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Enclosure(s)

Yours sincerely,

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Update 2018 Shakemaps for "Maximum Considered Earthquake" Scenario in Groningen

A report prepared for the National Coordination of Groningen

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1. Introduction

The Royal Netherlands Meteorological Institute (KNMI) presents an update of the shakemaps analysis for industry areas in Groningen. The latest Ground Motion Model (GMM) v5 is used in the new shakemaps calculations. GMM v5 replaces GMM v4 which was used in the shakemaps report update 2017 (Spetzler et al. 2017, KNMI report). The five main industry areas under investigation are in Delfzijl, Eemshaven, Hoogezand, Veendam and Winschoten where the latter is a new addition to the shakemaps analysis of industry areas in Groningen. The five locations with industry are shown in Figure 1.

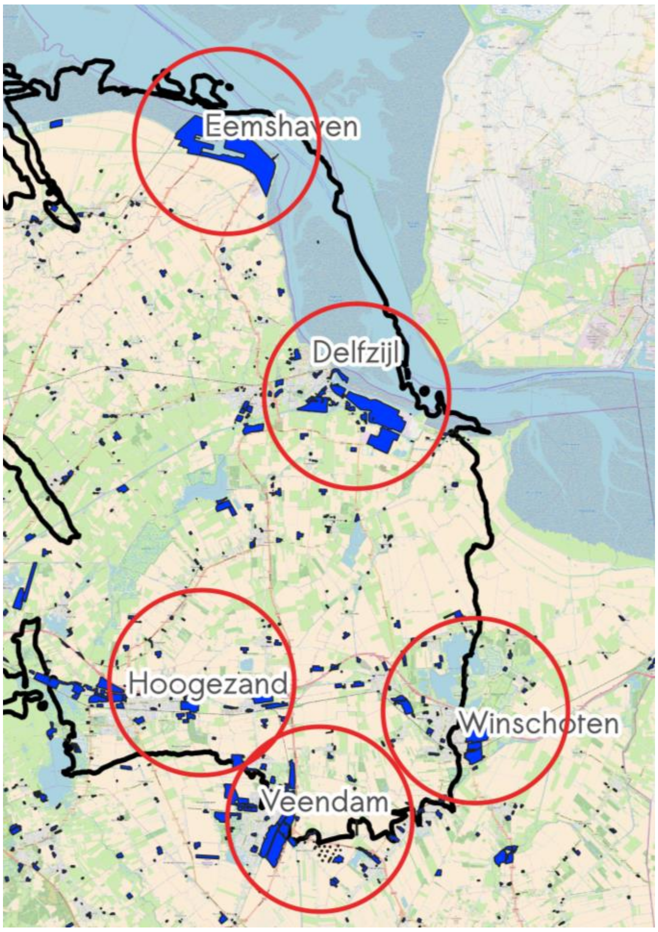


Figure 1: Map of Groningen with industrial sites under investigation (red circles). The extension of the Groningen field is marked with the black line.

An new step in the shakemaps analysis is the addition of the production forecast for the Groningen field for average winters (also called midcase in figures) between 2018 to 2027 when considering the maximum contributing induced event for the industry areas in the five cities. The seismological source model based on recorded events in the KNMI induced earthquake catalog is still part of the report.

The single Mmax = 5 and the magnitude distribution for induced and tectonic events in Groningen are considered again in the shakemaps analysis. Hence, two sets of shakemaps for industry locations are delivered. One shakemap for the single Mmax = 5 and another shakemap for the Mmax distribution.

This report starts with an explanation of the new GMM v5. The discussion of the “maximum credible“ magnitude for an induced event in Groningen is repeated. Afterwards, the KNMI seismological source model and the production forecasting model are briefly mentioned. The epicenter locations of the “maximum credible” earthquake for the two seismological source models are derived from a disaggregation analysis in the seismic hazard analysis. The newly estimated epicenter locations for induced earthquakes near Delfzijl, Eemshaven, Hoogezand, Veendam and Winschoten are discussed. The shakemaps and spectra for the single Mmax = 5 and the Mmax distribution for the five industrial sites are presented. Finally, the updated shakemaps results are concluded.

2. Ground motion model v5

The GMM v4 and v5 have the same formal structure (Bommer et al., 2017, 2018). Both GMM’s are based on a two-layer model of Groningen with the reference level at the strong layer discontinuity at -800 m (the bottom of the North Sea layer). Figure 2 shows the principle of the two-layer model with a half space layer below the near-surface layer. An induced earthquake takes place in the gas reservoir (on average 3km) and seismic wave energy propagates upward to the surface through the half-space model and the near-surface layer with site-specific soil properties. It is in the near surface layer that the amplification of the seismic signal takes place. Both GMM v4 and v5 work with an amplification factor having a magnitude-distance dependence. This means that not only the magnitude of the induced earthquake affects the amplification factor, but the distance between the hypocenter and site plays a role. The rupture distance is used for the distance measure in GMM v4 and v5. In principle, the extension of the fault rupture should be incorporated in the hazard and shakemaps calculations. This type of geological information for Groningen often contains large uncertainties. Effectively, the hypocenter distance definition is still used in GMM v4 and v5. For example , the shortest distance between a hypocenter directly below the site to the surface is 3 km.

The zonation model for the amplification factor which was compiled by Deltares (Kruivert et al., 2017) for GMM v4, is as well used in GMM v5. There are 160 zones in the zonation model. Generally, the largest shear wave velocities are still found in the south where near-surface amplification effects are less severe and vice versa. The zonation model with geological zones for GMM v4 and v5 is shown in Figure 3, (Kruiver et al., 2017).

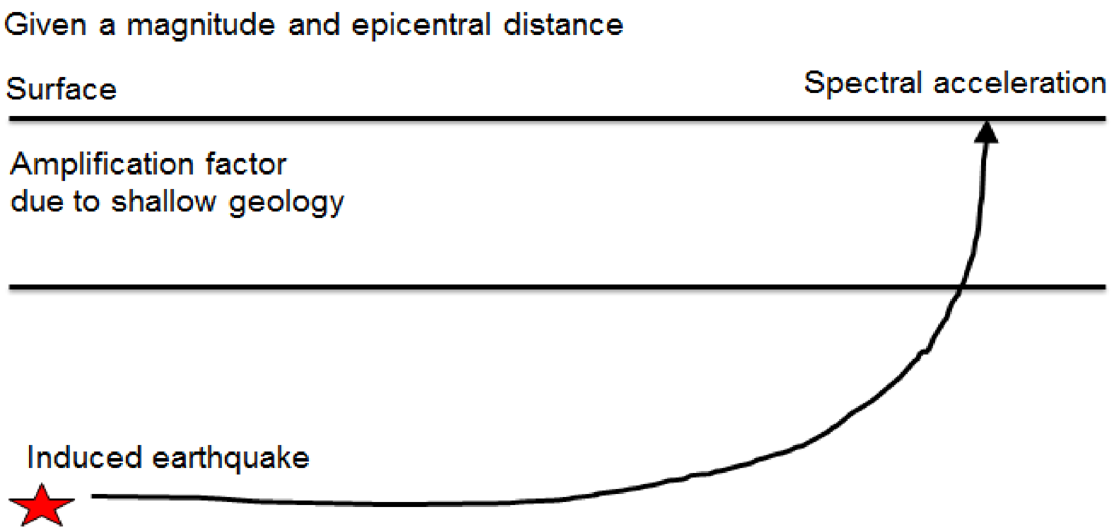


Figure 2: Schematics of the two-layer model used to define the GMPE v4 and v5.

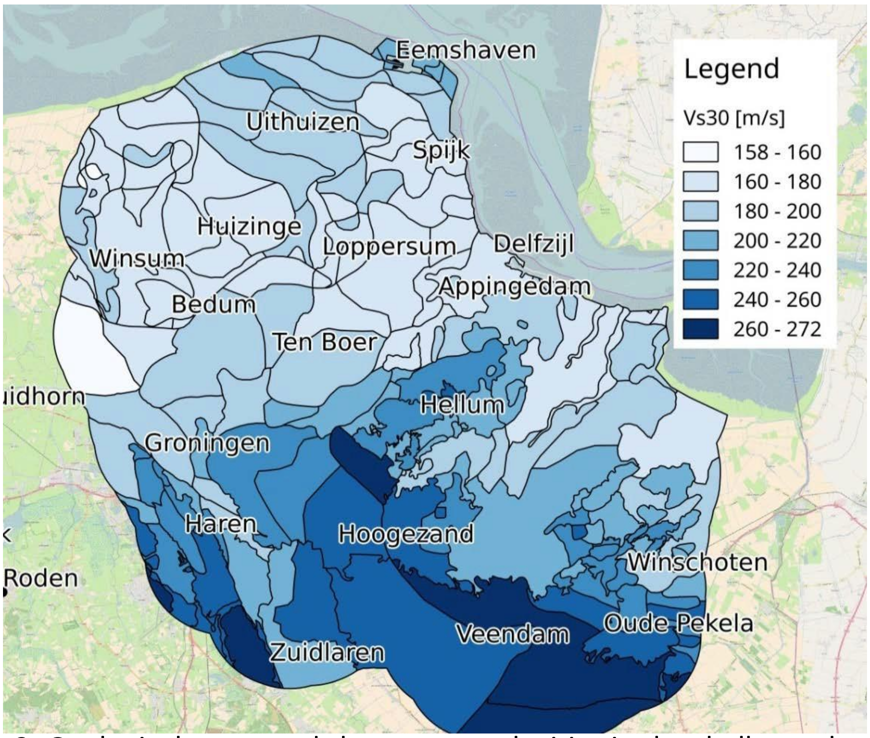


Figure 3: Geological zones and shear wave velocities in the shallow subsurface (Kruiver et al., 2017).

The GMM v4 and v5 introduces an uncertainty coming from fitting the observed data from the Groningen station network and the synthetically modelled data with the amplification factor for measured soil properties. The standard deviation (std) is used to express the uncertainty of the calculated spectral accelerations. The shakemaps approach to compute the standard deviation follows the traditional ergonic hazard approach (Rodriguez-Marek et al., 2014), and is considered to be rather conservative. In this report, the range of the median spectral acceleration (*SA*) is defined in-between one standard deviation. The lower and upper spectral acceleration (*Y*) is given by

$$Y = SA \pm std,$$

where *SA*, *Y* and *std* are in the unit [cm/s^2], [m/s^2] or [g]. To convert between cm/s^2 or m/s^2 to g, the conversion factor 1/(100*g) or 1/g, where g = 9.82 m/s^2. For example, an acceleration of 100 cm/s^2 converted to the unit of [g] is equal to 0.102 g.

3. Maximum credible magnitude for Groningen

The KNMI has defined the maximum magnitude Mmax = 5 in the seismic hazard work in Groningen. The value for Mmax has been determined by comparing with other produced fields worldwide.

The Mmax distribution was suggested by an international workgroup of experts during the Mmax workshop on March 8-10, 2016 (Report on Mmax Expert Workshop, July 2016*)*. The Mmax distribution takes into account the possibility of induced and tectonic events in Groningen. The expert panel was rather certain that strong events in Groningen would have to be tectonic. It is still a point of discussion whether the conditions for tectonic events are present at the fault structures at or under the gas reservoir. There are no records of tectonic events before the gas production in Groningen was initiated in the late 1960's indicating a non-existing-to-weak initial stress field. It is questionable whether a triggered event with a magnitude 7 in Groningen could take place since a tectonic earthquake with such a magnitude would have to partly take place outside the gas filled reservoir and would be associated with a deep fault in the carboniferous layer. The Mmax distribution is given in Table 1. The Mmax distribution is defined in the range from M4 to M7. Notice that the average magnitude of the Mmax distribution is M = 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

The strongest induced earthquakes recorded in Groningen is the magnitude 3.5, 3.6 and 3.4 event in 2006, 2012 and 2018. The station network in 2012 was much sparser than the current network configuration in Groningen with 100 station locations in and around the Groningen gas field. The available accelerometers during the 3.6 event in Huizinge recorded PGA values about 80 cm/s^2 and 10 cm/s^2 for the epicentral distances 2 km and 10 km, respectively. Figure 4 shows the recorded PGA values as function of epicentral distance for larger induced earthquakes in Groningen (Bommer et al., 2018).

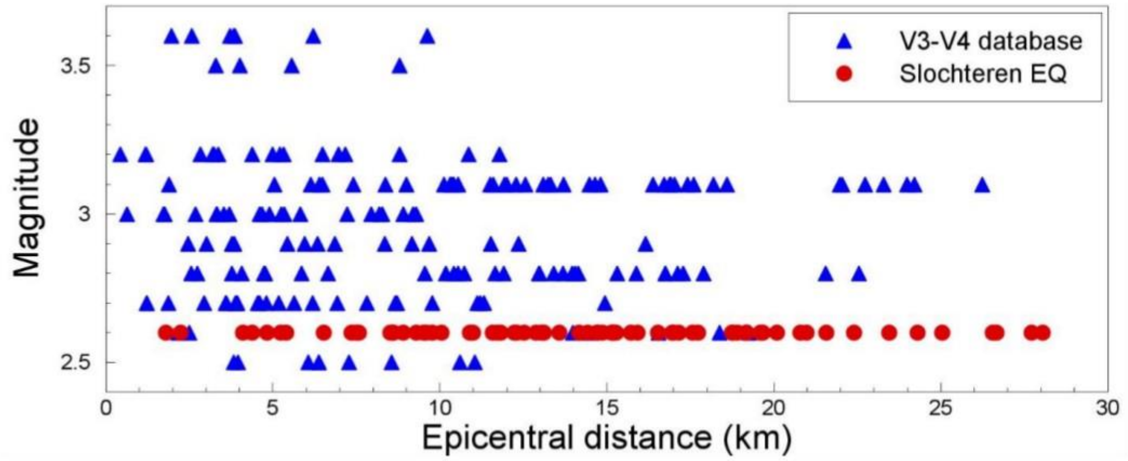


Figure 4: The event data base used in the construction GMM V5. (The GMM v5 report by Bommer et al., 2018).

4. Seismological Source Models for Groningen

Next to the KNMI seismological source model, a production forecasting model for seismicity in the 10 years in the Groningen field was used in Spetzler et. al. (2018). In this shakemaps update, the production forecast for the average winter scenario is applied to defined the source model. Like in Spetzler et al., 2018, the 10 years period for the production prognosis is divided into three sub periods. The three sub periods are t1, t2 and t3 for the times 2018-2020, 2020-2023 and 2023-2027, respectively. The average annual activity rate in the average winter scenario is around 15, 11 and 6 events/year (magnitude > 1.5) for the periods t1, t2 and t3, see Figure 5.

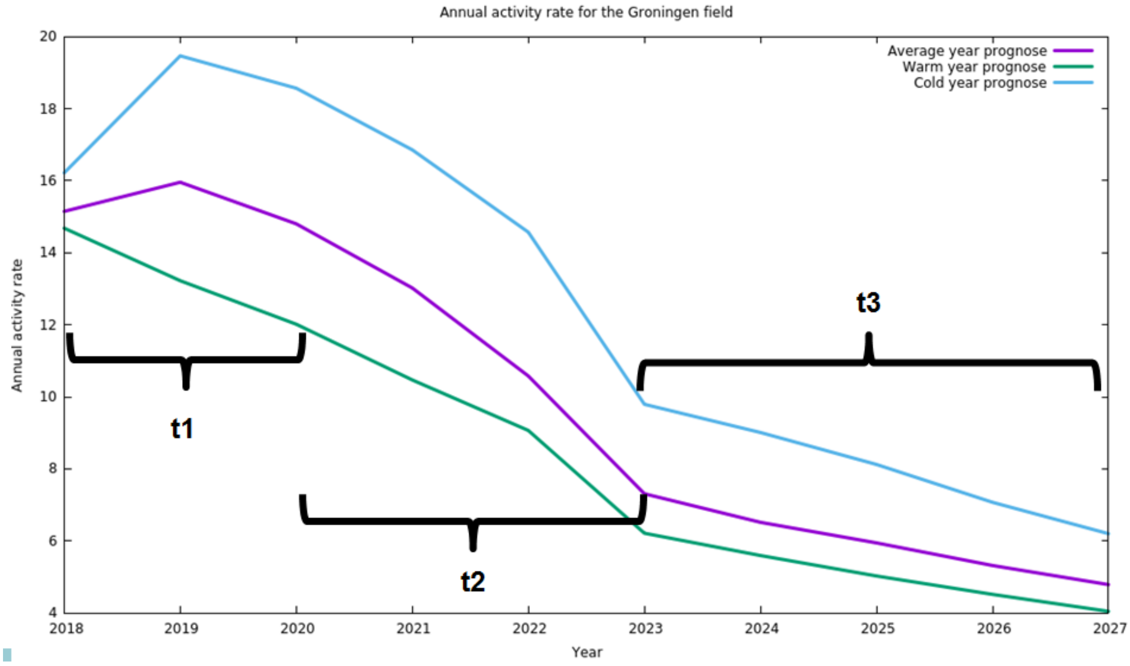


Figure 5: Definition of periods for levels of activity rates between 2018 and 2027. The number of events per year is counted for M > 1.5.

It is not enough just to define the annual activity rate in the seismological source model, but the lateral distribution of the activity rate and the b-value (i.e., parameter in the Gutenberg-Richter graph describing the ratio between weak and stronger earthquakes) must be specified as well. The distribution of b-values and the activity rate density for the average winter case are presented in Figure 6. The central gas field and the southern part with Hoogezand and Groningen city are areas with lower b-values. A lower b-value implies that events with relative larger magnitude may be more frequent. However, the activity rate density distributions for the three periods shows that most events is in the central part of the Groningen field, with a decreasing event number over the next 10 years. Very few events are expected to take place in the remaining areas of the Groningen field, even in sections with b-values lower than one. The zonation model used to define the seismological source model for the average winter scenario consists of five zones (i.e., Z1, Z2, Z3, Z4 and Z5) which are similar b-values and activity rate densities.

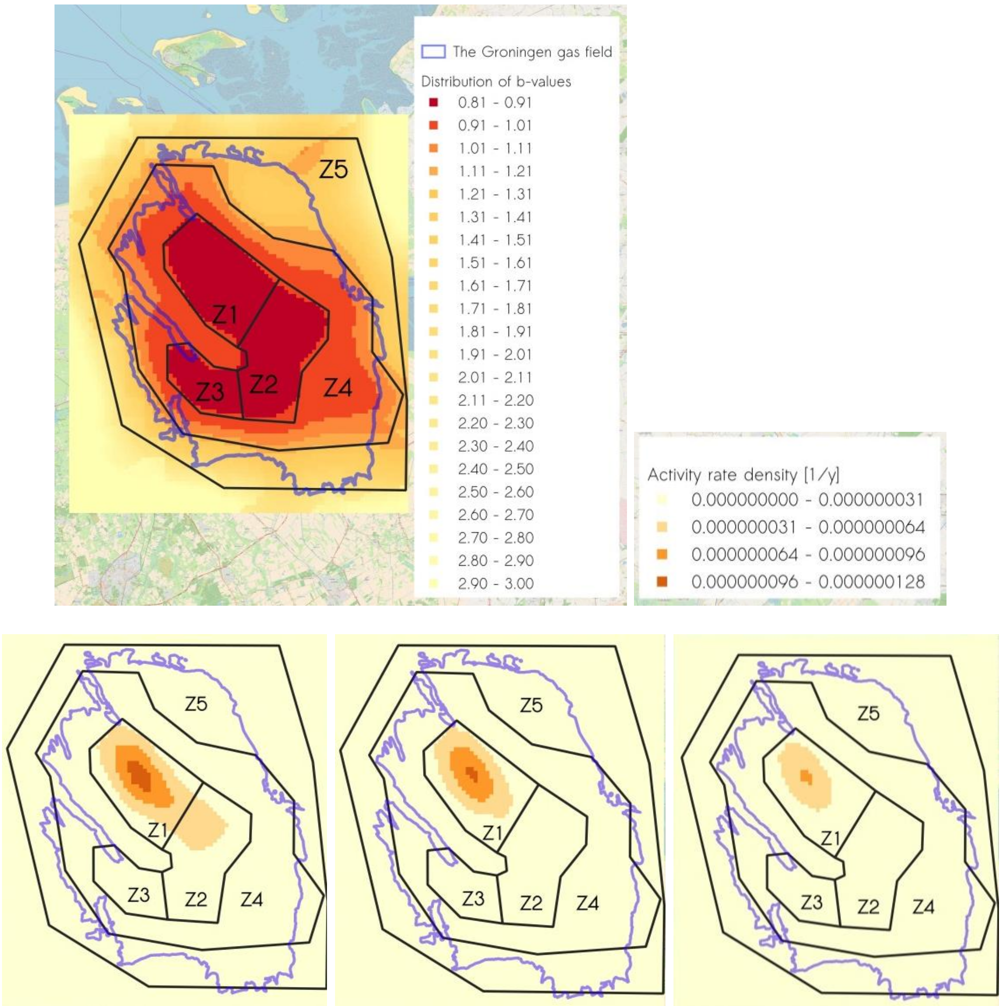


Figure 6: Lateral distribution of b-values (top) and activity rate density for three time periods for the mid-winter scenario (lower three panels). The activity rate panels are from left to right: for 2019, 2022 and 2025. The zones in the zonation model are indexed Z1, Z2, Z3, Z4, Z5.

The KNMI seismological source model is derived from the last 3 years of recorded induced seismicity in the KNMI earthquake catalogue. The annual distribution of induced earthquakes with a magnitude above 1.5 is shown in Figure 7. The graph clearly indicates a reduction of recorded seismic event after 2014 where the production of gas from Groningen was strictly regulated. The spatial distribution of induced earthquakes in Groningen in Figure 8 is for the period 2015- January 2018. The M3.4 event on January 2018 is added to the list of events in this shakemaps update. Based on this distribution, the zonation model in the KNMI hazard update June 2017 is used again. This zonation model consists of three zones; 1) The central north zone for the Loppersum area, 2) the central south zone for southern part with Hoogezand, Harkstede and Froombosch and the 3) Active area with the remaining part of the Groningen field. There is no reason to change the zonation model for Groningen.

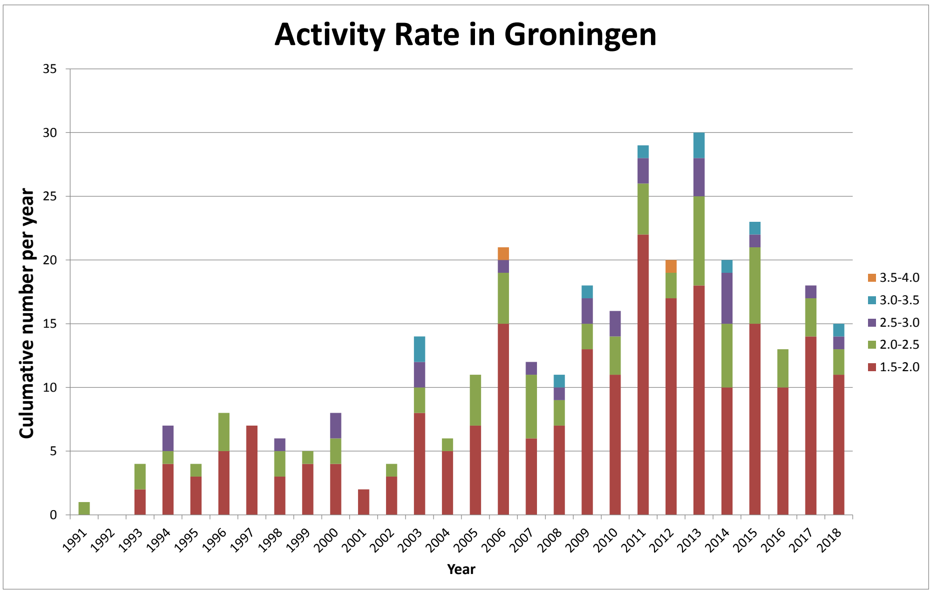


Figure 7: Activity rate of observed induced earthquakes in Groningen over the years. Only events with a magnitude greater than 1.5 are used in the KNMI earthquake catalog. The graph is valid per December 5, 2018.

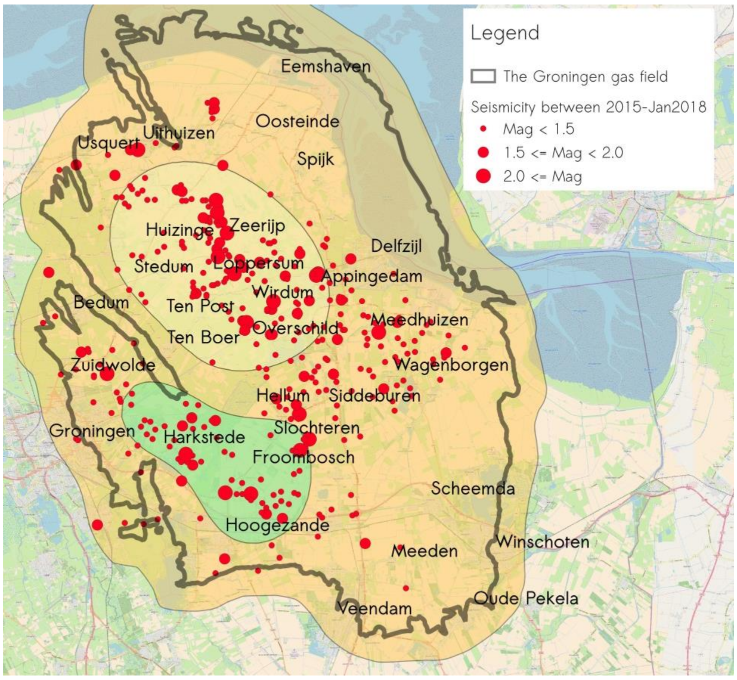


Figure 8: Distribution of induced earthquakes in Groningen between January 2014 and January 2017 and the corresponding zonation.

5. Shakemaps v5 for single event scenarios

The shakemaps program developed at the KNMI in last year shakemaps report for GMM v4 has been extended to include the GMM v5. For both GMM v4 and v5, there are 23 spectral periods between 0.01 s (the Peak Ground Acceleration, PGA) to 5 s. In contrast, the shakemaps application by the USGS (United States Geological Survey Earth Hazard Program) only allows to calculate four spectral periods (i.e., 0.01 s, 0.3 s, 1.0 s and 3. 0 s) . The KNMI shakemaps for GMM v4 and v5 can be used for earthquake scenario calculations only and is not intended for the usage of generating shakemaps after a larger induced earthquake has occurred in Groningen. For the reduction of plots in the report, only shakemaps for the spectral periods 0.01 s, 0.3 s, 1.0 s and 3. 0 s are presented. For specific site locations, spectra with all 23 spectral periods are available.

The shakemaps developed by the KNMI will simply provide the expected spectral acceleration with an errorbar (that is the standard deviation of the probability distribution of all possible accelerations) at a specific location for a defined earthquake scenario. Spectra with expected values of accelerations and errorbars at all spectral periods are intended to be used in a geo-technical hazard assessment of industrial constructions and structures in Groningen.

The shakemaps program for a maximum considered earthquake has been tested by comparing with outputs of the USGS shakemaps program for the periods 0.01 s, 0.3 s, 1.0 s and 3.0 s. The results from both programs for a given earthquake epicenter and Mmax case are very similar. Consequently, the new shakemaps program has been properly tested and can be uses for earthquake simulations in this report.

6. Assessment of “maximum considered earthquake” for industry areas in Groningen

The disaggregation results in the hazard analysis of Groningen for the production forecast for the average winter scenario for the periods t1, t2 and t3 in Spetzler et al. (2018) have been used to determine the distance of most contributing induced events with respect to the five cities with industry. For the case of the hazard analysis using the KNMI source model, the hazard calculations have been carried out but are not yet published. Again, the disaggregated distances to Delfzijl, Eemshaven, Hoogezand, Veendam and Winschoten have been estimated.

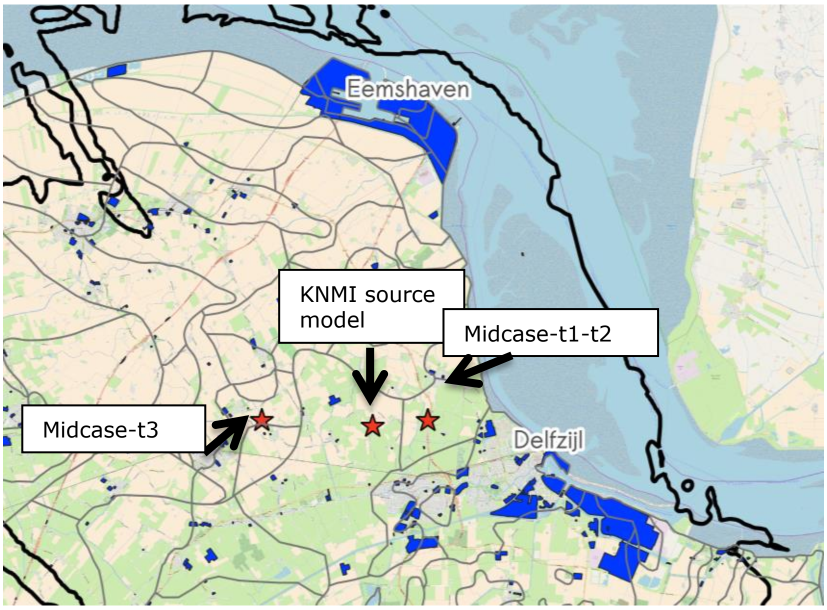


Figure 9: “Maximum considered earthquake” scenario for industry in Delfzijl and Eemshaven.

The method for the estimation of the location of the most contributing induced earthquake to a city is described in the shakemaps report for GMM v4 by Spetzler et al. (2017). It is found for Delfzijl that the seismological source model certainly has an impact on the location of the induced event. The disaggregation results for the KNMI source model produce for GMM v5 the same location as was estimated for GMM v4. However, the hazard analysis with the production forecasting source model and GMM v5 return two epicenter locations. One location for the average winter scenario for the periods t1 and t3 (between 2018-2023) is closer to Delfzijl, while for the last period t3 (2023-2027) is moved farther away from Delfzijl. Figure 9 shows the epicenters of the most contributing induced earthquake near Delfzijl and Eemshaven. For Hoogezand and Veendam, it is found that the epicenter of the most contributing event is unchanged from last year’s shakemaps update (Spetzler et al. , 2017, KNMI report) regardless of the seismological source model. See Figure 10 for a map with the epicenter location.

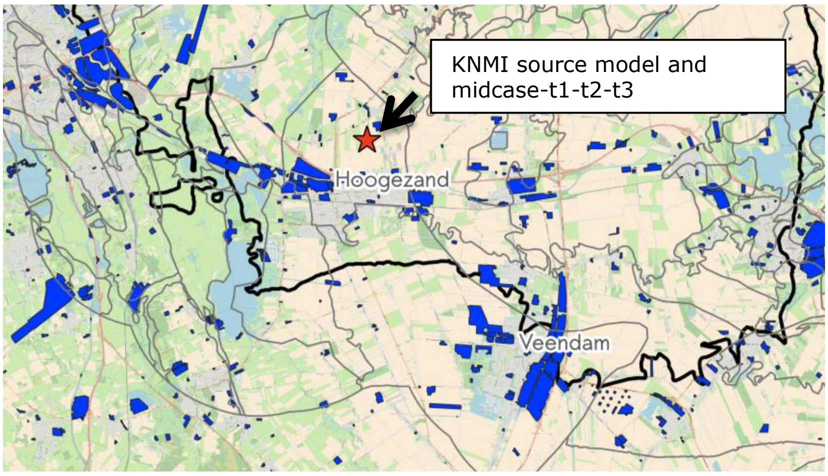


Figure 10: “Maximum considered earthquake” scenario for industry in Hoogezand and Veendam.

For the newly added city, Winschoten, the most maximum contribution induced earthquake is estimated to be at a distance farther away from the industry area. The epicenter location of the induced earthquake for the shakemaps calculations is an area with recorded seismicity in the past years. Figure 11 illustrates the epicenter location for the Winschoten shakemaps.

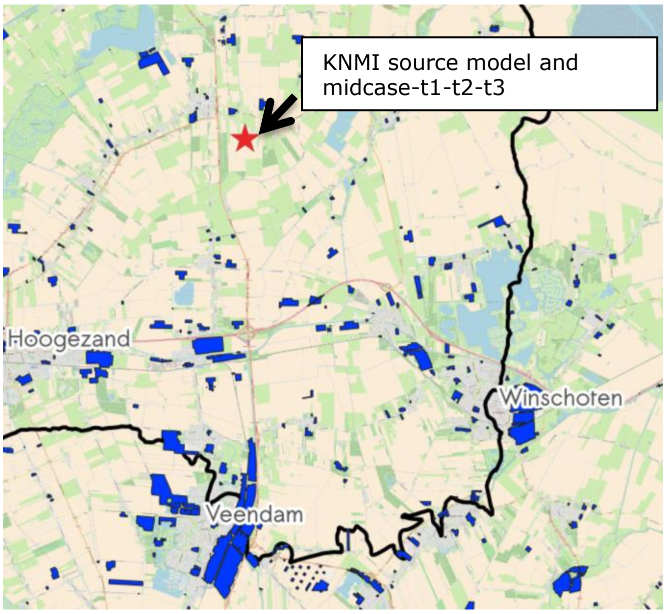


Figure 11: “Maximum considered earthquake” scenario for industry in Winschoten.

Shakemaps for all periods for the KNMI source model and the average winter scenario for all three periods t1, t2 and t3 have been calculated. Shakemaps for the province of Groningen for the period T = 0.3 s (i.e., the period with a high spectral acceleration) are presented in the next sections for the Mmax = 5 and the Mmax distribution case. Shakemaps for the periods T = 0.01 s, 0.3 s, 1.0 s and 3.0 s plots are available in appendix A, B, C, D and E depending on the epicenter location of the maximum considered contributing induced event. Shakemaps for all 23 spectral periods are available in a ncf-file format and spectra at site-specific locations are delivered in files in an asci format. The coordinate of the location is in the "Rijksdriehoekscoordinaat" (RD) system and is indicated in the filename. Each file for a spectrum has five columns: The first column is the spectral period in seconds [unit: s]. The next two columns are for the spectral acceleration per period in the units [m/s^2] and [g], respectively. The last two columns are for the standard deviation also in the units [m/s^2] and [g]. To find out which spectrum file corresponds to which company or site for the near-surface zonation, tables with industry names and sites and their geographical and RD coordinates can be found in appendix F.

7. Shakemaps for Chemiepark in Delfzijl

The shakemaps for the epicenter locations closest to Delfzijl and Eemshaven are presented in Figure 12, 13 and 14 for the KNMI source model, the average winter for period t1-t2 and the average winter for period t3, respectively. From the figures, it is seen that the distance between the epicenter and Delfzijl determines the spectral acceleration values. Of course, this is not a surprise because the spectral acceleration is increasing for decreasing epicentral distance. Some geological zones have greater spectral accelerations than their neighbouring zones. This is because of the site-specific amplification factor which depends on local soil properties. The effect of the distance dependent amplification effect is most clear in Figure 13 with the greater spectral acceleration in the geological zone west of the epicenter location. It does not make a significant difference whether the shakemaps are calculated for the single Mmax = 5 or the Mmax distribution.

A) B)

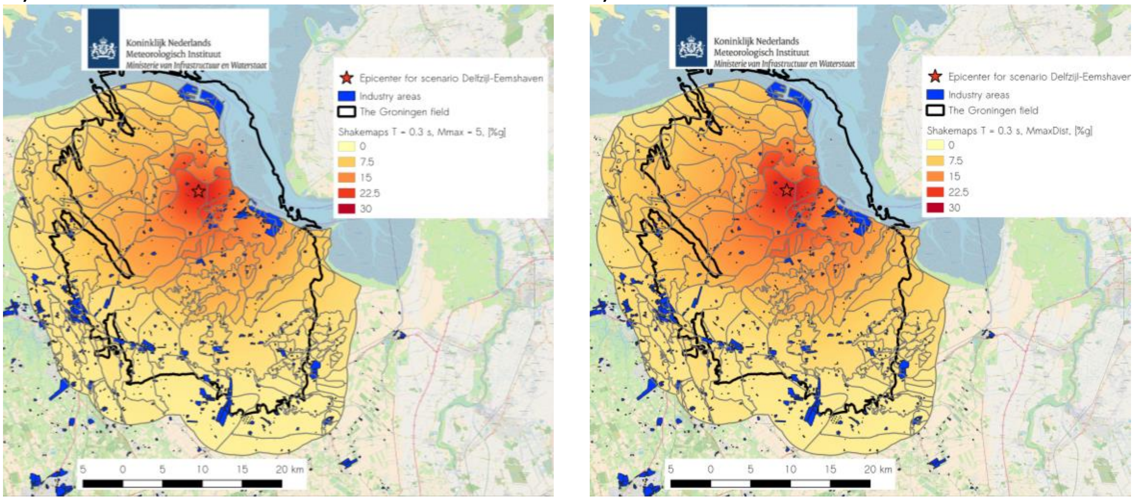


Figure 12: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario. The earthquake scenario is based on the KNMI source model.

A) B)

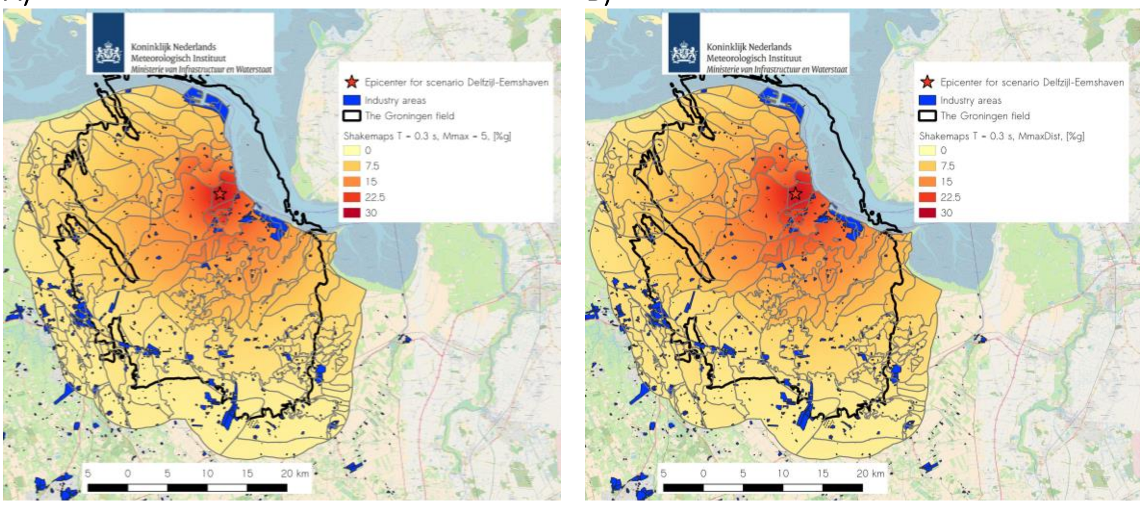


Figure 13: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario. The earthquake scenario is based on midcase t1-t2.

A) B)

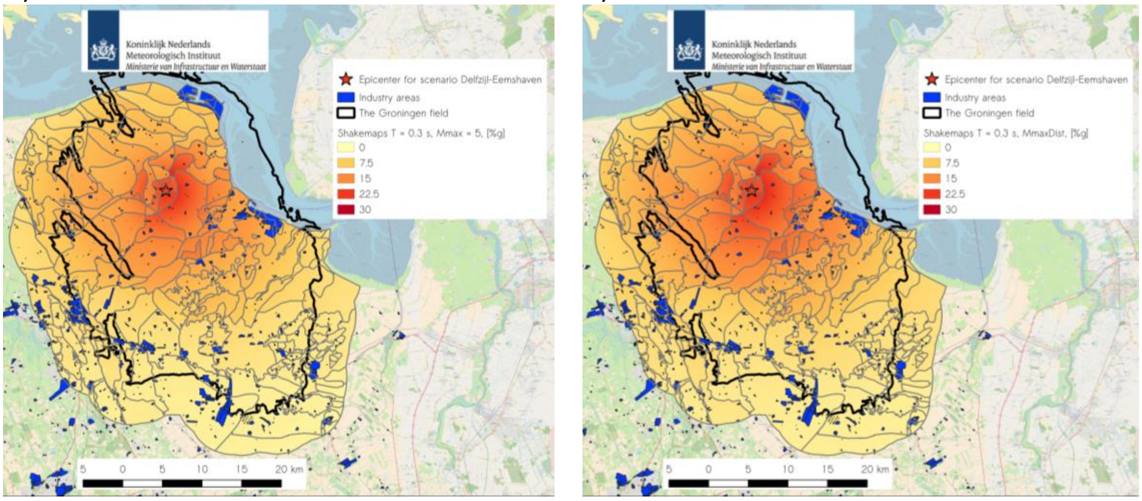


Figure 14: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario. The earthquake scenario is based on midcase t3.

A detailed section with the industrial area at the Chemiepark in Delfzijl is presented in Figure 14. Examples of industry in the area are Contitank, Akzo Nobel, Noord Gas Transport, Lubrizol Advanced Materials and NAM (see green circles). To provide spectral accelerations at other locations in Delfzijl, arbitrary locations in all geological zones have been selected (see yellow circles). For locations where the spectrum is not explicitly calculated, an estimate can be made by using the site location closest to one of the specified sites with spectra or by interpolation of values at more nearby sites.

An example of the spectrum with spectral accelerations for all 23 spectral periods for Akzo Nobel is presented in Figure 15 for the Mmax = 5 and the Mmax distribution scenario. The spectral acceleration values are given in the unit of [g]. The spectra for the two Mmax cases have a similar shape and max value. The peak value is found around the period T = 0.4 s in all spectra. The spectra calculated with the GMM v5 are significant lower spectral accelerations compared to the older spectra in the shakemaps report update 2017 (Spetzler et al., 2017, KNMI report) which were based on the GMM v4. The reduction in spectral accelerations can be explained by the GMM v5 which is better in fitting recorded data in Groningen.

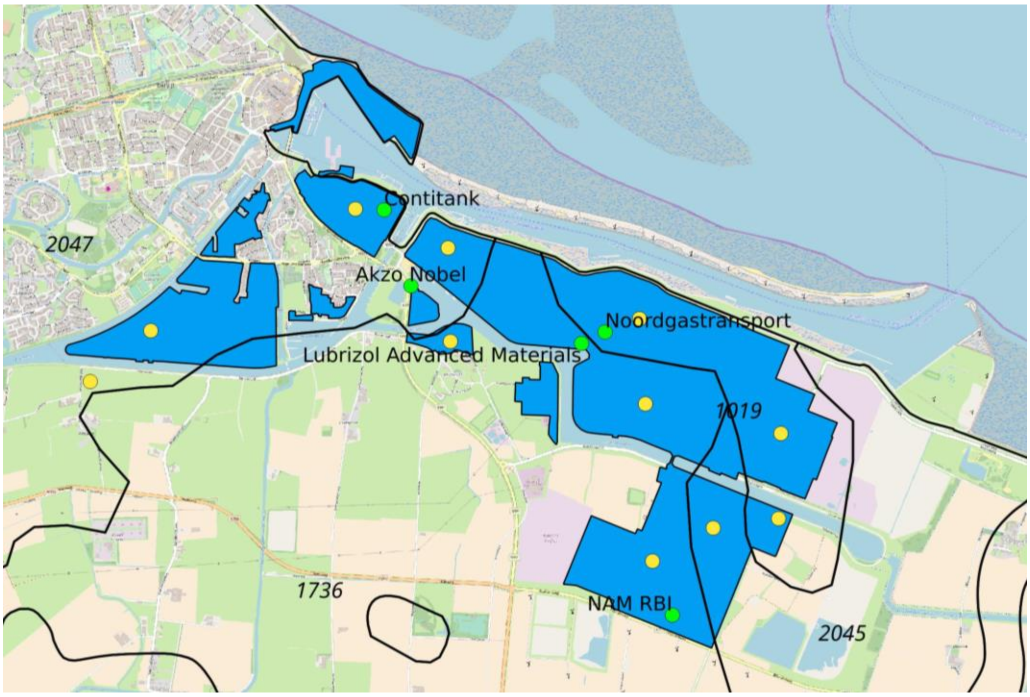
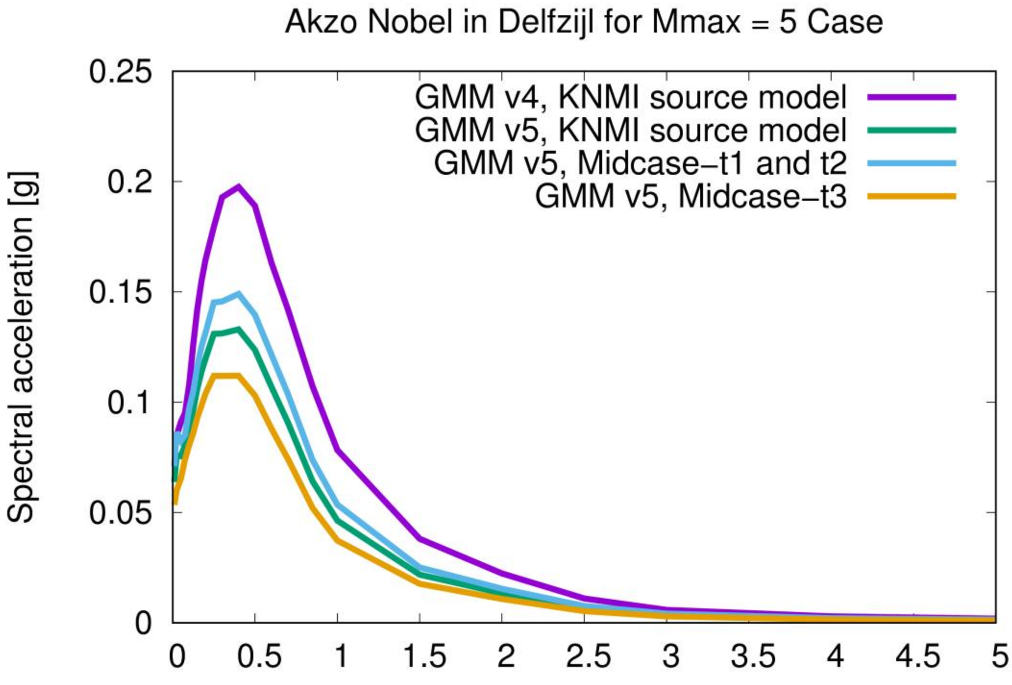


Figure 15: View of industrial area in Delfzijl with the location of industry and sites in different geological zones.

A)



B)

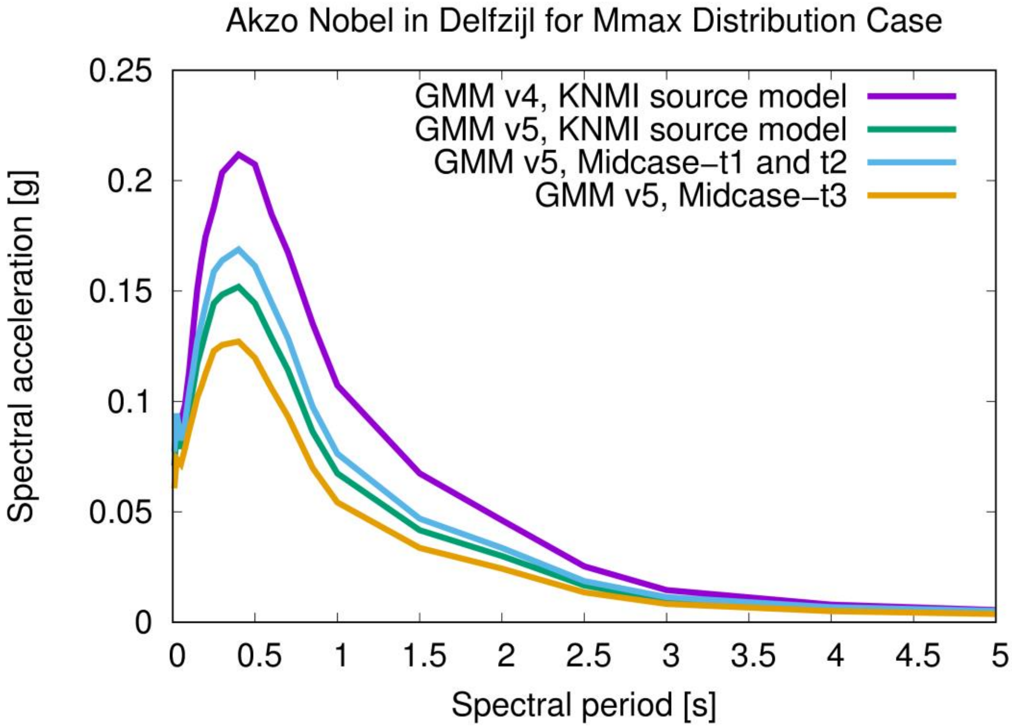


Figure 16: Spectra with spectral accelerations for Akzo Nobel in Delfzijl for A) the Mmax = 5 and B) Mmax distribution case.

8. Shakemaps for Eemshaven

A local map for Eemshaven with the industry and sites in different geological zones in Eemshaven is shown in Figure 17. Vopak and GDF Suez are located in Eemshaven. The shakemaps relevant for Eemshaven are presented in Figure 12, 13 and 14. The Vopak location is chosen for the site-specific spectrum for the two Mmax cases in Figure 18. The different epicenter locations do not change the epicentral distance to Eemshaven a lot and accordingly spectral acceleration values in the spectra calculated in this report have similar values for all spectral periods. The maximum spectral acceleration values are in the range between 0.2 s and 0.5 s. The new spectra have significant lower spectral accelerations than the previous spectra calculated with GMM v4.

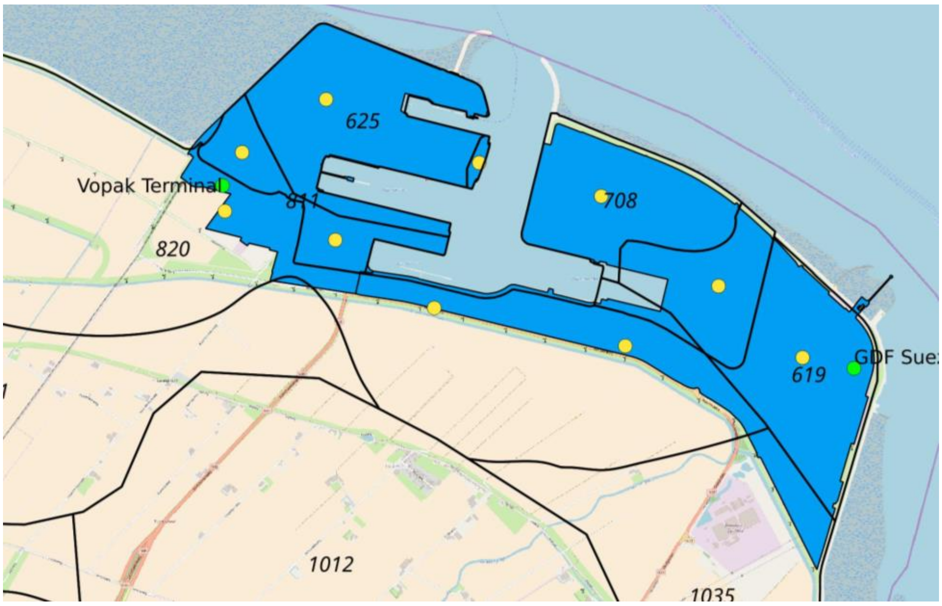
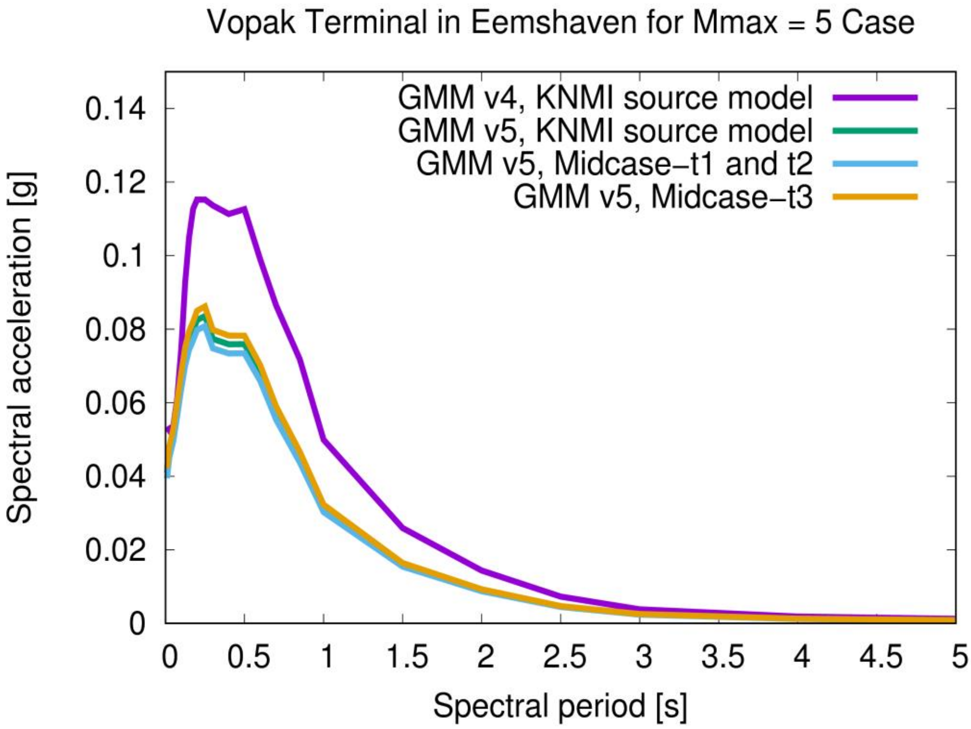


Figure 17: View of industrial area in Eemshaven with the location of industry and sites in different geological zones.

A)



B)

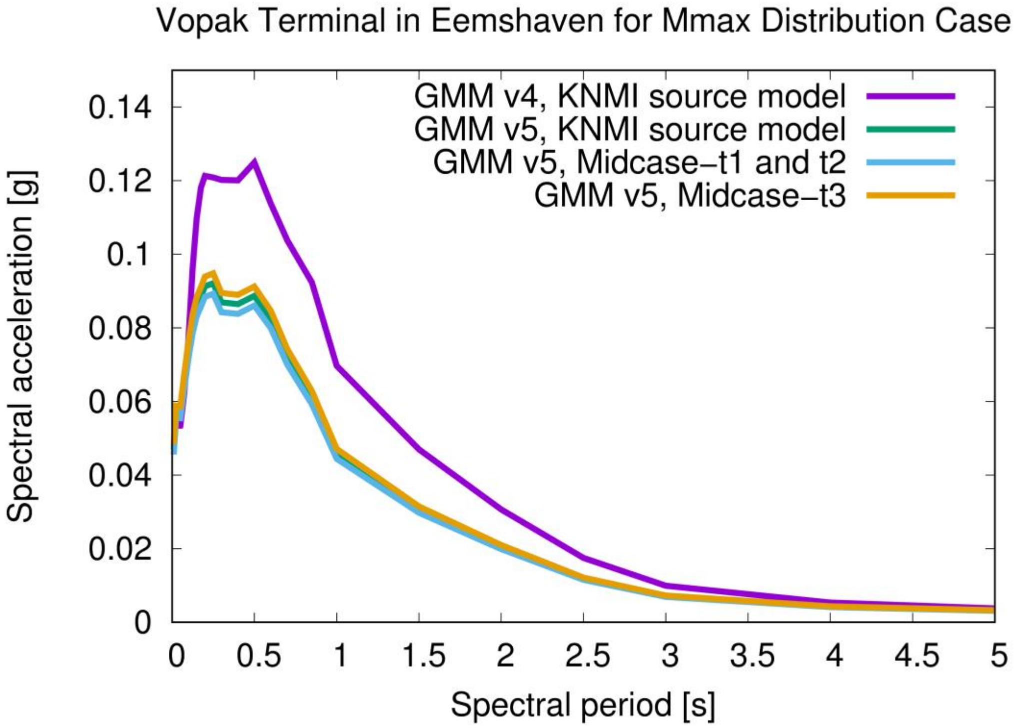


Figure 18: Spectra with spectral accelerations for Vopak in Eemshaven for A) the Mmax = 5 and B) Mmax distribution case.

9. Shakemaps for Hoogezand

The shakemaps for the KNM source model and the average winter t1-t2-t3 scenario have the same epicenter location for the most contributing induced earthquake. The shakemaps for the single Mmax = 5 and Mmax distribution are presented in Figure 19. The two shakemaps do not differ much from each other. The shakemaps for the province of Groningen for the periods T = 0.01 s, 0.3 s, 1.0 s and 3.0 s are shown in appendix D. Bayer material science, DFE Pharma, Reining Warehouse, Koopman Warehouses and C. G. Holthauser are situated in Hoogezand. A map of the industry and sites with geological zones is shown in Figures 20. The spectra for the two Mmax cases are presented in Figure 21. The maximum spectral accelerations are found at the spectral period at 0.2s -0.3 s. The spectra for GMM v5 have again lower spectral accelerations compared to the older spectra for GMM v4.

A) B)

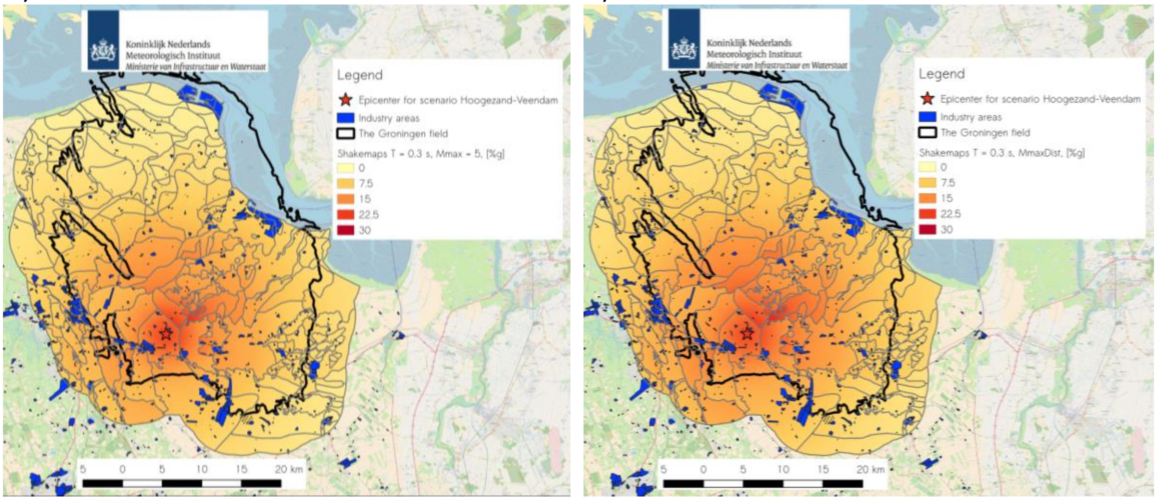


Figure 19: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

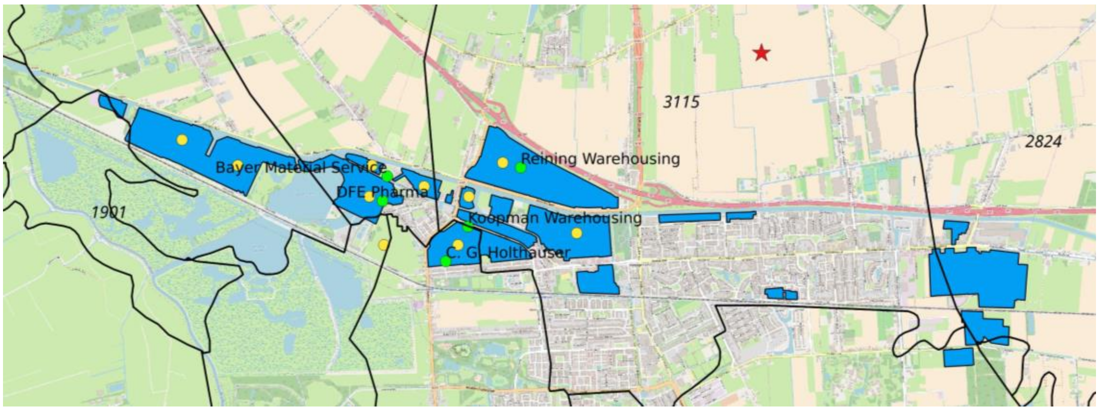


Figure 20: View of industrial area in Hoogezand with the location of industry and sites in different geological zones.

A)

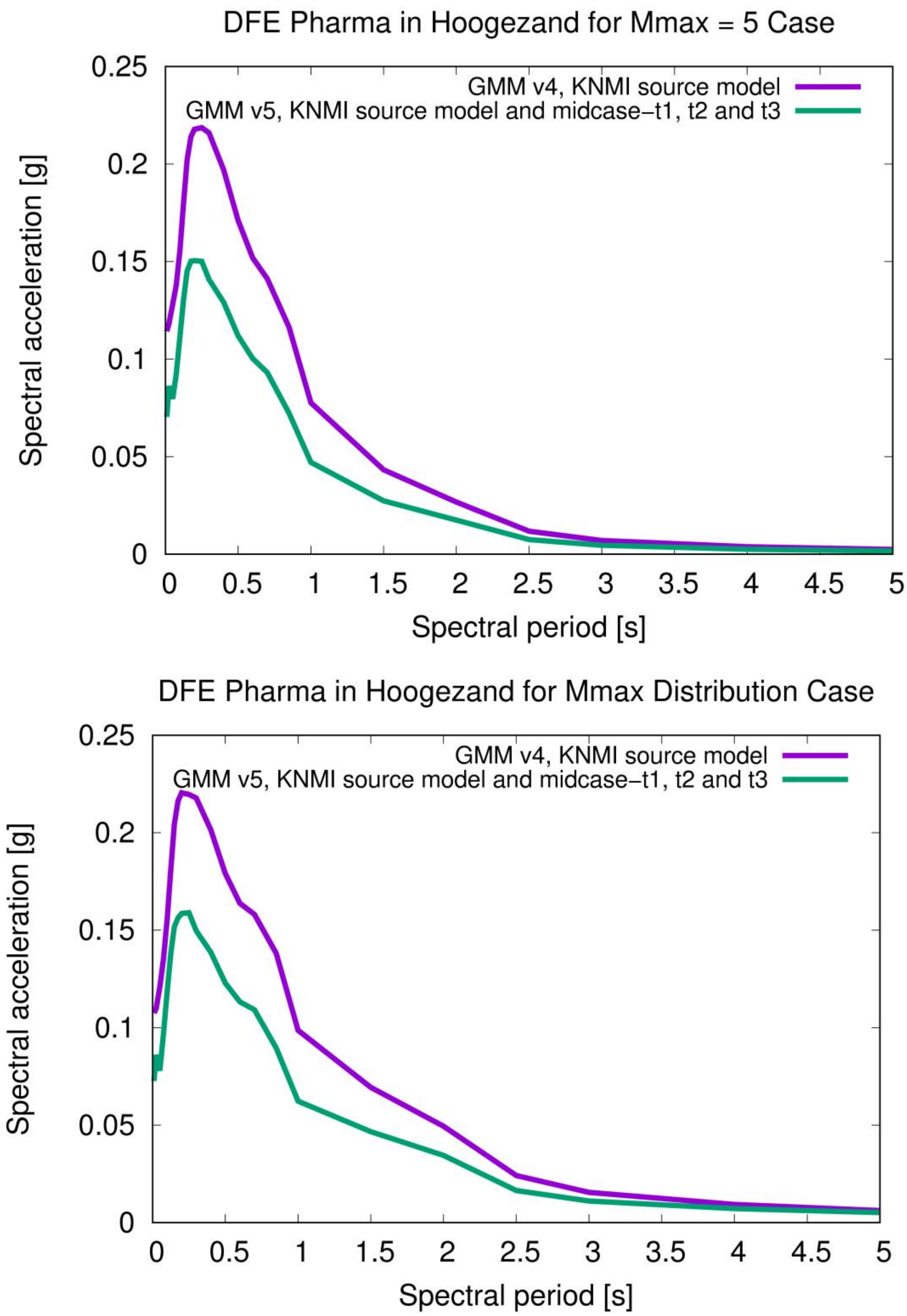


Figure 21: Spectra with spectral accelerations for DFE Pharma in Hoogezand for A) the Mmax = 5 and B) Mmax distribution case.

10. Shakemaps for Veendam

The results presented for Veendam are similar to the previous plots from Hoogezand. The plots with the industry locations and the spectra for Stinoil are in Figure 22 and 23. Other industry in Veendam are Groningen Railport, Kisuma Chemicals and Sita Ecoservice. Spectral accelerations at Veendam are lower compared to the ones in Hoogezand because of the greater distance. The new spectral accelerations for GMM v5 are again lower than the ones for GMM v4.

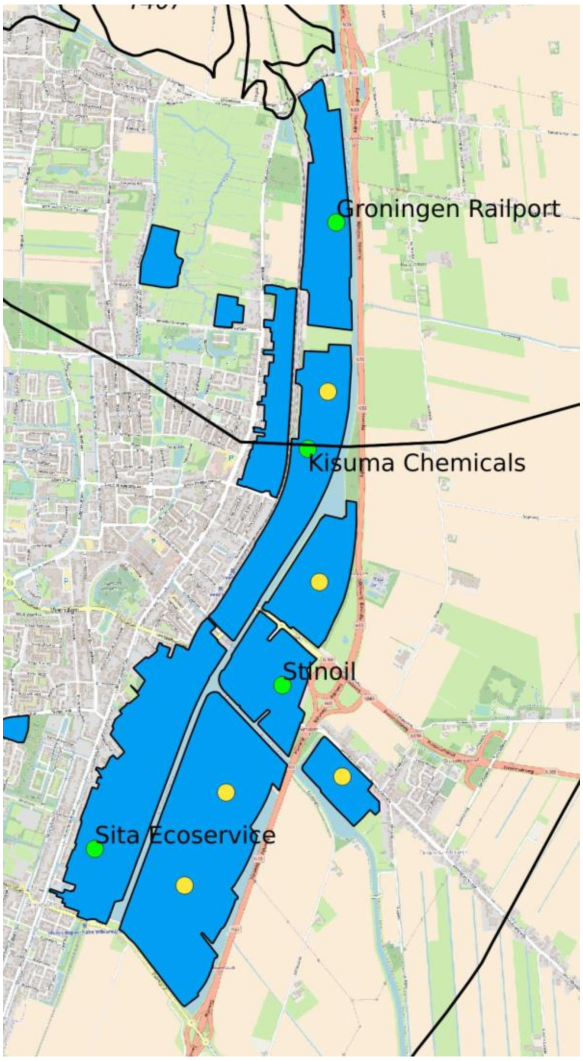
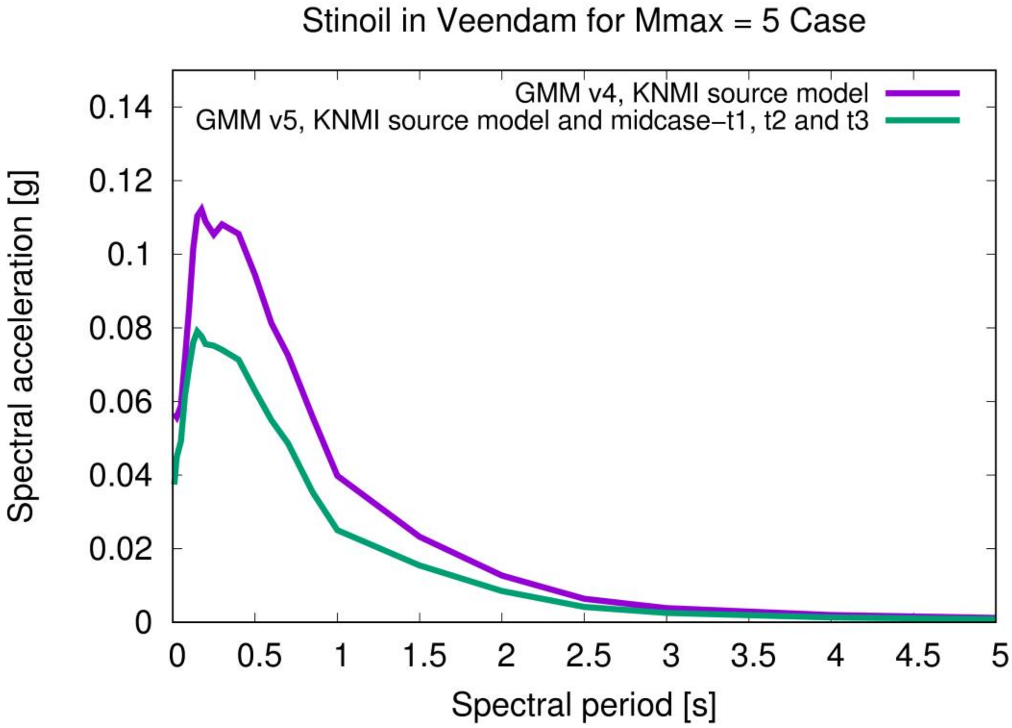


Figure 22: View of industrial area in Veendam with the location of industry and sites in different geological zones.

A)



B)

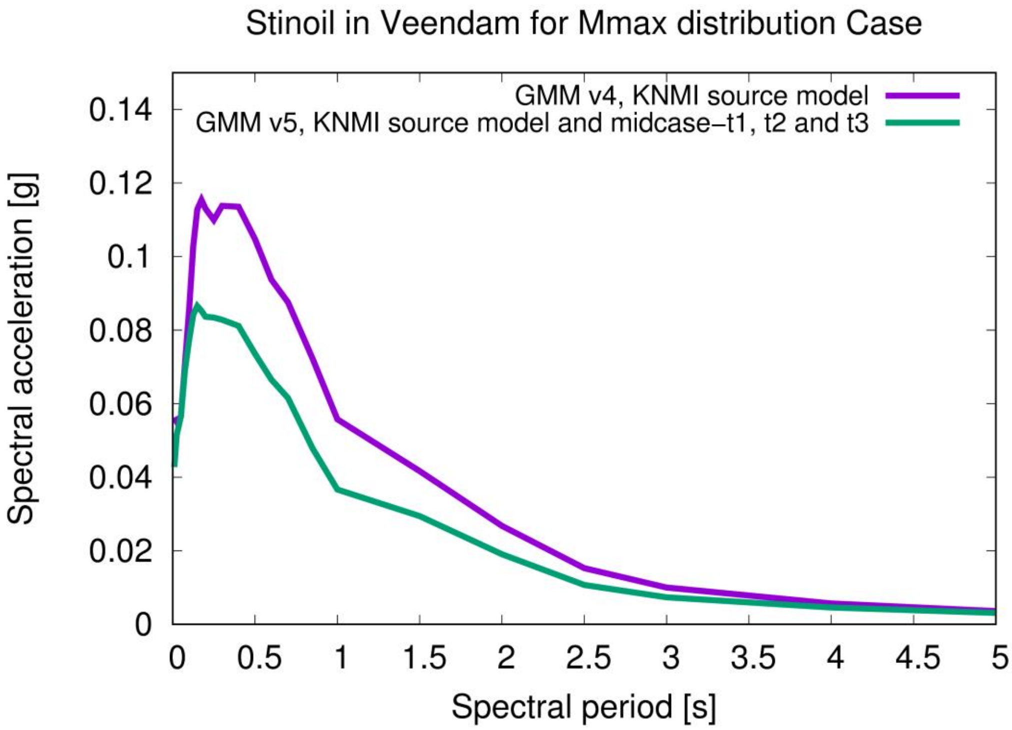


Figure 23: Spectra with spectral accelerations for Stinoil in Veendam for A) the Mmax = 5 and B) Mmax distribution case.

11. Shakemaps for Winschoten

The shakemaps for Winschoten for the spectral period T = 0.03 are shown in Figure 24 for the two Mmax cases. The industry/site locations and the spectra for the company JPB are plotted in Figure 25 and 26. Spectra are available at sites in zones with different near-surface amplification effects. The new spectra for GMM v5 have once more lower values than the ones for GMM v4 (originally not part of the shakemaps report for GMM v4).

A) B)

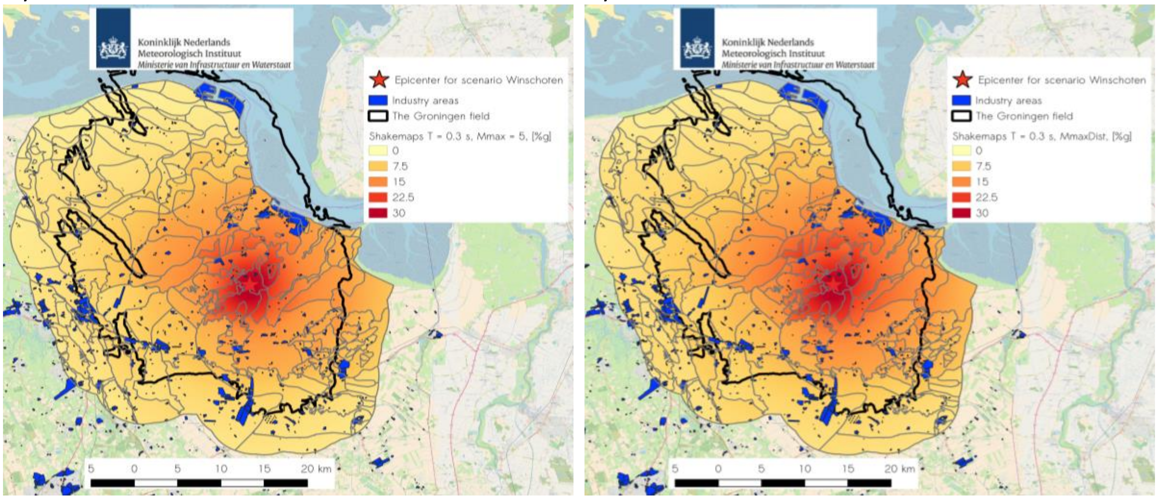


Figure 24: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

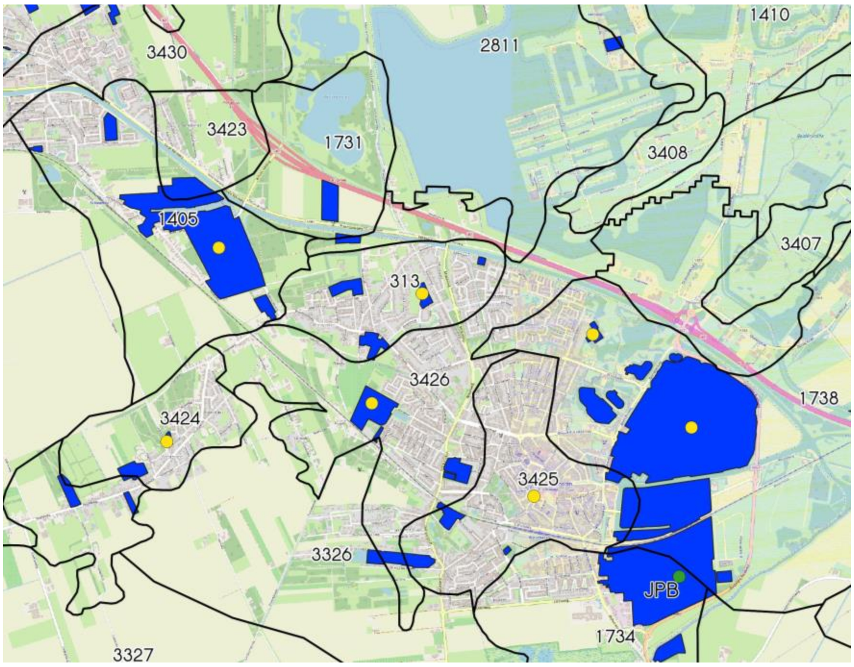
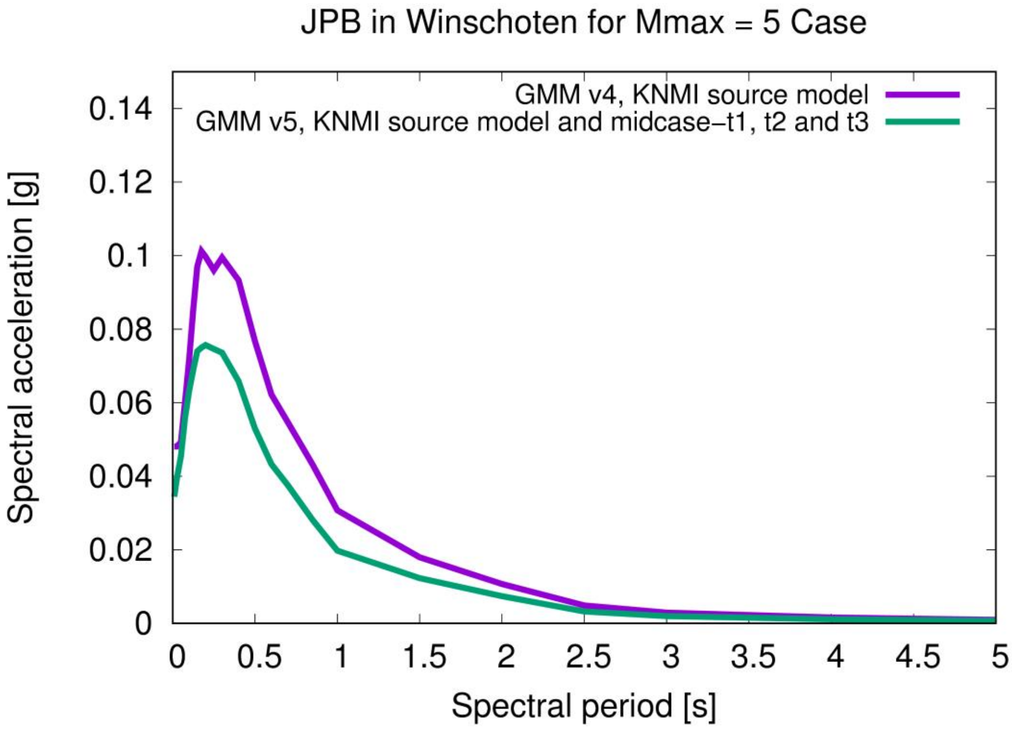


Figure 25: View of industrial area in Veendam with the location of industry and sites in different geological zones.

A)



B)

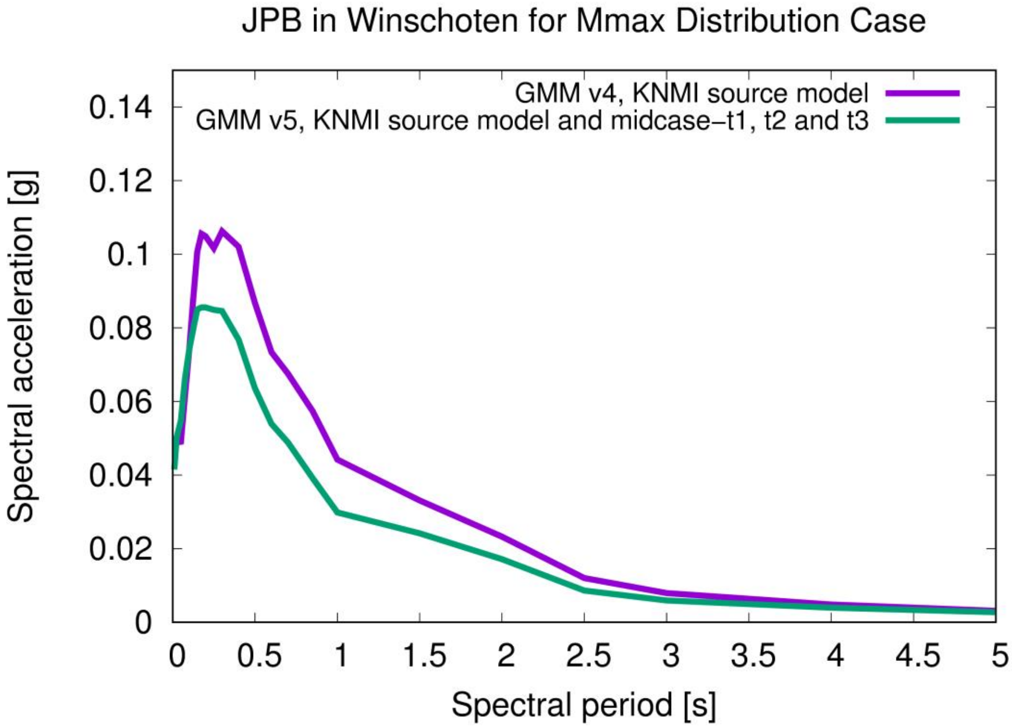


Figure 26: Spectra with spectral accelerations for JPB in Winschoten for A) the Mmax = 5 and B) Mmax distribution case.

12. Conclusions

Shakemaps and spectra for industry locations in Delfzijl, Eemshaven, Hoogezand and Veendam have been updated with respect to a new ground motion model and seismological source model in 2018. Locations with industry and sites in zones with different amplification factors in Winschoten have been added to this shakemaps update. The new GMM v5 is constructed from a larger data base of seismological recordings of induced earthquakes in Groningen. The data fitting is better in GMM v5 than in GMM v4. Two seismological source models are considered: 1) The KNMI source model and 2) the production forecast for average winters in the next 10 years.

The new hazard calculations based on GMM v5 produce spectral accelerations which are considerably lower than the values calculated with GMM v4. This is not a surprising result since GMM v5 is derived from a larger data base of Groningen data and fits the data much better.

For Delfzijl and Eemshaven, not one but three epicenters for the most contributing induced event were estimated from disaggregation results from the KNMI source model and the average winter scenario. The latter source model resulted in two epicenter locations with one location closer to Delfzijl for the production years 2018 to 2023, and farther away from Delfzijl for the remaining production period from 2024. For Hoogezand and Veendam, the epicenter location of the most contribution induced earthquake is unchanged from the Shakemaps report for GMM v4 (Spetzler et al., 2017, KNMI report). The epicenter location for the “maximum considered” induced earthquake for Winschoten is relative farther away, hence has a lower impact on the industry in the southern part of Groningen.

Two Mmax cases are taken into account. The Mmax = 5 scenario takes only one induced earthquake into account, while the Mmax distribution includes a combination of induced earthquakes for the lower magnitudes and the possibility of tectonic events for the larger magnitudes. The shakemaps and site-specific spectra for the Mmax = 5 and Mmax distribution case show the same pattern inherent to the Groningen specific amplification factor and similar spectral accelerations for the whole spectral period range.

The spectra calculated in this shakemaps update for Groningen consist of 23 spectral periods between 0.01 to 5 s. Previous results from the seismic Loss-of-Containment (LoC) assessment of industry in Groningen are no longer valid since older and more inaccurate GMM’s were used to calculate the shakemaps. Instead, the seismic LoC test for industry in Groningen should be repeated using the new spectra based on GMM v5.

13. References

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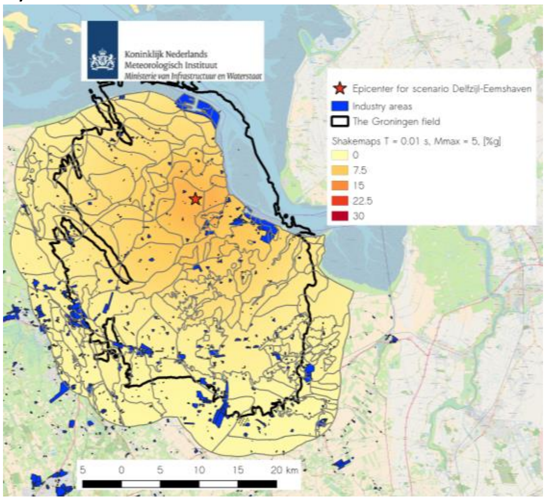
Appendix

A: General Shakemaps for Delfzijl and Eemshaven, earthquake scenario KNMI source

A)



B)

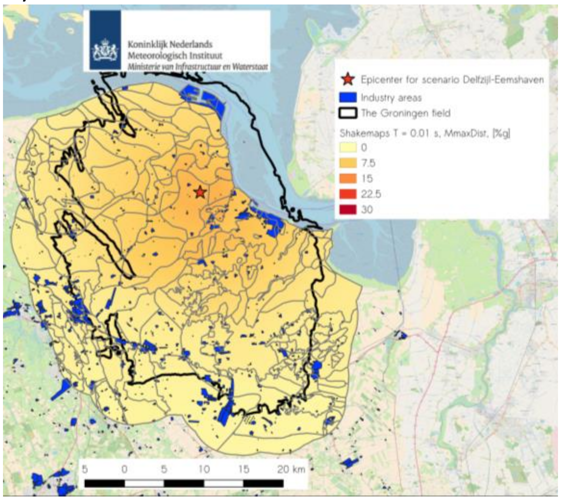
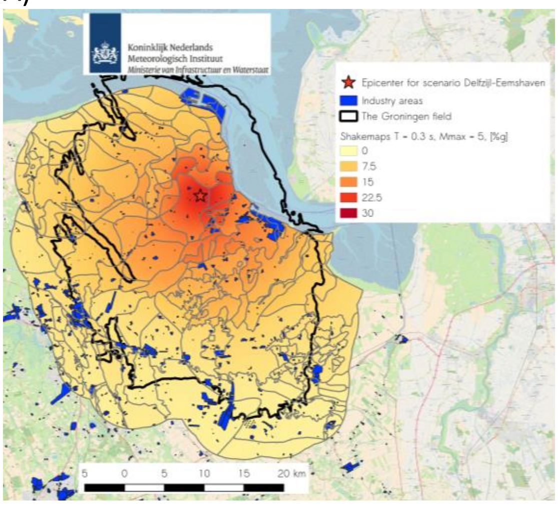


Figure A1: Shakemap with spectral acceleration for the period T = 0.01 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A)



B)

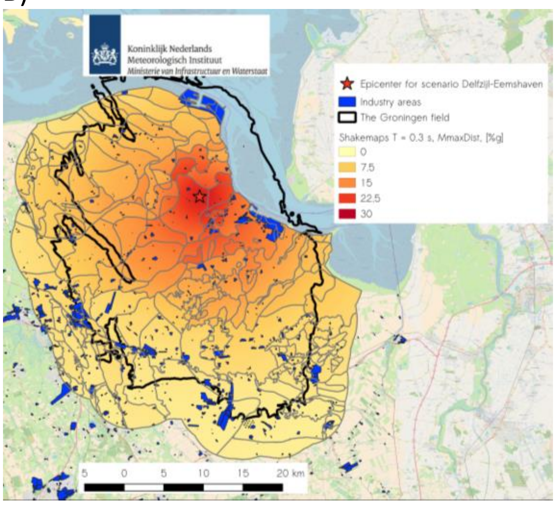
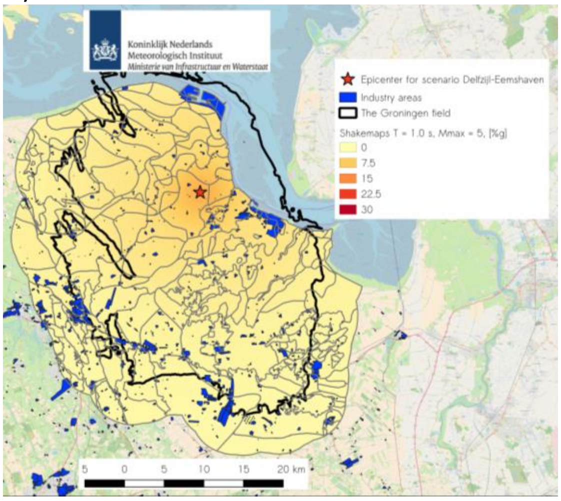


Figure A2: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A)



B)

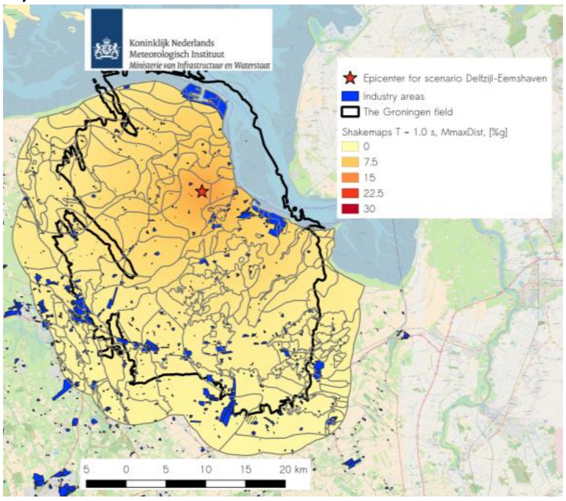
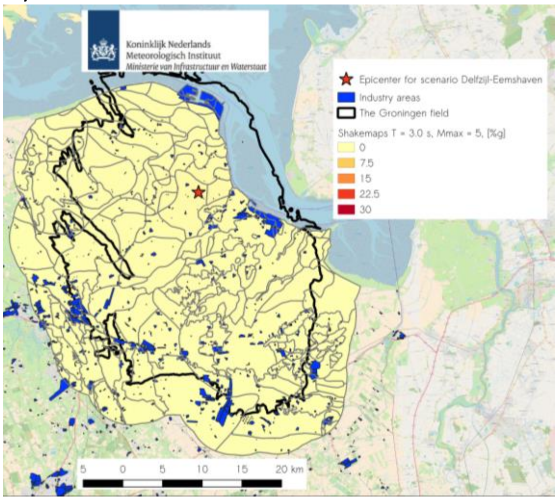


Figure A3: Shakemap with spectral acceleration for the period T = 1.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A)



B)

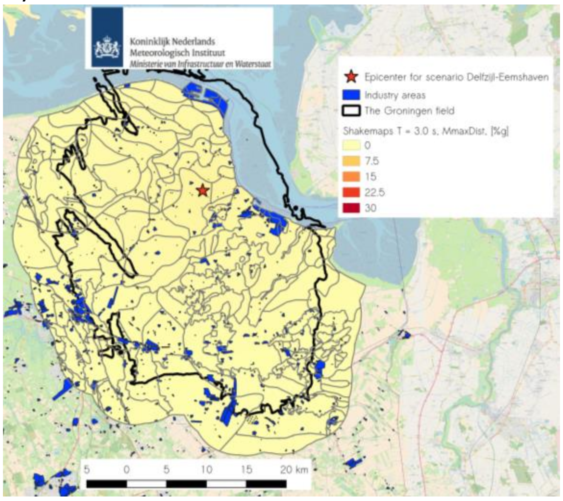


Figure A4: Shakemap with spectral acceleration for the period T = 3.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

B: General Shakemaps for Delfzijl and Eemshaven, earthquake scenario for average winter for period t1-t2

A) B)

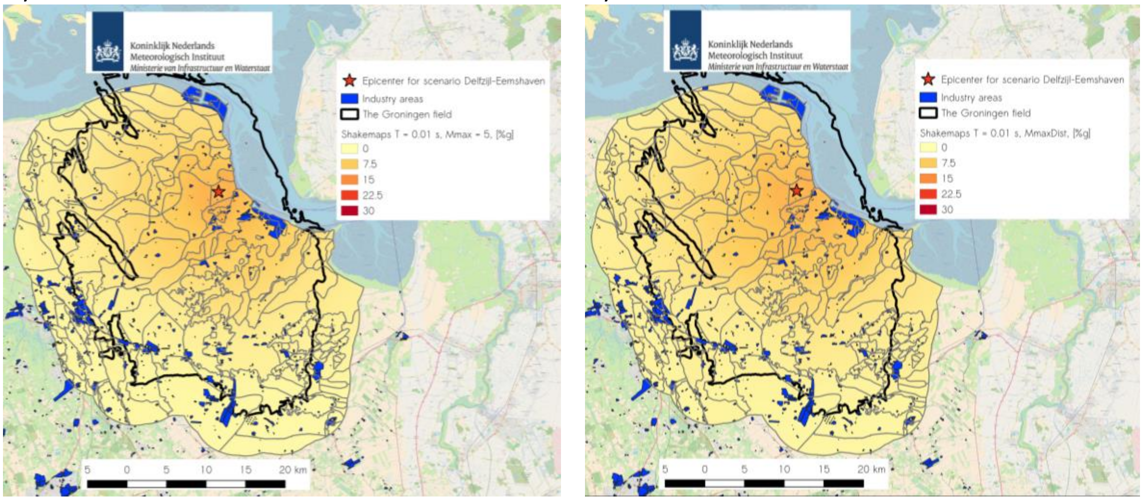


Figure B1: Shakemap with spectral acceleration for the period T = 0.01 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

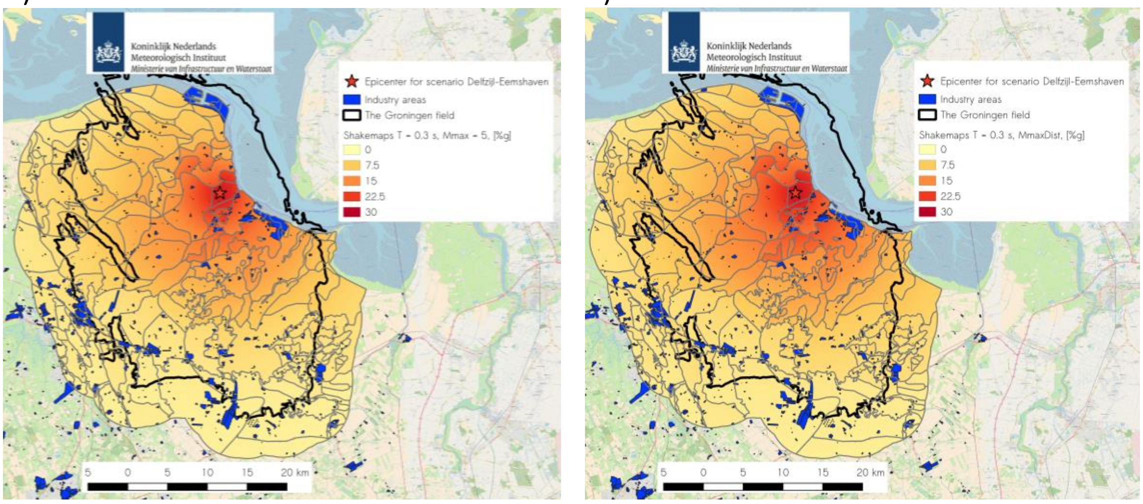


Figure B2: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

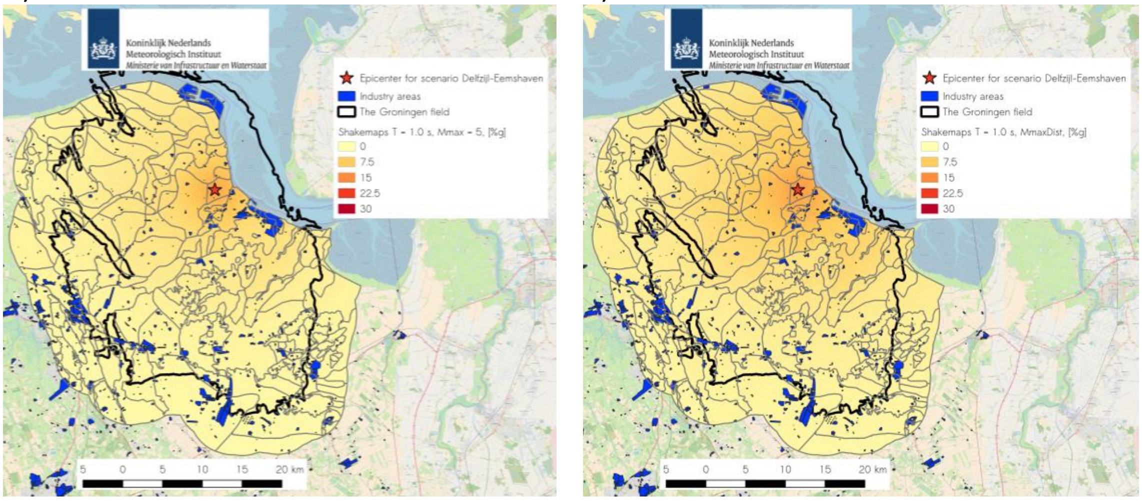


Figure B3: Shakemap with spectral acceleration for the period T = 1.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

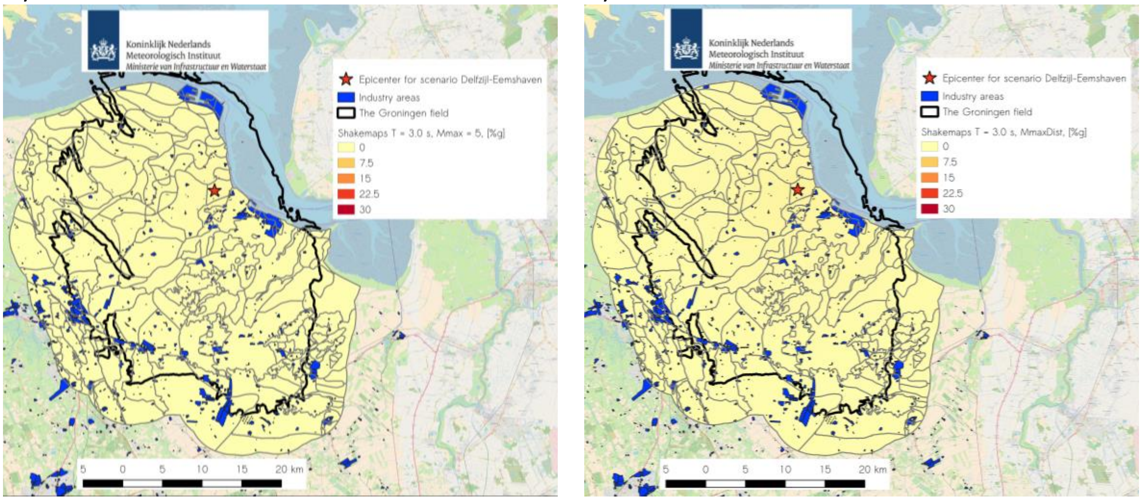


Figure B4: Shakemap with spectral acceleration for the period T = 3.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

C: General Shakemaps for Delfzijl and Eemshaven, earthquake scenario for average winter for period t3

A) B)

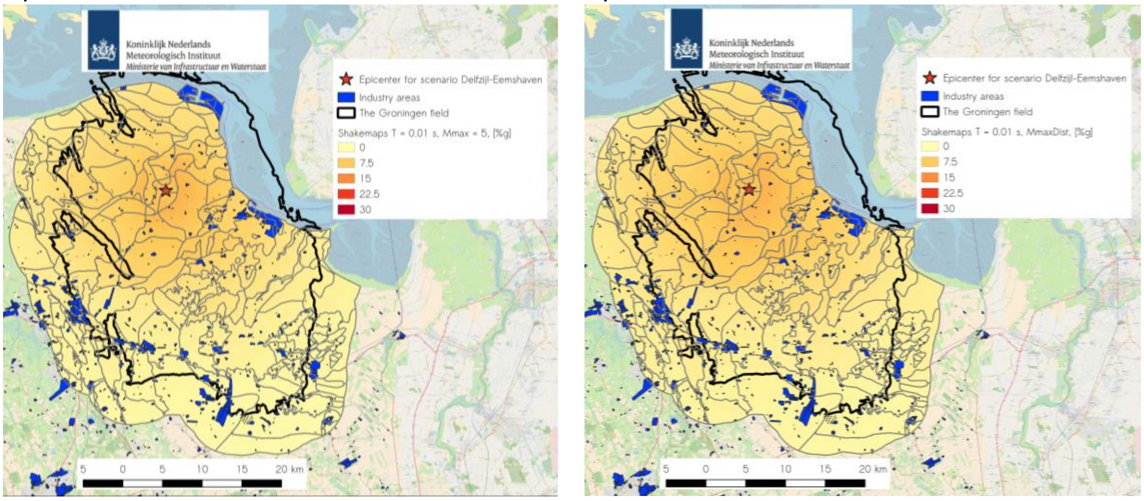


Figure C1: Shakemap with spectral acceleration for the period T = 0.01 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

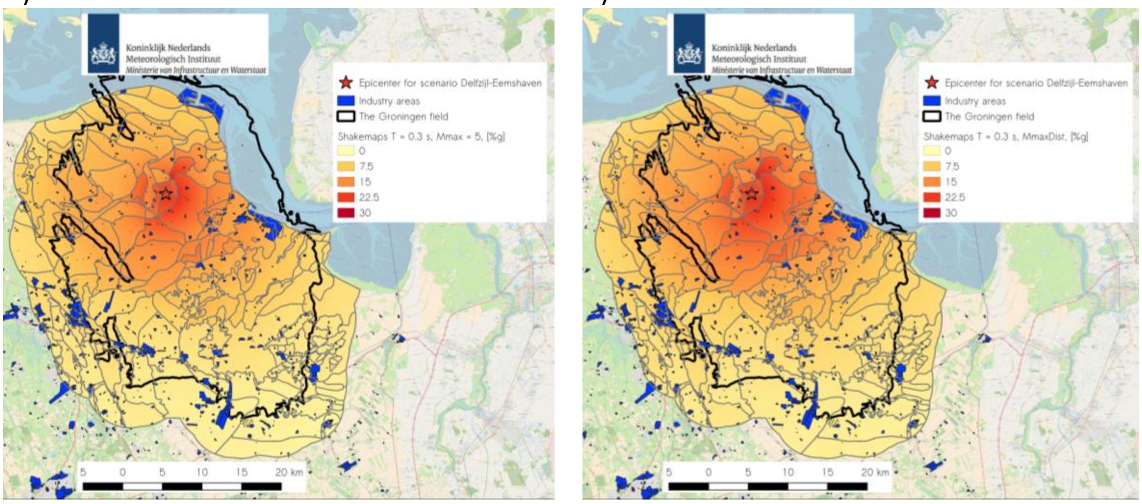


Figure C2: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

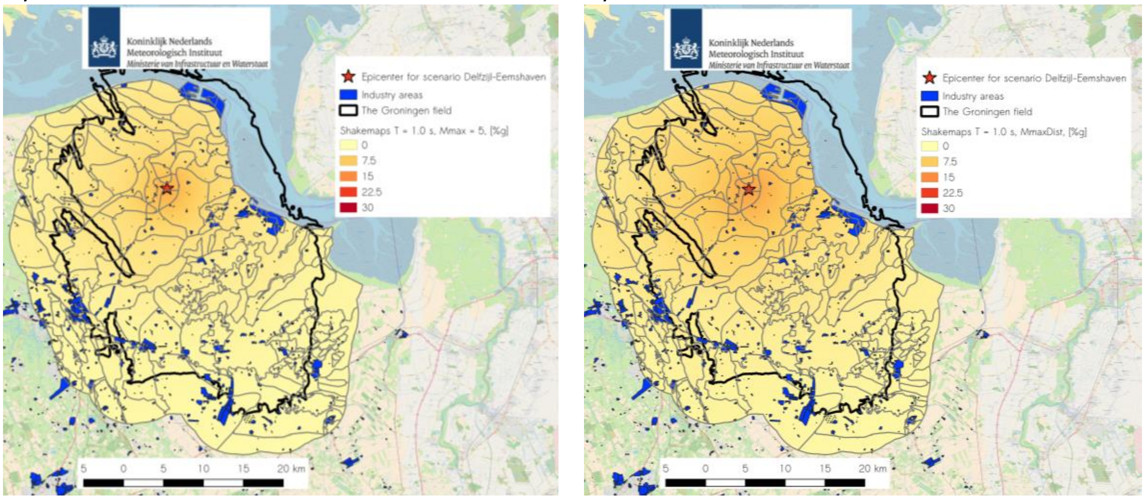


Figure C3: Shakemap with spectral acceleration for the period T = 1.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

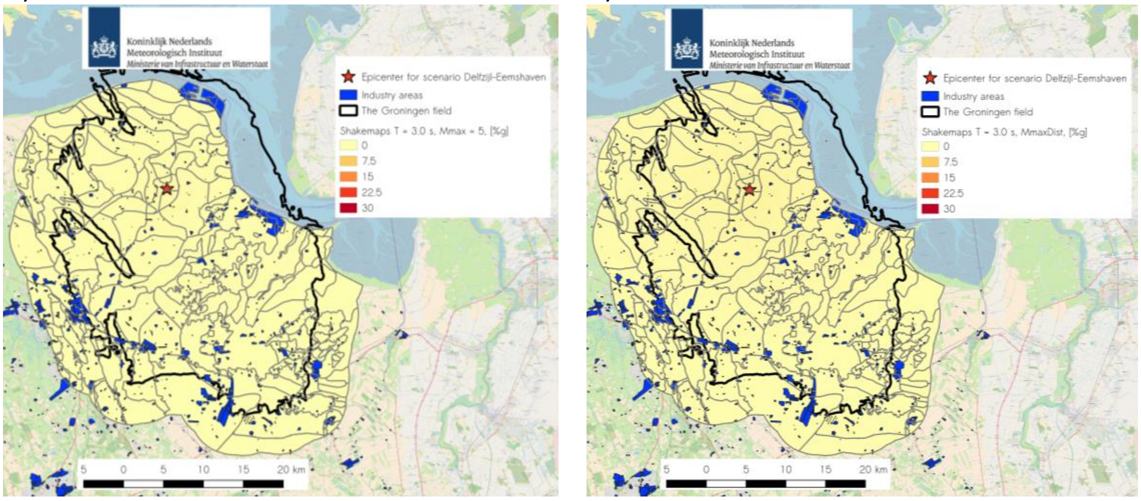


Figure C4: Shakemap with spectral acceleration for the period T = 3.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

D: General Shakemaps for Hoogezand and Veendam, earthquake scenario for KNMI model and average winter for periods t1-t2-t3

A) B)

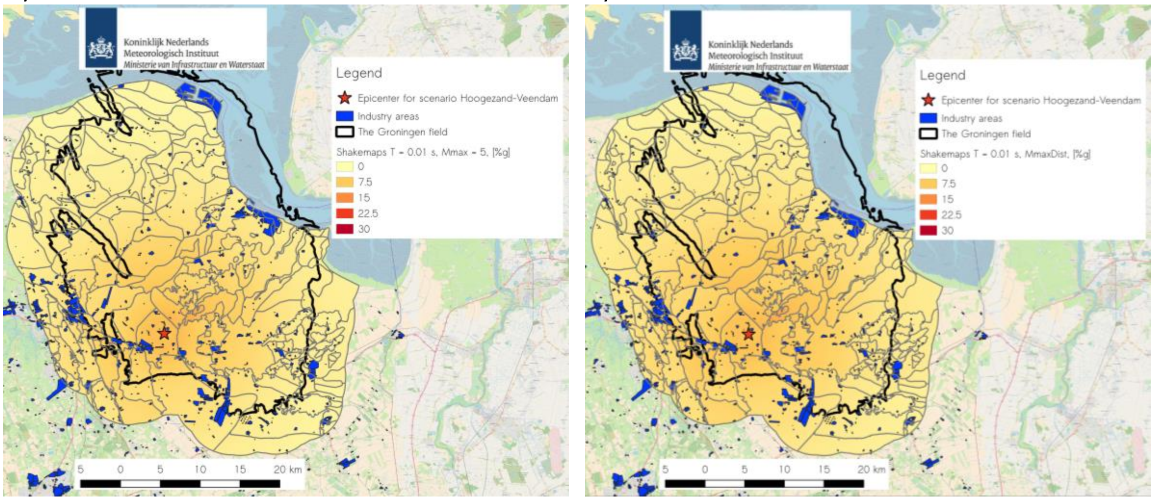


Figure D1: Shakemap with spectral acceleration for the period T = 0.01 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

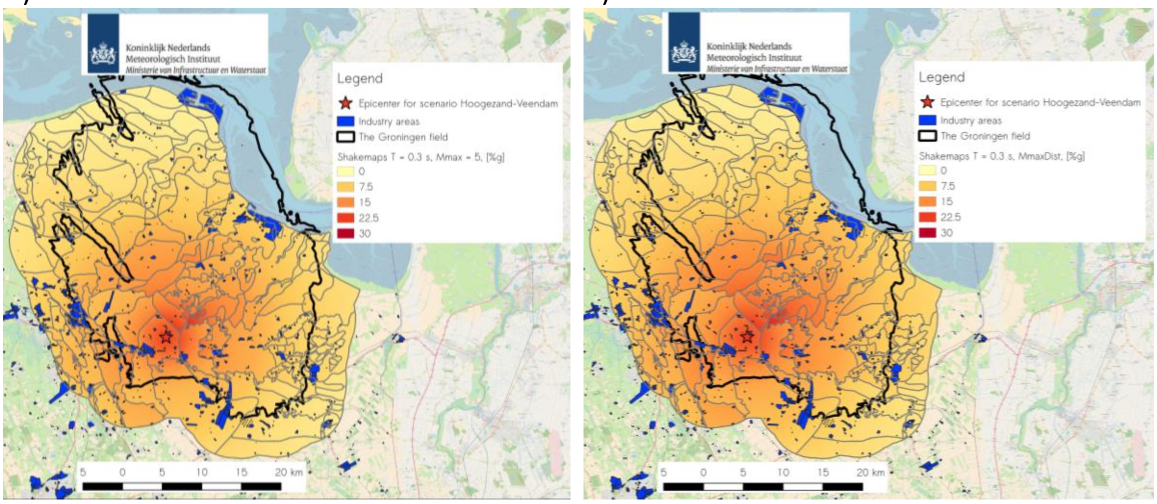


Figure D2: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

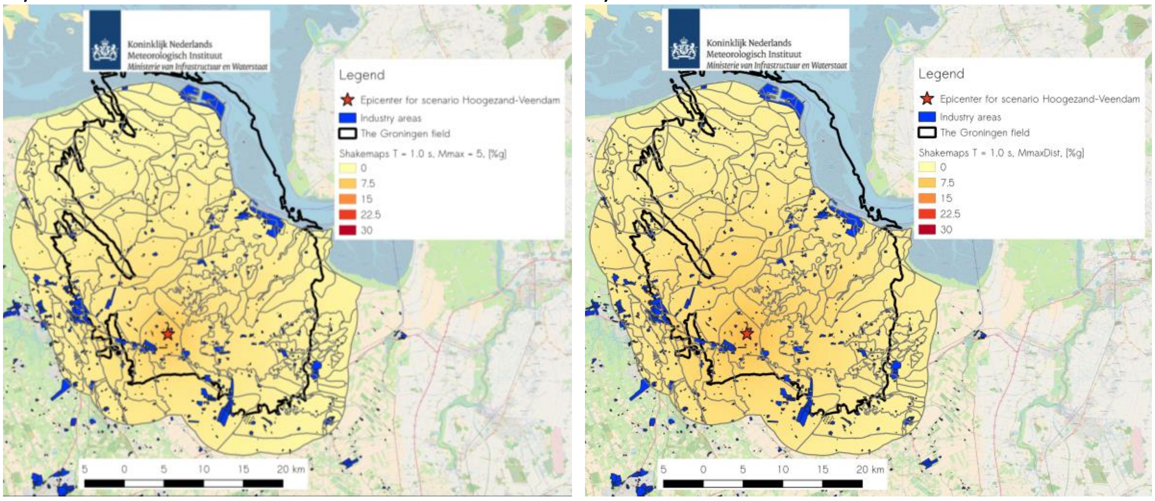


Figure D3: Shakemap with spectral acceleration for the period T = 1.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

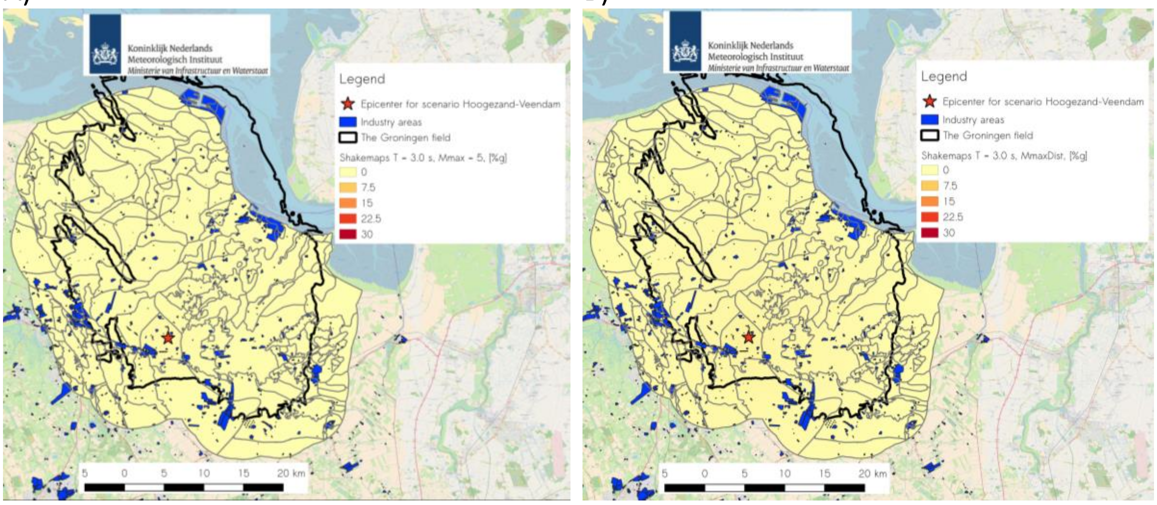


Figure D4: Shakemap with spectral acceleration for the period T = 3.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

E: General Shakemaps for Hoogezand and Veendam, earthquake scenario for KNMI model and average winter for periods t1-t2-t3

A) B)

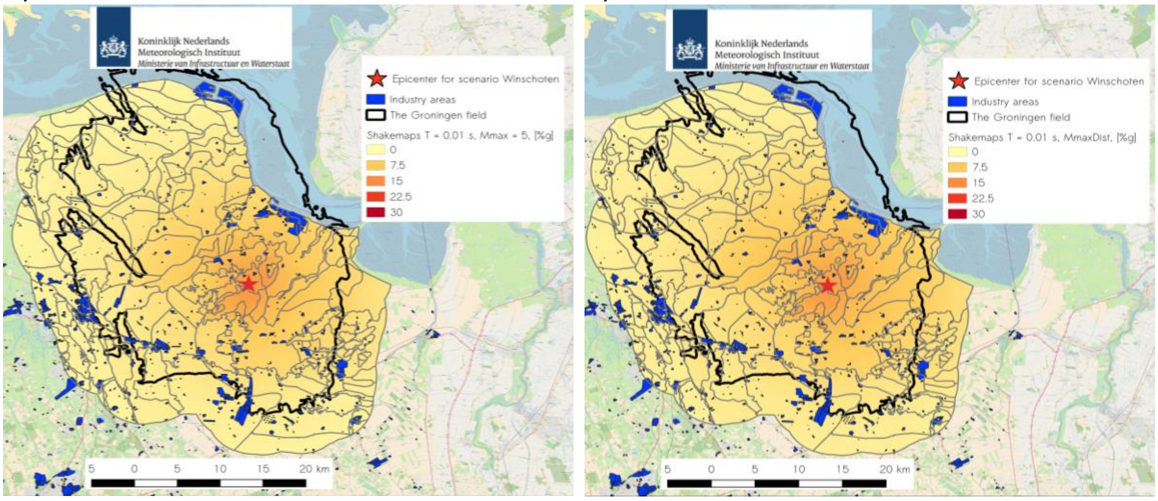


Figure E1: Shakemap with spectral acceleration for the period T = 0.01 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

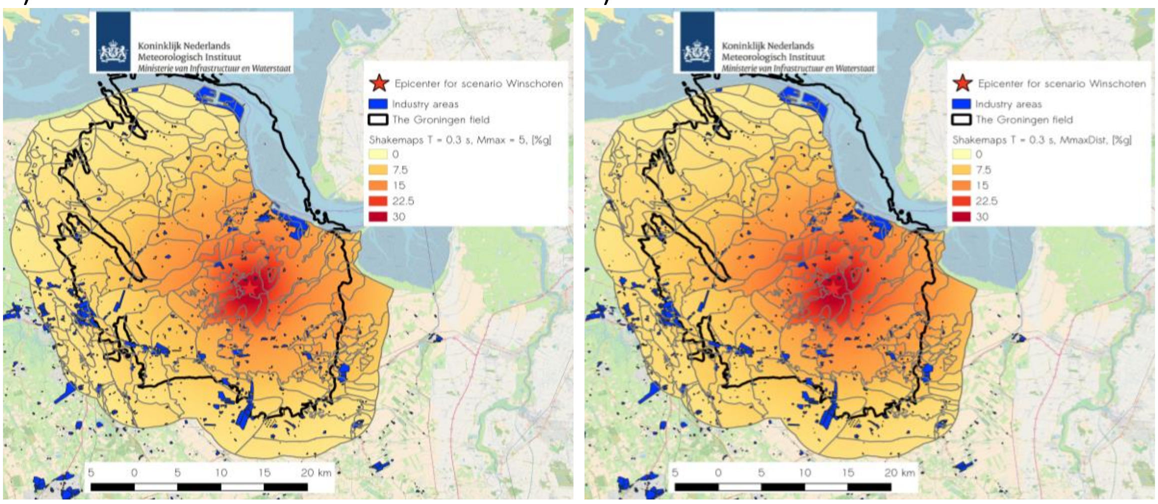


Figure E2: Shakemap with spectral acceleration for the period T = 0.3 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

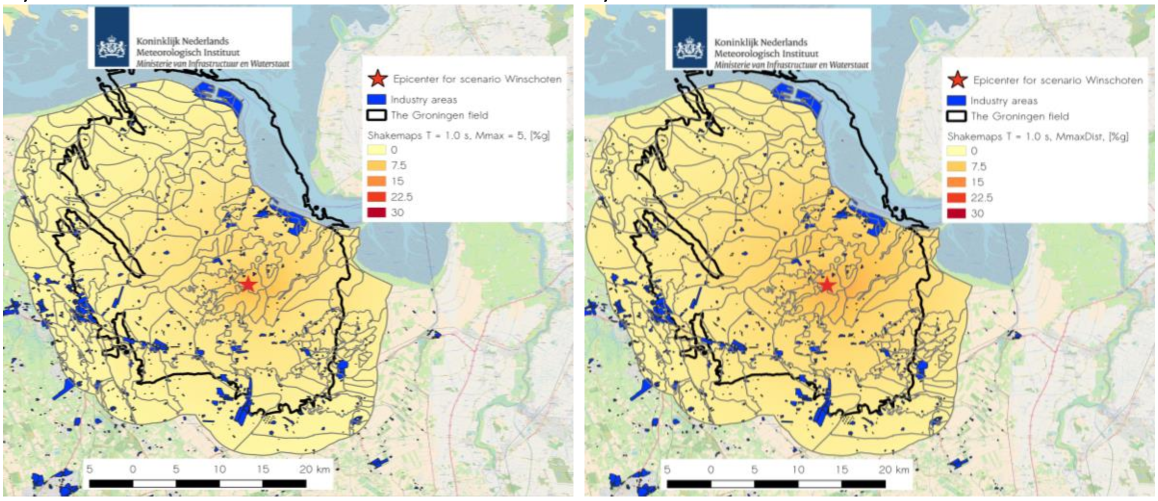


Figure E3: Shakemap with spectral acceleration for the period T = 1.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

A) B)

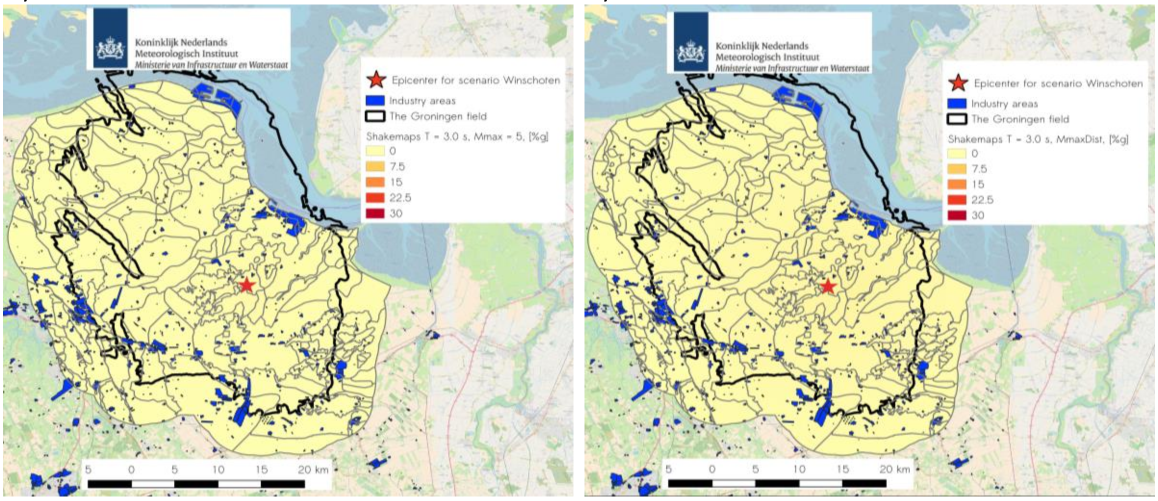


Figure E4: Shakemap with spectral acceleration for the period T = 3.0 s. A) Mmax = 5 scenario. B) Mmax distribution scenario.

F: Tables for industry, sites and location coordinates

Table F1: Coordinates for industry locations.

Company	Lon	Lat	RD_X	RD_Y
Noordgastransport	6.965814	53.31408	260207	593111
Vopak Terminal	6.800963	53.451345	248921	608157
GDF Suez	6.879396	53.436785	254165	606642
GasUnie Transport	6.859493	53.406097	252913	603200
Contitank	6.939494	53.323294	258432	594098
Lubrizol Advanced Materials	6.96294	53.313288	260018	593018
Akzo Nobel	6.942524	53.317738	258647	593484
Aardolie Opslag Groningen	6.562888	53.239586	233491	584307
Bayer Material Service	6.716619	53.17206	243893	576972
C. G. Holthauser	6.725536	53.163967	244506	576083
DFE Pharma	6.71581	53.169758	243843	576715
GasUnie Mengstation	6.886298	53.156098	255274	575419
GasUnie	6.874151	53.150399	254475	574768
Groningen Railport	6.897239	53.125705	256077	572052
Kisuma Chemicals	6.893934	53.112165	255887	570541
Koopman Warehousing	6.729106	53.16719	244738	576446
NAM RBI	6.973165	53.293422	260748	590823
Reining Warehousing	6.73753	53.172644	245290	577063
Sita Ecoservice	6.871923	53.088437	254468	567870
Stinoil	6.890917	53.098018	255718	568962
JPB	7.053	53.1357	266537	573395

Table F2: Coordinates for sites in near-surface zonation model.

Industry zone	Lon	Lat	RD_X	RD_Y
Eemshaven	6.814132	53.457615	249782	608872
Eemshaven	6.8035117	53.453786	249085	608432
Eemshaven	6.8012156	53.449437	248942	607945
Eemshaven	6.8149424	53.447127	249859	607706
Eemshaven	6.8331012	53.452662	251053	608346
Eemshaven	6.8271254	53.441914	250680	607142
Eemshaven	6.8482603	53.44999	252066	608069
Eemshaven	6.8626861	53.443119	253040	607324
Eemshaven	6.8508892	53.438797	252266	606827
Eemshaven	6.8730029	53.437664	253738	606731
Eemshaven	6.8706812	53.412279	253642	603904
Delfzijl	6.9036216	53.311284	256069	592711
Delfzijl	6.9110563	53.314883	256556	593122
Delfzijl	6.9360331	53.323407	258200	594106
Delfzijl	6.9471074	53.320433	258945	593791
Delfzijl	6.9471466	53.313639	258964	593035
Delfzijl	6.9699902	53.314984	260483	593217
Delfzijl	6.9704832	53.308795	260531	592529
Delfzijl	6.9867353	53.306432	261620	592290
Delfzijl	6.9862212	53.300256	261601	591602
Delfzijl	6.9783241	53.299678	261076	591526
Delfzijl	6.9709186	53.297367	260588	591258
Delfzijl	6.987638	53.284267	261735	589825
Hoogezand	6.6846476	53.175833	241748	577352

Hoogezand	6.6932923	53.173331	242331	577084
Hoogezand	6.7137764	53.170185	243707	576759
Hoogezand	6.7159243	53.165614	243860	576253
Hoogezand	6.7142845	53.1731	243735	577084
Hoogezand	6.7223721	53.171033	244280	576864
Hoogezand	6.7347313	53.173133	245101	577113
Hoogezand	6.7293399	53.170012	244748	576759
Hoogezand	6.7274947	53.165485	244634	576253
Hoogezand	6.7460961	53.16639	245875	576377
Veendam	6.8948074	53.104165	255964	569651
Veendam	6.8966852	53.092467	256117	568352
Veendam	6.885102	53.09166	255343	568246
Veendam	6.8807764	53.086133	255066	567625
Veendam	6.8960554	53.115572	256022	570922
Winschoten	6.9937	53.1615	262445	576175
Winschoten	7.0203	53.1579	264233	575814
Winschoten	6.9869	53.1463	262028	574473
Winschoten	7.0137	53.1493	263813	574847
Winschoten	7.0426	53.1547	265732	575492
Winschoten	7.0555	53.1474	266614	574700
Winschoten	7.0349	53.1420	265250	574067