# Probabilistic Seismic Hazard Analysis for Induced Earthquakes in Groningen, Update June 2017

Jesper Spetzler and Bernard Dost
KNMI, de Bilt

## Introduction

This report presents the results of a new Probabilistic Seismic Hazard Assessment (PSHA) for induced seismicity in Groningen, resulting in the KNMI v4 hazard model. This is an update of the KNMI v2 hazard model, as described in Spetzler and Dost (2016). New developments over the last year include the further development of the Ground Motion Prediction Equation (GMPE) for Groningen, now called Ground Motion Model (GMM), by addition of new data and improving the methodology. The latest version for the Groningen GMM is v4 (Bommer et al., 2017b) and is used in the update of the hazard map and spectra.  Similar to the previous update, comparisons between KNMI and NAM results are discussed, both using the same GMM.

The GMM v4 model is constructed in much the same way as the v2 model, which was used in Spetzler and Dost (2016). Both models share a lateral varying site response model using non-linear site amplification functions (Bommer et al., 2015). The depth of the reference horizon changed from 350m in v2 to 800m in v4, where a strong contrast between the bottom of the North Sea Group and Chalk Group (Van Dalfsen et al., 2006) has been identified. In addition, the zonation of the near-surface geology has been modified in the latest GMM and the calculation of the amplification due to laterally varying site effects improved. These modifications with respect to v2 were introduced in the intermediate v3 version (Bommer et al., 2017a). In v4 the Groningen region is divided into 160 zones with similar site response characteristics. The strong motion data base increased from 146 records in 2016 to 178 records in 2017.

A new feature in the GMM v4 model is the introduction of extended fault rupture calculations. In previous versions earthquakes have been modelled as point sources. This modification required the introduction of a new distance metric: the rupture distance, defined as the shortest distance between the site and fault rupture. In addition a  magnitude– and rupture distance dependent amplification factor was introduced. This added complexity in the description of near-surface effects required a generalization of the PSHA method applied in Spetzler and Dost (2016). Epistemic uncertainty is incorporated in the GMMs in the form of a logic tree. The v4 model has four branches, replacing the three branches in previous versions, corresponding to different stress-drop models. Also, the range of spectral periods has been fine-tuned in v4 ,the number of spectral periods increased from 16 to 23 and an additional PGV component is included.

We will present an update of the non-stationary seismicity in Groningen and discuss the parameters derived from it and used as input in the PSHA method. We adopted the outcome of the expert panel on $M_{max}$ for Groningen (Bommer and van Elk, 2017), which is presented as a distribution of most probable values for this parameter for Groningen and based on expert judgement. We show and discuss the influence on the hazard results of a fixed $M_{max}$=5 value and the suggested $M_{max}$ distribution. Next, the implementation of the v4 hazard model is discussed. A new PGA hazard map and spectra at five selected locations in province of Groningen are presented for a 475 year return period, equivalent to a 10% probability of exceedance in 50 years, and a 2475 year return period. Since the spectra are location dependent, the model is made available on internet in the form of a clickable map.

## Characteristics of seismicity in Groningen

The PSHA calculations require a characterization of the seismic activity in the area of interest, usually in terms of spatial variation assuming a stationary process. This leads to a proposed seismic zonation for the region. Each zone is characterized by two parameters: 1] activity rate and 2] b-value, the slope of the linear part of the frequency-magnitude (FM) curve. Since seismicity in the region is non-stationary, an estimate of both parameters will be based on a chosen time frame in which the activity is assumed to be approximately stationary. Activity rate is defined in this report as the annual amount of events at or larger than the magnitude of completeness, which is estimated for Groningen at Mc= 1.5.

*Temporal distribution*

Figure 1 shows the temporal development of seismic activity for events with a magnitude greater than $M_L$=1.5 until May 31st, 2017. The activity rate was fairly constant in 2014 and 2015, between 20 and 25 events per year. For 2016, the annual activity rate in Groningen decreased to 13 events. For the first 6 months of 2017, the number of events is 8. In previous updates a time frame of 5 years was selected to estimate activity rate and b-values. This time frame was chosen as a compromise between a short duration to capture changes in seismicity due to production changes and the availability of a dataset large enough to calculate statistical parameters. In the current update this period could be lowered to 3 years (2014-2017). Since early 2014 production changes were made, this period will better sample the effects of these changes on seismicity.

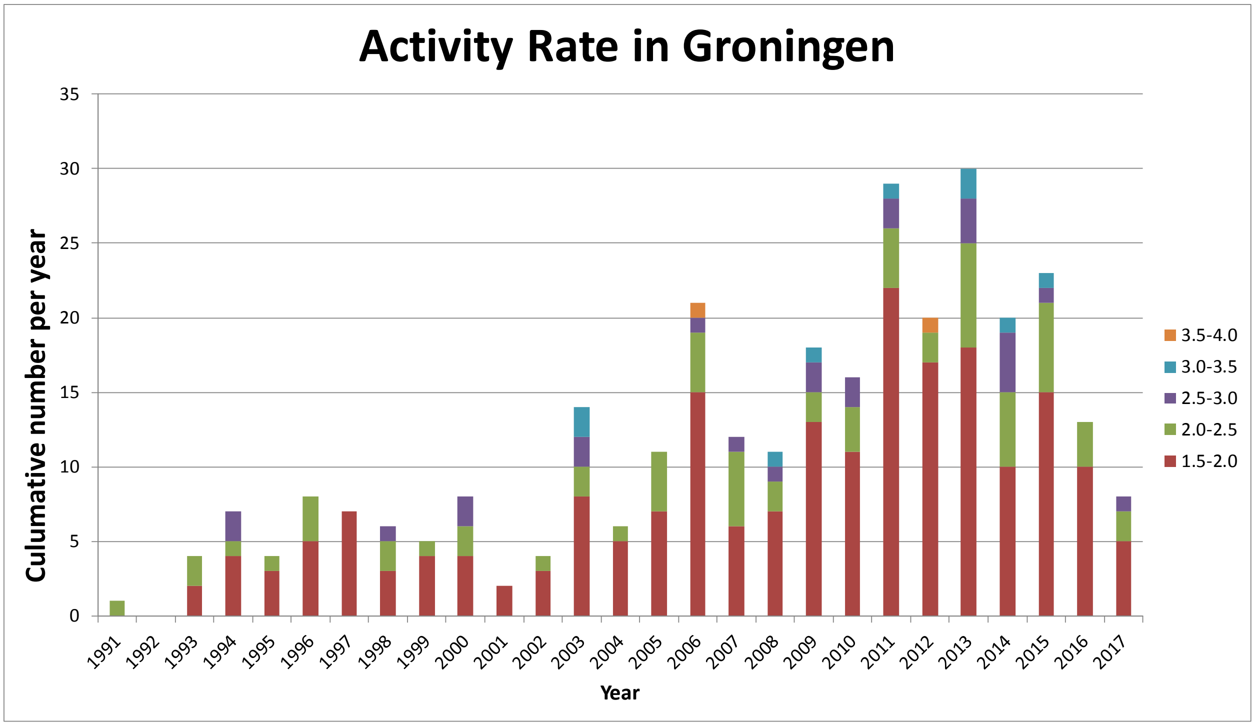


*Figure 1: Activity rate of observed induced earthquakes in Groningen over the years. Only events with a magnitude greater than 1.5 are used in the KNMI earthquake catalog. The graph is valid for the time period until June 14, 2017.*

In 1995 a regional borehole network was installed to monitor induced seismicity in the north of the Netherlands. The magnitude of completeness (Mc) for the region was calculated at $M_L$=1.5. Recently the new borehole network for Groningen became operational and this lowered the Mc for Groningen (Dost et al., 2017). This effect is taken into account in the present study when estimating hazard parameters.

*Spatial distribution*

The spatial distribution of induced earthquakes in Groningen for the period 2014-2017 is shown in Figure 2. Since a decision was made to evaluate seismicity after the production change early 2014, only this dataset is taken into account

Evaluation of the seismicity in the period 2014-2017 shows a continuation of the activity in the central north and central south zones. The latter zone could even be extended to the north west and north east, but it is unclear if this is a temporary or a persistent feature. Therefore, it was decided to keep the same shape of the zones as in the previous update. The active- and background area in the zonation for the hazard analysis in 2016 have been merged together to form one larger zone named active area. There was no reason to make this division based on the observed seismicity patterns.

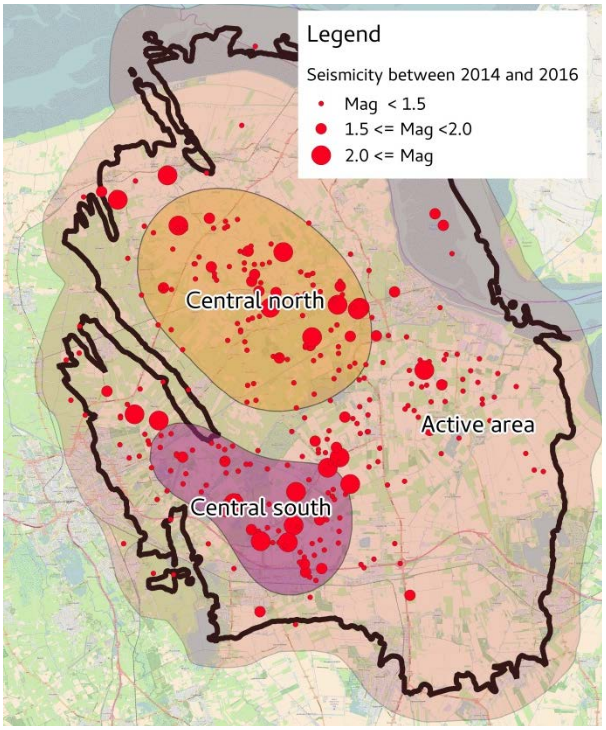


*Figure 2: Distribution of induced earthquakes in Groningen between January 2014 and January 2017 and the corresponding zonation.*

An update of the seismic borehole network started in 2014, therefore a decrease in the magnitude of completeness (Mc) was expected in the selected time frame. It was decided to calculate both Mc, activity rate and b-values for the three zones. The maximum curvature method (Wiemer and Wyss, 2000) was used to calculate Mc and the b-value was calculated using the maximum likelihood estimator derived by Tinti and Mulargia (1987). Since small magnitudes are used, a correction on the local magnitude was required (Deichmann, 2017). This correction was derived from an empirical relation between $M_w$ and $M_L$: $M_w = 0.056262*M_L^2 + 0.655528*M_L + 0.496753$ (Dost and Edwards, in prep.) and is valid for $0.5<M_L<2.6$.

The seismological hazard parameters for the new zonation are summarized in Table 1. An important difference with respect to the 2016 update is the b-value for both the central north and central south. A modest increase in b-value for the central north zone from 0.8 to 0.9 and a similar decrease in the central south zone from 1.0 to 0.9 is observed. Activity rate shows a decrease in the central north zone and an increase in the central south zone, although its influence on the hazard is less than the change in b-value. As expected, the magnitude of completeness in all zones drops to values at and below $M_L$= 1.0, allowing the use of a larger database for this time period to estimate hazard parameters compared to Spetzler and Dost (2016). Although the b-values are calculated based on seismicity for magnitudes larger than the magnitude of completeness, activity rate in table 1 is specified for Mc=1.5, the lowest magnitude taken into account in the hazard calculations.

*Table 1: Seismological hazard parameters for the three zones in the zonation.*

| Zone | Central north | Central south | Active area |
|---|---|---|---|
| b-value | 0.9 | 0.9 | 1.1 |
| activity rate (events/yr) | 7.9 | 5.8 | 8.8 |
| Mc | 0.8 | 0.9 | 1.0 |
| Surface area [$km^2$] | 167 | 90 | 1079 |

*Maximum Magnitude*

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, the GMM v4 is 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 |

**Hazard model**

Similar to the results presented in the previous report (Spetzler and Dost, 2016), the method by Cornell (1968) was used to calculate the PSHA. However, a more general hazard integral is required due to the newly introduced magnitude-distance dependence in the near-surface amplification factor.

The hazard model v4 is still a two-step approach as introduced in Spetzler and Dost (2016) and illustrated in Figure 3. In general terms, 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, which has been moved to a strong interface contrast at 800 m in v4. 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. However, in v4 the amplification factor has a magnitude and distance dependence. Consequently, the site specific hazard at the surface is calculated in a general convolution integral where the contribution of the probability distributions of magnitudes, distances, amplification factor and ground motion are summed up (Bob Young, pers. comm.). The calculation of the generalized hazard integral is much more cpu intensive compared to the v2 implementation. Therefore, a network distributor system has been used at KNMI to carry out the computations of spectra for the v4 hazard update, sharing the workload between multiple computers. The computation time of one site-specific spectrum on a desktop computer, with two cores in use, is about 6-10 minutes, depending on the site location in Groningen.

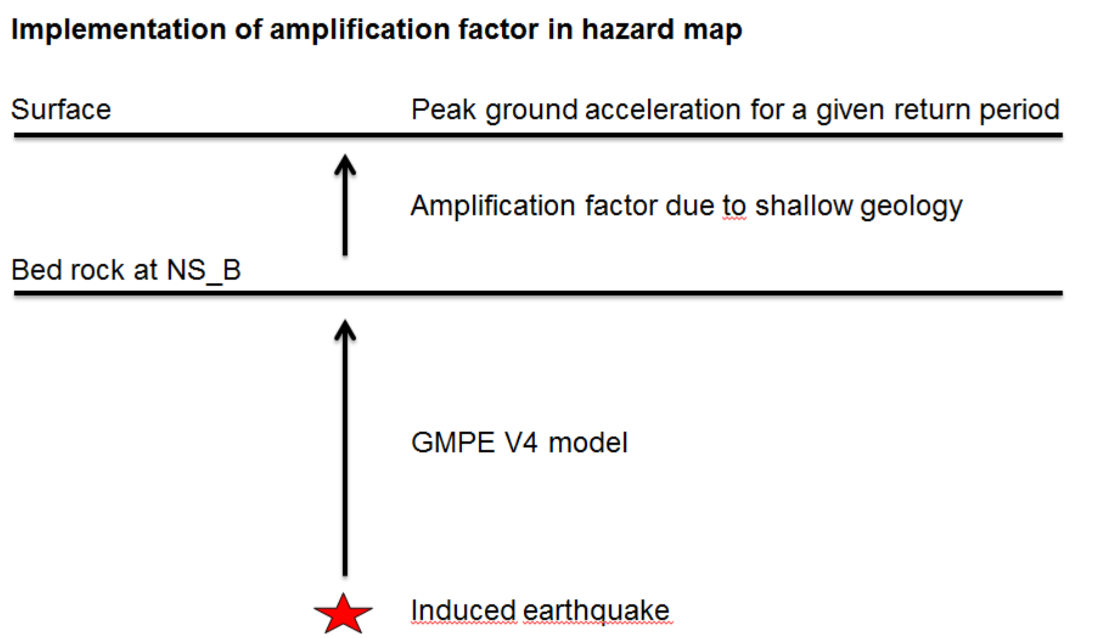


*Figure 3: Illustration of methodology in the hazard v4 model. The bedrock is at the bottom of the North Sea layer.*

In GMM v4 rupture distance is introduced. To correctly apply the rupture distance the location of active faults and their extension should be known. Although the general fault structure in Groningen is well-known, it is not completely evident to snap events to specific faults. As a consequence, we are still using a point-source approach in the current hazard model and the implication is a possible underestimation of the hazard. In the NAM model a Monte Carlo method is used, including an implementation of extended faults. The influence of the implementation of extended faults on the hazard is evaluated by comparing results from both models for Groningen.

*Ground Motion Model*:

Most important new features of the v4 model with respect to v2 are the introduction of extended fault ruptures, the transfer of the reference level from 350 to 800m depth, an extension of number of spectral periods from 16 to 23, improving the sampling of the period range between 0.01 to 5s and the addition of a PGV component. The stress-drop models have been modified to capture the epistemic uncertainty, resulting in eight alternative models. In addition, the zonation for the amplification factor due to the shallow geology structure has been modified. Figure 4 shows the mean Vs30 values in Groningen in the latest zonation. The number of zones with areas of similar near-surface properties decreased from 167 in v2, through 161 in v3 (Kruiver et al., 2017) to 160 in v4 (Bommer et al., 2017b). With the largest shear-wave velocities in the south, this part of Groningen is less affected by seismic amplification compared to the north.

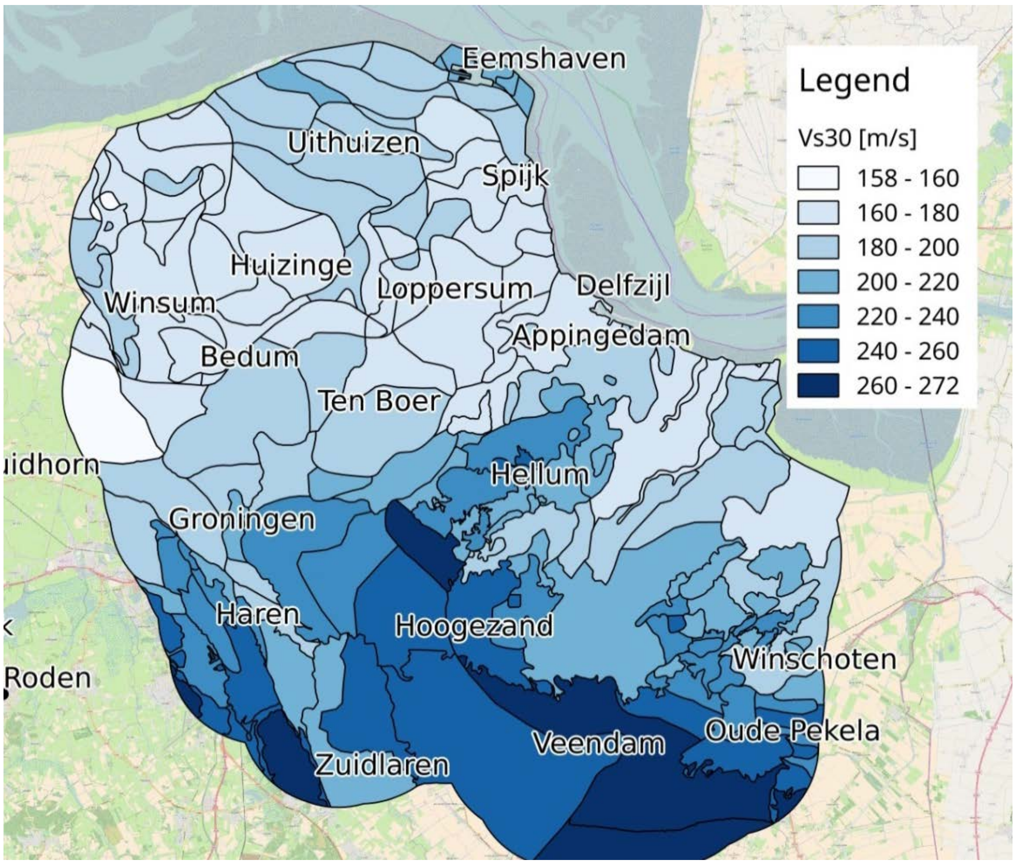


*Figure 4: Geological zones and shear wave velocities in the shallow subsurface (Kruiver et al., 2017).*

It should be noted that the GMM is calibrated for M=2.5 and above, while in the KNMI hazard calculations also lower magnitudes are included (1.5<M<2.5). Although events in this category will only have a minor effect on the hazard, the GMM is most probably conservative.

Since the measured accelerations at the surface are still small (< 1 m/s$^2$), non-linear behavior of the upper layers is not yet observed. However, this effect should be taken into account in the hazard analysis because much larger magnitude earthquakes are considered than recorded thus far. Bommer et al. (2015) used an Equivalent Linear (EQL) approach based on Random Vibration Theory (RVT) to model the non-linear behavior and discussed at length (chapter 8) the difference with the fully non-linear approach. Based on a literature review it was concluded that RVT based EQL can be regarded a conservative estimate.

## Results

The new PGA hazard map, calculated using GMM v4 at a return period of 475 y is presented in Figure 5. The maximum PGA values are 0.24 g or 2.4 m/s$^2$. The larger PGA values (0.22-0.24g) are located near Ten Boer and between Hoogezand and Hellum. East of Ten Boer an artificial high PGA feature is observed at the location of the "Schildmeer" lake. Areas with PGA values lower that 0.05 g are located at the wide boundaries around the Groningen field. Table 3 gives a summary of the most important parameters used in the PSHA calculations.

*Table 3: Hazard parameters applied in this study.*

| Hazard model | Return period | GMM weights for the 4 stress-drop models | Activity rate model |
|---|---|---|---|
| v4 | 475 y | (0.1, 0.3, 0.3,0.3) | KNMI zonation based on observed induced earthquakes, 22.5 events/year (M≥ 1.5) |

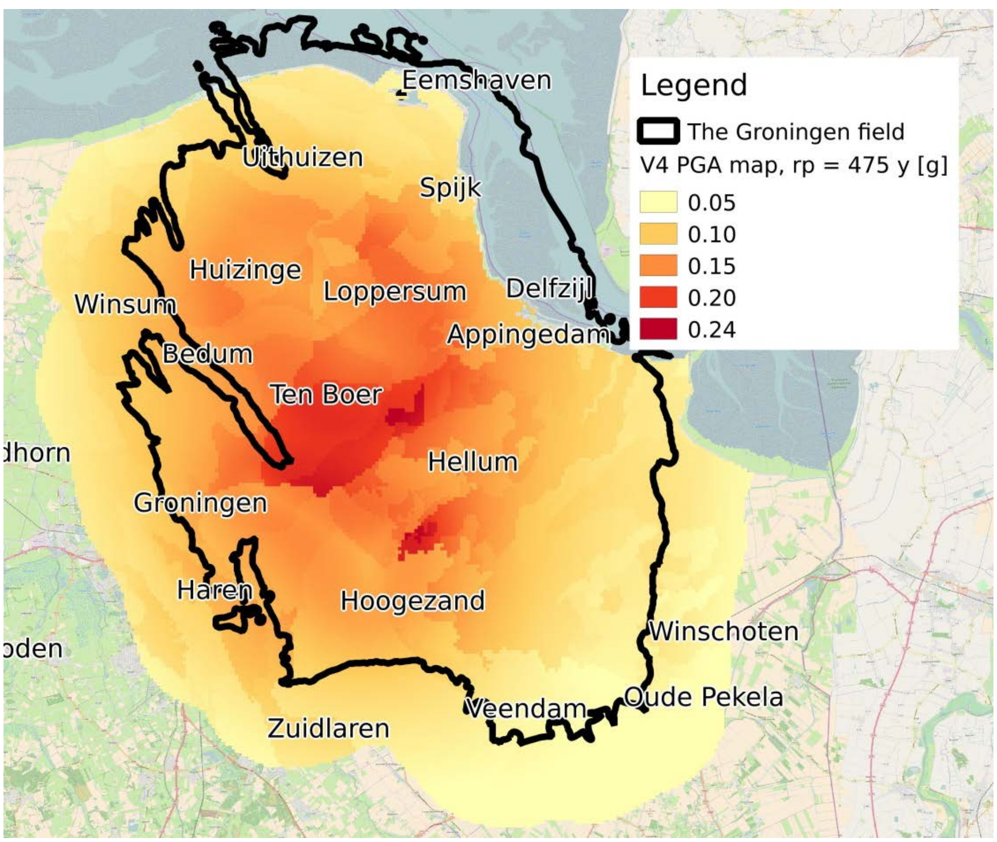


*Figure 5: Probabilistic seismic hazard map for Groningen for the period T = 0.01 s. The return period is 475 y according to Eurocode 8. The maximum PGA is 0.24g. The black solid line indicates the boundary of the Groningen gas field.*

For a comparison between the PGA map for the v4 and v2 hazard model, the difference map is shown in Figure 6. A shift in hazard is observed from decrease in the north to an increase in the southern part of the field. These differences are partly explained by the update of the seismological source model, mainly due to small changes in b-value and to a lesser extend in activity rate. In addition improvement in the site effect estimation also contributed to this change in hazard pattern. The maximum PGA value on the map is 0.24g, which is approximately at the same level of the 2016 update, which was 0.22g.

For comparison with earlier PSHA results, the hazard maps for the v0, v1 and v2 models are presented in the appendix.

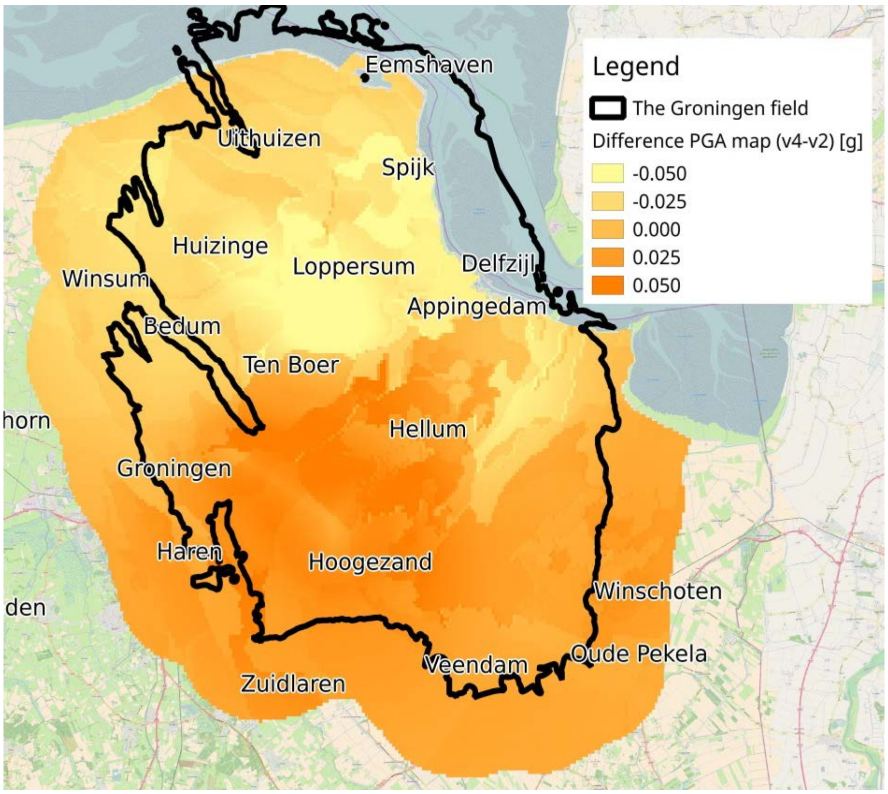


*Figure 6: Difference PGA map between the v4 PGA hazard map in Figure 5 and the v2 PGA hazard map in Spetzler and Dost (2016). The black solid line indicates the boundary of the Groningen gas field.*

The PGA map is useful to illustrate how the spatial distribution of hazard is changing. However, PGA is equivalent to the Spectral Acceleration (SA) at 0.01s and the total form of the spectra [0.01 to 5 s] is of interest to risk and safety estimations and for building engineers. Starting with GMM v2, spectral acceleration is location dependent and cannot be presented as one universal hazard spectrum for the entire field. The site-specific spectra are available through a clickable map on the KNMI website ( http://rdsa.knmi.nl/hazard/ ). Results are available for four return periods: 95 year, 475 year, 975 year and 2475 year.

A screen shot of the clickable map for the four spectra at a location in Groningen city is shown in Figure 7. Data selected from the clickable map can also be downloaded in different formats.

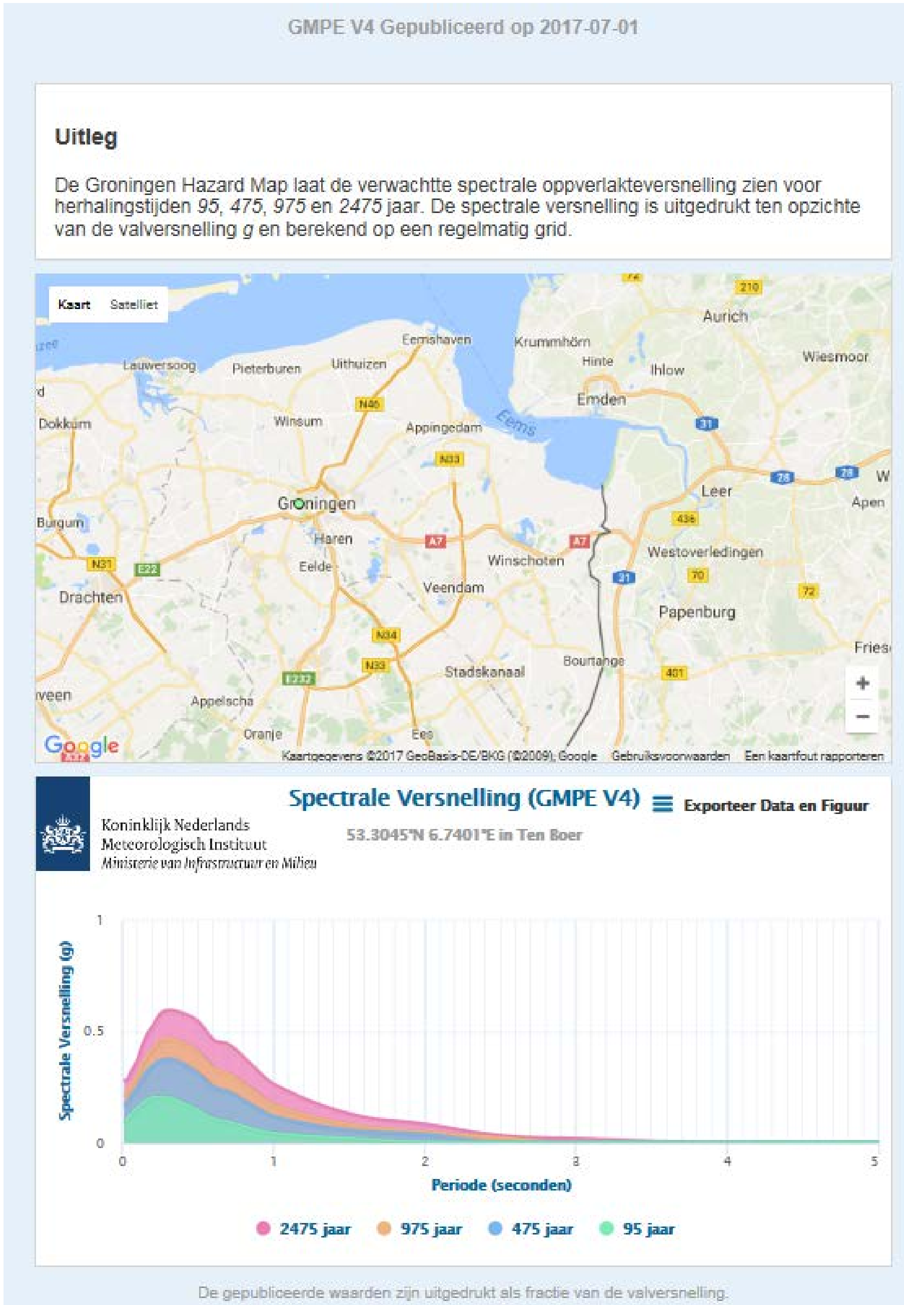


*Figure 7: Screen shot of the KNMI website for the clickable map with spectra for the GMM v4 model for Groningen.*

Finally, we present a comparison of Spectral Accelerations calculated by the KNMI and NAM at five locations in Groningen. The five locations are Groningen City (coordinates: X: 234.120; Y: 582.057), Delfzijl (coordinates: X: 256.684; Y: 594.883), Loppersum (coordinates: X: 245.598; Y: 594.788), Ten Boer (coordinates: X: 242.561; Y: 588.795) and Hoogezand (coordinates: X: 246.421; Y: 575.974). The coordinates in km are given in Dutch coordinate system (Rijksdriehoekstelsel). See Figure 8 for the selected locations in the province of Groningen.

Spectral accelerations at the selected locations are presented in Figure 9-13. In each plot, three curves are shown. Two calculated by the KNMI: one for $M_{max}$ = 5 and the other for the proposed $M_{max}$ distribution. These curves are compared with results from the NAM (pers. comm.), computed for a production scenario of 24 bcm and the proposed $M_{max}$ distribution. Two return periods are selected: 475 year, as proposed by Eurocode 8, and the longest period assessed: 2475 year.

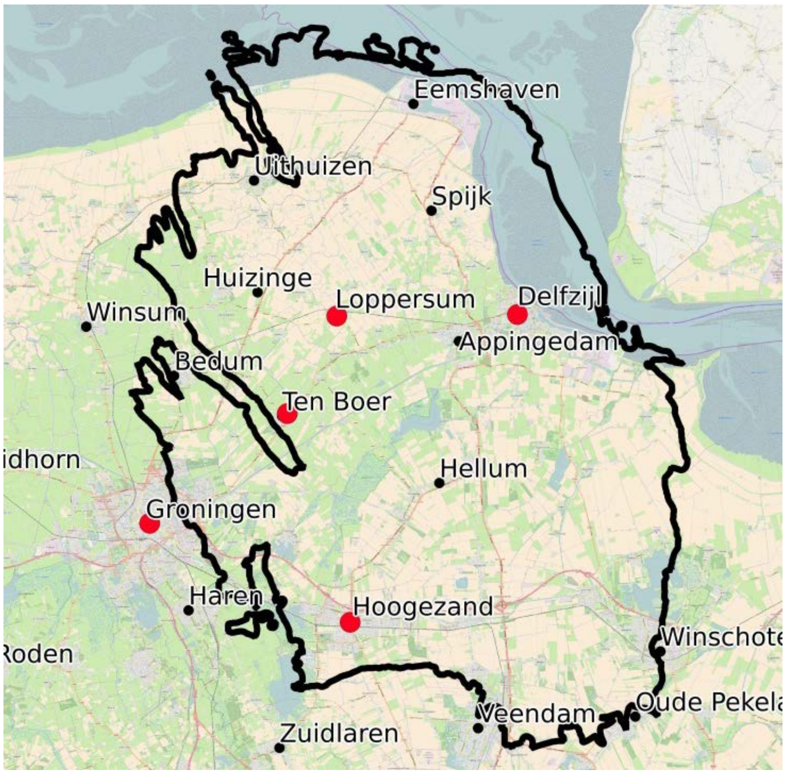


*Figure 8: Locations (red points) for the site-specific analysis in Loppersum, Delfzijl, Ten Boer, Groningen city and Hoogezand. The boundary of the Groningen field is indicated with the black line.*

The spectra calculated by KNMI and NAM are similar in shape and amplitude for the shorter and longer return period at the locations Delfzijl, Groningen and Ten Boer. The KNMI model has higher hazard levels for Hoogezand and smaller levels near Loppersum. This trend is consistent with the update of the seismological source model. Comparison of calculations using the 2016 source model combined with GMM v4 with calculations using the 2017 model combined with the same GMM show the same trends and corroborate the conclusion that the difference is due to the source model.

The differences between the spectra calculated using the $M_{max}$ distribution and the $M_{max}$= 5 scenario are also small, as expected for these return periods. Deaggragation shows that the main contribution at these return periods is from events of magnitude between 4.5 and 5.5. In general it can be observed that the longer periods (> 1s) and larger return periods (2475 year) are more effected by the $M_{max}$ distribution.

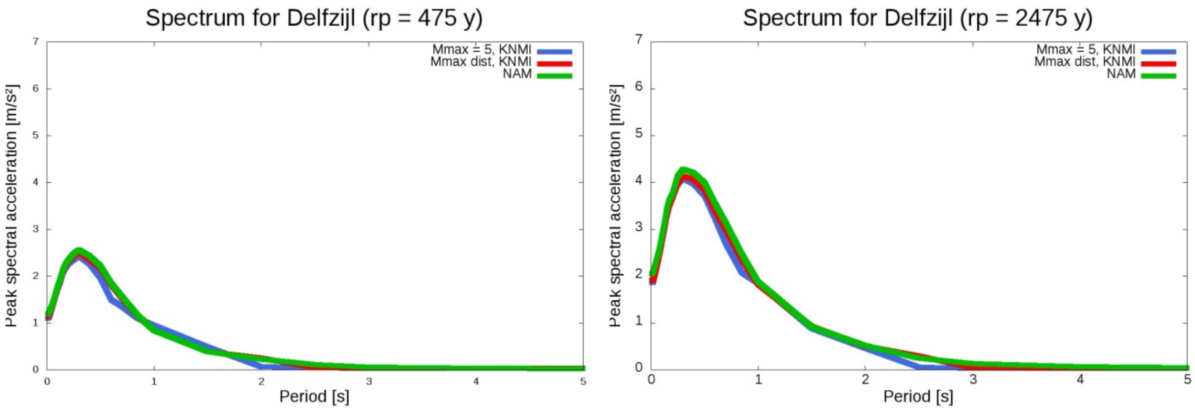


*Figure 9: Comparison of spectra in Delfzijl. The return period is 475 y and 2475 y.*

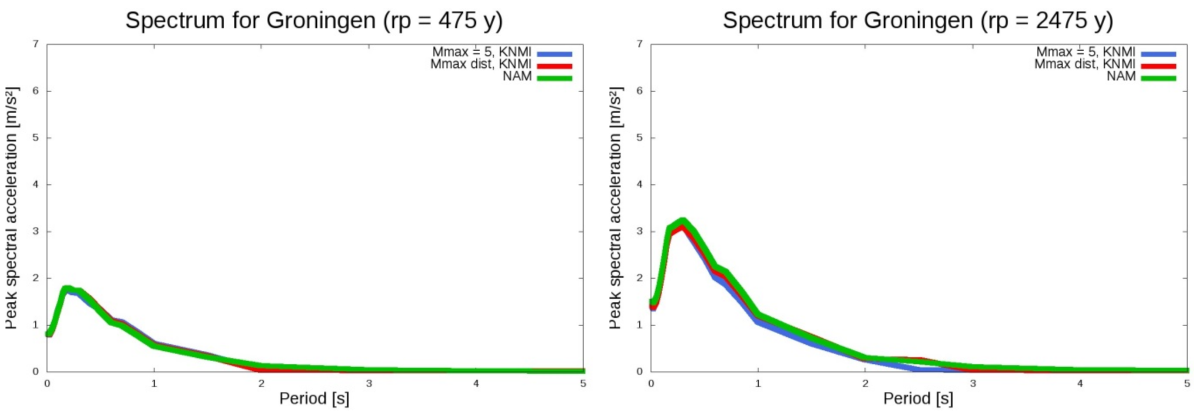


*Figure 10: Comparison of spectra in Groningen city. The return period is 475 y and 2475 y.*

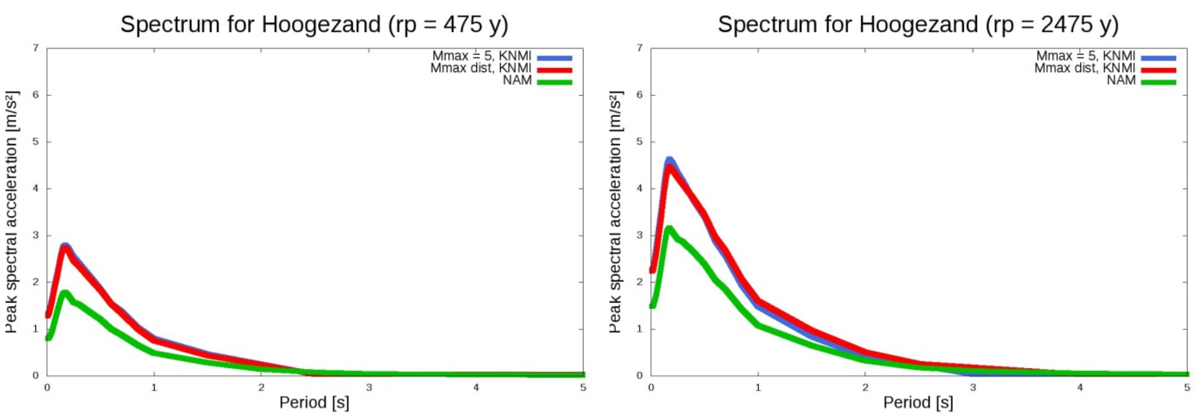


*Figure 11: Comparison of spectra in Hoogezand. The return period is 475 y and 2475 y.*

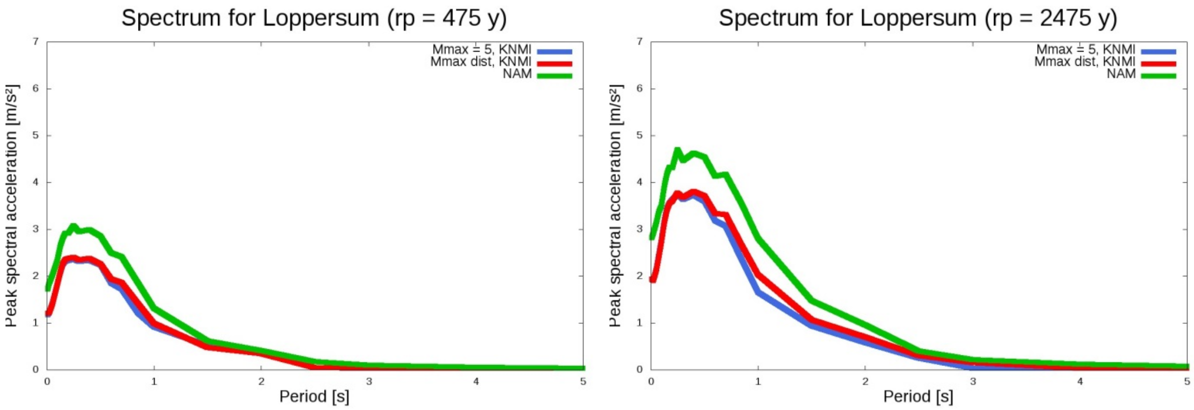


*Figure 12: Comparison of spectra in Loppersum. The return period is 475 y and 2475 y.*

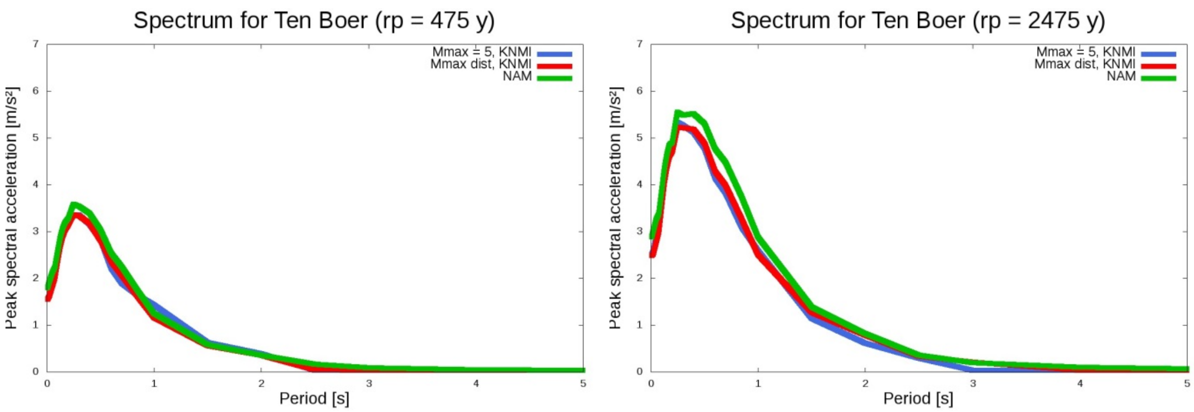


*Figure 13: Comparison of spectra in Ten Boer. The return period is 475 y and 2475 y.*

## Discussion and conclusions

A new version of the hazard map for Groningen is presented, motivated by an important update of the GMM (v4) for induced seismicity in the region. The main features of the latest update are the selection of a new reference level, the introduction of extended fault rupture and an improvement of the site-effect model. In addition, the sampling of the period range at which spectral acceleration is evaluated improved. The maximum PGA value in the hazard map did not change significantly with respect to the previous update (2016), namely from 0.22g to 0.24g. The introduction of a new model for $M_{max}$ , based on expert judgement and in the form of a $M_{max}$ distribution, did not significantly influence the presented results.

A qualitative comparison with the implementation of GMM v4 by NAM for a 24 bcm scenario (pers. comm.) shows a good correspondence. This finding gives a confirmation that the PSHA results for Groningen are robust. The differences in the hazard models of KNMI and NAM can mainly be explained by the differences in their source model and to a lesser extend in the method to calculate the hazard.

Further development of the GMM is not expected to bring major changes. The new monitoring network is in operation and will provide new data that can be used to improve our understanding of the processes at depth. Outstanding questions include the implementation of extended fault geometries for Groningen

The KNMI hazard model based on the v1 version of the GMM was used by the NPR committee of the NEN in their national guideline (NPR-9998:2015). It was limited to the PGA map (spectral accelerations at 0.01s). An adjustment was made to include non-linear site response. The current model includes both the spectral acceleration at relevant periods and non-linear site effects and is recommended to be used in the upgrade of the NPR.

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**Appendix**

The hazard maps for the v0 and v1 model developed by the KNMI in the past years are shown in this appendix. For details about the hazard analysis previously carried out, we refer to Dost and Spetzler (2015). The hazard parameters for each respective map are repeated in a table before the hazard map is presented.

| Hazard model | Return period | GMPE weights | Activity rate model |
|---|---|---|---|
| v0 | 475 y | Only one GMPE | KNMI zonation based on observed induced earthquakes, 40 events/year |

*Table A1: Hazard parameters applied in the v0 hazard model.*

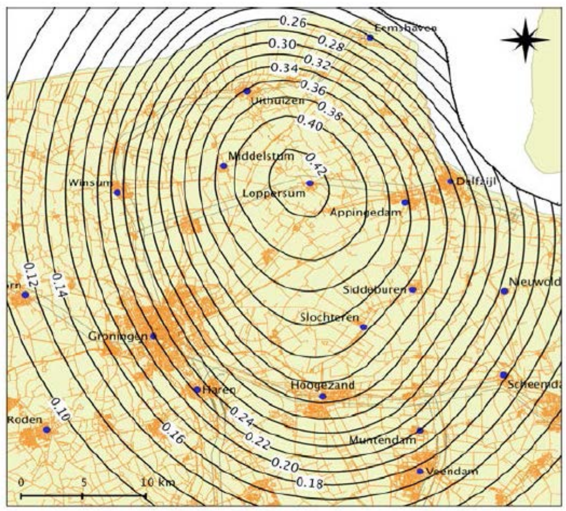


*Figure A1: v0 Hazard model. The hazard map for Groningen for the period T = 0.01 s. The maximum PGA is 0.42 g.*

| Hazard model | Return period | GMPE weights | Activity rate model |
|---|---|---|---|
| v1 | 475 y | (0.3, 0.5, 0.2) | KNMI zonation based on observed induced earthquakes, 22.8 events/year |

*Table A2: Hazard parameters applied in the v1 hazard model.*

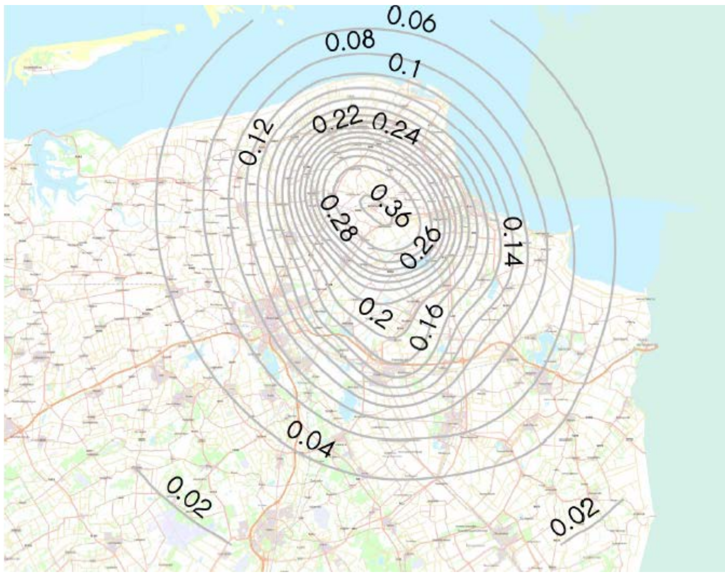


*Figure A2: v1 Hazard model. The hazard map for Groningen for the period T = 0.01 s. The maximum PGA is 0.36 g.*

| Hazard model | Return period | GMPE weights | Activity rate model |
|---|---|---|---|
| v2 | 475 y | (0, 0.5, 0.5) | KNMI zonation based on observed induced earthquakes, 22.8 events/year |

*Table A3: Hazard parameters applied in the v2 hazard model.*

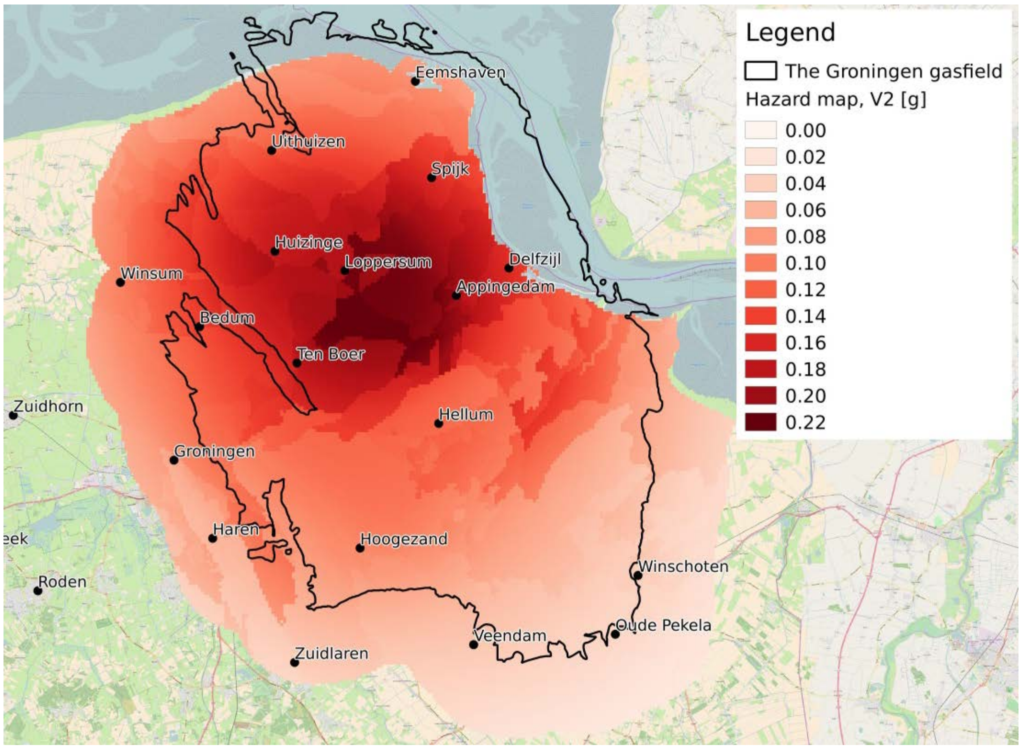


*Figure A3: v2 probabilistic seismic hazard map for Groningen for the period T = 0.01 s. The return period is 475 y according to Eurocode 8, the maximum PGA is 0.22 g. The black solid line indicates the borders of the Groningen gas field.*