

Technical Addendum to the Winningsplan Groningen 2016

Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field

Part I Summary & Production

The report “Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field” consists of five separate documents:

Document 1	Chapters 1 to 5;	Summary and Production
Document 2	Chapter 6;	Subsidence
Document 3	Chapter 7;	Hazard
Document 4	Chapter 8;	Risk
Document 5	Chapter 9;	Damage and Appendices.

Each of these documents is also available as a *.pdf file of a size smaller than 10Mbyte, allowing sharing through e-mail.

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Samenvatting

Achtergrond bij deze technische bijlage

Op 1 april 2016 heeft de NAM het Winningsplan Groningen Gasveld 2016 ingediend bij de Minister van Economische Zaken (EZ). Dit Winningsplan gaat vergezeld met een Technische Bijlage C, waarin technische verdieping en achtergronden zijn gegeven ten behoeve van het Winningsplan.

Deze bijlage presenteert diverse scenario's voor de productie van gas uit het Groningen gasveld en geeft de beoordeling van de effecten van elk van deze scenario's in termen van bodemdaling en geïnduceerde seismiciteit. Voor elk scenario worden de dreiging ('hazard') en de risico's ('risks') inclusief het schadepotentieel beoordeeld en daaromtrent verwachtingen gegeven.

Conclusies

Productie

- De productiescenario's beslaan drie niveaus: 21 miljard m³ (bcm) per jaar, 27 miljard m³ (bcm) per jaar en 33 miljard m³ (bcm) per jaar. Vervolgens wordt voor elk productieniveau een tweetal verdelingen over het gasveld gehanteerd: in aanvulling op de distributie van de winning over het gasveld zoals doorgevoerd op basis van het instemmingsbesluit van EZ van januari 2014 is een geoptimaliseerd scenario ontwikkeld. Deze optimalisatieoptie van de winning over het veld richt zich op de beperking van de seismiciteit. In totaal leidt dit tot een zestal beoordeelde scenario's.
- Met de mogelijke optimalisatie van de productieverdeling wordt tevens een andere clustering en regionalisatie van winningslocaties geïntroduceerd, inclusief bijpassende productieplafonds. In totaliteit blijft de productie voldoen aan de generieke beperkingen van productie uit het gehele gasveld.
- De beschikbare statische en dynamische modellen van het Groningen gasveld zijn verder verfijnd; suggesties gedaan door SGS Horizon (een onafhankelijk instituut dat toeziet op reserves binnen de olie- en gasindustrie), TNO en het Staatstoezicht op de Mijnen (SodM) zijn meegenomen in de aanpassingen. Het nieuwe reservoirmodel is nu niet alleen gekalibreerd op basis van de feitelijke, historische metingen ('history match') van productievolumes, reservoirdrukken en aquifers, maar ook bodemdaling.

Bodemdaling

- De meting van bodemdaling heeft plaats sinds het begin van de productie van aardgas in Groningen. Onder meer de volgende meettechnieken worden daarbij toegepast: waterpasmetingen en metingen met behulp van satellieten (InSAR en GPS).
- Zowel het gehanteerde 'Time decay model' als het 'Rate Type Compaction isotach Model' (RTCIM) voor de compactie geven een goede passing met de gemeten bodemdaling boven het gasveld.
- De waargenomen bodemdaling in het centrum van de bodemdalingsschotel was circa 33 centimeter in 2013. De verwachting is dat daar de daling na afloop van de productie ongeveer 50 centimeter zal zijn.

Het RTCIM-model is verkozen als het basismodel voor de compactie, omdat deze de beste overeenkomsten in tijd en ruimte geeft met de waargenomen reactie van bodemdaling op veranderingen in productie.

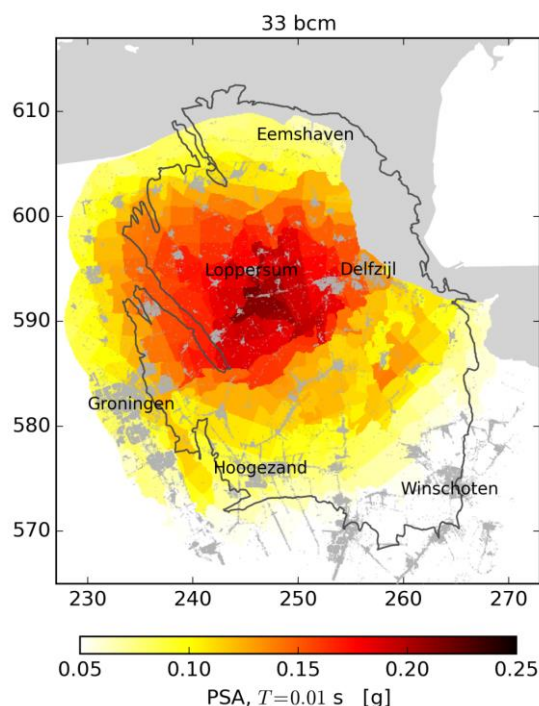
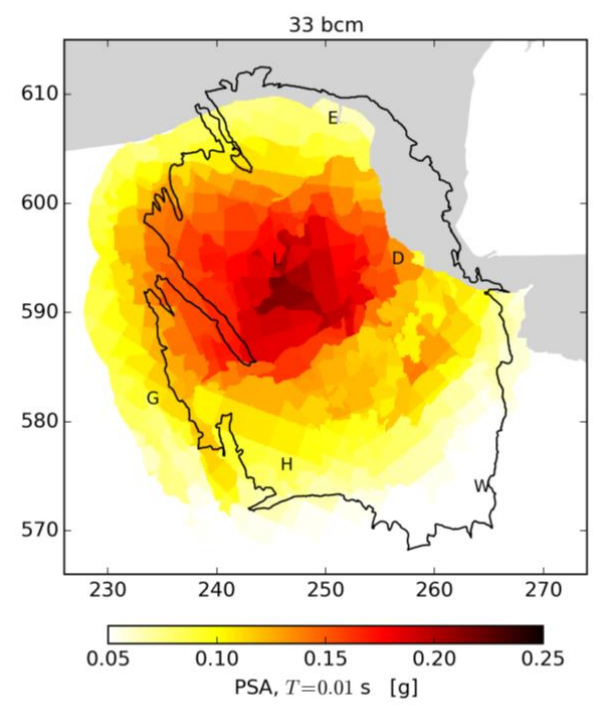
Seismiciteit

Voor de periode van 2016 tot 2021 zal de gemiddelde hoeveelheid aardbevingen en de gemiddelde energie die daarbij vrij zal komen – voor alle productiescenario's – naar verwachting van dezelfde orde zijn als in de periode van 2012 tot 2015.

Seismische dreiging

- De effecten van de lokale, ondiepe bodemsamenstelling op de groundbeweging bij een aardbeving zijn nu onderdeel van de analyse.
- In de voorliggende analyse is een correctie doorgevoerd in de software die gebruikt wordt om de bodembeweging te voorspellen. Deze omissie is recent ontdekt tijdens een detail-analyse en vergelijking van een tweetal modellen die worden gebruikt voor een parallelle berekening van de dreiging en risico's. De correctie is besproken met onder meer het KNMI, TNO, SodM en de Scientific Advisory Committee (SAC) die namens EZ toeziet op de kwaliteit van de risicobeoordeling. De waarde voor de variatie in lokale bodemsamenstelling, die werd gebruikt in het model dat ten grondslag lag aan de Hazard and Risk Assessment (HRA) van november 2015, was abusievelijk ingesteld op de maximale waarde. Dit onafhankelijk van de verwachte beweging van de diepere ondergrond, terwijl deze waarde variabel moet zijn aan de verwachte sterkte van aardbevingen. De doorgevoerde correctie heeft er toe geleid, dat zowel de seismische dreiging als het seismische risico in de onderhavige Technische Bijlage lager zijn dan in de HRA van november 2015.
- Het onderzoek en de beslisstructuur/-boom door middelen van zogeheten 'logic tree' omvat de meest significante onzekerheden. Het gewicht dat is toegekend aan deze onzekerheden is aangepast in overeenstemming met de verwachtingen die van overheidszijde zijn aangegeven (EZ's verwachtingenbrief van 15 februari 2016).
- Voor elk van de zes productiescenario's en voor een drietal tijdsbestekken zijn dreigingskaarten opgesteld en gepresenteerd. De dreigingskaart voor een productiescenario van 33 bcm per jaar in de periode van 2016 tot 2021 geeft een maximale grondversnelling (PGA) van 0.21g, dit met een gemiddelde jaarlijkse kans op overschrijding van 0.2%. De maximale PGA's voor de productiescenario's van 27 en 21 bcm per jaar zijn respectievelijk 0.20g and 0.19g. Beiden met dezelfde genoemde overschrijdingskans.
- De dreigingskaart voor het productiescenario van 33 Bcm per jaar voor de periode 2016-2021 – met een maximale PGA van 0.21 g – is onderstaand getoond.

Incl. topografie

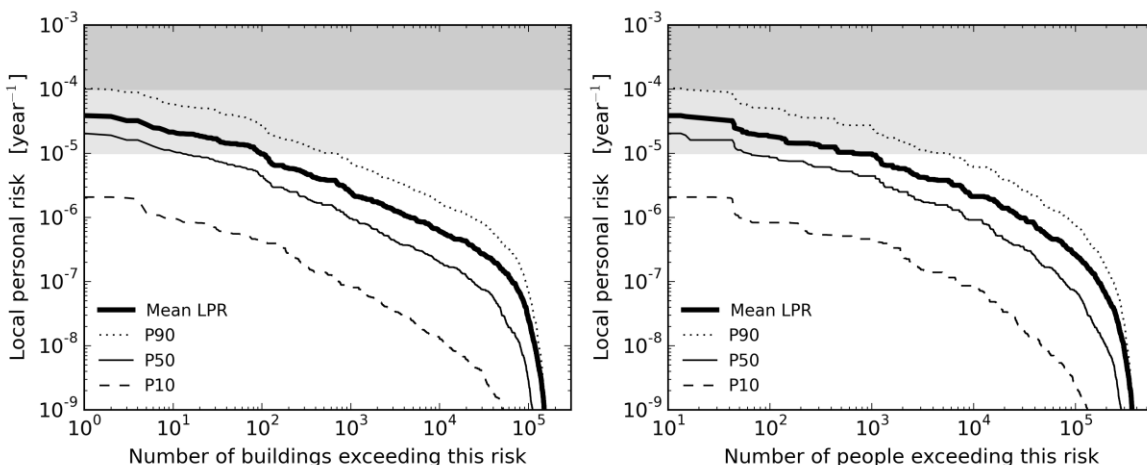


- Om aan te tonen welke aardbevingen de grootste bijdrage leveren aan de seismische dreiging is een onderscheid gemaakt naar een tweetal gebieden; het gebied rond Loppersum en de Stad Groningen. Wanneer wordt gekeken naar het Loppersum-gebied, blijkt dat de grootste bijdrage aan de seismische dreiging in dat gebied komt van aardbevingen binnen hetzelfde gebied (aardbevingen binnen een afstand van minder dan 5 kilometer en met een magnitude tussen de 4 en 5). Dit in tegenstelling tot de dreiging voor de Stad Groningen, die met name wordt gevormd door aardbevingen met een epicentrum die op ongeveer 10 kilometer afstand ligt, in de richting van Loppersum. Aardbevingen op grotere afstanden van de Stad zouden ook significante groundbewegingen in de Stad kunnen veroorzaken, maar deze moeten dan wel van een zwaardere magnitude zijn.

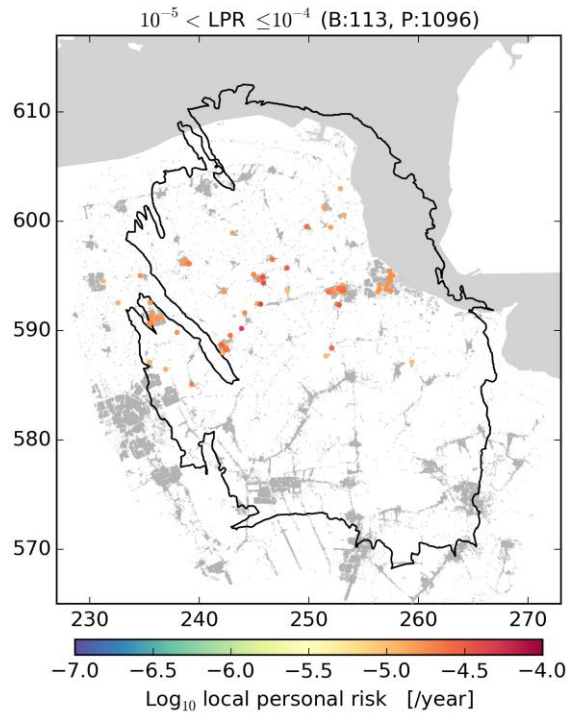
Seismische risico

- De risico-analyse omvat het bezwijken van gebouwen, met een focus op constructieve elementen van een bouwwerk. Potentieel vallende, niet-constructieve objecten zijn beoordeeld volgens een aparte methodiek en beschreven in een afzonderlijk rapport.
- De beoordeling van het individueel risico (op basis van ILPR, Inside Local Personal Risk) van bewoners in de regio toont, dat geen van de bewoners wordt blootgesteld aan een risico groter dan 10^{-4} per jaar in de periode van 2016 tot 2021. Geïllustreerd in onderstaande grafieken zijn er enkele honderden gebouwen waarin de bewoners mogelijk zijn blootgesteld aan een risico dat ligt tussen de 10^{-4} en 10^{-5} per jaar voor de genoemde periode.

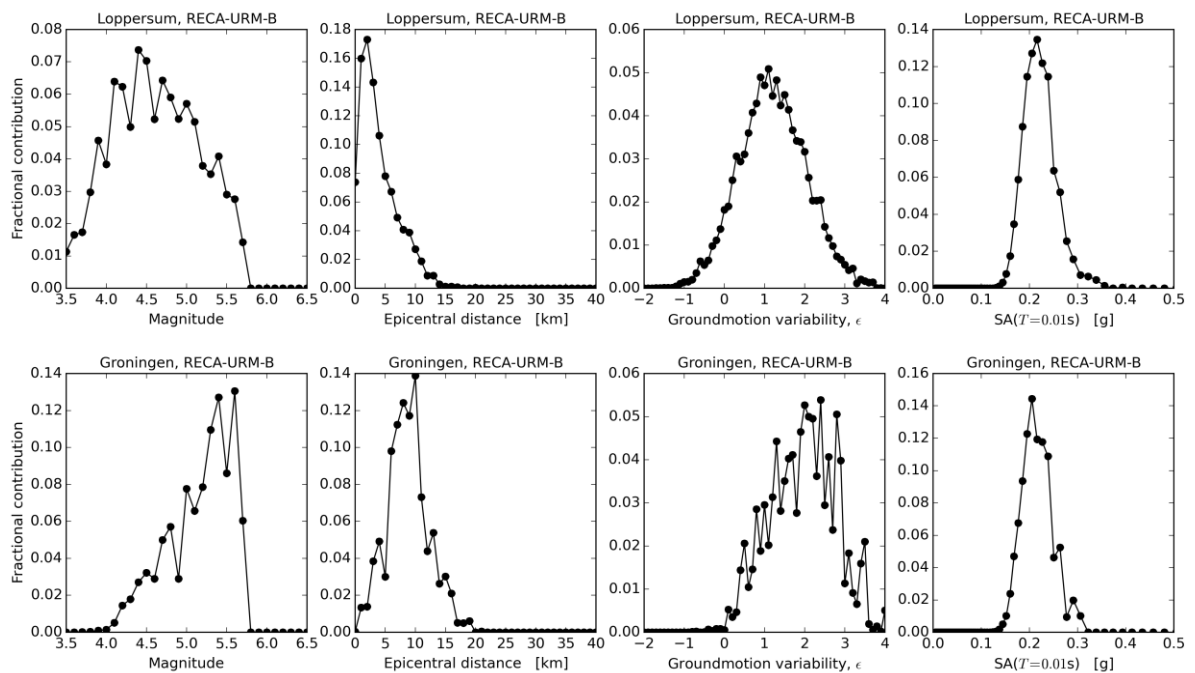
LPR Assessment for the 33 Bcm/year Scenario



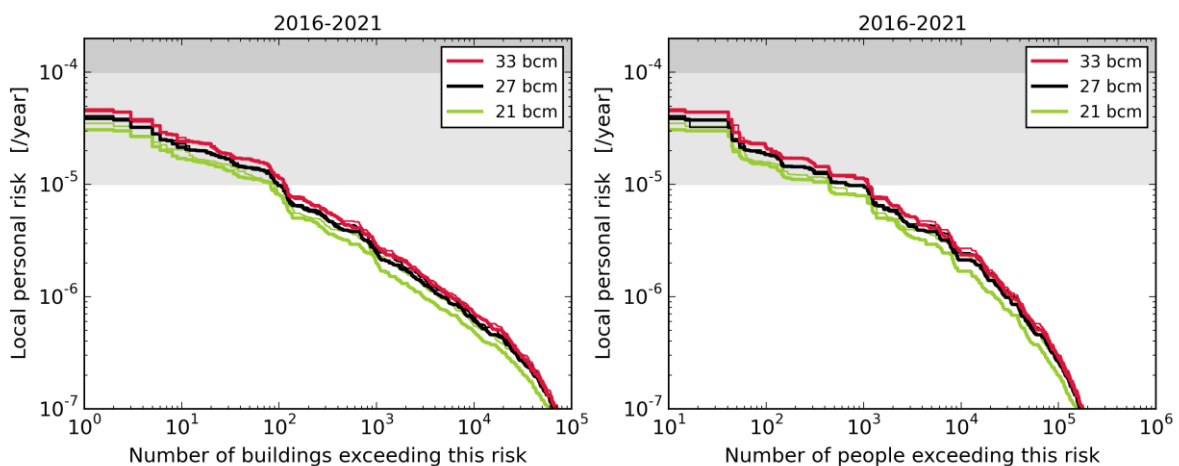
- De norm voor veiligheid die het Ministerie van EZ op basis van de adviezen van de Commissie Meijdam heeft gesteld kan worden behaald door het voorziene programma van bouwkundig versterken uit te voeren. Hierdoor kunnen alle betreffende gebouwen in een periode van 5 jaar worden verstrekt tot (onder) het risiconiveau van 10^{-5} . Op basis van de huidige onzekerheden (gereflecteerd in de bandbreedte) geldt voor ongeveer duizend gebouwen, dat er een kans van meer dan 10% bestaat dat de bewoners blootgesteld zijn aan een risico tussen de 10^{-4} en 10^{-5} .
- De gebouwen met een risico tussen de 10^{-4} en 10^{-5} per jaar bevinden zich met name op de lijn die zich uitstrekt van Delfzijl, via Loppersum, naar Bedum. In de onderstaande figuur zijn deze door middel van een kleuring gevisualiseerd.



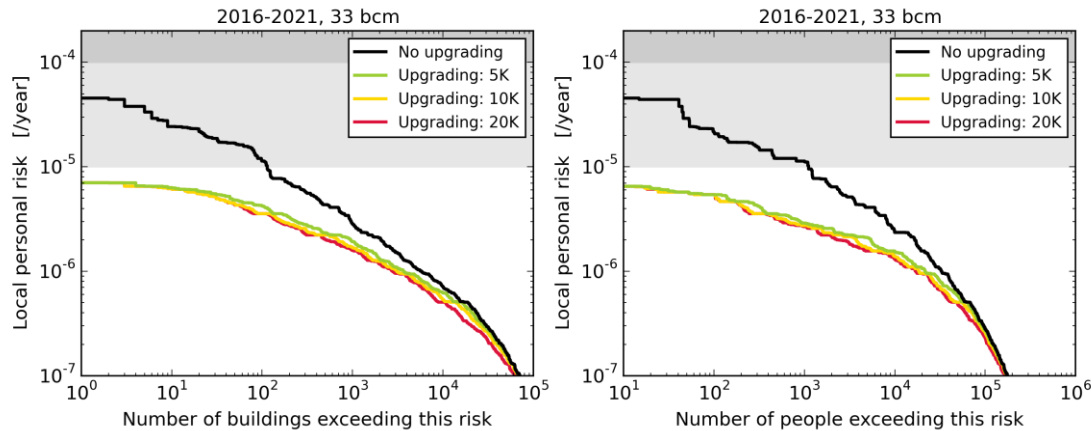
- Voor een tweetal types gebouwen (een ervan in de samenvatting getoond) is tevens een verbijzondering gemaakt in de bijdragen die [a] de magnitude, [b] de afstand tot het epicentrum, [c] de variatie in groundbeweging en [d] spectrale versnelling van het gebouw leveren aan het risico. In deze samenvatting is alleen deze verbijzondering van meerdere, getoond. Het risico gebonden aan particuliere woningen met enkelsteensmuren en silica-calcium draagmuren (het type 'RESA-URM-B') in het Loppersum-gebied tonen hetzelfde beeld als de eerder genoemde verdeling van de dreiging; net als bij de dreiging dragen de aardbevingen in dat gebied en op een afstand minder dan 5 kilometer het meeste bij aan het risico. Terwijl voor de Stad aardbevingen op een afstand van 10 kilometer, uit het Loppersum-gebied de grootste contributie vormen.



- Het onderscheid dat de verschillende (onderstaand getoonde) productiescenario's vormen op het risico is gering. Ook maakt het verschil in de opties om de productie te distribueren over het veld een zeer gering verschil in de blootstelling van gebouwen en bewoners aan dat risico



- Het effect van een drietal versterkingsopties is wederom onderzocht. Deze opties zijn dezelfde als die in HRA van november 2015 gebruikt en beslaan 5.000, 10.000 en 20.000 gebouwen. Voor alle drie de opties kan binnen 5 jaar het risiconiveau van 10^{-5} worden behaald.



- De huidige analyse toont verder aan dat het aantal gebouwen dat momenteel niet aan de norm voldoet aanzienlijk lager is dan bleek uit de analyse in november 2015. Hoewel dit een positieve ontwikkeling is binnen de inschatting van het seismische risico, betekent het niet meteen een navenante doorvertaling in de omvang voor het bouwkundig versterken. De genoemde (3) versterkingsopties worden vooralsnog gehandhaafd om de volgende redenen:
 - De beoordeling betreft een probabilistische analyse en wijst niet meteen elk individueel gebouw aan dat versterking behoeft. Met een goed ingericht en op risico's gebaseerd (voortgezet) inspectieprogramma is de verwachting echter dat de individuele gebouwen die niet voldoen aan de norm worden gevonden. De werkbaarheid van een dergelijk inspectieprogramma moet echter nog worden aangetoond.
 - Er zijn significante stappen gezet om de risico's van de geïnduceerde aardbevingen in Groningen in kaart te brengen. Er bestaan niettemin nog onzekerheden om het aantal gebouwen dat niet voldoet aan de norm nauwkeurig in te schatten. Toekomstige verfijning van de beoordeling, bijvoorbeeld op basis van de uitkomsten van aanstaande testen op de schudtafel in Italië, zullen deze onzekerheden nog verder moeten verkleinen.
 - Het bouwkundig versterken zal uiteindelijk plaats vinden op basis van de (definitieve) NEN-NPR en Bouwbesluit. Er kunnen verschillen (blijven) bestaan tussen de HRA van de NAM en de NEN-NPR. Bijvoorbeeld, de meest recente en bovengenoemde resultaten van de seismische dreiging zijn nog niet meegenomen in de NEN-NPR.
- Voor de komende periode wordt aangenomen dat het versterkingsprogramma in lijn blijft met het huidige Meerjarenplan van de National Coördinator Groningen (NCG). Voor de middellange en langere termijn zullen de resultaten van de beoordeling beschikbaar worden gesteld aan de NCG om hem in staat te stellen de omvang en prioritering van het bouwkundig versterken onder zijn plan te (her)definiëren.

Schade

- De relatie tussen de seismiciteit en schade blijkt complex.
- Voor de inschatting van het aantal toekomstige schadegevallen op basis van de momenteel berekende dreiging is een eenvoudige methode gehanteerd. Deze is gebaseerd op een kalibratiestudie van TNO en KNMI uit 2009. Deze inschatting is vervolgens vergeleken met de schadeclaims die in het verleden (in de periode 2012-2015) zijn gedaan. De genoemde studie is gekalibreerd op basis van schadegegevens van voor 2007 en laat een goede overeenkomst zien met de schades als gevolg van de Huizinge aardbeving in 2012. Voor de aardbevingen sinds 2012 blijkt deze methode echter niet geschikt om schade te relateren aan aardbevingen.

- De schade-gegevens wijzen naar een verhoogd, maar nog niet verklaard, aantal schadeclaims na de Huizinge aardbeving.
- Nadere studie is nodig naar:
 - De gebieden waar de aardbevingen een dusdanige energie kunnen genereren dat er schade ontstaat.
 - De precieze relatie tussen de schadeclaims (en rapportage daarvan) en de actuele schade.
 - De wijze waarop schades als A, B en C (al dan niet aardbevingsgerelateerd, of een combinatie daarvan) wordt geclassificeerd.
- Er lijkt een opwaartse trend te zijn ontstaan binnen het aandeel C-schades (schades die niet toegewezen kunnen worden aan aardbevingen) sinds medio 2015.
- De geïnstalleerde TNO-sensoren tonen dat gebouwen in de regio trillingen vertonen als gevolg van een diversiteit aan oorzaken, variërend van aardbevingen tot verkeer en bouwwerkzaamheden.

Management Summary

Background to this Report

On the 1st April 2016 NAM submitted the Groningen Winningsplan 2016 to the Minister of Economic Affairs. This Winningsplan is accompanied with a Technical Addendum providing further background to the technical assessments used in the Winningsplan.

This addendum presents scenarios for the gas production from the reservoir and an updated assessment of the consequences of the production for each scenario in terms of subsidence and induced seismicity. For each scenario, the hazard and risk (including damage) resulting from induced seismicity are assessed and forecasts are presented.

Conclusions

Production

- The gas production scenarios cover three annual production levels for the field: 21 Bcm/annum, 27 Bcm/annum and 33 Bcm/annum. Furthermore, for each production level, two different distributions of the offtake from the field are used. This is in addition to the distribution of the offtake over the field as imposed by the Ministerial decision of January 2014 an optimized scenario was developed. The further optimization of the distributions of the offtake over the field aims to minimize risk. This results in a total of six scenarios.
- The optimized field offtake introduces an alternative grouping of the production clusters and their production limits. The gas production scenarios adhere to the limitation of the Groningen production system.
- The static and dynamic reservoir models of the Groningen field have been further updated. Comments from a previous review of the model for Winningsplan 2013 by SGS Horizon (independent reserves auditor), and by TNO-AGE and SodM have been incorporated. The new reservoir model is now history matched with production data, measured reservoir pressures, data of water rise from the aquifer and subsidence data.

Subsidence

- Subsidence monitoring in Groningen is in place since the start of production. The following surveying techniques are applied: Spirit levelling, PS-InSAR (Satellite Radar Interferometry) and GPS.
- Both the Time decay and the RTCiM (Rate Type Compaction isotach Model) compaction models result in a good overall fit to the observed subsidence data above the Groningen field.
- The RTCiM compaction model is chosen as the base case compaction model because it results in the best fit to the temporal and spatial observed response of the subsidence to production changes.
- Maximum observed subsidence above the center of the field was around 33 cm in 2013. The forecasted maximum subsidence at the end of field life is approximately 50 cm.

Seismic Event Rate

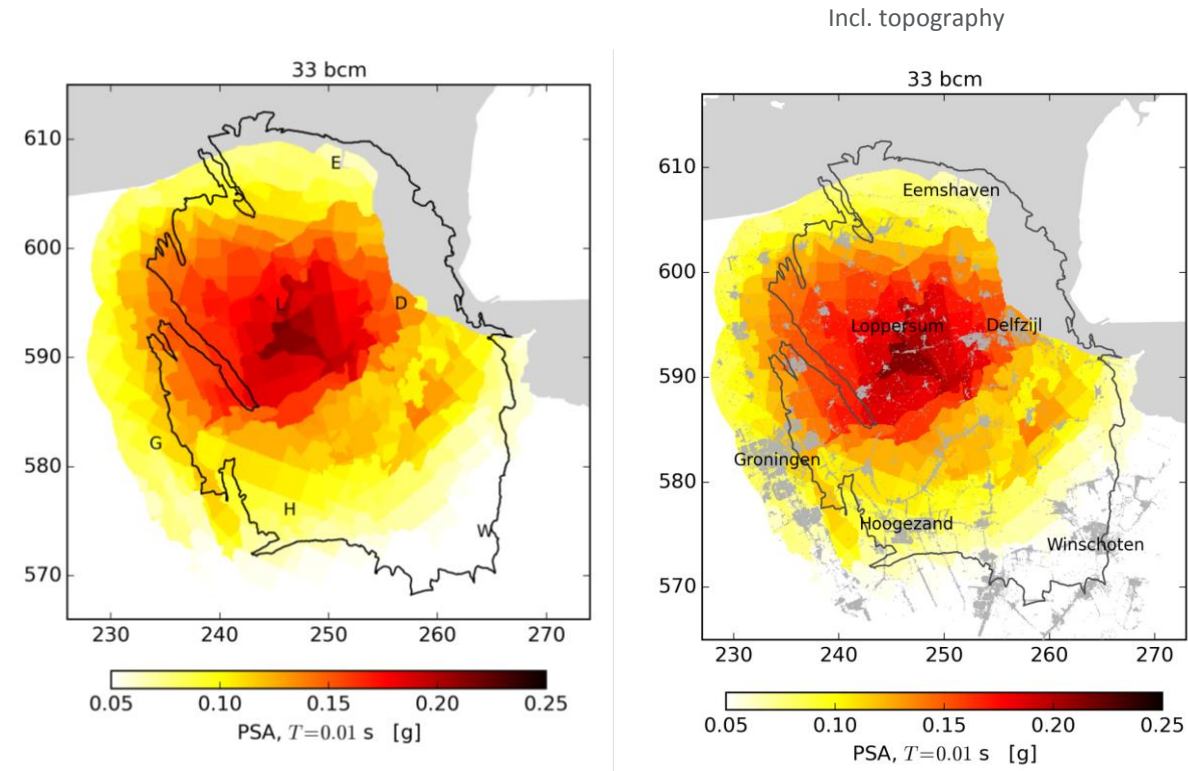
- For the period 2016 to 2021, both the median annual total seismic event rate and median annual seismic moments are, for all of the volume cases, forecasted to remain in a similar range as the actual seismic event rate and moment observed in the period 2012 – 2015.

Seismic Hazard

- The effects of the local soil conditions on the ground movement response to an earthquake have been incorporated in the hazard assessment.
- In the current hazard assessment an error in the software implementation of the model for ground motion prediction has been corrected. This was recently detected by a detailed comparison of hazard and risk results obtained from two independent software implementations and has been discussed with KNMI, TNO, SodM and SAC. As a result of this mistake in the interim update of the hazard and risk assessment of November 2015, the variability in the local site response was effectively set to its maximum value irrespective of the level of shaking expected in the underlying rock, whereas this variability should increase with the strength of

shaking. Correcting this mistake has resulted in a lower assessment of the probabilistic hazard and risk in the current Technical Addendum than in the interim update of the hazard and risk assessment of November 2015.

- The logic tree capturing the main uncertainty scenarios and their weights has been updated in line with the guidance in the expectation letter (verwachtingenbrief) of 15 February 2016.
- A Hazard Map is presented for each of the six production scenarios for three time periods. The hazard map for the production scenario of 33 Bcm/annum shows for the period 2016 to 2021 a maximum PGA of 0.21g with an average 0.2% annual chance of exceedance. The maximum PGA for the production scenario of 27 Bcm/annum and 21 Bcm/annum are 0.20g and 0.19g respectively with an average 0.2% annual chance of exceedance.
- The Hazard Map for the production scenario of 33 Bcm/annum for the period 2016 to 2021 with a maximum PGA of 0.21 g is shown below, where PGA is equal to the PSA for $T=0.01$ s.

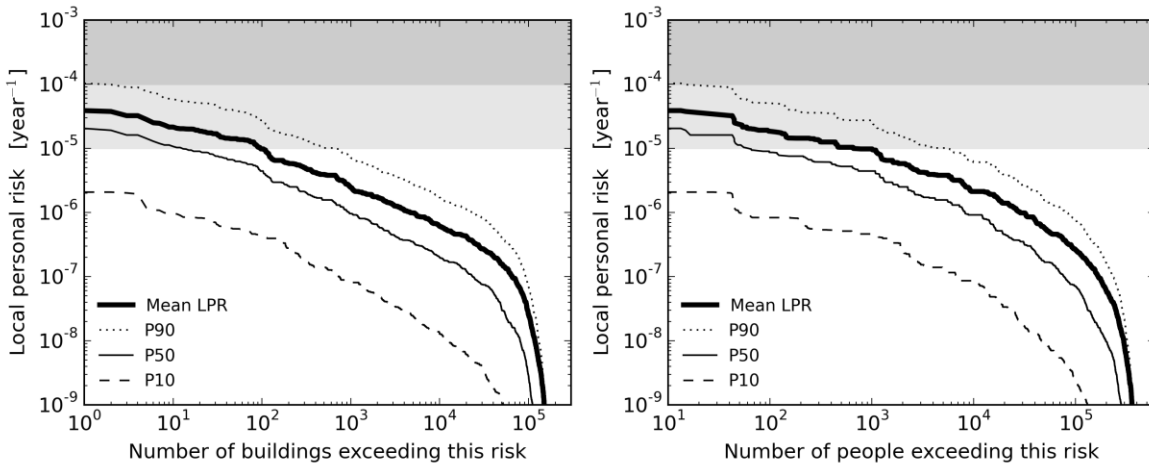


- To show which earthquakes have highest impact on the hazard assessment, a disaggregation of the hazard was performed for two areas; Loppersum and Groningen city. The disaggregation for the Loppersum area shows that the largest contribution to the hazard is from earthquakes within the Loppersum area (distance less than 5 km with a magnitude ranging from 4 to 5). In contrast the largest contribution to the hazard in the Groningen city is from earthquakes with an epicenter approximately 10 km away from the city (towards the Loppersum area). The earthquakes located further away can also cause significant ground acceleration in the city of Groningen, but need to have a larger magnitude.

Seismic Risk

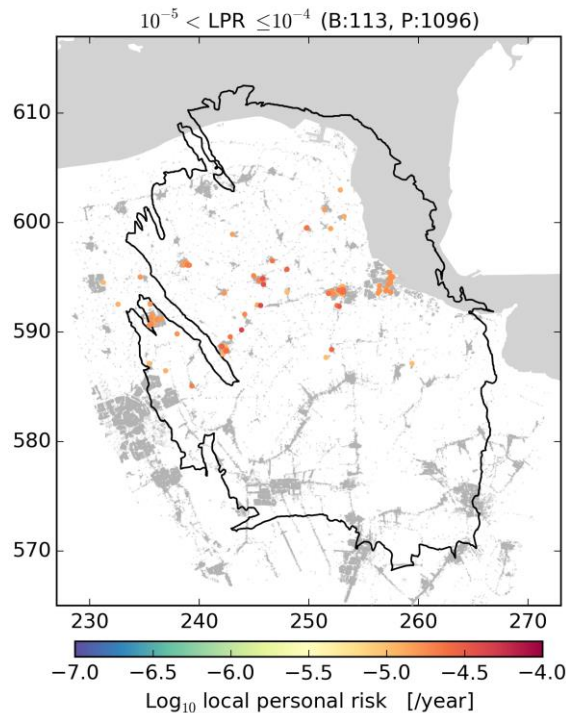
- The scope of this risk assessment covers building collapse risk (focused on the structural elements of buildings). Falling object risk (non-structural elements) is assessed through a separate methodology and described in a separate report.
- The assessment of ILPR (Inside Local Personal Risk) shows there are no buildings where the inhabitants are exposed to a mean ILPR in excess of 10^{-4} /annum for the period 2016 to 2021. There are some 100 buildings where the inhabitants are exposed to a mean ILPR between 10^{-4} /annum and 10^{-5} /annum for the same period.

LPR Assessment for the 33 Bcm/year Scenario

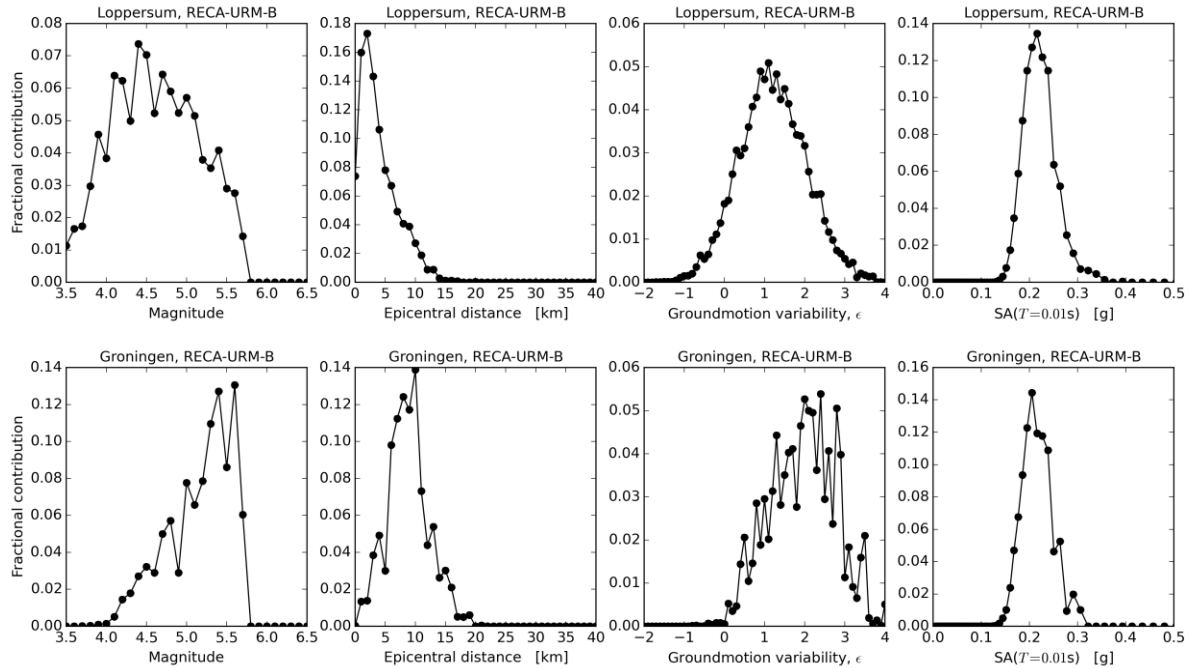


The safety norm for LPR as set by the Minister based on the advice of the Meijdam Committee will be met by executing a structural upgrading program to ensure that inhabitants of all buildings are exposed to a LPR below 10⁻⁵/annum within 5 years. Based on the current uncertainties, for some 1,000 buildings there is a more than 10% chance that the inhabitants are exposed to an ILPR between 10⁻⁴/annum and 10⁻⁵/annum.

- The buildings with an ILPR between 10⁻⁴/annum and 10⁻⁵/annum are located primarily in a zone from Delfzijl – Loppersum – Bedum. Values in the figure have been clipped for this range.

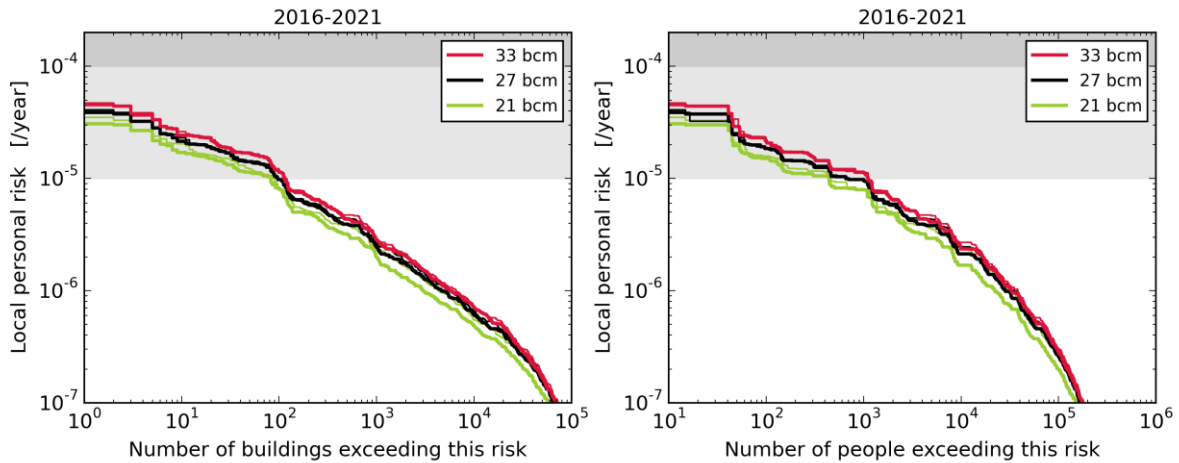


- For two building typologies a disaggregation was also performed for contributions to the base-case ILPR for magnitude, distance from the epicentre, ground motion variability measure, and spectral acceleration causing building collapse. In this summary, only the disaggregation is shown. The ILPR disaggregation results for the residential apartment buildings of unreinforced masonry with silica-calcium load bearing walls (type B) in the Loppersum area (typology RESA-URM-B) show results similar to the disaggregation of the hazard.

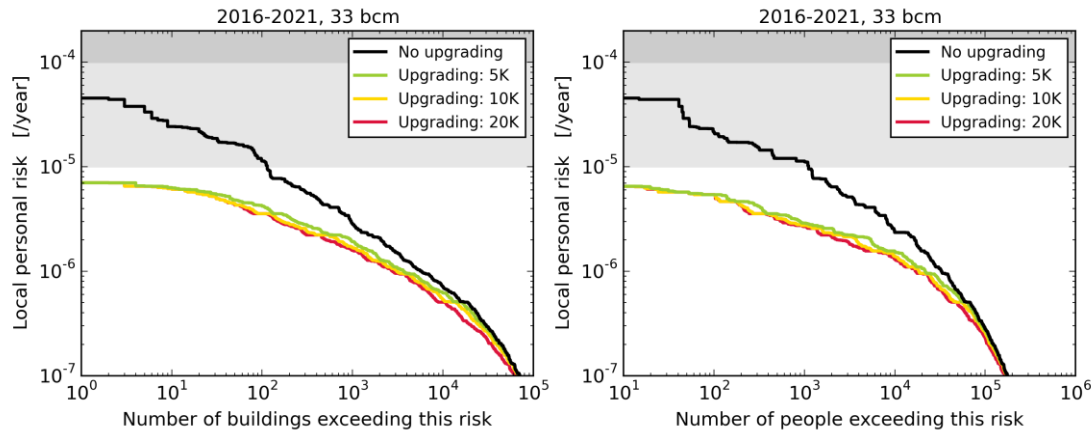


As for hazard, earthquakes in the Loppersum area (i.e. at epicentral distances less than 5 km) contribute most to the risk for this area, while for Groningen city, earthquakes at an epicentral distance of 10 km (i.e. in the Loppersum area) are the most important contribution.

- The sensitivity of the number of houses with an ILPR between 10^{-4} /annum and 10^{-5} /annum to changes in the production level is small. The difference in number of buildings or people exposed to a LPR between the two options for distribution of the production over the field is very small.



- The impact of three structural upgrading programs has also been investigated. The programs are the same as used in November 2015 and target 5,000, 10,000 and 20,000 buildings. All three programs yield a safety level where all buildings reach an ILPR below 10^{-5} /annum within 5 years.



- The current risk assessment indicates that the number of buildings that do not meet the norm of 10^{-5} /year for ILPR (~ 100 buildings) may be considerably lower than the estimate in the previous interim update assessment of November 2015. While this is good news in terms of the seismic risk in Groningen, it does not immediately translate into a smaller structural strengthening scope. Consequently, the three structural upgrading scenarios used for the November 2015 interim update have been retained for this risk assessment. There are three main reasons for this:
 - This is a probabilistic assessment and does not directly indicate each individual building that needs to be upgraded. In time, with a well-designed and risk-based inspection program it is expected that individual buildings with ILPR $>10^{-5}$ can be found with reasonable efficiency, however this efficiency has not yet been proven.
 - Significant progress has been made towards assessing the risk from Groningen earthquakes, however considerable uncertainty remains in the estimate of the number of buildings that do not meet the norm based on mean ILPR $>10^{-5}$. Future updates of the risk assessment could result in a different mean value of the risk, such as when new shake table tests are taken into account.
 - Ultimately the structural upgrading scope will be based on the NEN-NPR building code, and differences may exist between this code and the NAM hazard and risk assessment. For example the latest results for the seismic hazard have not yet been adopted in the NEN-NPR.
- In the short-term, the structural upgrading program is expected to be in line with the current plan of the National Coordinator Groningen (NCG). For the medium to long-term, the results of this risk assessment will be available to help NCG define the scope and prioritisation of the structural upgrading program.

Damage

- A simple forecasting method for D1 damage state, based on the 2009 Kalibratiestudie by TNO/KNMI, was used to forecast the chance of damage based on hazard data. These forecasts were compared with historical damage claim data (period 2012- 2015). This study is calibrated on damage data from before 2007 and also provides good results for building damage (claims) for the Huizinge 2012 earthquake. However, for earthquakes after 2012, this method is not able to match building damage claims.
- The relationship between seismic activity and damage claims appears to be complex.
- Empirical evidence pointing to strong increase in the number of claims post-Huizinge (early-2013).
- Further research is required into:
 - The area where earthquakes could release sufficient energy to cause damage
 - the precise relationship between damage claim reports and actual damage
 - The assessment of claimed damages as A-, B- or C-damage, or combinations thereof
- There appears to be a growing trend in the content of C-damage (damage which cannot be attributed to earthquakes) in damage claims from mid-2015 onwards.

- The TNO sensors show that buildings in Groningen experience accelerations due to a wide variety of causes. Traffic and construction work also cause building acceleration.

1 Introduction

This report provides technical support to the Winningsplan 2016 and consist of the following sections:

1. Introduction
2. Static and dynamic model update
3. The Groningen production system,
4. Reduction of seismic risk through production management,
5. Forecasting with optimized production distributon,
6. Subsidence,
7. Hazard assessment,
8. Risk assessment,
9. Building damage.

The assessment of hazard and risk in the Winningsplan 2016 is based on technical studies for the “Hazard and Risk Assessment - Interim Update November 2015”. The sections on hazard and risk assessment in this Technical Addendum should be read in conjunction with the “Hazard and Risk Assessment - Interim Update November 2015”.

To enable a critical review of this addendum it is presented in English. The conclusions however are summarized in the Dutch summary and in the main text of the Winningsplan 2016, which is prepared in Dutch.

2 Static and dynamic model update

2.1 Introduction

This section of the report describes the updates to the reservoir model of the Groningen field since Winningsplan 2013. Emphasis is on the latest updates.

For the Technical Addendum to the Winningsplan Groningen 2013, two subsurface realisations of the Groningen field were used. These models were labelled as G1 and G2:

- The G2 model (base case) was the best history matched dynamic model with respect to the reservoir pressure data (SPTG and RFT) and gas-water contact movement (PNL logs). An update of this G2 model (GFR2013) has been used for business planning and reserves reporting purposes. The G2 model assumed weak aquifer support to the north and had a mismatch with subsidence data in the north-western part of the model area.
- An alternative G1 realization had moderately strong aquifer support to the north and showed improved subsidence match but with less good match to gas-water contact movement.

In support of the WP2016 update, a new Groningen field review was started in 2015. The main reasons for initiating the Groningen Field Review 2015 (GFR2015) and thus replacing the existing models are:

- To incorporate new data, insights and modelling approaches.
- The need for a single dynamic model that matches pressure and water contact movement, but also Groningen subsidence data.
- Larger model area to allow for improved pressure and subsidence prediction to the west of the field, including the city of Groningen.
- Local reservoir pressure matches (at the cluster level) should be improved to ensure good well capacity prediction (gas rate vs. tubing-head pressure).
- Aquifer behaviour resulting in water rise was not adequately well matched.
- New data have been acquired since the last model update.

In addition to the reasons above, a number of comments and recommendations resulting from reviews of the previous static and dynamic model by TNO and SGS Horizon have now been incorporated.

The primary objectives for the updated static and dynamic model are usage in:

- Winningsplan 2016
- the Seismic Hazard and Risk Assessment process

Secondary objectives include:

- Business planning process
- Annual Reporting of Petroleum Resources (ARPR)
- Identification and maturation of development opportunities

2.2 What is new in GFR2015

The conceptual geological concepts that form the framework for the Groningen subsurface models have not been changed. They are described in an introduction to the geology of the Groningen Field area which is attached to this document for reference (Appendix). The main changes to the static reservoir model include:

- The model grid area has been extended approximately 8-10 km to the West and 5 km to the South (Figure 2.1) because:
 - The previous model was mainly focused on the Groningen closure since the objectives of the model were different. However, for geomechanical studies like prediction of subsidence, the area outside of the Groningen closure is also of importance.

- Subsidence in the greater Groningen area, including the city of Groningen, is not only affected by pressure depletion in the main Groningen gas field, but also by pressure depletion in adjacent aquifers and surrounding small fields. To improve the forecast of subsidence in this extended area, an expanded larger subsurface model area is required.
- Historical and forecasted pressure values for the extended numerical grid provide a better physical basis for geomechanical calculations. In the previous model pressures in the aquifer were modelled using analytical correlations.
- The model grid has been optimized ;
 - Locally, fault connections have been simplified and small faults have been switched off to improve the grid geometry
 - Locally, minor modifications have been applied to faults to better honor the well data
 - The number of layers in the reservoir zones has been revised
 - The definition of model segments has been adjusted, also because of the extension of the model area.
- The property modelling has been revised;
 - Property trend maps have been updated
 - Data from new wells has been included, and the well stock used for property modelling extended
 - The porosity distribution has been modelled by steering the interpolation between well locations with an acoustic impedance inversion model. This model was derived from a Promise inversion study carried out in 2003.

The extended model area now includes the following Land asset fields:

1. Annerveen-Veendam
2. Bedum
3. Bedum South
4. Rodewolt
5. Usquert
6. Zuidwending East
7. Feerwerd
8. Warffum
9. Kiel-Windeweer

All available data (pressure, production, PNL etc.) for those fields were included in the history matching process in the same way as those from the main Groningen field. In addition to updated historical data, new well data have been included. This includes newly drilled Groningen wells Borgesweer-5 and Zeerijp-2 and 3 and data from the abandoned non-Groningen well Sauwerd-1. The 2012 and 2015 models are compared in Figure 2.1, with initial gas distribution shown in blue.

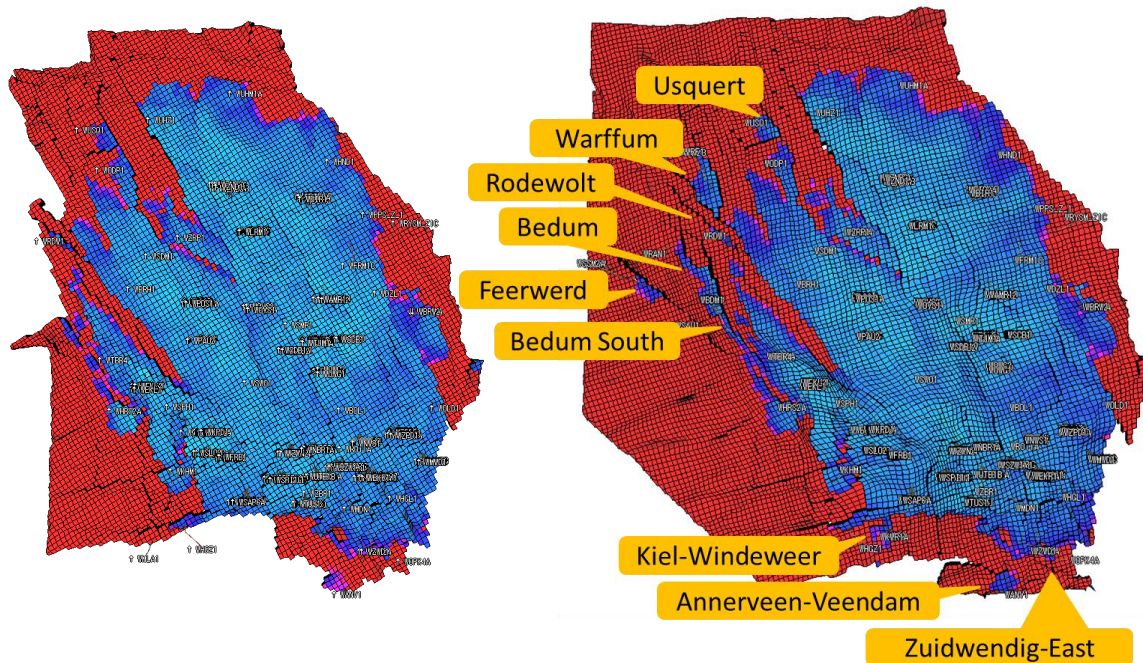


Figure 2.1 GFR2012 (left) and GFR2015 (right) grid boundary comparison.

The main updates to the dynamic model are listed below:

- The same dynamic modelling package is used for GFR2015 (Shell software; MoReS and Reduce++), but all input has been revised – tuning parameters have been removed, scripts have been cleaned-up and standard functionality used where possible.
- New subsidence proxy calculation and match quality indicator (normalised RMSE for subsidence) in MoReS
- Modified assignment of analytical aquifers, combined with different approach to tuning their parameters for history matching and uncertainty evaluation
- Revised set of saturation functions including Brooks-Corey based capillary pressure correlation and improved relative permeability model
- Revised fluid (PVT) properties including implicit modelling of condensed water in the gas phase based on Wehe-McKetta
- More constrained history matching workflow, with 3 matching parameters instead of 2.

One of the main objectives of the new dynamic model update is to achieve a history match to measured subsidence data, in addition to the more conventional match on reservoir pressure and gas-water contact. The approach chosen is to build an approximate, fast and integrated subsidence proxy in Mores. The proxy guides the history matching and is used in the uncertainty management workflow. It is important to note that the history match of subsidence is mostly used to improve our prediction of reservoir pressure, especially where we don't have measured well data like for example in the aquifer. The final prediction of subsidence will be done using a separate full-physics geomechanical model, taking predicted reservoir pressure as input. Figure 2.2 and Figure 2.3 below show the theory and schematic representation of this proxy.

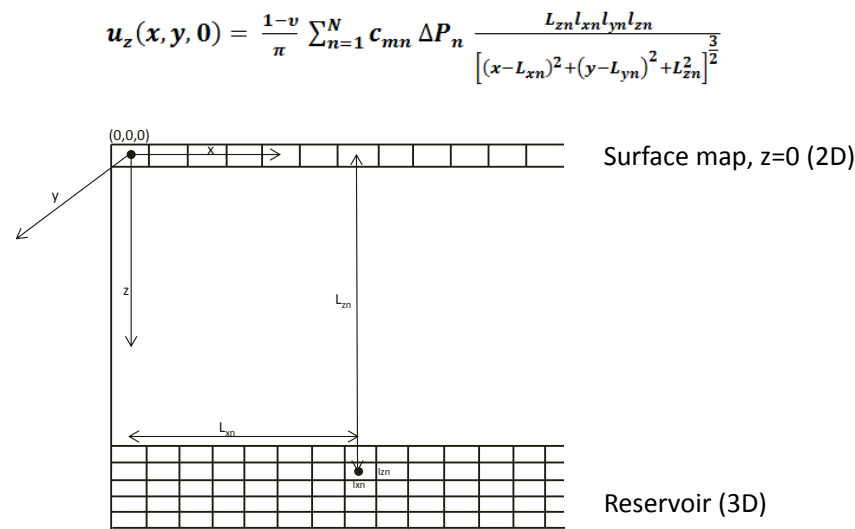


Figure 2.2 Subsidence modelling schematic

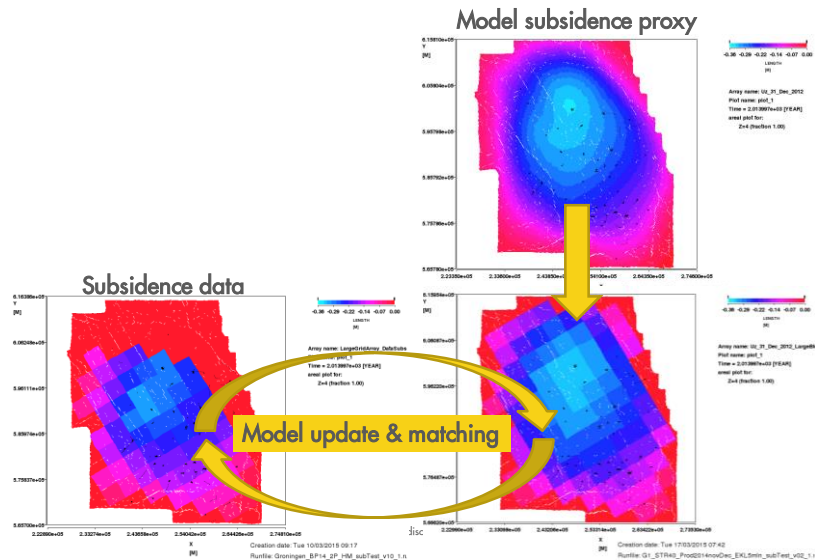


Figure 2.3 Subsidence proxy implementation and workflow

2.3 Dynamic model update since November 2015 HRA

In November 2015 NAM prepared an intermediate report to the Hazard and Risk Assessment where an earlier version of the model described here was used. That model is referred to as “Dynamic model version 2 (GFR2015_v2)”. Since then several changes have been made to the model. The updated model that is used for this Winningsplan submission is referred to as GFR2015_v2.5.

The underlying static model of both versions is the same and was described in Section 2.2. Also, the reservoir behaviour, drive mechanisms and most of the match parameters did not change. However, there are some tuning parameters that have been changed to improve the quality of the simulation model. The differences are discussed in the History Matching section. Below are the main differences between the two models in descending importance.

1. All permeability multipliers in the aquifers have been removed while maintaining an equal or better history match. The higher pressure in the aquifer, needed to achieve a match to subsidence, is now obtained by changing the sealing behaviour of faults rather than from reducing aquifer permeability. There are now only three global permeability multipliers left in the model:
 - a. Ten Boer reduction
 - b. Ameland shale reduction
 - c. Heterolithics reduction
 2. Improved match on non-Groningen wells such as Bedum, Sauweerd, Kiel-Windeweer, Annerveen-Veendam etc. The match was improved by the following steps:
 - a. Closer cross discipline collaboration with the Land Asset staff to better understand particular reservoir features including fault sealing.
 - b. Volume corrections of Land fields according to the latest ARPR data.
 3. Updated subsidence dataset resulting in improved match across the field
 4. Update to relative permeability model where residual gas saturation is a function of porosity
 5. Changes to PVT model, resulting in improved match of condensed water production
 6. Well interface properties (kdh, Re) are derived from the fine scale model using the flow based upscaling.
- Also, a vertical permeability reduction factor was introduced in the dynamic model in consultation with geologists.

2.4 Dynamic Compartments and Initialization

The initial pressure in Groningen at the free water level (FWL) is assumed to follow the hydrostatic gradient. However, there is not a single contact level across the Groningen field even though all parts are in pressure communication. No significant changes to FWLs are introduced for this work compared to the GFR2012 dynamic models. The set of FWLs are determined from a combination of open-hole logs, RFT and SPTG measurements, and define the set of dynamic compartments. The exact delineation between compartments follows faults and structures and also remains largely unchanged. There is also a temperature variation across the field, with a variation from about 80 to 120° C, resulting in different gas properties. All these variations are taken into account during the hydrostatic initialization. For the additional land fields, contact information is obtained from the corporate database, with a single level for each field. Figure 2.44 shows the dynamic compartments with corresponding FWLs (left). The area of the model that has an initial GWC within the Slochteren formation is also shown (right). In the south the contact is located in the Carboniferous.

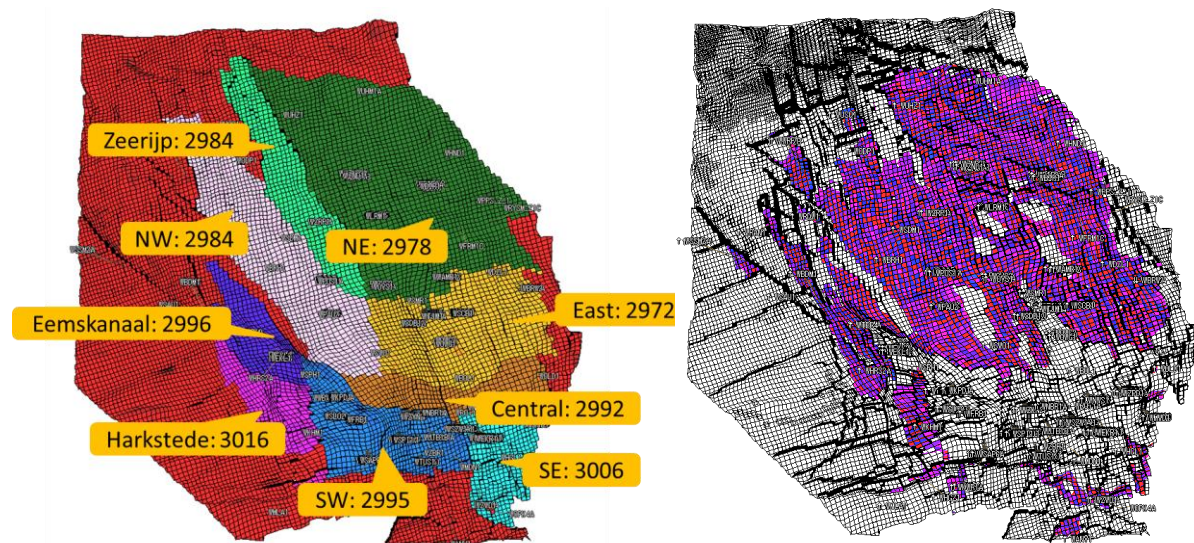


Figure 2.4 Groningen field compartments with different FWL in TVNAP (left). GWC in the model (right)

Geological fault throws and sand face juxtaposition as well as the origin of the faults define the sealing capability of the faults, and consequently the flowing paths for the fluid. In Figure 2.5 two east-west cross sections are shown. The major faults separating the north-east (where the ZND cluster is located) from Zeerijp and the north-west (where the ZRP wells are found) are clearly visible (top). Similarly there are faults separating the north-west from the east (bottom).

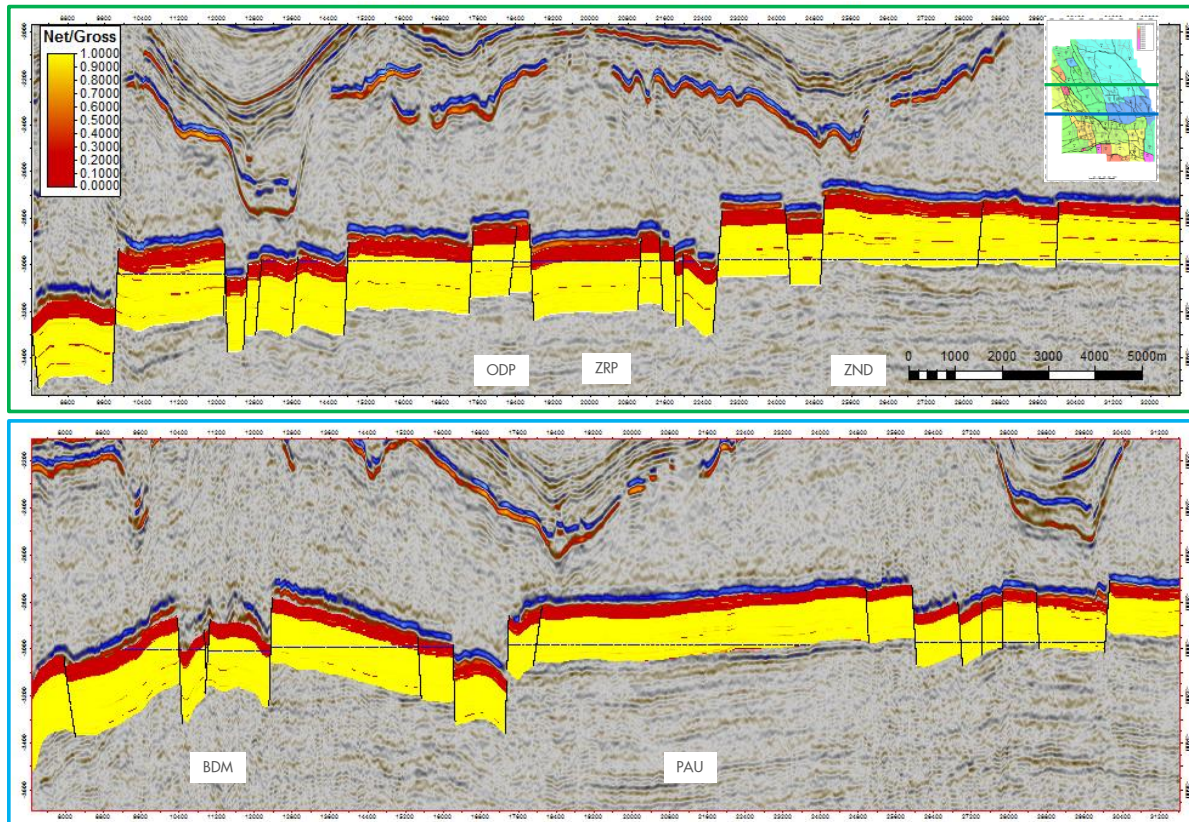


Figure 2.5 Faults with significant throw control the dynamic behaviour of the field

While the main input to the history matching process is agreement to pressure, PNL and subsidence data, the model was also checked to ensure that the hydrostatic initialization remains stable in time. It is clear that all parts of the Groningen field are in pressure communication, although many of the faults act as baffles between the different initialization regions. To validate the stability of the initialization, the model has been simulated for 1000 years without any production. In Figure 2.6 the gas water contact (GWC) at various locations is depicted as a function of time.

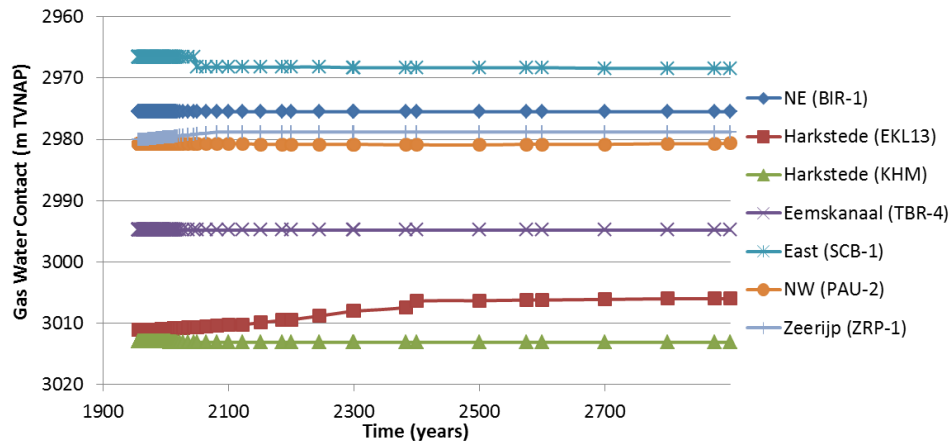


Figure 2.6 Stability of GWC in selected regions over a simulation period of 1000 years

From Figure 2.6 it is clear that the GWC in the different regions do show sufficient stability for the purposes of dynamic modelling. Only in the northern part of the Harkstede block (Eemskanaal-13 well location) is there some movement of the contact due to equilibration with the Eemskanaal region. However, the process is quite slow and the contact remains stable within the timeframe where the field is under production.

2.5 History matching workflow

GFR 2015 dynamic model is constrained by the following historical data:

- Production and injection data as controlling parameters
- Pressure data including SP(T)Gs, CITHPs, BUs and RFTs
- PNL data (water rise)
- Subsidence data

Fluid composition data is not directly used in the history-matching process, however the changing gas composition in certain wells was evaluated during the analysis of the reservoir behaviour.

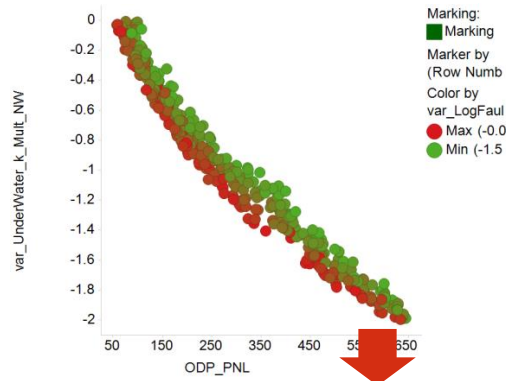
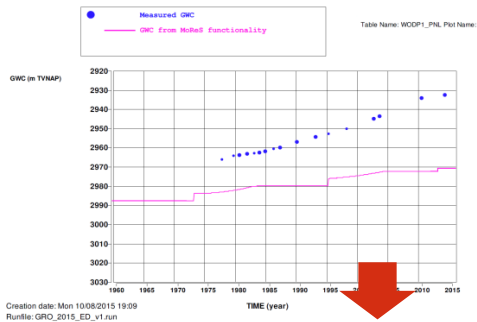
The subsidence data was matched using the subsidence proxy calculation and match quality indicator (normalised RMSE for subsidence) using MoReS (Shell's in-house dynamic simulator). An example of the proxy results is shown in Figure 2.122.

An initial "reference" model was manually tuned based on the general understanding of the reservoir behaviour and results from the previous Groningen field reviews. A preliminary understanding of the behaviour of the surrounding Land asset fields had to be created, ensuring that no pressure communication exists with main Groningen field. Then the reference model was used as an input to the Assisted History Matching (AHM) workflow. This workflow serves to investigate many realisations with different variables and hence gives an insight into the various history matching possibilities. The following matching parameters were used to tune the model:

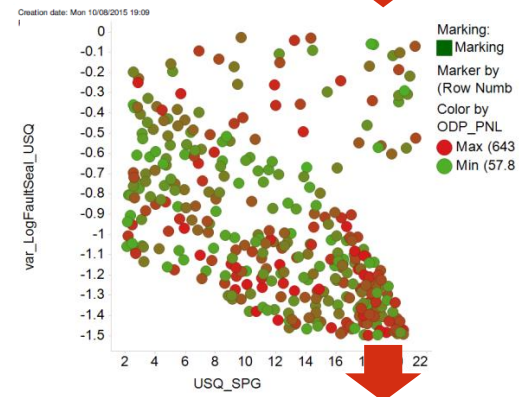
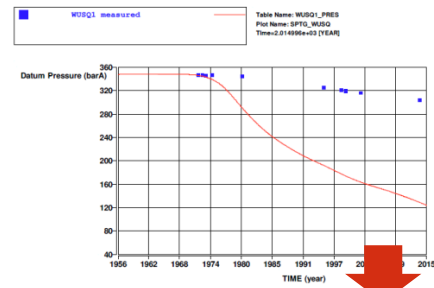
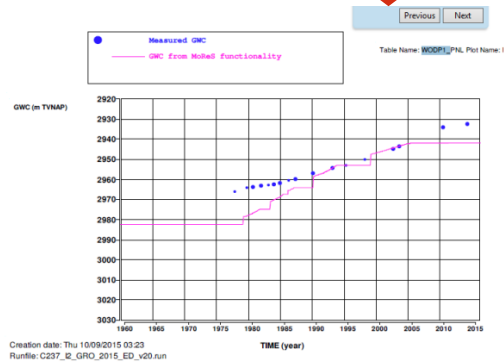
- 24 global and local Gross Block Volume (GBV) and permeability multipliers
- 38 fault grouping sealing factors
- Other tuning parameters like aquifer properties, well inflow properties (skin) etc.

Figure 2.7 shows two examples of the assisted tuning of permeability and fault transmissibility to better match PNL and historical pressure data. Local match quality indicators suggest tuning parameters, e.g. an exact value of fault transmissibility in order to minimise the mismatch in certain areas.

A map with the fault groupings are shown in Figure 2.8. It demonstrates that the transmissibility of the vast majority of fault groups had to be calibrated in order to match the dynamic behaviour of the field. Only a relative small set (marked in black) of faults were set to fully sealing. This increases the confidence that the impact of faults on reservoir behaviour is well understood.



Increase the NW
underwater permeability



Set the USQ fault seal
to ~-1.1

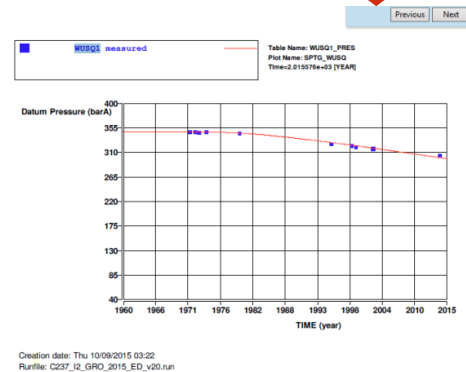


Figure 2.7 Examples of the tuning process using the underwater permeability and fault transmissibility.

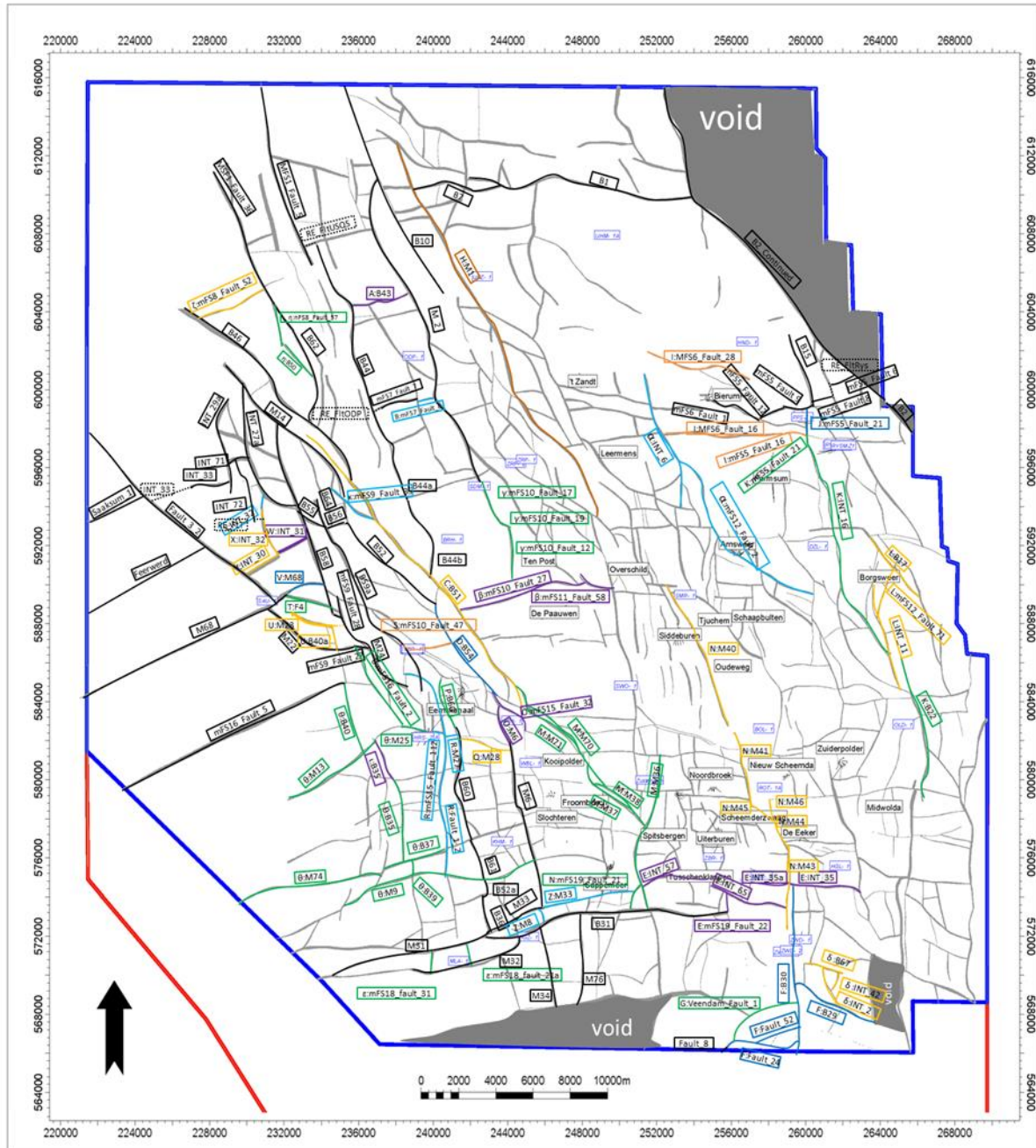


Figure 2.8 Sealing factor multipliers of fault group that were used as matching parameters in the history match, black faults are fully sealing. Other colours are only indicating different fault groups and no sealing factor value

The history match quality from resulting runs was assessed using 3 criteria (see 3 axes scatter plot on Figure 2.9):

- Pressure mismatch (simulated and measured SPTG at well locations)
- PNL mismatch (simulated and measured water rise at selected well locations)
- Subsidence mismatch (simulated and measured subsidence across the field)

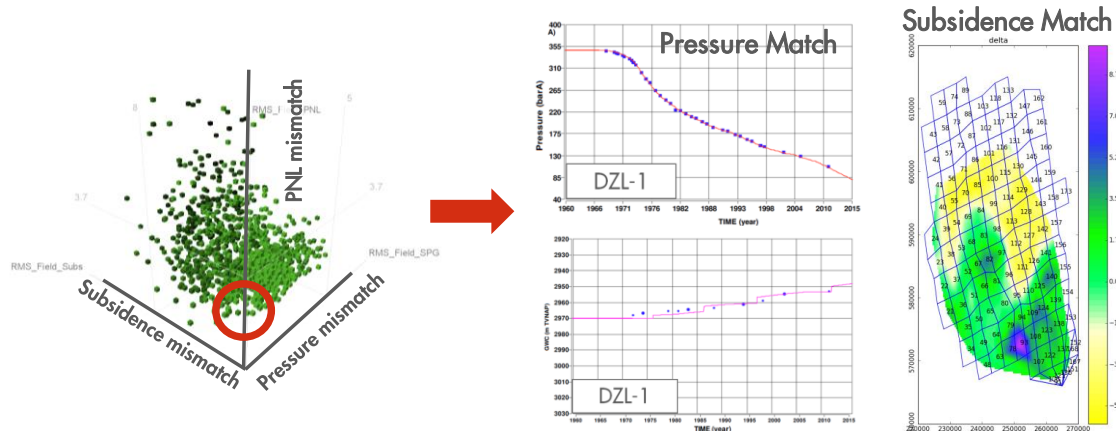


Figure 2.9 Assisted History Matching workflow from the space filling exercise towards the manual tuning. The best matched models are located in the red circle.

2.6 History matching results

The model that was finally chosen is very well matched on all three parameters with a very small difference in Gas Initially In Place (GIIP) values between GFR 2012 and 2015 models.

A few examples of the history model match quality can be seen from the figures below.

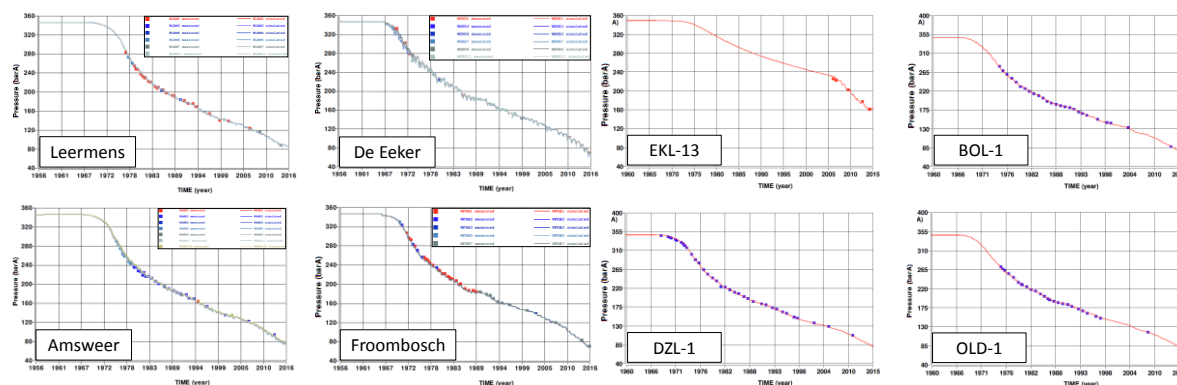


Figure 2.10 Reservoir pressure history match quality for a few typical Groningen clusters, Eemskanaal 13 and some observation wells

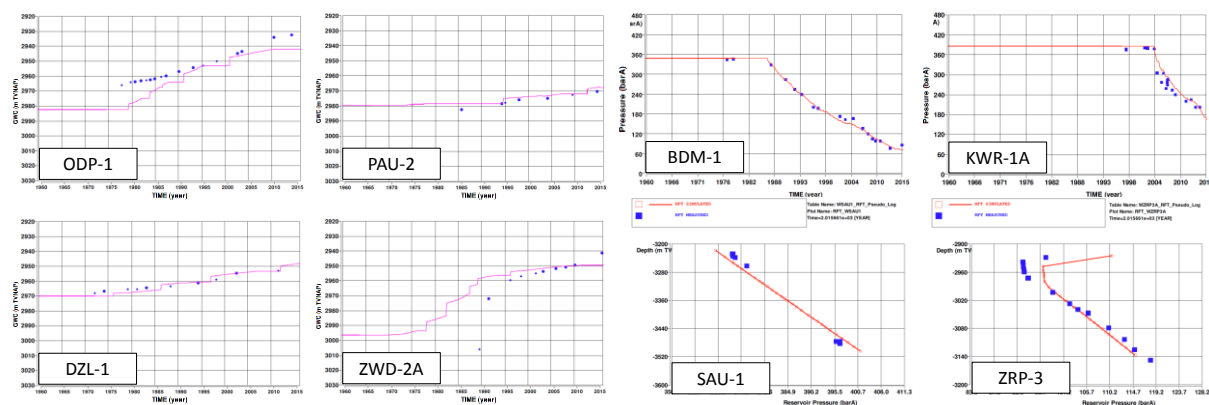


Figure 2.11 PNL history match quality for some Groningen wells (left), and reservoir pressure history match quality for Land wells and ZRP3.

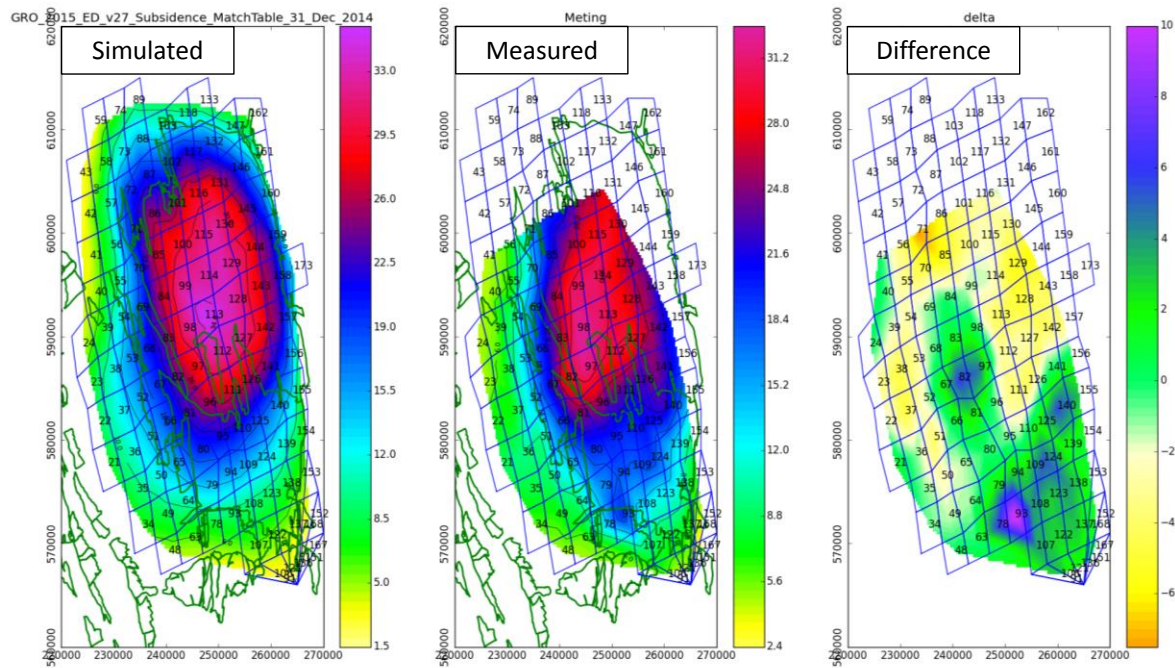


Figure 2.12 History match quality on subsidence using the proxy in Mores (scale is in cm).

2.7 Uncertainty analysis workflow and results

The calibrated dynamic model provides reservoir pressures for the selected production scenarios and possibly includes the uncertainty range in reservoir pressures associated with subsurface uncertainty.

The history matched model and the resulting variable space will be used in the determination of ultimate recovery for a simplified production scenario. It is very important to use UR instead of GIIP for the uncertainty analysis, because the late field life uncertainty parameters are screened out in the selection based on GIIP, e.g. aquifers or relative permeability parameters. For reserve purposes the uncertainty in field UR at the end of economic field production life is important. For infill projects the uncertainty in project UR or project value is looked for and for hazard and risk assessment of earthquakes the uncertainty in maximum subsidence may be the parameter. This would imply that a different set of P10/P50/P90 models is used depending on the objectives.

The goal is to have a set of models with a sufficient history match quality that captures the potential spread in the forecast and this is schematically shown in Figure 2.13. The top 2 graphs represent the screening criteria of the variables:

1. Left side box – less uncertain variables, because the history match quality is very sensitive to the change of those variables
2. Right side box – variables that are not so sensitive for the history match, but might be important in late life

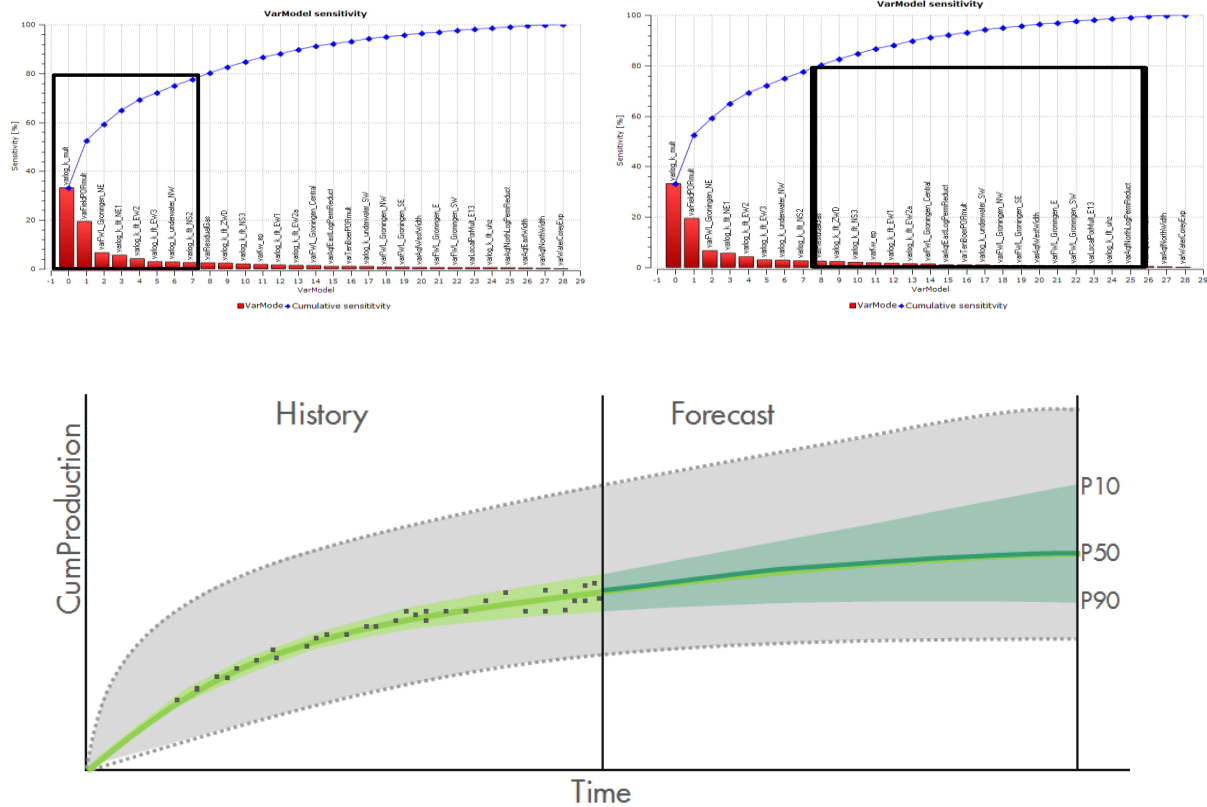


Figure 2.13 Schematic representation of the uncertainty for ultimate recovery (UR).

The applied uncertainty analysis workflow for the ultimate recovery is as follows:

1. Generate a set of variables with sufficiently wide ranges to capture the uncertainty.
2. Assess which model parameters affect the uncertainty in ultimate recovery without affecting the history match.
3. Simulate the history match and the forecast for a large number of models – all with a varying set of parameters.
4. Quantify the sensitivity of the mismatch functions to independent variable parameters.
5. Discard parameters that could reduce the history match.
6. Simulate the forecast with an ensemble of models by varying parameters that do not impact the history match.
7. Determine P10, P50 and P90 members of the range based on ultimate recovery.
8. Test the range of ultimate recovery by investigating a larger set of variable parameters.

The top left picture in Figure 2.14 shows the actual results using the workflow above. The red line is the base case and the grey cloud is generated from 1000 runs used for the uncertainty analysis, from which the P10/P50/P90 model realisations were selected (top right figure).

Also in this analysis the reservoir models which are different conceptually but still have an acceptable history match were analysed. This was done in order to check the potential impact in case the current reservoir understanding is not fully right. Bottom right picture in Figure 2.14 shows the results of those runs in terms of UR. They all fall within the initial grey cloud, i.e. uncertainty range.

The bottom left picture shows the correlation between the UR and Subsidence values generated from the 1000 models. It is clearly seen that no correlation exists between to parameters and 3 separate low/mid/high models should be used for UR and subsidence calculations.

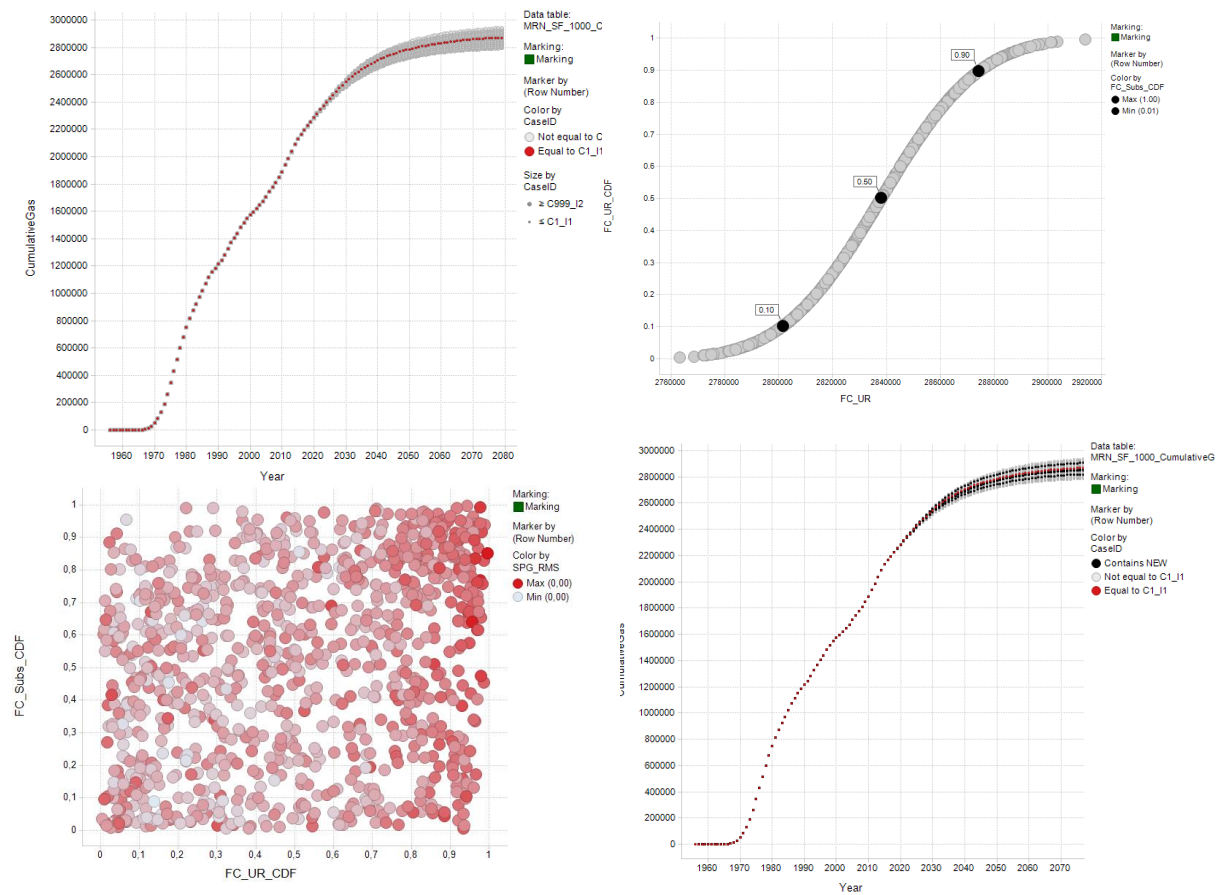


Figure 2.14 History match quality on subsidence using the proxy in MoRes (scale is in cm).

3 The Groningen System

3.1 Gas Production System

The Groningen System consists of the Groningen Field and the three Underground Gas Storages (UGS), the hi-cal UGS in Grijpskerk, the lo-cal UGS in Norg and the lo-cal PGI Alkmaar operated by TAQA.

The Groningen field is currently produced at 20 production clusters and two satellite production clusters. At the production clusters, produced gas is compressed and processed. The clusters are connected via a pipeline network, (the Groningen ring), see Figure 3.1, via which gas is supplied to the national gas grid through seven custody transfer stations (a.k.a. “Overslagen”). Water and condensate is separated from the gas at the production clusters and transported via separate pipeline (Waco) to the Delfzijl tankenpark.

At the custody transfer stations the gas is metered and delivered to the Gasunie Transport Services (GTS) pipeline system. In order to fulfill the market demand, distribution of the gas over the custody transfer stations is joint effort of GTS and NAM. This distribution is mainly impacted by the geographical location of clusters and Overslagen. GTS is responsible for redistribution of the gas in the national grid to supply the market.

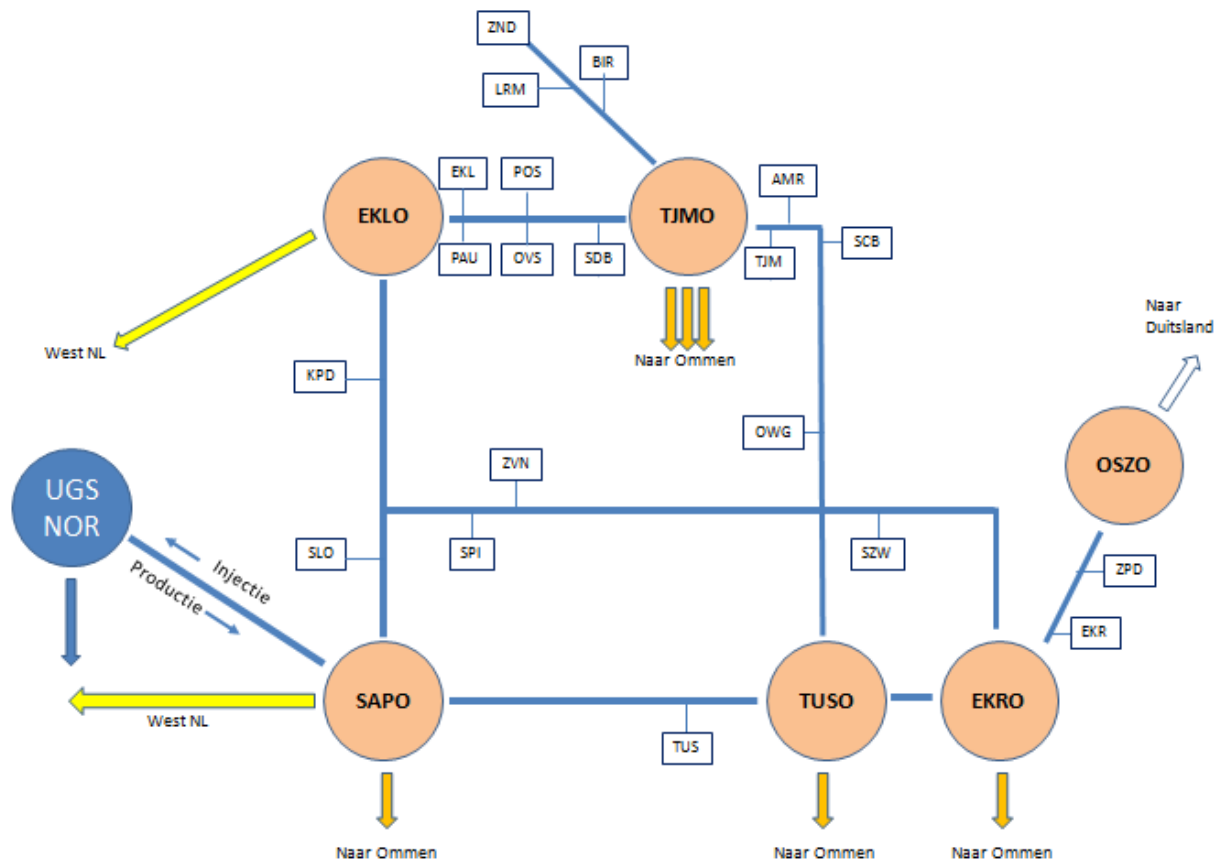


Figure 3.1 Schematic overview of the Groningen ring

The Underground Gas Storage (UGS) Norg is an integral part of the Groningen production system. The UGS is used to assist the Groningen field production in periods of high capacity demand (winter) and is refilled during periods of low market demand (summer), resulting in a flattened production profile of the Groningen field. In 2015, the UGS capacity expansion project was completed and a dedicated pipeline (NorGroN) between the Groningen Ring and the UGS was taken into operation.

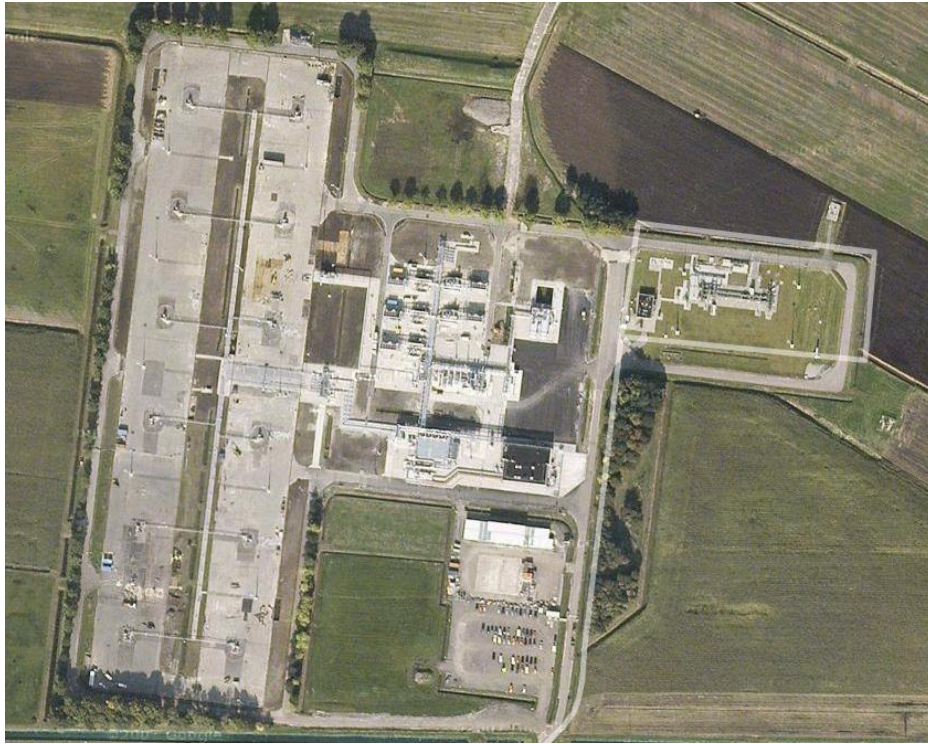


Figure 3.2 Areal overview of the Eemskanaal Cluster

3.2 Operational constraints

The system is operated within a set of contractual and technical constraints impacting the flexibility of the system, for instance related to distribution and gas quality constraints. Some of these technical constraints are listed below.

- **Maintenance**
In order to keep up the high reliability of the system, an extensive maintenance and inspection program is being executed. Available capacity is impacted because of maintenance, testing, and other activities which typically take place in summer.
- **Gas quality**
The gas needs to be delivered at the custody transfer stations within a very tight gas quality specification band. However, gas produced from the Eemskanaal cluster has a different composition and a calorific content above the higher limit of the quality specification (average Wobbe Index of 45.7 MJ/Nm^3 , compared to 43.7 MJ/Nm^3 for most of the other Groningen clusters). The maximum contractual Wobbe value is 44.2 MJ/Nm^3 . Gas from the Eemskanaal cluster therefore needs to be mixed with gas from other clusters in the Groningen pipeline system to meet the export quality specification (Ref. 1).
- **Distribution**
The distribution is mainly impacted by the geographical location of clusters and Overslagen. For instance, gas delivered at the Oude Statenzijl Overslag (OSZO) is supplying the German market whilst gas delivered at the Eemskanaal Overslag (EKLO) and the Sappemeer Overslag (SAPO) is primarily used to accommodate gas demand in the West of the Netherlands.
- **Seismic risk minimization**
Based on hazard and risk assessment, a production distribution over the field will be proposed and the effect of the distribution will be controlled by means of a Measurement and Control Protocol (in Dutch “Meet- & Regelprotocol”; MRP).

- Other factors
Other constraints impacting available capacity and/or system flexibility include ambient temperature, GTS system pressure and local demand, unforeseen unavailability of clusters

3.2.1 UGS injection requirements

The UGS expansion project has led to a working volume increase from 3 to 7 bcm. In order to be able to inject the full 7bcm, the injection compressors require a high level of availability and a minimum level of suction pressure which can only be supplied via the NorGroN pipeline combined with a specific pressure segregation of the Groningen Ring. This segregation impacts the operational flexibility in terms of distribution.

3.2.2 Minimum flow

Minimum flow rates at the overslagen

Every single custody transfer system (overslagen, OV) requires a minimum of 1 mln Nm³/day to keep it in operation. Also the combination of OV's with flows to the West (SAP and EKL), South (TJM, EKR, TUS and SAP) and East (OSZ) requires a minimum flow of 3 mln Nm³/day per direction (East, South, East) for direct delivery to GTS.

Oudestatenzijl (OSZ) has a different character compared to other custody transfer stations, because of operational limitations in the GTS system, pressure and flow is required from the Groningen Ring (so called open pipe).

Minimum flow rates at clusters

Quick response to increase demand can only be facilitated from clusters in operation or in standby mode. The standby mode requires a minimum flow which is related to ambient temperature.

Minimum flow at high ambient temperatures: 1 mln m³/d (above 0 degrees Celsius)

Minimum flow at low ambient temperatures: 3 mln m³/d (between -10 and 0 degrees Celsius)

If the ambient temperature is below -10 degrees Celsius, the required minimum flow is higher.

4 Reduction of seismic risk through production management

4.1 Introduction

This chapter investigates the possibility of reducing seismic risk by optimizing the offtake distribution over the field at a given annual total offtake level. This comes down to reducing the offtake from higher risk areas balanced by increasing offtake in lower-risk areas based on the current knowledge of the field. The approach and the optimization can be updated when new data become available and regularly reviewed as part of the measurement and control protocol. The seismic response to the changes in the distribution of the field offtake and resulting impact on risk can then guide future cycles in this optimization process.

Gas production leads to pressure depletion, which in turn leads to reservoir compaction. Compaction and the consequential fault slip is the driving force for seismic activity. Therefore, pressure depletion is a preamble for seismic activity. Different production scenarios result in different pressure depletion trends in the field, and hence potentially in a different distribution of seismic risk. The operational constraints discussed in the previous chapter have to be incorporated in the design of production allocation scenarios.

The optimisation approach and choices made therein is subject of a review process and are to be evaluated amongst others through steps described in the Measurement and Control Protocol. The effects of gas production from the Groningen field are monitored using different parameters such as pressure, subsidence, ground motion and seismic activity rate. A Measurement and Control Protocol has been written up in which a number of measured signal parameters have been identified which have an impact on the Hazard and Risk level. Based on these signal parameters values and observed trends, production distribution can or may be confirmed or redistributed over the field, taking into account the overall volume limitations. Regular reporting of measurements, trends, redistribution of production, and when required recalibration of the HRA models is part of the protocol.

The “Hazard and Risk Assessment – interim update November 2015” (Nov 2015 HRA) is used as a starting point for the optimization as described in this chapter. In subsequent chapters of this technical addendum, hazard and risk assessments will be presented for both production allocation scenarios. This enables evaluation of the impact of production management on seismic risk. Further investigations to achieve a more robust and mathematically more rigorous optimization in the future are described in the “Study and Data Acquisition Plan”.

4.2 Hazard and Risk Assessment – Interim update November 2015

4.2.1 January 2015 regions

The first initiative to influence, or rather reduce, seismic activity in the near term was taken by SodM, who advised to subdivide the Groningen field into four production regions (Figure 4.1) and assign production caps for each region. This advice was adopted and set as permit conditions by the Minister of Economic Affairs and implemented by NAM as follows:

- LOPPZ¹ clusters: 3.0 N.Bcm per year²
- Eemskanaal cluster: 2.0 N.Bcm per year
- South-West clusters: 9.9 N.Bcm per year
- East clusters: 24.5 N.Bcm per year

leading to a field total of 39.4 N.Bcm.

¹ LOPPZ = Leermens, Overschild, De Paauwen, Ten Post and 't Zandt

² N.Bcm refers to a volume of a billion normal cubic meters. Normal means the volume is measured at a standard temperature (0 degreeC) and pressure (1 bar).

These caps have been revised in 2015. The Council of State (Raad van State) ruled that the LOPPZ clusters could only be produced to ensure security of supply, effectively reducing production to the volume required to keep these clusters on warm stand-by (see Chapter 3). Later in that year, the total field production cap was further reduced to 33 Bcm and 27 Bcm.

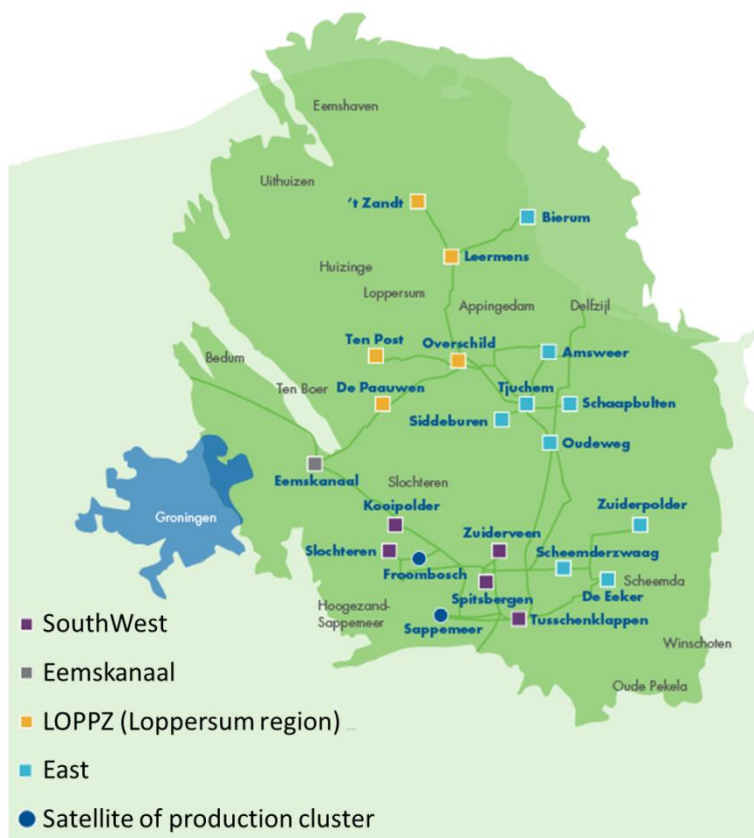


Figure 4.1 Production regions as per January 2015

4.2.2 Pressure response driven by January 2015 regions

The production profiles as used in the Nov 2015 HRA were driven by the regions as they were enforced by the (revised) decision on the Winningsplan 2013. Figure 4.2 presents the forecasted reservoir pressure distribution for 2021 assuming a continuous cap on LOPPZ, showing a strong North-South trend in the associated pressure depletion. A consequence of the almost complete close-in of the five LOPPZ clusters is that the northern-most area of the field is less drained and only reaches a reservoir pressure of around 80 bar in 2021. The reservoir pressure in the south-eastern area of the field is expected to decline to some 50 bar, resulting in a pressure difference between these areas of 25 – 30 bar by 2021. The small depleted (blue) area to the west of the Groningen field is the Bedum field.

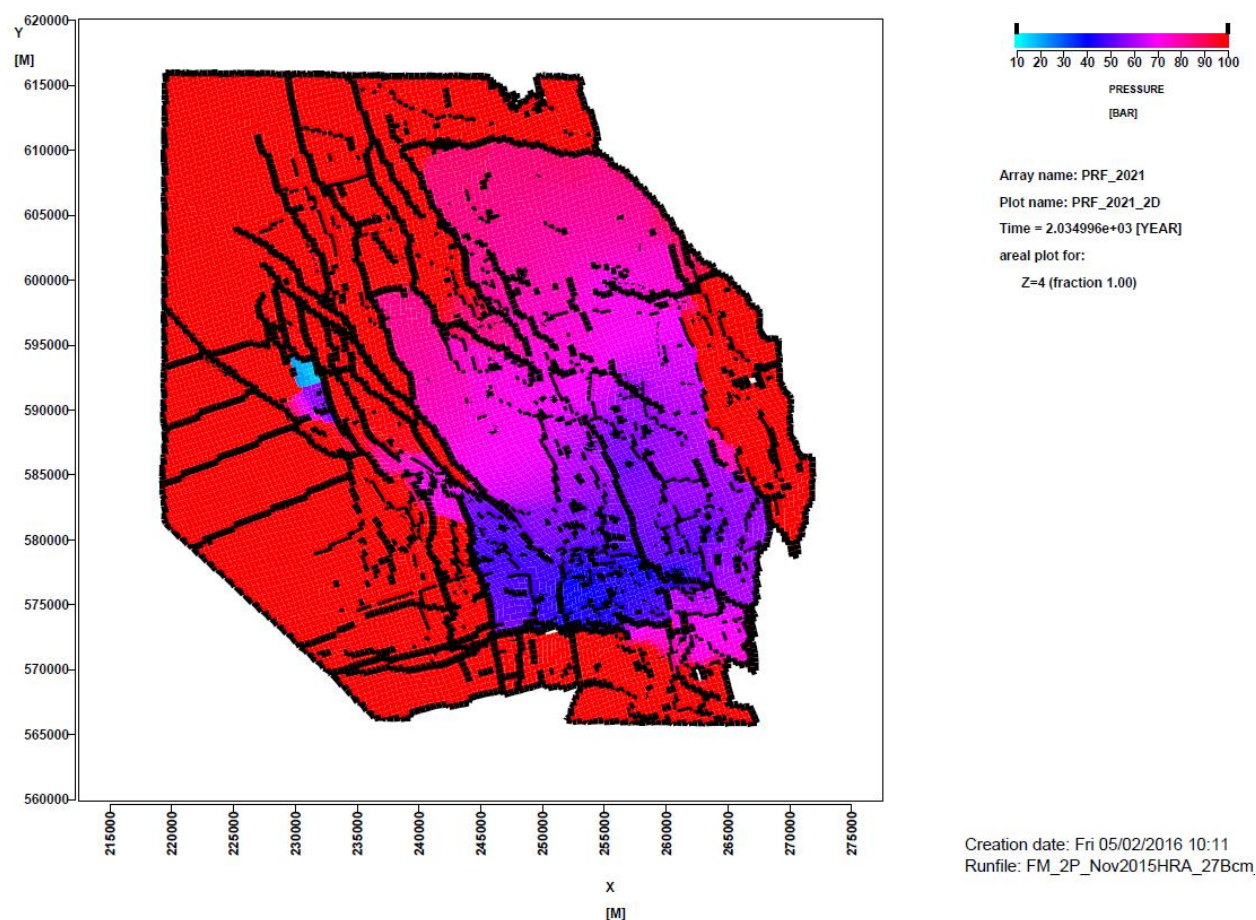


Figure 4.2 *Groningen reservoir pressure prediction at 1/1/2021, from the 27Bcm production profile as per the Nov 2015 HRA. Note that in order to enhance detail within the field contour, the color scale is clipped at 100 bar; pressures outside the reservoir contour are in fact higher.*

The Groningen reservoir consists of high quality reservoir rock with high net-to-gross, thick column, and good permeability. The field is heavily faulted with more than 1,500 major and minor faults identified on seismic. Across most faults there is a good sand-to-sand juxtaposition. Therefore many of the faults do not present major baffles to gas flow. Consequently, in most areas there is a good pressure communication across the field. However, due to the size of the field reducing the offtake in one region will cause a pressure imbalance. Initially, the pressure decline in a low offtake area will slow down. But over time, when the pressure imbalance at the field scale becomes larger, this becomes a driving force causing the gas in the higher pressured region to flow towards the lower pressure regions. This effect will be seen over distances of many kilometers, because of the good pressure communication across the field. The pace at which the pressure equilibration process takes place is slow because of the high compressibility of gas at reservoir conditions. Pressure equilibration can take several years. Furthermore, a few large faults without gas-to-gas juxtaposition will regionally act as baffles. Examples are the NW-SE trending major faults to the north of the Loppersum area.

The process of long range pressure equilibration is illustrated in Figure 4.3 for the LOPPZ clusters. The initial response to the production constraints is a stabilization of reservoir pressures (from January 2014 to January 2016). However, from January 2016 onwards, the pressure continues to decline. The production reduces to 10% of the volumes produced before January 2014, but the pressure depletion rate reduces by 50% only. This demonstrates that gas from the LOPPZ region is also drained by the other Groningen clusters.

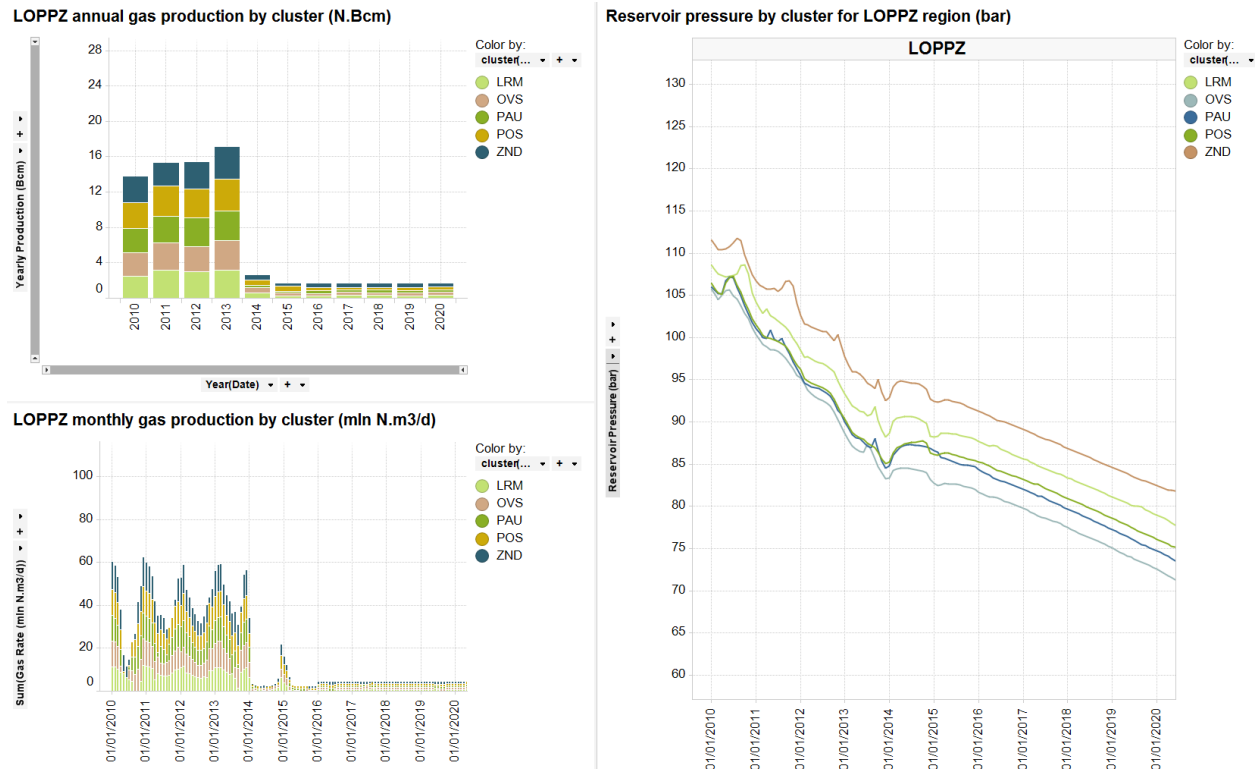


Figure 4.3 Impact of the production restriction on the pressure decline in the Loppersum area, using November 2015 HRA production profile for 27Bcm annual offtake.

4.2.3 Observations from Nov 2015 HRA

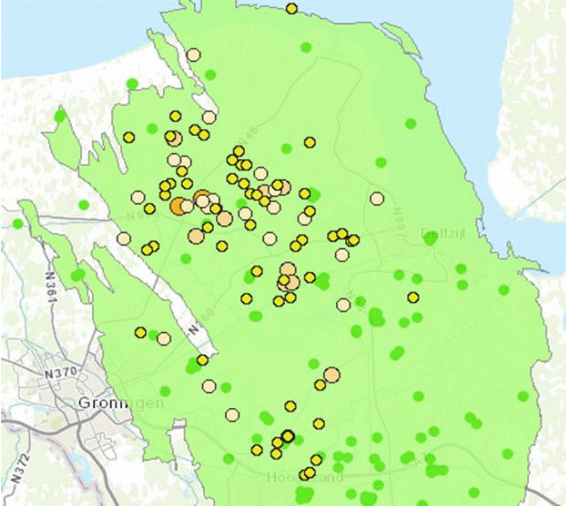
The optimization of the distribution of the production over the field, will use as a starting point the interim update of the hazard and risk assessment of November 2015. In the current assessment the hazard and risk consequences for two production distribution cases will be compared: (a) the production distribution imposed early 2015 as used in the November assessment and (b) an optimized production distribution.

The Nov 2015 HRA has presented earthquake location maps and seismic hazard and risk maps, which will be briefly described here. Earthquake locations are shown in Figure 4.4. The top left-hand map shows all monitored earthquakes with a magnitude larger than M=2, the map at the top right-hand side shows all earthquakes with a magnitude larger than M=1.5 that have occurred in the last ten years. These figures show:

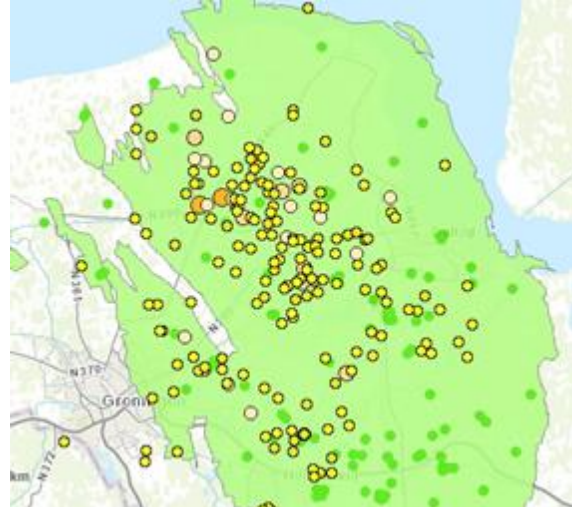
- a higher density of earthquakes around Loppersum,
- few earthquakes have occurred in the north east; above an imaginary line from Uithuizen to Leermens, three earthquake larger than M=2 has been recorded.
- In the south of the field, from Ten Boer to Hoogezand, a second clustering of earthquakes has been recorded.

The seismic hazard is expressed in terms of maximum peak ground acceleration (PGA) and presented in hazard maps. Figure 4.5 is taken from the Nov 2015 HRA. It is based on production scenarios of 33, 27 and 21 Bcm/annum and a distribution of production over the field which is in line with the 2015 regions and caps. It shows that the highest PGAs are concentrated around the Loppersum area.

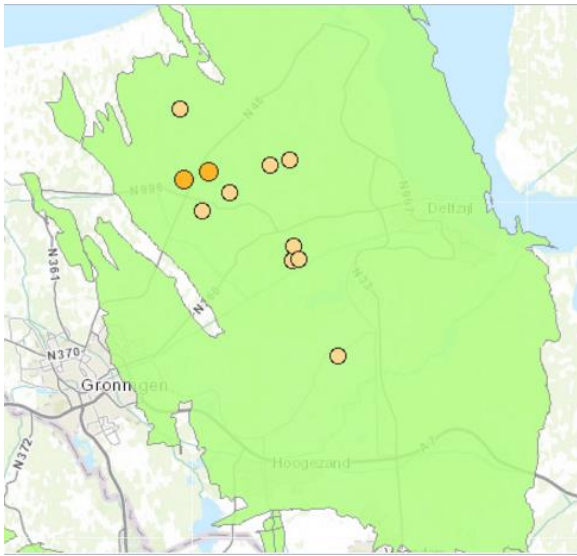
Risk maps as in Figure 4.6 are based on the same hazard maps, but also incorporate the location of buildings in the area and their occupancy. The relatively thinly populated northern part of the area and the denser-populated municipalities are clearly reflected in the risk maps. The buildings with Inside Local Personal Risk (ILPR) between 10^{-5} and 10^{-4} ($10^{-5} < \text{ILPR} < 10^{-4}$) are mainly located in a band from Delfzijl to Bedum.



Period: 1986 – 2016, Earthquakes $M \geq 2.0$



Period: 2006 – 2016, Earthquakes $M \geq 1.5$



Period: Up to January 2016

Figure 4.4 Historical earthquakes in Groningen. Top row on the left all earthquakes with a magnitude larger than $M = 2$ are shown, while at the right all earthquakes with a magnitude larger than $M=1.5$ for the last ten years are shown. Bottom row gives all historic earthquakes with a magnitude larger than or equal to $M=3.0$

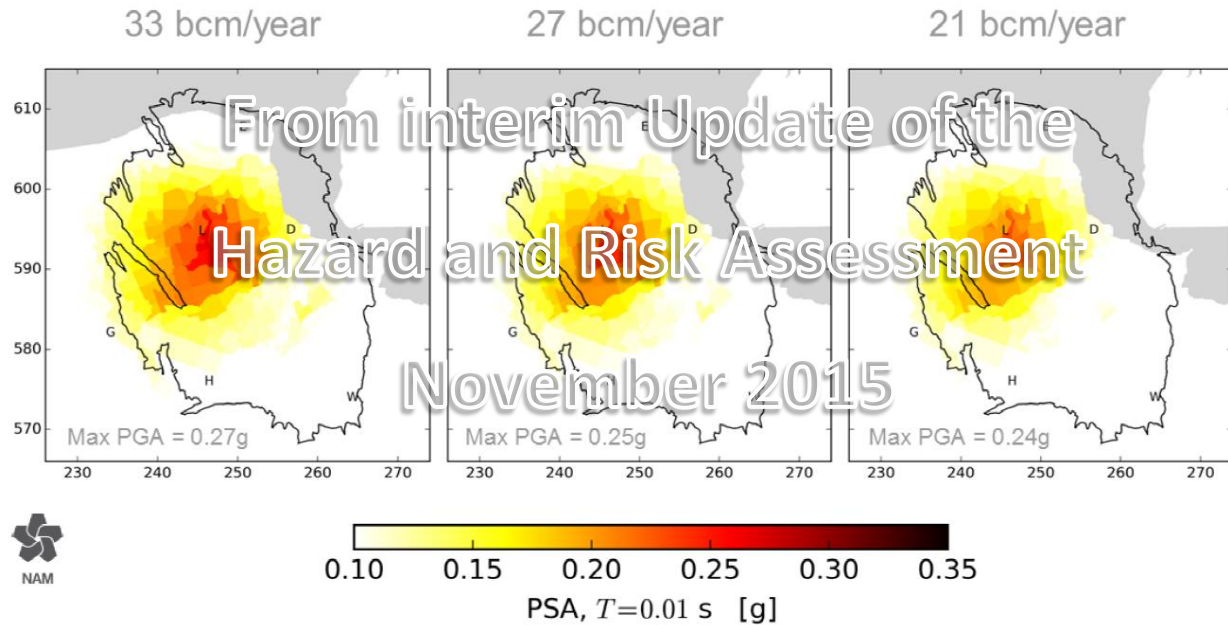


Figure 4.5 Mean PGA hazard sensitivity to production rates. Period: 2016/1 – 2021/1 (from Figure 4.14 of Nov 2015 HRA)

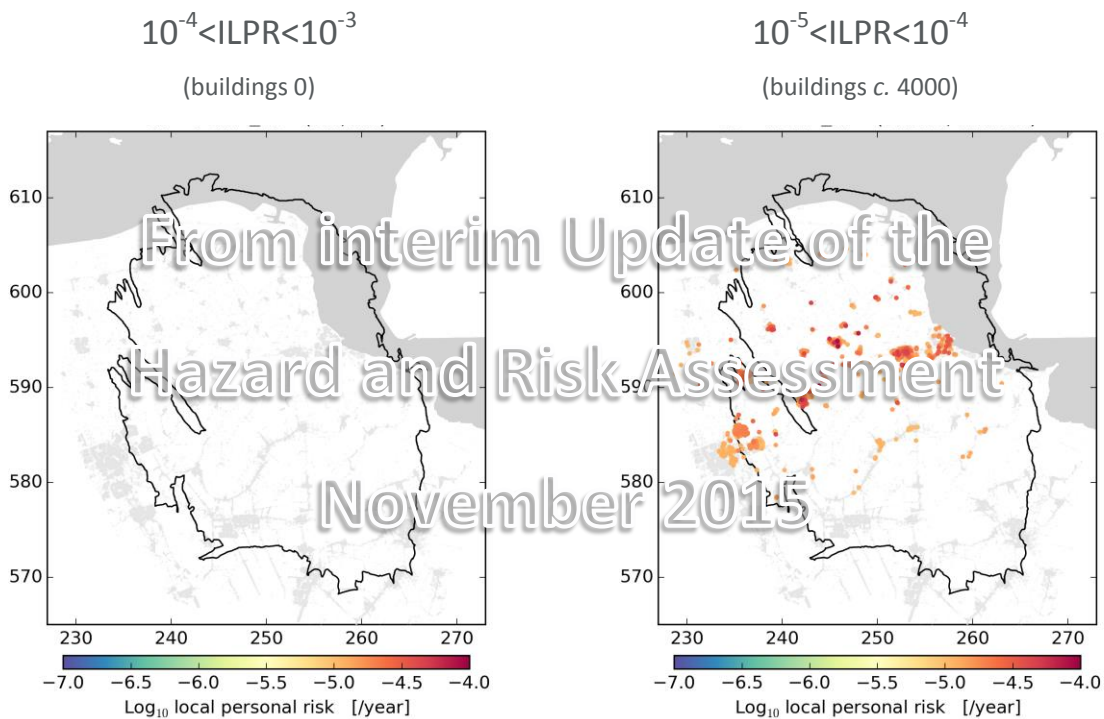


Figure 4.6 Mean inside local personal risk, ILPR for every individual building within two equal risk bands (from 10^{-5} to 10^{-4} /year, and from 10^{-4} to 10^{-3} /year) for the 5-year assessment period 2016 to 2021 under the 33 Bcm production scenario without structural upgrading. (from Nov 2015 HRA)

Figures 4.5 and 4.6 have been taken from the Interim Update of the Hazard and Risk Assessment of November 2015, which served as the starting point for the optimisation of the production distribution over the field.

4.3 Optimisation of the production distribution

4.3.1 Considerations

The January 2015 production regions were introduced to steer production distribution over the field. In order to influence seismic risk these regions should be defined in line with the gas flow behavior of the field. The following factors need to be taken into account:

- Gas flow and pressure behavior in the reservoir
- The distribution of clusters in the field
- Operational constraints in the production and pipeline systems

Figure 4.7 combines all these elements. It gives a saturation map of the reservoir with a schematic of the production system, the net hydrocarbon column map for the field, and two streamline graphs. One graph shows the streamlines colored by arriving producer, indicating the direction of flow. The other graph is colored by drainage time, i.e. the time it takes for a gas particle to travel along a streamline from a position in the reservoir to a producer well. Streamlines seem to be preferentially oriented along a NW-SE trend. The same trend is also seen in the orientation of structural elements. This suggests that those elements are affecting gas flow through the reservoir. Hence, from a gas flow and reservoir pressure perspective it makes more sense to define production regions in line with these NW-SE trends.

The net hydrocarbon column map of Figure 4.7 can be considered as a proxy for the hypothetical compaction that may occur in response to pressure depletion. It was mentioned earlier in this chapter that compaction is thought to be the driving force for induced seismicity. Particularly those locations where differential compaction occurs on either side of a fault may be prone to slippage. Therefore, the net hydrocarbon column map also provides insights for the definition of production regions.

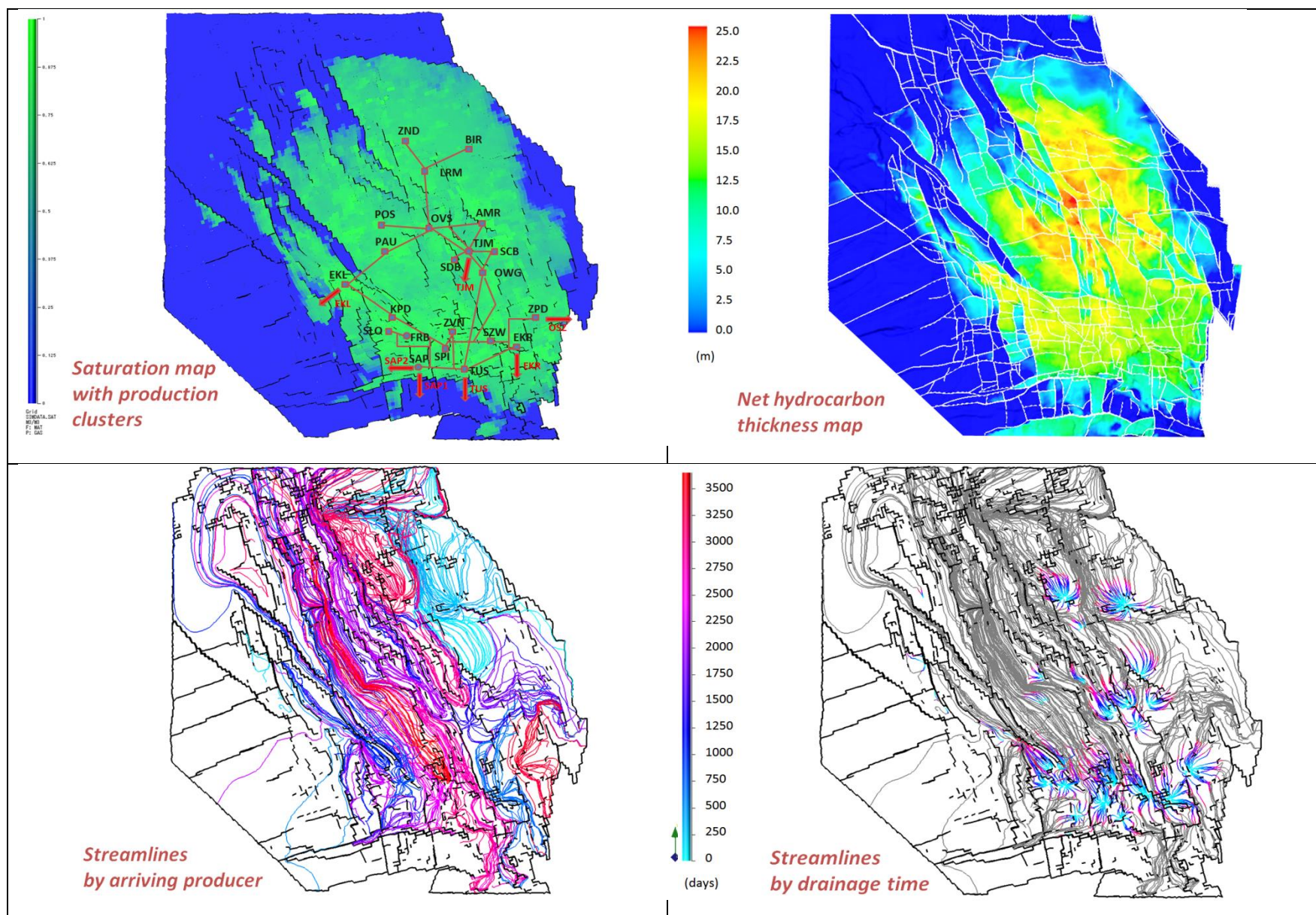


Figure 4.7 Drainage of the Groningen field

4.3.2 New areas

Based on the above observations on reservoir pressure behavior, gas flow patterns and structural-geological aspects, an update is proposed for the subdivision of the Groningen field into production offtake areas. The newly defined areas are described below and are used to evaluate the effect of production optimization to reduce seismic risk.

4.3.2.1 North area

The most northern area of the Groningen field is characterized by a low fault density and a relatively high net gas column. The column height decreases gradually to the north-east. This region has seen very limited seismic activity to date.

4.3.2.2 Northwest area

This area is characterized by a high fault density and a high but laterally varying net gas column. The area was historically most prone to seismic activity and production from clusters located in this area has been set to a minimum level in January 2015. The area is bounded in the north by a fault.

4.3.2.3 Southwest area

This area has a slightly higher pressure than other areas of the Groningen field. This can be attributed to the presence of faults and a limited juxtaposition window with other areas of the field. Fault density is high in this region and the gas column is modest on average but laterally variable.

4.3.2.4 South area

The southern part of the Groningen field has the highest density of production clusters, and consequently has a uniform pressure distribution. Fault density is also high but the net column height is limited. Therefore, the expected total compaction is limited and seismic activity levels are expected to be limited as well.

4.3.2.5 Central area

The Central area is characterized by a high fault density and a high net gas column, but with limited lateral variability. Seismic activity has slightly increased over the past years. The area is geographically close to the industrialized zone around Delfzijl.

The new areas are schematically shown in figure 4.8 as ellipses. The subdivision in production regions as used in 2015 is indicated by the colours of the clusters.

These areas have been defined based on the latest insights into reservoir behavior and seismicity. They form the basic building blocks for the optimization of the distribution of production over the field. The Measurement and Control Protocol describes the procedures for monitoring both production in the regions and the seismic activity, which should allow for further optimization of production in the future.

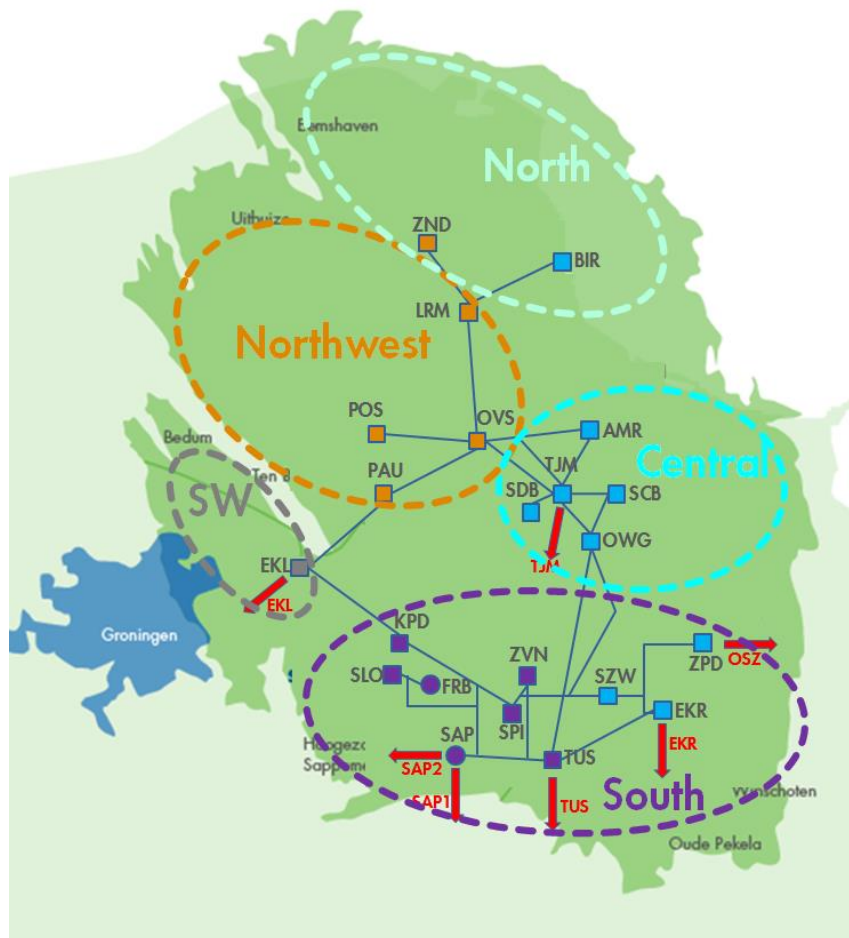


Figure 4.8 New production areas (dotted ellipses). The regional division of the field as used in 2015 is given by the colours of the clusters.

5 Forecasting with the optimised production distribution

5.1 Introduction

For the production forecasting, a combination of the subsurface model (MoRes) and surface network model (GenRem) has been used. The operational constraints as mentioned in section 3.2 and in addition, the forecast constraints as mentioned chapter 4.3 are taken into account.

5.2 Annual Demand profile

SodM advice (of December 2015) and the expectation letter from the Minister (February 2016) request NAM to avoid rapid production fluctuations as this may reduce the seismic risk. The production strategy was therefore changed to targeting a constant average production volume level per month (with an operational margin).

This flat production target has been applied both on a field level, and on an areal level. Also, the latest long term shutdown planning (LTSP) including scheduled cluster shutdowns is taken into account.

5.3 Capacity

The installed capacity in the Groningen field depends on the reservoir pressure and the operational status of the production clusters. Based on the applied maintenance strategy, the recorded performance and risk failure probability, an availability curve is established for the production facilities in the Groningen system. This availability curve indicates the expectation that a certain capacity is available for production.

In order to be able to produce the annual volume target at a flat annual demand profile, a minimum capacity is required and given the capacity per cluster consequently a certain number of production clusters. However, additional capacity is necessary because of the availabilities, the physical limitations of Groningen Ring and the GTS network, filling the UGS Norg and PGI Alkmaar, and any market restrictions.

5.4 Production logic

In order to manage seismic risk, optimized offtake is such that production will be redistributed from areas of higher risk to areas of lower risk. The following logic was established to define the production policies:

- Increase offtake in the *North* region.
From streamlines, HC thickness map and pressure maps, it is clear that the North is under-utilized, and does not seem to interfere much with the *Northwest* region.
- Reduce production from Southwest region.
- Production from North-West utilization is limited.

5.5 Production Scenarios

Three optimized production scenarios were simulated, which all honour the constraints as per section 3.2. Each production scenario assumes a constant offtake which has not been convoluted with market demand and does not cover for security of supply.

- **21 Bcm** ; Regional productions are *North* 4 Bcm, *Northwest* 1.5 Bcm, *Southwest* 0.5 Bcm, *South* 10 Bcm, and *Central* 5 Bcm. Within the *South* region highest priority is on ZPD/EKR/TUS/SZW/SAP, while the clusters closest to the high risk North-West area (KPD/ZVN/SLO/SPI) will only produce gas when required.
In the *Central* region a low priority is given to SDB, since it is closest to North-West area (will only produce when required).
- **27 Bcm**; Regional productions are *North* 5.5 Bcm, *Northwest* 1.5 Bcm, *Southwest* 0.5 Bcm, *South* 14 Bcm, and *Central* 5.5 Bcm.
- **33 Bcm**; In order to maximise the production plateau the load factors per region were kept similar: the production from the *South* region was increased with 1 Bcm to an annual total of 15 Bcm, and the *Central* region to 10.5 Bcm.

All forecasts were started at 1/1/2016, at the end of the history match. Figure 5.1 gives their respective offtake profiles in annual volumes and monthly rates. Figure 5.2 gives the reservoir pressure depletion over the next 5 years (between 1/1/2016 and 1/1/2021) for the three scenarios. It can be seen that for all scenarios, pressure depletion is minimized in the Central-Western part of the field. However, for the high offtake scenario (33 Bcm), this effect becomes less pronounced, and especially the South is further depleted.

Figure 5.3 gives a direct comparison of the next 5 year's depletion between the Nov 2015 HRA forecasts and the optimized new regional offtake pattern, for 21/27/33 Bcm annual offtake, together with their respective corresponding pressure differences. It is clear that with the new regions, the relatively benign North-Eastern area of the field is further utilized, at the benefit of the Southwestern (Eemskanaal) area, and extending the spared North-West area further South/East.

Note that the monthly production volumes are flat, taken into account maintenance, i.e. field loadfactor is the same every month.

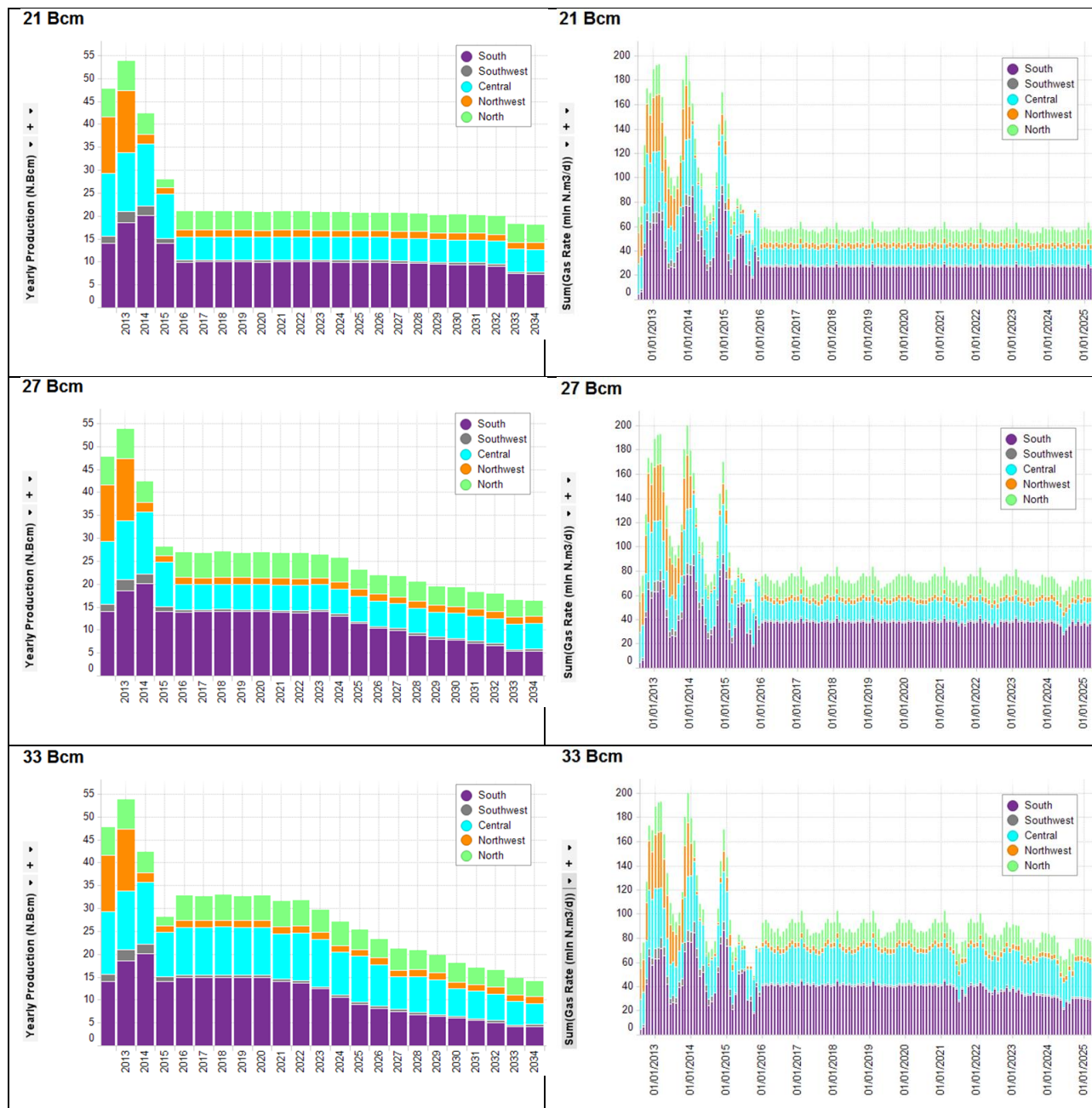


Figure 5.1 Annual and monthly production volumes by region, for 21/27/33 Bcm annual production

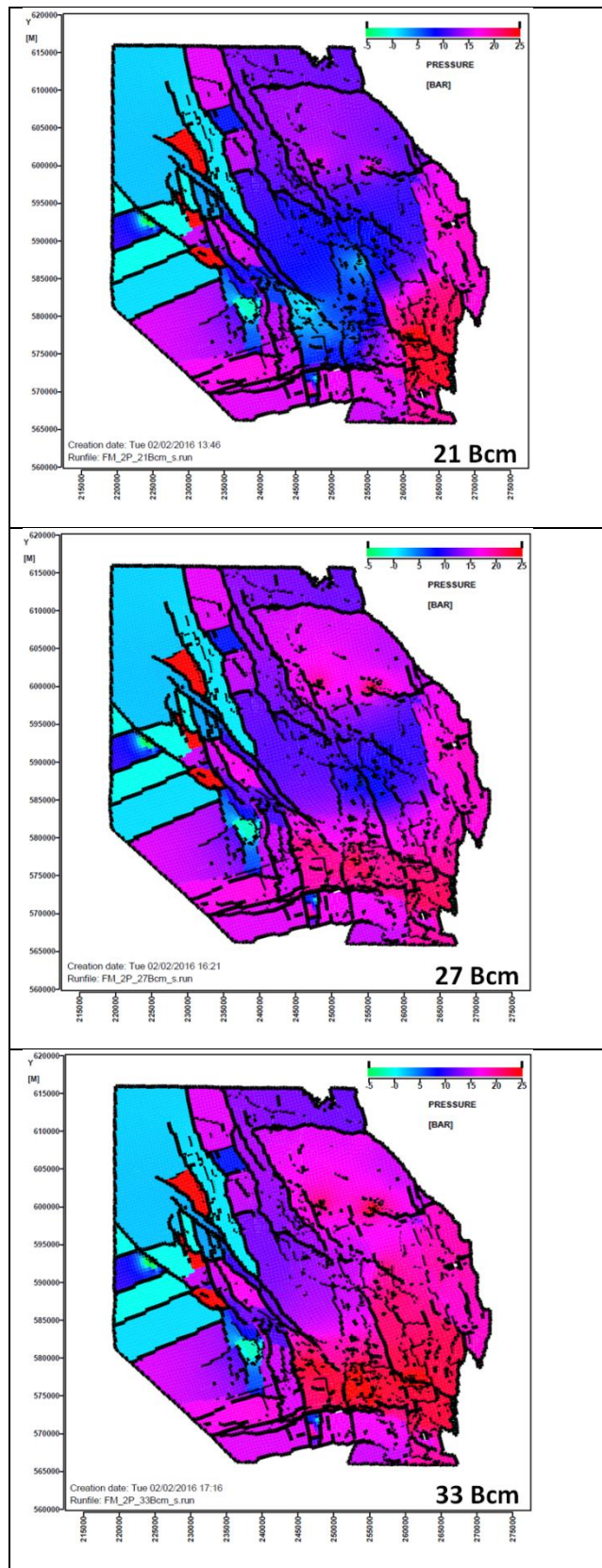
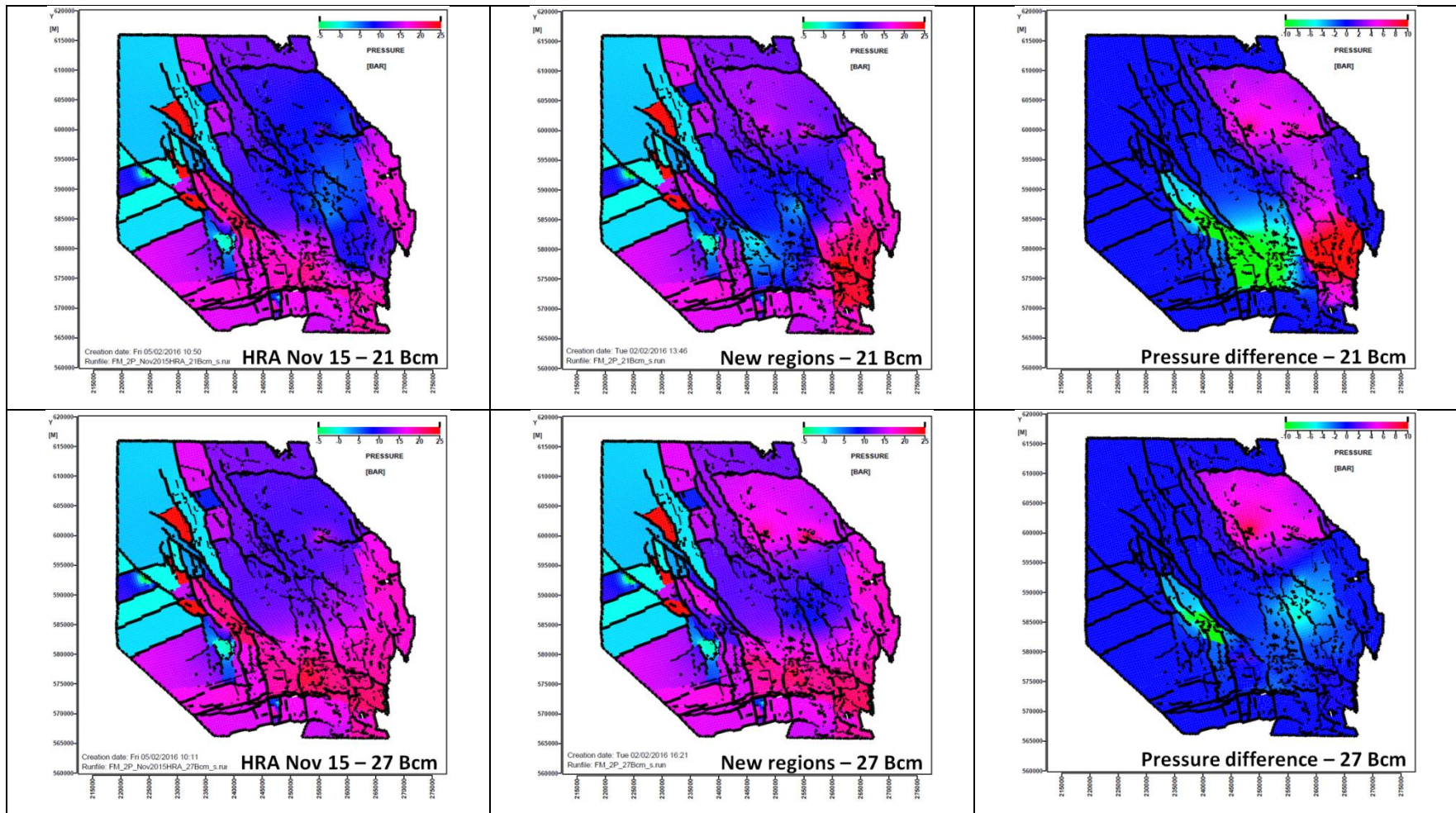


Figure 5.2 Depletion between 1/1/2016 and 1/1/2021



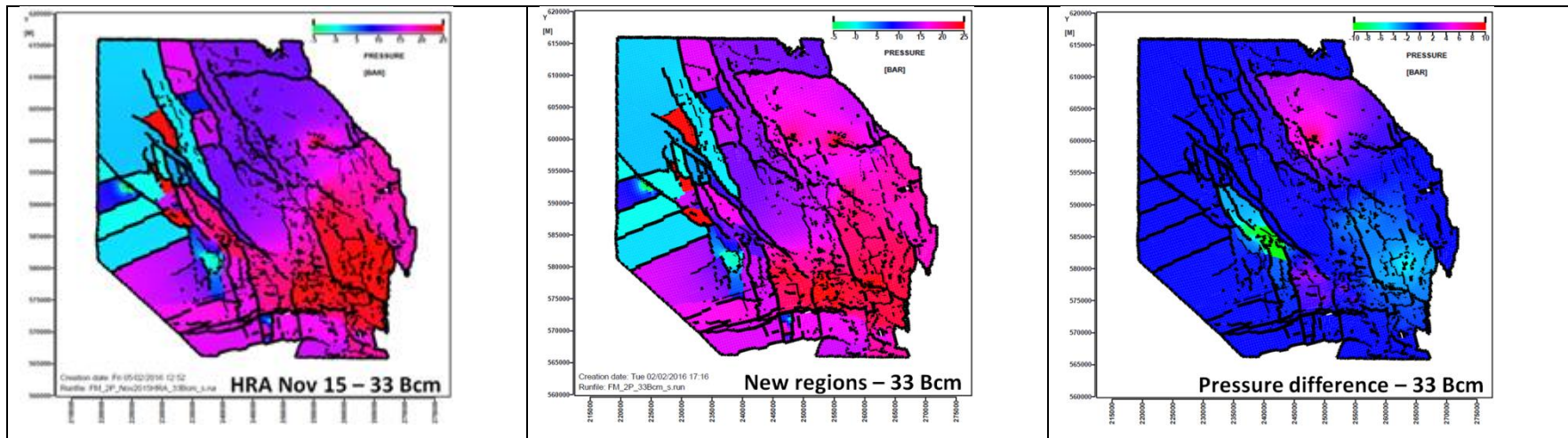


Figure 5.3 Pressure depletion between 1/1/2016 and 1/1/2021 for 21/27/33 Bcm annual offtake scenarios, comparing the “Nov 2015 HRA” production profile with the optimised production distribution from the “New regions”

Appendix Introduction to the Geology of the Groningen field (Static Model Description)

Structural setting

The reservoir rocks of the Groningen field are dissected by a large number of natural faults. Some of these natural faults are thought to play an important role in the creation of earthquakes. They represent zones of weakness along which movement of volumes of reservoir rock can take place. Hence, it is key to understand the distribution and character of the natural faults in the subject area. This section describes the development of the fault system through time and its main geometrical characteristics.

The Groningen field is located on the Groningen High that has been a tectonically stable block since the late Kimmerian uplift. The current depth of the Rotliegend reservoir, around 2600-3200 mTVD (true vertical depth), reflects the maximum burial depth. The Groningen High is surrounded in the east by the Ems Graben and Lower Saxony Basin and in the west by the Lauwerszee Trough (

Figure A.1). The Groningen field is mainly fault-closed in all directions with dip closures present only locally. Top seal of the Groningen field is provided by the overlying Zechstein salt. Figure A.2 shows a seismic line from NW to SE illustrating these features.

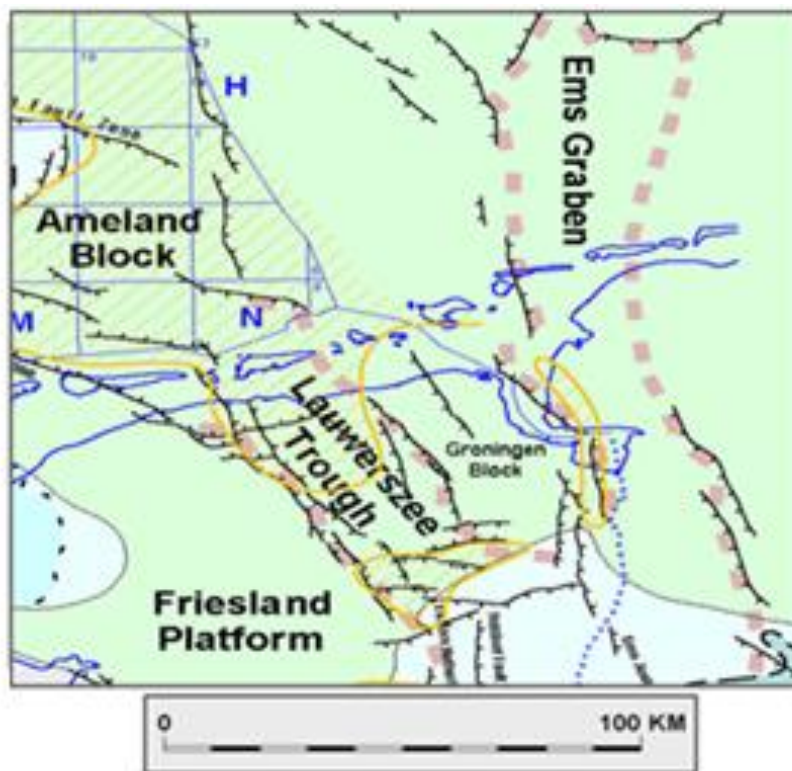


Figure A.1 Main structural elements in the northern Netherlands

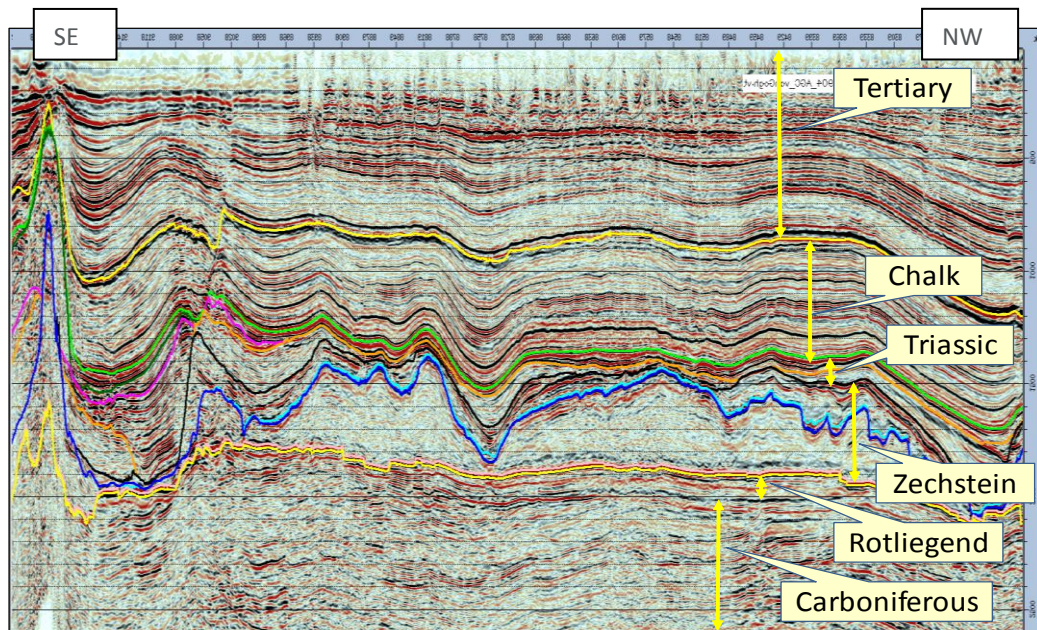


Figure A.2 SE-NW seismic cross-section through the Groningen field (see Figure A.4 for detailed interpretation)

The Ems Graben and Lauwerzee Trough are results of a Late Carboniferous / Early Permian rifting phase (extensional). The Groningen High was formed by the development of large North to West trending faults. Initiation of these faults started prior to the Saalian erosional event which marks the Carboniferous-Permian boundary across the region.

Most of these faults have been reactivated by two major tectonic events. The first was a period of SE-NW extension which began during the Triassic and continued into the Late Jurassic. An inversion stage followed during the late Jurassic-early Cretaceous (Kimmerian). Movement of the Zechstein salt also took place during Cretaceous times. With the onset of the Alpine orogeny the area underwent a period of N-S compression, lasting into the early Tertiary. This resulted in a second period of reactivation, evidenced in some areas by transpressive skinny grabens and pop-up structures.

Detailed analysis of fault orientations, timing and kinematics has enabled to subdivide different structural domains (SD1 to SD9 in Figure A.3). Note that only a selection of the most important faults is included in the structural model. Moreover, not all faults present in the subsurface are necessarily identified in the seismic interpretation. SD1 in the South-Western periphery of the Groningen field is the most complex and intensely faulted domain. It has experienced the most pronounced shortening and inversion, mainly along NW- and E-trending faults, and manifested by pop-up structures.

SD5 in the Zeerijp area is another structurally complex domain. It is interpreted to be a depressed graben feature bounded by two NNW-oriented oblique slip faults, which originated from a deep-seated older fault zone. The difference in orientation between this fault zone and the Triassic-Jurassic stress field led to strike-slip movement along the graben boundary faults, and to rotation of fault blocks within the graben.

SD6 in the North-East is an example of a structurally quiet domain. E-W trending faults are branching from a deeper-seated fault system, probably as a result of Jurassic extension and without evidence for later-stage inversion.

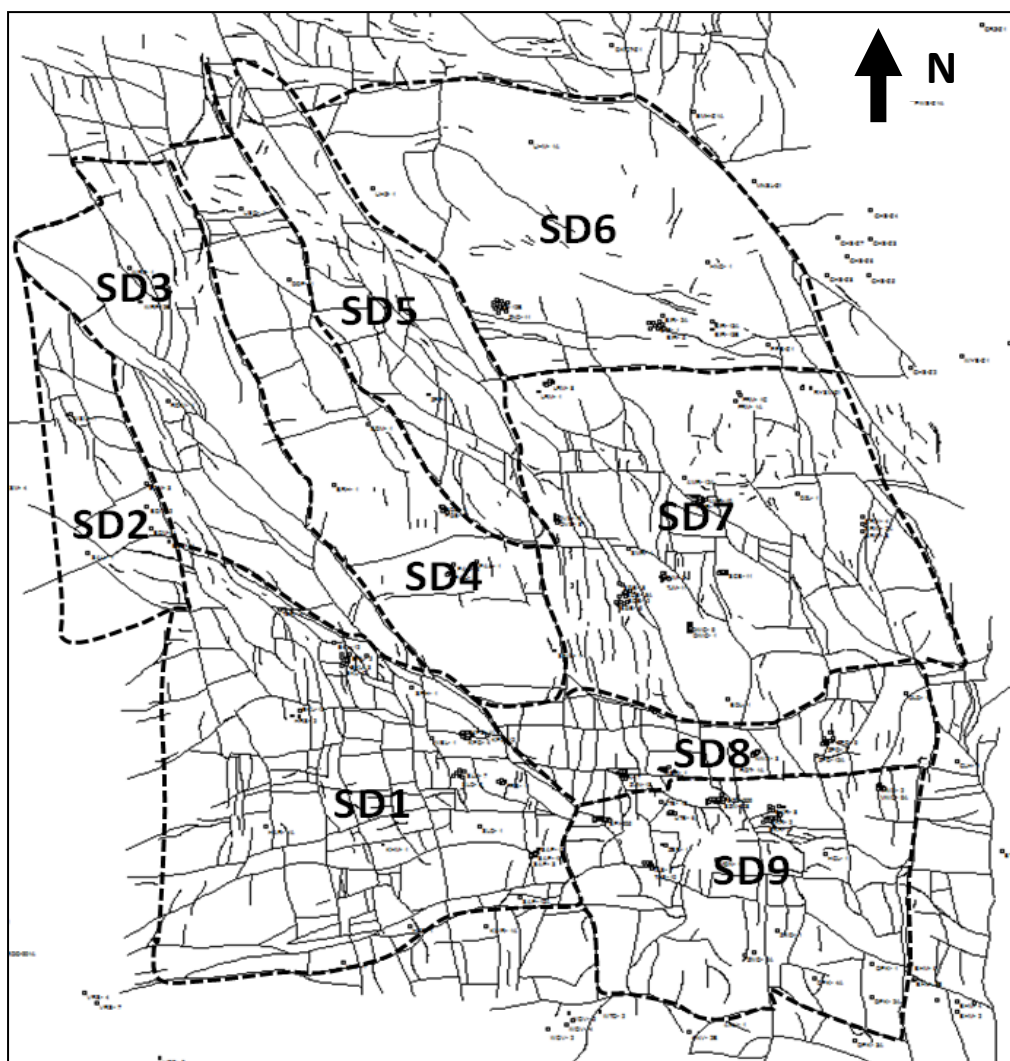


Figure A.3 Structural domains in the Groningen field (total area ~ 40 x 40 km); faults shown are at Top_Rotliegend level

Stratigraphy and depositional setting

A second important factor in the study of induced earthquakes, next to the structural model described above, is the distribution of rock properties in the reservoir. For example: the higher its porosity, the higher is the potential for the rock to compact as a result of gas production. The key role of compaction in generating seismicity is described in this technical addendum. Porosity is high in sandstone rock and low in claystones. The depositional processes that formed the sandstones are also important in the sense that rocks formed by wind action (aeolian sediments) generally have higher porosities than those formed by river currents (fluvial sediments). In the following, an overview is given of the important rock formations present in the subsurface of Groningen.

The gas-bearing interval in the Groningen field comprises both Upper Rotliegend Group (Permian) and Limburg Group (Carboniferous) sediments, separated by the Saalian Unconformity.

The Carboniferous sediments range in age from Westphalian-A to Westphalian-D. They represent lower to middle delta plain deposition under humid, subtropical conditions. The Carboniferous strata have been tilted and eroded during the Variscan orogeny (Figure A.4). This created a depositional relief that was gradually filled by the Rotliegend.

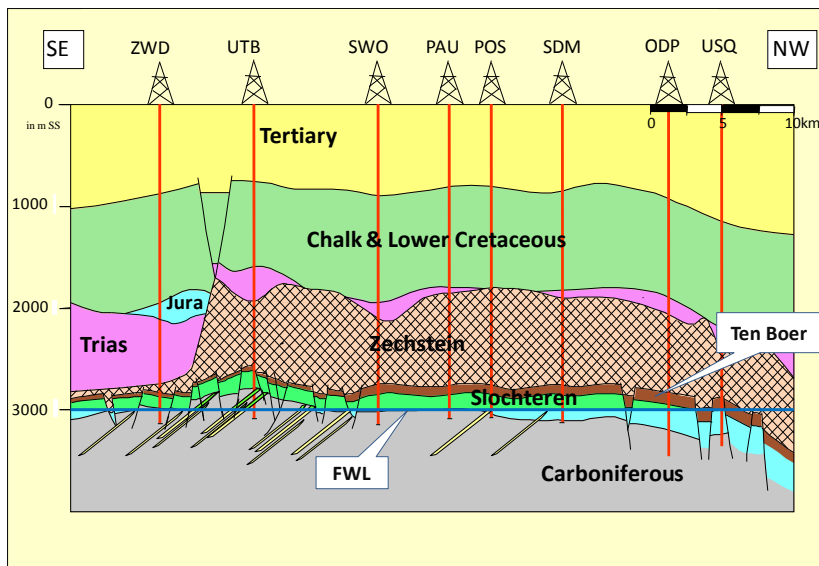


Figure A.4 Schematic cross-section through the Groningen field indicating the main stratigraphic intervals. FWL indicates the free water level.

The Upper Rotliegend Group comprises the Silverpit and Slochteren Formations. These are subdivided into the following lithostratigraphic members (top to bottom): Ten Boer Claystone (ROCLT, heterolithic shale/silt/sand), Upper Slochteren Sandstone (ROSLU, mainly sand), Ameland Claystone (ROCLA, heterolithic shale/silt/sand) and the Lower Slochteren Sandstone (ROSLL, mainly sand).

Table A.1 Lithostratigraphic Subdivision

Time	Group	Formation	Member	REGEO CODE
Permian	Zechstein			ZE
Permian	Upper Rotliegend	Silverpit	Ten Boer Claystone	ROCLT
		Slochteren	Upper Slochteren Sandstone	ROSLU
		Silverpit	Ameland Claystone	ROCLA
		Slochteren	Lower Slochteren Sandstone	ROSLL
Carboniferous	Limburg			DC

The Silverpit- and Slochteren Formations form a wedge of continental sediments that is onlapping southwards onto the Carboniferous relief, and thickening towards the northwest (Figure A.5). Rotliegend sediments were deposited under arid, desert climate conditions. In the south of the Groningen area, along the basin margin, the sediments consist of mixed alluvial/braided river deposits. These grade northwards into mixed fluvial-aeolian deposits (Lower and Upper Slochteren Sandstone Members) and ultimately into lake margin and desert lake fines (the Ten Boer and Ameland Claystone Members).



Figure A.5 Lithostratigraphic subdivision of the Rotliegend in the Groningen area

The Ameland and Ten Boer Claystone Members are characterized by silty to shaly wet sandflat deposits, representing lake level highstands of regional scale as a response to climatic variations. The Ameland Claystone can be clearly distinguished as a separate lithological unit in the northern half of the field, but pinches out towards the South. Total thickness of Rotliegend sediments ranges from 140 m in the SSE to 300 m in NNW.

The Rotliegend is overlain by the sediments of the Zechstein Group. The Zechstein is dominated by evaporate deposits, mainly halite, which forms a perfect seal for Rotliegend reservoirs. The lowermost part of the Zechstein comprises a very competent and high-density carbonate/anhydrite interval which is referred to as the Basal Zechstein. It is present throughout the greater Groningen area with a remarkably constant thickness (~50 m in average). The large acoustic impedance contrast between the Basal Zechstein and the overlying halite package creates a very strong seismic reflector, which is well-suited for mapping the structural features described in the foregoing. The interval may also play an important role in the transmission of seismic signals from a deeper source area to the surface.

Reservoir model and rock properties

The Rotliegend interval has been subdivided into the five Slochteren reservoir zones, four Slochteren heterolithic zones, and three Ten Boer zones. A further vertical refinement was made by dividing the zones into thinner layers. The resulting static framework consists of 12 reservoir zones, 175 layers and a total of nearly 6 million grid cells. Approximately 90% of all grid cells have a thickness between 1 and 2 m.

Models to describe the distribution of reservoir properties in the Groningen field are based on the extensive database of wireline log and core data. The modeling methodology applied is Gaussian Random Function Simulation (GRFS), supported by trend maps that reflect the regional depositional trends. The distribution of porosity in the model area is steered by an acoustic impedance property derived from a seismic inversion study.

The mean Net-to-Gross for the Ten Boer Claystone ranges between 8 and 15%, but is typically larger than 95% for the Slochteren reservoir zones. The thin heterolithic zones separating the reservoir zones still have mean NtG values as high as 75 - 80%. The distribution of porosity shows comparable trends, with mean values of 6 - 10% for sandy interbeds in the Ten Boer Claystone, 15 - 18% for the reservoir zones, and only slightly lower mean values for the sandy parts of the heterolithic intervals.

Best reservoir quality is seen in the central parts of the field where aeolian processes have played an important role. Properties decrease towards the southern margin of the field, and towards the north. This is in line with depositional trends of becoming more clay-rich towards the north, and more fluvial-dominated or conglomeratic towards the south. as an example gives the porosity distribution of one of the reservoir zones.

The mean permeability of the reservoir zones ranges from tens to hundreds of milliDarcies, gas saturation ranges from 60 to 80%.

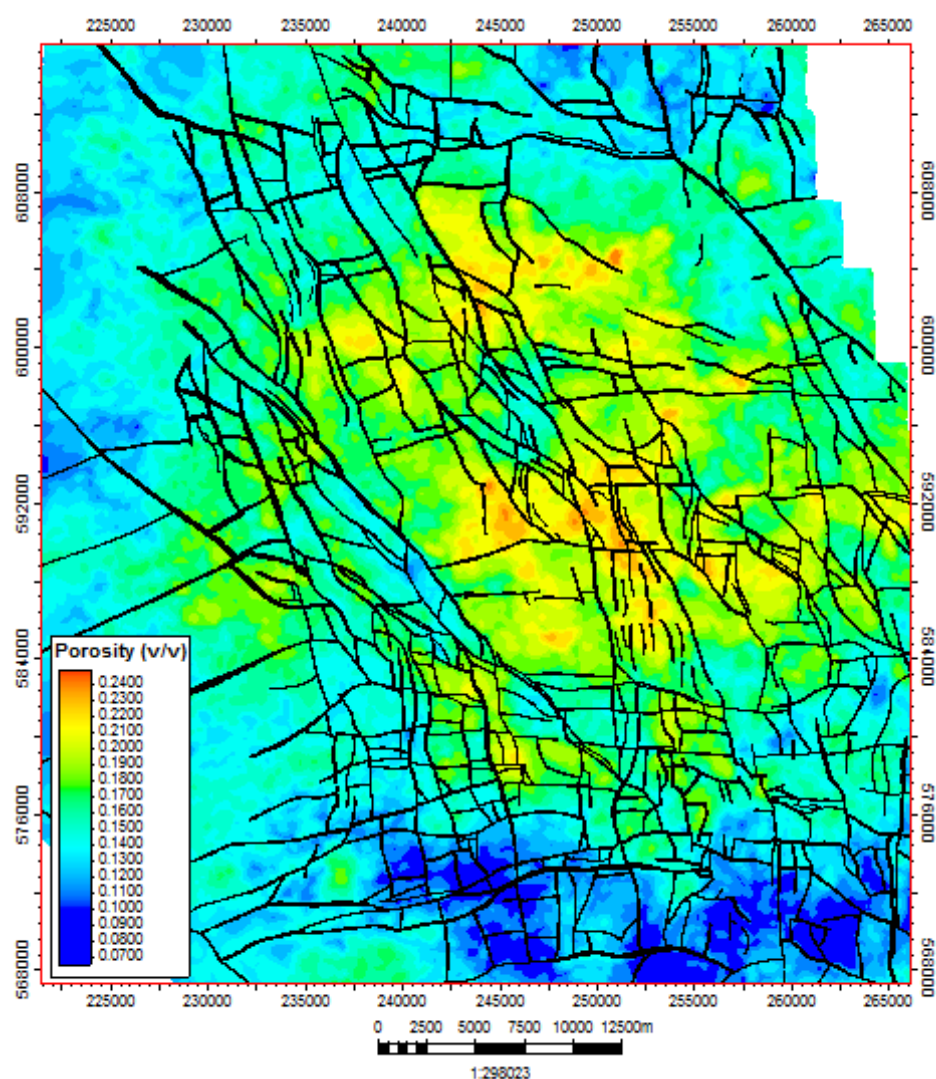


Figure A.6 Average porosity of one of the Upper Slochteren Sst reservoir zones

