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Report

Date : June 19, 2018
Subject: Seismic Hazard Assessment of Production Scenarios in Groningen[1]

Dear Mr. Verdaas,

With reference to the letter of Mr. E. Wiebes, Minister Economic Affairs and Climate Policy, dated April 20, 2018 we hereby send you the report "Seismic Hazard Assessment of Production Scenarios in Groningen[1]" as requested in his letter.

If you need additional information, please do not hesitate to contact us.

Yours sincerely,

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[1] "Adviesvragen rond veiligheidsrisico's en versterkingsopgave"

Royal Netherlands
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and Water Management

Seismic Hazard Assessment of Production Scenarios in Groningen[1]

A report prepared for the Ministry of Economical Affaires and Climate Policy

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June 15, 2018

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[1] "Adviesvragen rond veiligheidsrisico's en versterkingsopgave"

Summary

The effects of proposed changes to gas production from the Groningen gas field have been investigated for the period 2018-2027. Three scenarios have been evaluated in terms of expected seismicity and a Probabilistic Seismic Hazard Assessment (PSHA) was carried out. The time interval was subdivided into three periods with comparable seismic activity rates. The first period (2018-2020) shows a spread of seismic activity over the central part and the south-western part of the field. For the two later periods (2020-2023 and 2023-2027) the activity rate drops and mainly the central north part of the field (Loppersum area) shows activity. The b-value, the ratio between large and small magnitude events, remains stable over all time periods. PSHA calculations on a coarse grid and with simplifications to allow for fast calculations, show a decrease of the hazard over time from a maximum Peak Ground Acceleration of 0.16g to 0.12g. The pattern of the hazard map did not change significantly. For all three scenarios and three time periods PSHA results are presented and made available in digital form. Apart from maps of Peak Ground Acceleration, a set of spectra with spectral accelerations are presented at a coarse grid over Groningen for each scenario and time period.

Table of Contents

1. Introduction

The Royal Netherlands Meteorological Institute (KNMI) was asked by the minister of economical affairs and climate policy (EZK) to perform a seismic hazard analysis for three production scenarios for the Groningen gas field (Letter from EZK with reference number 18072342). These production scenarios are chosen to represent the production needed for warm, average and cold winters. Specifically, the questions from the minister are

Verwijderd:

1. What are the expected changes in the geographic spread of seismicity due to a reduction in gas production for the average scenario used by the Cabinet (see Figure 2 from the letter to parliament d.d. March 29, 2018), including the spread between scenario's for warm- (orange line) and cold winters (blue line) in the period of a reduction in gas production[1].
2. How do the changes in seismicity influence the ground movement and the resulting probability of (large) induced earthquakes according to KNMI[2]

Both questions can be answered by carrying out a Probabilistic Seismic Hazard Analysis (PSHA) for Groningen. The PSHA requires as input an estimate of the activity rate of seismicity and the ratio between large and small magnitude of expected events (b-value). In addition, a Ground Motion Model (GMM) is required and an estimate of the maximum magnitude expected in the region (for Groningen a Mmax distribution is applied).

For the source model (activity rate and b-value), KNMI has used up to now an extrapolation of recent seismicity to the next few years. This method is not capable to calculate the effects of the proposed production changes. The only method available at this moment to calculate the effects of production change on activity rate and b-values is 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 of this information to answer the first question and how this information was used in the PSHA calculations

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[1] "Welke verwachtingen heeft het KNMI voor veranderingen in de geografische spreiding van seismiciteit ten gevolge van de afname van de gaswinning, voor het gemiddelde scenario van het basispad zoals gehanteerd door het Kabinet (zie figuur twee uit de kamerbrief van 29 maart 2018), ook rekening houdend met een bandbreedte tussen warme (oranje lijn) , dan wel koude (blauwe lijn) in de periode van afbouw?"

[2] "In hoeverre beïnvloeden deze seismische veranderingen volgens het KNMI de bodembeweging, en de hieruit voortvloeiende kans op (zware) geïnduceerde aardbevingen."

The PSHA uses the most recent Ground Motion Model (GMM) for Groningen: GMM v5 (Bommer et al., 2018). This GMM is based on the latest update of the Groningen seismological data base. The output of the seismic hazard method is given as peak spectral accelerations (PSA) values and presented as peak ground acceleration (PGA) maps and spectra with PSA values for the spectra period range from 0.01 s to 5 s for a dense grid of site-specific locations in Groningen. The PGA (= PSA at 0.01 s) maps and spectra for the different production scenarios allows to estimate the consequences about the variability of the seismic hazard level during the reduction of gas extraction from the Groningen field.

In the first part of the report a brief introduction is given to the recent GMM v5 and the most important parameters, such as the maximum magnitude, used in the PSHA method applied by the KNMI. Then the implementation of the production scenarios in the seismic hazard method is explained. The seismic hazard maps and spectra are presented for an average, cold and warm winter scenario. A comparison with hazard results from June 2017 based on the previous GMM v4 is presented, as well as a comparison with hazard results calculated by NAM for the same production scenarios and the GMM v5.

In view of the short time available to carry out these analyses, simplifications had to be made in order to ensure that results can also be used by other parties in a timely fashion. In the following chapters we will discuss these simplifications in detail.

2. Ground Motion Model v5

The structure of the previous GMM v4 and current GMM v5 are identical (Bommer et al., 2017, 2018). Both GMM's are based on a two-layer model of Groningen. 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 1 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.

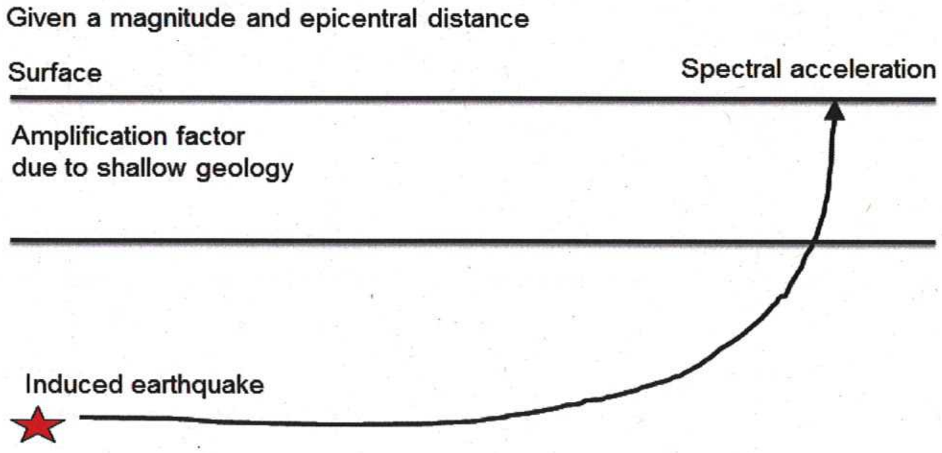

Figure 1: Schematics of the two-layer model used to define the GMM v2 to v5.

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 2 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).

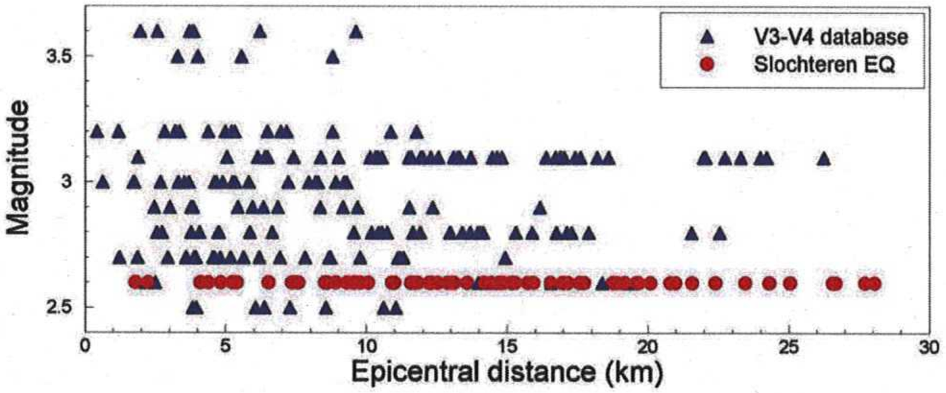

Figure 2: The event data base used in the construction GMM V5. (The GMM v5 report by Bommer et al., 2018).

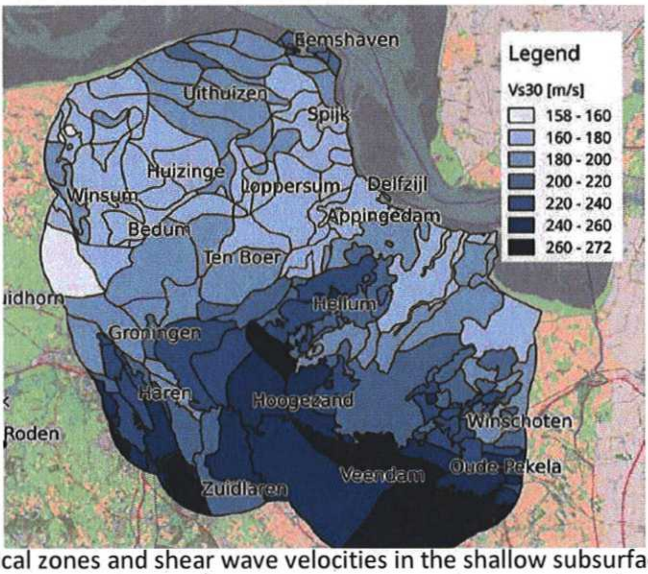

Figure 3: Geological zones and shear wave velocities in the shallow subsurface (Kruiver et al., 2017).

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 3, (Kruiver et al., 2017).

3. Maximum Magnitude (Mmax) Distribution for Groningen

An international workgroup of experts met on March 8-10 2016 to discuss the question: what is the best value of Mmax to be used in seismic hazard calculations for Groningen (Report on Mmax Expert Workshop, July 2016*)*. The workshop resulted in a proposed distribution of Mmax, given in table 1. The Mmax distribution is defined in the range from M4 to M7. The average magnitude of the Mmax distribution is <Mmax> = 5.

Table 1: Mmax distribution for Groningen (Bommer and van Elk, 2017).

Mmax	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

Incorporation of this Mmax distribution requires a separate calculation of the PSHA for each value of Mmax for Groningen. In view of the limited time available for the calculations it was decided to simplify the Mmax distribution. An alternative 3 point distribution was proposed by Stephen Bourne (pers. comm.), who showed that the 3-point Mmax distribution is slightly more conservative in the prediction of spectral acceleration values compared to the original 7 point distribution. The modified Mmax distribution is presented in table 2. The average magnitude of the Mmax distribution is <Mmax> = 5.1.

Table 2: Modified Mmax distribution for Groningen (Source: Stephen Bourne).

Mmax	4.5	5.4	6.8
Weight	0.46	0.43	0.11

4. Probabilistic Seismic Hazard Analysis Method

The PSHA is identical to the approach in the KNMI hazard update June 2017 (KNMI report, June 2017), except for the implementation of the latest GMM v5, the use of another source model and a different Mmax distribution. 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. GMM v5 is like the previous GMM v4 version a two-step approach as introduced in Spetzler and Dost (2016). In general, the two-step method 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 in the two most recent GMM's. 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.).

The application of the generalized hazard integral is rather computer intensive. To calculate spectra for a large number of sites over the Groningen field, a network distributor system at the KNMI is used to access all computers.

5. Production simulations for Average, Cold and Warm Winters

The proposed scenarios for the reduction of gas production from the Groningen gas field in the coming 10 years is presented in Figure 4. Three scenarios are considered for the case of warm, average and cold winters. Generally, the gas production volume will decline every year. Depending on the winter scenario, the extracted gas volume is lowered to less than 12 billion cubic meters (bcm) in the period 2020 - 2022.

NAM used a statistical method to calculate lateral variating b-values and activity rate densities per year for the production scenarios (Bourne and Oates, 2017). The annual activity rate for M>1.5 for Groningen for the three winter scenarios is shown in Figure 5. An inspection of the figure reveals that for the average and cold winter scenario, the number of events is increasing in the first years. For the remaining years, the activity rate is decreasing. In the prognosis for warm winters, the activity rate is 4 events per year in 2027.

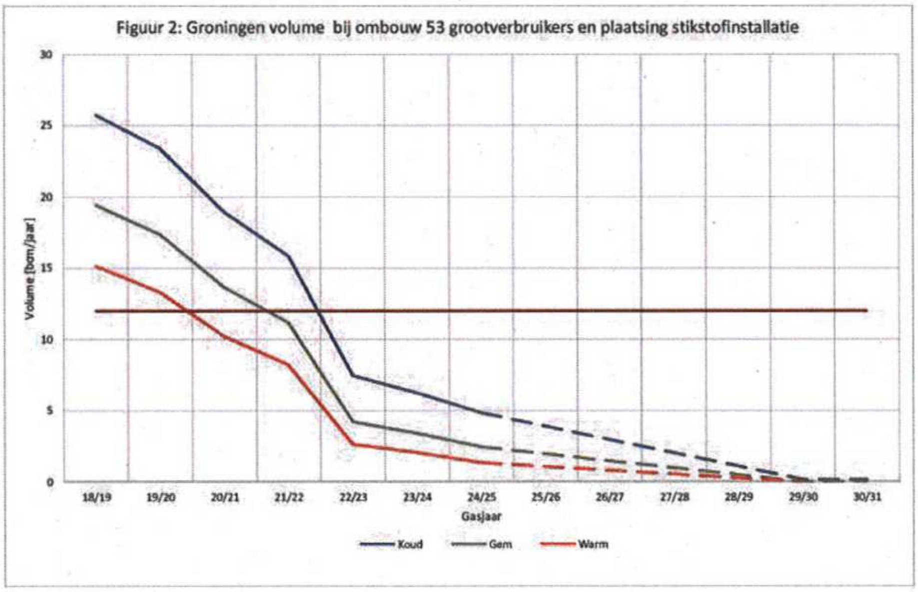

Figure 4: Production scenarios for the next decade for warm, average and cold winters (labels in Dutch). The 12 bcm production limit advised by SodM is shown with the brown horizontal line (Letter from EZK with the reference number 18072342).

In order to limit the time needed for PSHA calculations, a reduction of time intervals was required. Looking at the activity rate forecast for the three winter scenarios, a division in three time periods with similar characteristics was proposed. These periods are 2018-2020, 2020-2023 and 2023-2027, respectively named **t1, t2, t3.** Figure 5 shows a specification of the three period ranges. For period **t1**, the activity level is highest. For period **t2** and **t3**, the annual activity rate is constantly decreasing with a change of the slope of the lines in 2023. The change in gradient in 2023 defines the separation between the period range **t2** and **t3**.

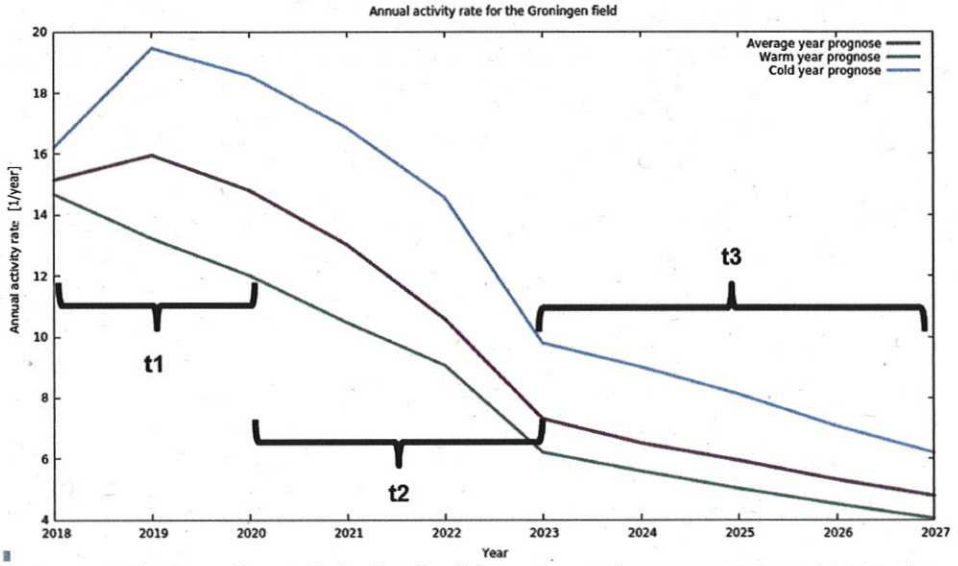

Figure 5: Definition of periods for levels of activity rates between 2018 and 2027. The number of events per year is counted for M > 1.5.

6. Lateral Variations of Seismic Source Models for Production Scenarios

The seismic source model was produced by NAM following the method by Bourne and Oates (2017). Grid files with the activity rate per grid cell (i.e., activity rate density) and b-values distributed over Groningen were delivered to the KNMI. The lateral variation of activity rate densities and b-values between 2018 and 2027 were inspected. Figure 6 shows an example of the variation of activity rate densities and b-values in the Groningen field. It was concluded that the b-value distribution is rather stationary between 2018 -2027. The area characterized by relatively low b-values (0.8-0.9) extends from central Groningen towards Appingedam and further in the southward direction. The area with highest activity rate densities is mostly concentrated in the central part of Groningen. There are areas with more moderate activity rate densities to the south-east and to the south. Based on the distributions of b-values and activity rate densities, zones of distinct characteristics of predicted seismic activity were identified to construct a seismic zonation model for the PSHA calculations. The zonation model consists of five zones with the indexes Z1, Z2, Z3, Z4 and Z5. Zone Z1 is characterized by having low b-values and the highest activity rate densities and will mostly contribute to the seismic hazard. Zone Z2 and Z3 still have low b-values, but the density of events is been reduced leading to a lower contribution to seismic hazard. The remaining two zones Z4 and Z5 have b-values above 1.3 and a low density of activity rates. These two latter zones will contribute very little to the seismic hazard.

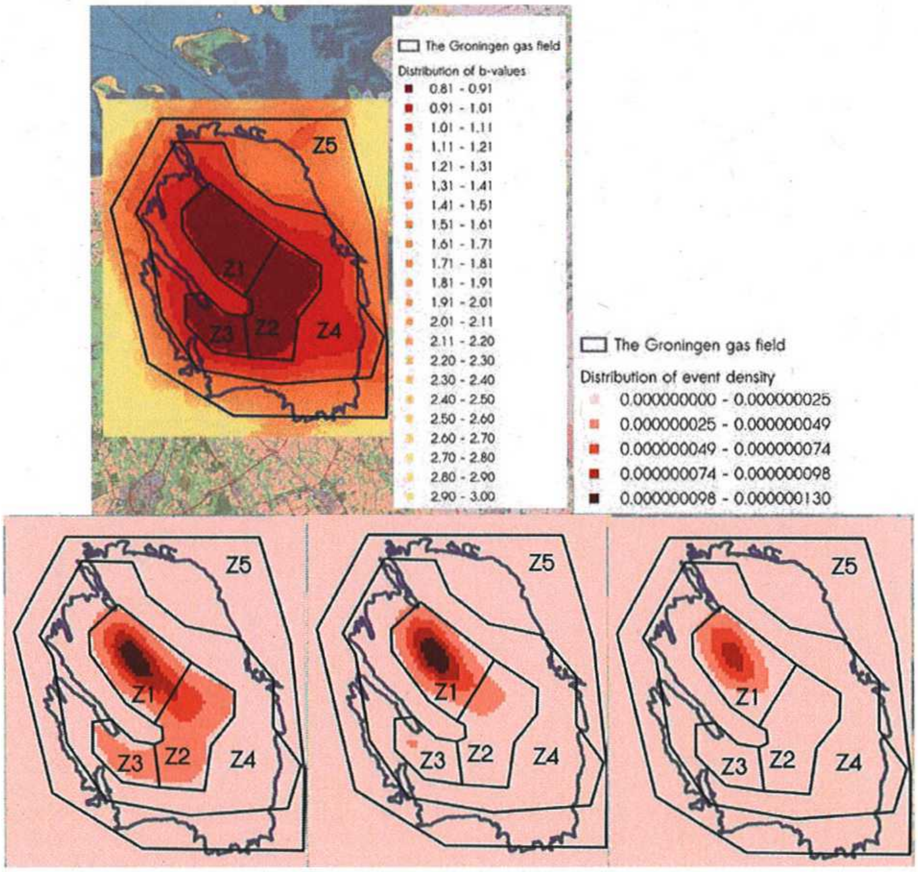

Figure 6: Lateral distribution of b-values for one production scenario (top) and activity rate density for three time periods for the cold winter scenario (lower three panels). The activity rate panels are from left to right: for 2019, 2022 and 2025. The zones in the zonation model are indexed Z1, Z2, Z3, Z4, Z5.

7. Seismic Hazard Assessment for Average, Cold and Warm Winters

The assessment of seismic hazard in Groningen based in the three winter scenarios in the next 10 years is presented in terms of PGA maps and site-specific spectra. With three winter scenarios and three time periods per winter type, we have nine production cases. For each production case, a set of one PGA map and the corresponding spectra is digitally available. Figure 7 shows a plot of the grid with site-specific spectra. There are 1567 locations with spectra on the grid.

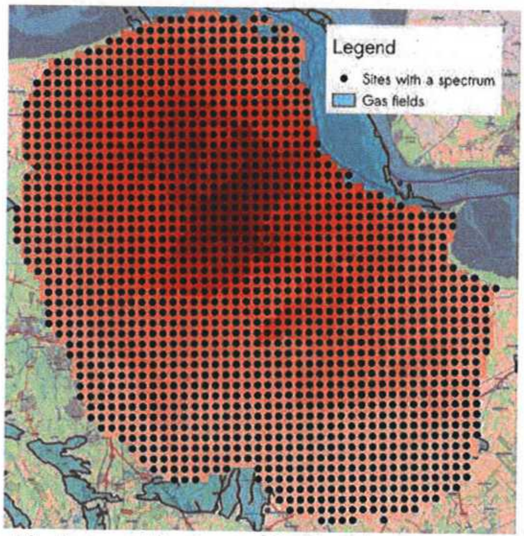

Figure 7: Locations with site-specific spectra for the three winter scenarios.

Evidently, a clear overview of results will be lost by showing all 1567 spectra for nine cases. Instead, we have selected five places in Groningen for which spectra are presented. The considered cities are Loppersum, Delfzijl, Ten Boer, Groningen city and Hoogezand, see Figure 8.

To give an overview of the variation of peak spectral accelerations (PSA) for the average, cold and warm winter scenarios for the following 10 years, we show for each of the locations the predicted hazard values for

- the average winter scenario between 2018-2020
- the cold winter scenario between 2020-2023
- the warm winter scenario between 2023-2027

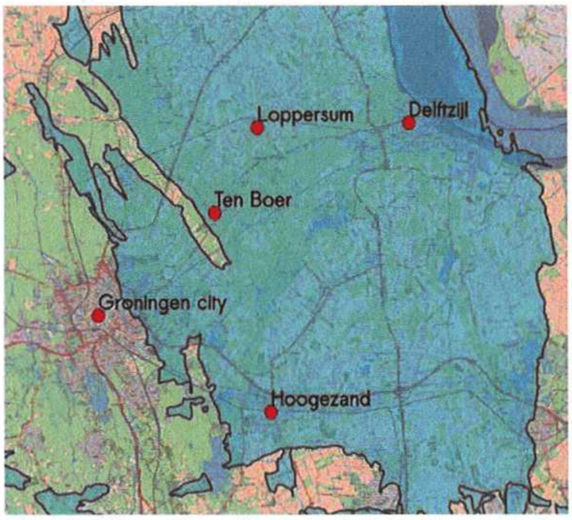

Figure 8: Locations for the illustration of spectra for the three winter scenarios.

These three cases are presented in the next subsections. The structure of plots is the same in the subsections. First the PGA map for the return period 475 y is shown, followed by the spectra for Loppersum, Delfzijl, Ten Boer, Groningen city and Hoogezand. Spectra are generated for the return periods 95 y, 475 y, 975 y and 2475 y which are digitally available, upon request. The KNMI spectra for the return period 475 y and 2475 y are shown with a thick light blue and brown line, respectively. For the latter return period, the site-specific hazard spectrum calculated by the KNMI is compared with the equivalent spectrum computed by NAM using a Monte Carlo method for a 2475 year return period , shown with a thin red line.

The GMM v4 spectra are available on a clickable map on the NEN webpage (http://seismischekrachten.nen.nl/webtool.php?lang=en). We have extracted the NEN spectra at the locations in Loppersum, Delfzijl, Ten Boer, Groningen city and Hoogezand for the return period 475 y and 2475 y. The NEN spectra inherent to GMM v4 are compared to the spectra calculated with the GMM v5 for the period 2018-2020 in this report. NEN spectra have mid-thickness purple and green line for the return period 475 y and 2475 y. The appendix contains the PGA maps for all nine production cases.

Seismic Hazard Assessment for the Average Winter Scenario between 2018-2020

The PGA map for the average winter scenario between 2018-2020 is given in Figure 9. Generally, the central area in Groningen is characterized by the highest hazard in the range of 0.1 to 0.15 g. The max PGA value (the location is indicated with the blue point) is 0.151 g. Seismic hazard decreases in the outer areas of Groningen.

For the time period 2018-2020, the seismic source model provides similar activity rates and b-values to the one used in the KNMI June 2017 hazard update for Groningen (KNMI, June 2017 report). GMM v4 was used to calculate the PGA map and spectra in the 2017 report. The PGA map based on GMM v4 for a similar seismic source model showed a max PGA of 0.22 g. This change is mainly due to reduced uncertainty in the GMM V5 model.

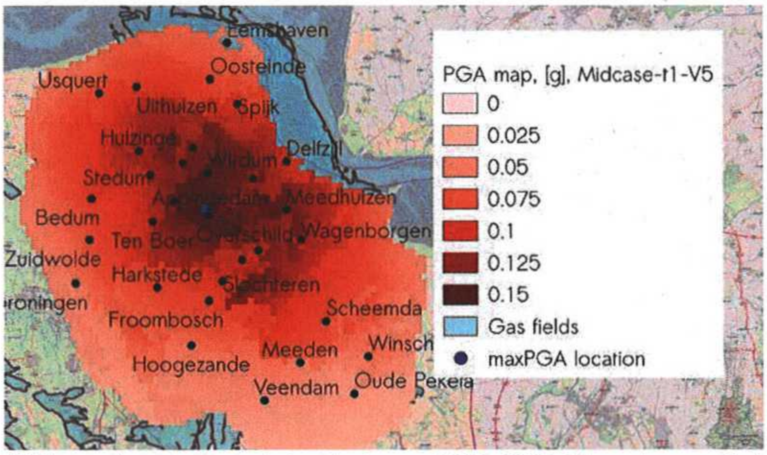

Figure 9: PGA map for average winters between 2018-2020. The return period is 475 y. The max PGA = 0.151 g.

In Figures 10 to 14, a comparison was made between the spectra for GMM V4 (NEN) and the spectra for GMM v5 calculated by the KNMI and NAM at the five cities mentioned above. An inspection of the figures shows that the hazard level of the spectra based on GMM v5 is considerably reduced compared to the NEN spectra obtained with GMM v4. For Loppersum, Ten Boer and Groningen city, the reduction in seismic hazard is almost 50 %, while for Delfzijl the reduction is less and for Hoogezand more. A rule of thumb in hazard analysis is a reduction in uncertainties in the GMM results in a lower hazard, unless the b-value is decreasing at the same time.

Comparison of the spectra for the return period 2475 y calculated by the KNMI and NAM shows a similar pattern for PSA values for all spectra periods between 0.01 s and 5 s. The maximum PSA values are found between 0.3 s to 0.5 s, and decrease rapidly from 0.5 s to 5 s. The seismic source model used by the KNMI is averaged over the specific time period, while NAM applies an annual source model in the hazard analysis.

The KNMI used a classical PSHA integration method and NAM a Monte Carlo method to solve the hazard integral. These different approaches may lead to minor differences in the calculated seismic hazard for the selected cities.

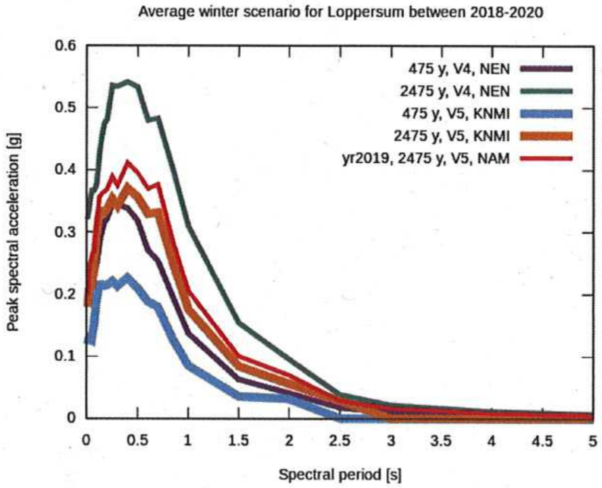

Figure 10: Comparison of spectra at Loppersum for the case of average winters between 2018-2020. The return period is 475 y and 2475 y.

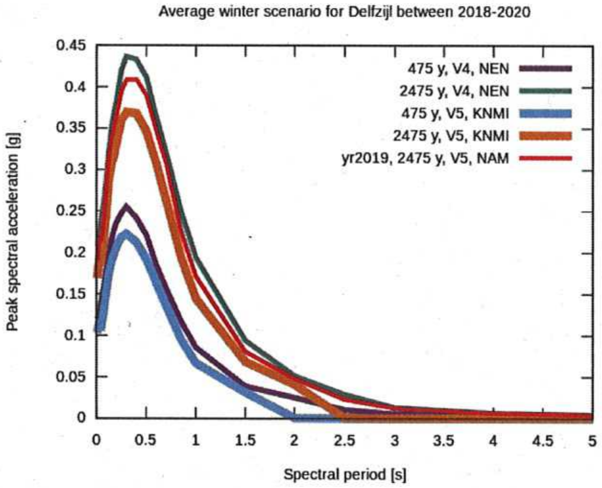

Figure 11: Comparison of spectra at Delfzijl for the case of average winters between 2018-2020. The return period is 475 y and 2475 y.

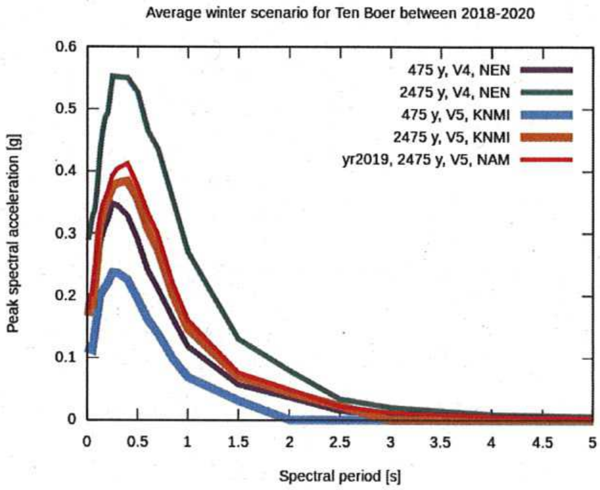

Figure 12: Comparison of spectra at Ten Boer for the case of average winters between 2018-2020. The return period is 475 y and 2475 y.

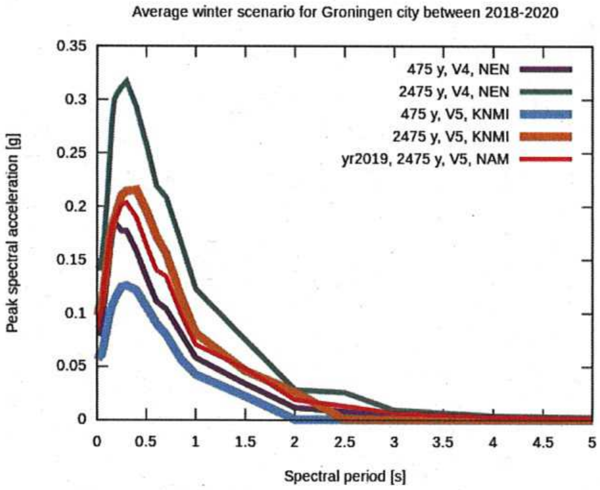

Figure 13: Comparison of spectra at Groningen city for the case of average winters between 2018-2020. The return period is 475 y and 2475 y.

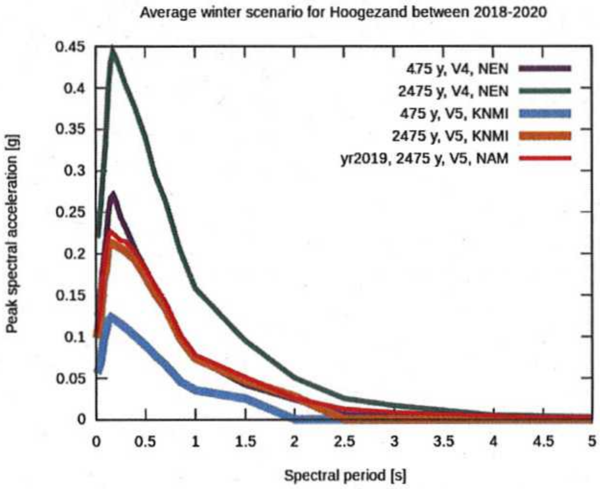

Figure 14: Comparison of spectra at Hoogezand for the case of average winters between 2018-2020. The return period is 475 y and 2475 y.

Seismic Hazard Assessment for the Cold Winter Scenario between 2020-2023

The next case to investigate is the cold winter scenario between 2020-2023. The average total activity rate for this scenario is slightly higher than the previous considered case. See Figure 5 for the development of activity rates between 2018 to 2027. The PGA map is presented in Figure 15. The Loppersum area still has the highest PGA values. The max PGA is 0.156 g and the location is unchanged compared to the PGA map in Figure 9.

The spectra for the cold winter scenario between 2020-2023 are given in Figures 16-20. This time, NEN spectra are no longer part of the plots because the hazard prediction is done for a time 5 years in the future compared to the seismic input for the NEN spectra. A comparison between KNMI and NAM spectra for the return period 2475 y in the five cities is still applicable. The spectra calculated by the KNMI and NAM have again similar characteristics and PSA values. The hazard level for the cold winter scenario between 2020-2023 and for the average winter case between 2018-2020 is more or less the same because the produced volumes of gas lead to similar activity rates and b-values.

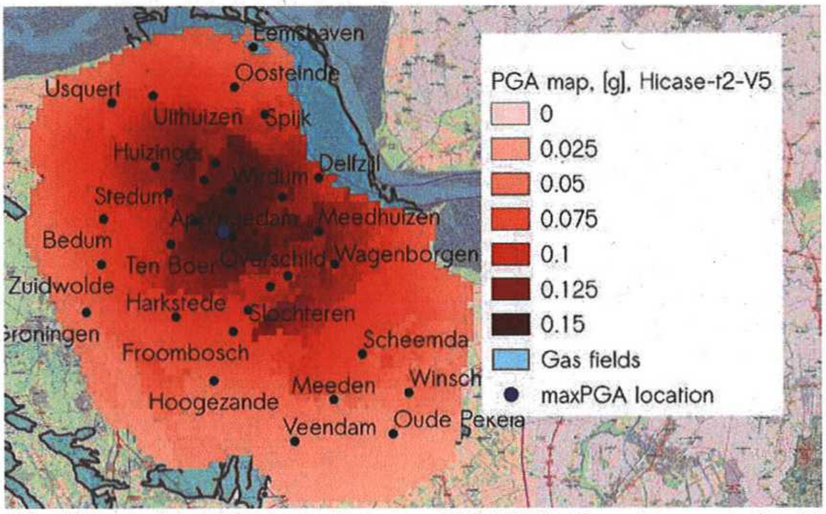

Figure 15: PGA map for cold winters between 2020-2023. The return period is 475 y. The max PGA = 0.156 g.

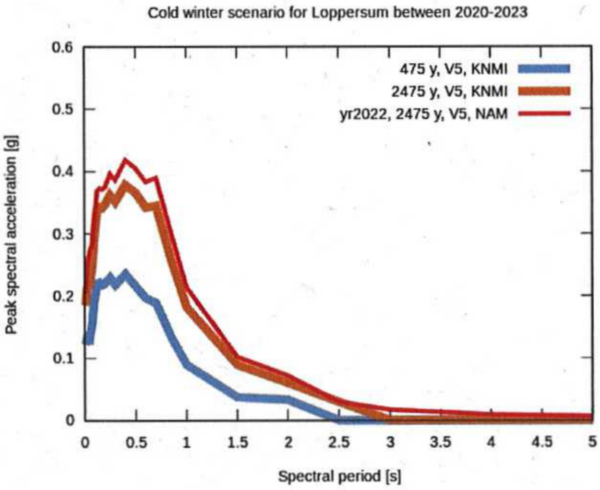

Figure 16: Comparison of spectra at Loppersum for the case of cold winters between 2020-2023. The return period is 475 y and 2475 y.

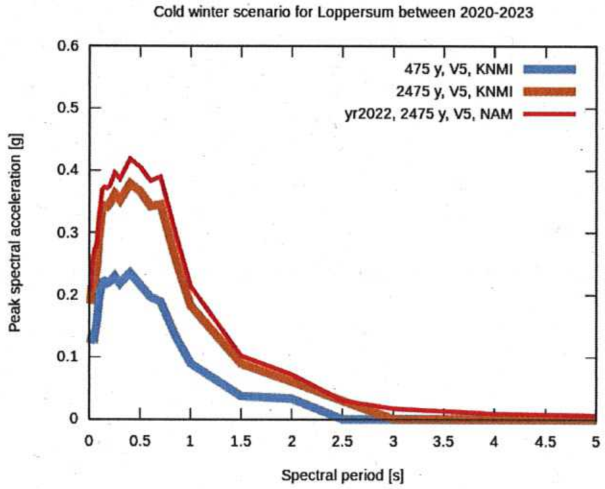

Figure 17: Comparison of spectra at Delfzijl for the case of cold winters between 2020-2023. The return period is 475 y and 2475 y.

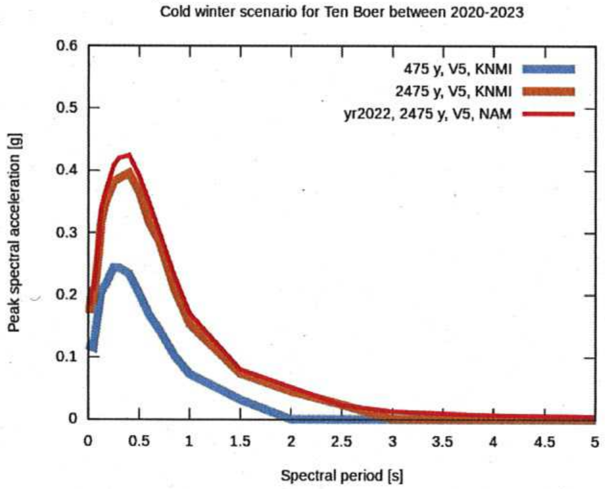

Figure 18: Comparison of spectra at Ten Boer for the case of cold winters between 2020-2023. The return period is 475 y and 2475 y.

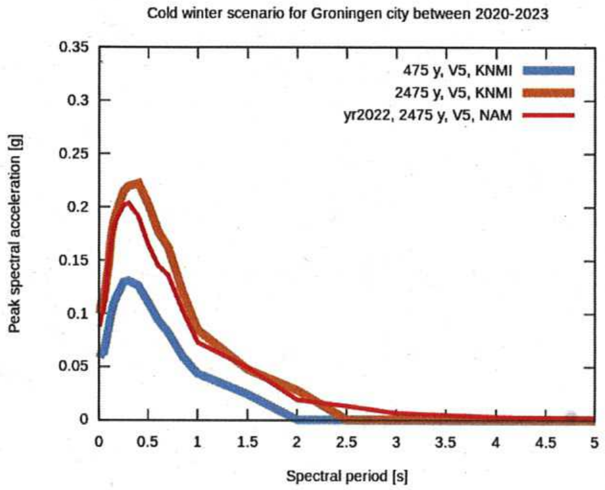

Figure 19: Comparison of spectra at Groningen city for the case of cold winters between 2020-2023. The return period is 475 y and 2475 y.

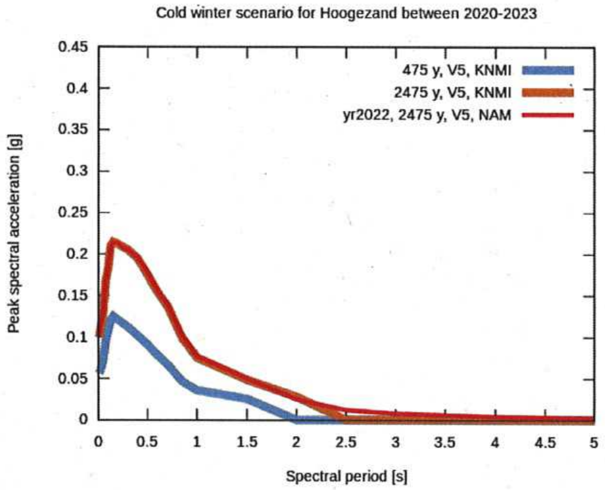

Figure 20: Comparison of spectra at Hoogezand for the case of cold winters between 2020-2023. The return period is 475 y and 2475 y.

Seismic Hazard Assessment for the Warm Winter Scenario between 2023-2027

The last case to look at is the warm winter scenario between 2023-2027. The average total activity rate for this scenario is about 5 events per year (M>1.5), while in the two previous cases it was in the order of 15 events per year, see Figure 5. The PGA map is presented in Figure 21. The colour scale is like in the two PGA maps in Figure 9 and 15 between 0 g and 0.15 g. The max PGA value is 0.115 g in the PGA map in this subsection due to the reduced number of events per year. The Loppersum area has the highest hazard level, and the max PGA location has moved slightly to the north.

Figures 22-26 present the spectra for the warm winter scenario between 2023-2027. No NEN spectra are added to the graphics. The KNMI and NAM spectra for the return period 2475 y are again quite similar in pattern and PSA values at the five cities. The hazard level in the spectra for the return period 475 and 2475 y is reduced compared to the presented spectra for both the average winter scenario between 2018-2020 and cold winter scenario between 2020-2023.

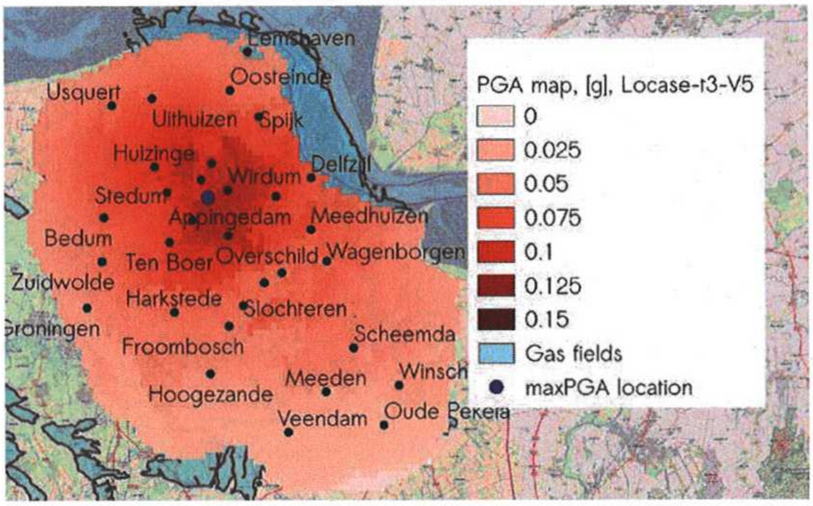

Figure 21: PGA map for warm winters between 2023-2027. The return period is 475 y. The max PGA = 0.115 g.

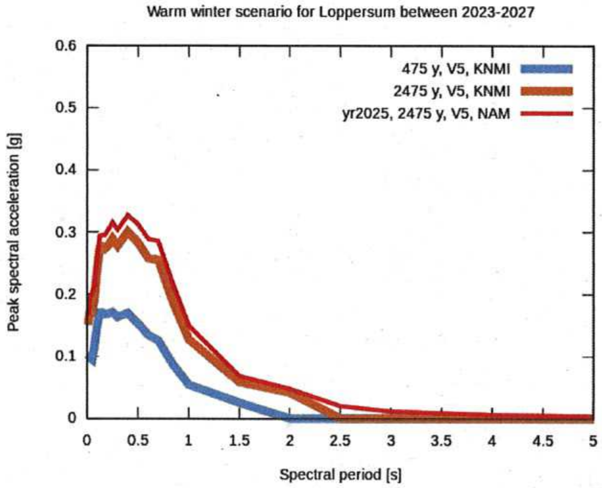

Figure 22: Comparison of spectra at Loppersum for the case of warm winters between 2023-2027. The return period is 475 y and 2475 y.

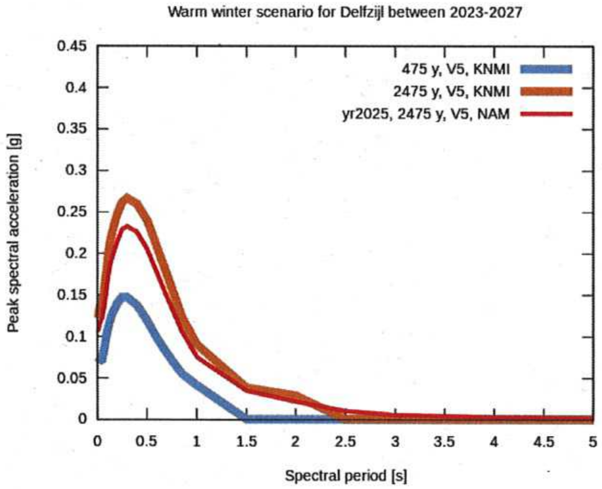

Figure 23: Comparison of spectra at Delfzijl for the case of warm winters between 2023-2027. The return period is 475 y and 2475 y.

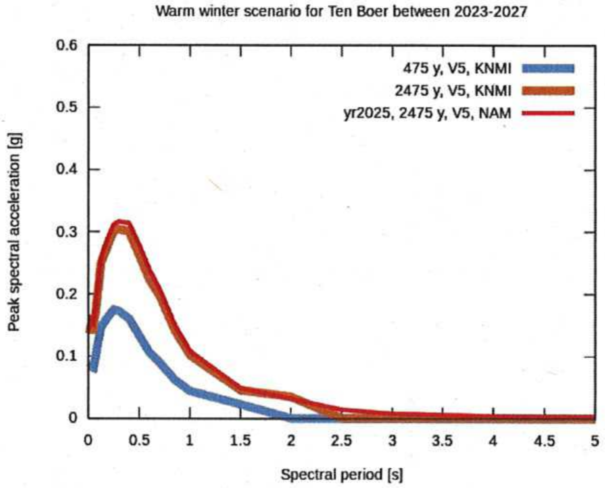

Figure 24: Comparison of spectra at Ten Boer for the case of warm winters between 2023-2027. The return period is 475 y and 2475 y.

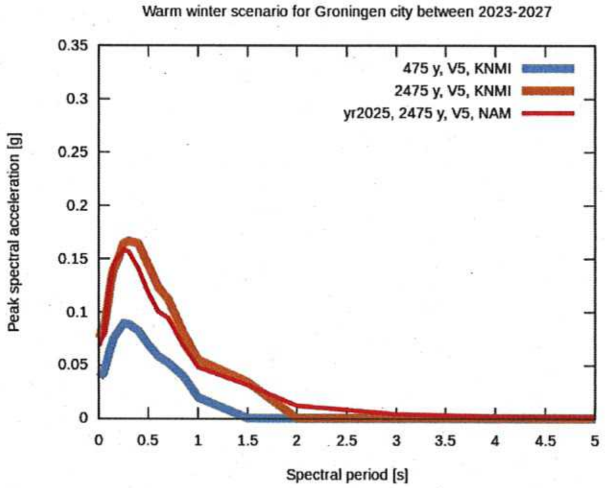

Figure 25: Comparison of spectra at Groningen city for the case of warm winters between 2023-2027. The return period is 475 y and 2475 y.

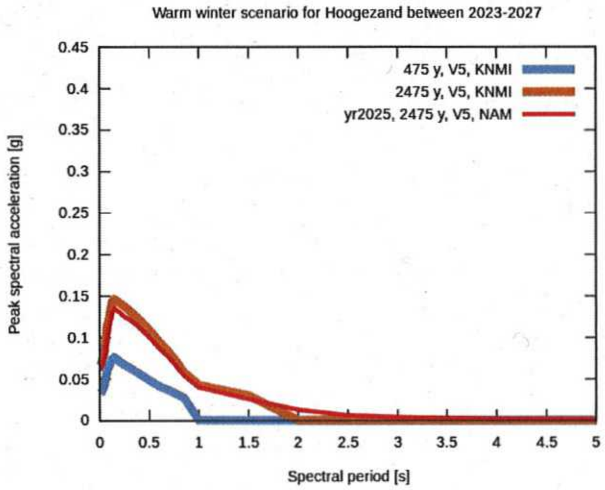

Figure 26: Comparison of spectra at Hoogezand for the case of warm winters between 2023-2027. The return period is 475 y and 2475 y.

8. Conclusions

A seismic hazard assessment for three gas production scenarios for the time period 2018-2027 has been carried out for the Groningen gas field. The production scenarios take into account the variation of warm, average and cold winters where the demand for gas in the Netherlands varies accordingly. Seismic source models were extracted from the production scenarios by NAM and delivered to the KNMI. The source models characterizing the influence of gas extraction from the Groningen gas field on the induced seismicity show lateral and temporal variations. The most active seismic area is in the Loppersum area for all times. However as the extraction of gas is reduced, the expected number of events per year decreases. In between 2018 and 2020, the annual activity rate is around 15 to 18 (M>1.5) for average to cold winters. In the final year of the investigated period, 2027, the annual activity rate is 4 for the warm winter scenario.

The seismic hazard analysis based on the production scenarios generates the typical hazard results such as PGA maps and site-specific spectra with peak spectral accelerations. The most recent GMM v5 is applied in the hazard analysis. The production scenario based PGA maps predicts max PGA values in the order of 0.15-0.16 g in the first years of the produced gas reduction. In the final years of the production plan for the warm winter scenario, the max PGA value is 0.12 g. The PGA map in the KNMI hazard update on June 2017 for a similar seismic source model predicted a max PGA of 0.22 g.

A similar conclusion is made for the spectra calculated for the production scenarios. A comparison with the NEN spectra as published in July 2017 for Groningen was carried out for the return periods 475 y and 2475 y. The reduction in peak spectral accelerations was generally 50%. At some locations, a smaller reduction was observed, while at other sites in Groningen is the hazard level was diminished even more.

The calculated spectra have been compared with the equivalent spectra calculated by NAM for the return period 2475y. For the five cities used for comparison in this report, the KNMI and NAM spectra are very similar. The main difference between the KNMI approach and the NAM method is in the method of calculation, specifically the way the hazard integral is solved. The comparison of KNMI and NAM spectra shows that the respective methods are producing stable results.

Acknowledgements

We are grateful for the support of Olaf Tuinder (KNMI), who made it possible to complete the calculations of spectra for all nine production scenarios on the KNMI network over a short period of time.

9. References

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Appendix: PGA maps

The appendix contains the PGA maps for the return period 475 y for the three scenarios and three time periods, in total nine maps. The max PGA values are indicated with three instead of two decimals in order to better show the variability of the seismic hazard for the different cases.

PGA maps for average winters:

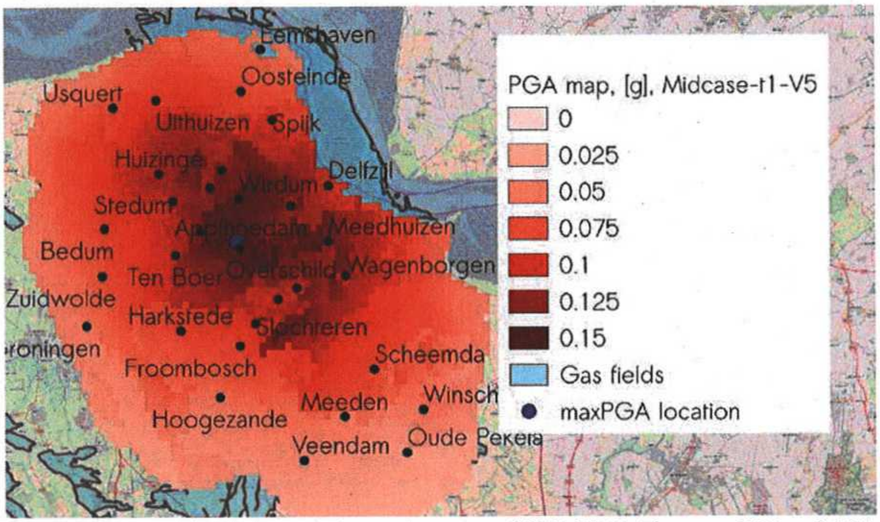

Figure A1: PGA map for average winters between 2018-2020. The max PGA = 0.151 g.

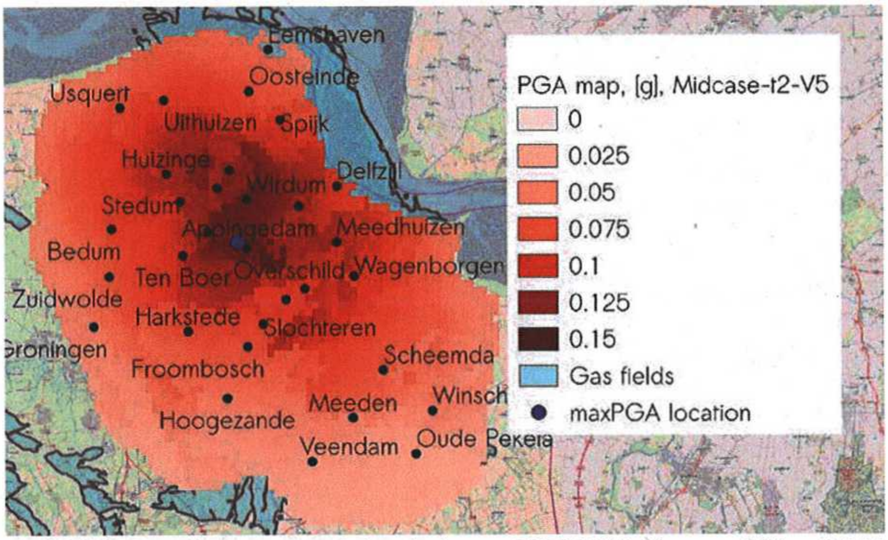

Figure A2: PGA map for average winters between 2020-2023. The max PGA = 0.144 g.

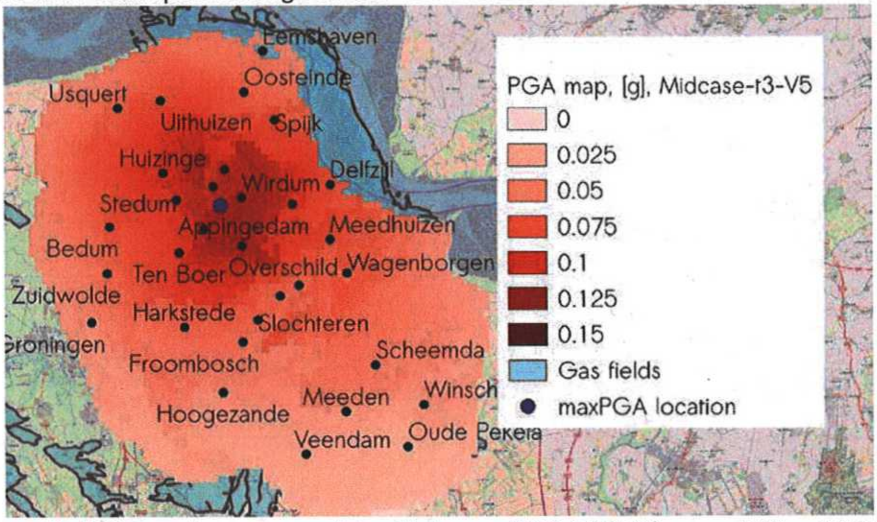

Figure A3: PGA map for average winters between 2023-2027. The max PGA = 0.121 g.

PGA maps for cold winters:

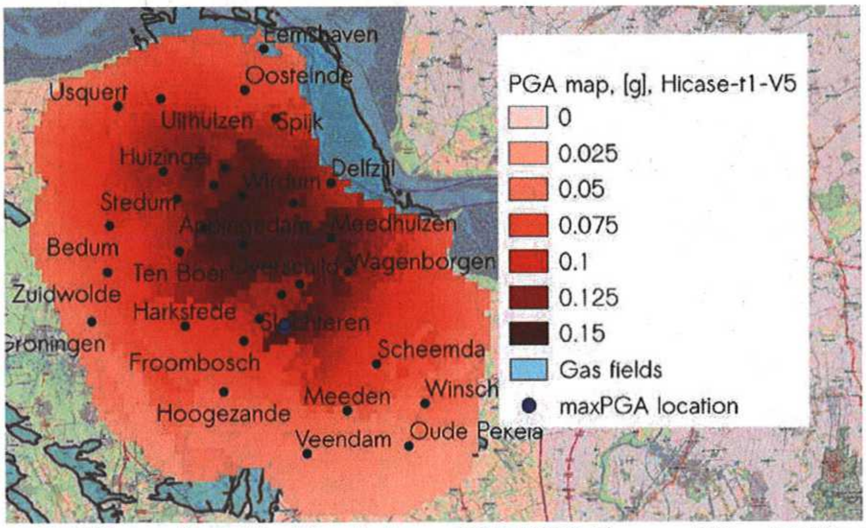

Figure A4: PGA map for cold winters between 2018-2020. The max PGA = 0.165 g.

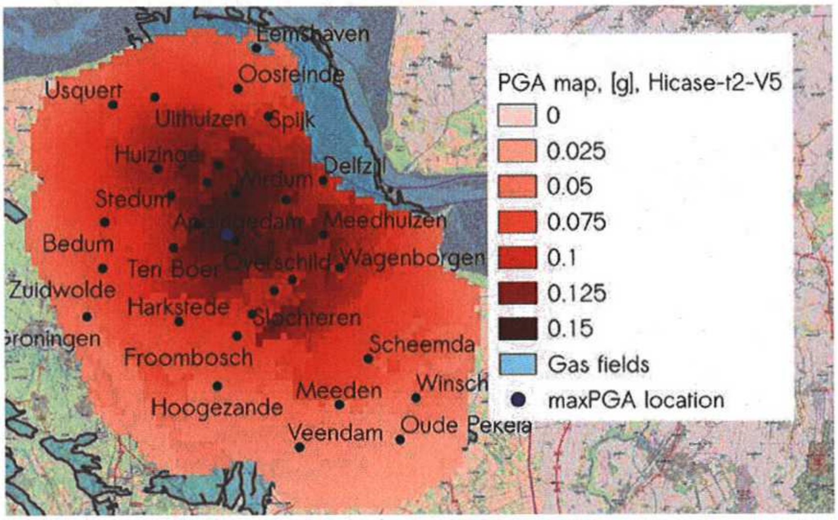

Figure A5: PGA map for cold winters between 2020-2023. The max PGA = 0.156 g.

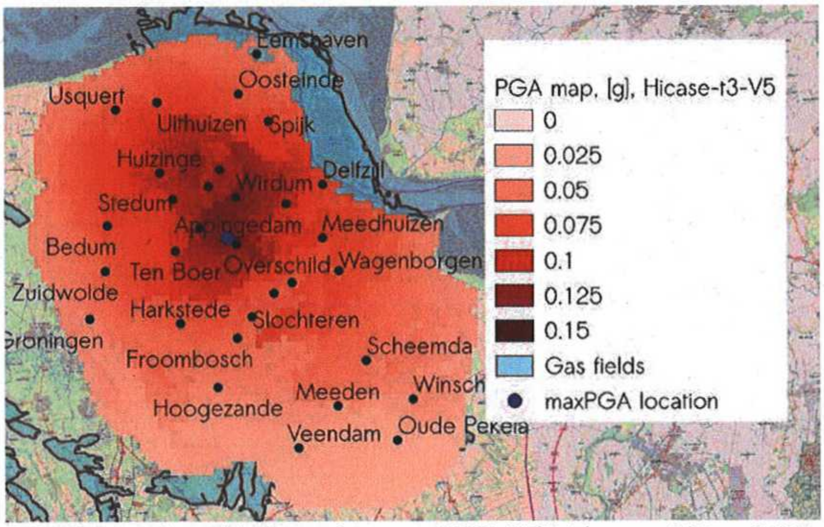

Figure A6: PGA map for cold winters between 2023-2027. The max PGA = 0.135 g.

PGA maps for warm winters:

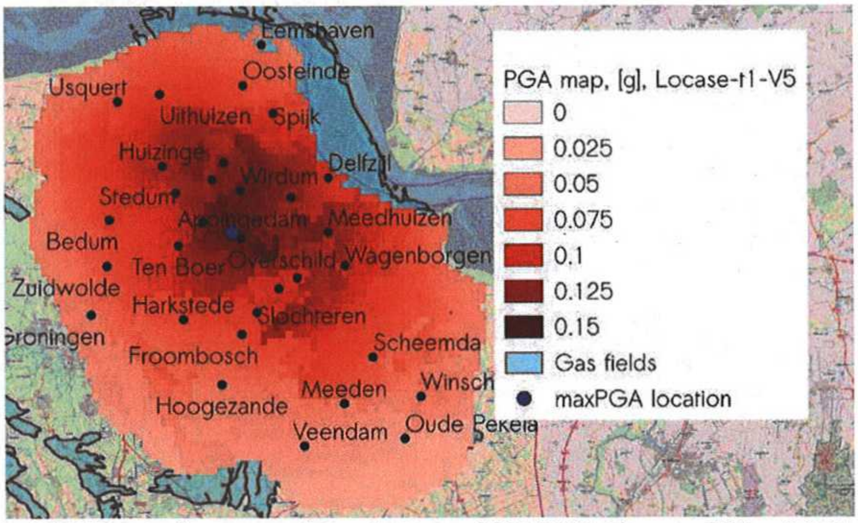

Figure A7: PGA map for warm winters between 2018-2020. The max PGA = 0.146 g.

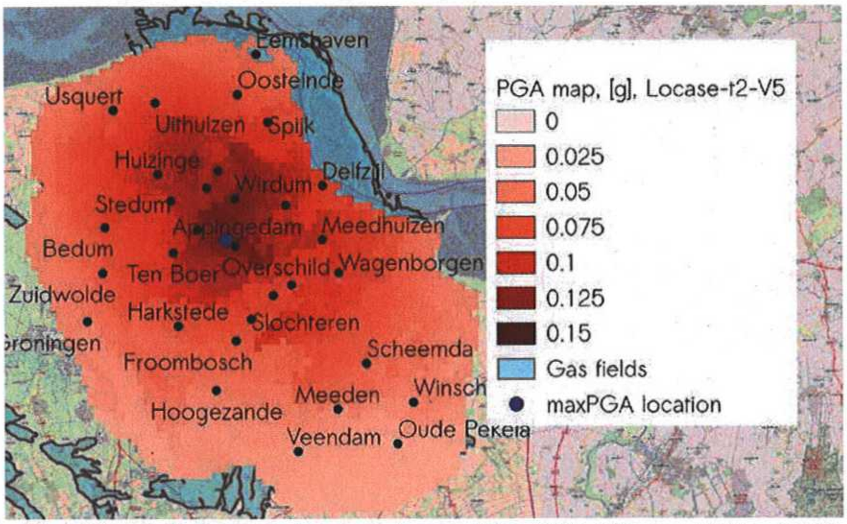

Figure A8: PGA map for warm winters between 2020-2023. The max PGA = 0.136 g.

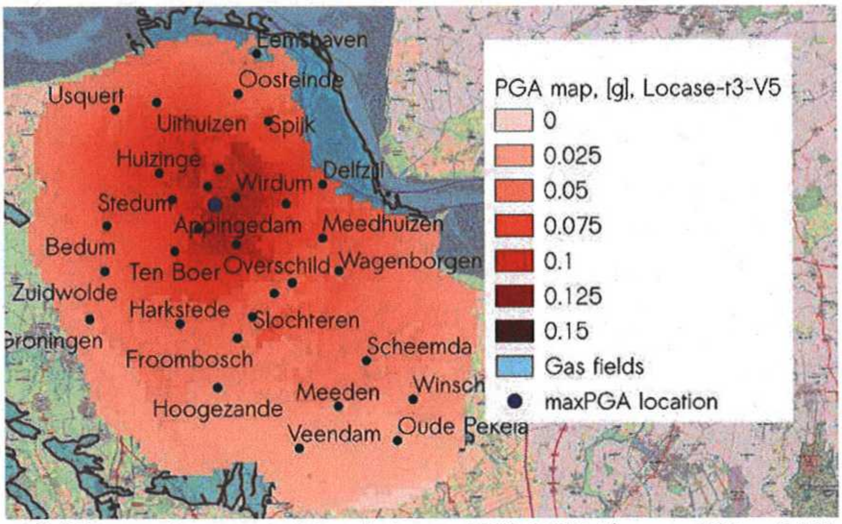

Figure A9: PGA map for warm winters between 2023-2027. The max PGA = 0.115 g.