The influence of gas production on seismicity in the Groningen field

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Abstract. *In this paper we investigate the effect of gas production volumes on seismicity in the Groningen field by means of a log-linear Poisson model. First, we consider the annual counts and then refine to the temporal point pattern of earthquake occurrence times.*

Keywords. *Count data; Gas extraction; Induced seismicity; Log-linear Poisson model; Point pattern.*

1. Introduction

Discovered in 1959, the Groningen gas field, the largest gas field in Europe with an estimated recoverable gas volume of around 2,900 billion cubic meters (bcm), has been a massive boost to the Dutch economy. Production in Groningen started in 1963, initially only to accommodate the high demand for gas during the winter months [8]. However, the closure of smaller fields in the country led to an increase in production. By 2012, annual production volumes had climbed to over 40 bcm per year [6].

Increasing production volumes and the resulting depletion of the gas field have led to induced earthquakes in the previously tectonically inactive Northern Netherlands. Depletion causes a decrease of the gas pressure, which causes compaction of the gas reservoir, noticeable by subsidence. Additionally, a drop in gas pressure increases stress in the faults of the region. Due to the increased stress, faults slip and cause seismicity [10]. The most significant event to date, in August 2012 near Huizinge with a magnitude of 3.6, attracted massive public attention, prompting the Ministry of Economic Affairs to reduce production volumes.

Numerous studies have been conducted, of which we mention a few. For example, [5] models the times in between earthquakes in terms of the cumulative and annual production rates, pressure, subsidence and fault zones. A more recent example of such a study is [12]. Van Hove *et al.* [7] propose a Poisson auto-regression model for the annual hazard maps in terms of subsidence, fault lines and gas extraction in previous years. Sijacic *et al.* [14] focus on the detection of changes in the rate of a temporal Poisson point process by Bayesian and frequentist methods. Moreover, [1] modify Ogata's space-time model [11] to include changes in stress level and estimate the probability of fault failures. Other papers [2, 3, 13] discuss the modelling of seismicity in relation to stress changes based on a differential equation. Both [6] and [15] explore the temporal development of seismicity in Groningen by proposing a linear model for the relation between the number of earthquakes over specific periods and gas production volumes. In this paper, we take a similar approach towards the temporal development of seismicity in Groningen including data up to 2020. Details on the methodology used can be found, e.g., in [9].

2. Data

An earthquake catalogue for The Netherlands is being maintained by the Royal Dutch Meteorological Office (KNMI) at `www.knmi.nl/kennis-en-datacentrum/dataset/aardbevingscatalogus`. Data on the period before 1995 are not reliable due to the inaccuracy of the equipment used. Moreover, a threshold on the magnitude is necessary to guarantee data quality. According to [4], earthquakes with a magnitude of 1.5 or larger can be reliably recorded. We therefore restrict ourselves to induced earthquakes with a magnitude of 1.5 or higher between January 1st, 1995, and December 31st, 2020. The resulting pattern of occurrence times consists of 322 earthquakes.

Monthly production figures are available at the site of the Dutch Oil Company (NAM) at `https://www.nam.nl/feiten-en-cijfers/gaswinning.html`, both for the gas field as a whole and per individual well. The figures are published in cubic meters, which we re-scale to bcm. Since we focus on the temporal aspects, we use only the cumulative numbers over the entire field.

3. Annual counts

To explore the relationship between seismicity and gas production, Figure 1 plots the total annual production in bcm for the years 1994, ..., 2019 and the annual number of earthquakes in the next year against time. A dip in the produced volumes is observed during the late 1990s, followed by a steep increase. After 2014 the volumes decrease following government regulations. As for the number of earthquakes, there seems to be a general upwards trend up to about 2013. From 2014 onward, the frequency of earthquakes also tends to decrease.

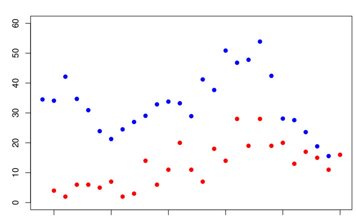

Figure 1: Plots of the annual number of earthquakes (1995–2020) in the Groningen gas field (red dots) and annual gas production volumes (1994–2019, blue dots, in bcm) against time.

A statistical model that captures these aspects is the following. Assume that the number of earthquakes $N(t)$ in year $t \in \{1995,\dots,2020\}$ is Poisson distributed with intensity parameter $\lambda(t)$ such that

$$\log\lambda(t) = \alpha_1 + \alpha_2 C(t-1) + \alpha_3 \log(\tilde{C}(t-1)). \tag{1}$$

Here $C(t-1)$ denotes the gas produced in year $t-1$, $\tilde{C}(t-1)$ is the cumulative gas production up to year $t-1$. By maximizing the likelihood function we obtained the parameter estimates $\hat{\alpha}_1 = -2.23$, $\hat{\alpha}_2 = 0.025$ and $\hat{\alpha}_3 = 0.64$. We are especially interested in α_2 as it quantifies the effect of the gas production in each consecutive year. Its asymptotic approximate 95% confidence interval is $(0.015, 0.035)$, from which we conclude that an increase in production leads to increased seismicity.

To validate the model, Figure 2 shows the Pearson residuals (left-most panel) and the empirical inhomogeneous auto-correlation function (central panel). We conclude that the model fits reasonably well. The estimated and predicted number of earthquakes are shown in the right-most panel. For $\lambda(2021)$, an approximate 95% confidence interval is $(7.16, 13.69)$. The actual number was 12. For comparison [6] predicted a 16 ± 8 events in 2016. Our prediction for 2016 is tighter, 15.67 ± 2.61. In reality, there were 13 earthquakes.

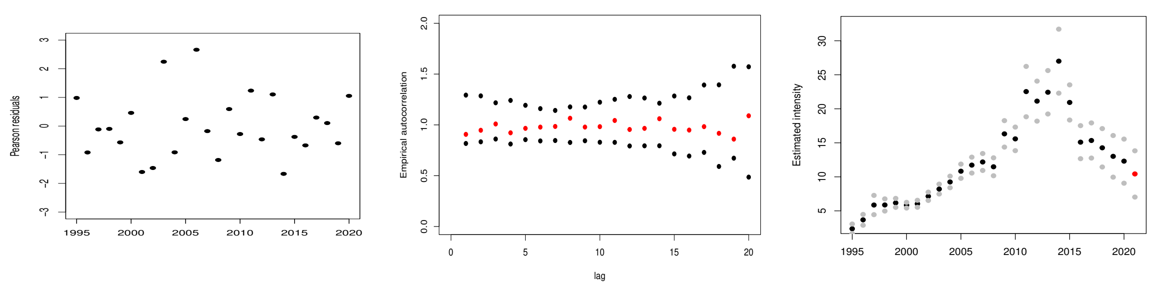

Figure 2: Left: Pearson residuals plotted against time. Central panel: empirical inhomogeneous auto-correlation function for lags $h = 1,\dots,15$ and local envelopes based on 19 simulations from the fitted model. Right: estimated number of earthquakes (black dots) and predicted number (red dot) for 2021 with associated approximate 95% confidence intervals (grey dots).

4. Temporal point pattern

So far, we used aggregated count data. Since the earthquake times are being recorded, we may also consider a temporal Poisson point process model. Taking days as our unit of time, suppose that the intensity function λ satisfies

$$\log\lambda(t) = \alpha_1 + \alpha_2 C(t,12) + \alpha_3 \log(\tilde{C}(t)). \tag{2}$$

for $t \in (0, 9497]$. Here $C(t,12)$ denotes the amount of gas produced over the twelve months preceding time $t \in (0, 9497]$ and $\tilde{C}(t)$ is the cumulative amount produced from 1994 and preceding time t. The maximum likelihood estimates are $\hat{\alpha}_1 = -8.56$, $\hat{\alpha}_2 = 0.023$ and $\hat{\alpha}_3 = 0.72$.

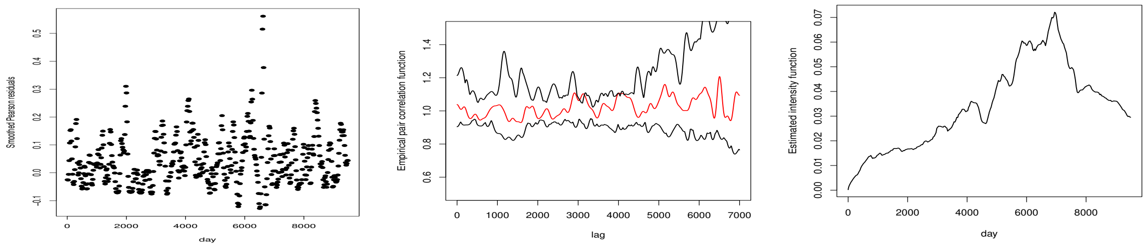

Figure 3: Left: smoothed Pearson residuals using a Gaussian kernel with $\sigma = 30$. Central panel: empirical inhomogeneous pair correlation function for lags $h = 1, \ldots, 7000$ and local envelopes based on 19 simulations from the fitted model. Right: estimated intensity function.

Figure 2 shows the smoothed Pearson residuals (left-most panel) and the empirical inhomogeneous pair correlation function (central panel). We conclude that the model fits reasonably well. The estimated intensity function is shown in Figure 3. Compared to Figure 2, it is more detailed, but the general interpretation is similar. The approximate 95% confidence interval for α_2 is $(0.010, 0.036)$. Since it does not contain 0, $C(t, 12)$ is significant. The earthquake hazard $\lambda(t)$ at the dawn of the new year, January 1st, 2021, based on the gas production $C(9498, 12) = 7.95$ in 2020, has an approximate confidence interval $(0.018, 0.0413)$. The first induced earthquake with a magnitude of at least 1.5 happened on January 24, 2021, near Tjuchem.

Acknowledgments

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