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TNO report

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Toolbox subsidence (KEM-16). Discriminating subsidence contributions from multiple mining activities; case study Diever, Vinkega and Eesveen area

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Summary

In the Netherlands subsidence due to mining activities often involves a combination of subsidence caused by production from several adjacent or stacked gas fields. Also in some areas salt production and gas production are close to each other with both activities contributing to a subsidence bowl. Generally the contribution of each individual activity is modelled and disseminated with a focus on the maximum subsidence after production due to regulatory requirements. As a result aspects like subsidence development through time and combined effects due to multiple mining activities in one area remain unclear for stakeholders such as municipalities, provinces and the water authorities.

KEM-16 aims to address these issues and related questions by providing a toolbox with working methods for a number of distinct topics. The PySub Modelling Framework (PySub) is developed within in the KEM-16 project as an element of the toolbox with the aim to model and show how contributions from multiple mining activities be discriminated.

In this report we show how PySub can be used to discriminate between different subsidence contributions using a case study in Diever, Vinkega and Eesveen area. This area is a typical example of an area with a combination of subsidence caused by production from several adjacent and stacked gas fields in the Netherlands. Based on prevailing production plans and expected production in the area we model the subsidence development through time for different deterministic scenarios. We use these scenarios to illustrate the visualisation capabilities within PySub. These include a variety of different map view and cross section options aimed to differentiate the contributions of the different gas reservoirs. PySub also offers a possibility to compare observation with the model predictions and show the overlap between the subsidence contributions of different reservoirs.
Lastly we explore the Bucket Ensemble method of PySub, here an ensemble of multiple models is run with varying input. We show both a best fit scenario of the subsidence observations with the model using a Mean Absolute Error method and the a scenario where 90% percentile scenario[1] is examined. Both scenarios give a better understanding of the uncertainties associated with the model prognosis.

The newly developed visualization options in PySub give more insight in the different contribution of different mining activities to a subsidence bowl and help to visualize the development of subsidence through time. Furthermore PySub can be used to visualize and help understand the uncertainties associated with the subsidence prognosis.

The current PySub version only has a limited model-observation comparison capability and does not support model parameter inversion. Such an inversion scheme will improve model parameter calibration and therefore improve the history matching of the observed subsidence. This will help decrease the uncertainty in prognosis.

[1] P90 in this case means that the maximum subsidence is not exceeded with 90% probability.

Contents

1 Introduction

As a follow-up to recommendations from the Knowledge Program on Effects of Mining (KEM 3a project: Mining effect hazard and risk assessment models Toolbox), the Ministry of Economic Affairs and Climate Policy (EZK) asked TNO to develop generic methods for evaluating subsidence due to mining activities and other subsidence mechanisms relevant in the Netherlands.

The practical questions posed by various authorities and local interest groups on the accumulation of causes and effects of subsidence require a toolbox with working methods for specific issues.
One of the questions addressed within the KEM-16 project is: How can contributions from multiple mining activities be discriminated? To support answering this question the PySub Modelling Framework is developed within in the KEM-16 project as an element of the toolbox. The PySub framework is capable of modelling subsidence predictions caused by mining activities and can determine relevant statistical characteristics of the model predictions. Visualisation of the results is an important feature of the tool. Alongside this report a technical reference report on the modelling framework (TNO, 2023) is available. The PySub framework is made publicly available on the Github platform (github.com/TNO/PySub). The PySub code repository includes an user manual and workflow examples.

In the Netherlands, subsidence due to multiple mining activities involves a combination of salt production and gas production or production from several adjacent gas fields .A prognosis of the contribution of each individual activity is usually modelled and often heavily focused on the maximum subsidence at the end of the gas/salt production due to regulatory requirements. Therefore the total subsidence and its development through time, due to multiple mining activities in one area, can be unclear for stakeholders such as municipalities, provinces and the water authorities.

The objective of this report is to explicitly model the subsidence of the contributions of different mining activities in a combined effort for a selected case study area using the PySub Modelling Framework to clarify this. A key focus is demonstrating the visualisation capabilities of the tool.

First, we define the case study area in the next section. In Chapter 2 we give the methodology and modelling choices made for the case study. Furthermore the available model input data and subsidence observations for the case study, as well as the limitations and uncertainties of both are discussed. We describe the results of different modelling scenarios for the case study with focus on showing the different visualisation options of the tool in Chapter 3. Chapter 4 concludes the report with recommendations for further tool development.

1.1 Area case study

The area used to demonstrate the PySub Modelling Framework is the area around Diever, Vinkega and Eesveen, covering parts of the province of Drenthe, Friesland and Overijssel (Figure 1-1). In this area multiple adjacent and vertically stacked gas bearing reservoirs are present in various stages of production (see Figure 1-1). In addition, there are (production) plans proposed for development of new fields. This interplay of multiple adjacent fields and newly planned production in coming years makes it very difficult for stakeholders to have a clear idea of the (maximum) subsidence and the development of subsidence through time and space. This makes the area well suited to model the subsidence of the contributions of different mining activities. Furthermore, since production in this area is ongoing since 1998, there is surface deformation monitoring data available to compare and/or validate the modelling results.

As mentioned, one of the questions of stakeholders is to have a clear idea of the (maximum) subsidence at the end of production and its development through time and space. Other typical stakeholder questions include the desire to have a clear visualization of the cumulative effects of multiple gas fields and a better understanding of different future subsidence development (for example the local and cumulative effect on subsidence of a new producing field). The aim of the case study is to help answer these questions.

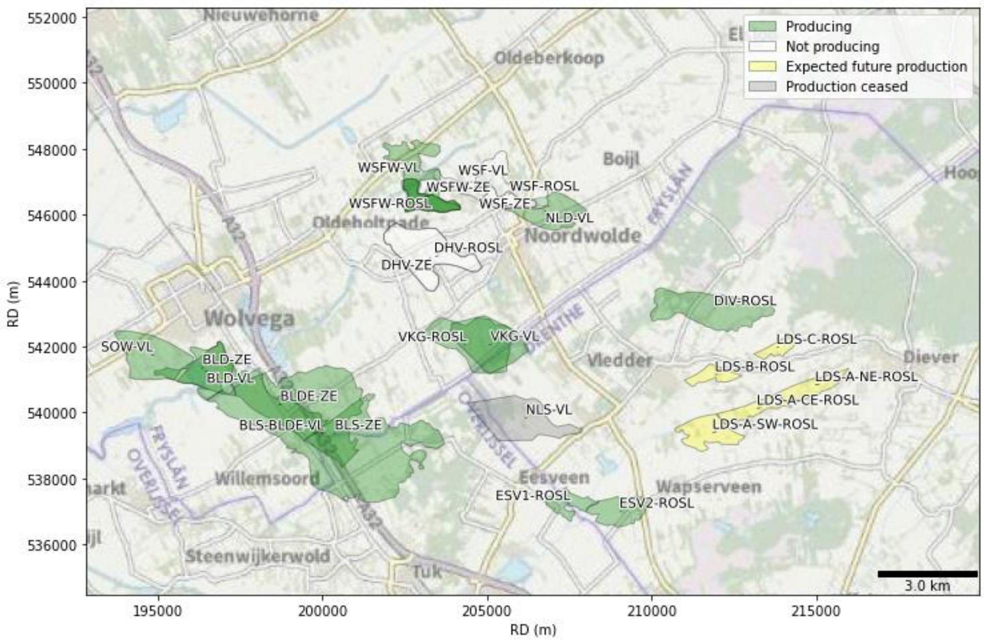

Figure 1-1 Gas fields in the Diever, Vinkega and Eesveen area (province of Friesland & Drenthe). BLD is the abbreviation for Blesdijke, BLS for De Blesse, DHV for De Hoeve, DIV for Diever, ESV for Eesveen, NLS for Nijensleek, NLD for Noordwolde, SOW for Sonnega-Weststellingwerf, VKG for Vinkega an WSF for Weststellingwerf. ROSL is the abbreviation for Rotliegend, VL for Vlieland and ZE for Zechstein, indicating the producing reservoir interval of the fields. Status: 1-12-2022, modelling is limited to indicated fields

Table 1-1 Overview of gas reservoirs present in case study area. Start production, status of reservoirs and data source is given as well.

Reservoir name	Start production	Status	Production plan
Blesdijke Oost Zechstein	2009	Producing	De Blesse- Blesdijke vs. 3.0 2018
Blesdijke Vlieland	2009	Producing	De Blesse- Blesdijke vs. 3.0 2018
Blesdijke Zechstein	2009	Producing	De Blesse- Blesdijke vs. 3.0 2018
De Blesse Zechstein	1999	Producing	De Blesse- Blesdijke vs. 3.0 2018
De Blesse-Blesdijke Oost Vlieland	1999	Producing	De Blesse- Blesdijke vs. 3.0 2018
De Hoeve Rotliegend	2012	Not producing	Den Hoeve 2017
De Hoeve Zechstein	2013	Not producing	Den Hoeve 2017
Diever Rotliegend	2015	Producing	Diever vs. 3.0 2018
Eesveen Rotliegend	2015	Producing	Eesveen vs. 2.0 2017
LDS-A-CE	Planned production	Expected future production	Leemdijk-De Bree-Smitstede vs. 1.0 2020
LDS-A-NE	Planned production	Expected future production	Leemdijk-De Bree-Smitstede vs. 1.0 2020
LDS-A-SW	Planned production	Expected future production	Leemdijk-De Bree-Smitstede vs. 1.0 2020
LDS-B	Planned production	Expected future production	Leemdijk-De Bree-Smitstede vs. 1.0 2020
LDS-C	Planned production	Expected future production	Leemdijk-De Bree-Smitstede vs. 1.0 2020
Nijensleek Vlieland	2000	Production ceased	Nijensleek, 2003
Noordwolde Vlieland	1998	Producing	Addendum by Noordwolde, 2012
Sonnega-Weststellingwerf Vlieland	2015	Producing	Sonnega-Weststellingwerf 17 2020
Vinkega Rotliegend	2011	Producing	Vinkega Addendum. vs. 3.3 2018
Vinkega Vlieland	2011	Producing	Vinkega Addendum. vs. 3.3 2018
Weststellingwerf-Oost-Rotliegend	2001	Not producing	Weststellingwerf vs. 2.0 2018
Weststellingwerf-Oost-Vlieland	2019	Not producing	Weststellingwerf vs. 2.0 2018
Weststellingwerf-Oost-Zechstein	1998	Not producing	Weststellingwerf vs. 2.0 2018
Weststellingwerf-Oost-Zechstein	1998	Not producing	Weststellingwerf vs. 2.0 2018
Weststellingwerf-West-Rotliegend	2021	Producing	Weststellingwerf vs. 2.0 2018
Weststellingwerf-West-Vlieland	2021	Producing	Weststellingwerf vs. 2.0 2018
Weststellingwerf-West-Zechstein	2021	Producing	Weststellingwerf vs. 2.0 2018

1.2 Feedback subsidence visualisation

During the KEM-16 project at the request of EZK feedback on the visualisation capabilities was asked from the KEM representatives and local stakeholders. On 26 April 2022 preliminary results were discussed with the KEM-panel and EZK.
On 23 September 2022 the PySub tool capabilities were discussed with GasDrOvF. GasDrOvF is a local stakeholder who is concerned of gas production activities in the case study area. In this meeting TNO showed different figures, mainly focused on showing the effect on new production.
The main takeaways from the discussions was that clearly showing overlap between subsidence bowls due to gas production of different reservoirs in map view, as well as visualization of the subsidence contribution based on reservoir type/age was as desired result. This is included in the PySub visualization possibilities and shown in Figure 3-10 and Figure 3-11**.**

2 Methodology and Data

This chapter discusses the methodology, data availability and model variations of the case study. The limitations of the chosen approach and input data for the different scenarios are discussed as well.

2.1 Methodology

Subsidence due to mining activities in the case study area is caused by gas production. When gas is produced, a reduction in reservoir pressure occurs that subsequently causes compaction of the gas bearing reservoir rock. The compaction is expressed as subsidence at the surface level.
The approach used in PySub Framework (TNO, 2023) to model subsidence due to gas extraction is as follows. First the compaction of the reservoir rock is modelled and then the (modelled) compaction volume is translated to subsidence at surface level using an influence function. There are currently three different compaction models (linear, time-decay and rate-type compaction) and three different influence functions (Geertsma, Van Opstal and Knothe) available in PySub. Depending on the different needs, rock behaviour and/or data availability one model is more suitable than another. The technical report on the PySub Modelling Framework gives an extensive explanation of the different compaction models, influence functions and their implementation.

2.1.1 Compaction model & influence function

The model used in the case study to calculate the compaction is the time-decay model (Mossop, 2012). The time-decay model is chosen over the rate-type compaction model because of limited availability of rate-type compaction model parameters in de public domain. In the case study and other areas of the Netherlands delay in subsidence is observed compared to the production and subsequent pressure decline. The time-decay compaction model uses an exponential decay function with the time parameter τ, which is a factor determining the delay in compaction. The parameter τ is often determined from observations by comparing the delay of observed subsidence to the relative pressure drop in the reservoir.
The influence function used to model the subsequent subsidence is the Geertsma-Van Opstal method (Geertsma, 1973; van Opstal, 1974). In 1973 Geertsma published an analytical poroelastic model for determining subsidence from compaction in a reservoir applicable for a homogeneous half-space. The reservoir is assumed to be overlain by rock with constant elastic properties. In 1974 this method was expanded on by Van Opstal, which added a correction for a perfectly rigid basement at a finite distance below the reservoir. From the known influence functions, the Van Opstal method, the modelled subsidence bowl shape and maximum subsidence represent observations better (e.g. Van Thienen-Visser et al., 2015, Fokker and Osinga, 2018).

2.1.2 Model scenarios

The general approach is to have three different modelling scenarios. In the first more general scenario, the total subsidence due to gas production from the different reservoirs that are or have been in production and their development trough time is modelled. The second scenario extents on the first scenario by adding the planned

production of the LDS fields. The last modelling scenario focuses on evaluating the impact of uncertainties in subsidence modelling. All scenarios show the full spectrum of visualisation capabilities of the tool.
The first two scenarios are deterministic scenarios where one parameter set is used per reservoir. These scenarios are used to visualise the subsidence trough time based on the production plans. In the third scenario an ensemble of multiple models of the same field(s) is run where the input parameters are varied within the uncertainty range. This is often reported in production plans to show the uncertainty of the subsidence prognosis due to uncertainty in the parameters. Scenario 3 will run this ensemble using the Bucket Ensemble method described in the PySub Modelling Framework technical report (TNO, 2023)

2.2 Data

This section gives an overview on the data that is used for subsidence modelling of the case study as well as the observations that are used for comparison with the model results. In this case study publicly accessible data is used. Typical input data includes reservoir pressure though time, reservoir specific parameters (e.g. depth, volume, porosity, extent of potential connected aquifers and rock compressibility) along with uncertainty ranges depending on the scenario. The user manual and technical report (TNO, 2023) gives an extensive description of the required input (format) and constraints.

2.2.1 Input model data

Most of the data used in modelling the subsidence is extracted from production plans (available at www.nlog.nl). A production plan is required by the mining law for production of oil and gas. In a production plan it is, among others things, obligatory to prognose subsidence due to the gas production and generally used model parameters are reported.
Table 2-1 gives an overview of all gas reservoirs and relevant reservoir and compaction model specific parameters used for scenario 1. Table 2-2 gives the additional gas reservoirs and relevant reservoir and compaction model specific parameters in addition to Table 2-1 used for scenario 2. The used input parameters correspond to the approved maximum subsidence level within the license area. In general this corresponds to high (production) scenarios. In scenario 3 an ensemble of multiple model realizations is run, each with different input parameters, based on the expected variability. In this scenario all possible combinations of the minimal, maximum and mean values of the different parameters are sampled. Scenario 3 focuses on an subset of the case study area, the Blesse and Blesdijke fields, for clarity. Table 2-3 gives an overview of the input parameters with a corresponding probability for scenario 3. All the possible combinations of the specified variables are run. Sub-scenario 3.1 will highlight the parameter combination that best fits the observations and sub-scenario 3.2 will highlight the set of parameters which is indicative for an upper bound subsidence scenario.
For some of the reservoirs in the case study area the aquifer connected to the gas accumulation (partly) depletes as well or is assumed to deplete in a high case scenario. Figure A-1 and Figure A-2 of Appendix A show the reservoir contours used for all modelling scenarios. For the visualisation of the results in Chapter 3 we chose to show the reservoirs with their gas water contact as this is common practice. This provides a clearer visualisation and is comparable with the similar existing visualisations in the production plans and other sources such as nlog.nl.

Table 2-1 Overview of all gas reservoirs and relevant input parameters included for scenario 1. For all reservoirs a Poisson's ratio of 0.25 is used. The source of the data is the production plan as is referred in Table 1-1.

Reservoir name	Rigid basement factor	Reservoir depth (m)	Reservoir thickness (m)	Compaction coefficient ($1/bar*10^{-5}$)	Tau (year)
Blesdijke Oost Zechstein	1.05	1780	15	0.5	5
Blesdijke Vlieland	1.2	1750	3	1.50	5
Blesdijke Zechstein	1.05	1810	15	0.45	5
De Blesse Zechstein	1.05	1780	30	0.5	5
De Blesse-Blesdijke Oost Vlieland	1.2	1750	20	1.50	5
De Blesse Zechstein	1.5	2040	43.7	2.25	1
De Hoeve Rotliegend	1.5	1976	14,3	1.00	3
De Hoeve Zechstein	1.05	2079	43	0.6	5
Diever	1.001	2045	26	0.9	5
Eesveen1	1.001	2035	23,2	0.9	5
Eesveen2	1.01	1788	17.7	2.00	5
Nijensleek	1.05	1877	7	1.31	5
Noordwolde Vlieland	1.2	1814	4	1.41	5
Vinkega Extended	1.15	1900	24.25	0.6	5
Vinkega Rotliegend	1.1	2014	29	0.6	5
Vinkega Vlieland	1.05	1819	15	1.0	5
Weststellingwerf-Oost-Rotliegend	1.05	2000	37	0.6	3
Weststellingwerf-Oost-Vlieland	1.05	1900	0.8	1.50	3
Weststellingwerf-Oost-Zechstein	1.05	1950	15	0.35	3
Weststellingwerf-West-Rotliegend	1.01	2000	34.4	0.6	3
Weststellingwerf-West-Vlieland	1.2	1900	3	1.50	3
Weststellingwerf-West-Zechstein	105	1950	7.2	0.45	3

Table 2-2 Overview of the extra reservoirs and relevant input parameters included for scenario 2

Reservoir name	Rigid basement factor	Reservoir depth (m)	Reservoir thickness (m)	Compaction coefficient ($1/bar*10^{-5}$)	Tau (year)
LDS-A-CE	1.05	2175	37	0.40	5
LDS-A-NE	1.05	2175	37	0.60	5
LDS-A-SW	1.01	2163	36	0.80	5
LDS-B	1.05	2129	28	0.80	5
LDS-C	1.01	2156	23	0.80	5

Table 2-3 Overview of all gas reservoirs and relevant input parameters included for scenario 3. The probability for the different parameters is either 100% when there is only one parameter option or 30%-40%-30% for when there are 3 (low-mid-high) values. This is equivalent to the probability chosen by the operator in the production licence De Blesse- Blesdijke vs. 3.0 2018. This is based on the approach of Hammond and Bickel, 2013 to use discrete approximations for continuous distributions of parameters.

Accumulation name	Rigid basement factor	Reservoir depth (m)	Reservoir thickness (m)	Compaction coefficient (1/bar*10^{-5})	Tau (year)
Blesdijke Oost Zechstein	1.05	1780	15-20-25	2.5-5.0-7.0	2-4-7
Blesdijke Vlieland	1.05-1.2-1.25	1750	1-2-3	0.9-1.5-2.3	2-4-7
De Blesse Zechstein	1.05	1780	25-30-35	2.5-5.0-7.0	2-4-7
De Blesse-Blesdijke Oost Vlieland	1.2	1750	10-20-30	0.9-1.5-2.3	2-4-7
Blesdijke Zechstein	1.01-1.05-1.1	1780	10-15-20	2.5-5.0-7.0	2-4-7

2.2.2 Pressure data

Reservoir pressure depletion due to gas extraction is the driver for reservoir compaction and ultimately subsidence. In the production plans in general only an initial (discovery) pressure and abandonment pressure of gas accumulations is given. For the time-decay model and for visualising the subsidence through time this information is not sufficient and a more detailed pressure profile is needed.
In the PySub Model Framework a pressure profile can be approximated based on the starting and end pressure in combination with (expected) production volume. This approximation is based on known pressure profiles of existing fields. As of 2003 operators are obliged to report monthly production data. This historic data can be found on nlog.nl. The expected future production is reported in the production plan.

The following example for the Diever Rotliegend reservoir explains this method. First a cumulative production profile is made, which is shown in Figure 2-1. Depending on the production status (currently producing, future planned production, production ceased) this is based on actual historic gas production data, expected production profiles from a production plan or a combination of both. In the case of the Vinkega Rotliegend (currently producing, start production 2009) profile, it is a combination of historic gas production data and expected production.

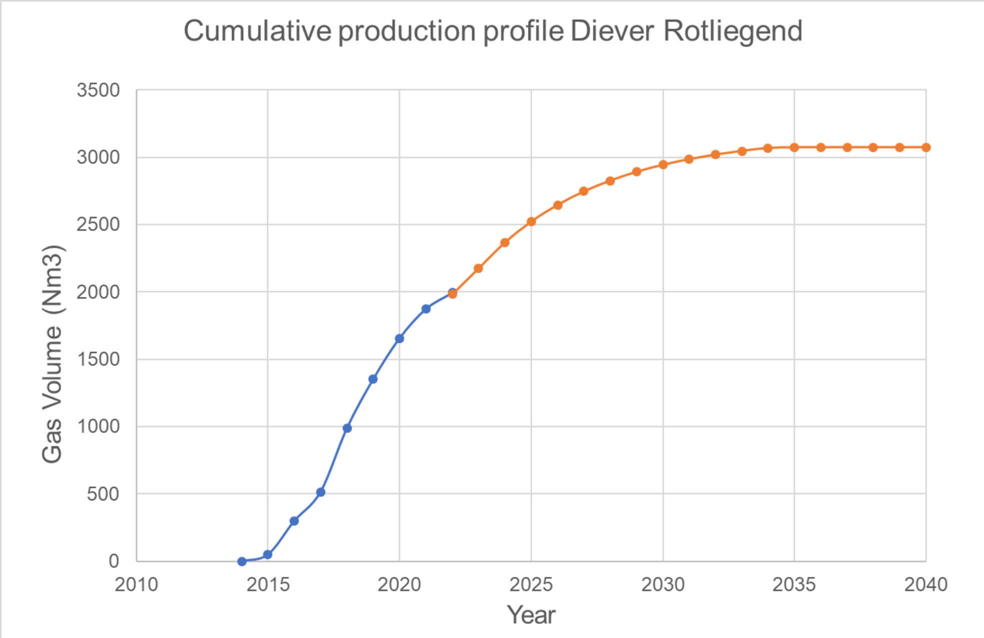

Figure 2-1 Cumulative production profile Diever Rotliegend based on historic data (blue; nlog.nl) and planned production (orange; production plan Diever).

For this approximated pressure profile, a linear relation between the total production volume and (expected) pressure depletion is assumed. For example if a reservoir produced 10 percent of the expected total production volume, there is a 10 percent depletion of the total expected pressure decline. In this way a yearly pressure profile can be estimated. Figure 2-2 shows how the estimated reservoir pressure based on the cumulative production profile (Figure 2-1) which can be used as input for the PySub Modelling Framework.

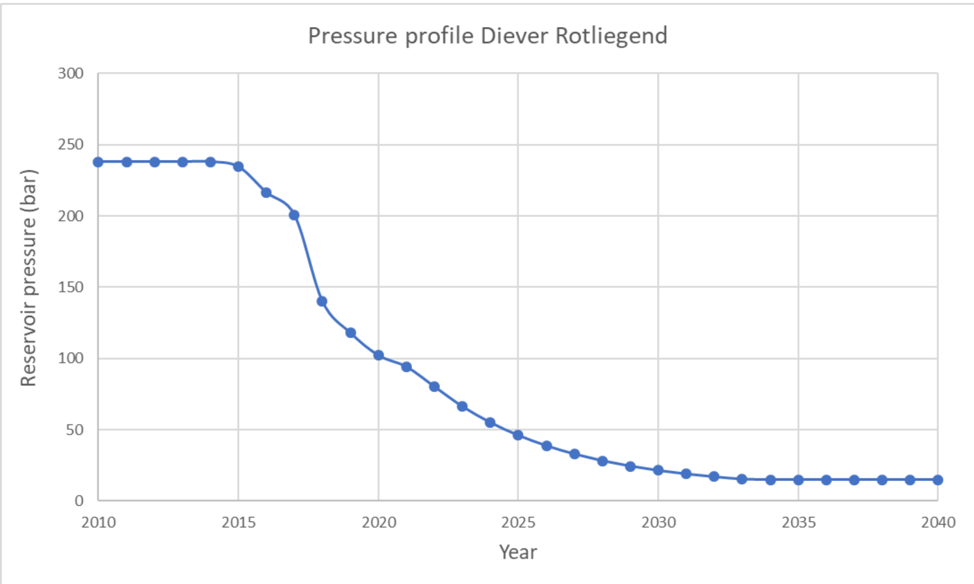

Figure 2-2 Reservoir pressure in bar based on production profile shown in Figure 2-1.

The initial pressure and expected end pressure is extracted from the production plans as described above. In some of the production plans a low, mid and high

scenario is given for the expected end pressure. For modelling scenario 1 and 2 the high scenario, i.e. the highest pressure depletion (and lowest end pressure) is used. Table A-1 in Appendix A gives per reservoir the start pressure and end pressure for all different modelling scenarios in this report.
This approximation has some inherent uncertainties. The production data is available per well and it is possible that one well produces from multiple reservoirs. This is the case for example for the Vinkega field where simultaneously there is production from the Vinkega Vlieland and Rotliegend reservoirs. In these instances the production data were assigned based by a ratio of the expected gas in place of the different reservoirs(in this case 90% Rotliegend and 10% Vlieland). Furthermore note that a linear relation is assumed between production and reservoir pressure. This is a reasonable assumption given that small fields in the case study are expected to show tank-like pressure behaviour mostly producing from one reservoir block (Hagoort, 1998). Lastly, expected profiles for reservoirs that have yet to be drilled such as the LDS-reservoirs are more uncertain. Summarizing, this method can give an reasonable estimation of the expected reservoir pressure through time for the reservoirs in the case study. Note that end pressure can also be dependent on production choices & strategies. In the model approach this can be addressed by the use of different scenarios.

2.2.3 Subsidence observations

Operators are obligated by law to monitor the surface deformation as a result of the production of gas, oil or other mining materials. These observations are acquired in accordance with a measurement plan, in which the method, extent and period of the monitoring (network) is described. In general, the observations are acquired by levelling campaigns. The first measuring campaign should be carried out before production starts as a reference. In the case study area, next to levelling data, also some yearly GNSS (Global Navigation Satellite System) measurements at different locations are conducted (see Figure 2-3). Table 2-4 gives an overview of the subsidence observation data available for the case study.

Table 2-4 Overview of subsidence measurements conducted by the operator in case area study

Measurement plan	Type	Start	Periodicity	Last measurements
De Blesse-Blesdijke-Sonnega	Levelling	1999	Every 5 years	2019
Diever- Eesveen[1]	Levelling and GNSS measurements	2015	Every 5 years (levelling) Every year (GNSS)	2017 (levelling) 2021 (GNSS)
Nijensleek[1]	Levelling	2000	Every 5 years	2015
Noordwolde, Weststellingwerf, Vinkega en De Hoeve[1]	Levelling and GNSS measurements	1997 (levelling) 2011 (GNSS)	Every 5 years (levelling) Every year (GNSS)	2017 (levelling) 2021 (GNSS)

[1] The measurement plans of Diever-Eesveen, Nijensleek and Noordwolde, Weststellingwerf, Vinkega en De Hoeve are merged at the time of writing and new measurements will be reported for the combined measuring plan.

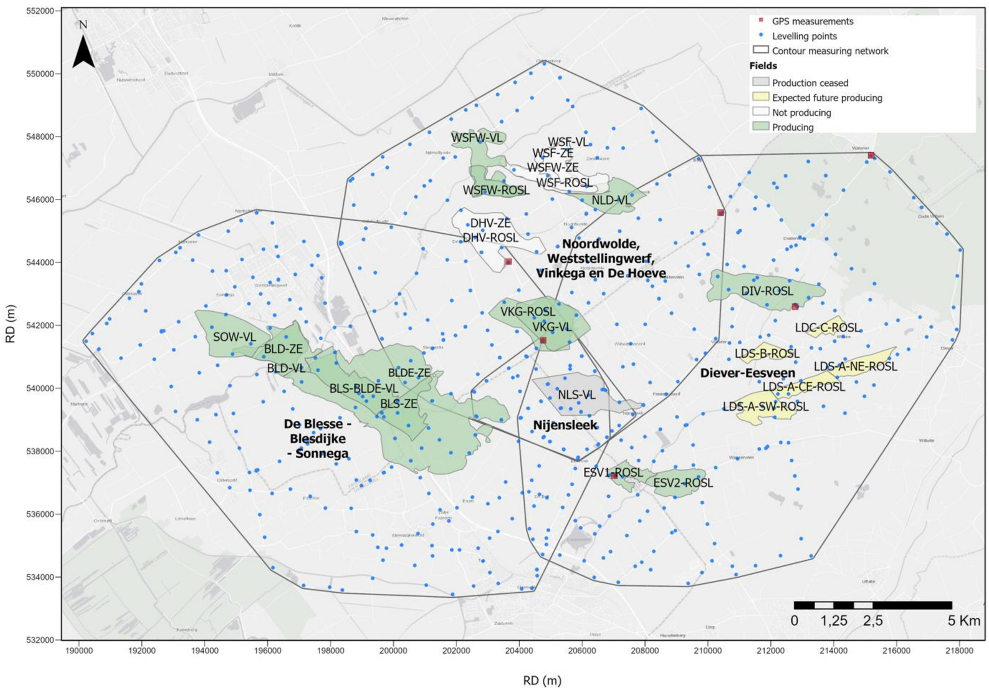

Figure 2-3 Overview of levelling data and GNSS data for case study area.

3 Results

This chapter shows the results of the subsidence modelling for the case study. The following scenarios are examined. First, the scenario is considered where the maximum subsidence prognosis of the production licenses are used as a base case. The results of this scenario are compared with the available surface deformation observations. Secondly, the first scenario is extended with new planned production in the case study area. Finally, a scenario is considered where an ensemble of multiple models for the reservoirs in the De Blesse-Blesdijke area is run with varying input parameters. This is often done in production plans to show the uncertainty of the subsidence due to uncertainty in the parameters and is also used in this case to give a best fit model prognosis compared with the available subsidence observations.
The main focus is to show the visualization capabilities of the PySub framework. Therefore the model results are shown using different capabilities (e.g. contour maps and cross sections) and time steps.

3.1 Modelling Scenario 1: Maximum subsidence ‘approved’

Here we show the results of the modelled subsidence based on the subsidence prognosis described in the prevailing production plans. In a production plan an operator is required by the mining law to give a subsidence prognosis. In this scenario we want to show the maximum subsidence that is approved by the licensing authority. Therefore the input parameters used are the parameters corresponding to a maximum or high scenario. Different visualisation options of the framework are shown with focus on the discriminating subsidence contributions from multiple gas fields on the basis of these prognosis.

3.1.1 Current modelled subsidence (maximum)

Figure 3-1 gives a contour map overview of the subsidence prognosis for 1-1-2022 for the case study. The deepest point of the subsidence bowl is around 4 cm and is located between Vinkega and Nijensleek. Figure 3-2 and Figure 3-3 show cross sections of the modelled subsidence for the line A-B and C-D annotated in Figure 3-1. The contribution to the subsidence bowl of each individual reservoir is shown in different colours. This figure illustrates that for almost every point along this line the total subsidence bowl is a combination of the subsidence from different reservoirs, including the deepest point.

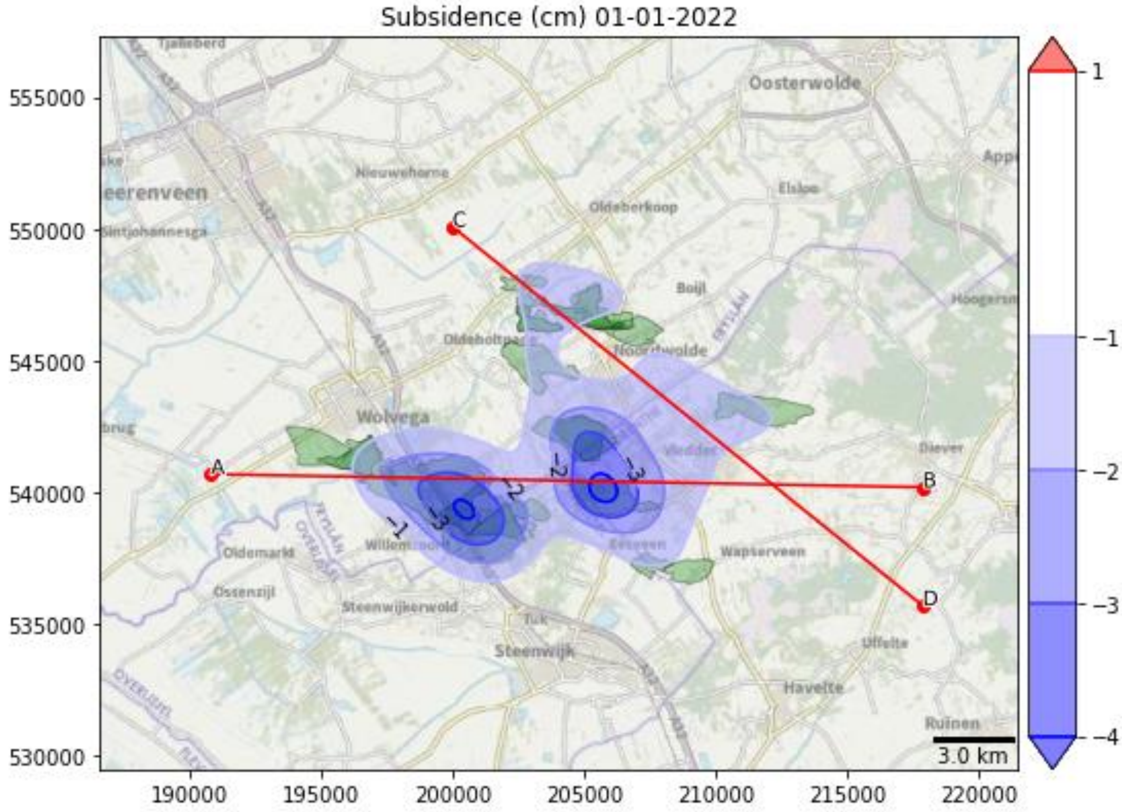

Figure 3-1 Map overview modelled subsidence at 1-1-2022 for case study scenario 1

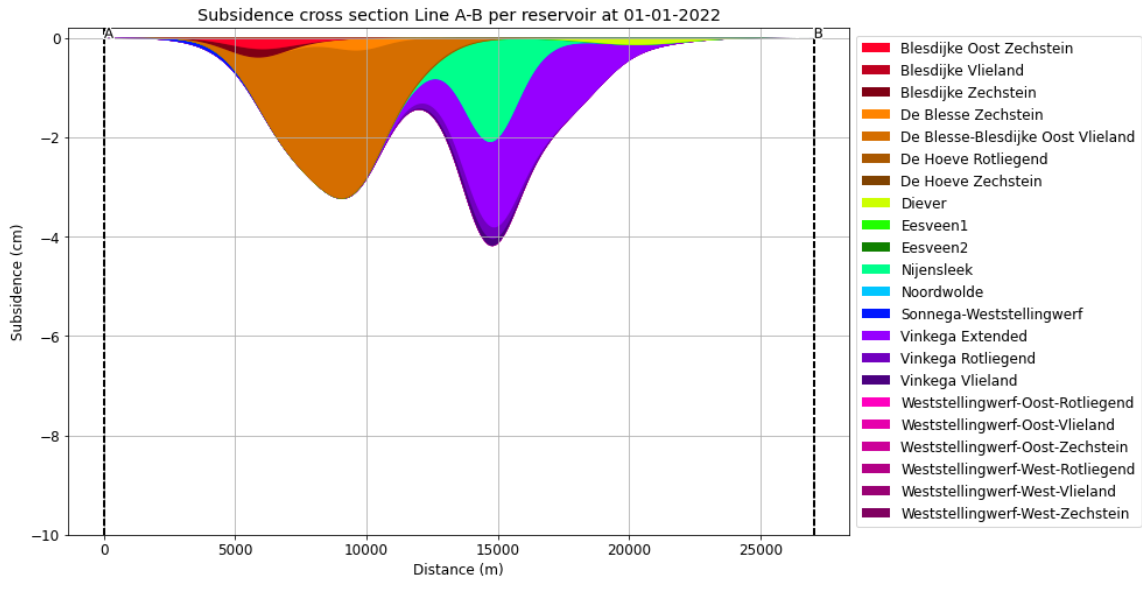

Figure 3-2 Modelled subsidence per reservoir for cross section line ‘A-B’ shown in Figure 3-1.

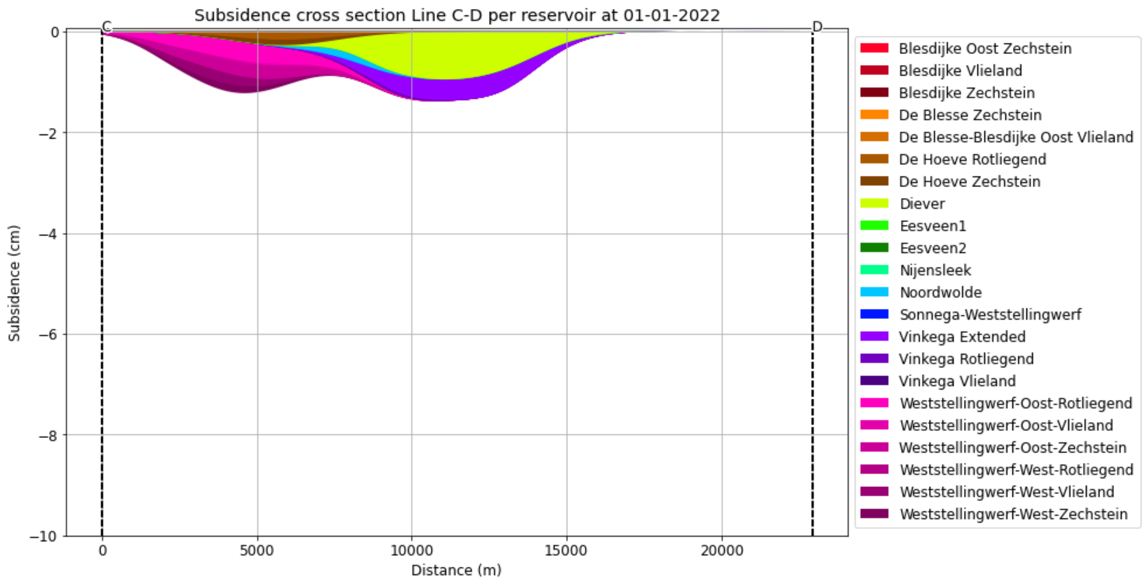

Figure 3-3 Modelled subsidence per reservoir for cross section line ‘C-D’ shown in Figure 3-1.

Comparison with observations

To show a simple comparison of the model prognosis with the observations three points, i.e. two levelling benchmarks and one GNSS-point are chosen. The points are chosen with the purpose to compare the subsidence observations and the model prognosis at the locations where the subsidence is expected to be high (i.e. above gas fields). Figure 3-4 shows the locations and corresponding observations and modelled prognosis.

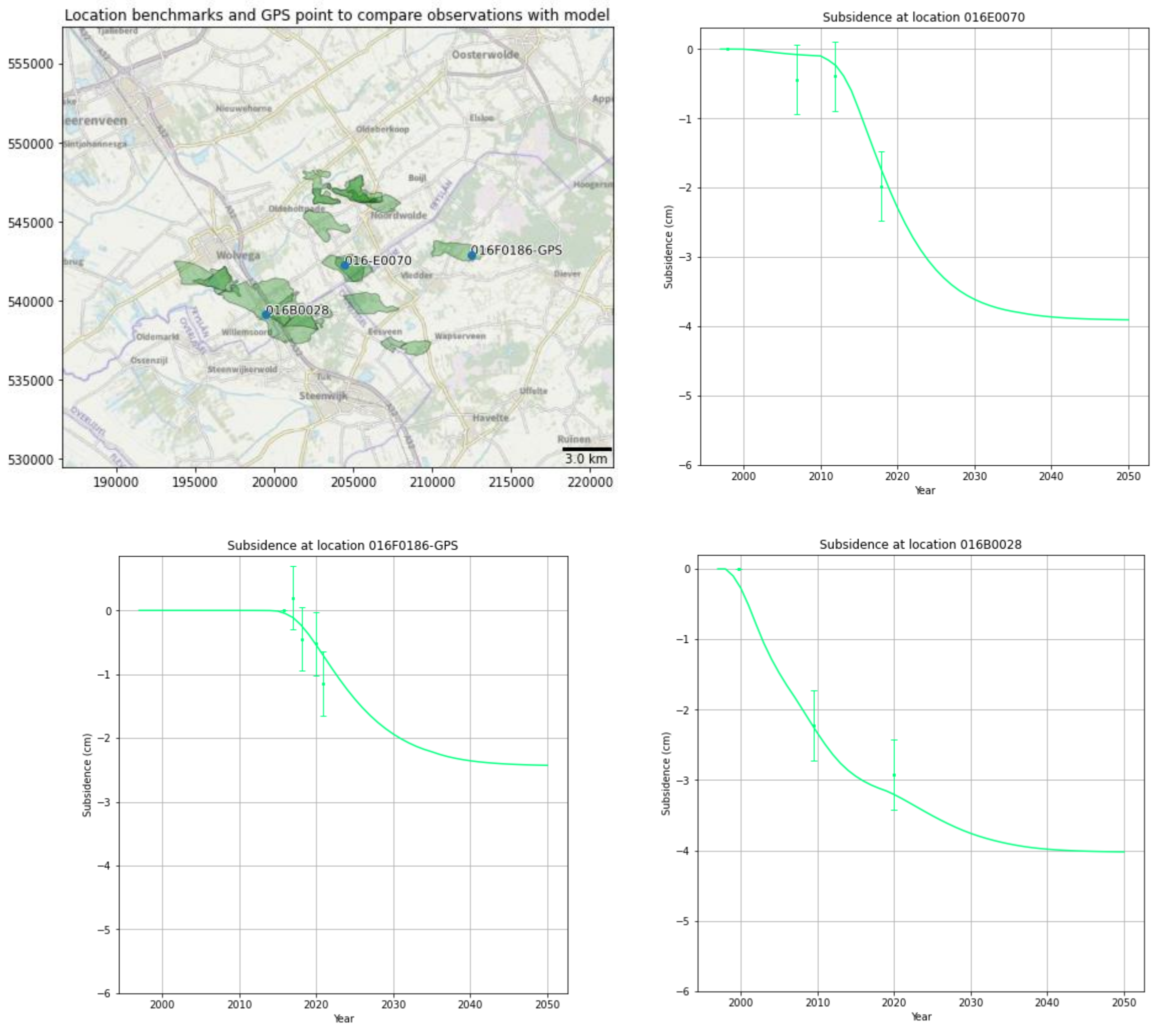

Figure 3-5 Top left: Location of levelling bench marks and GNSS point. Top right, lower left and lower right; model prognosis and observations for benchmark 016E0070, GNSS point 016F0186-GPS and benchmark 016B0028. For the observations an uncertainty range of ±0.5 centimeter is assumed.

3.1.2 *Subsidence prognosis at the end of production*

Figure 3-6 gives a contour map overview of the final subsidence prognosis for 1-1-2045 for the case study. The date of 1-1-2045 is chosen as end date, more than 10 years after end of planned production, to include the effects of a delay in the final subsidence prognosis. The deepest point of the subsidence bowl is around 5 cm deep and is located between the Vinkega and Nijensleek reservoirs. The location of the deepest point and the amount of subsidence has not changed much compared to the 1-1-2022 prognosis. In this case the approved planned production is mostly from reservoirs that only in a limited way contribute to the current deepest point.

Figure 3-7 and Figure 3-8 show cross sections of the modelled subsidence for the line A-B and C-D annotated in Figure 3-6.

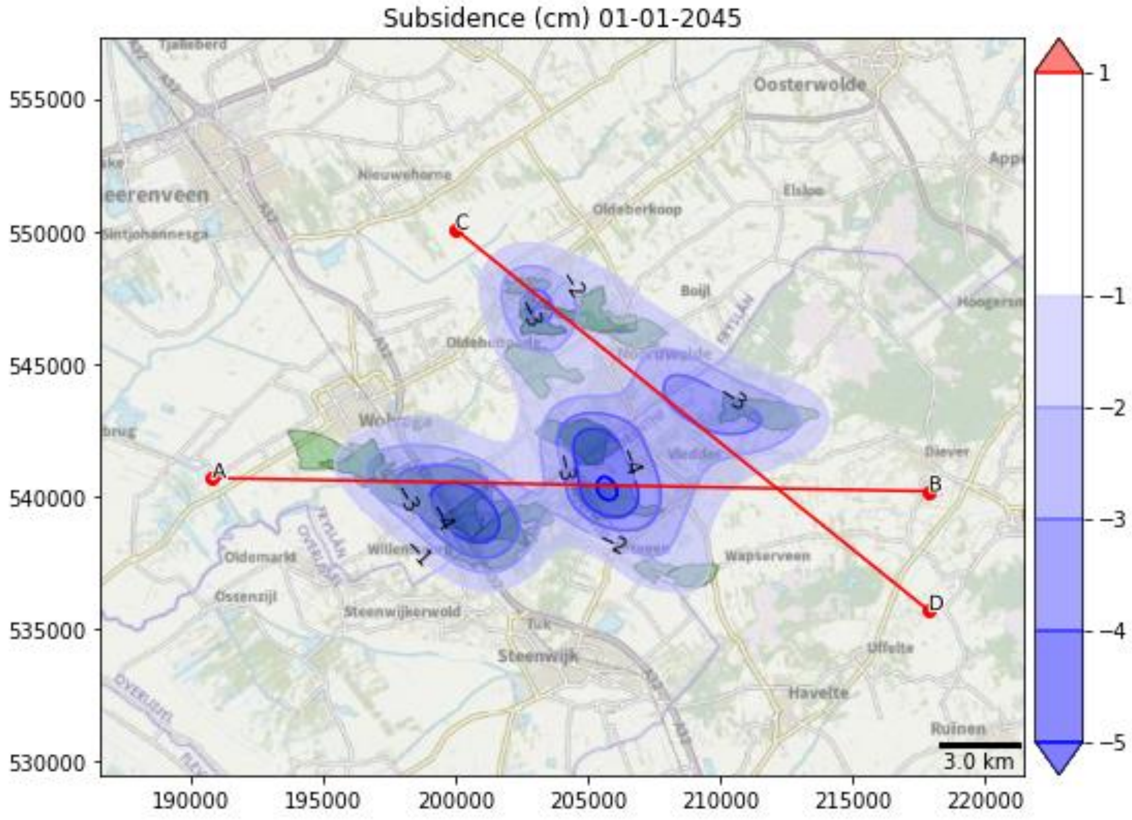

Figure 3-6 Map overview modelled subsidence at 1-1-2045 for case study scenario 1

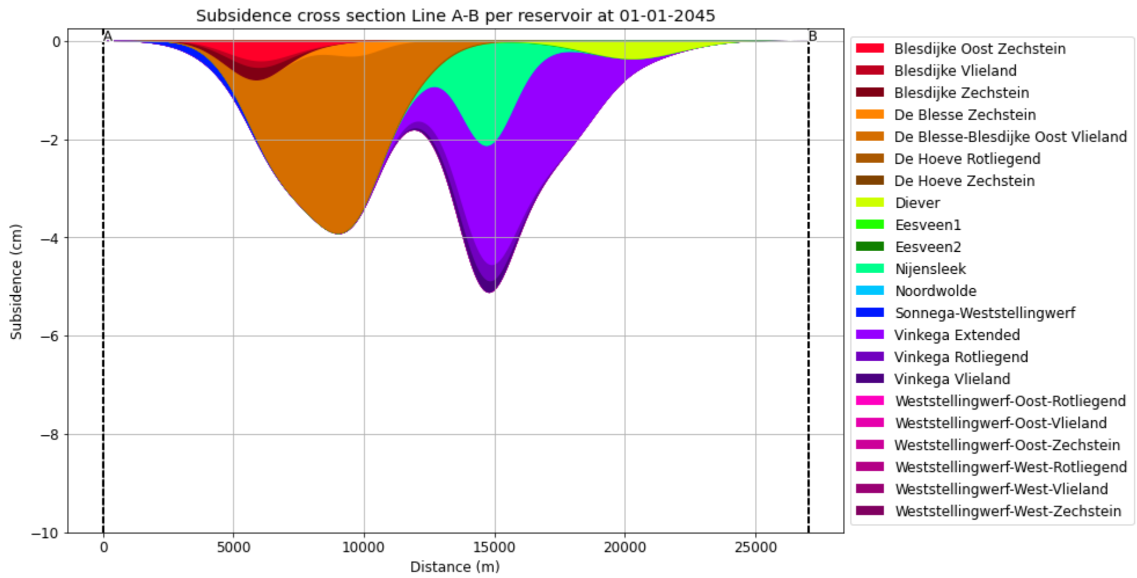

Figure 3-7 Modelled subsidence per reservoir for cross section line ‘A-B’ shown in Figure 3-6

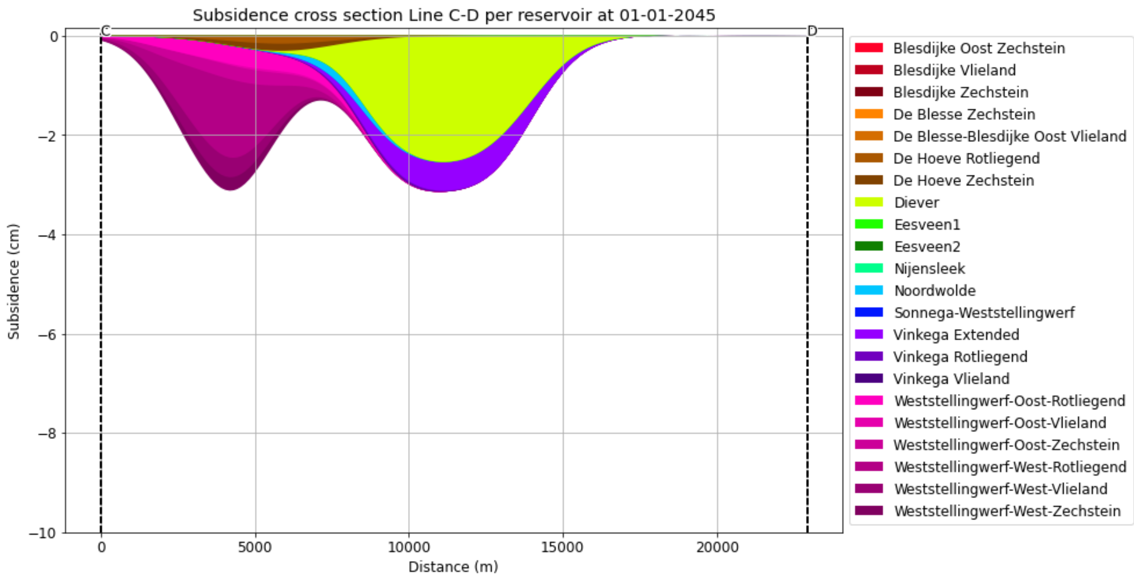

Figure 3-8 Modelled subsidence per reservoir for cross section line ‘C-D’ shown in Figure 3-6

3.1.3 Other visualisation options

The PySub Modelling Framework also offers other visualisation options; which are shown below. Figure 3-9 shows the modelled subsidence for cross section line ‘A-B’ which passes through the deepest point shown in Figure 3-6 for different dates starting at 1995-01-01 and ending at 01-01-2045, 10 years after assumed end of production. Figure 3-9 illustrates subsidence through time. The red line in Figure 3-9 is the maximum approved subsidence threshold from the prevailing production plans. This kind of figure can be used to evaluate if, when and where the subsidence prognosis of a production plan or an area will exceed the legal imposed limit.

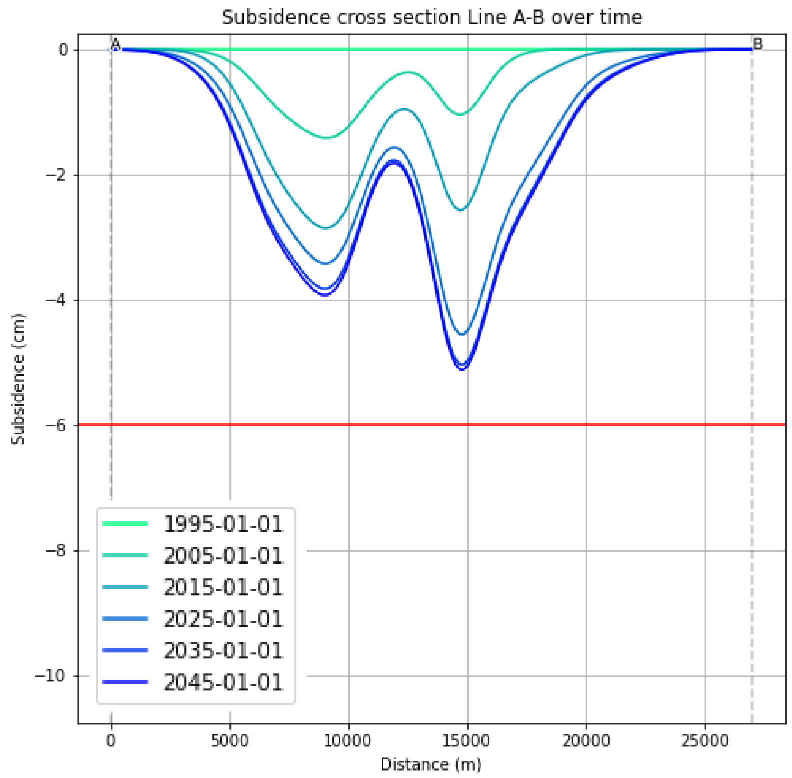

Figure 3-9 Modelled subsidence for cross section line ‘A-B’ shown in Figure 3-6 for different dates starting at 1995-01-01 and ending at the end of production. The red line represent the maximum approved subsidence threshold from the prevailing production plans.

Overlap subsidence bowl between reservoirs

PySub also makes it possible to show the overlap between subsidence bowls of different reservoirs in map view. Figure 3-10 shows the overlap of the individual subsidence bowls of the reservoirs in the case study at 01-01-2045, 10 years after assumed end of production. The area of a subsidence bowl is defined, in this case, as the area where a single reservoir causes 1 or more cm subsidence. In green, the area is shown of an individual subsidence bowl. When the subsidence bowl of two areas overlap, the area is blue, indicating that two reservoirs cause >1 cm each in that area. Figure 3-10 illustrates for this case study, that although there are many different reservoirs contributing to the total subsidence bowl, only in a relatively small area significant overlap between individual contributions occurs. In this case significant overlap is quantified as more than 1 cm overlap caused by each of two or more individual subsidence bowls.

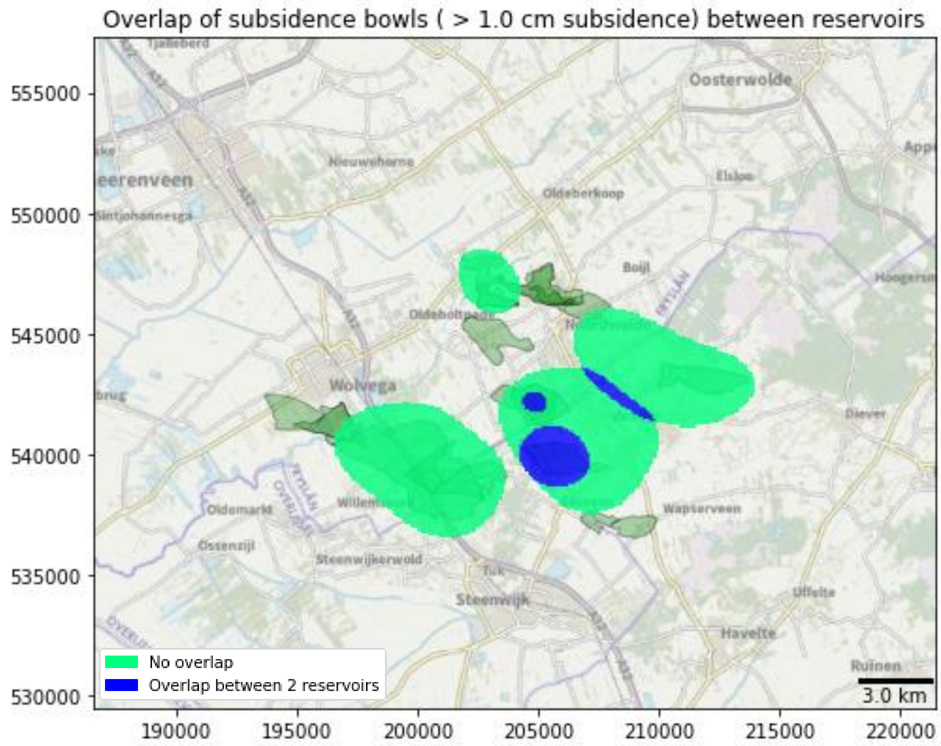

Figure 3-10 Overlap of the subsidence bowls of the reservoirs in the case study at the end of production. The green colour shows the area where the subsidence bowl of individual reservoirs are more than one cm. The blue colour indicates the area where the individual subsidence bowls with more than one centimetre overlap with each other.

Subsidence prognosis based on reservoir type

Figure 3-11 shows the different contribution on the subsidence bowl per lithology type of the different reservoirs at the end of production. This figure illustrates that there is minimal contribution to the total subsidence bowl of the Zechstein reservoirs, less than 1 cm over the whole area in the case study. The contribution of both the Rotliegend and the Vlieland reservoir are significant. However, the subsidence bowl of the Vlieland and Rotliegend formation each have a different spatial extent; the location of the deepest point of the subsidence bowl is different.

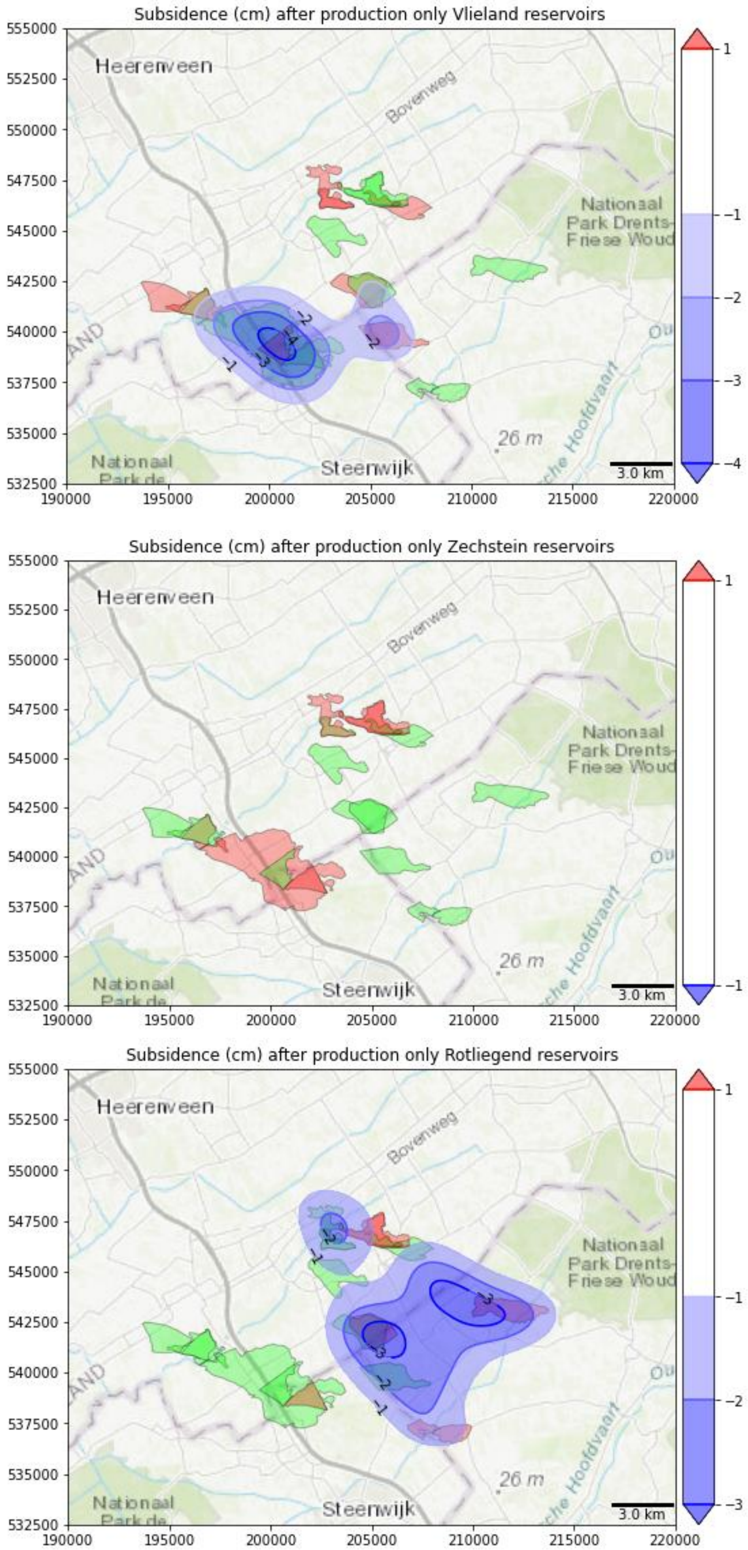

Figure 3-11 Subsidence contribution per lithology type of the different reservoirs at the end of production. In each figure in red the reservoir of the lithology modelled, in green the other reservoirs with a different lithology which are not modelled.

3.2 Modelling Scenario 2: Effect of new production

In this scenario the effect of the planned production of the LDS-fields is examined. The location of the proposed new fields is shown in Figure 3-1 in yellow. The production plan for these fields is approved, but the production has not started yet. This is therefore a good scenario to show the effect of planned production in an area with already producing fields. In Table 2-2 the input data for this scenario is summarized. Figure 3-12 gives a contour map overview of the final subsidence prognosis for 1-1-2045 for the case study scenario 2. In red the additional LDS fields are shown. The date of 1-1-2045 is chosen as end date, 5 years after end of planned production in the high case, to include the effects of a delay in the final subsidence prognosis and to be comparable with scenario 1. The location of the deepest point and the magnitude of subsidence is changed compared to the present prognosis. The planned production is in an area at more than 5 km distance from the deepest point in Figure 3-6. As can be seen, the planned production results in an increase in subsidence above the Eesveen field and particularly to the west of the Diever field in the order of 1 cm.

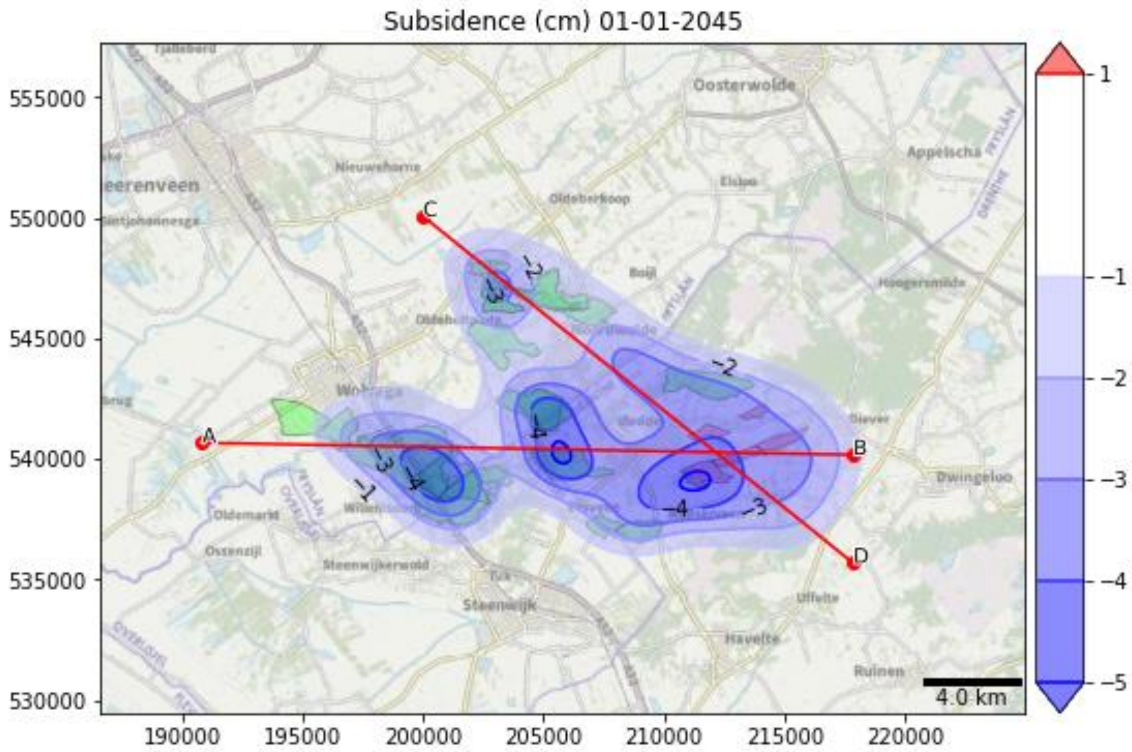

Figure 3-12 Map overview modelled subsidence at 1-1-2045 for case study scenario 2. The LDS fields are shown in red.

Figure 3-13 and Figure 3-14 show the cross section of the modelled subsidence for the lines A-B and C-D in Figure 3-12. The contribution to the subsidence bowl of each individual reservoir is shown in different colours and the LDS fields are annotated with white dotted lines.

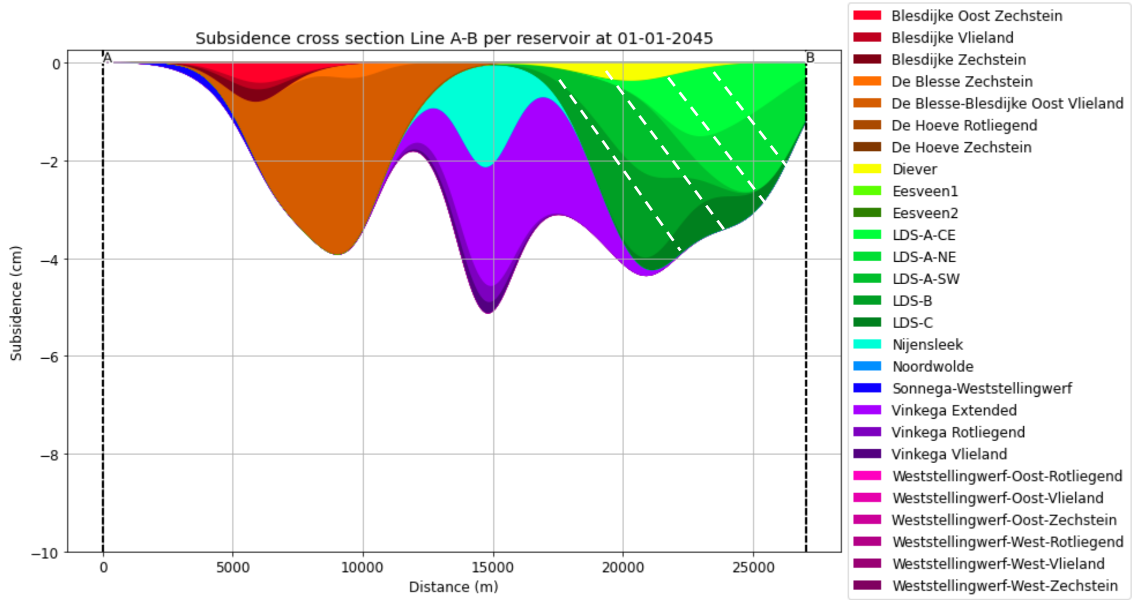

Figure 3-13 Modelled subsidence per reservoir for cross section lines 'A-B' shown in Figure 3-12. In with stripes the LDS reservoirs are annotated, i.e. LDS-A-CE, LDS-A-NE, LDS-A-SW, LDS-B and LDS-C.

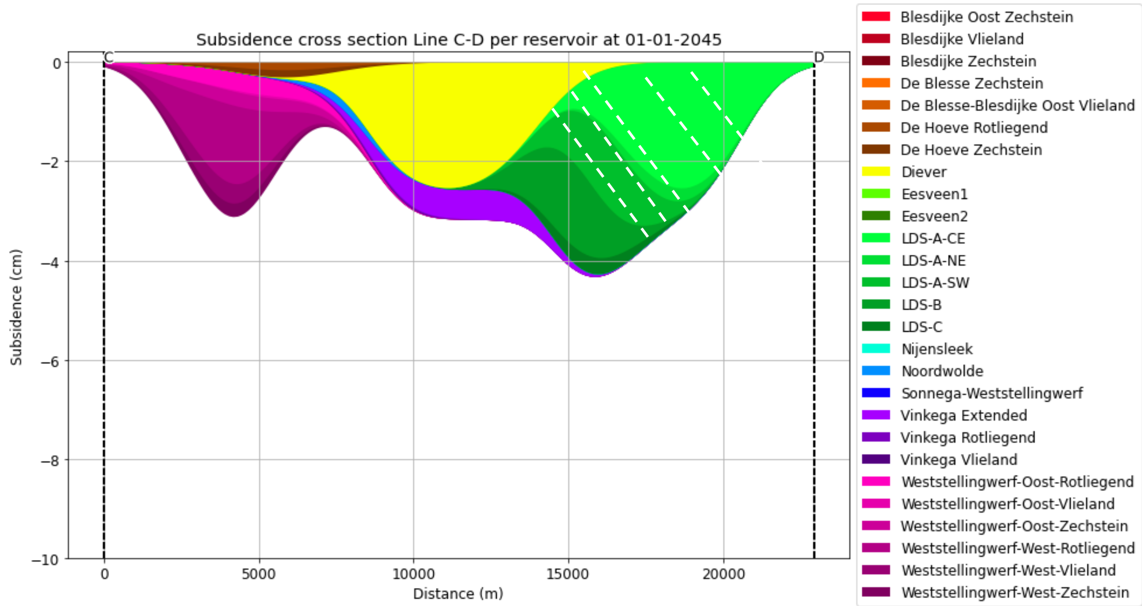

Figure 3-14 Modelled subsidence per reservoir for cross section lines 'C-D' shown in Figure 3-12. In white stripes the LDS reservoirs are annotated, i.e. LDS-A-CE, LDS-A-NE, LDS-A-SW, LDS-B and LDS-C.

3.2.1 *Other visualisation options*

In scenario 1 the relevant visualization options of PySub are shown and therefore only one additional figure is shown for scenario 2. Figure 3-15 shows the overlap of the individual subsidence bowls of the reservoirs for scenario 2 at the end of production.

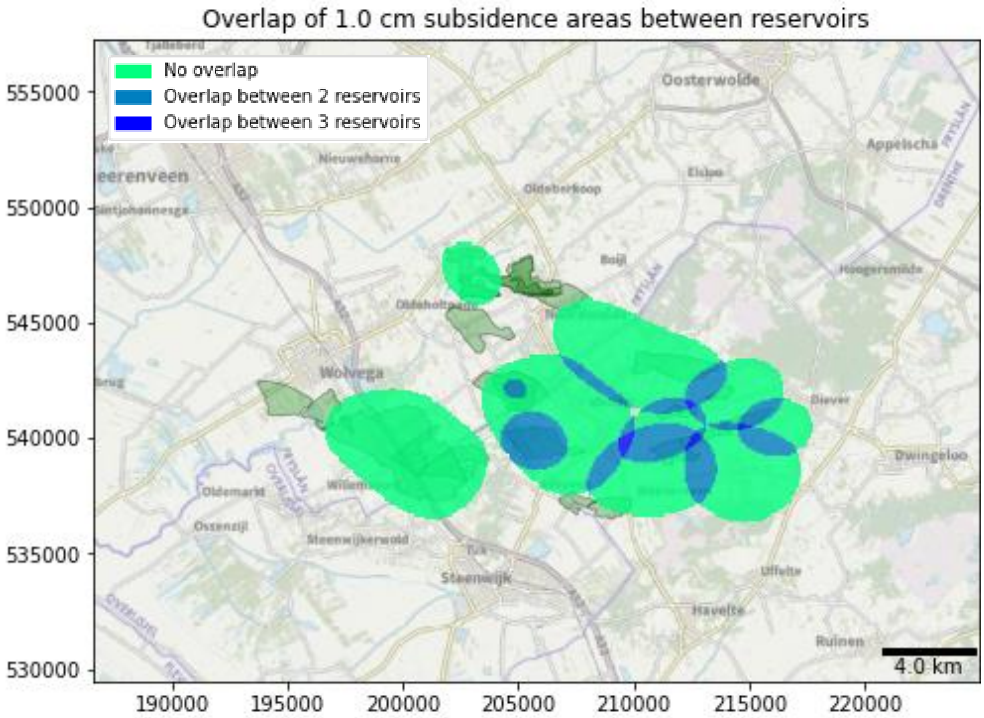

Figure 3-15 Overlap of the subsidence bowls of the reservoirs in the case study at the end of production. The green colour shows the area where the subsidence bowl of individual reservoirs are more than one cm. The blue colour indicates the area where the individual subsidence bowls with more than one centimetre overlap

The green colour shows the area where the subsidence bowl of individual reservoirs are more than one cm. The lighter blue colour indicates the area where two individual subsidence bowls with more than one centimetre overlap, the darker blue the overlap between three reservoirs. Compared with Figure 3-10 of scenario 1 Figure 3-15 illustrates that the added planned production of the LDS fields causes al lot more complexity and overlap between the individual reservoirs.

3.3 Modelling scenario 3: Results ensemble runs

Scenario 3 shows two sub-scenarios exploring the Bucket Ensemble part of the PySub Modelling Framework. With the Bucket Ensemble method it is possible to either run all possible model parameter combinations, or sample the parameters according to their probability. For a more extensive explanation see the accompanied report on the modelling framework (TNO, 2023).
For modelling scenario 3 it is chosen to randomly sample 100 times the input parameters with accompanying probabilities as presented in Table 2-3 to make a subsidence prognosis. From these results the prognosis with the best fit with the observations is determined (sub-scenario 3.1) and the 90 percentile (conservative) results (sub-scenario 3.2). In both scenarios a small area of the case study is used

to simplify the case for demonstration purposes. The selection covers the reservoirs in the De Blesse-Blesdijke area (see Table 2-3 for parameters).

3.3.1 Sub-scenario 3.1: best fit

As described in section 2.2.3, operators are obligated by mining law to monitor the subsidence as a result of the production of gas, oil or other mining materials. It is insightful to know if the subsidence prediction of the production plan is in line with the observations. This scenario explores how the PySub Modelling Framework can be used for a first order comparison between the observations and model results. For the De Blesse-Blesdijke area levelling data is available. The first levelling campaign was conducted before the start of production and the most recent campaign in 2019. Here it is assumed the vertical displacement over time recorded by these observations has been caused only by gas production. For each possible parameter combination the modelled subsidence can then be compared to observations.

As a comparison metric the Mean Absolute Error method (MAE) is used. The Absolute Error is determined by taking the absolute difference between each observation point and the modelled subsidence at the location of the observation for the whole time series. The mean of the Absolute Error is taken to give one number representing the fit of the model to the observations. A lower MAE implies a better fit to the observations. Here, the lowest MAE is chosen to represent the best fit based on the given input data (Table 2-3). Furthermore this gives a best fit for the total model (over time) and might not give the best fit for the deepest point of the subsidence bowl.

The observation locations are shown in Figure 3-16, together with their observed vertical displacement between the start of production and 2019. Also shown in this figure is the subsidence bowl caused by the parameter set which has the lowest MAE for the year 2019.

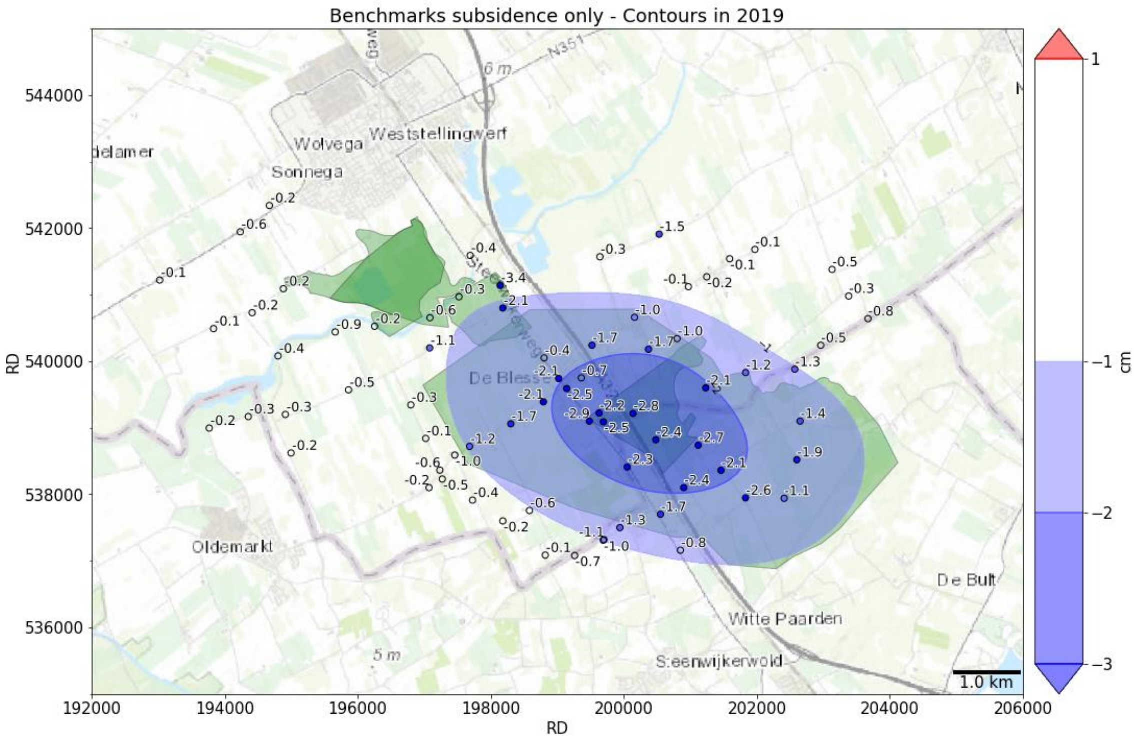

Figure 3-16 Locations of the observation points and the vertical displacement they have recorded between start of production and 2019. The contours are the vertical displacement caused by the parameter combination with the best fit

3.3.2 *Sub-scenario 3.2: 90% percentile*

In some cases in production plans a 90% percentile of the maximum subsidence is presented. This value is meant to represent the maximum subsidence that is not exceeded in 90% of all the explored runs. In this scenario the bucket ensemble method of the PySub Modelling Framework is used to determine this 90% percentile for the De Blesse-Blesdijke area.

Using the Bucket Ensemble method, multiple parameter combinations (Table 2-3) are run. Each combination of parameters has a probability of occurring, acquired by multiplying the corresponding probability of the picked parameters. This gives per combination a maximum subsidence and corresponding probability. The sum of each parameter combinations probability is 100%. From the ensemble results a cumulative distribution function (CDF) can be constructed. This probability distribution and the resulting P90 value for the maximum subsidence is displayed in Figure 3-17. The subsidence bowl for the 90% percentile parameter combination at the end of production is shown in Figure 3-18.

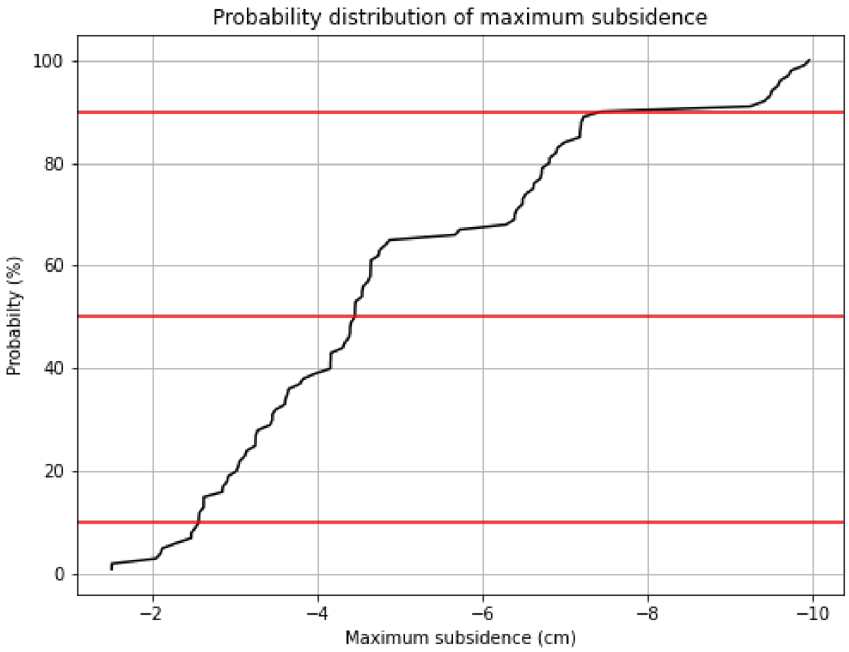

Figure 3-17 Cumulative distribution function of all the parameter combinations that have been sampled, and their resulting maximum subsidence. On the x-axis are the maximum subsidence of the parameter combination and on the y-axis the cumulative probability of each corresponding parameter combination. The horizontal red lines are placed at the 10%, 50% and 90% percentiles, intersecting with the probability distribution with the 10%, 50% and 90% maximum subsidence.

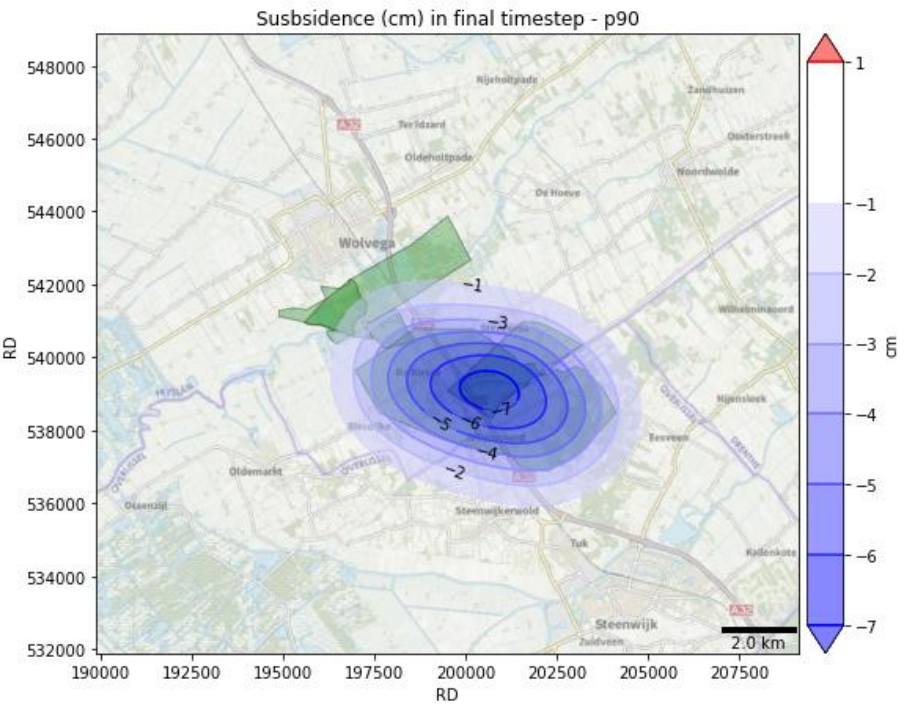

Figure 3-18 The P90 subsidence bowl after production as determined using 100 samples from the Bucket Ensemble.

4 Conclusions

The objective of this report was to explicitly model and visualize the subsidence of the contributions of different mining activities. Therefore, the subsidence of different gas fields in the selected case study area of Diever, Vinkega and Eesveen area was modelled in a combined effort using the PySub Modelling Framework.
In order to show the various visualisation options within the PySub Modelling Framework and possibilities to discriminate between subsidence contributions different scenarios were run. The first and second scenario are deterministic scenarios where the subsidence prognosis is based on the prevailing production plans and expected production in the case study area and subsidence development is modelled through time. These scenarios show the visualisation options within PySub including a variety of different map view and cross section options aimed to differentiate the contributions of the different gas reservoirs. Also the option to compare observation with the model prediction and a visualisation option to get insight in the overlap between the subsidence contributions of different reservoirs is shown. In the third scenario the Bucket Ensemble method is explored. In this scenario an ensemble of multiple models is run with varying input parameters for a part of the case study area. Here a best fit scenario with the observations and a 90% percentile scenario[2] is examined.
The results of the different scenarios show the different options and capabilities of the PySub tool. The newly developed visualization options are expected to give more insight in the different contribution of different mining activities to a subsidence bowl.

In future work the following additions/improvements are useful:

- The current PySub Modelling Framework does not support model parameter inversion, but only has a limited model-observation comparison capability using the Mean Absolute Error method, described in section 3.3.1. This can be expanded using inversion methodology (Candela et al, 2022). Such an inversion scheme will improve model parameter calibration and therefore improve the history matching of the observed subsidence. This will help decrease the uncertainty in prognosis.
- The current ensemble method uses discrete parameter values which can be improved using continuous distribution of the input parameter set.

[2] P90 in this case means that the maximum subsidence is not exceeded with 90% probability.

5 References

Candela Thibault, Chitu A. G., Peters E., Pluymaekers M., Hegen D., Koster Kay, Fokker Peter A. (2022) Subsidence Induced by Gas Extraction: A Data Assimilation Framework to Constrain the Driving Rock Compaction Process at Depth, Frontiers in Earth Science volume 10.

Deltares (2023), Mining-induced subsidence and water level management; KEM-16 WP3. Reference 11205981-003-BGS-0001

De Waal J (1986) On the rate type compaction behaviour of sandstone reservoir rock, PhD thesis, Delft University of Technology, Delft, the Netherlands, available at: http://repository.tudelft.nl/view/ir/ uuid:b805782b-2eb4-4f72-98f4-f727c4ea9df0.

Fokker PA, Osinga S (2018) On the use of influence functions for subsidence evaluation, American rock mechanic's association, 52nd US Rock Mechanics/Geomechanics Symposium

Geertsma J (1973) Problems of rock mechanics in petroleum engineering. Proc. First Congr. Of the Int. Soc. Of Rock Mech., 1, 585.

Hagoort, J. (1988) Fundamentals of gas reservoir engineering, Elsevier.

Hammond, R., Bickel E., (2013) Reexamining Discrete Approximations to Continuous Distributions", Decision Analysis, vol. 10, p. 6, 2013

Mossop A (2012) An explanation for anomalous time dependent subsidence, 46th US Rock Mechanics/Geomechanics Symposium, Chicago, Illinois, USA, 24–27 June 2012, 12-518.

Pruiksma J, Breunese JN, Thienen-Visser K, De Waal JA (2015) Isotach formulation of the Rate Type Compaction Model for sandstone, Int. J. Rock Mech., 78, 127–132.

TOTAL E&P Nederland B.V. (2003), Winningsplan Nijensleek

TNO, (2023), The PySub Subsidence Model Framework: Technical Reference Manual, reference TNO2022_R1196,

Van Opstal GHC (1974) The effect of base-rock rigidity due to reservoir compaction, Adv, in Rock Mech., 3, 1103-1111.

Van Tienen-Visser K, Pruiksma JP, Breunese JN (2015) Compaction and subsidence of the Groningen gas field in the Netherlands, Proceedings of the International Association of Hydrological Sciences 372: 367-373

Vermillion Energy Netherlands B.V. (2018) Winningsplan De Blesse-Blesdijke vs. 3.0

Vermillion Energy Netherlands B.V. (2017) Winningsplan De Hoeve

Vermillion Energy Netherlands B.V. (2018) Winningsplan Diever vs. 3.0

Vermillion Energy Netherlands B.V. (2017) Winningsplan Eesveen vs. 2.0

Vermillion Energy Netherlands B.V. (2020) Winningsplan Leemdijk-De Bree-Smitstede

Vermillion Energy Netherlands B.V. (2012) Addendum by Winningsplan Noordwolde 2012
Vermillion Energy Netherlands B.V. (2018) Addendum bij Winningsplan Vinkega vs. 3.3.

Vermillion Energy Netherlands B.V. (2018) Winningsplan Wesstellingwerf vs. 2.0

6 Signature

Utrecht, 13/10/2023	TNO
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Head of department	Author

A Additional information input data

Table A-1 Initial pressure and end pressure used in the different modelling scenarios for the case study

Reservoir	Initial Pressure	End Pressure
Blesdijke Oost Zechstein	230	30
Blesdijke Oost Zechstein	230	30
Blesdijke Vlieland	207	30
Blesdijke Zechstein	207	30
De Blesse Zechstein	230	30
De Blesse-Blesdijke Oost Vlieland	230	30
De Hoeve Rotliegend	248	218
De Hoeve Zechstein	203	20
Diever	238	10
Eesveen1	230	15
Eesveen2	230	15
LDS-A-CE	249	10
LDS-A-NE	249	60
LDS-A-SW	248	10
LDS-B	244	20
LDS-C	247	10
Nijensleek	206	15
Noordwolde	215,5	15
Sonnega-Weststellingwerf	220	15
Vinkega Extended	227	20
Vinkega Rotliegend	227	10
Vinkega Vlieland	205	15
Weststellingwerf-Oost-Rotliegend	230	200
Weststellingwerf-Oost-Vlieland	220	125
Weststellingwerf-Oost-Zechstein	222	125
Weststellingwerf-West-Rotliegend	220	15
Weststellingwerf-West-Vlieland	225	15
Weststellingwerf-West-Zechstein	230	15

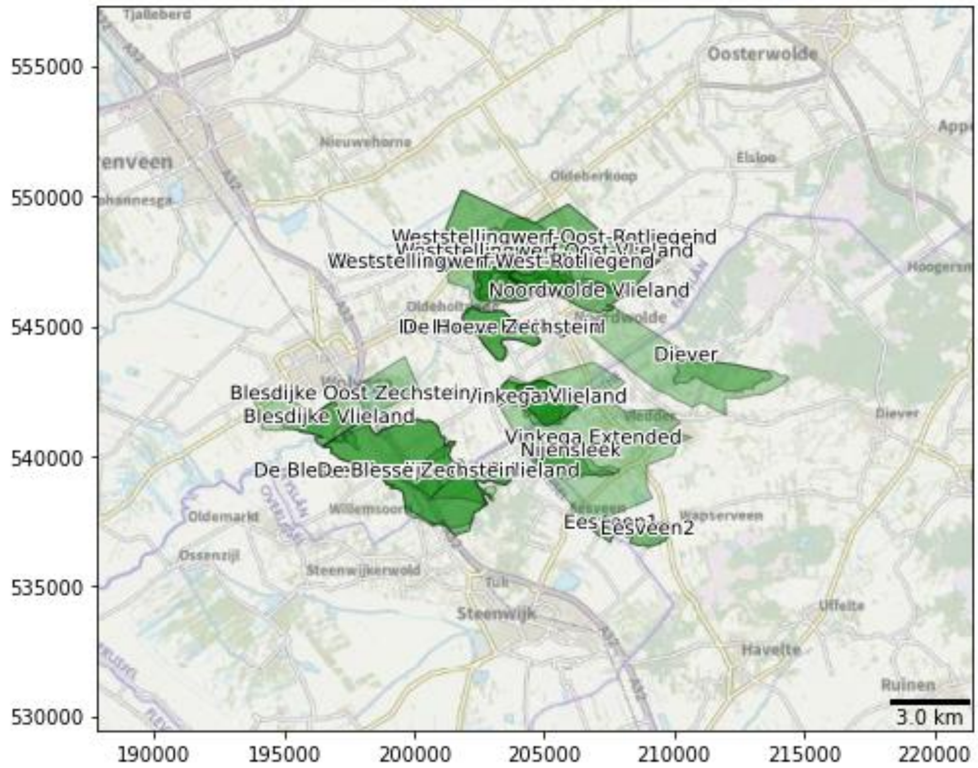

Figure A-1 Overview of all reservoir shapes used for modelling scenario 1

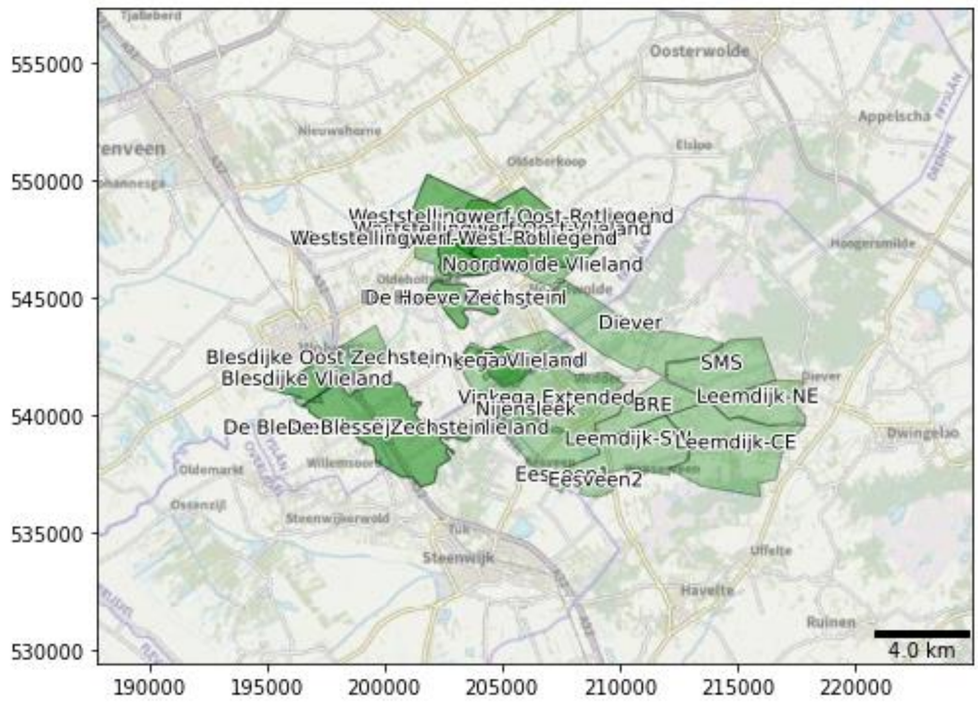

Figure A-2 Overview of all reservoir shapes used for modelling scenario 2