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Rapport KNMI-2019/1130.01

Datum 8 mei 2019
Betreft Advies "Seismic Hazard Assessment of Two Production Strategies for 2019-2020 in Groningen"

Geachte mevrouw [redacted]

Zoals u verzocht in uw brief van 27 maart 2019 sturen wij u hierbij het rapport "Seismic Hazard Assessment of Two Production Strategies for 2019-2020 in Groningen".

Voor meer informatie kunt u altijd contact met ons opnemen.

Hoogachtend,

[redacted]

Prof. dr. [redacted]

Seismic Hazard Assessment of Two Production Strategies for 2019 in Groningen[1]

A report prepared for the Ministry of Economic Affairs and Climate Policy

[redacted]

Royal Netherlands Meteorological Institute,
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May 8, 2019

1 “Verzoek tot advies met betrekking tot voorgestelde Operationele Strategieën Groningenveld”

Summary

The effects of two operational strategies for production from the Groningen gas field, proposed by NAM (Van Elk et al., 2019), have been investigated for warm, average and cold winters in the period 2019-2020. The two operational strategies differ in the distribution of production clusters to extract gas during the year. The first operational strategy (OS1) is focused on minimizing the expected population weighted Peak Ground Velocity (PGV), while the second operational strategy (OS2) is focused on minimizing event count.

The seismic models derived from the operational strategies show that the b-value (i.e., the ratio between the cumulative annual number of large and small magnitude events) remains stable, while the expected rate of seismicity (activity rate) is highest in the Loppersum area and to a lesser extent significant around Hoogezand for especially cold winter production. The difference in activity rate of OS2 with respect to OS1 shows an increase in expected seismicity in the southern part of the field and a decrease in the Loppersum area.

A Probabilistic Seismic Hazard Assessment (PSHA) was carried out for the return period 475 y for all production scenario's using a coarse grid (400X400m) to allow for fast calculations. The resulting maximum Peak Ground Acceleration (PGA) is in the range of 0.13g to 0.14 g for both operational strategies from the warm, average and cold winter cases, respectively. The pattern of the hazard maps does not change significantly from one operational strategy to the other. Differences between OS2 and OS1 PGA maps show a north-south pattern for a warm winter (low case), while the other scenarios show a northwest-southeast pattern These findings are similar to those of NAM. For all production scenario's, a PGA map is presented and made available in digital form.

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Introduction

The Royal Netherlands Meteorological Institute (KNMI) has been asked by the ministry of Economic affairs and climate policy (EZK) to perform a seismic hazard analysis for the Groningen field. This time, two operational strategies for which a warm, average and cold winter production scenario for the Groningen gas field are considered (Letter from EZK with reference number GKE-PGG/1906521). The specific questions from the director Gas transition Groningen are

1. What are the expected changes in the geographic spread of seismicity and the probability of occurrence of (stronger) induced events in view of the recent HRA's for the operational strategies[1].
2. What is the expected seismic hazard for the year 2019-2020 considering all (if required corrected) field data? Are there differences in seismic hazard compared with the expected results by NAM? If so, what is the reason for any observed differences[2]
3. Can the KNMI present a graphical illustration of the seismic hazard (specifically PGA for the return period 475 y)[3]

The first question can only be discussed using a seismic source model that includes the effect on production changes. At this moment the NAM model is the only available model for Groningen. The effects of production change on activity rate (number of events per year) and b-values (ratio between expected cumulative annual number of large and small magnitude events) are calculated using the activity rate model (Bourne & Oates, 2017). This method requires detailed information on production of the field and on subsurface parameters. Information was obtained from NAM, who calculated activity rate and b-values for the scenario's. We will discuss the results of an analysis based on this information obtained from NAM to answer the first question and how this information was used in the PSHA calculations

Questions 2 and 3 can be answered by carrying out a Probabilistic Seismic Hazard Analysis (PSHA) for Groningen. The PSHA requires as input the activity rate and b-values from the source model, a Ground Motion Model (GMM) to calculate the effect from a seismic source at depth at the surface and an estimate of the maximum magnitude expected in the region (for Groningen a M_{max} distribution is applied).

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1. Welke verwachtingen heeft u ten aanzien van veranderingen in de geografische spreiding van seismiciteit en de kans op (zwaardere) geïnduceerde aardbevingen gelet op de meest recente HRA's behorende bij de operationele strategieën?

2. Welke seismische dreiging verwacht u in het gasjaar 2019-2020, mede op grond van alle (waar nodig gecorrigeerde) waarnemingen in het veld? Zijn er verschillen met de seismische dreiging die NAM verwacht, en zo ja, hoe zijn die verschillen te verklaren?

3. Kunt u de verwachtingen grafisch weergeven in de seismische dreigingskaart (PGA die eens in de 475 jaar voorkomt)?

The PSHA uses the Ground Motion Model (GMM) for Groningen: GMM v5 (Bommer et al., 2018). The output of the seismic hazard method is in this report limited to Peak Ground Acceleration (PGA) maps. The PGA maps for the different production cases allows to estimate the consequences about the variability of the seismic hazard level during the reduction of gas extraction from the Groningen field.

Both NAM and KNMI calculate PSHA, however taking a different approach. NAM uses Monte Carlo sampling to calculate hazard, while KNMI applies an integration procedure over seismicity zones. This implies that results may differ slightly, but results should be comparable.

In the first part of the report, the two operational strategies and their respective seismic models are briefly introduced and the implications in terms of seismic activity rate and b-values discussed. Then, GMM v5 is introduced and the most important parameters used in the PSHA, such as the maximum magnitude and the PSHA method applied by the KNMI. The seismic hazard maps are presented for the operational strategies. A comparison of the presented hazard results with the ones calculated by NAM for the same production scenarios and the GMM v5 are discussed.

Production strategies for Average, Cold and Warm Winters

The seismic hazard related to a production strategy for gas extraction of the Groningen field was introduced in a KNMI hazard report in June 2018 (Spetzler et al., 2018). Three production prognosis for the case of warm, average and cold winters between 2018 and 2028 had been prepared by NAM earlier in 2018. In the present report, two production strategies for 2019-2020 are suggested by NAM and once more are applied for a warm, average and cold winter scenario (van Elk *et al*., 2019).

The first operational strategy (OS1) is intended to minimize the population weighted Peak Ground Velocity. The production of gas is preferentially from the south-east. If the demand for gas increases, production clusters in the South-West and central-East region are opened. The OS1 strategy is similar to the production plan for the gas year 2018-2019 which was selected by the Minister of EKZ in instemmingsbesluit 2018. The second operational strategy (OS2) has the objective to minimize the event count. The production of gas takes place at clusters in the southern part of the field. Clusters in the central-east region and near Bierum are only applied at a higher production demand.

The two current operational strategies have a reduced annual gas production for the first three years compared to the NAM production planning from 2018. Figure 1 shows the annual production for the three winter scenarios for the next 10 years (van Elk *et al*., 2019). In terms of expected induced earthquakes, the two production strategies investigated in this report show a similar trend. The annual number of events (M >= 1.5) from 2010 to 2032 is shown in Figure 2 (van Elk *et al*., 2019).

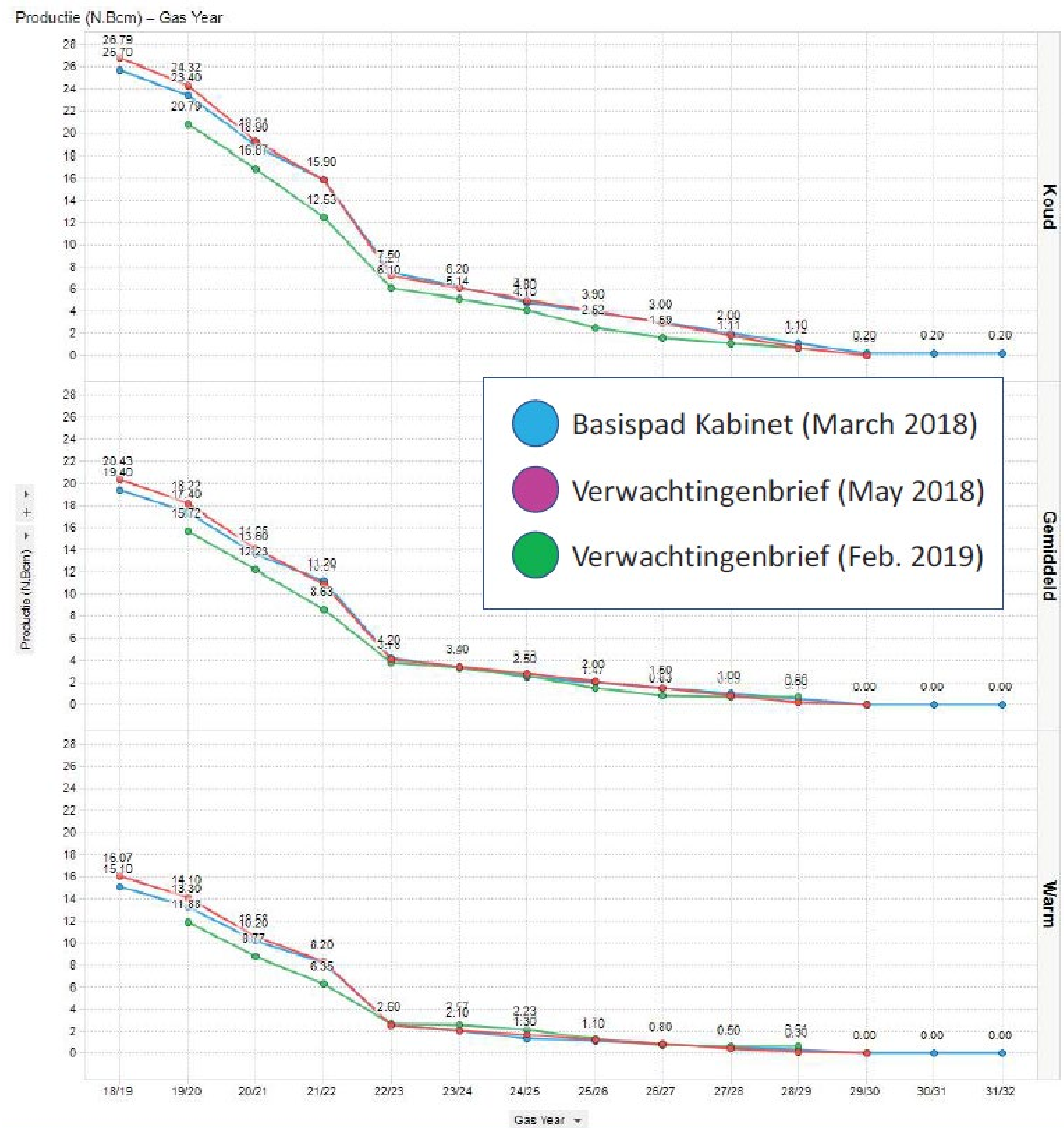


Figure 1: Adjustment of production strategies for the three temperature cases (van Elk et al., 2019).

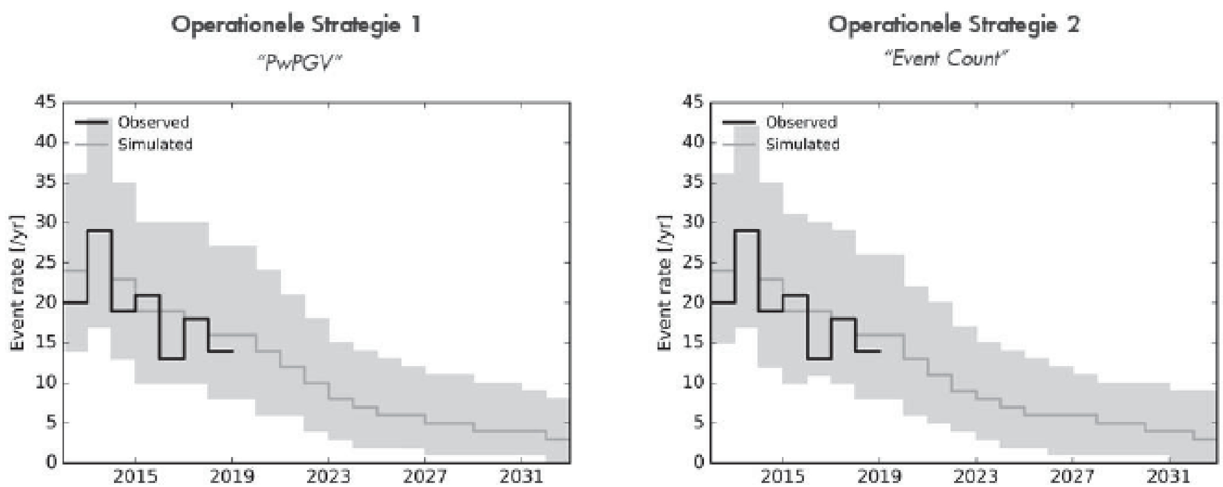


Figure 2: Annual number of induced events (M=>1.5) for the two production strategies (van Elk et al., 2019).

The expected number of induced earthquakes distributed over the Groningen gas field, inherent to the two operational strategies, has been converted into lateral variant distributions of activity rate density and b-values which are parameters used in the seismic hazard analysis. A low b-value (often less than 1) indicates that higher magnitude events are more likely to take place in a region and vice versa. The activity rate density shows which parts of an area are more or less seismic active. Two operational strategies and three winter scenarios result in six cases for which each one has a specific set with the distribution of the activity rate density and b-value over the Groningen field. The activity rate density and b-value distributions are illustrated in Figure 3.

For all six cases, the b-value distribution is identical, while the activity rate densities are similar, but clearly show an increase in the number of expected induced events for increasing production level from warm to cold winters. Most of the induced seismicity is expected in the Loppersum area and to a lesser extent in the southern part of the field near Groningen and Hoogezand.

The zones with similar seismic hazard properties in the zonation model, which is used in the KNMI hazard analysis, have indices Z1, Z2, Z3, Z4, Z5. The dominant seismicity in zone Z1 will contribute mostly to the seismic hazard. To a much lesser extent, the zones Z2 and Z3 will add to the seismic hazard, while the zones Z4 and Z5 with hardly any seismicity has very little effect on the seismic hazard.

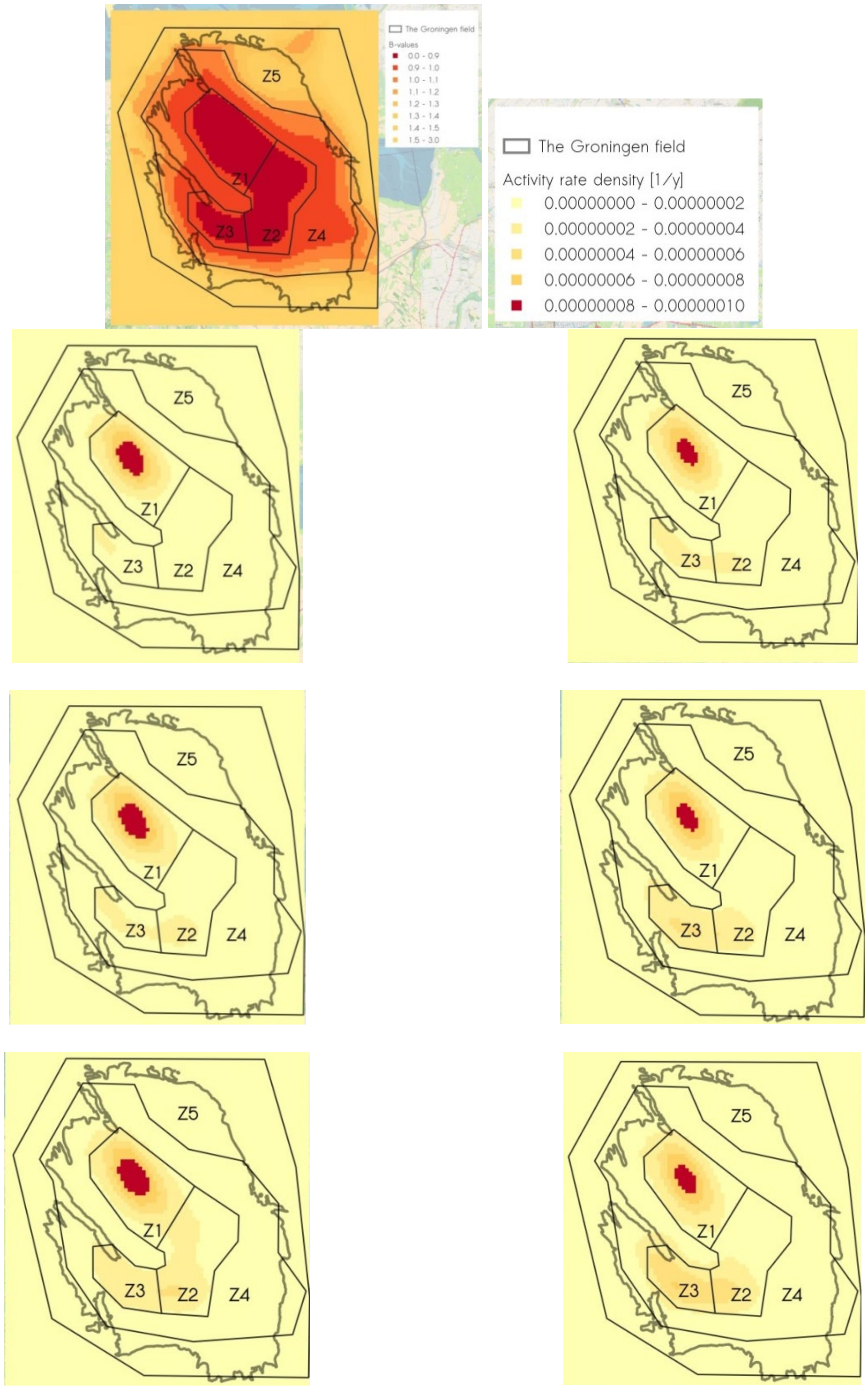
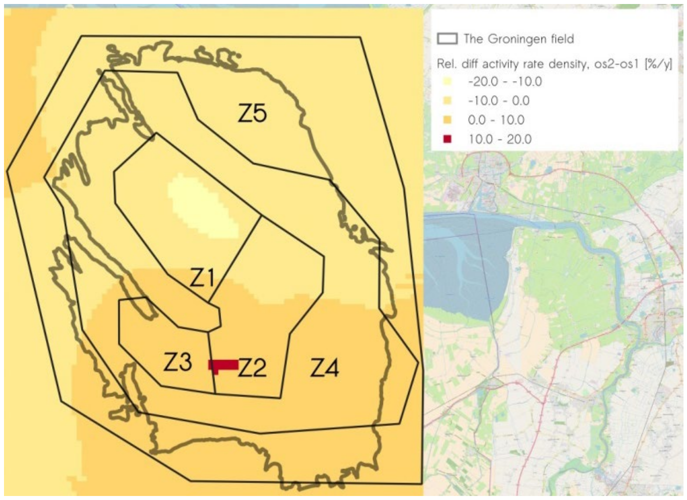


Figure 3: Lateral distribution of b-values (top) and activity rate density for the two production strategies in 2019 for the warm, average and cold winter scenario (from top row downward). The column on the left shows results for OS1, on the right for OS2.

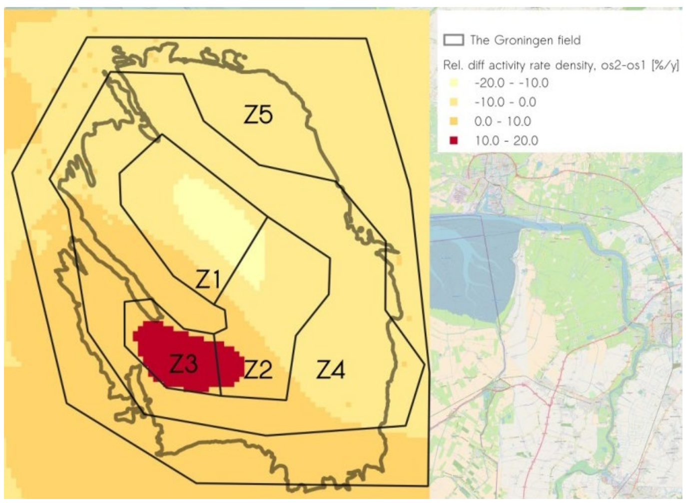
The difference between the activity rate density for operational strategy 1 and 2 for the three winter cases are presented in Figure 4. The trend in the change of seismic activity from one operational strategy to the other is similar for all three gas production scenarios.

Selection of OS2 implies that the activity rate density with respect to OS1 is lowered in the Loppersum area. The preferential gas production at clusters in the South result in an increase in expected seismic activity in that part of the field. The average and cold winter case show an increase in the activity rate density in the South-West compared to the warm winter case where the gas demand is lower.

Lowcase: OS2-OS1



Midcase: OS2-OS1



Highcase: OS2-OS1

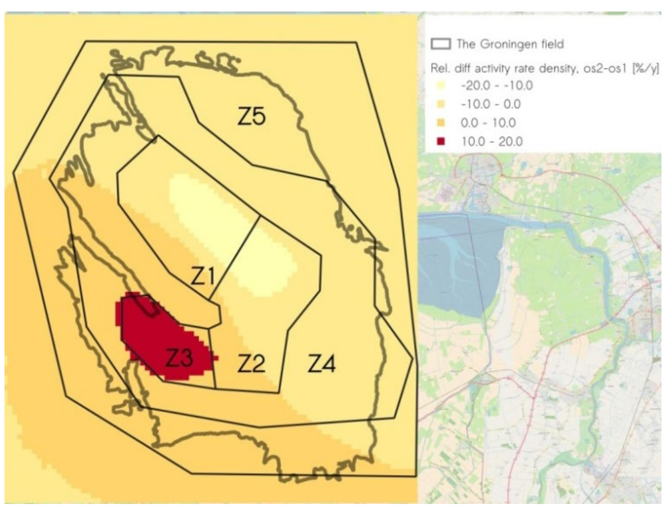


Figure 4: Lateral distribution of the relative difference between activity rate density for the two production strategies in 2019-2020 for the warm, average and cold winter scenario (from top row downward).

Ground Motion Model (GMM) v5

GMM v5 is based on a two-layer model of Groningen (Bommer et al., 2017a,b, 2018). The upper layer is defined by the North Sea group and has a thickness of 800 m. The lower layer is defined by the structure between the reservoir (at 3 km) and the bottom of the North Sea group. Figure 5 illustrates the two-layer approach. An induced earthquake is initiated in the gas reservoir and the seismic energy propagates upwards through the deeper subsurface and the near-surface layer with site-specific soil properties where the amplification of the seismic signal takes place. The amplification factor in the two most recent GMM's has a magnitude-distance dependence. This means that not only the magnitude of the induced earthquake affects the amplification factor as it is the case in GMM v2, but the distance between the hypocenter and site is also taken into account. The rupture distance is used for the distance measure in GMM v5. The shortest distance between a hypocenter directly below the site to the surface is 3 km.

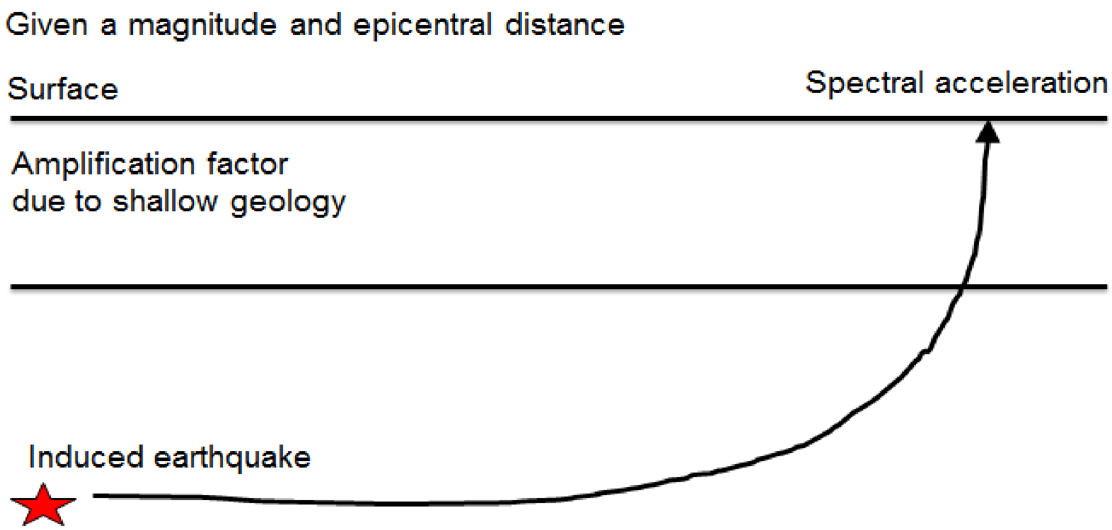


Figure 5: Schematics of the two-layer model used to define the GMM v2 to v5.

GMM v5 is compiled from a larger event data base than before. The KNMI earthquake catalog reports relatively strong induced events. The M3.5 event on August 8, 2006 and the M3.6 event on August 16, 2012 are in the data base. The M3.4 event on January 8, 2018 took place after the GMM had been finalized and is not added to the event data base. Figures 6 shows the contents of the event data base that is used to construct GMM v5 (data with blue triangles are as well in the v3-V4 data base, while data with red circles are only added to the GMM v5 data base).

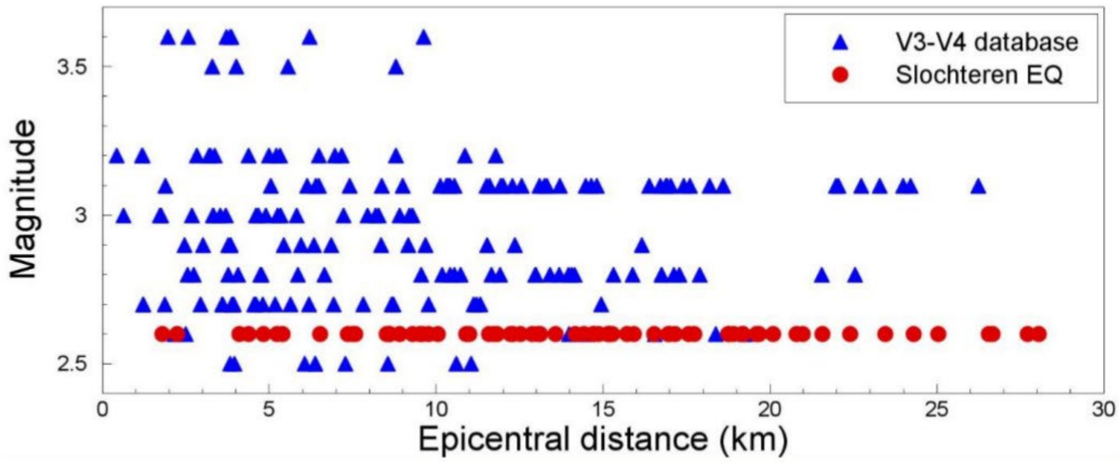


Figure 6: The event data base used in the construction GMM V5. (The GMM v5 report by Bommer et al., 2018).

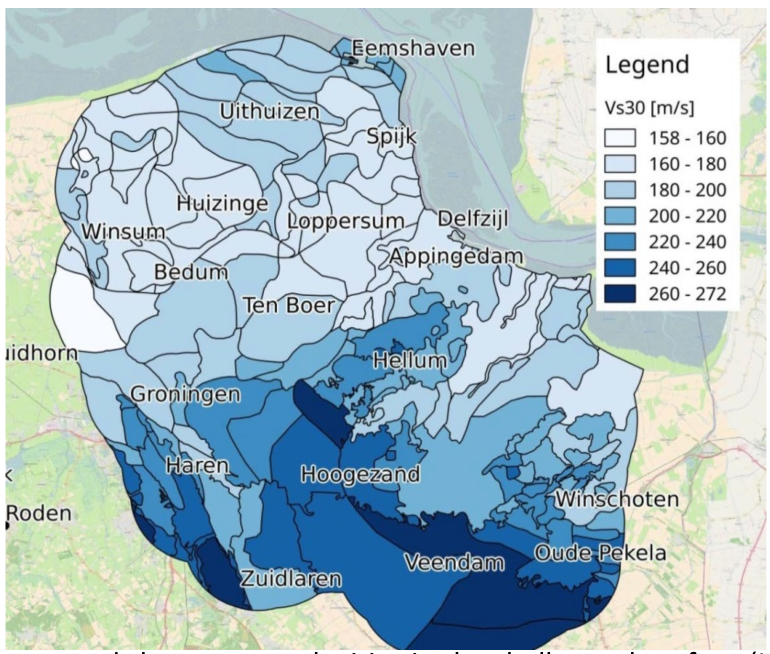


Figure 7: Geological zones and shear wave velocities in the shallow subsurface (Kruiver et al., 2017).

The zonation model for the amplification factor is unchanged from GMM v4 to v5. Kruiver et al., 2017 explains in details how shallow seismic experiments conducted by Deltares, low-passed filtered 3D reflection seismics and an improved time-to-depth model from seismic imaging contributed to the compilation of an integrated shear-wave velocity model for the top column from the reference level to the surface. The number of zones is 160. In general, the largest shear wave velocities are found in the south where near-surface amplification effects are less severe due to the presence of sand in the top layer. In the north, the top soil consists of more unconsolidated clay and peat resulting in a larger amplification effect. The current geological zones for the GMM v4 and v5 is shown in Figure 7, (Kruiver et al., 2017).

Maximum Magnitude Distribution for Groningen

In 2016 an international panel of experts advised on the issue of M_{max} for Groningen. Based on all available information presented to the panel, the experts proposed a distribution of M_{max} values, peaked at M_{max}= 4.5 (Bommer and Van Elk, 2017). Both induced and triggered events were taken into account. The distribution of M_{max} values is implemented in the logic tree for the calculation of the seismic hazard in Groningen.

For triggered events with a magnitude above M=5.5, the section of the fault that moves is larger than the reservoir thickness and therefore hypocenter depth of events may be larger than 3 km. However, all GMM's for Groningen are constructed for seismological events originating at reservoir depth and therefore will provide conservative results. On the other hand for return periods less than 2500 years, the contribution of events M > 5.5 is minimal. The M_{max} distribution is presented in table 2. The average magnitude of the M_{max} distribution is <M> =5.

Table 2: M_{max} distribution for Groningen (Bommer and Van Elk, 2017).

M_{max}	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Weight	0.0863	0.400	0.2438	0.1125	0.0788	0.0525	0.0263

Probabilistic Seismic Hazard Analysis Method

The method of calculation of the PSHA is identical to the approach in the 2018 KNMI hazard update (KNMI report, June 2018). In brief, a more general version of the method by Cornell (1968) was introduced to add the effect of magnitude-distance dependence in the near-surface amplification factor to calculate spectral accelerations in the PGA map and spectra. The two-step approach in the GMM v5 works as follows: First, the hazard probability due to an induced event at reservoir level (on average 3 km) is calculated at the reference level at 800 m depth. Second, the hazard curve at the surface is obtained by convolving the probability density function of the spectral acceleration at the reference level with the probability density function of the amplification factor. The amplification factor has a magnitude and distance dependence and this is accounted for in a general convolution integral wherein the contribution of the probability distributions of magnitudes, distances, amplification factor and ground motion are summed up (Bob Young, pers. comm.).

Seismic PGA Hazard Maps for Average, Cold and Warm Winter

The results of the PSHA hazard analysis for Groningen is presented in the form of PGA maps for the two production strategies for the warm, average and winter scenario's in Figure 8, 9 and 10, respectively. The return period in the PGA maps is 475 y according to Eurocode 8. Due to the large number of production scenario's and a short time to perform the calculations, the resolution of the PGA maps is 400x400 m.

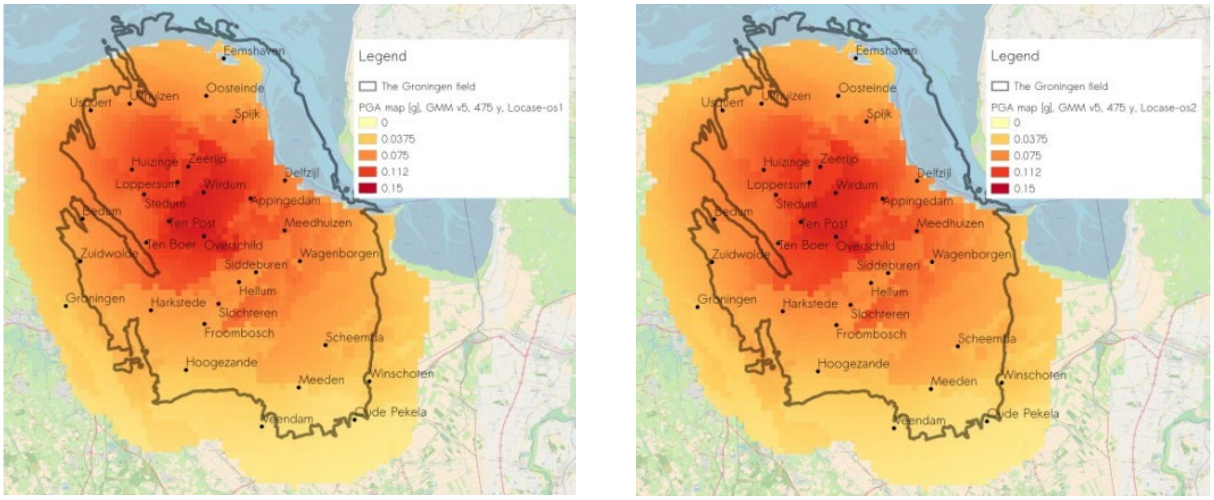


Figure 8: PGA map for Groningen for the period T = 0.01 s for GMM v5 and the two production strategies for a warm winter. The return period is 475 y according to Eurocode 8. The maximum PGA is 0.13g in both maps. The black solid line indicates the boundary of the Groningen gas field.

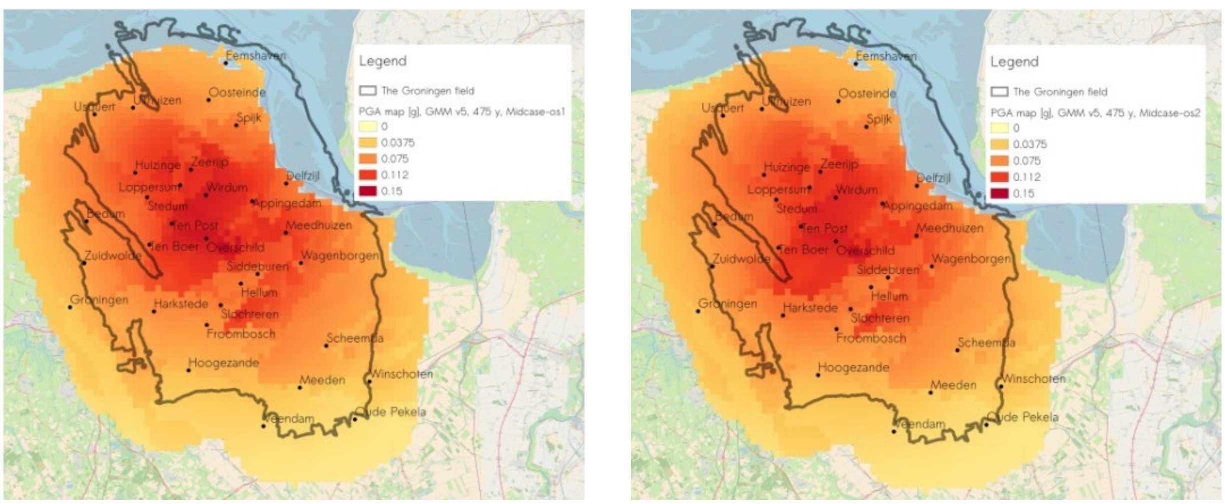


Figure 9: PGA map for Groningen for the period T = 0.01 s for GMM v5 and the two production strategies for an average winter. The return period is 475 y according to Eurocode 8. The maximum PGA is 0.14g and 0.13g, respectively. The black solid line indicates the boundary of the Groningen gas field.

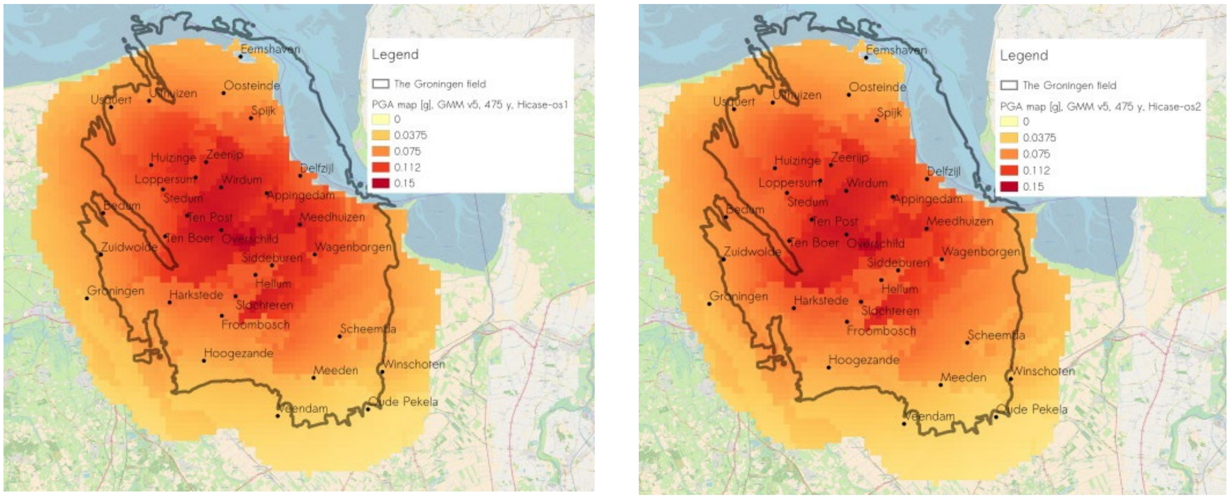
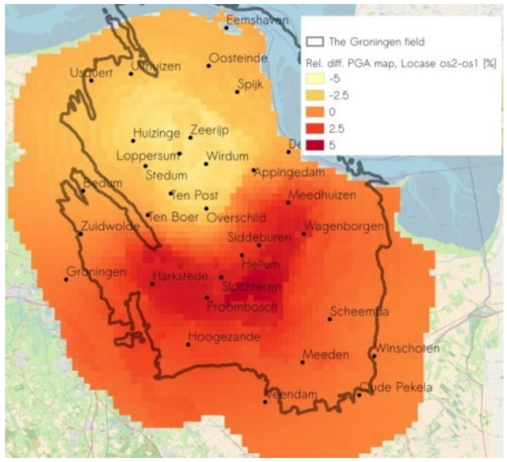


Figure 10: PGA map for Groningen for the period T = 0.01 s for GMM v5 and the two production strategies for a cold winter. The return period is 475 y according to Eurocode 8. The maximum PGA is 0.14g in both maps. The black solid line indicates the boundary of the Groningen gas field.

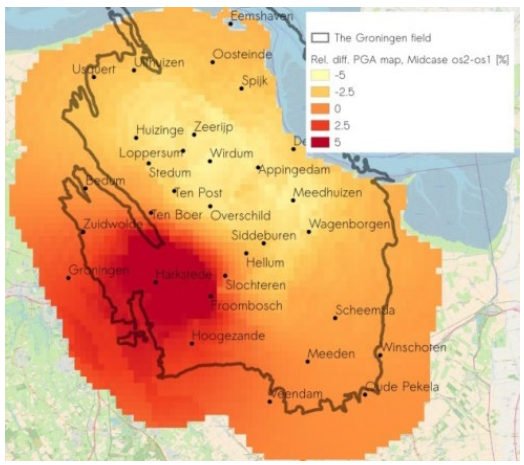
Generally, the maximum PGA value in the hazard maps in Figure 8,9 and 10 in the order of 0.13-0.14g. Warm winters require a lower production of gas which is observed in the respective PGA maps with the lowest maximum PGA values. The opposite is true as well for the cold winter scenario's. The differences in PGA maps between the two operational strategies are rather small. The maximum PGA values for OS1 are found to be marginally higher than for OS2. The max PGA values are found in the Loppersum area. A comparison with the PGA hazard maps for the two operational strategies and three winter cases on pp. 96-98 in van Elk et al. (2018) show very similar patterns. The minor differences in maximum PGA value can be attributed to the lower resolution of the PGA maps presented in this report with respect to the NAM results.

The difference between the PGA maps for the two operational strategies for the warm, average and cold winter scenario are shown in Figure 11. Generally, the level of PGA values in the Loppersum area is lower in the operational strategy OS2 compared to OS1. On the other hand, the seismic hazard level is higher in the south of the field for the warm winter case, and especially higher in the South-West region for the two remaining winter scenario's. These patterns are comparable to the NAM results (Van Elk et at., 2019).

Lowcase: OS2-OS1



Midcase: OS2-OS1



Highcase: OS2-OS1

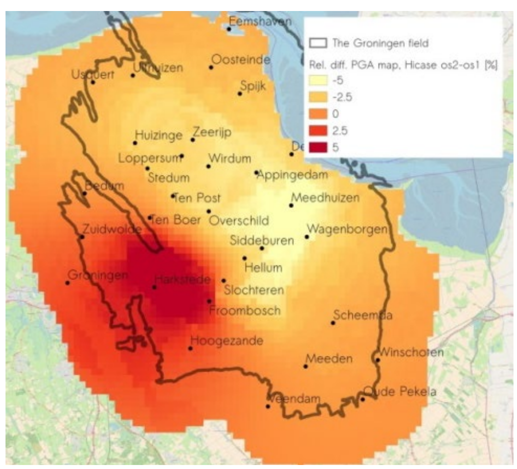


Figure 11: Difference between the PGA maps for the two operational strategies for the warm, average and cold winter scenario in Figure 10. The black solid line indicates the boundary of the Groningen gas field. PGA differences are indicated in %.

Conclusions

A seismic hazard assessment for two operational strategies and three winter scenario's for the period 2019-2020 has been carried out for the Groningen gas field in response to questions from the director gastransition Groningen. The difference between the two operational strategies comes from the distribution of extracted gas over the production clusters during the year. In the first operational strategy, relatively more gas is produced from the southeast of the field to reduce the personal-related hazard. The second operational strategy is optimized to the minimum number of expected induced earthquakes.

The first question on the expectations on the changes in the geographical spread of seismicity was answered by an evaluation of the activity rate density for the two strategies. Results show for strategy OS2 an expected increase in the activity rate density with respect to OS1 in the southern part of the field and a decrease in the Loppersum area. This general result was found for all three winter scenarios.

The second and third questions were related to the expected hazard in the same period (2019-2020) and differences with the hazard calculated by NAM. PGA hazard maps have been calculated which are based on seismic source models for the six production cases suggested by NAM and delivered to the KNMI.

The GMM v5 is applied in the hazard analysis and the return period is 475 y. The production scenario based PGA maps predicts max PGA values in the order of 0.13-0.14 g for the warm, average and cold winter scenario's, respectively. The calculated PGA hazard maps have been compared with the equivalent maps by NAM. The PGA hazard maps show a similar pattern and the same order of maximum PGA values. Minor differences between the PGA hazard maps by the KNMI and NAM come from the lower resolution for which the KNMI PGA maps were calculated due to the lack of available time. The KNMI approach and the NAM method differ in the method of calculation, specifically the way the hazard integral is solved. The comparison of KNMI and NAM PGA hazard maps shows that the respective methods are producing stable and comparable results.

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