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interim report: correlations between reservoir pressure and earthquake rate

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The views expressed in this paper are those of the author and do not necessarily reflect the policies of Statistics Netherlands.

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Contents

Samenvatting

Deze rapportage is een interim verslag van onderzoek dat is uitgevoerd in het kader een onderzoeksproject door het CBS in opdracht van Staatstoezicht op de Mijnen (SodM) sinds 2014. Dit onderzoek is ten behoeve van een statistische onderbouwing van het meet- en regelprotocol voor optimale gasexploitatie in de provincie Groningen, met in het bijzonder de aandacht gericht op de relatie tussen de gasdrukafname in het reservoir, die in de tijd varieert vanwege de gas productie bij de diverse clusters, en de aardbevingen in Groningen.

Conclusies van eerdere rapportage Pijpers (2016a) worden ondersteund, voor zover de beperkingen van de verschillende analyse-technieken een vergelijking toelaten. Tijdreeksen van de lopende gemiddelden van de dalingssnelheid van de reservoir gasdruk en van de aardbevingsdichtheid zijn anti-gecorreleerd. Een anti-correlatie betekent in dit geval dat wanneer de gasdruk in het reservoir langzamer daalt (de drukafnamesnelheid van het gasreservoir minder groot negatief is) dat dan ook de aardbevingsintensiteit lager is.

Summary

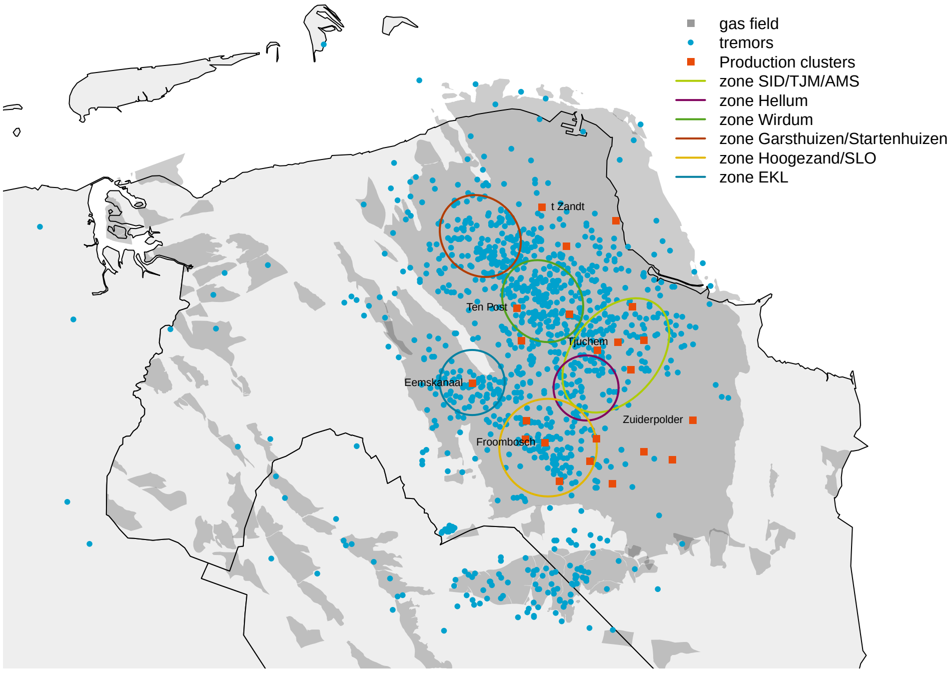
This report is an interim report, concerning continuation of research, commenced in 2014, which is part of a research project being carried out by Statistics Netherlands and commissioned by State Supervision of Mines (SSM). This research is part of the underpinning of the statistical methods employed to support the protocol for measurement and control of the production of natural gas in the province of Groningen. In this research the particular focus is on the relationship between reservoir gas pressure variations and the earth quakes in Groningen.

Previous conclusions, reported on in Pijpers (2016a) are corroborated to the extent that the limitations of the data analysis techniques allow such a comparison to be made. Moving average time series for reservoir gas pressure rate of decrease anticorrelate with moving average time series of the earthquake rate. This anticorrelation between the decrease rate of the pressure and the earthquake intensity implies that when the decrease of pressure of the reservoir gas is slower (less negative) the earthquake intensity is lower.

1 Introduction

For some decades earthquakes of modest magnitudes have occurred in and around the Groningen gas field. It is recognized that quakes can be induced by the production of gas from a field eg. (Wetmiller, 1986); (Grasso and Wittlinger, 1990); (Bourne et al., 2014). An extensive study program is in place to improve the understanding of the risk and hazard due to gas production-induced earthquakes in the Groningen field (Nederlandse Aardolie Maatschappij BV, 2013). A protocol is being established with the aim of mitigating these risks and hazards by adjusting the production strategy in time and space. Also the NAM is active in improving safety of housing through structural strengthening of buildings. In order for this to be effective it is necessary first to understand whether quake frequency and ground subsidence can be influenced at all by adjusting production. If so, it needs to be established how quickly the system reacts to production adjustments. Even if causality can be demonstrated, and the reaction time scale shown to be sufficiently short, implementation of the regulation protocol with adaptive control of production will require regular measurement of the effects on subsidence and earthquakes to provide the necessary feedback for production control.

Figure 1.1 The locations of all quakes within the zone in Groningen relevant to this analysis, recorded after 1 January 1995. The red squares are locations of the production clusters, some of which are identified by name. The production field is also shown in dark gray, overplotted on a map of the region.



The causality relationship between gas production and eartquakes is difficult to establish unequivocally, purely on the basis of time series analyses. For instance, a constant rate of gas extraction might lead to a likelihood of quakes that increases with time through the compaction of the reservoir layer, cf. (Bourne et al., 2014), but a correlation analysis would not necessarily provide any evidence of this. Because in practice the rate of production does vary periodically throughout the year, as well as incidentally for operational reasons, it becomes possible to pursue a correlation analysis between variations in quake incidence and production variations. Several correlation studies have been carried out and reported on: cf. Pijpers (2015b), Pijpers (2016a), and also sect. 5 of Pijpers (2016b).

As with the CBS reports from the previous phases of this project, starting point for the analysis of the statistics of quakes is the catalog of quakes as reported by the Royal Netherlands Meteorological Institute (KNMI) based on their processing of the network of seismometers that they manage. Further selections from that catalog are made as necessary, for instance in order to filter out quakes that have occurred outside of the zone of interest, or quakes from an epoch when the seismometer network was less sensitive and may suffer from more serious completeness issues. The selection/filtering criteria are chosen to be consistent with those of the previous Statistics Netherlands reports, (Pijpers, 2014), (Pijpers, 2015a), (Pijpers, 2015c): quakes before 1995 are always excluded, as are quakes with magnitudes below 1. For this specific analysis some selected spatial regions of interest are smaller than in previous reports although they generally cover the same part of Groningen province as those reports (see fig. 1.1). Also, the analysis presented her has as its primary interest the developments since January 2011.

The gas pressure inside the reservoir can be modelled, by making use of detailed geophysical mapping of the reservoir and its material properties, that together determine the diffusive flow of gas through the reservoir, induced by the gas production at the various clusters. These are available in the form of the reservoir modelling tool MoReS (Por et al., 1989).

2 Background

In the standard reporting of monitoring of the intensity of earthquakes in Groningen, event density maps are regularly produced. An example can be found in eg. van Thienen-Visser et al. (2015). These densities are determined using a standard GIS application kernel density with a radius of 5 km and a cell size of 50 m. In the present application the resulting maps are an input. The other inputs are reservoir gas pressures as modelled using MoReS, provided by NAM, with history matching to the pressures at dedicated measurement well sites.

In figure 1.1 are indicated, in addition to the locations of quakes, 6 separate elliptical regions which are of interest for SSM for monitoring purposes. Within each ellipse, an average of the reservoir gas pressure is calculated, where the averages are over:

- the vertical extent of the reservoir: a volume average is taken.
- a uniformly weighted (horizontal) average over the elliptical region.
- a uniformly weighted average in time over windows of either 1 year length or 9 months length. These are used in moving averages with monthly sampling.

This provides, for each zone, a time series of reservoir gas pressures or the rate (per year) at which the reservoir gas pressure decreases. For the earthquake density functions, the local maximum within each ellipse is determined, and the local value of that density, at the same time as the sampling times of the reservoir gas pressure and also using an average value over a window of either a year or 9 months in length, is used as a time series. The reason to choose two separate lengths of window in the moving average in time, is that for official reporting and monitoring purposes a period of 1 year has been agreed. For the purpose of capturing some of the seasonal effects, that have until recently been present in the gas production, a window length of precisely a year is inconvenient. In Pijpers (2016a) a window length of 9 months is used as a compromise between a window large enough to provide reasonably reliable statistics, and a window that does not suppress all forms of seasonality. In this way, time series are constructed that are 75 monthly samples long: starting January 2011, up to the present, March 2017.

3 cross-correlation

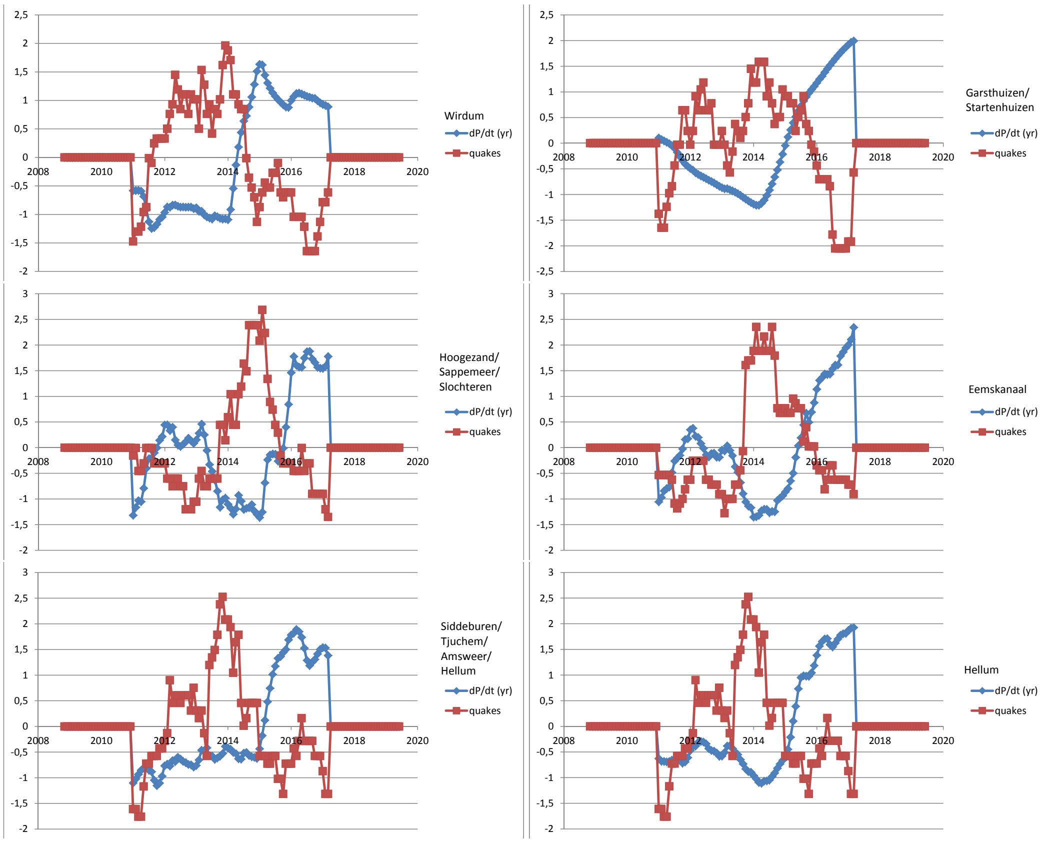
The primary purpose of the present analysis is to assess the correlation function of the reservoir pressure time series and the earthquake density time series. In order to achieve this, two steps are taken:

- For each of the time series its average over the 75 samples is subtracted, so that by definition the variation of the resulting series is around 0 in all cases considered.

– For each time series the standard deviation is calculated for the 75 samples, which is then used to normalize each of the time series.

Since the time series are oversampled, this standard deviation ought to be corrected if it were to be used as a statistical measure, but that is not the purpose here. For the use as a normalisation factor, such a purely numerical correction is identical for all series with the same averaging window, and hence drops out of the analysis producing the correlation function.

Figure 3.1 The 1 year windowed time series for the decrease rate of the pressure (blue) and the earthquake intensity (red), for the six zones indicated in Fig. 1.1. As described in the text, the average for each series is subtracted, and each series is scaled by its standard deviation. The symmetric zero-padding is shown explicitly.



If P and Q are the time series, thus treated, for respectively the rate at which the reservoir gas pressure drops, and the earthquake intensity, the correlation function is defined as:

$$\rho(\tau) \equiv \int P(t)Q(t+\tau)dt \quad (1)$$

In particular for a time-delay $\tau = 0$ this definition corresponds to the usual correlation coefficient between two sets of data X and Y which would be defined as:

$$\rho \equiv \frac{E\left((X-\overline{X})(Y-\overline{Y})\right)}{\sigma(X)\sigma(Y)} \quad (2)$$

where E refers to calculating the expectation value and σ to the standard deviation. A correction factor for the covariance between points in the windowed time series appears in both the numerator and denominator and therefore can be ignored at present.

The correlation functions are most conveniently calculated by taking the Fourier transform of the time series, multiplying, and then performing an inverse Fourier transform. This is done most

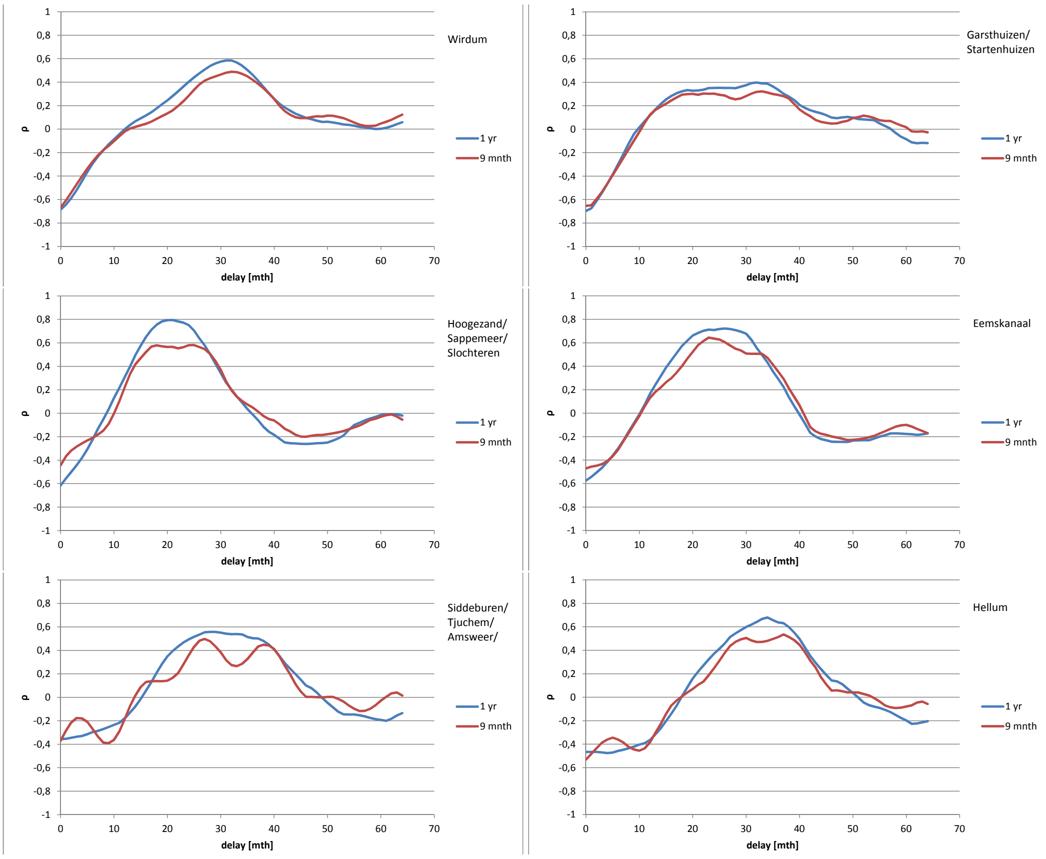
Table 3.1 Values at $\tau = 0$ for the correlation functions for all zones and the two lengths of time window.

region	$\rho(\tau = 0)$ 1 year wind.	$\rho(\tau = 0)$ 9 mnth. wind.
Wirdum	-0.686	-0.666
Garsthuizen/Startenhuizen	-0.697	-0.653
Hoogezand /SLO	-0.616	-0.444
Eemskanaal	-0.574	-0.471
SID/TJM/AMS	-0.357	-0.370
Hellum	-0.466	-0.531

quickly by symmetrically padding out the time series with 0's to a length of 128 samples, so that a Fast Fourier Transform can be carried out (cf. Bracewell (1965)).

In all cases the correlation function ρ can take values between 1 and -1 where 1 indicates that the two time series are identical, and -1 that they are identical up to a sign-change. $\rho = 0$ indicates no correlation. A peak value at a delay other than $\tau = 0$ would indicate that the time series appear to be shifted with respect to each other. Given that the time series come from oversampled moving averages, any peak in the correlation function has a width detemined by the width of the windowing function. Shifts in time by less than the windowing function width are poorly determined. In general one would expect the correlation function to tend to 0 at large time delays. Also, with time series that have been constructed to have a 0 average, the average of the correlation function over all delays must also be 0. A consequence of this is that if at $\tau = 0$ ρ has a non-zero value, the function $\rho(\tau)$ must cross through 0 for some value of the time delay τ.

Figure 3.2 The correlation functions between the decrease rate of the pressure and the earthquake rate of 1 year windowed time series (blue) and 9 months windowed time series (red), for the six zones indicated in Fig. 1.1.



In table 3.1 the value of the correlation function at time delay $\tau = 0$ are shown. There is no evidence, with these window lengths for the moving average, that there is a non-zero delay between the two time series. Any time delay is therefore considerably smaller than the window length. Fig. 3.2 shows the correlation functions for each zone. Note that the zone Hellum overlaps for the most part with the zone SDB/TJM/AMS. This zone is added because in recent years the earthquakes appear to be concentrated in this zone rather than the full SDB/TJM/AMS zone, and a better correlation would be expected (as is borne out by the data) with the time series where the averages for the reservoir gas pressure are limited to this zone. The same time series for the earthquake intensity is used for these two zones.

For the three zones Wirdum, Garsthuizen/Startenhuizen, and Hellum the shape of the cross-correlation functions is similar, and there is very little difference between the ρ with lengths of windows of 1 year or 9 months. The amplitude of the cross correlation function, and therefore also the value at $\tau = 0$ is smaller for the Hellum region than for the other two zones. For the zones Hoogezand/SLO and Eemskanaal the correlation is less strong than for the zones Wirdum and Garsthuizen/Startenhuizen. The correlation for the zone SDB/TJM/AMS is by comparison quite poor.

In order to assess wether or which of these cross-correlation values is significantly different from 0 it is necessary to have confidence intervals for the individual points in the time series. For the reservoir gas pressure the random component of the error is likely to be very small. It may well be that the uncertainty due to the assumptions concerning reservoir properties and geometries are larger than this, but a relative error of near 10^{-3} given the calibration to measured reservoir pressures at a number of locations appears not unreasonable. Similarly the uncertainty in the time series for earthquakes is likely to be dominated by the arbitrariness in the choice of smoothing kernel rather than a random component. If this is correct then the level of random relative error in the resulting correlation coefficient is also of the order of $10^{-3} - 10^{-2}$ and so in all cases the non-zero values at $\tau = 0$ are statistically significant. The figures of the time series (fig. 3.1) show that the earthquake time series do have more signal at higher frequencies than the time series for the reservoir gas pressure decrease do, but that on the whole the anticorrelation that is obtained is visible in the figures.

4 Conclusions

The windowed moving average time series for the reservoir gas pressure decrease and the earthquake rate appear to show a clear anticorrelation for most of the regions considered in this paper, except in one case where the pre-defined zone is probably too large and contains two subregions with separate behaviours both in terms of reservoir gas pressure and earthquake rate. In this way the previous work reported on in Pijpers (2016a) is supported using different data or spatial selections of data, and different analysis methods. Given the width over the moving averages used in this analysis, the relative time delays that were found between production variations and earthquake rate would not be expected to be recovered here. Also, the delay between production variations and reservoir gas pressure variations away from those cluster locations is already accounted for in the MoReS model.

An anticorrelation between the decrease rate of the pressure and the earthquake intensity implies that when the decrease of pressure of the reservoir gas is slower (the series has values that are less negative) the earthquake intensity is lower.

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