including the 16^{th} of June 2016 is referred to as the post shut-in epoch, or *post* for short in tables and graphs. The 16th of June 2016 was the date on which the earthquake catalogue (EC) as used in this study was downloaded from the KNMI website.
- The period prior to the 1^{st} of January 2014 is partitioned into a number of epochs such that the numbers of events that occurred within each of these "pre shut-in epochs" are equal to the number of events observed in the post shut-in epoch.
- The number of EQ occurrences per unit of time is also referred to as the "activity rate".
- M: the magnitude of an earthquake
- g: the vector with coordinates (easting and northing) of the epicenter of events
- d: the time (date) of events
- D: a user specified inter-event distance, used in catalogue declustering (see below).
- T: a user specified inter-event time, used in catalogue declustering (see below).
- Subscript q is used to denote the four regions of the Groningen field. The four regions are Loppersum, Oost, Eemskanaal and Zuidwest (see Figure 3.1 and Paleja and Bierman [2016]).
- The EC, with or without aftershocks, is divided into four regional subsets with each subset containing events above a certain magnitude threshold. Two magnitude thresholds are considered in this report. These are M⩾ 1.5 and M⩾ 1.0 with and without aftershocks.
- The four EC subsets before 1st January 2014 are divided into k_q number of pre-epochs. Subscript j is the indicator of the pre-epoch ($j \in 1, 2, ...k_q$). The division of four EC subsets into k_q number of pre-epochs is such that the number of events in the $post^q$ and all the pre_j^q epochs are identical. This (i.e. the number of events in an epoch for each regional subset) is indicated by n_q.
- The subscript a_q is the indicator for epoch in the subset: $a_q \in \{post^q, pre_1^q, pre_2^q, ..., pre_{k_q}^q\}$
- $S_{\{a_q,q\}}$ is used to indicate the sum inter-event times for epoch a_q with n_q number of events.
- The time difference between the date on which the EC was downloaded (16th June 2016) and the date of the last event in the four EC subsets is the "censored" observation time and is indicated by T_q^{cens} (see Paleja and Bierman [2016]).
- The expected inter event time is denoted by the symbol ν. The difference in the expected inter event time between the $post^q$ epoch and pre_j^q epoch is indicated by $\Delta\nu(post - pre_j)$.
- The 95% CI of $\Delta\nu(post - pre_j)$ is used to infer if the EQ occurrence rate in the *post* epoch is lower, higher or equal to the pre_j epoch. If the lower bound of the CI range is greater than 0, the EQ occurrence rate in the *post* epoch is lower than in the pre_j epoch. If the upper bound of the CI is less than 0, the EQ occurrence rate in the *post* epoch is higher than in the pre_j epoch.

3.Description of regions

Differences between epochs in average inter-event times are estimated separately for subsets of the catalogue for events that occurred in each of the four different regions as shown in figure 3.1.

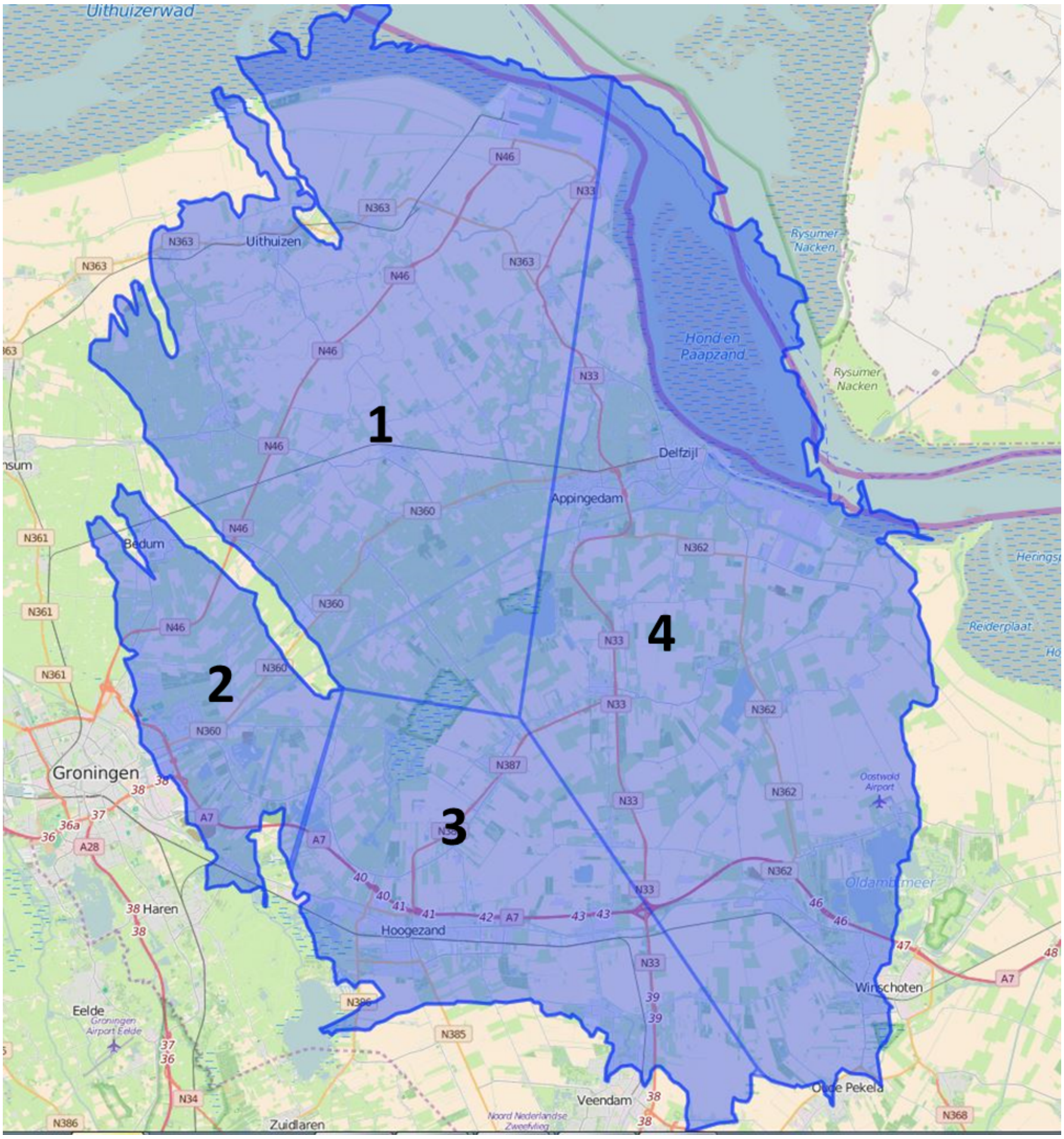

Figure 3.1: An outline of the Groningen gas field, with the four regions used in this report. 1: “Loppersum region”, 2: “Eemskanaal region”, 3: “Zuidwest region”, 4: “Oost region”

4.Identification of potential aftershocks

Aftershocks are identified using the window method proposed by Gardner and Knopoff (Gardner and Knopoff [1974]). Aftershocks, following a mainshock (d_o, g_o, M_o) are identified within space-time windows:

$$d_o < d < d_o + T, |g - g_o| < D, M < M_o \tag{4.1}$$

Where d, g and M are time, epicentre coordinates and magnitude of the potential aftershock respectively. D is set to 5 km while T is set to 5 days and M_o, the mainshock magnitude was 2.0. This means that an event within 5 days and a radius of 5 km from the mainshock ($M_o \geqslant$2.0) is considered to be an aftershock event.

5.Results based on all events (no potential aftershocks removed)

5.1. Results for events with associated magnitudes M⩾ 1.5

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 5.1 for all regions. Estimates of differences in average inter-event times between the post epoch and all pre-epochs are given in Table 5.2 and Figure 5.1 for all regions.

In the post epoch a total of $n_q = 15$ events with associated magnitudes $M \geq 1.5$ occurred within the Loppersum region. The difference in the average inter event time between the post epoch and the most recent pre-epoch (pre_{10}: 7/02/2013 to 15/11/2013; see Table 5.2) was estimated (95% confidence interval) at $\Delta\nu(post - pre) = 44.6$ (17.1, 92.6) days. The average inter-event time in the post-epoch was estimated to be higher than all of pre-epochs from pre_3 up to pre-epoch pre_{10} which started on 03/03/2003 (see Table 5.2 and Figure 5.1). This indicates that the activity rate in the period following the 1^{st} of January 2014 was consistently lower compared to the activity rate in the period preceding this date up to 2003.

In the post epoch a total of 12 events were observed in the Oost region. There was no evidence of a difference in the average inter event time between the post epoch and the most recent pre-epoch (pre_2: 15/11/2011 to 26/11/2013): $\Delta\nu(post - pre) = 15.5$ (-48.5, 89.5) days. There was evidence that the activity rate was higher in the post epoch compared to the first pre-epoch (pre_1: 10/05/2002 to 09/11/2011) with $\Delta\nu(post - pre) = -272.8$ (–598.6, -114.7) days.

In the post epoch a total of 15 events have been observed in the Zuidwest region. There was evidence that the activity rate was higher in the post epoch compared to the most recent pre-epoch (pre_1: 05/08/2005 to 11/02/2013): $\Delta\nu(post - pre) = -113.8$ (-263.9, -18.2) days.

The numbers of events that occurred in the Eemskanaal region in the post epoch are too small (n_q = 4) to obtain reliable estimates of average inter-event times.

Table 5.1: Data for M⩾1.5 with aftershocks retained.. Epochs, their start and end dates, number of earthquakes and duration of each epoch.

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	$n_q(\#)$	$S_{\{a_q,q\}}$ (days)
remainder	05/12/1991	08/06/1994	-	-	-
pre_1	27/06/1994	24/08/1998	-	15	1537.3
pre_2	12/12/1998	30/01/2003	-	15	1619.9
pre_3	03/03/2003	26/11/2004	-	15	666.2
pre_4	09/01/2005	16/04/2006	-	15	506.3
pre_5	19/04/2006	15/08/2007	-	15	485.7
pre_6	17/09/2007	14/04/2009	-	15	608.6
pre_7	20/04/2009	24/07/2010	-	15	465.2
pre_8	14/08/2010	04/11/2011	-	15	468.7
pre_9	27/11/2011	07/02/2013	-	15	461.2
pre_{10}	07/02/2013	15/11/2013	-	15	280.8
post	03/02/2014	30/10/2015	229.3	15	943.3
Oost Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	$n_q(\#)$	$S_{\{a_q,q\}}$ (days)
remainder	15/05/1995	15/06/2000	-	-	-
pre_1	10/05/2002	09/11/2011	-	12	4164.6
pre_2	15/11/2011	26/11/2013	-	12	748.4
post	15/03/2014	02/06/2016	13.2	12	932.0
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	$n_q(\#)$	$S_{\{a_q,q\}}$ (days)
remainder	23/11/1993	18/02/2005	-	-	-
pre_1	05/08/2005	11/02/2013	-	15	2914.6
post	11/03/2014	25/03/2016	82.9	15	1220.5
Eemskanaal Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	$n_q(\#)$	$S_{\{a_q,q\}}$ (days)
remainder	23/08/1997	13/04/2006	-	-	-
pre_1	16/02/2007	21/06/2010	-	4	1529.9
pre_2	27/05/2011	07/01/2012	-	4	565.1
pre_3	05/02/2013	22/09/2013	-	4	624.3
post	26/01/2014	15/12/2015	183.7	4	997.4

Table 5.2: Results for Aftershocks retained M⩾1.5

Loppersum Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	109.7	-121.9	-39.5	21.5
pre_2	115.8	-130.6	-45.5	15.9
pre_3	47.6	-22.3	18.5	67.8
pre_4	36.2	-5.3	29.3	77.9
pre_5	34.7	-3.4	30.6	79.8
pre_6	43.6	-16.6	22.2	71.5
pre_7	33.2	-0.9	32.0	81.0
pre_8	33.4	-0.8	31.8	80.5
pre_9	33.0	-0.7	32.3	80.7
pre_{10}	20.0	17.1	44.6	92.6
post	62.9	-	-	-
Oost Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	377.8	-589.6	-272.8	-114.7
pre_2	67.9	-48.5	15.5	89.5
post	77.7	-	-	-
Zuidwest Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	208.0	-263.6	-113.8	-18.2
post	81.4	-	-	-
Eemskanaal		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	511.0	-1137.3	-134.7	515.6
pre_2	189.3	-269.4	108.1	740.6
pre_3	208.0	-325.7	93.9	726.1
post	249.3	-	-	-

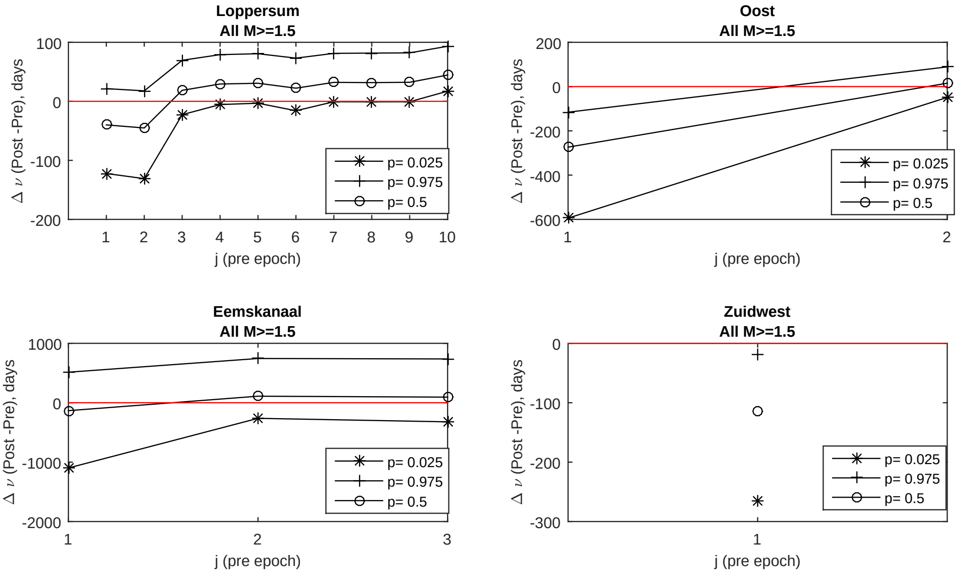

Figure 5.1: $\Delta\nu(post - pre)$ for $M \geq 1.5$ with aftershocks retained. x-labels indicate the pre epoch number. See Table 5.1 for the dates.

5.2. Results for events with associated magnitudes M⩾ 1.0

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 5.3 for all regions. Estimates of differences in average inter-event times between the post epoch and all pre-epochs are given in Table 5.4 and Figure 5.2 for all regions.

In the post epoch a total of $n_q = 40$ events with associated magnitudes $M \geq 1$ occurred within the Loppersum region. The difference in the expected inter event time between the post epoch and the two most recent pre-epochs (pre_6 and pre_7: from 29/07/2011 to 23/12/2013) are estimated (95% confidence interval) at $\Delta\nu(post - pre) = 12.0$ (4.9, 21.3) days for epoch pre_7 and $\Delta\nu(post - pre) = 11.3$ (4.1, 20.8) days for epoch pre_6. This indicates that the activity rate in the period following the 1^{st} of January 2014 was significantly lower in the post epoch compared to the activity rate in the two most recent pre-epochs.

In the post epoch a total of 30 events were observed in the Oost region. The difference in the expected inter event time between the post epoch and the two most recent pre-epoch (pre_2 and pre_3: 03/02/2009 to 08/12/2013) were estimated (95% confidence interval) at $\Delta\nu(post-pre) = 8.8$ (-4.8, 24.5) days for epoch pre_3 and $\Delta\nu(post - pre) = -6.9$ (-26.7, 11.1) days for epoch pre_2. Thus, there is no evidence that the average inter-event was different between the post epoch and the two most recent pre-epochs. There was evidence that the activity rate in the post epoch was higher compared to the activity rate in the first pre-epoch (pre_1: 06/06/1997 to 15/01/2009) with an estimated $\Delta\nu(post - pre) = -112.4$ (-179.5, -69.2) days.

In the post epoch a total of 35 events have been observed in the Zuidwest region. There was evidence that the activity rate in the post epoch was higher compared to the activity rate in the first (and only) pre-epoch (pre_1: 30/09/2007 to 22/12/2013): $\Delta\nu(post-pre) = -44.2$ (-74.5, -22.6) days.

In the post epoch a total of 12 events have been observed in the Eemskanaal region. There was no evidence that the activity rate time in the post epoch was higher than the activity rate in the two most recent pre epochs (pre_2 and pre_3: 20/09/2008 to 29/09/2013). There was evidence that the activity rate in the post epoch was higher compared to the activity rate in the earliest pre-epoch (pre_1: 18/03/2001 to 23/07/2008) with $\Delta\nu(post - pre) = -171.6$ (-405.8, -46.1) days.

Table 5.3: Data for Aftershocks retained.M⩾1. Epochs, their start and end dates, number of earthquakes and duration of each epoch.

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	05/12/1991	20/11/1995	-	-	-
pre_1	29/02/1996	18/01/2003	-	40	2616.7
pre_2	23/01/2003	30/05/2005	-	40	862.9
pre_3	22/06/2005	23/06/2007	-	40	753.4
pre_4	15/08/2007	20/11/2009	-	40	881.3
pre_5	04/12/2009	27/07/2011	-	40	614.4
pre_6	29/07/2011	23/10/2012	-	40	453.9
pre_7	13/11/2012	23/12/2013	-	40	425.3
post	03/02/2014	01/06/2016	14.7	40	906.0
Oost Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	12/02/1993	04/05/1997	-	-	-
pre_1	06/06/1997	15/01/2009	-	30	4274.4
pre_2	03/02/2009	19/02/2012	-	30	1130.3
pre_3	07/03/2012	08/12/2013	-	30	657.4
post	16/01/2014	02/06/2016	13.2	30	920.9
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	11/12/1992	13/04/2007	-	-	-
pre_1	30/09/2007	22/12/2013	-	35	2445.3
post	02/01/2014	24/04/2016	52.3	35	906.1
Eemskanal Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	23/08/1997	08/04/2000	-	-	-
pre_1	18/03/2001	23/07/2008	-	12	3028.4
pre_2	20/09/2008	23/12/2011	-	12	1247.6
pre_3	07/01/2012	29/09/2013	-	12	646.3
post	04/01/2014	28/05/2016	18.9	12	990.2

Table 5.4: Results for aftershocks retained. M⩾1

Loppersum Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	67.1	-69.0	-42.9	-24.0
pre_2	22.1	-9.0	1.1	11.5
pre_3	19.3	-5.5	3.8	13.8
pre_4	22.6	-9.8	0.6	11.2
pre_5	15.7	-0.9	7.3	17.2
pre_6	11.7	4.1	11.3	20.8
pre_7	10.9	4.9	12.0	21.3
post	22.6	-	-	-
Oost Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	147.4	-179.5	-112.4	-69.2
pre_2	38.9	-26.7	-6.9	11.1
pre_3	22.7	-4.8	8.8	24.5
post	30.7	-	-	-
Zuidwest Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	72.0	-74.5	-44.2	-22.6
post	25.9	-	-	-
Eemskanaal		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	275.7	-405.8	-171.6	-46.1
pre_2	113.5	-120.2	-21.3	62.0
pre_3	58.7	-29.3	28.7	105.7
post	82.5	-	-	-

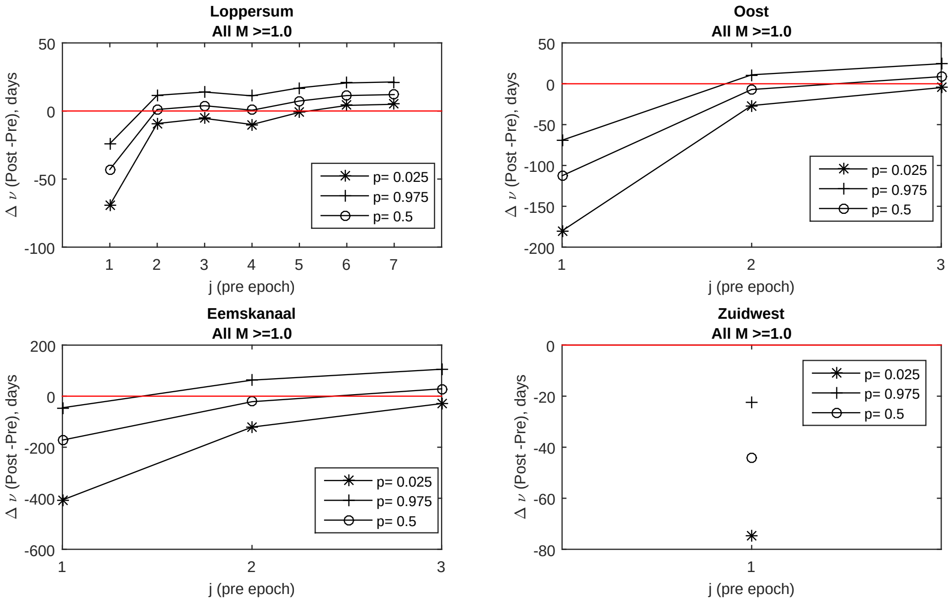

Figure 5.2: $\Delta\nu(post - pre)$ for $M \geq 1$ with aftershocks retained. x-labels indicate the pre epoch number. See Table 5.3 for the dates.

6. Results based on a catalogue with potential aftershocks removed

Aftershocks were removed using the Gardner and Knopoff method described in chapter 4. The date, magnitude and location of the aftershocks are shown in Table 6.1. There were 25 aftershocks in all. The aftershock events appeared to be unevenly distributed across the four regions as 20 of these aftershocks have occurred in Loppersum. Given that most of the events of M⩾ 2.0 have historically occurred in Loppersum, this is not surprising. We also note that post shut-in, no aftershocks have been observed in the Loppersum region and there seems to be a tendency for aftershocks to occur in the Zuidwest region in the post shut-in era. Given the small sample size, we are not able to provide any firm conclusions on this observation.

Table 6.1: Aftershock dates, magnitude and region (see Figure 3.1) based on the Gardner and Knopoff method as describes in chapter 4.

Date	Magnitude	Location	Year	Easting	Northing	Region
30/07/1994	1.3	Middelstum	1994	234203.2	598279.6	Loppersum
12/06/2000	2.5	Loppersum	2000	245238.6	595691.8	Loppersum
26/10/2003	1.2	Hoeksmeer	2003	248380.2	591744.4	Loppersum
10/11/2003	1.4	Westeremden	2003	243088.9	596653.7	Loppersum
23/03/2006	2.2	Overschild	2006	247758.8	589394.7	Loppersum
08/08/2006	2.5	Westeremden	2006	242889.2	596650	Loppersum
26/10/2006	1.4	Oldenzijl	2006	242664.2	601655.3	Loppersum
17/02/2007	0.9	Harkstede	2007	241533.4	583156.1	Eemskanaal
04/02/2009	1.7	Garsthuizen	2009	245163.1	599697.9	Loppersum
20/04/2009	1.5	Wirdumerpolder	2009	249730.9	590880.3	Loppersum
05/05/2010	1.6	Oosternieland	2010	247299	602855.7	Loppersum
27/06/2011	1.4	Appingedam	2011	247666.3	590728.7	Loppersum
27/06/2011	1.1	Appingedam	2011	249311.2	591873.9	Loppersum
16/08/2012	1.2	Zeerijp	2012	245858.2	598152.6	Loppersum
17/08/2012	0.6	Middelstum	2012	239271.9	597809.5	Loppersum
07/02/2013	3.2	Zandeweer	2013	240146.4	601053.2	Loppersum
11/02/2013	1.8	Garrelsweer	2013	247072.7	590383.3	Loppersum
15/02/2013	2	Wirdum	2013	248814.1	593422.7	Loppersum
18/02/2013	0.7	Leermens	2013	247883.2	596744.2	Loppersum
20/07/2013	1.9	Wirdum	2013	247472.9	593841.9	Loppersum
21/07/2013	0.7	Overschild	2013	247750.2	589839.8	Loppersum
01/09/2014	1.6	Froombosch	2014	250282.4	579870.6	Zuidwest
30/12/2014	0.8	Luddeweer	2014	246184.4	584466.5	Zuidwest
30/10/2015	0.9	Meedhuizen	2015	257545.3	590373	Oost
29/02/2016	0.3	Froombosch	2016	247975.9	578155.8	Zuidwest

6.1. Results for events with associated magnitudes M⩾ 1.5

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 6.2 for all regions. Estimates of differences in average inter-event times between the post epoch and all pre-epochs are given in Table 6.3 and Figure 6.1 for all regions.

In the post epoch a total of $n_q = 15$ events with associated magnitudes M⩾1.5 occurred within the Loppersum region, with aftershocks removed. The activity rate was consistently lower in the post epoch compared to the activity rate in the seven most recent pre-epochs (pre_3 through to pre_9: from 22/09/2003 to 15/11/2013). The estimated difference in average inter-event time was statistically significantly different from zero at the 95% confidence level for several of these pre-epochs, but the confidence interval just clipped 0 for the most recent pre-epoch. Nevertheless, these results clearly indicate that the activity rate in the period following the 1^{st} of January 2014 was significantly lower in the post epoch compared to the activity rate in the two most recent pre-epochs.

In the post epoch a total of 12 events were observed in the Oost region. There was no evidence that the activity rate in the post epoch was different compared to the activity rate in the most recent pre epoch (pre_2: 15/11/2011 to 26/11/2013). There was evidence that the activity rate was higher in the post epoch compared to the activity rate in the first pre-epoch(pre_1 : 10/05/2002 to 09/11/2011): $\Delta\nu(post - pre) = -274.0$ (-588.3, -115.0) days.

In the post epoch a total of 14 events have been observed in the Zuidwest region. There was evidence that the activity rate in the post epoch was higher compared to the activity rate in the first (and only) pre-epoch (pre_1: 04/03/2006 to 11/02/2013): $\Delta\nu(post - pre) = -109.3$ (-269.1, -7.6) days.

The sample size for Eemskanaal is small and we cannot offer any quantitative assessment on changes in EQ occurrence rate in this region.

Table 6.2: Data for Aftershocks removed; M⩾1.5. Epochs, their start and end dates, number of earthquakes and duration of each epoch.

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	05/12/1991	02/11/1995	-	-	-
pre_1	04/11/1995	20/12/1999	-	15	1509.5
pre_2	12/02/2000	07/08/2003	-	15	1325.8
pre_3	22/09/2003	22/06/2005	-	15	685.3
pre_4	17/07/2005	27/09/2006	-	15	462.3
pre_5	06/10/2006	07/11/2008	-	15	771.7
pre_6	15/12/2008	09/01/2010	-	15	427.8
pre_7	19/02/2010	06/09/2011	-	15	605.4
pre_8	07/09/2011	15/08/2012	-	15	343.9
pre_9	16/08/2012	15/11/2013	-	15	456.9
post	03/02/2014	30/10/2015	229.3	15	943.3
Oost Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	15/05/1995	15/06/2000	-	-	-
pre_1	10/05/2002	09/11/2011	-	12	4164.6
pre_2	15/11/2011	26/11/2013	-	12	748.4
post	15/03/2014	02/06/2016	13.2	12	932.0
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	23/11/1993	05/08/2005	-	-	-
pre_1	04/03/2006	11/02/2013	-	14	2746.7
post	11/03/2014	25/03/2016	82.9	14	1220.5
Eemskanal Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	23/08/1997	13/04/2006	-	-	-
pre_1	16/02/2007	21/06/2010	-	4	1529.9
pre_2	27/05/2011	07/01/2012	-	4	565.1
pre_3	05/02/2013	22/09/2013	-	4	624.3
post	26/01/2014	15/12/2015	183.7	4	997.4

Table 6.3: Results for Aftershocks removed M⩾1.5

Loppersum Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	107.8	-118.5	-37.7	22.8
pre_2	94.7	-96.1	-25.7	32.1
pre_3	48.9	-24.5	17.3	68.3
pre_4	33.1	-1.0	32.1	82.0
pre_5	55.0	-33.8	11.4	63.6
pre_6	30.6	2.5	34.5	84.0
pre_7	43.3	-16.1	22.4	73.5
pre_8	24.6	11.1	40.3	89.4
pre_9	32.6	-0.2	32.4	82.5
post	62.9	-	-	-
Oost Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	378.6	-588.3	-274.0	-115.0
pre_2	68.0	-48.5	15.5	89.4
post	77.7	-	-	-
Zuidwest Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	210.5	-269.1	-109.3	-7.6
post	87.2	-	-	-
Eemskanaal		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	512.5	-1131.5	-135.7	509.4
pre_2	188.2	-269.6	111.6	742.9
pre_3	207.6	-312.3	95.5	730.4
post	249.3	-	-	-

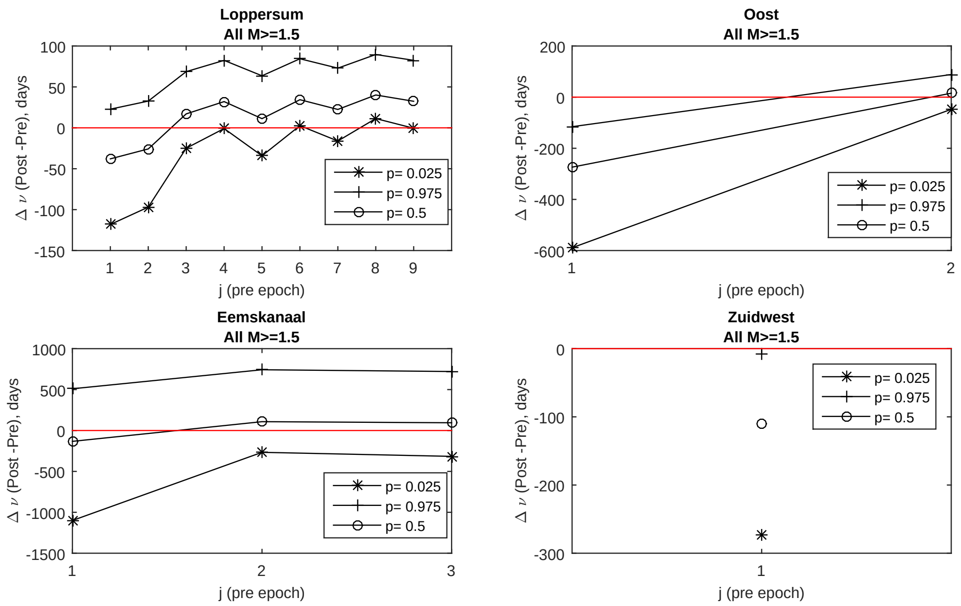

Figure 6.1: Results for $\Delta\nu(post - pre)$ for $M \geq 1.5$ with aftershocks removed. x-labels indicate the pre epoch number. See Table 6.2 for the dates.

6.2. Results for events with associated magnitudes M⩾ 1.0

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 6.4 for all regions. Estimates of differences in average inter-event times between the post epoch and all pre-epochs are given in Table 6.5 and Figure 6.2 for all regions.

In the post epoch a total of $n_q = 40$ events with associated magnitudes $M \geq 1$ occurred within the Loppersum region, with potential aftershocks removed. The difference in the average inter event time between the post epoch and the two most recent pre-epochs (pre_6 and pre_7: from 24/06/2011 to 23/12/2013) were estimated (95% confidence interval) at $\Delta\nu(post - pre) = 9.9$ (2.3, 19.4) days for epoch pre_7 and $\Delta\nu(post - pre) = 12.6$ (5.6, 21.8) days for epoch pre_6. This indicates that the activity rate in the period following the 1^{st} of January 2014 was significantly lower in the post epoch compared to the activity rate in the two most recent pre-epochs.

In the post epoch a total of 30 events were observed in the Oost region. There was no evidence of a difference in the activity rate in the post epoch compared to the two most recent pre epochs (pre_2 and pre_3: 03/02/2009 to 08/12/2013). There was evidence that the activity rate was higher in the post epoch compared to the activity rate in the earliest pre epoch (pre_1: 06/06/1997 to 15/01/2009) : $\Delta\nu(post - pre) = -112.6$ (-180.4, -68.9) days.

In the post epoch a total of 34 events have been observed in the Zuidwest region. There was evidence that the activity rate in the post epoch was higher compared to the activity rate in the first (and only) pre-epoch (pre_1: 24/01/2008 to 22/12/2013): $\Delta\nu(post-pre) = -40.3$ (-70.3, -18.8) days.

In the post epoch a total of 12 events have been observed in the Eemskanaal region. There was no evidence that the activity rate time in the post epoch was higher than the activity rate in the two most recent pre epochs (pre_2 and pre_3: 20/09/2008 to 29/09/2013). There was evidence that the activity rate in the post epoch was higher compared to the activity rate in the earliest pre-epoch (pre_1: 18/03/2001 to 23/07/2008) with $\Delta\nu(post - pre) = -171.1$ (-401.7, -45.0) days.

Table 6.4: Data for Aftershocks removed M⩾1. Epochs, their start and end dates, number of earthquakes and duration of each epoch.Aftershocks removed.

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	05/12/1991	22/12/1993	-	-	-
pre_1	04/02/1994	09/12/1999	-	40	2178.3
pre_2	20/12/1999	24/11/2004	-	40	1812.4
pre_3	26/11/2004	06/10/2006	-	40	680.2
pre_4	23/10/2006	07/05/2009	-	40	944.0
pre_5	07/05/2009	23/06/2011	-	40	777.3
pre_6	24/06/2011	30/07/2012	-	40	403.2
pre_7	14/08/2012	23/12/2013	-	40	510.5
post	03/02/2014	01/06/2016	14.7	40	906.0
Oost Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	12/02/1993	04/05/1997	-	-	-
pre_1	06/06/1997	15/01/2009	-	30	4274.4
pre_2	03/02/2009	19/02/2012	-	30	1130.3
pre_3	07/03/2012	08/12/2013	-	30	657.4
post	16/01/2014	02/06/2016	13.2	30	920.9
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	11/12/1992	30/09/2007	-	-	-
pre_1	24/01/2008	22/12/2013	-	34	2275.3
post	02/01/2014	24/04/2016	52.3	34	906.1
Eemskanaal Region					
Epoch	First EQ	Last EQ	T^{cens} (days)	n_q(#)	$S_{\{a_q,q\}}$ (days)
remainder	23/08/1997	08/04/2000	-	-	-
pre_1	18/03/2001	23/07/2008	-	12	3028.4
pre_2	20/09/2008	23/12/2011	-	12	1247.6
pre_3	07/01/2012	29/09/2013	-	12	646.3
post	04/01/2014	28/05/2016	18.9	12	990.2

Table 6.5: Results for Aftershocks removed M⩾1

Loppersum Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	55.8	-54.0	-31.8	-15.5
pre_2	46.5	-41.5	-22.8	-8.1
pre_3	17.5	-3.2	5.6	15.4
pre_4	24.2	-11.8	-1.0	9.7
pre_5	19.9	-6.3	3.2	13.4
pre_6	10.3	5.6	12.6	21.8
pre_7	13.1	2.3	9.9	19.4
post	22.6	-	-	-
Oost Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	147.4	-180.4	-112.6	-68.9
pre_2	39.0	-26.7	-7.0	11.0
pre_3	22.7	-4.7	8.8	24.5
post	30.7	-	-	-
Zuidwest Region		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	68.9	-70.3	-40.3	-18.8
post	26.6	-	-	-
Eemskanaal		$\Delta\nu$(Post-Pre) (days)		
Epoch	$\nu(days)$	2.5%	median	97.5%
pre_1	274.6	-401.7	-171.1	-45.0
pre_2	113.6	-120.9	-21.6	64.6
pre_3	58.8	-29.5	28.8	106.7
post	82.5	-	-	-

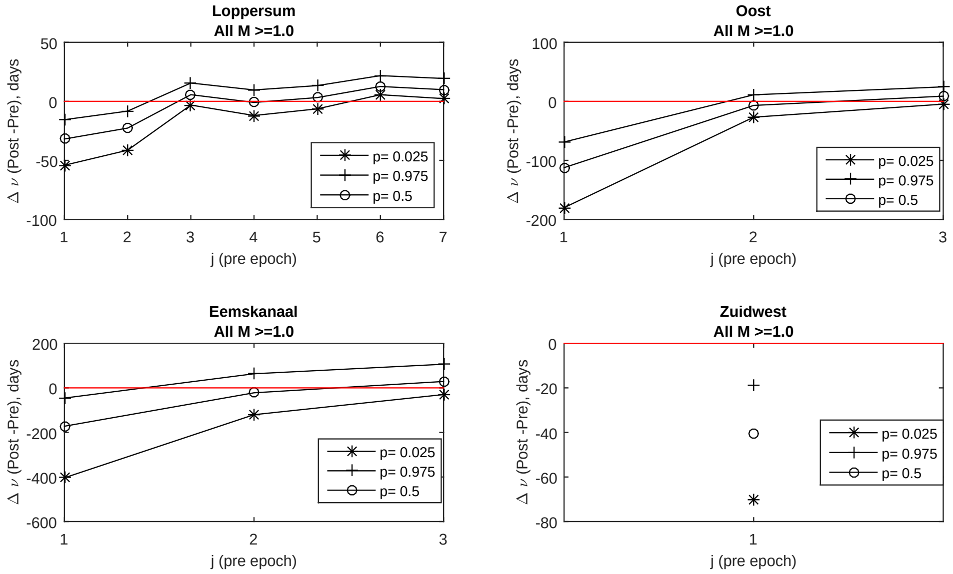

Figure 6.2: Results for $\Delta\nu(post - pre)$ for $M \geq 1$ with aftershocks removed. x-labels indicate the pre epoch number. See Table 6.4 for the dates.

7.Conclusions

Differences between epochs in earthquake (EQ) occurrence rates were estimated, for each of four different regions within the Groningen gas field. The number of EQ occurrences per unit of time is also referred to as the "activity rate". On the 1^{st} of January 2014, gas production at a number of production clusters in a part of the gas field near the town of Loppersum was greatly reduced. Of particular interest is the question whether there is evidence that EQ occurrence rates have changed following this reduction in gas production rates. The period following the 1^{st} of January 2014 is referred to as the "post shut-in epoch". The period prior to this date is partitioned into a number of epochs such that the numbers of events that occurred within each of these "pre shut-in epochs" are equal to the number of events observed in the post shut-in epoch.

The statistical methodology for estimating EQ occurrence rates for a given epoch, as well as differences in EQ occurrence rates between epochs, has been described in detail in Paleja and Bierman [2016]. The results as presented in Paleja and Bierman [2016] were based on the earthquake catalogue (EC) as downloaded from the website of the Royal Dutch Meteorological Institute (KNMI) which was complete up to and including the event recorded on the 9^{th} of September 2015 near the town of Harkstede, with associated magnitude of M=1.2. **In this report, we provide an update of the estimates of differences between epochs in EQ occurrence rates, using an EC which was complete up to and including the event recorded on the 16^{th} of June 2016 near the town of Hellum, with associated magnitude of M=0.5.**

The results of the statistical analyses as presented in this report are similar to the results as presented in Paleja and Bierman [2016]. However, given the additional monitored time and recorded event occurrences in the catalogue since the 9^{th} of September 2015, the weight of evidence has shifted towards a further decrease in the activity rate in the Loppersum region since the 1^{st} of January 2014 (the post shut-in epoch). For example, for events with associated magnitudes $M \geq 1.5$ in the Loppersum region (without removal of potential aftershocks), the difference in the average inter-event time between the post epoch and the most recent pre-epoch (pre_{10}: 7/02/2013 to 15/11/2013; see Table 5.2) was estimated (95% confidence interval) at 44.6 (17.1, 92.6) days. This means that in the epoch following the 1^{st} of January 2014 the average time between two consecutive earthquakes has *increased* by an estimated 44.6 (95% confidence interval: between 17.1 and 92.6) days compared to the time between events in the epoch preceding this date. Further, if the inter-event times in the period following the 1^{st} of January 2014 are compared to the inter-event times in a number of epochs preceding this date, then the 95% confidence intervals of the differences in average inter-event times either just exclude 0 or in some cases (for example following declustering of the catalogue) just include 0. This indicates that, with the current methodology and catalogue, there is an estimated chance of about 5% that the differences in average inter-event times between the post and pre shut-in epochs would have been observed if the underlying true rate of event occurrence was the same between these epochs. Lastly, there are indications that the average inter-event time in Loppersum has decreased in the years leading up to January 2014. Assuming that the decrease in average inter-event time had continued into the post January 2014 epoch, there would be a more pronounced difference between this expected (given the extrapolation from a trend model) rate and the actual observed decrease in event occurrence rate. We recommend therefore that methodology is developed to estimate the probability that the post January 2014 inter-event times would have occurred given an assumed trend model(s). For events of $M \geq 1.0$ the difference in the expected inter event time between the post epoch and the two most pre epoch is statistically significant with and without declustering.

In the Oost region, for events with associated magnitudes M$\geqslant$ 1.5 there was no evidence that the activity rate in the epoch after the 1^{st} of January 2014 (post shut-in epoch) was different to the activity rate in the most recent pre-epoch (15/11/2011 to 26/11/2013). However, there is evidence that the activity rate in the post epoch was higher than the activity rate in the earlier pre-epochs. Similar results were obtained for events with associated magnitudes M$\geq$ 1, regardless of the choice to decluster the catalogue or not.

For the Zuidwest region, evidence was found that the activity rate was higher in the epoch after the 1^{st} of January 2014 (post shut-in epoch) compared to the epoch preceding this date. The evidence of a increase in activity rate following the 1^{st} of January 2014 in the Zuidwest region compared to the years preceding this date was consistent regardless of whether the catalogue was declustered or not, and regardless of the choice of threshold for magnitudes associated with events which were included in the analyses. For example, for events with associated magnitudes $M \geq 1.5$ in the Zuidwest region the average time between two consecutive earthquakes in the epoch following the 1^{st} of January 2014 has *decreased* by 113.8 (263.9, 18.2) days compared to the time between events in the epoch preceding this date.

The numbers of event occurrences in the Eemskanaal region for events with associated magnitudes M$\geqslant$ 1.5 were too small to obtain reliable estimates. For events with associated magnitudes M$\geqslant$ 1, there was no evidence that the activity rate in the Eemskanaal region in the post shut-in epochs was different from the activity rate in the epochs preceding this date, dating back to September 2009. There was good evidence that the activity rate in the Eemskanaal region in the post epoch was higher compared to earlier epochs, and this evidence was consistent regardless of whether the catalogue was declustered or not.

We recommend that the presented analyses are regularly updated to monitor evidence of changes in event occurrence rates over time. Additionally, in future analyses we recommend that alternative distributions are used to model inter-event times to assess the sensitivity of the inferences to the potential presence of larger variability in inter-event times than expected given the exponential distribution (over-dispersion).

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