Seismic Hazard Assessment of Two Production Strategies for Groningen

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

[redacted], [redacted] and [redacted]

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Summary

The Royal Netherlands Meteorological Institute (KNMI) was asked by the Ministry of Economic Affairs and Climate (EZK) to advice on the seismic hazard for Groningen, based on two proposed operational strategies (OS1 and OS2) for the production year 2020-2021. OS1 minimizes the strength of induced earthquakes and OS2 the number of induced earthquakes.

Two seismological source models were evaluated in terms of the foreseen geographical spread in seismicity and probability of occurrence of larger events. Results show comparable values for the expected seismicity between the operational strategies.

It was found that, both scenarios lead to a marginal differences in seismic hazard, with maximum Peak Ground Accelerations (PGA) of 0.085g and 0.081g respectively. The KNMI and NAM hazard maps were compared and an average difference of 0.033g in the absolute value of the PGA was found, next to comparable regional distribution of the hazard. Difference plots between KNMI and NAM hazard maps show a large scale NW-SE pattern, where KNMI results show lower values in the NW and higher values in the SE. The most likely cause is the application of seismic source zones in the KNMI calculations, which provides a smoothing of the hazard, combined with the use of a mean seismic source model.

It is concluded that, the variations in hazard between OS1 and OS2 are marginal and that the hazard patterns from KNMI and NAM are comparable, but there are differences in absolute values.

Introduction

The Royal Netherlands Meteorological Institute (KNMI) has been asked by the ministry of Economic affairs and climate policy (EZK) to give advice on the decision to determine an operational strategy for the production of the Groningen gas field. Two operational strategies are proposed, the first one (OS1) is a continuation of the selected strategy in 2019, adapted to the equation for the determination of degree days for 2020-2021. The second strategy (OS2) is based on the first, but only involving two specific clusters (Bierum and Eemskanaal) if necessary based on the gas demand.

The specific questions from the director Gas transition Groningen are:

1. Validate the calculations and results thereof for the operational strategies produced by NAM, specifically with respect to changes in the geographical spread of seismicity and the probability of occurrence of (larger) induced earthquakes.
2. What is the expected seismic hazard for the gas year 2020-2021 considering all (if required corrected) field data? Are there differences in seismic hazard compared with the expected results by NAM? If so, what is the reason for any observed differences?
3. Are you able to present a graphical illustration of the seismic hazard (specifically PGA for the return period 475 y).[1]

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1. [1] Valideer de berekeningen en de resultaten van de operationele strategieën geproduceerd door NAM waar het gaat om veranderingen in de geografische spreiding van seismiciteit en

The first question can only be discussed using a seismic source model that includes the effect of production changes. At this moment two models are available for Groningen, both developed by NAM (Bourne & Oates, 2017; 2019). The first model is characterized by a stress dependent b-value (ratio between expected cumulative annual number of large and small magnitude events, or also referred to as the slope of the Gutenberg Richter (GR) curve), while the second model is characterized by a constant b-value but a stress dependent taper on the GR curve. The characteristics of the tapers are defined in the zeta-values (Bourne et al., 2019). Application of these methods requires detailed information on production of the field and on subsurface parameters. Information was obtained from NAM, who also shared their results for the two scenario's. Since both models are used in the hazard calculations, we will discuss implementation of these models and compare our results with NAM calculations.

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

The PSHA uses the Ground Motion Model (GMM) for Groningen: GMM v6 (Bommer et al., 2019). The output of the seismic hazard method is in this report limited to Peak Ground Acceleration (PGA) maps. The PGA maps for the different production cases allows to estimate the consequences about the variability of the seismic hazard level during the reduction of gas extraction from the Groningen field. Both NAM and KNMI calculate PSHA, however taking a different approach. NAM uses Monte Carlo sampling to calculate hazard, while KNMI applies an integration procedure over seismicity zones. This implies that results may differ. We will investigate differences between the two approaches.

In the first part of the report, the two operational strategies and the seismic source models used are briefly introduced and the implications in terms of input parameters for PSHA are discussed. Then, GMM v6 is introduced and the most important parameters used in the PSHA, such as the maximum magnitude and the PSHA method applied by the KNMI. The seismic hazard maps are presented for the operational strategies. A comparison of the presented hazard results with the ones calculated by NAM for the same production scenarios and the GMM v6 are discussed.

Production Strategies

The seismic hazard related to a production strategy for gas extraction of the Groningen field was introduced in a KNMI hazard report in June 2018 (KNMI report, 2018). In the present report, two production strategies are considered, based on the estimated gas volume

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de kans op (zwaardere) geïnduceerde aardbevingen

2. Welke seismische dreiging verwacht u in het gasjaar 2020-2021, mede op grond van alle (waar nodig gecorrigeerde) waarnemingen in het veld? Zijn er verschillen met de seismische dreiging die NAM verwacht, en zo ja, hoe zijn die verschillen dan te verklaren?
3. Kunt u de verwachtingen grafisch weergeven in de seismische dreigingskaart (PGA die eens in de 475 jaar voor komt)?

requirement, shown in Figure 1. Due to time constraints we limited our analysis to an average winter (green line).

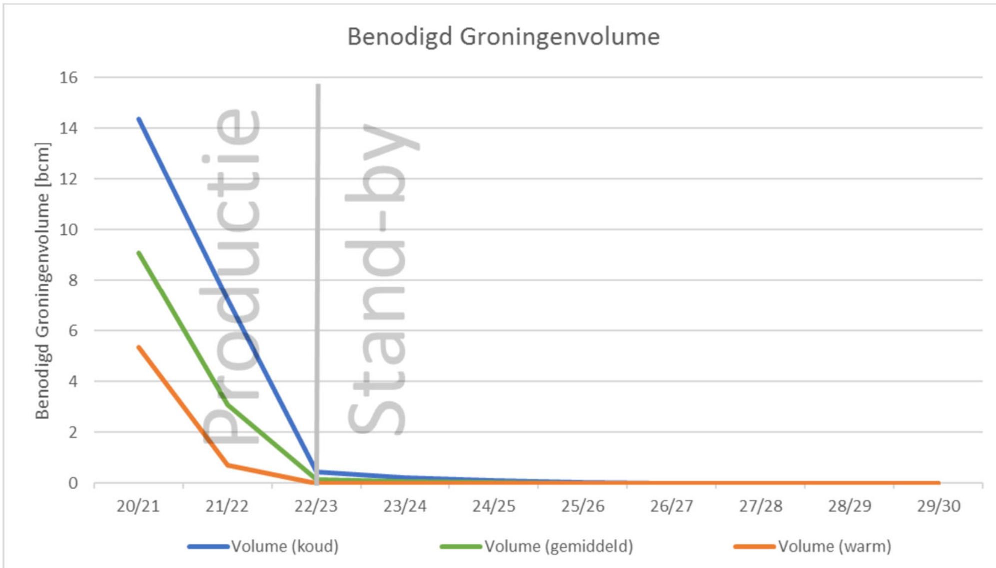

Figure 1. Overview of total gas volume to be produced in gas years 2020/21 – 2029/30[2]

The first operational strategy (OS1) is a continuation of the operational strategy (OS1 2019/20) for the current gas year (2019/20), adapted to the requirements for the coming gas year. The strategy is intended to minimize the population weighted Peak Ground Velocity. The production of gas is preferentially from the south-east. If the demand for gas increases, production clusters in the South-West and central-East region are opened. The second operational strategy (OS2) has the objective to minimize the event count. The production of gas takes place at clusters in the southern part of the field. Clusters Eemskanaal and Bierum are only used at a higher production demand.

Figure 2 shows the development of total production volumes for both operational strategies. The main differences between the strategies are the inclusion of the Bierum cluster in OS1 for gas year 2020/21. The Bierum cluster is situated in the north-eastern part of the gas field.

2 Source: GTS-raming benodigd Groningenvolume en capaciteit gasjaar 2020-2021 en verder dd. 31 januari 2020.

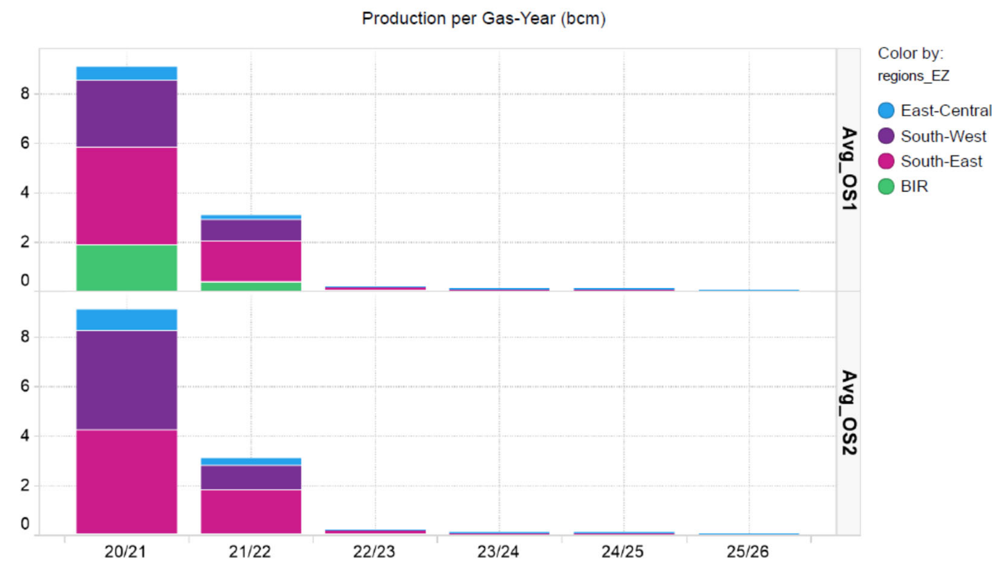

Figure 2. Regional distribution of production volume per gas year for OS1 (top) and OS2 (bottom) for the average winter scenario. BIR= Bierum cluster (source NAM, 2020)

Seismological source model

Based on the estimated pressure changes over the field, calculated for OS1 and OS2 and kindly shared with us by NAM, we calculated from these data the expected number of induced earthquakes per year and their geographical distribution over the Groningen field. For these calculations, we used both the stress-dependent b-value method (Bourne et al., 2018) and the stress-dependent taper method (Bourne & Oates, 2019). The former provides laterally varying activity rates and b-values, while the latter provides laterally varying activity rates and taper (zeta) values and a constant b-value over the field. These parameters are input to the PSHA calculations. Both source models are used in the calculations, with weighting assigned: 20% stress-dependent b-value and 80% stress-dependent taper method.

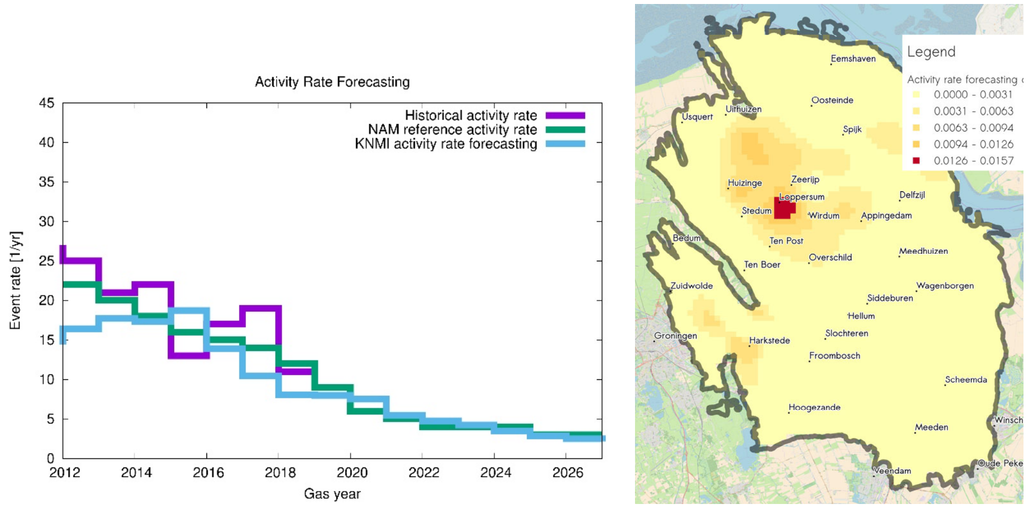

Figure 3. Forecast of activity rate for scenario OS1. Development of activity rate in time (left) and spatial variation of activity rate density for gas year 2020/21 (right).

For the total activity rate for the Groningen gas field (Figure 3, left), both KNMI and NAM predictions are comparable for the period 2020-2027. For the period before gas year 2020/21, calculations show larger differences and these are subject of ongoing research at KNMI.

For the spatial variation of activity rate (Figure 3, right), patterns show similarity with NAM results (Figure 5). The region characterized by the largest activity rate centers around Loppersum and a second region of increased activity is visible around Harkstede.

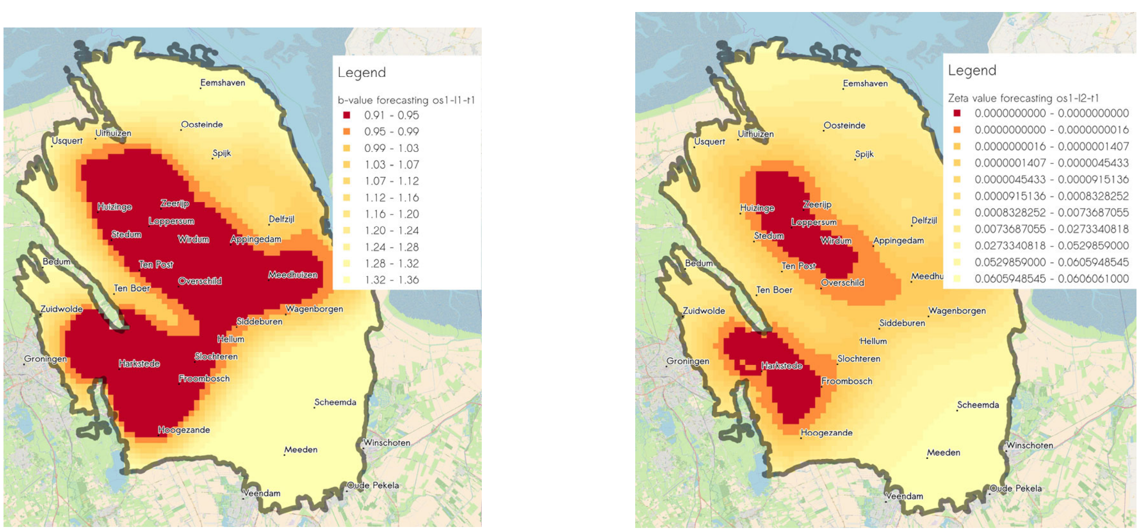

Figure 4. Spatial variation of b-values (left) and zeta values (right) over the Groningen gas field.

For the b- and zeta-values a similar variation is seen over the gas field (Figure 4), but the patterns do not exactly match the NAM patterns. Although we were able to calculate activity-rate, b-values and zeta-values from the pressure maps and obtained comparable results, a detailed comparison was not finished in time to be taken into account in the present advice. However, from the calculations we carried out, we are confident that the results published by NAM are valid. The procedure knows many steps in smoothing and regularization of the different parameters and this will easily result in small changes.

Due to time constraints, we decided to continue our calculations with the results from NAM and use these values to define zonations for activity rate, b-values and zeta values. The output files from the calculations from NAM are from the Maximum A posterior Probability (MAP) model from the posterior distribution of models. We use this model in our calculations without including the uncertainties in the model parameter values, since the evaluation of the uncertainty and its implementation in the hazard calculation was not ready yet.

In Figure 5, we compare for gas year 2020/2021 the variations in activity rate for os1 and os2 for the stress-dependent b-value model. The same is shown in Figure 6 for the stress dependent taper model.

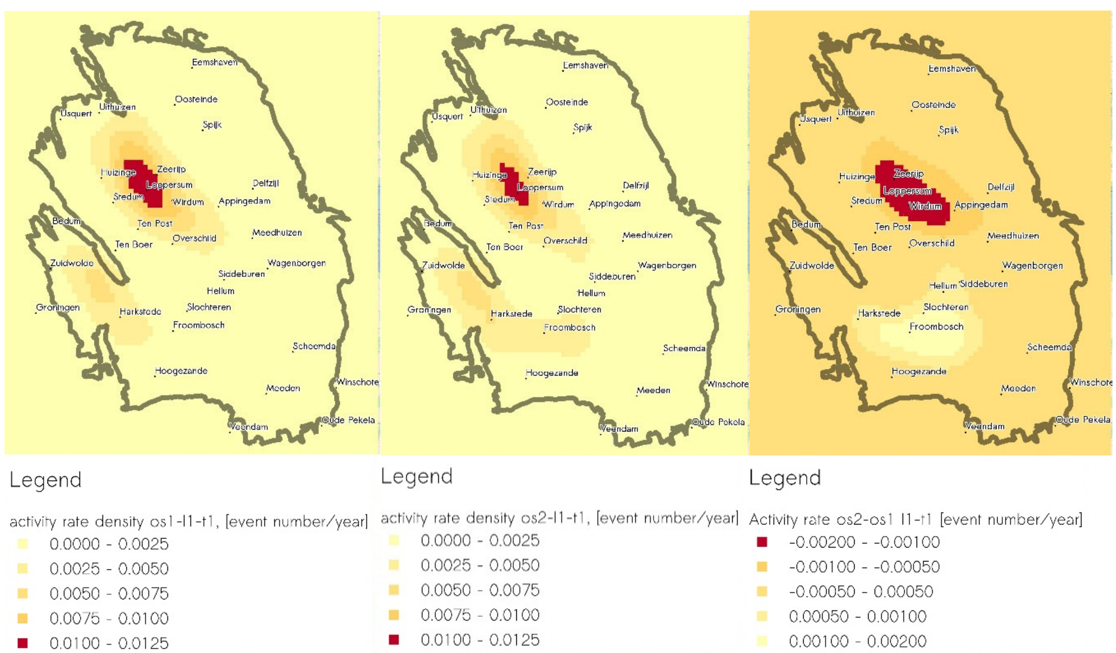

Figure 5. Activity rate density for the stress dependent b-value model for gas year 2020-21 for OS1 (left), OS2 (middle) and the difference between the scenario’s (right).

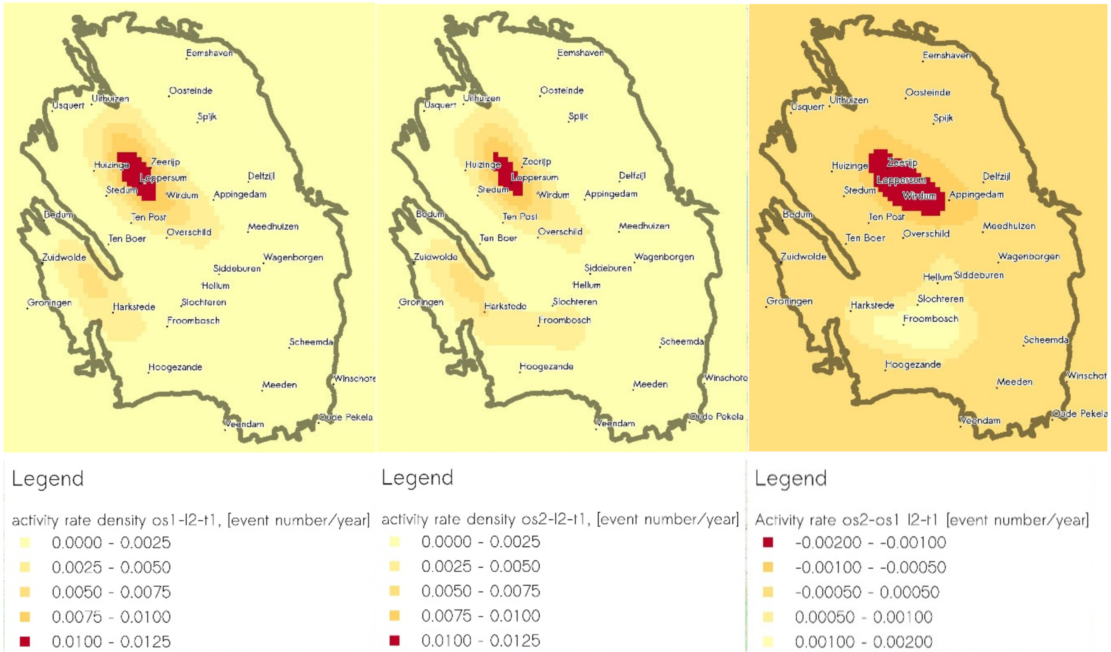

Figure 6. Activity rate density for the stress dependent taper model for gas year 2020-21 for OS1 (left), OS2 (middle) and the difference between the scenario's (right).

In terms of expected induced earthquakes, the two production strategies investigated in this report show a similar trend. The annual number of events (M >= 1.5) from 2010 to 2032 is shown in Figure 7. We confirm these small changes from our own calculations.

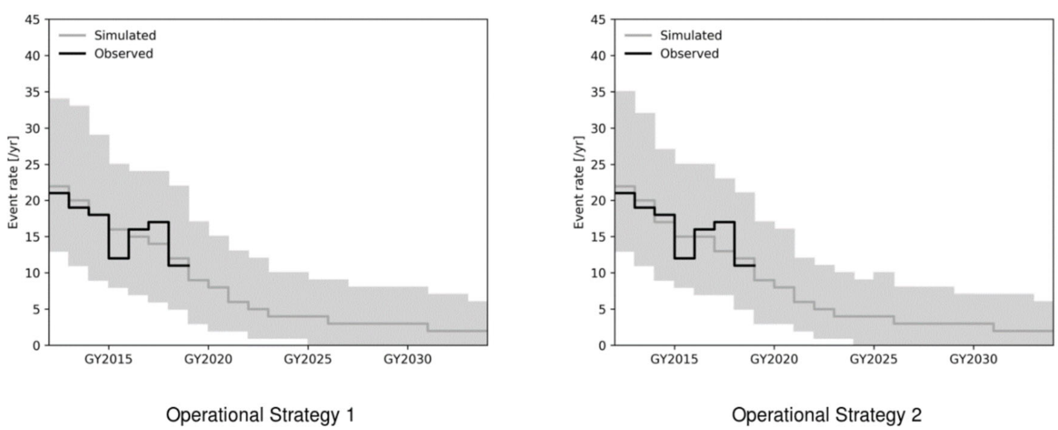

Figure 7. Seismic event rate for the average winter scenario for OS1 (left) and OS2 (right), source NAM report (2020).

Zonation

Based on the output of the seismic source model, zones were defined where activity rate, b-values and/or zeta functions are assumed constant (Figure 8).

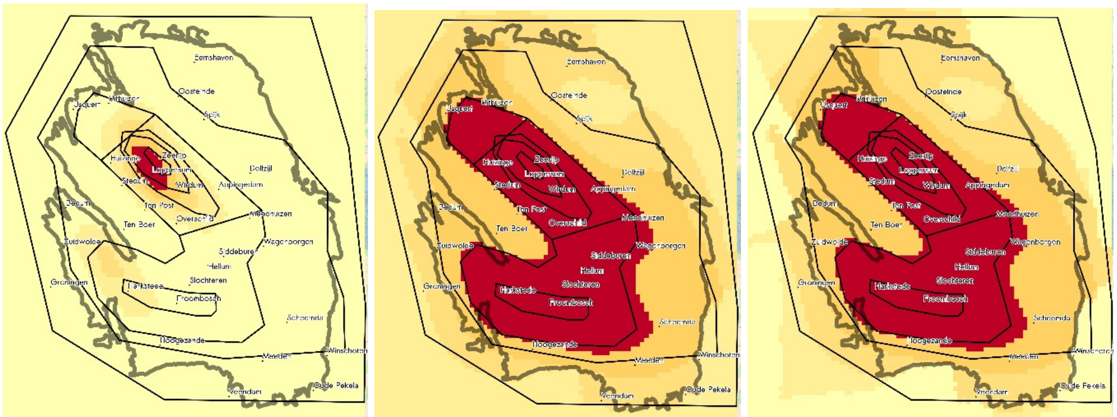

Figure 8. Zonations defined to include variations in activity rate (left), b-values (middle) and zeta-values (right).

Due to the integration over zones, we average the PSHA results over a larger surface and therefore our results will not show sudden changes in hazard. If we make the integration zone too small, the computing time will go up considerably. Therefore, we carried out some experiments with different zonations and compared results. Please note that we use one zonation for all three parameters and our final choice is displayed in Figure 8.

Ground Motion Model

The most recent version of the Ground Motion Model (GMM) for Groningen is version v6 (Bommer et al., 2019). Although the structure of the model did not change with respect to v5, new data were added to the database and a different subset of the dataset was used in construction of the model. When v6 was under development a calibration problem was detected in the gain setting of part of the accelerometer data at the surface (G-network). These data were not used in previous versions of the GMM, but were used for the first time in v6. The data were corrected before the model was constructed. Thus, the calibration problem did not influence the GMMs. Main features of v6 are further an update of the site response model and a correction of a processing error.

Rupture distance

In the development of the GMM for Groningen the simulation of larger events (M> 3.6) changed in v4 from a point source approximation to a simulation for an extended rupture. This implied also a change in the distance parameter and rupture distance was introduced. This distance is defined as the shortest distance from the observation point to the part of the fault that moved. In order to calculate this distance, assumptions should be made on which faults are capable to show large movements.

In recent studies (e.g. Willacy et al. (2018, 2019), Spetzler and Dost, 2017) it is shown that re-locations of events in the Groningen field all group along the main known faults in the reservoir. Therefore we would suggest to use the known set of faults to calculate the rupture distance. However, since NAM decided to take a more conservative approach and assumed that on each of the grid points in the calculations a fault could exist, characterized by the average strike direction of faults in the field (NNW-SSE), we followed their approach. This way we can compare results.

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, all GMM's for Groningen are constructed for seismological events originating at reservoir depth and therefore will provide conservative results. On the other hand for return periods less than 2500 years, the contribution of events M > 5.5 is minimal. The M_{max} distribution is presented in table 1. The average magnitude of the M_{max} distribution is <M> =5.

In view of the limited time available for the calculations it was decided to simplify the M_{max} distribution. An alternative 3 point distribution was proposed by Stephen Bourne (pers. comm.), who showed that the 3-point M_{max} distribution is slightly more conservative in the prediction of spectral acceleration values compared to the original 7 point distribution (see KNMI report, 2018). The modified M_{max} distribution is presented in table 1. The average magnitude of the M_{max} distribution is $<M_{max}>$ = 5.1.

Table 1: Modified M_{max} distribution for Groningen (Source: Stephen Bourne).

M_{max}	4.5	5.4	6.8
Weight	0.46	0.43	0.11

The selection of M_{max} is more important for the seismic source model used in the 2019 hazard calculation than for the more recently developed alternative, due to the taper effect.

Probabilistic Seismic Hazard Analysis Method

The method of calculation of the PSHA is identical to the approach in the 2019 KNMI hazard update (KNMI report, 2019). In brief, a more general version of the method by Cornell (1968) was introduced to add the effect of magnitude-distance dependence in the near-surface amplification factor to calculate spectral accelerations in the PGA map and spectra. The two-step approach in the GMM v6 works as follows: First, the hazard probability due to an induced event at reservoir level (on average 3 km) is calculated at the reference level at 800 m depth. Second, the hazard curve at the surface is obtained by convolving the probability density function of the spectral acceleration at the reference level with the probability density function of the amplification factor. The amplification factor has a magnitude and distance dependence and this is accounted for in a general convolution integral wherein the contribution of the probability distributions of magnitudes, distances, amplification factor and ground motion are summed up (Bob Young, pers. comm.).

Seismic hazard maps for an average winter for gas year 2020-2021

The results of the PSHA hazard analysis for Groningen are presented in the form of PGA maps for the two production strategies for the average winter scenario in Figure 9 and 10, respectively. The return period in the PGA maps is 475 y according to Eurocode 8.

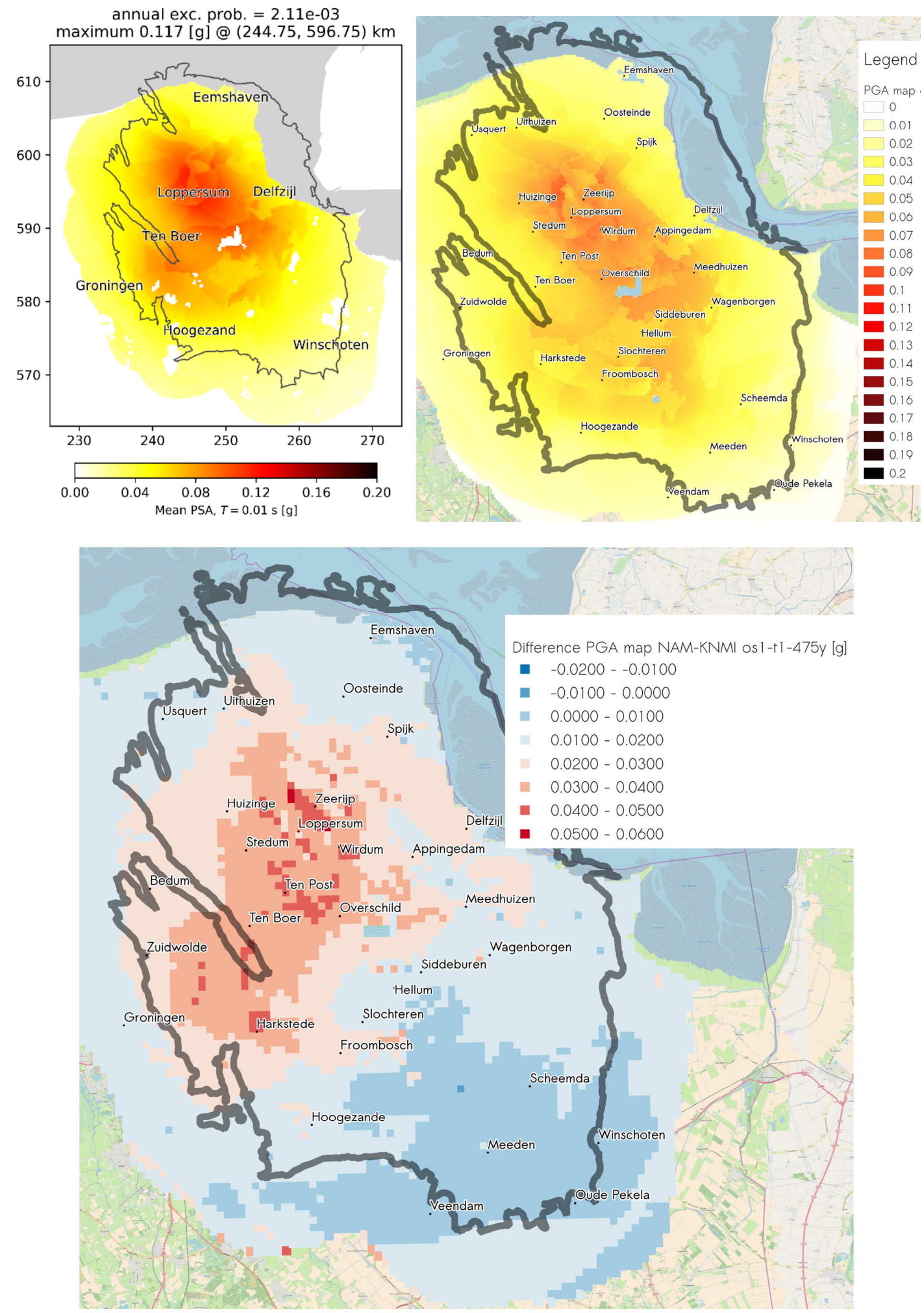

Figure 9. PGA map for gas year 2020-21, an average winter scenario and operational strategy 1 (OS1). Results by NAM (top left), KNMI (top right) and difference between the models (bottom).

The maximum PGA value for the OS1 scenario (Figure 9, top right) is 0.085g, which is 0.032g lower compared to the NAM results (Figure 9, top left). The spatial difference between the two maps (Figure 9, bottom) shows at first sight a correlation with the variation in b- or zeta-values (Figure 4), although these results were not used as input in the PSHA calculations.

For OS2 the results are comparable: a maximum PGA value of 0.081g, which is 0.034g lower compared to the NAM model. The spatial difference map between KNMI and NAM model (Figure 10) shows a similar pattern as for OS1.

In these difference plots a general pattern of larger PGA values to the south-east and lower values to the north-west is visible, suggesting that the smoothing effect of the zonations may at least explain some of the differences. The zones themselves are not visible in the difference plot. In addition to the zonation, uncertainty in the seismic source model was not incorporated in the hazard calculations. Further research is required to explain these features in more detail.

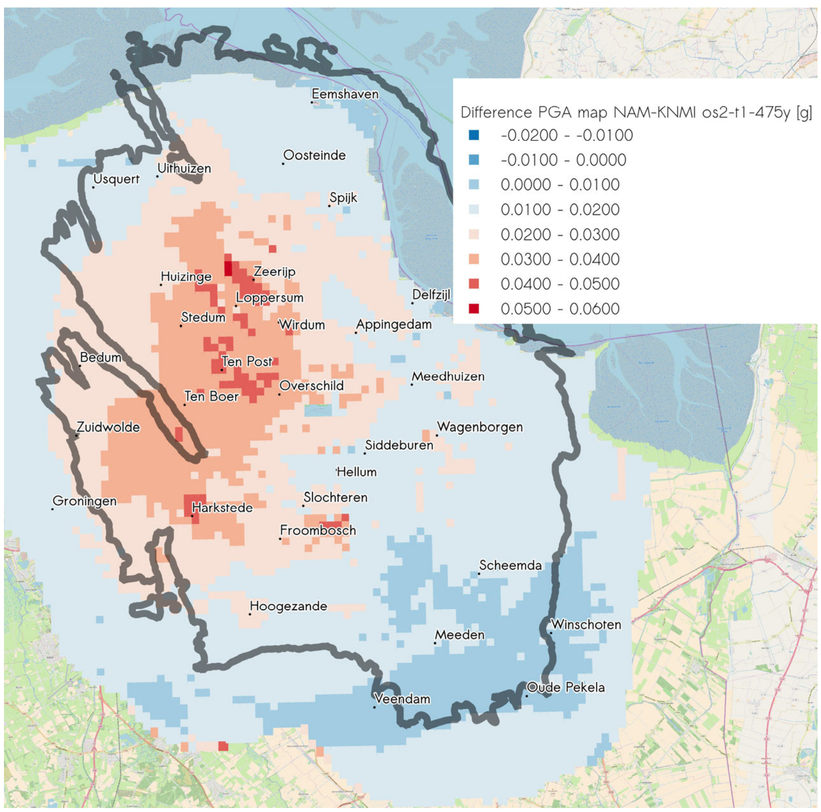

Figure 10. Difference between KNMI and NAM hazard maps for gas year 2020-21, an average winter scenario and operational strategy 2 (OS2).

The differences in PGA maps between the two operational strategies are rather small (maximum PGA difference: 0.004g). The maximum PGA values for OS1 are found to be marginally higher than for OS2. The max PGA values are found in the Loppersum area.

Conclusions

A seismic hazard assessment for two operational strategies for the gas year 2020/21 has been carried out for the Groningen gas field in response to questions from the director gas transition Groningen. The difference between the two operational strategies comes from the distribution of extracted gas over the production clusters during the year. In the first operational strategy, relatively more gas is produced from the southeast of the field to reduce the personal-related hazard. The second operational strategy is optimized to the minimum number of expected induced earthquakes.

The first question on the expectations on the changes in the geographical spread of seismicity was answered by an evaluation of the activity rate density, b- and zeta-values for the two strategies. Preliminary calculations using two seismic source models show comparable results with NAM. However, since these results are preliminary, the results from NAM have been used as input for the hazard calculations.

The second and third questions were related to the expected hazard in the same period (2020/21) and differences with respect to the hazard calculated by NAM.

The GMM v6 is applied in the hazard analysis and the return period is 475 y. The production scenario based PGA maps predicts max PGA values in the order of 0.081-0.085 g for the average winter scenario's and OS2 and OS1 respectively. The calculated PGA hazard maps have been compared with the equivalent maps by NAM. The PGA hazard maps show a similar pattern, but around 0.033g lower maximum PGA values in the Loppersum area.

The spatial pattern of differences between the KNMI and NAM results show a NW-SE trend, where KNMI values in the NW are lower and higher in the SE. The KNMI approach and the NAM method differ in the method of calculation, specifically the way the hazard integral is solved. The smoothing effect of the zonation model and the absence of the uncertainty in the seismic source model in the PSHA calculations by KNMI may explain these differences. This will be investigated in more detail.

Since recent studies have shown that seismicity is connected to the known main fault structure, we think that the assumption in the hazard calculations that large seismic events may occur everywhere in the field is conservative and should be limited to the pattern of main faults.

The increasing complexity of the models for Groningen requires a significant increase in computing power for the PSHA calculations.

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