Subsidence inversion on Groningen using leveling data only

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Contents

Introduction

The modelled subsidence presented in the Groningen winningsplan, issued April 2016 (NAM, 2016a), was based on a calibration of the model to both spirit leveling and InSar monitoring data. The workflow used is presented in detail in the Technical addendum to the Winningsplan Groningen 2016 (NAM, 2016b). A condition in the approval document of the Minister of Economic Affairs (Ministerie van Economische Zaken, 2016) demands an update of the subsidence (actual and forecasted) using leveling data only. The same condition also demands an uncertainty analysis of the actual and future subsidence estimates in the Groningen Winningsplan (NAM, 2016a). The formal condition is stated below in Dutch.

"Artikel 6 De Nederlandse Aardolie Maatschappij B.V. dient uiterlijk op 1 januari 2017 een rapport in bij de Minister van Economische Zaken waarin:
a. inzichtelijk wordt gemaakt, op grond van waterpasmetingen, hoeveel bodemdaling er in totaal is opgetreden en hoeveel daarvan door gaswinning wordt veroorzaakt;
b. een voorspelling is opgenomen van de toekomstige bodemdaling ten gevolge van de gaswinning uit het Groningenveld die is gebaseerd op de onder a bedoelde vastgestelde bodemdaling en;
c. een analyse is opgenomen van de onzekerheden in de bepaling van de opgetreden bodemdaling en de rekenmodellen om de toekomstige bodemdaling te ramen." (Ministerie van Economische Zaken, 2016)".

This report describes the modelling process and calibration to the spirit leveling data (exclusively). Besides presenting the matched model contour it also presents subsidence contours of the model forecasts for the 24, 27 and 33 BCM production scenarios. All scenarios are based on the Winningsplan 2016 history matched reservoir model. Calibration to the spirit levelling data uses both the Time Decay and RTCiM compaction model. Besides the new calibration and forecast results, also the associated uncertainty ranges are explained in this report.
The geodetic dataset used in the calibration consists of only the spirit leveling data. The dataset contains measurements that were acquired in the period between 1964 and 2013. For the calibration only measurements at stable points were used (NAM, 2015a). A stable point implies that the subsidence observed at that specific point is considered to be the result of gas extraction only.

The epochs used in the calibration are:
H_15_04_1964, H_01_09_1972, H_01_09_1975, H_15_07_1978, H_01_07_1981, H_01_09_1985, H_01_08_1987, H_15_05_1990, H_14_05_1991, H_28_06_1993, H_13_06_1997, H_05_06_1998, H_17_06_2003, H_13_08_2008, H_25_04_2013

Methodology

In the Winningsplan 2016 a good spatial subsidence fit was obtained by inverting to a spatially varying Cm grid with a grid size of 1x1 km^2. However, inverting to Cm does not give a unique solution and can return large spatial scattering of the Cm. In order to reduce scatter, the inversion was regularized using the Cm porosity relation as a prior. In the inversion process penalties were put on:

1. The difference between the inverted Cm and porosity derived Cm
2. The residuals between modelled and measured subsidence.

Since Winningsplan 2016 the spatial Cm calibration to the levelling data is optimized by improving the second step: the derivation of the residuals.
The calibration step now uses all spirit leveling epochs, whereas the Winningsplan 2016 used only a subset of the spirit levelling and InSar epochs. Also each epoch combination in time has been given the same weight, whereas the weight of the epoch combination in the calibration of the Winningsplan 2016 model was dependent on the number of double differences in this time period. A drawback of the latter method was that the time period with the most double differences had the most influence on the calibration results, in general the time periods in later years.

Modelling/ Calibration to Cm grid

For the calibration of the spatial Cm grid all available spirit levelling data are used. A number of time intervals are selected representing the subsidence over time (Figure 1). This figure shows by the thickness of the lines that more recent periods have more measurements (also indicated by the numbers in the green bars). A possible bias in the calibration that results from the dataset is corrected for by normalizing the root mean square (RMS) of the difference between modelled and measured subsidence. Finally, the goal of the calibration is to minimize the sum of all normalized RMS values.
The calibration assumes a Time-decay compaction model using decay values between 0 and 7 years. The decay time of 0 years represents a linear model. This calibration resulted in a different spatial Cm grid for each different time decay value (Figure 2). The best Cm grid is the one where the normalized total error (RMS value) is the smallest, which is at a time decay of 5 years.

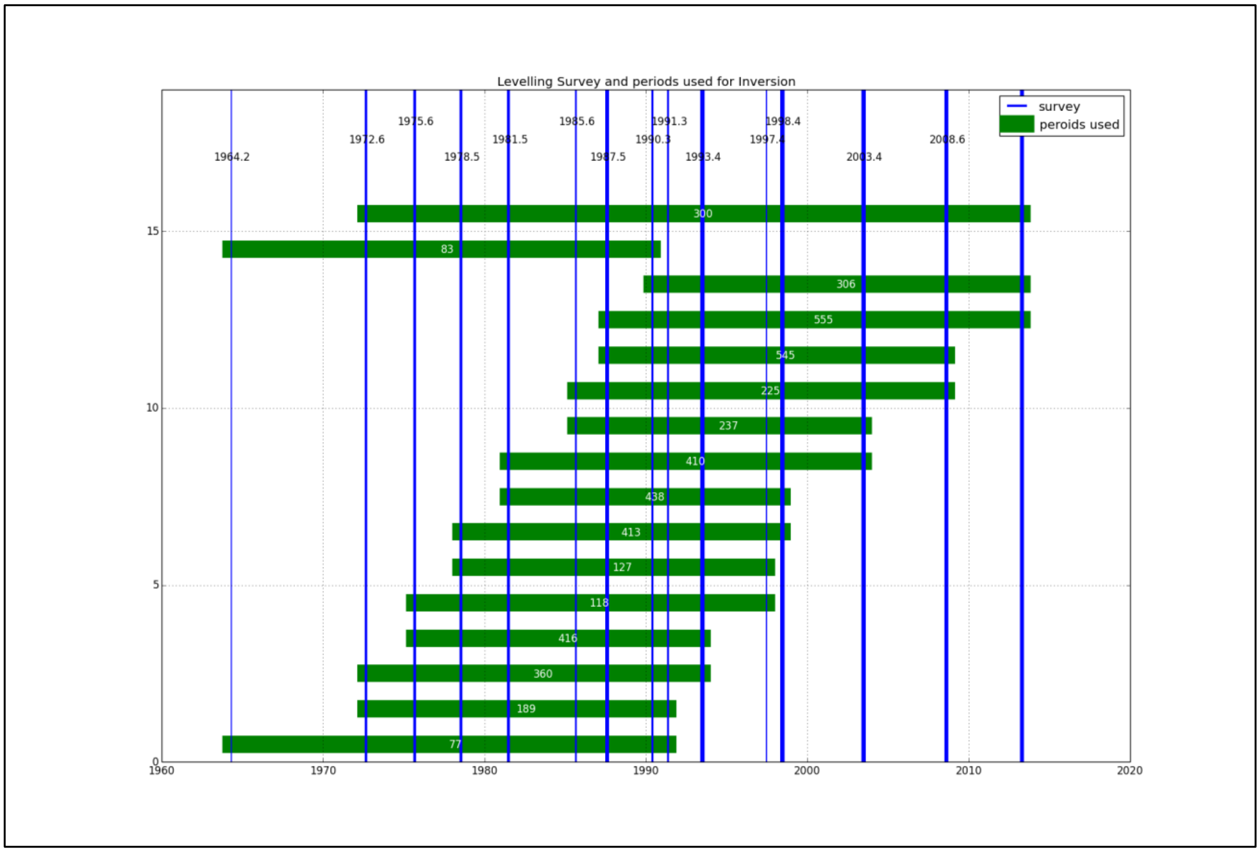


Figure 1 Used time periods (green bars) for the spatial Cm calibration, the numbers in the green bars are the number of double differences, the blue lines indicate the levelling time, where the thickness of these lines gives a relative indication of the number of benchmarks measured. X-axis represent the measurement date.

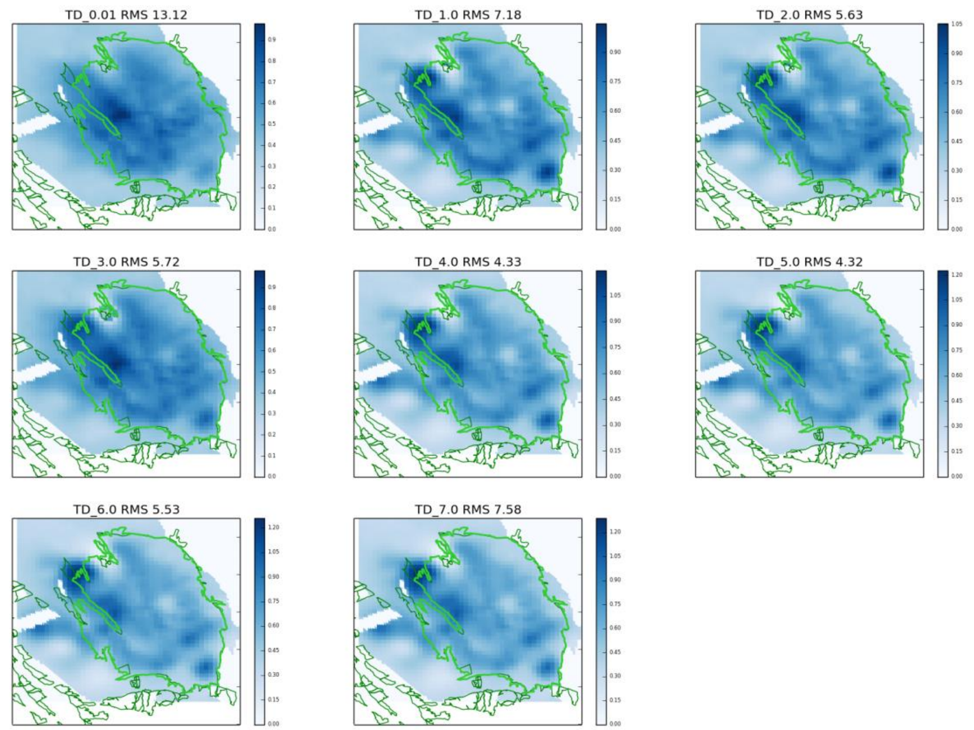


Figure 2 Spatial Cm grids for different time decay values (years), The reported RMS value is the total normalized RMS

The spatial Cm calibration that is obtained using a decay time of 5 years returned the lowest RMS value. Therefore, this spatial Cm grid was used as basis for further Time Decay and RTCiM matches and forecasts. In this subsequent step the Cm multiplication values that are used in further calibration steps are applied to the whole grid and not to individual grid cells.

Time-decay modelling

Further refined calibration resulted in a Cm multiplication factor of 1.04 and a decay time of 5.25 years, which is, as expected, very close to the outcome of the Cm grid calibration in the previous step.
The subsidence match is shown as a residual map in Figure 3 for the period between 1972 and 2013. Figure 8 and Figure 9 show the modelled and measured subsidence at several benchmarks in time. This selection is the same as used in the technical reference of the winningsplan (NAM, 2016b). Note that the grey bands represent a chosen offset of 1 and 2 cm from the modeled subsidence to allow for better comparison of the graphs having different scales. Figure 4 shows the measured and modelled subsidence between 1972 and 2013, in fact the same as Figure 3 but now as absolute subsidence.

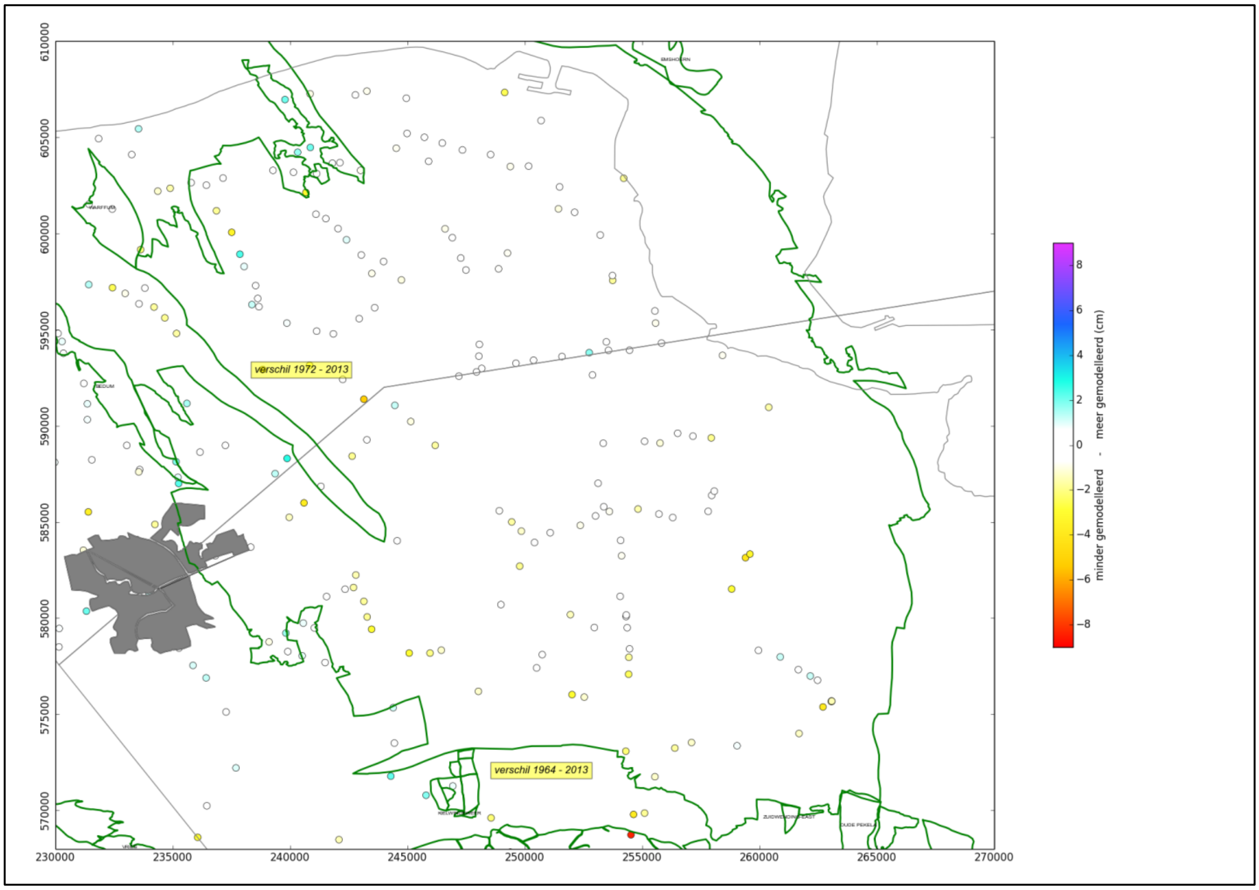


Figure 3 Residual map between leveling and model.

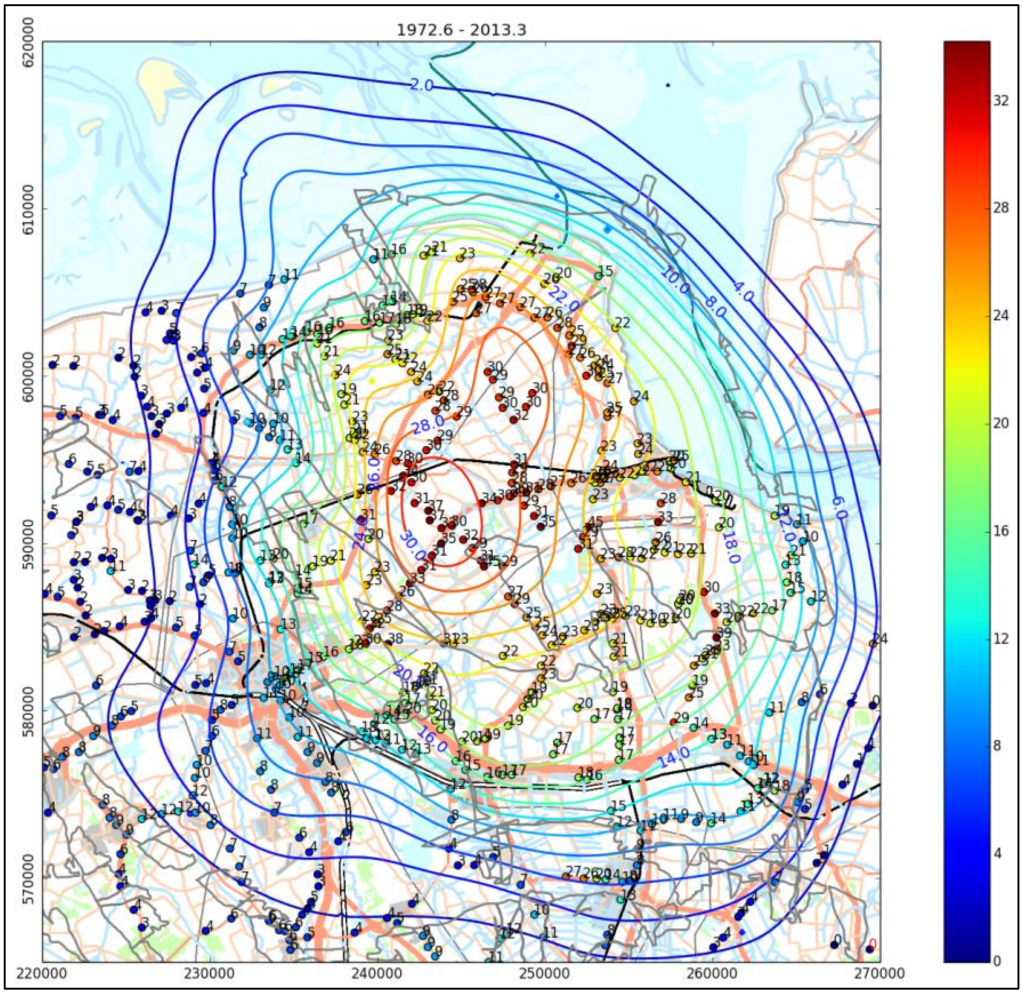


Figure 4 Modelled (contours) vs measured subsidence (benchmarks) in centimeters between1972 and 2013

Rate Time Compaction (RTCiM) modelling

The second compaction model considered is the RTCiM model (Pruiksma et al, 2013). This model uses the same spatial Cm grid as used in the Time decay modelling and is also based on spirit levelling data only. An optimal fit was found using the following values for the RTCiM input parameters:
$C_{m,ref}$ factor = 1.39, $C_{m,a}$ factor = 0.78 and b = 0.015.
For comparison the (almost similar) winningsplan 2016 parameters are:
$C_{m,ref}$ factor= 1.39, $C_{m,a}$ factor=0.75 and b= 0.018.

The match of this model to the data is shown in Figure 5 as a residual map for a period between 1972 and 2013. Figure 8 and Figure 9 show the modelled and measured subsidence at certain benchmarks in time. Note that the grey bands represent a chosen offset of 1 and 2 cm from the modeled subsidence to allow for better comparison of the graphs having different scales. Figure 6 shows the absolute values of both the measured and modelled subsidence between 1972 and 2013.

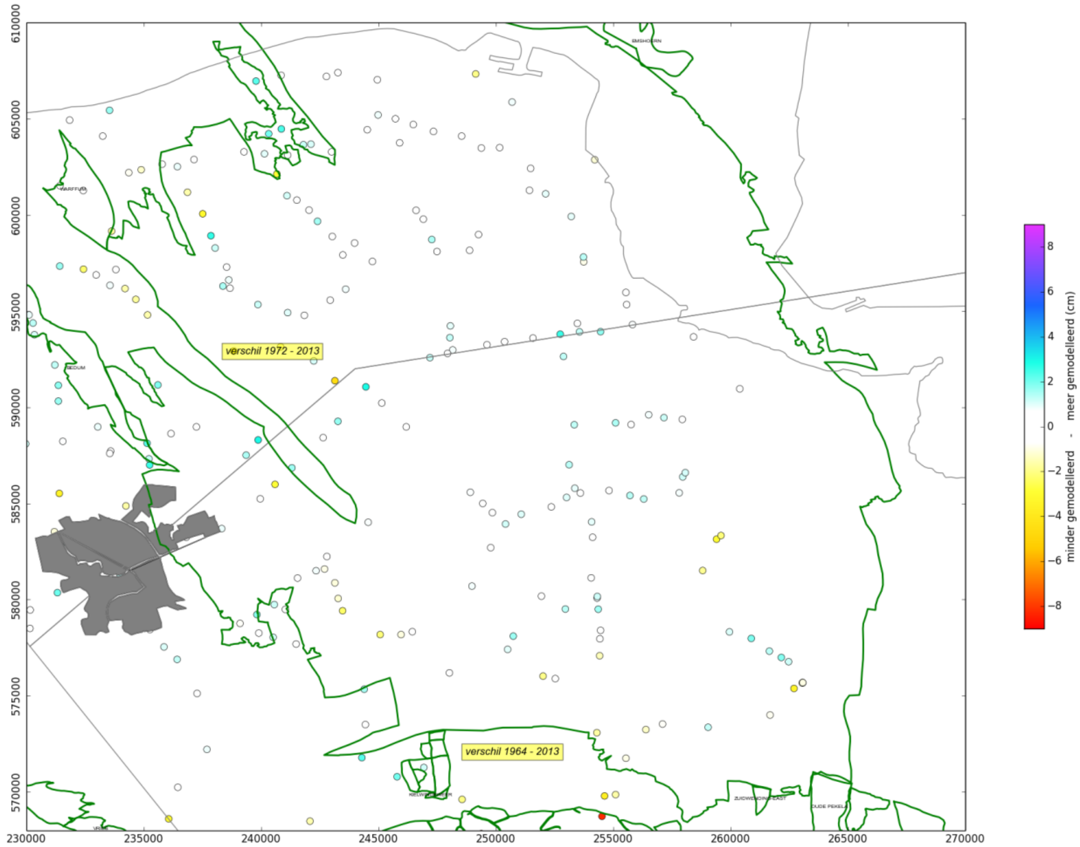


Figure 5 Difference between modelled and measured subsidence between first and last levelling measurement.

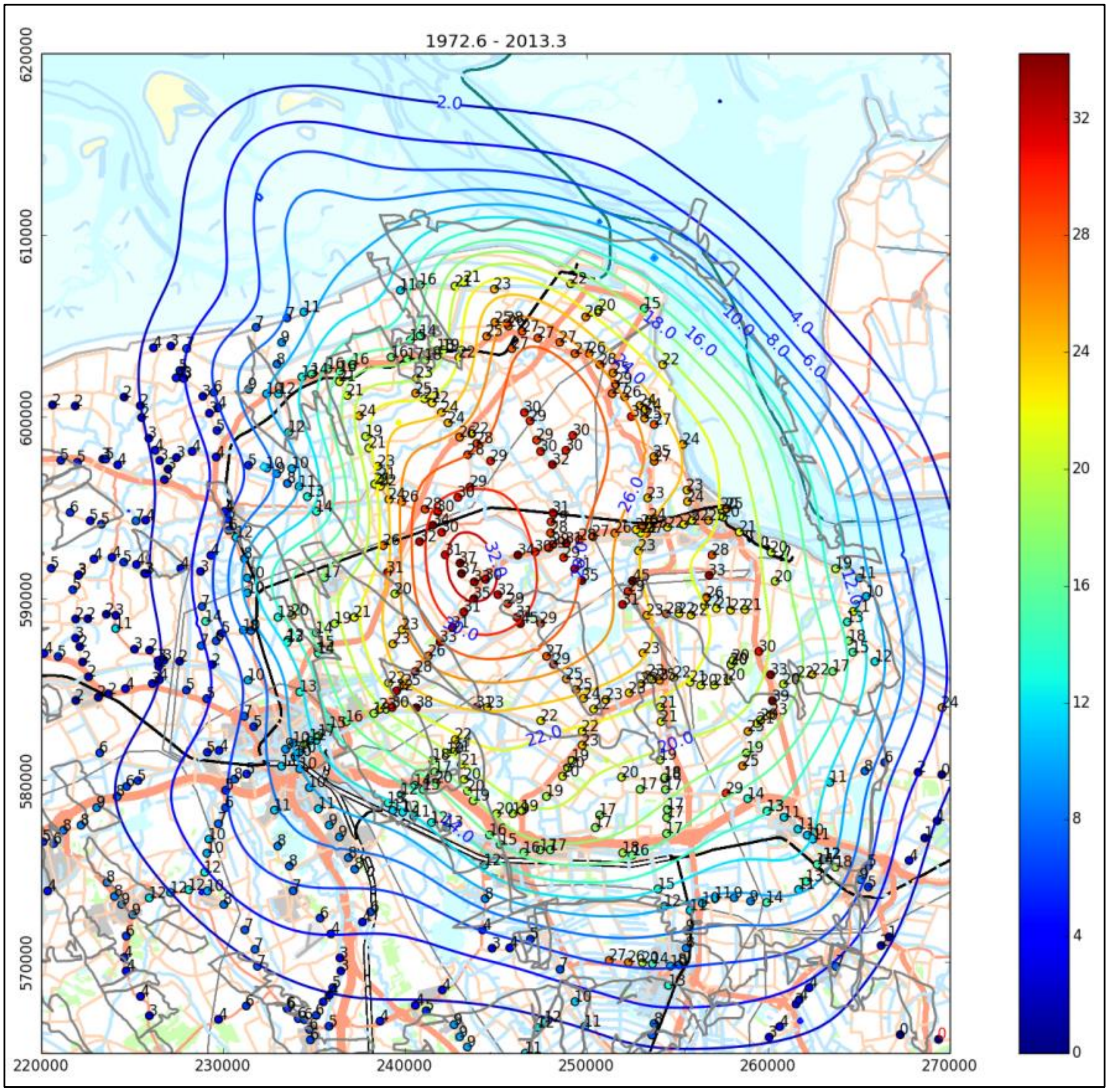


Figure 6 Modelled vs measured subsidence (1972 - 2013).

Comparison of compaction models

Both compaction models returned a good fit to the leveling data with the RTCiM model having a slightly better RMS value. Also the temporal fit on the individual benchmarks shows a better result for the RTCiM model. A comparison between the subsidence vs time at benchmark locations in Figure 7 is shown in Figure 8 and Figure 9. The starting year of the measurements differs per benchmark and therefore it is needed to tie the models to the first year of measurement. In Figure 8 the first leveling point is tied to the RTCiM model and in Figure 9 to the Time-decay model.

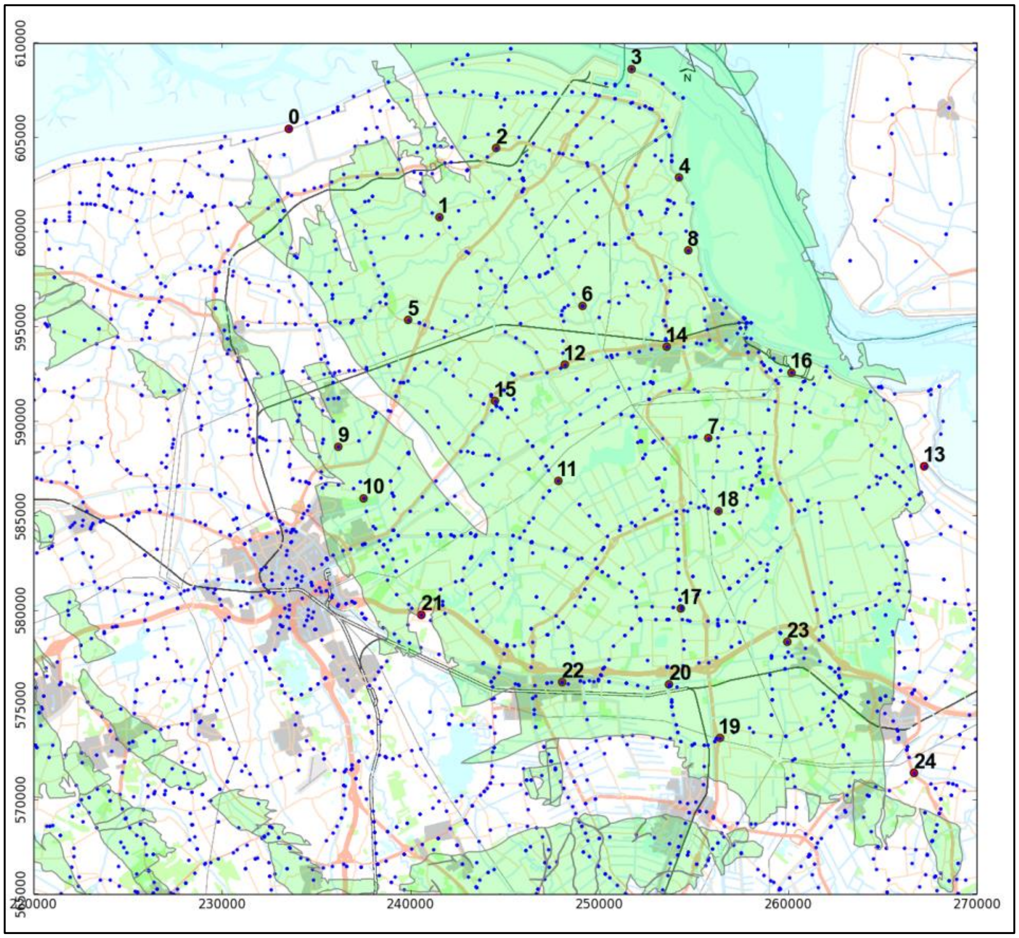


Figure 7 Location of the benchmarks used for the graphs in Figure 8 and Figure 9

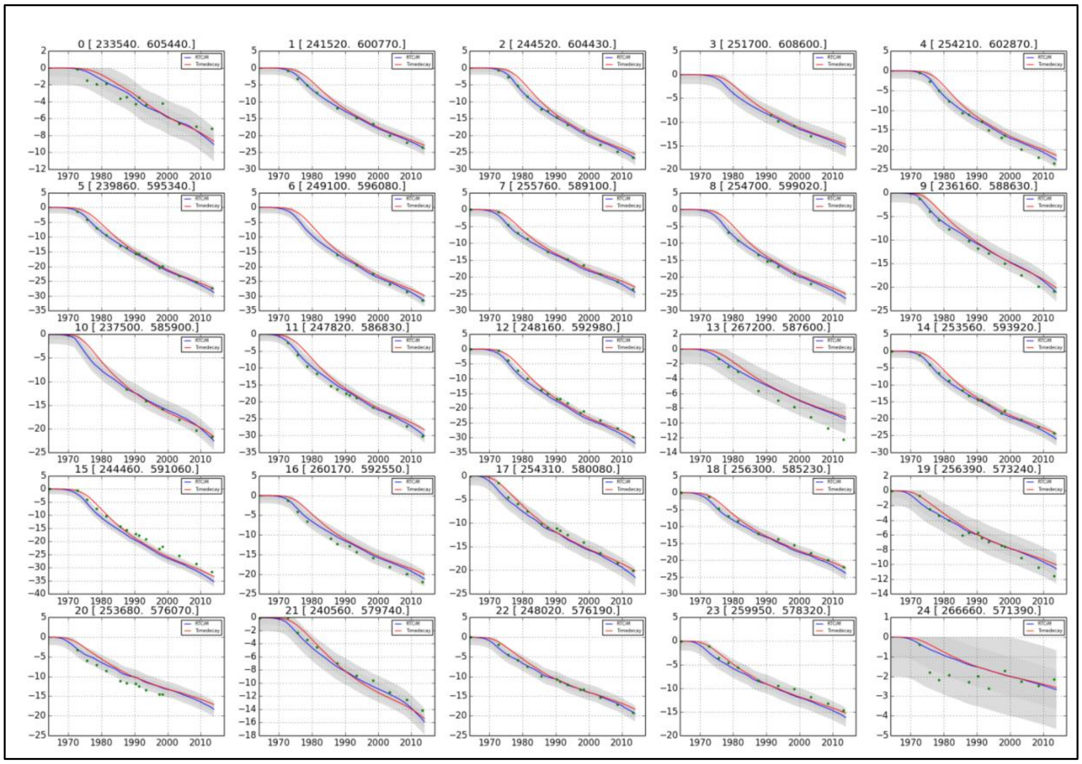


Figure 8 Comparison between RTCiM and Time-decay model vs spirit leveling with first measurement point tied to RTCiM modelled subsidence

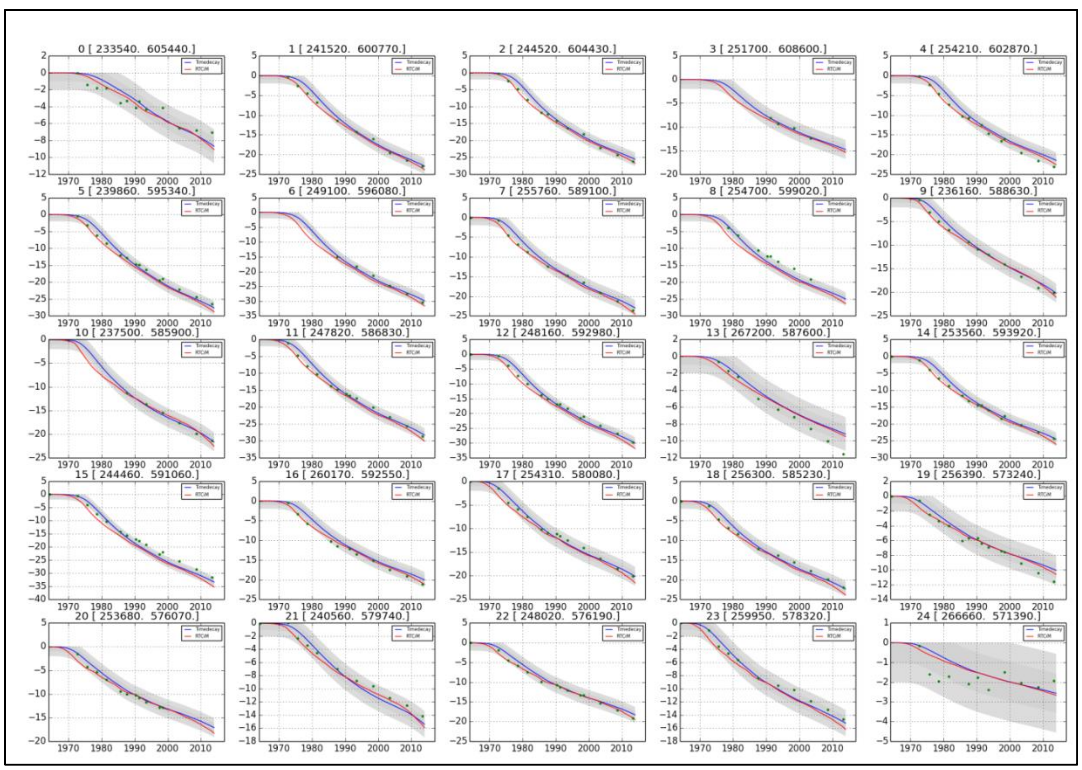


Figure 9 Comparison between RTCiM and Time-Decay model vs spirit leveling with first measurement point tied to Time-Decay modelled subsidence

Subsidence uncertainty analysis

The subsidence uncertainty analysis is based on a Monte Carlo method where Time-decay and RTCiM model parameters are varied. The Cm grid is spatially fixed but scalar multiplier values to the grid are varied in the Monte Carlo procedure.

The difference between the levelling data and modelled subsidence for each member in the Monte Carlo procedure is represented by the RMS value. All leveling benchmarks for all epochs are used in this calculation. For each simulation the model parameters and the resulting RMS value are stored.

Next a cutoff value is chosen for the RMS, i.e. only model members are accepted with a RMS value below the cutoff value.

For these members the subsidence is calculated on stable benchmarks within the Groningen field and compared with the measured data. All members with RMS values below the cut-off span the total range of modelled subsidence (see Figure 10 for an example). In the comparison with the data, the number of measured data points that fall within or outside the range is counted with a standard deviation of 3 mm (an average Move3 value).

A confident uncertainty range for the subsidence is reached when 95% (2 sigma) of the measurements fall within the modelled bandwidth. This range is used to forecast the subsidence. This is done both for the Time-decay and RTCiM model.

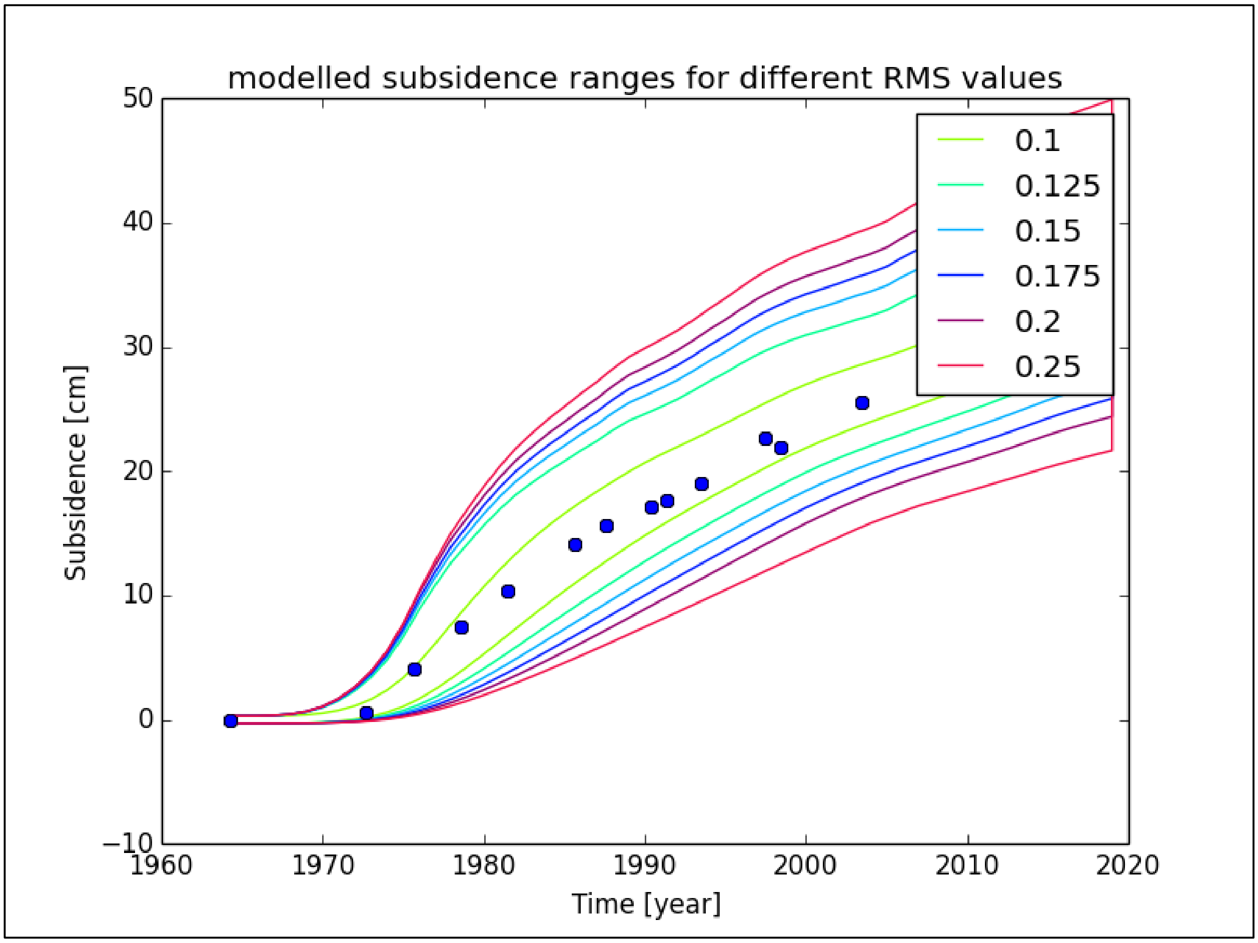


Figure 10 Subsidence ranges for different RMS values, the blue dots is the measured subsidence.

The percentage of measurements that fall within the RMS range per benchmark is shown in Figure 11 for the Time-decay model. This figure shows that 98% of all measurements fall within the modelled subsidence range using a RMS cutoff of 0.15. With this RMS range the uncertainty of the future subsidence is calculated. This is done to calculate the average subsidence (minimum of the range + maximum of the range) / 2). The uncertainty is calculated as (maximum of the range - minimum of the range) / 2. Results from both calculations are shown in Figure 12. This figure shows for example that the average deepest point of the range will be around 45 cm with an uncertainty of around 8 cm.

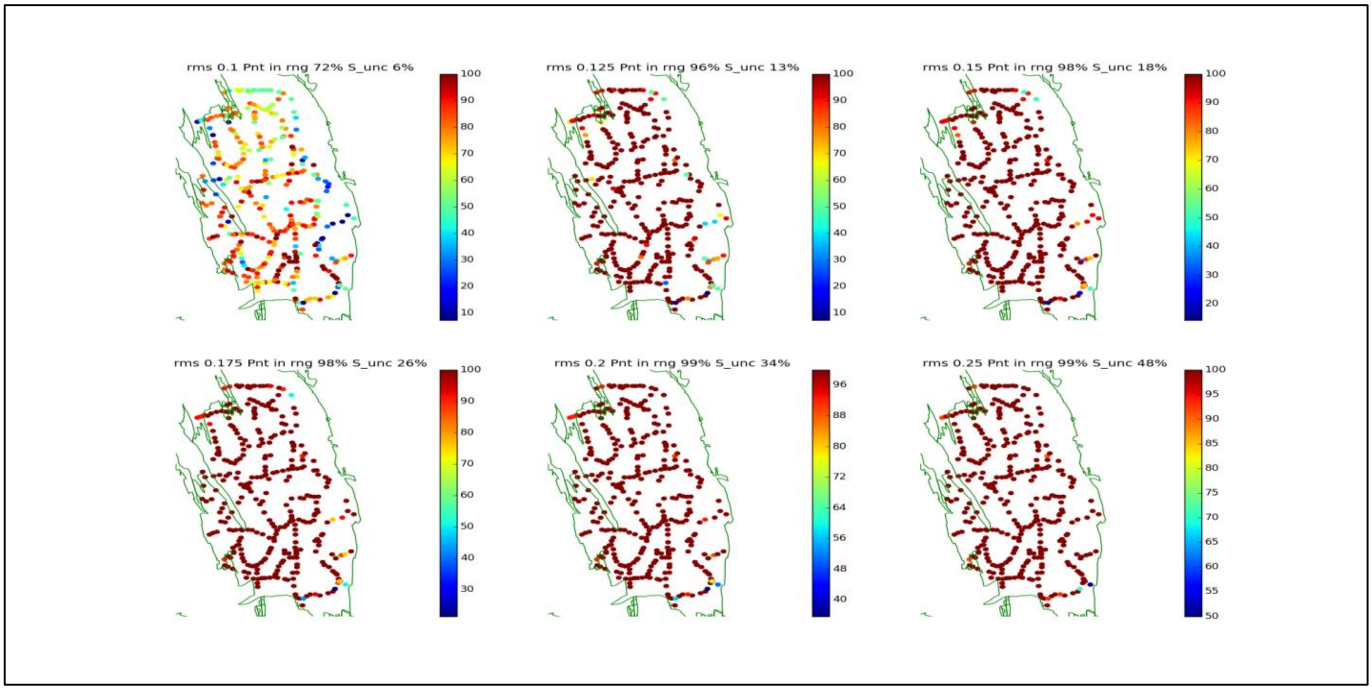


Figure 11 Percentage of measurements which fall within the subsidence range at a certain RMS value at benchmark level (Time-decay model).

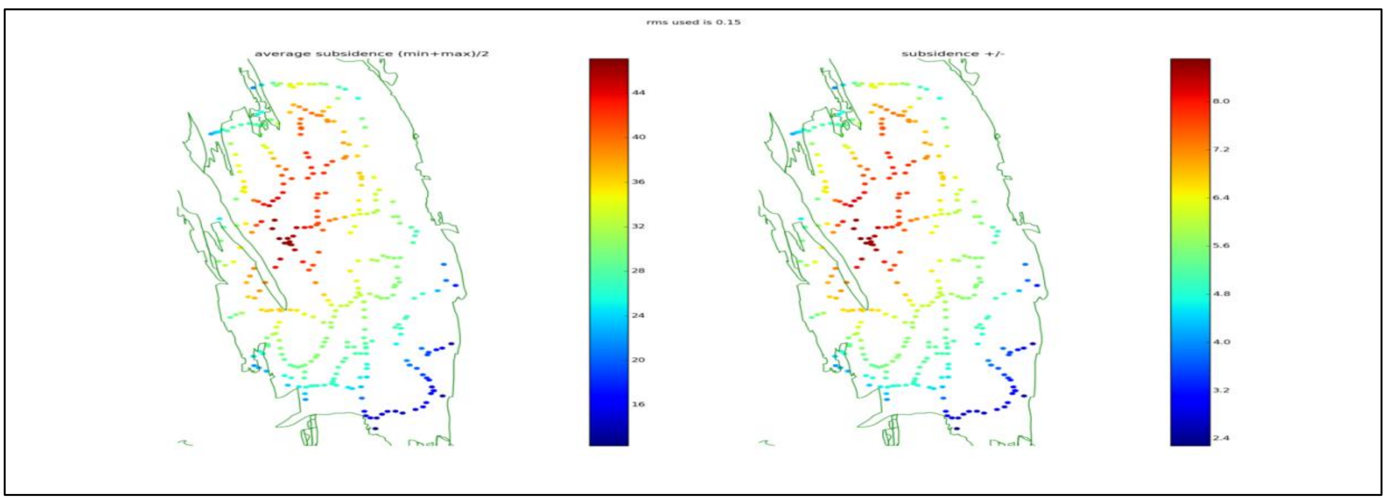


Figure 12 Average of the subsidence range and its uncertainty at end of production lifetime for a RMS range of 0.15 (Time-decay model).

The same methodology was applied using the RTCiM compaction model with a resulting uncertainty range comparable to the Time Decay model (Figure 13 and Figure 14)

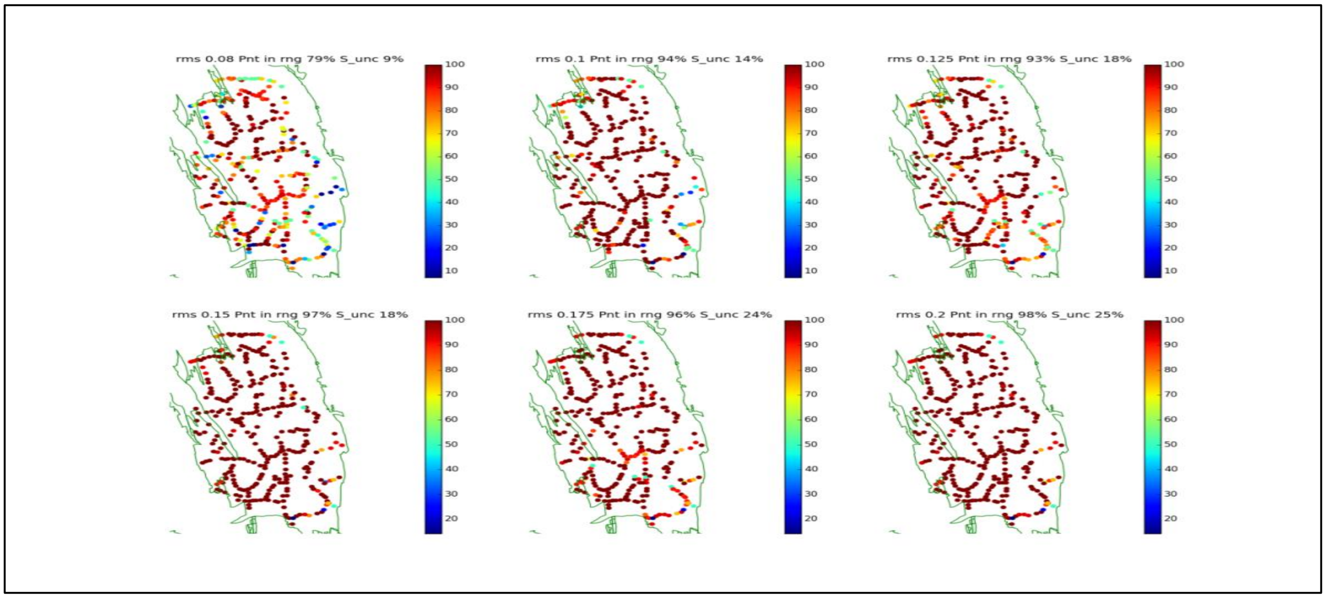


Figure 13 Percentage of measurements that fall within the subsidence range at a certain RMS value at benchmark level (RTCiM model).

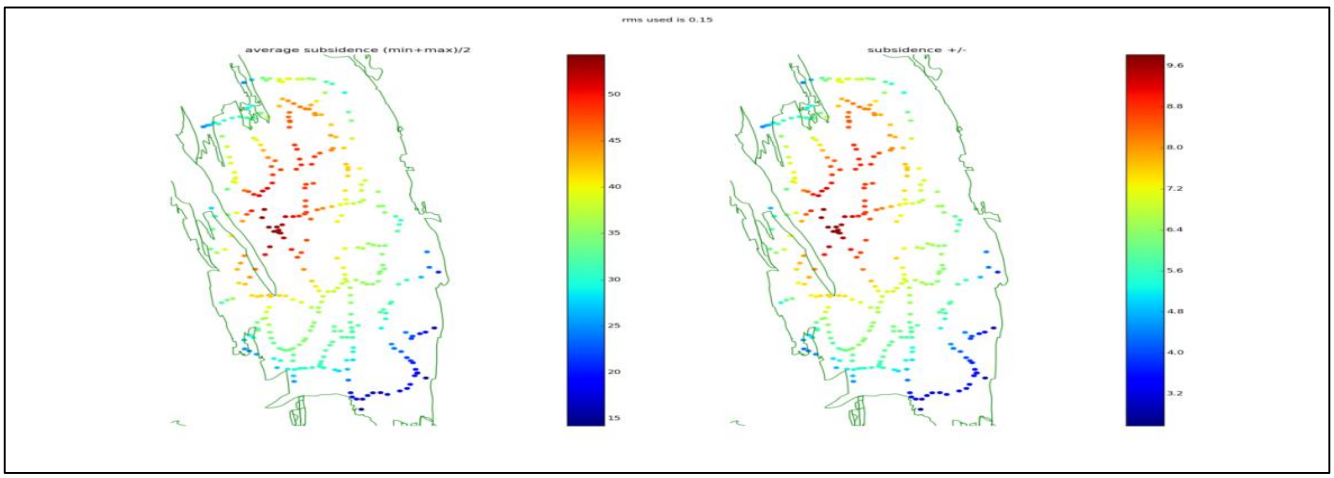


Figure 14 Average of the subsidence ranges and its uncertainty and end of production for a RMS range of 0.15 (RTCiM model)

A combined uncertainty range for both the Time-decay and RTCiM model has been made. Results for this combined range are visualized in Figure 16. The combined range is wider because of non-overlapping parts and as a consequence the average combined subsidence uncertainty range results in a value of about 25 %.

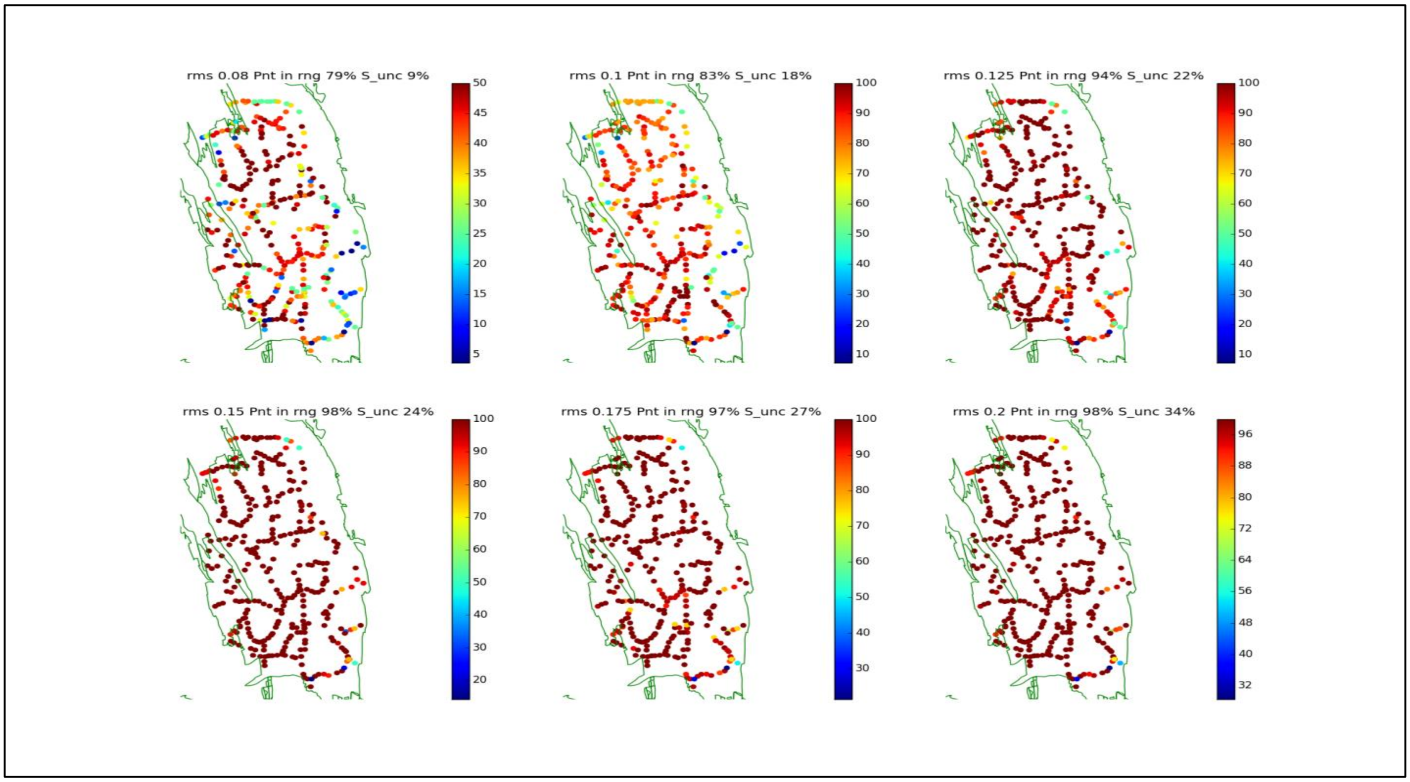


Figure 15 Percentage of measurements that fall within the subsidence range at a certain RMS value at benchmark level (combined Time-decay and RTCiM model).

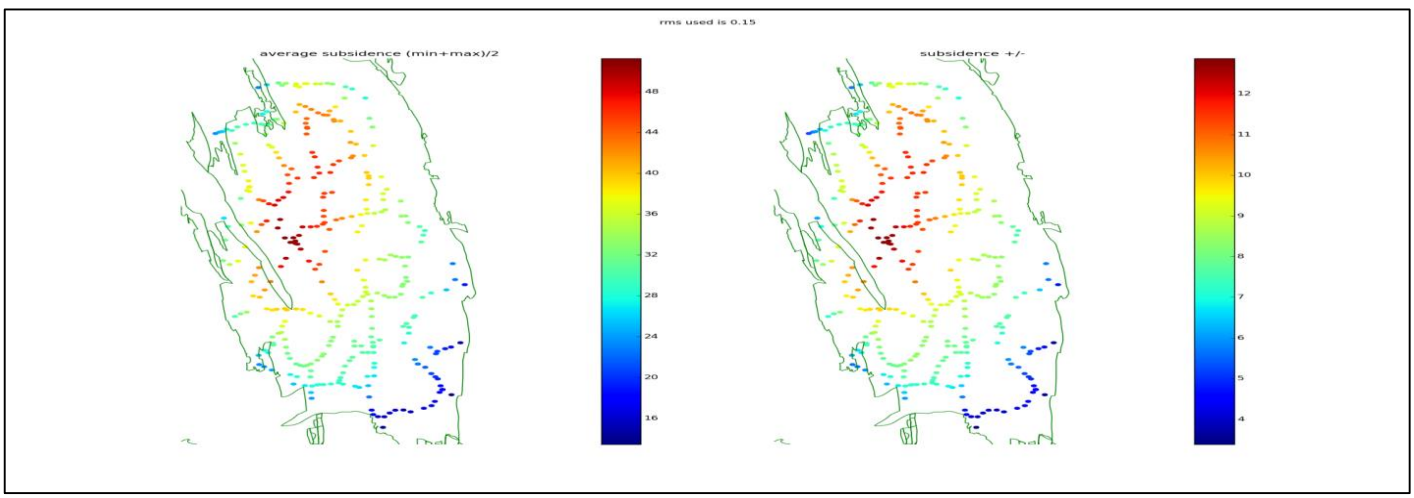


Figure 16 Combined (Time-decay and RTCiM) average of the subsidence range and its uncertainty and end of production life for a RMS range of 0.15.

Future subsidence compared with forecasts from the winningsplan (issued April 2016)

The Groningen winningsplan, issued in April 2016, presents a forecast based on a 33 bcm per year production scenario and a RTCiM compaction model. The calibration of this model is based on both levelling and Insar data. Figure 17 compares the winningsplan model outcome with the outcome of the model presented in this note. Subsequent figures visualize a same comparison for the years 2025, 2050 and 2100. The general conclusion is that the differences in the results are small.

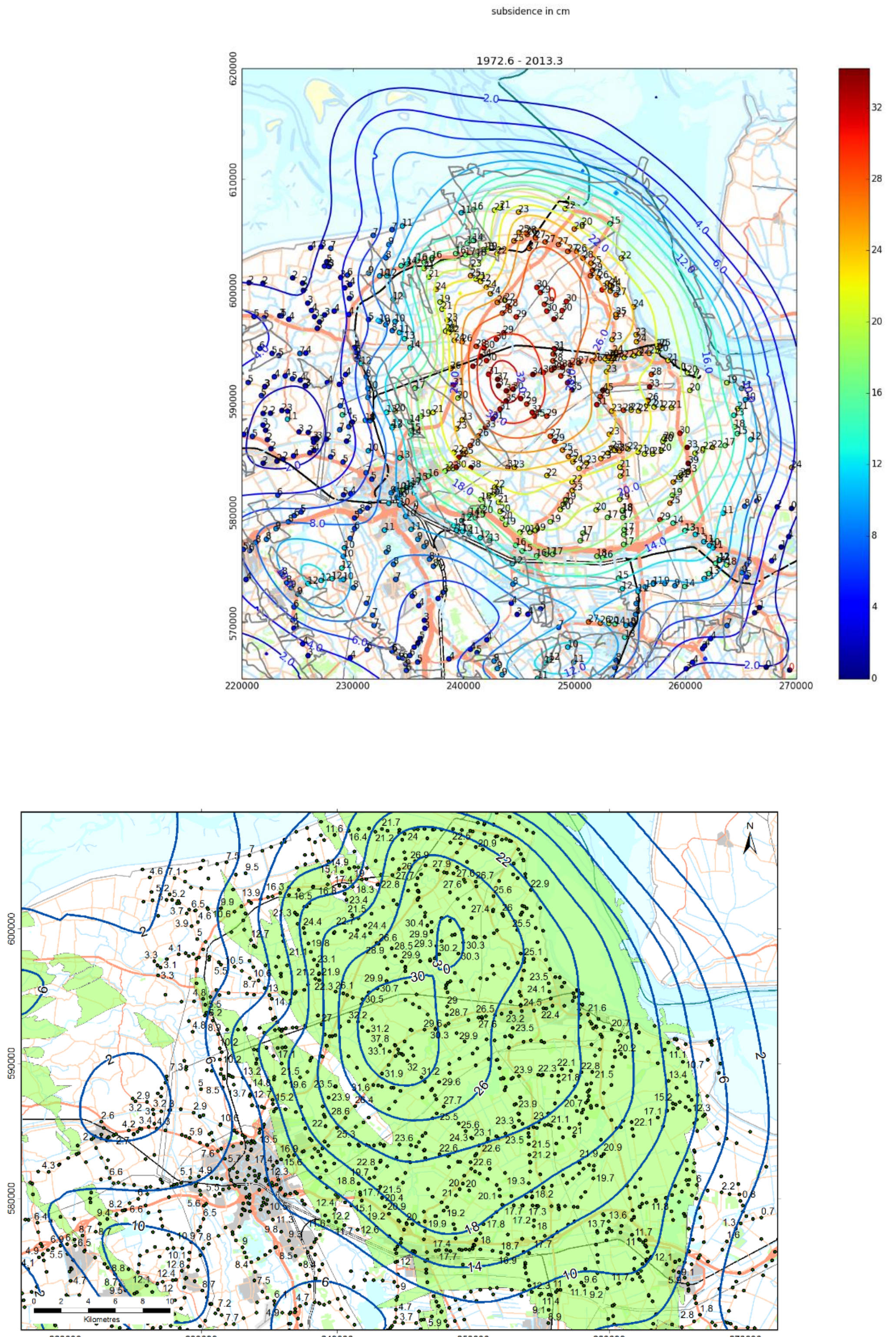
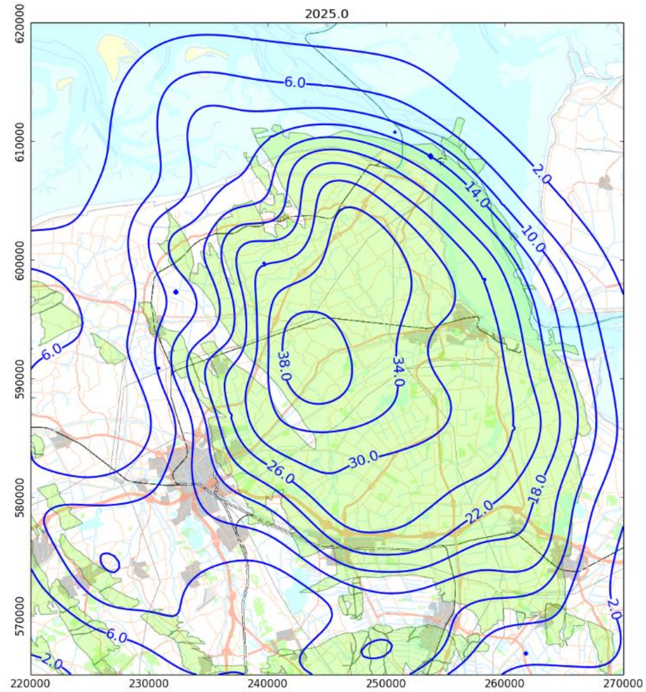


Figure 17 Comparison between the new (top) and winningsplan April 2016 (bottom) for the period 1972 2013



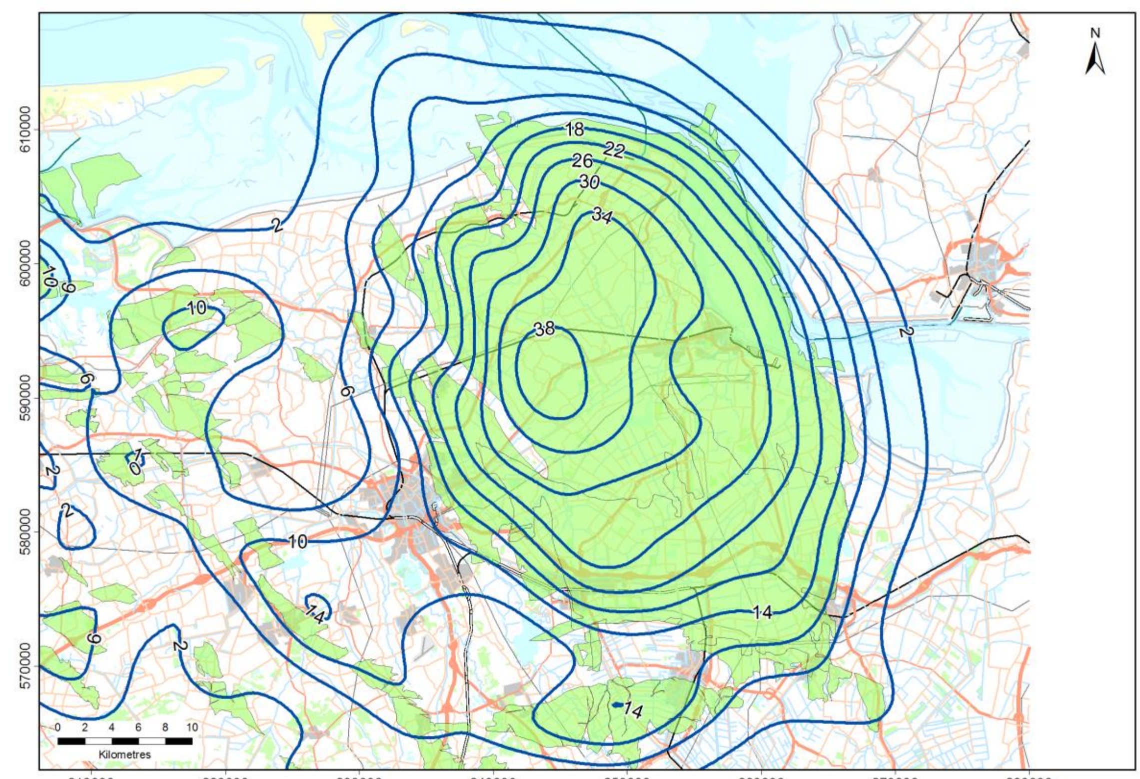
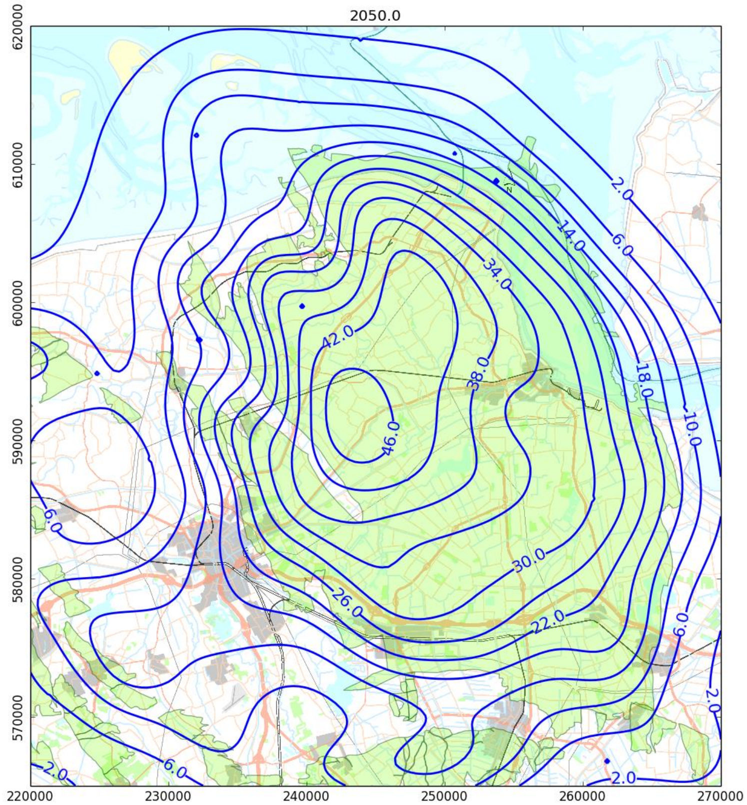


Figure 18 Comparison between the new (top) and winningsplan April 2016 (bottom) for 2025



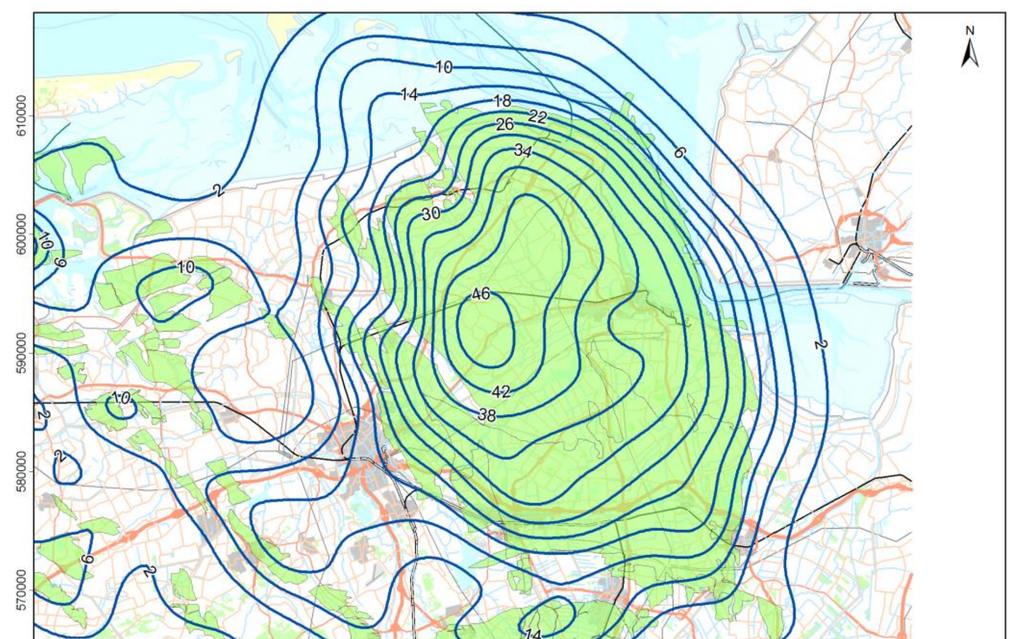


Figure 19 Comparison between the new (top) and winningsplan April 2016 (bottom) for 2050

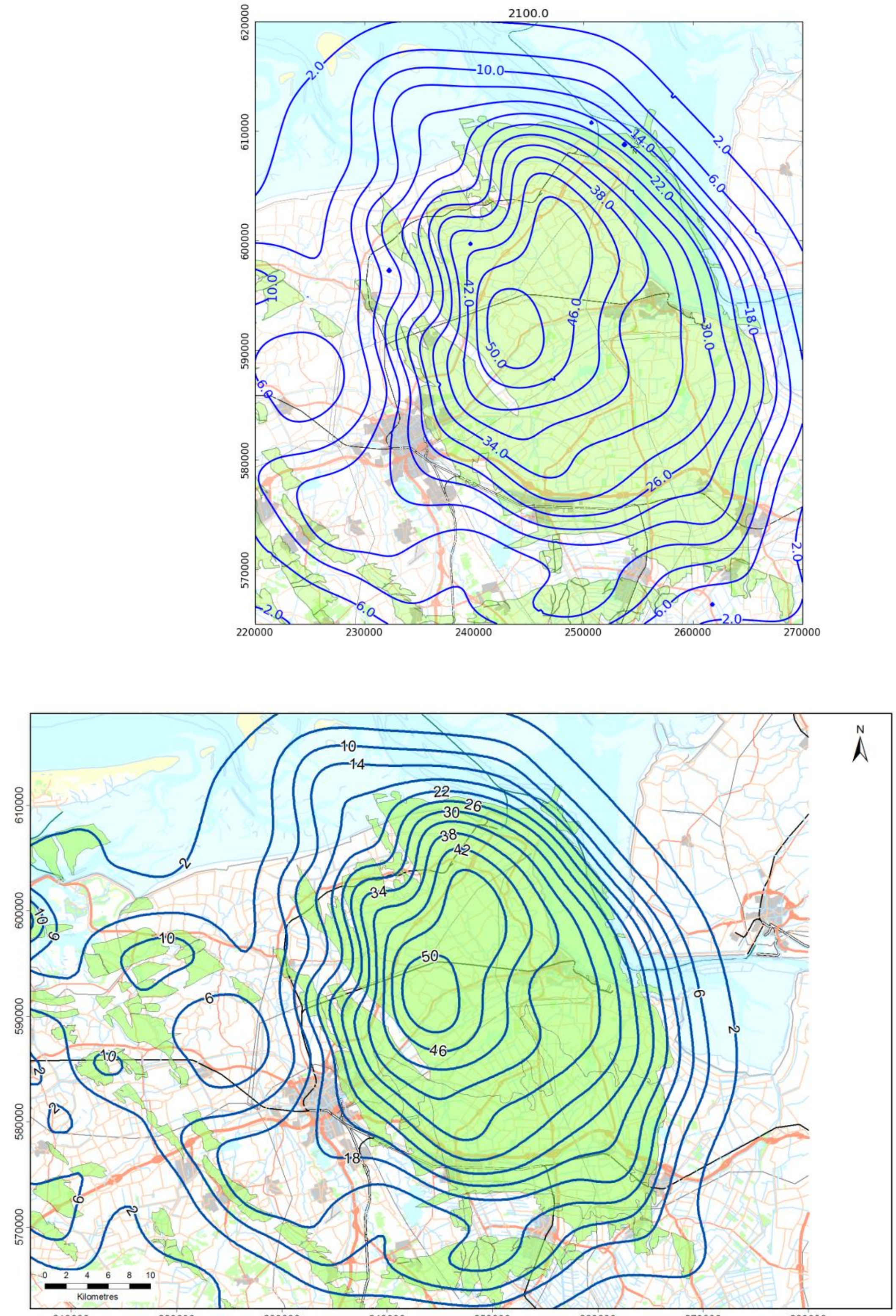


Figure 20 Comparison between the new (top) and winningsplan April 2016 (bottom) for 2100.

Subsidence forecast with 27 BCM production case

The technical addendum to the Groningen winningsplan, issued in April 2016, presented as well results that were based on a 27 BCM per year production scenario. The history match model is the same as the one used for the 33 BCM forecasts. Figure 17 compares the winningsplan model outcome with the outcome of the model presented in this note (calibrated to levelling data only) while Figure 21 shows the forecast for the years 2025, 2050 for two compaction models: RTCiM and Time decay. Both Figure 21 and Figure 22 show results for the forecasted subsidence based on only depletion of the Groningen field (including Bedum and Warffum fields) without the contribution of the other surrounding onshore fields. The general conclusion is that the differences in forecasted subsidence between the two compaction models are small.

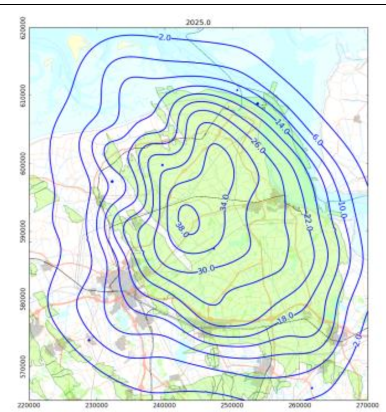
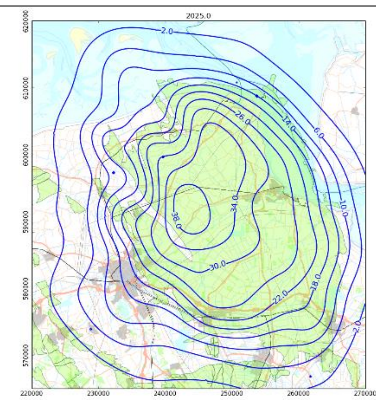
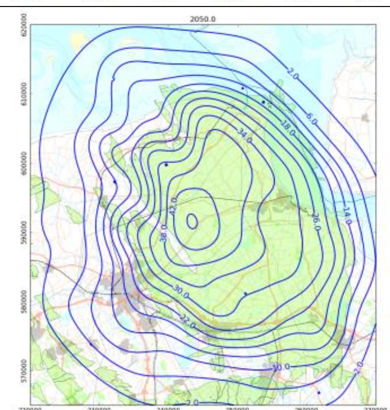
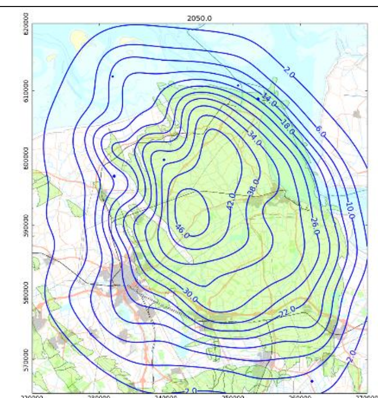
2025		
2050		
	Time-decay	RTCiM

Figure 21 Subsidence forecast for the Time-decay and RTCiM model using the 27 BCM production profile case

Subsidence forecast with 24 BCM production case

The “instemmingsbesluit” to the April 2016 winningsplan stated that the production should be capped to a production level of 24 BCM. To show the effect of different calibration choices for the subsidence model for this scenario, a 24 BCM production forecast was run, based on the same history matched reservoir model that was used for all Winningsplan 2016 scenarios. Results of the subsidence calculations based on this scenario are visualized in Figure 22 for the years 2025 and 2050.

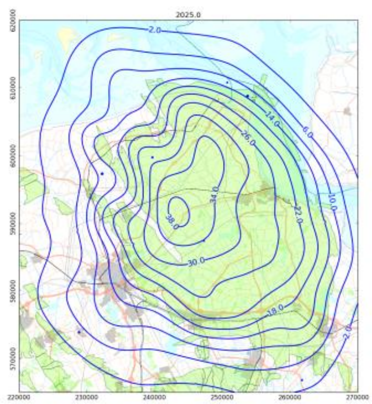
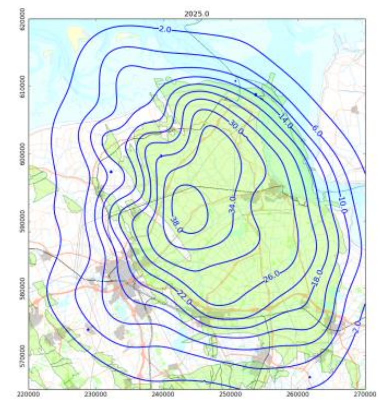
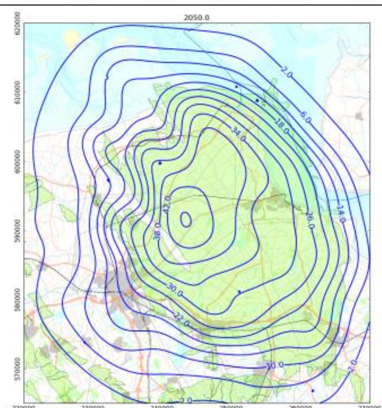
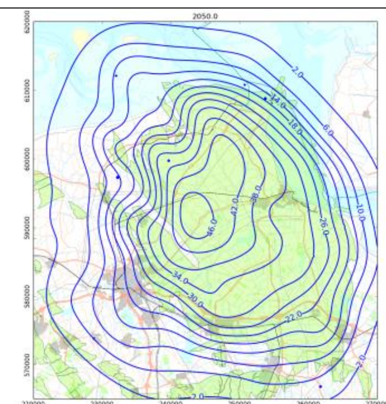
2025		
2050		
	Time-decay	RTCiM

Figure 22 Subsidence forecast for the Time-decay and RTCiM model using the 24 BCM production profile case.

Conclusions

The modelled subsidence presented in the Groningen winningsplan issued April 2016 (NAM, 2016a) is based on a calibration to both spirit leveling and InSar data. A condition in the approval document of the Minister of Economic Affairs (Ministerie van Economische Zaken, 2016) demands an update of this analysis using leveling data only, leading to the study described in this report. The following conclusions can be drawn from the obtained results:

1. A calibration to the levelling data (exclusively) was successfully performed applying an improved calibration scheme;
2. The calibrated model was compared with the Winningsplan 2016 subsidence model. The observed differences are small;
3. A methodology was defined to estimate the uncertainty of the forecasts. It basically counts the number of measurements that fit within an uncertainty bandwidth that is defined by a chosen RMS value. A possible condition of 95% of the data fitting the uncertainty bandwidth results an uncertainty of around 25% for the subsidence forecasts. The value of 25% was also the value for the uncertainty reported in the Winningsplan 2016.

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