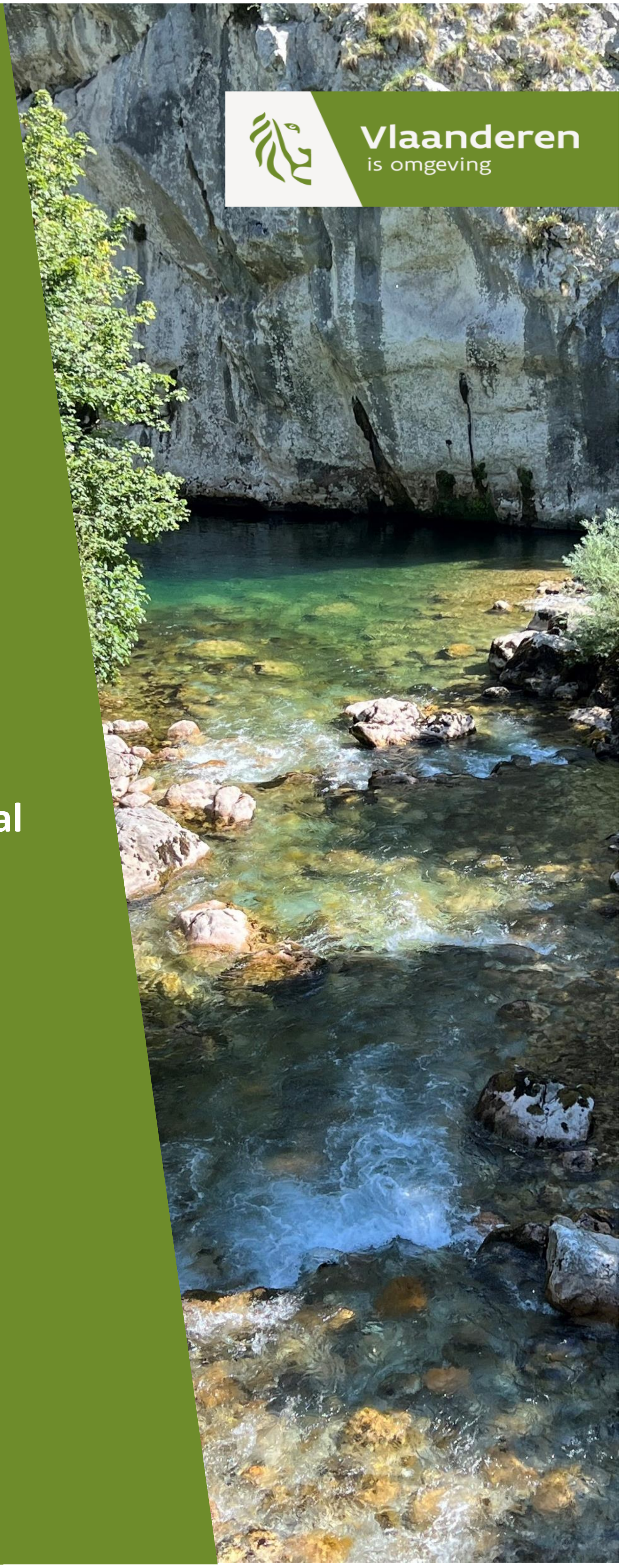

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Prospective dynamic modelling for an optimal definition of license volumes in the deep subsurface of Flanders

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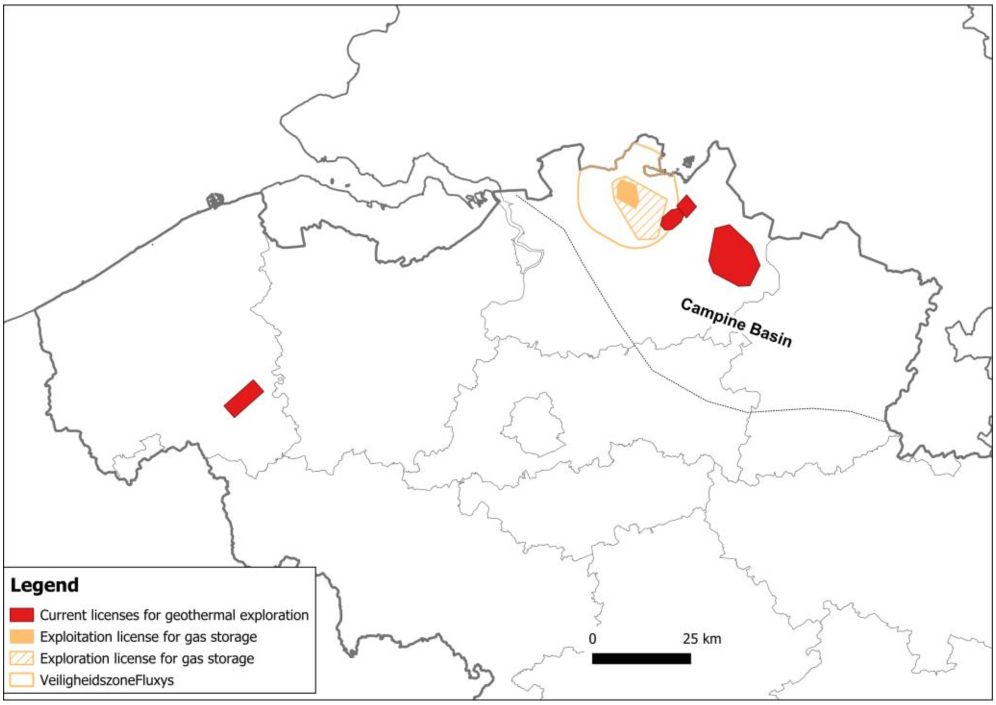
Context and Objective of the study

One of the ways to achieve a more sustainable energy supply and system is the use of geothermal heat from the deep subsurface. With additional future developments expected in the same subsurface reservoir, it is important to optimally delineate license volumes to avoid negative interference between projects and to ensure an efficient use of the deep subsurface, now and in the future.

An optimal delineation must allow to define the permitted volumes in such a way that:

1. *they are large enough so that different applications can safely coexist without negative interference (relevant impact limited to volume area)*
2. *they are small enough so that they do not unnecessarily take up space that can no longer be used.*



Overview of exploration licenses for deep geothermal energy (status December 2024) in Flanders, with 3 licenses in Antwerp and 2 licenses in West-Flanders. The current licenses for exploitation and exploration of gas storgae are also indicated.

The current study aims to improve insights for the definition of license boundaries by means of dynamic reservoir simulations. The objective is to simulate various concepts and scenarios, to use the results to gain insights into the aspects and boundary conditions of typical applications, and to make recommendations for the efficient delineation of 3D license volumes.

This study focuses on hydrothermal systems using a doublet (one production well combined with one injection well) in the Carboniferous Limestone Group in the Campine Basin.

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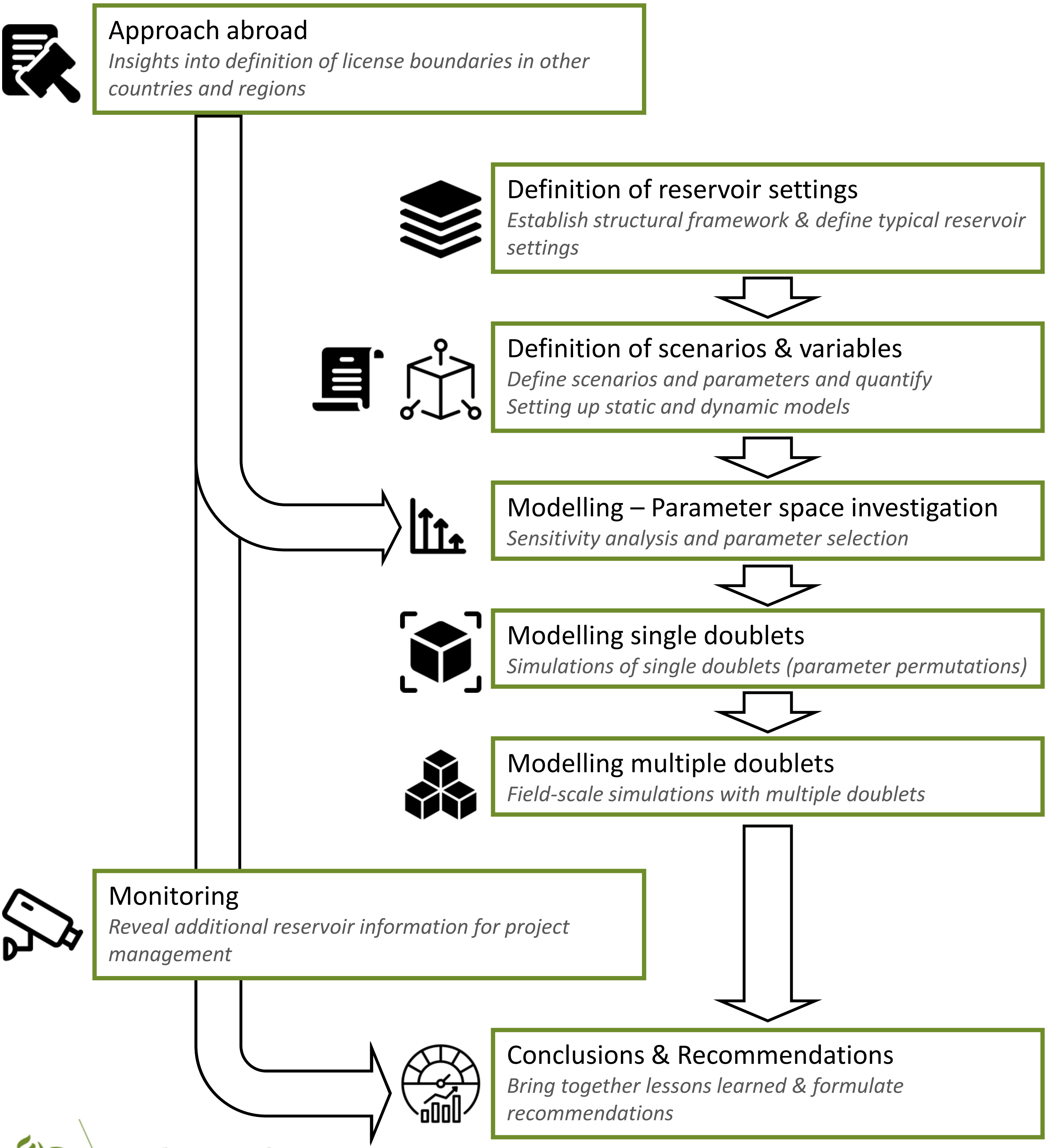
Methodology of the study



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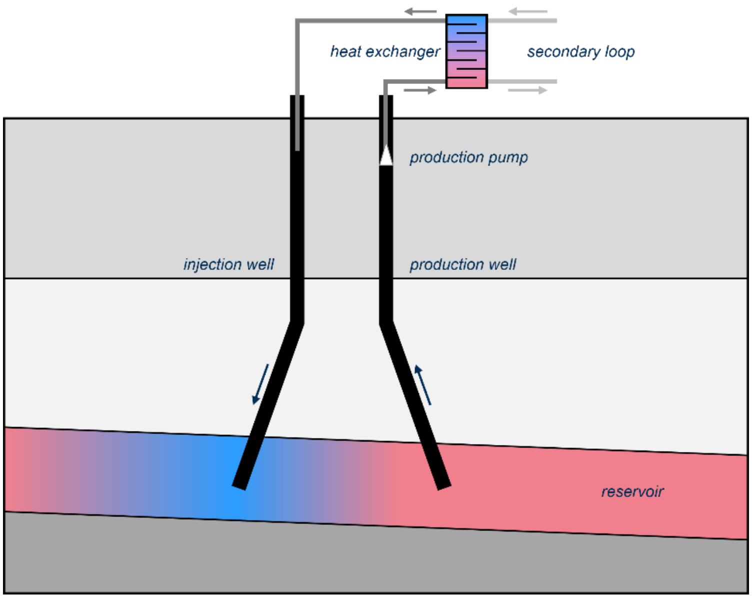
Deep geothermal energy in Flanders

Deep geothermal energy can be extracted by means of a closed-loop single well system or by operating a doublet system. A doublet system consists of one well for production of hot water and another well for injection of the water after the heat has been extracted. Doublet systems target subsurface reservoirs, which in Flanders are almost exclusively present in the Campine Basin. This study focuses on doublet systems.



Schematic representation of a geothermal doublet, with a production well to extract hot water (red) and an injection well to reinject colder water (blue) after the heat has been extracted by means of a heat exchanger.

Potential geothermal reservoirs in the Campine Basin are found in:

- *the chalk strata of the Upper Cretaceous,*
- *sandstone layers in the Triassic Buntsandstein Formation,*
- *sandstone and conglomerate of the Upper Carboniferous Neeroeteren Formation, and*
- *the limestone and dolomite layers of the (Lower) Carboniferous Limestone Group.*

The projects in Mol and Beerse both extract heat from the Carboniferous Limestone Group. Additional exploration licenses in the area are focused either on the same reservoir or on sandstone reservoirs in the Triassic Buntsandstein Formation and the Upper Carboniferous Neeroeteren Formation.

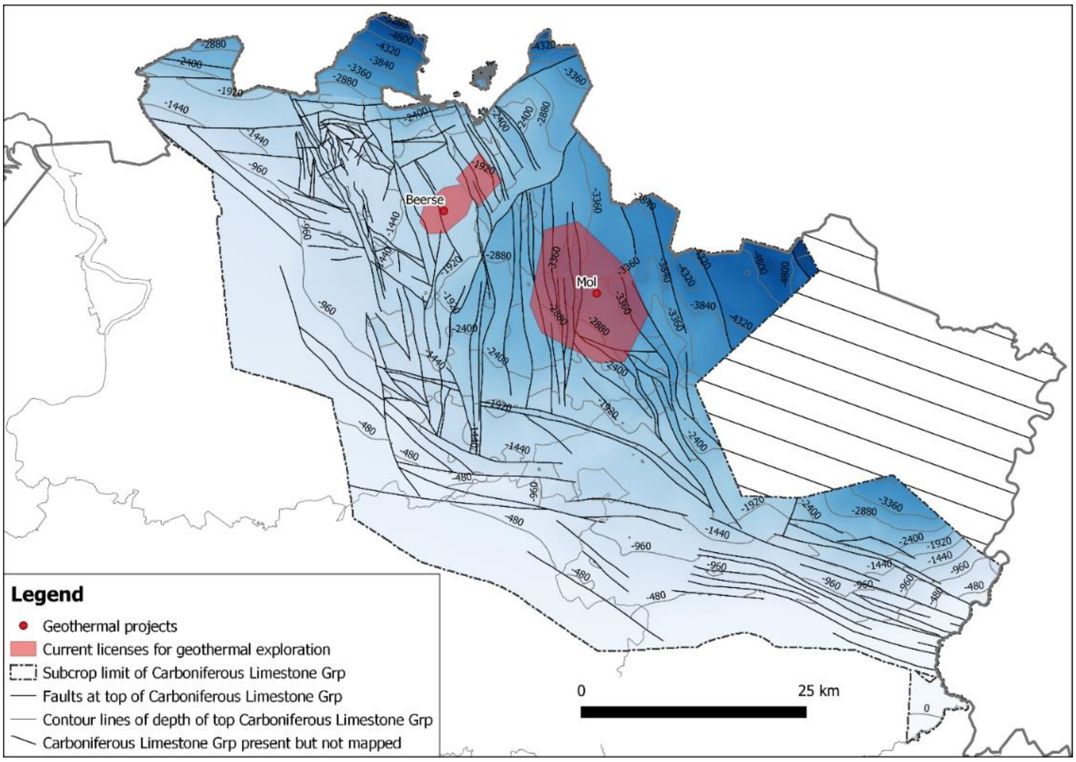
How are licenses defined and how are license applications evaluated?

The "Decreet Diepe Ondergrond" and the "Besluit Diepe Ondergrond" define the regulations applicable to geothermal licenses. They distinguish between exploration licenses and production licenses. An exploration license is required to explore the geothermal potential by means of drilling, a production license is needed for long-term extraction of heat.

Licenses should be large enough to contain all significant subsurface impact within the license volume, but they should not be too large claiming part of the subsurface which is not required. The latter would lead to inefficient use of resources.

Dynamic reservoir models should be used to evaluate the subsurface impact around the geothermal wells of a doublet and to verify if any interference occurs with other subsurface activities within a radius of 10 km. Dynamic modelling involves the use of a numerical and simplified representation of the reservoir to simulate transport of water and heat during exploitation of a doublet.

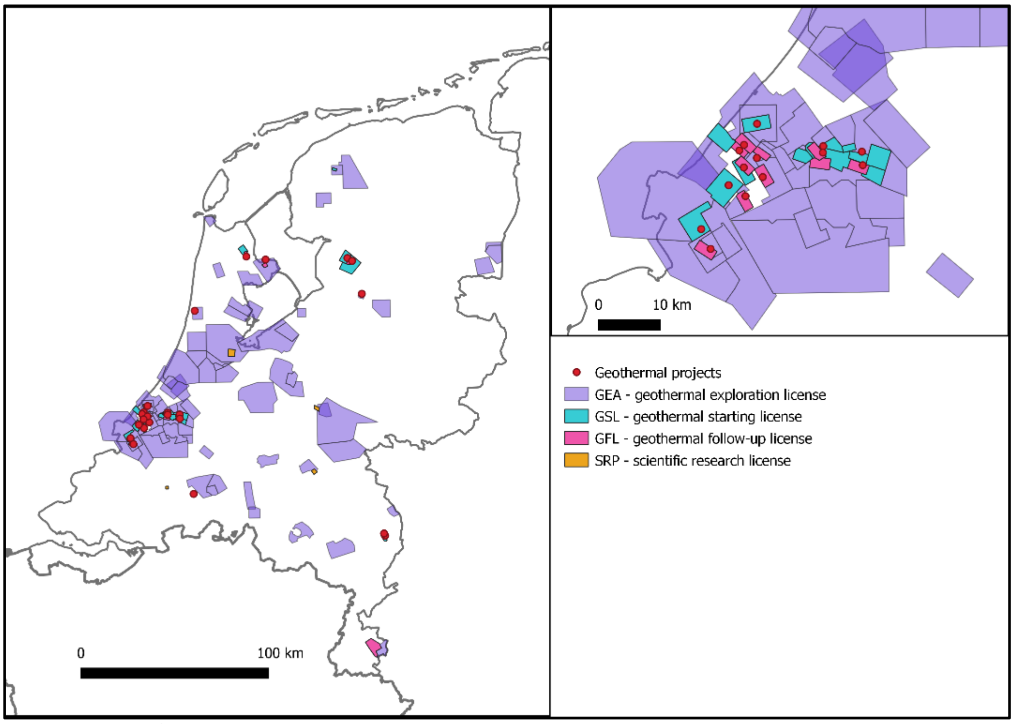
End of 2024, there are five active exploration licenses. Three of these are located in the Campine Basin and target the Carboniferous Limestone Group. Their large extent results from the significant uncertainty on reservoir characteristics at the time of application.



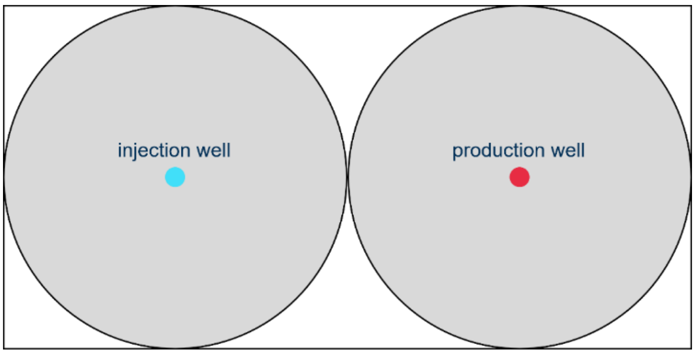
Overview of geothermal licenses in the Campine Basin (status December 2024). The depth of the top of the Carboniferous Limestone Group is shown as background (Rombaut et al., 2025).

Geothermal licensing abroad

Comparable situations exist in the Netherlands, France and Germany, where multiple geothermal projects are concentrated within a limited area.
In France and the Netherlands, the boundaries of geothermal production licenses are defined in a geometrical way, based on the spacing between the wells, In Germany (Bavaria), the approach is comparable to Flanders, with the size of exploration licenses related to the spatial work scope, and the boundaries of the production licenses based on the results of dynamic reservoir modelling. In Bavaria, maximum pressure and temperature impact on the license boundary are specified (1 bar and 1°C respectively).



Overview of geothermal licenses in the Netherlands, with the area of Zuid-Holland enlarged (status 2024)



Geometrical approach for the definition of the production license area in the Netherlands, using a rectangular area with a length of twice the well spacing and a width equal to the distance between the wells.

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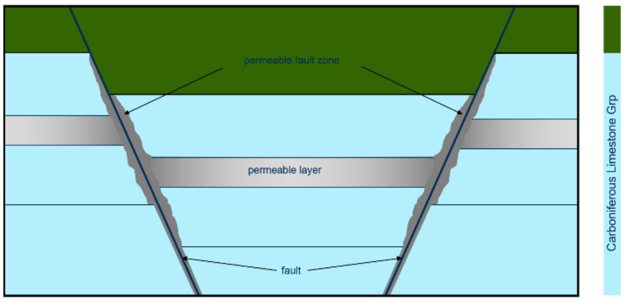
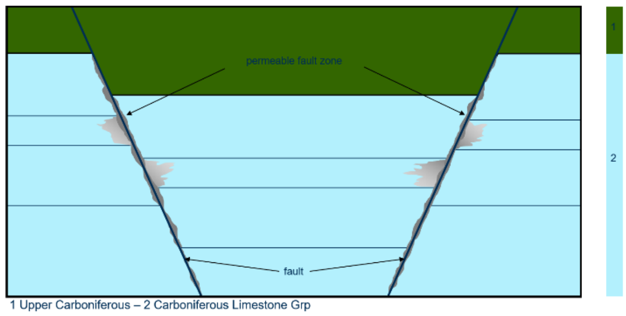
How are permeability and porosity distributed in the Lower Carboniferous reservoir?

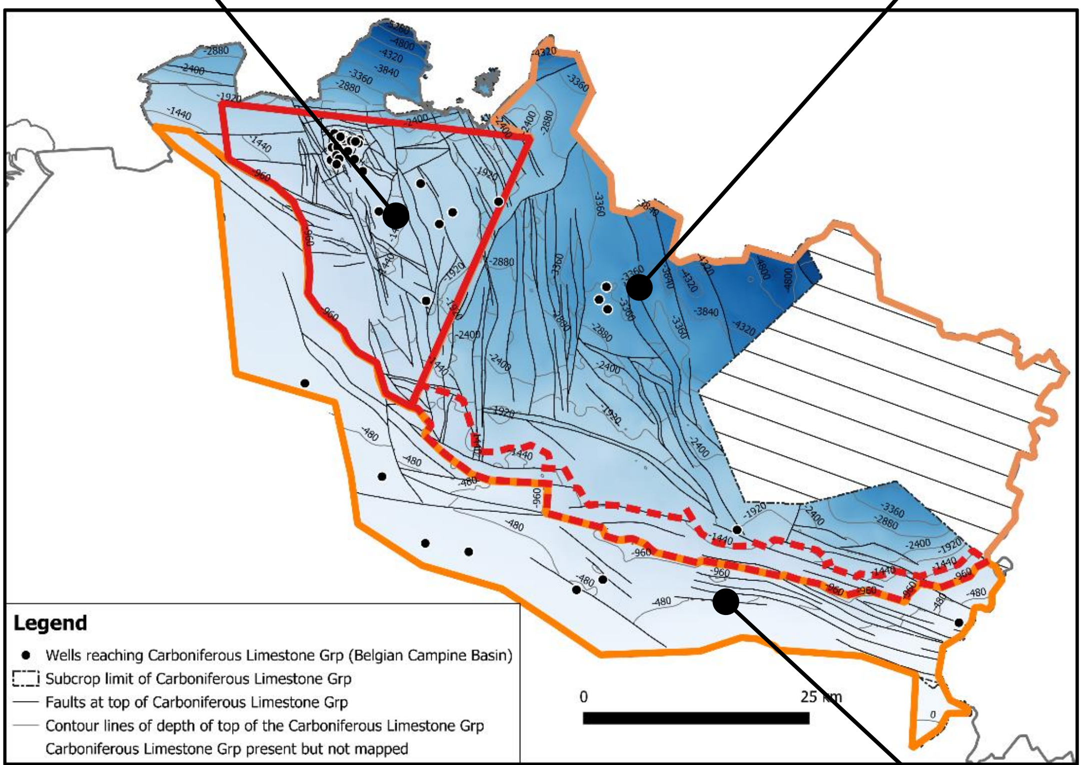
Typical reservoir concepts or settings were defined for this study. Concept 1 covers the northwest of the Campine Basin, where the reservoir is made up of permeable layers and fault zones. Permeability declines with increasing distance from the faults. A comparable setting is defined in the south, but with the addition of a permeable layer at the top (concept 2). Permeability in the eastern part of the basin is confined to the fault zones and to narrow zones in specific layers, close to those faults (concept 3).

Concept 1



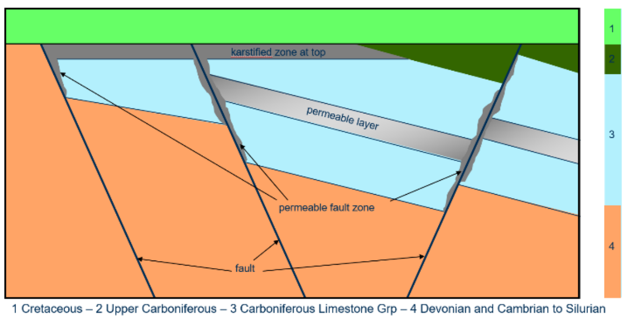
Concept 3





Overview of reservoir settings and concepts for the Carboniferous Limestone Group and their occurrence in the Campine Basin.

Concept 2



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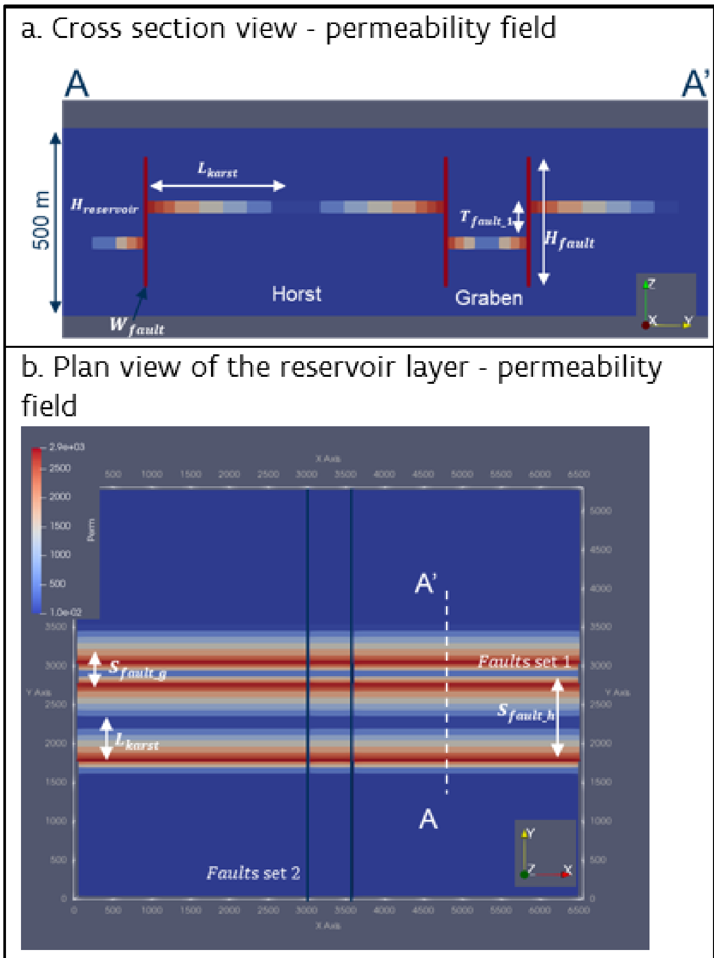
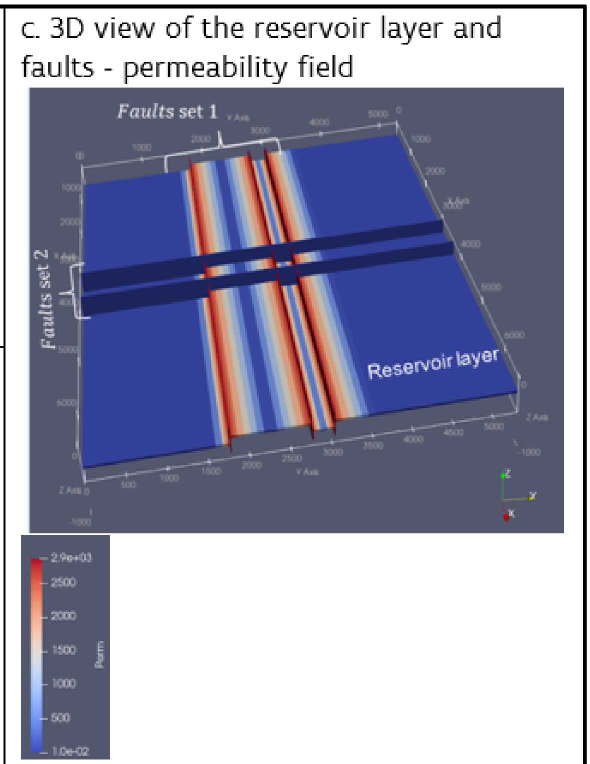
How does the reservoir model look like?

The reservoir concepts have been implemented into 3D reservoir models, with multiple layers and faults. The various parallel faults of set 1 result in a series of elevated areas (horsts) and downthrown areas (grabens).





Geometrical parameters

T_{fault_1}	Fault throw of set of faults 1
$H_{reservoir}$	Reservoir layer thickness
H_{fault}	Height or vertical extension of faults from sets 1 and 2
W_{fault}	Fault width of set of faults number 1 and 2
S_{fault_g}	Fault spacing of fault set 1 in the graben
L_{karst}	Karst extension of set of faults 1
S_{fault_h}	Fault spacing of fault set 1 in the horst

The reservoir model representation for concept 1, with cross-section view (top left), map view (bottom left) and 3D view (top right), with visualization of the permeability field (red = high values, blue = low values).

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What are the relevant reservoir properties?

There are a lot of properties required to completely characterize a reservoir. They involve petrophysical parameters such as the porosity and permeability of reservoir layers, of the matrix, of the fault zones, but also the thermal properties of the various rocks.

In addition there are geometrical parameters defining the various layers and zones of the reservoir, all of which can have different petrophysical properties, The thickness of the reservoir layers, height, width and spacing of the faults as well as the fault throw, and the extension of the karst layer or zone of enhanced permeability away from the faults belong to this category.

A selection of parameters was made for evaluation in the sensitivity analysis. For concept 2 this also includes properties of the top permeable layer, which is unique for this concept. Fault throw is not defined for concept 2 as it is already fixed by the vertical distance between the top and bottom layer.

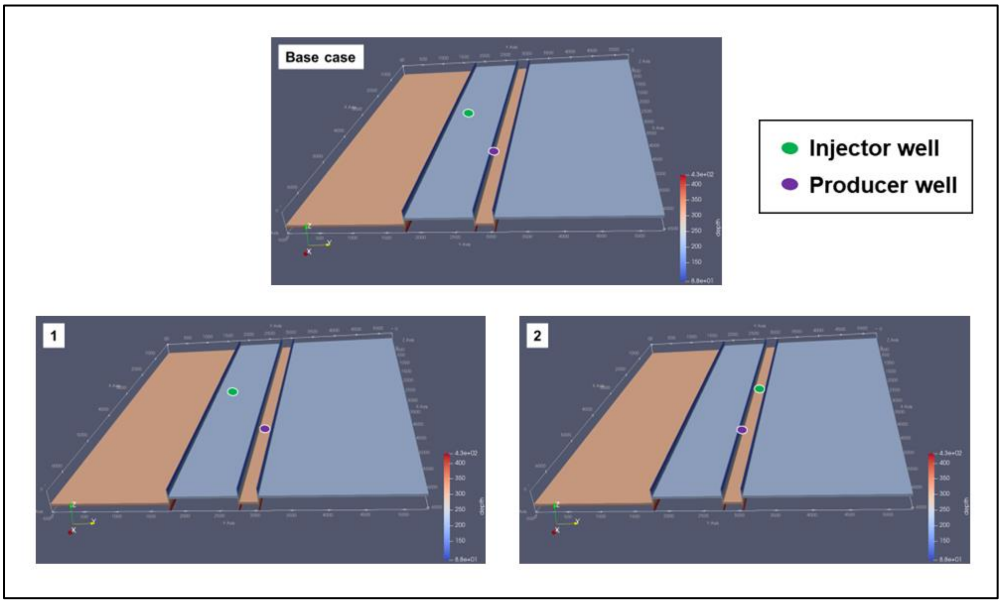
Concept 1	Concept 2	Concept 3
Porosity and permeability fault set 1	Porosity and permeability fault set 1	Porosity and permeability fault set 1
	Top & bottom layer separation	
Fault throw of fault set 1		Fault throw of fault set 1
Fault spacing for set 1 at graben	Fault spacing for set 1 at graben	Fault spacing for set 1 at graben
Maximum karst porosity -permeability	Maximum karst porosity (permeability)	Maximum porosity -permeability in the enhanced reservoir region
Minimum reservoir permeability	Minimum reservoir permeability	Minimum reservoir permeability
Karst extension from fault horst	Karst extension from fault horst [m]	Enhanced reservoir region extension from fault horst
Permeability anisotropy ky/kx	Permeability anisotropy ky/kx	Permeability anisotropy ky/kx
Porosity and permeability fault set 2	Porosity and permeability fault set 2	Porosity and permeability fault set 2
Well configuration	Well configuration	Well configuration
Reservoir layer thickness	Reservoir layer thickness	Reservoir layer thickness
	Permeability of top layer	
Fault height	Fault height	Fault height

Where are the wells positioned?

In addition to the petrophysical and geometrical parameters, the well configuration also plays a role. The well configuration defines the position of the wells with respect to geological structures and reservoir zones, and relative to each other. Three well configurations have been defined for each reservoir concept (including a base case used as reference throughout the study).

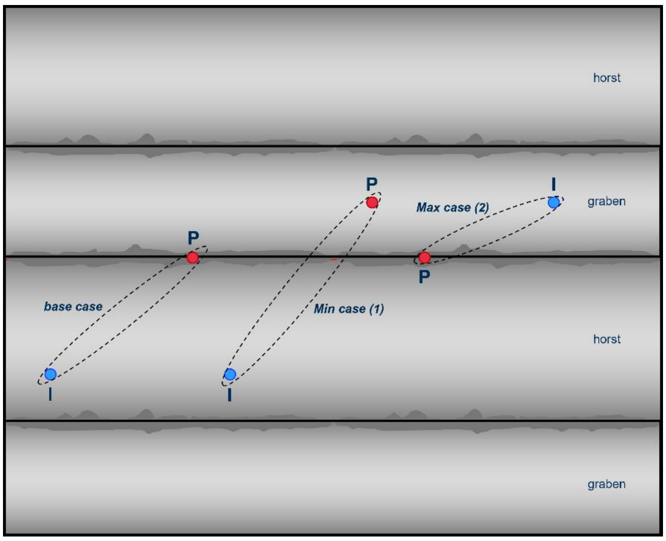
For concept 1 a base case is defined with the production well in the graben fault zone and the injection well in the horst, halfway between the middle and the next fault. This setup maximizes productivity and temperature for the production well, while positioning the injection well away from the faults and minimizing depth.

A first alternative situation has the production well in the center of the graben and an injection well with a position similar to the base case. This is comparable to the base case, but leaves more room between the production well and the fault(s).



3D view (left) and map view (below) of well configurations as defined for concept 1.

A second alternative setup combines a production well in the graben fault zone with an injection well in the center of the graben. Here the injection well is also placed away from the faults but in the deeper graben block.



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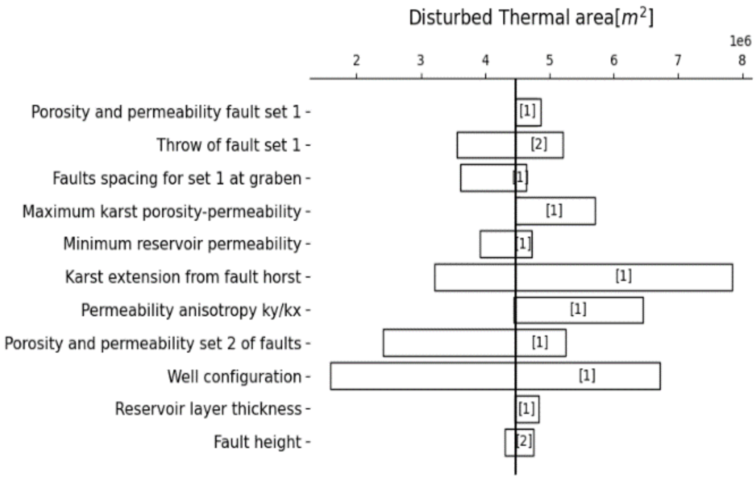
How far can the thermal impact around a doublet reach and what properties have most influence?

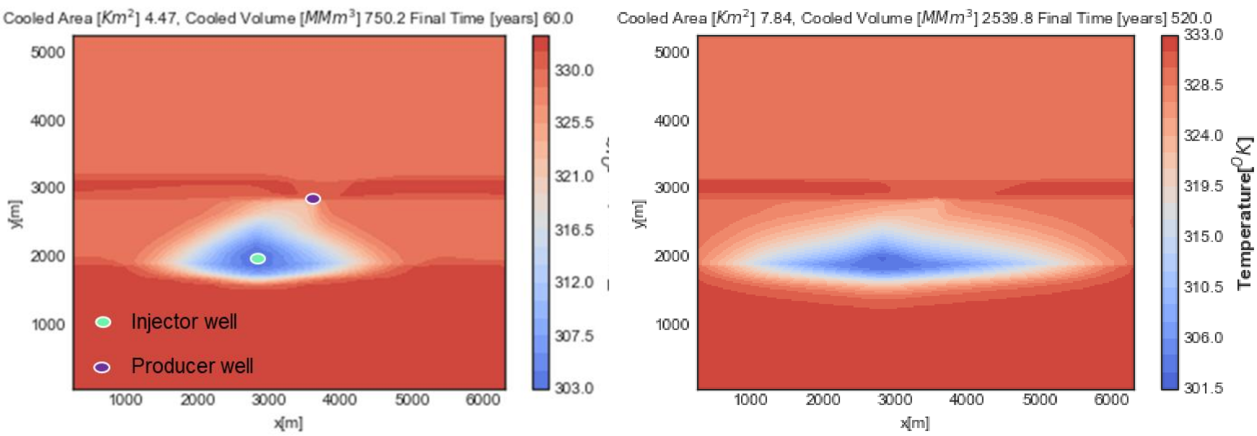
For the chosen settings in the base case in the base case concept 1, a thermally influenced (cooled; 1°C) volume area of almost 4,5 km² is simulated at the time of thermal breakthrough, for a production rate of 200 m³/h.

The cooled area may be smaller than 2 km² for another well configuration, or almost 8 km² in case karst permeability does not extend that far from the main faults.

Overall, karst extension from the fault, porosity and permeability of the secondary fault set, permeability anisotropy ky/kx, karst porosity and permeability, and reservoir layer thickness are the parameters with the highest impact on the extent of the cooled volume area.



Size of the cooled area (left) when choosing an extreme value for a single parameter, compared to the base case (only average values).
Final temperature distribution for the base case scenario (bottom left) and a scenario with minimum extension of the karst layer (bottom right). In the latter case, there is less connectivity between wells. Hence, cold water spreads further parallel to the faults, resulting in a larger temperature affected area.



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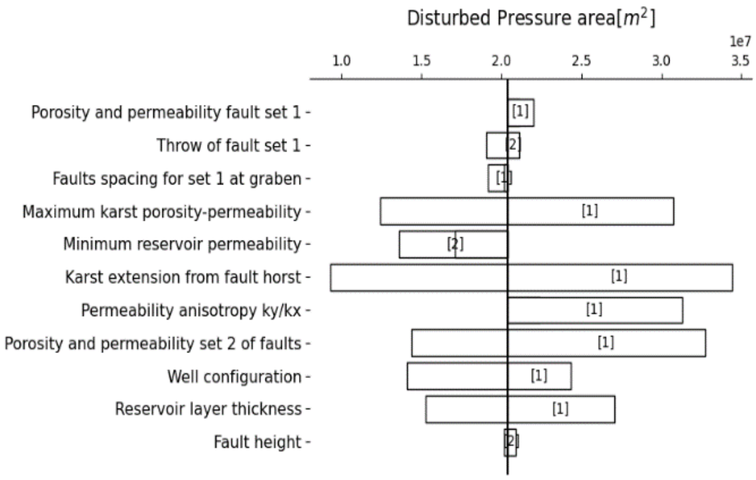
How far can the hydraulic impact around a doublet reach and what properties have most influence?

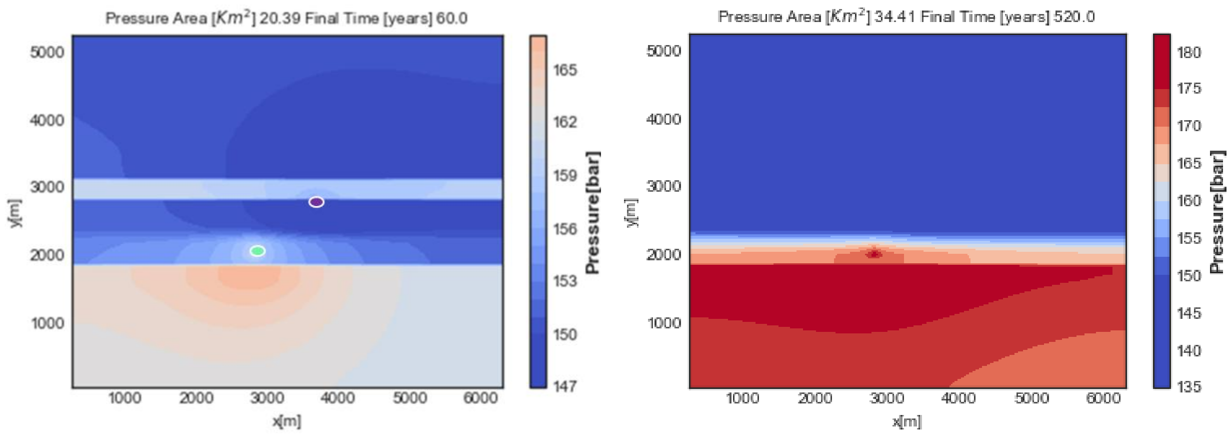
For the chosen settings in the base case in the base case concept 1, a hydraulically affected (1 bar) volume area of more than 20 km² in horizontal extent at the time of thermal breakthrough, for a production rate of 200 m³/h. Changing parameters results in a size varying between 10 and 35 km².

The extent of the hydraulically impacted area is an order of magnitude larger compared to the thermally affected area.

Overall, karst extension from the fault, porosity and permeability of the secondary fault set, permeability anisotropy ky/kx, and karst porosity and permeability are the parameters with the highest impact.



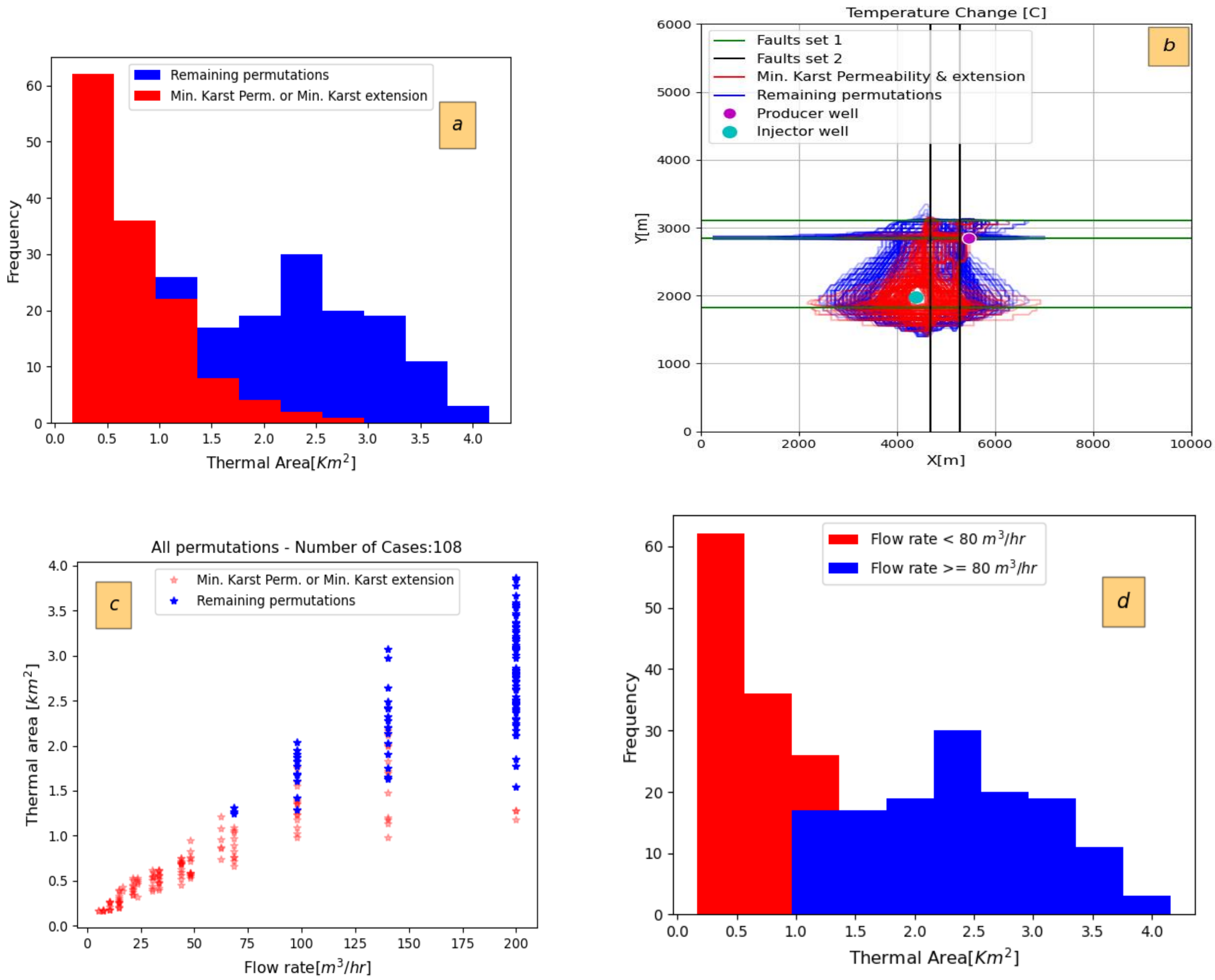
Size of the hydraulically impacted area (left) when choosing an extreme value for a single parameter, compared to the base case (average values only).
Final pressure distribution for the base case scenario (bottom left) and a scenario with minimum extension of the karst layer (bottom right). In the latter case, there is less connectivity between wells, resulting in larger pressure changes and a larger pressure affected area.



How far does the thermal impact reach if extreme parameter values are combined for concept 1?

The thermally influenced volume area varies even more in size when extreme parameter values are combined (for those having highest impact). Starting with a production rate of 200 m³/h, 35 years of exploitation would result in an area up to 4 km² (for concept 1). These results reflect the situation after 35 years of production, which is mostly shorter than the simulations in the sensitivity analysis.

The results of simulations of 243 combinations of parameter values reveal a bimodal distribution, mainly determined by the karst permeability and extension. Low values lead to reduced flow rate (and hence limited heat extraction) and therefore a smaller thermally affected area (0,1 – 1 km²). In contrast, high values allow high flow rates and hence more heat extraction, resulting in a larger area (2 – 3,7 km²).



Distribution of the size of the cooled area (a) and the extent of the 1°C area (b) for the various simulations. Cases with minimum values for karst permeability and extension are shown in red. Minimum karst permeability and minimum karst extension often lead to reduced flow rate (c), as there is less connectivity and permeability between the wells. Lower flow rate results in a smaller thermal area (c and d).

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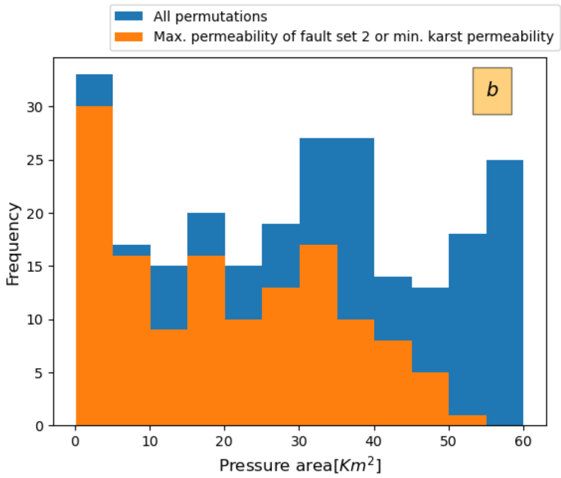
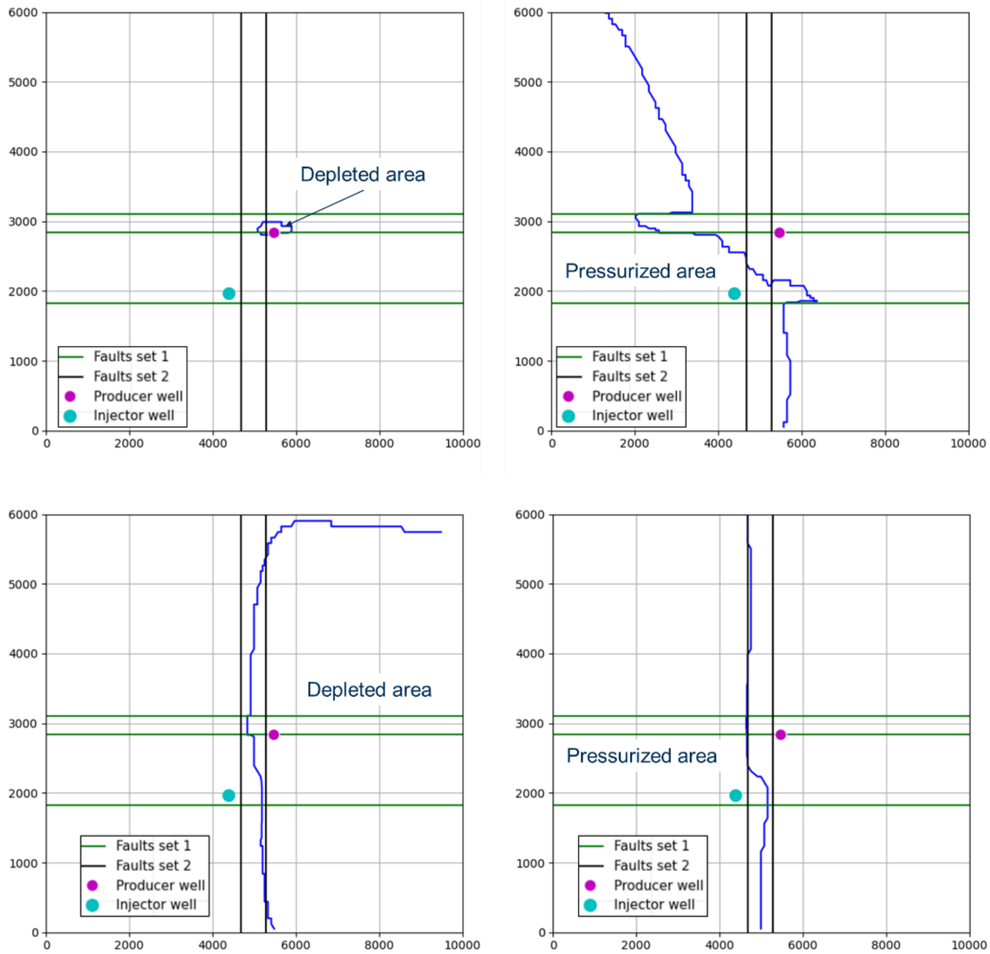
How far does the hydraulic impact reach if extreme parameter values are combined for concept 1?

Starting with a production rate of 200 m³/h, the hydraulically impacted area for concept 1 would vary in size up to 60 km² after 35 years of exploitation. Karst permeability and permeability of the secondary fault set stand out as the most relevant parameters.



Distribution of the size of the hydraulically impacted area (left), with cases with maximum permeability in the secondary faults or minimum karst permeability shown in orange.



Impact of permeability in the secondary faults and karst permeability on the extent of the areas with elevated pressure (pressurized, right) and lowered pressure (depleted, left).

The top images show the extent in case of high permeability in the secondary faults and low karst permeability (providing better connectivity in the Y direction).

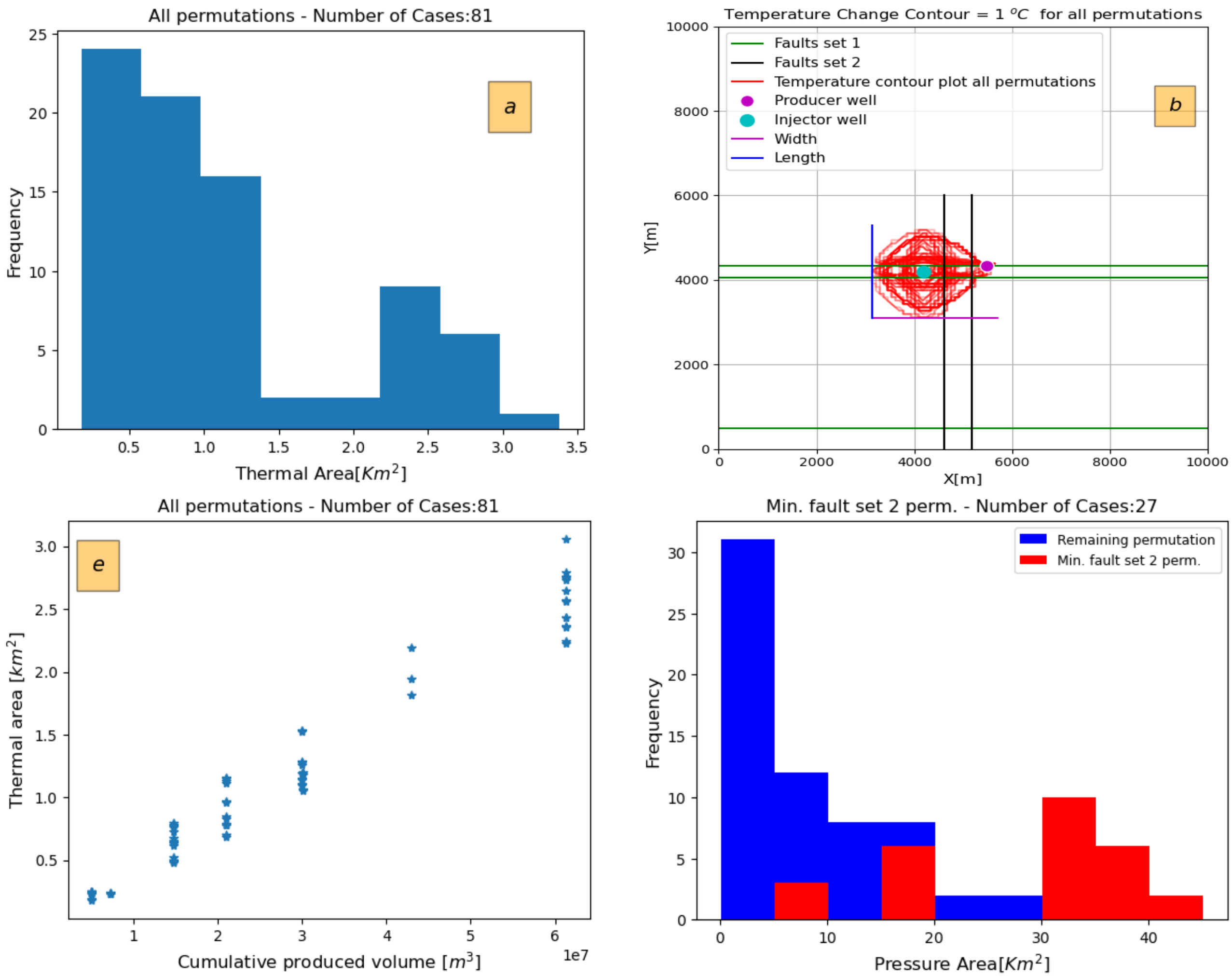
The lower images show the extent when secondary faults have low permeability and karst permeability is high.

How far does the impact reach if extreme parameter values are combined for concept 2?

For the reservoir setting in the southern part of the Campine Basin (concept 2), the combinations of parameter values would result in a thermally influenced volume smaller than 3.5 km² after 35 year of production and for an initial production rate of 200 m³/h.

Boundary conditions, permeability anisotropy, low permeability in the top layer and/or secondary faults often lead to a reduced flow rate (and total produced volume). These conditions result in a smaller cooled area (< 2 km²)

The pressure area varies up to 45 km². The area is larger in case of low permeability of the secondary faults.



Distribution (top left) and map view (top right) of the extent of the thermal area for concept 2. Flow rate (and cumulative produced volume) is reduced in many cases, resulting in a smaller cooled area (bottom left).

Pressure area (bottom right) varies up to 45 km², with larger areas resulting from low permeability in the secondary faults.

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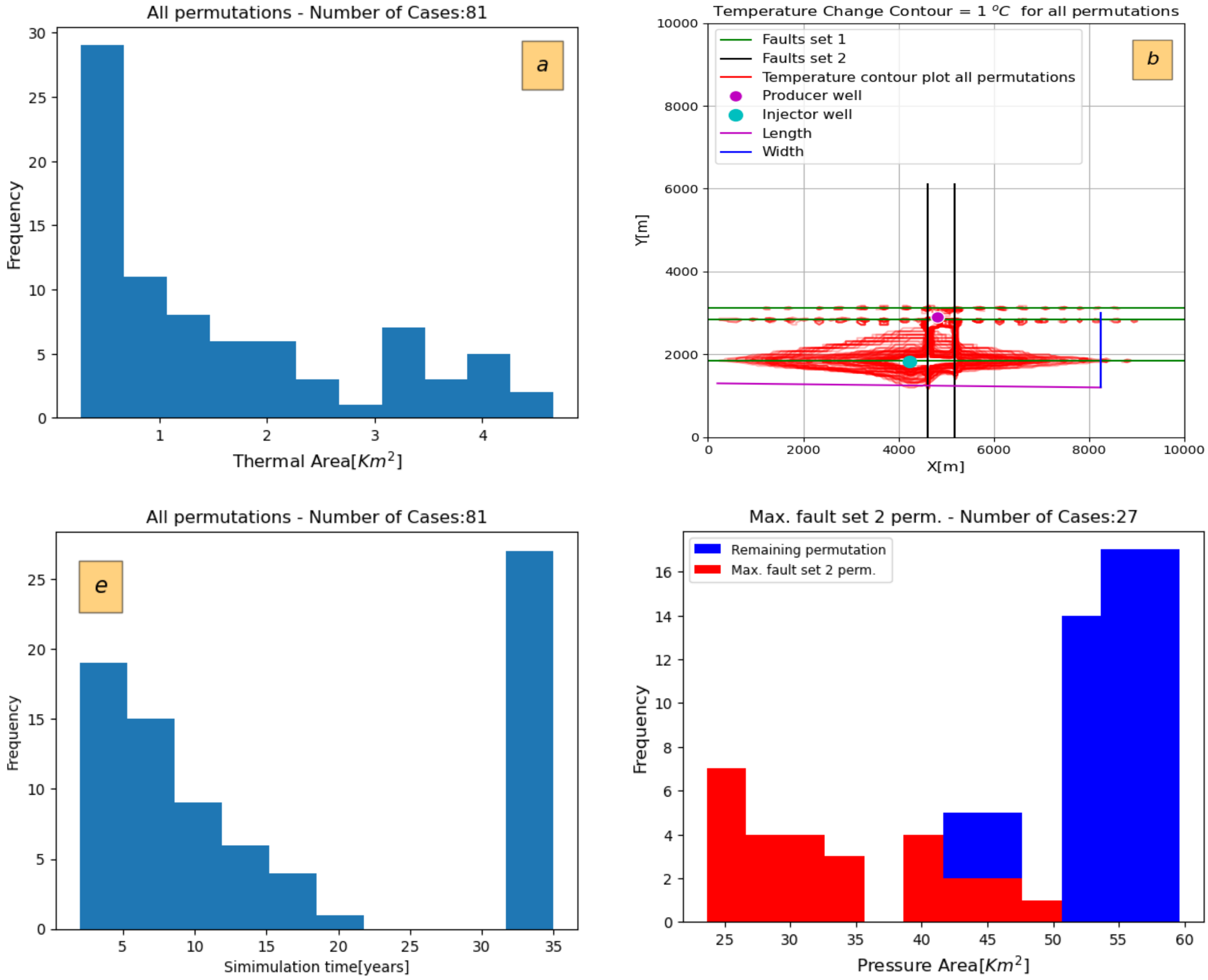
How far does the impact reach if extreme parameter values are combined for concept 3?

For concept 3 in the eastern part of the Campine Basin, the combinations of parameter values would result in a cooled area smaller than 5 km² after 35 year of production and for an initial production rate of 200 m³/h.

The thermal area remains rather small in a lot of cases, due to the permeability in the main faults, low matrix permeability and limited extension of the enhanced permeability zones. In addition, these conditions often result in early thermal breakthrough and therefore shorter simulation times.

Pressure areas range in size between 25 and 60 km². High permeability in the secondary faults lead to a smaller area as connectivity between the wells is improved, resulting in early thermal breakthrough.



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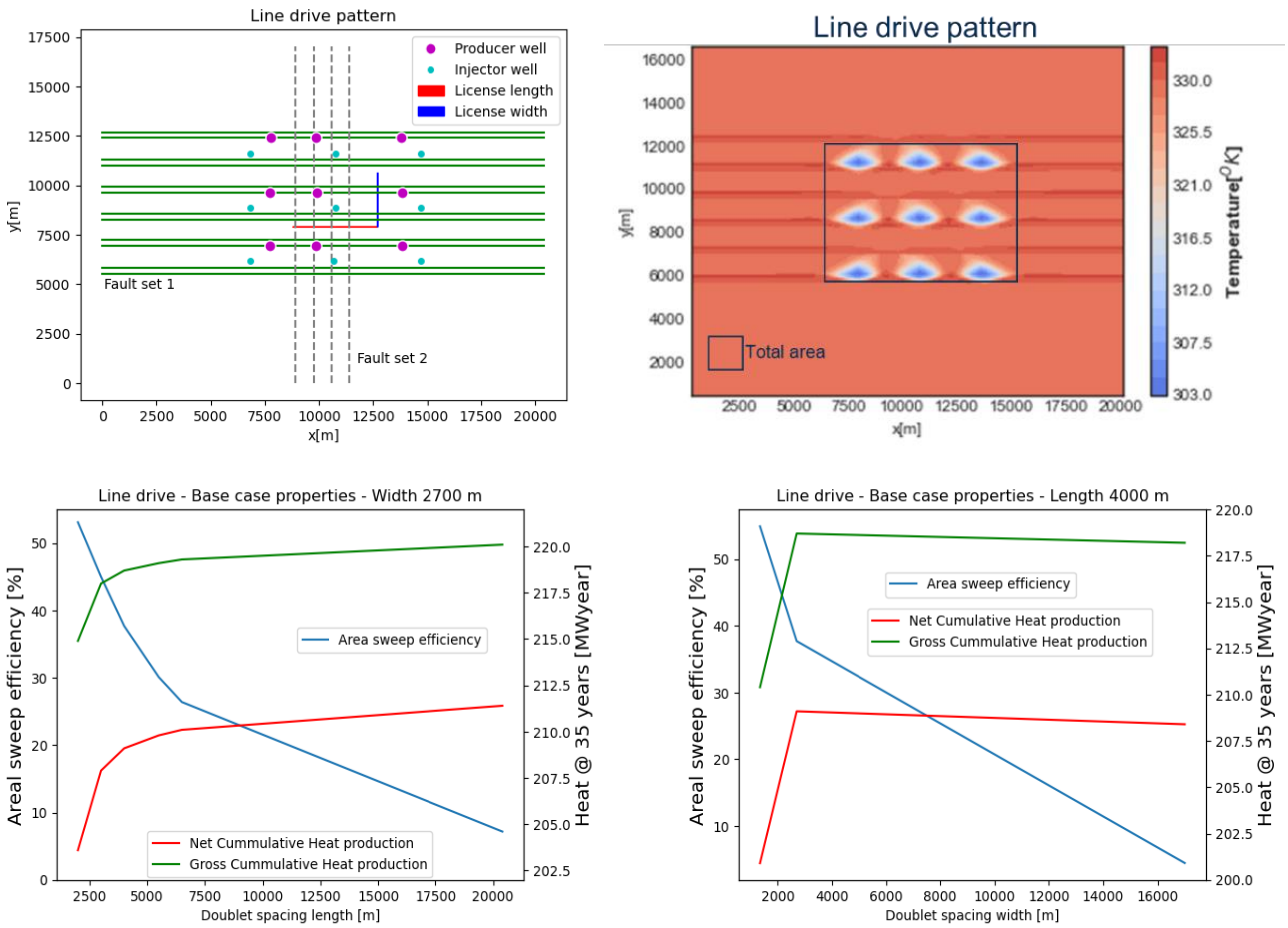
Distribution (top left) and map view (top right) of the extent of the thermal area for concept 3. Early thermal breakthrough occurs in the majority of cases (bottom left).
Distribution of the size of the hydraulically affected area (bottom right), with cases having high permeability in the secondary faults highlighted in red.

Can we make more efficient use of the subsurface by positioning doublets closer together (line drive)?

Temperature and pressure impact for a geothermal field with multiple doublets were analyzed for different emplacement patterns in concept 1. Decreasing the spacing between doublets and positioning them closer together either in length or width improves the efficiency of heat extraction across the entire geothermal field (areal sweep efficiency). However, at the same time the amount of heat extracted per individual doublet declines.

Following a line-drive pattern and in case of good hydraulic communication, a spacing between neighboring doublets parallel to the main faults (length) of 4000 m and a spacing perpendicular to the main faults (width) of 2500 m are required. If transmissivity is low, spacing needs to be increased (> 5000 m length).

Large spacing decreases field efficiency (larger areas remain at initial temperature), but leaves the possibility of future exploitation of these intermediate areas.



Position of injection and production wells and of the alignment of doublets (line-drive pattern, top left).
Temperature impact after 35 year in the base case scenario for the line-drive pattern and a length spacing of 2000 m (top right).
Areal sweep efficiency of the field (total area) and heat extraction per doublet in case of multiple doublets in a line-drive pattern, for varying length spacing (lower left) and varying width spacing (lower right).

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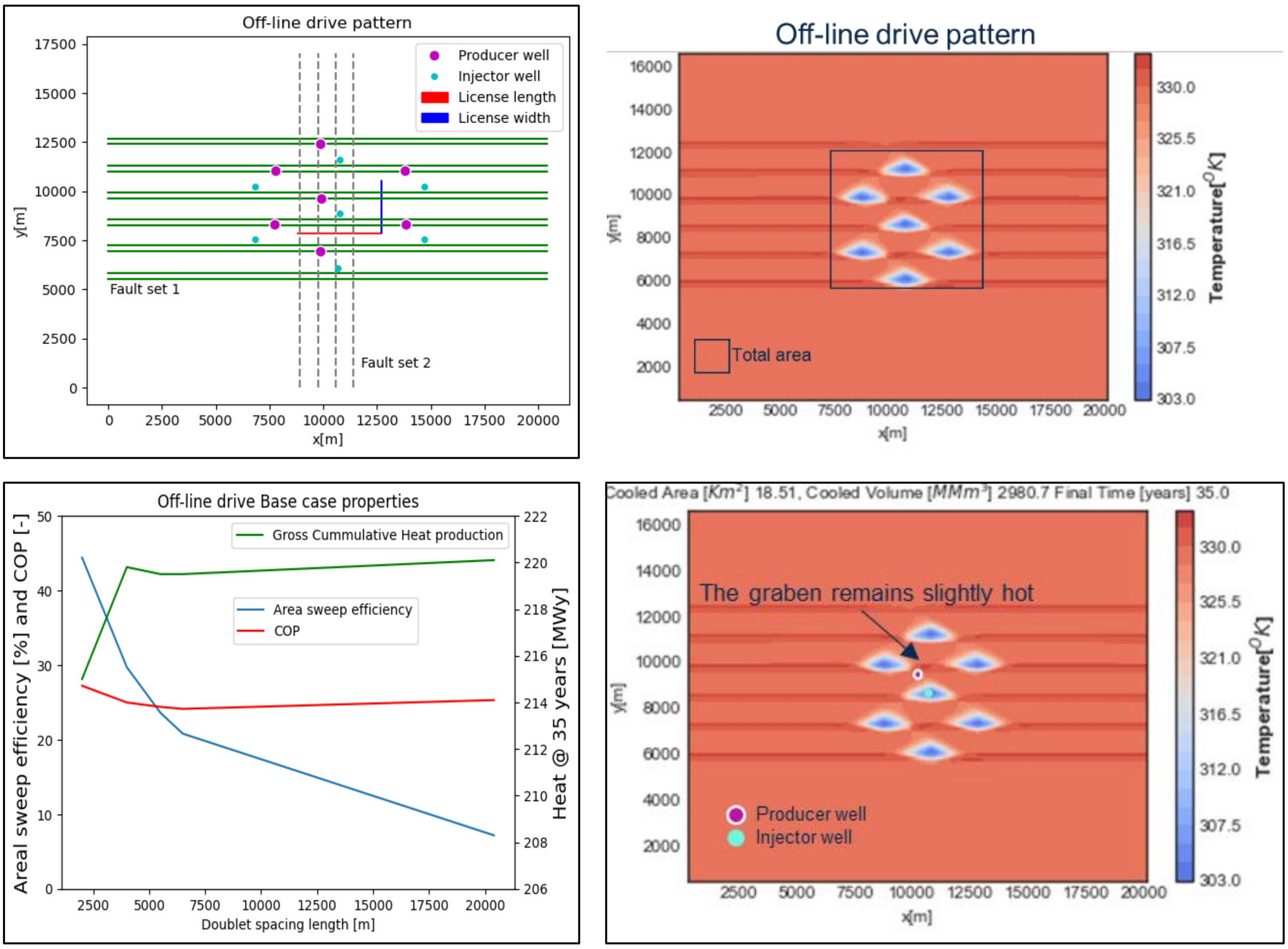
Can we make more efficient use of the subsurface by positioning doublets closer together (off-line drive)?

The off-line drive pattern offers an alternative for the emplacement of doublets in a geothermal field. The same general conclusions hold: when doublet spacing length and width are reduced, areal sweep efficiency improves while cumulative heat production per doublet declines.

In the off-line drive pattern, heat production is not as strongly dependent on doublet spacing length as in the line drive pattern. In addition, more heat can be extracted relative to the required pump energy (COP). This is especially the case at short spacing because of the positive interference between adjacent injection and production wells from different doublets.

Overall, the areal sweep efficiency is higher in the line drive pattern, but the off-line drive pattern is less prone to cause negative thermal and pressure interference.



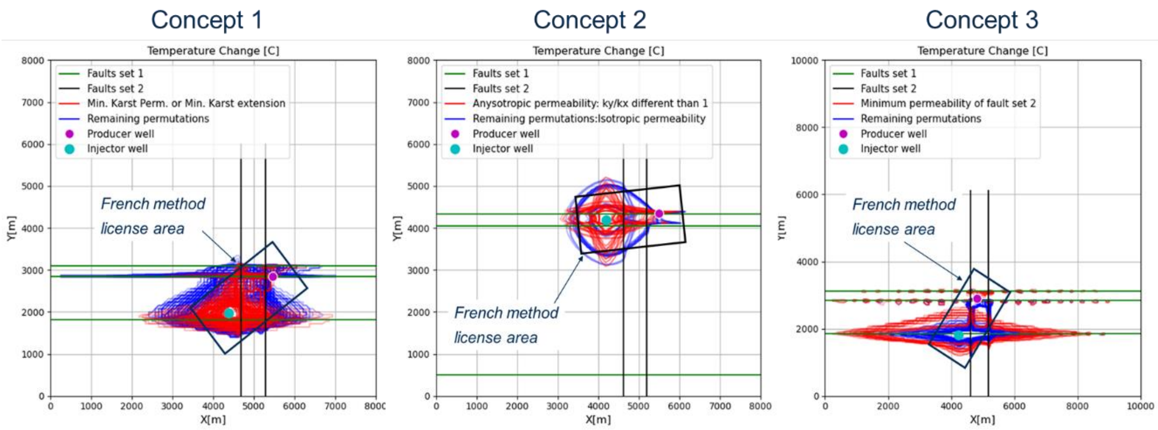
Position of injection and production wells and of the alignment of doublets (off-line-drive pattern, top left). The top right image show the temperature impact after 35 year in the base case scenario for the off-line drive pattern and a length spacing of 2000 m.
Areal sweep efficiency of the field (total area) and heat extraction per doublet in case of multiple doublets in an off-line-drive pattern, for varying length spacing (lower left). The lower right shows the situation where the area around the central production well remains at higher temperature because of positive interference..

Can a geometrical approach be adopted for to define the lateral boundaries of the license volume?

An entirely geometrical approach is used to define license boundaries in France and the Netherlands. It is based on the spacing between the injection and production well. This approach is adequate for homogeneous reservoirs.

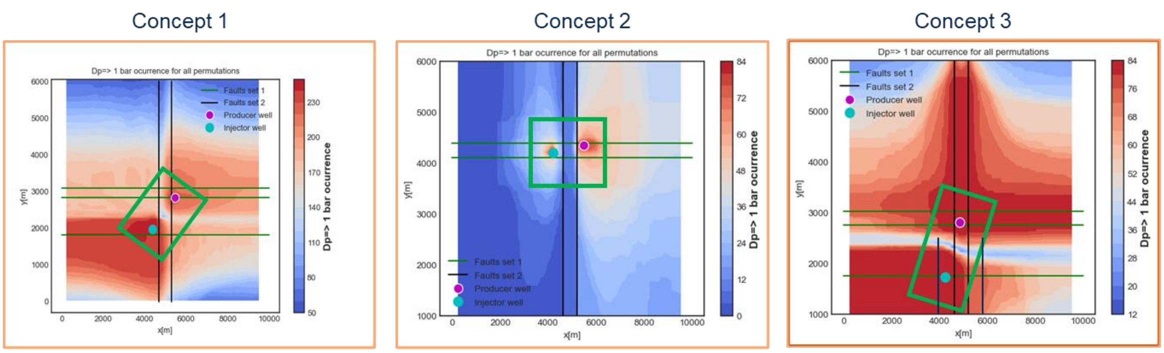
However, the Carboniferous Limestone Group in the Belgian Campine Basin present heterogeneous reservoir characteristics, with permeability related to karst and/or fault zones. Because of these heterogeneities, a purely geometrical approach is not adequate to draw license boundaries.

This geometrical approach works better for concept 2, because that includes a homogeneous upper reservoir layer.



Example of a license volume defined according to the French method (based on well spacing) applied to the results of the temperature affected area (top) for the analyzed parameter combinations for concept 1(left), 2 (middle), and 3 (right).

The results of the pressure affected area is shown below.

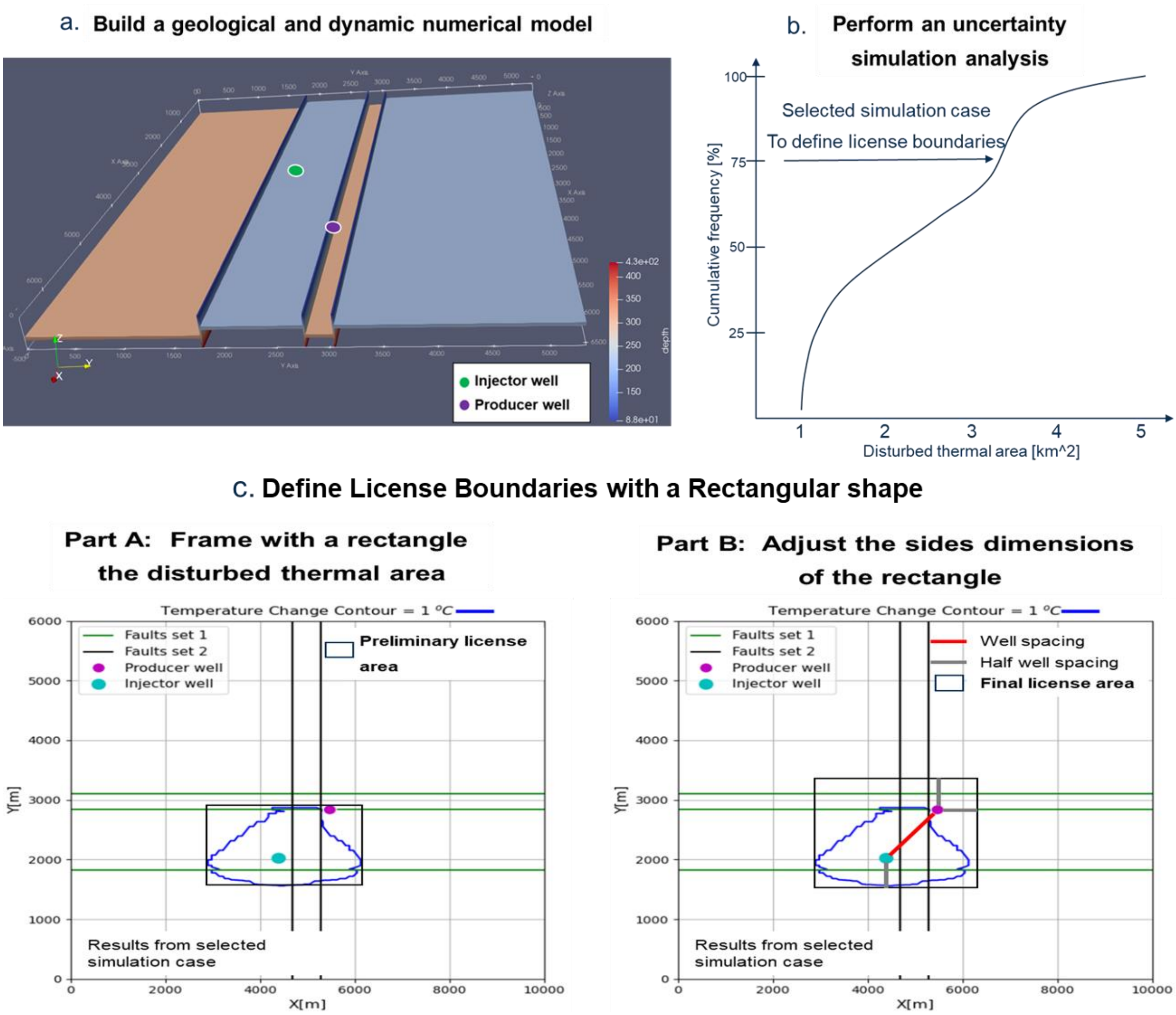


A possible approach to define the lateral boundaries of the license volume

Defining the lateral boundaries of the license volume based on thermal impact allows to improve the efficiency of heat extraction across the geothermal field. Mitigating thermal interference could ensure that each project can deliver its expected heat output.

Heterogeneous reservoirs, such as the Carboniferous Limestone Group in the Campine Basin, demand a tailored approach. A general procedure is proposed to define the area and boundaries of the production license, for each of the reservoir concepts. This can be done by combining a geometrical approach with the results of reservoir simulations.

First, a rectangle could be drawn around a conservative estimate for the cooled area. The rectangle could be adjusted where needed to make sure the minimum distance between the wells and the boundaries is at least half the well spacing.



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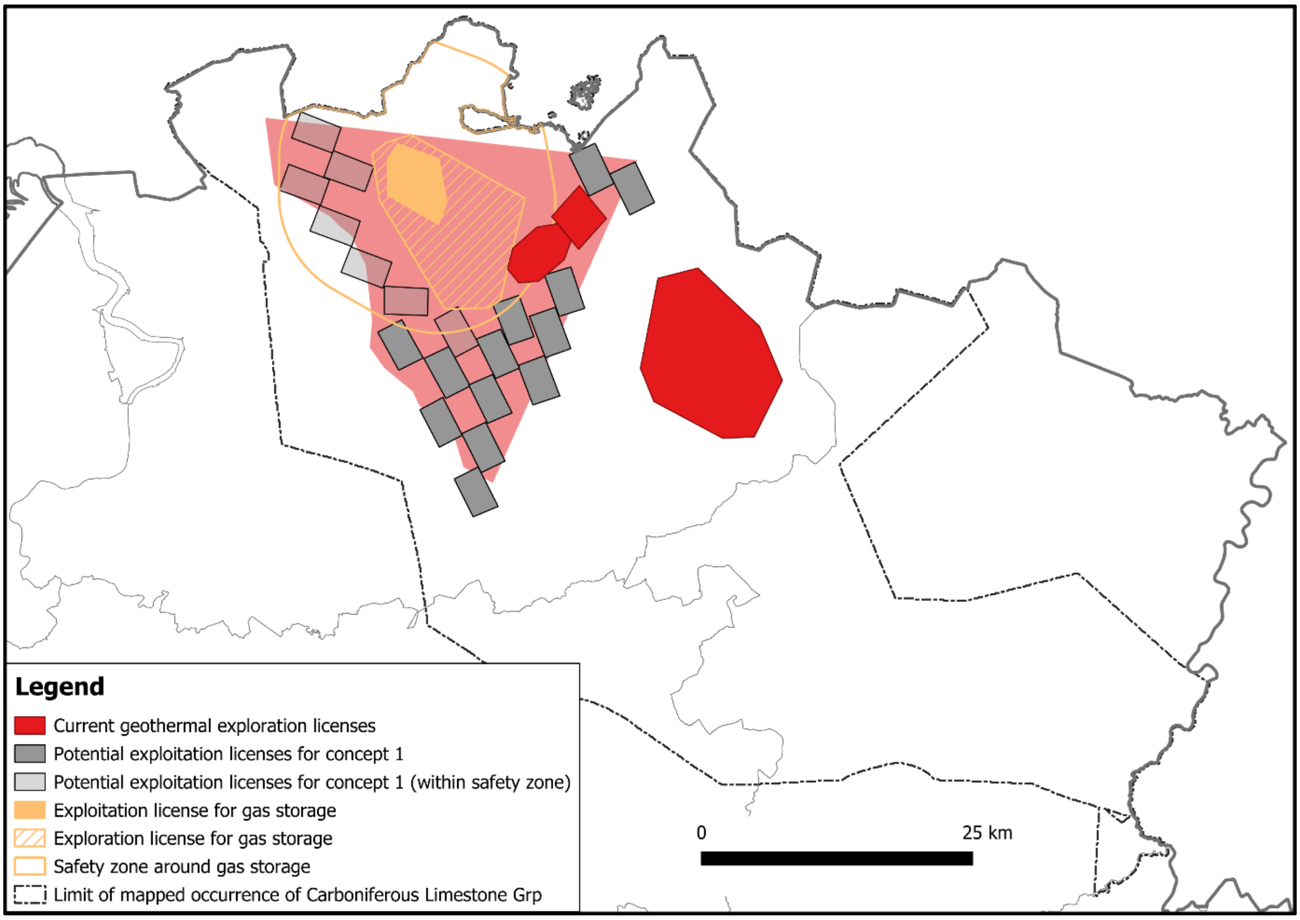
Procedure for definition of the lateral boundaries of a geothermal production license (example for concept 1).

How could a geothermal field be organized?

Licenses can be defined in the concept 1 area following the proposed procedure, considering the results of the simulations for concept 1.

For the concept 1 area in the western part of the Campine Basin, licenses can be positioned across the field taking into account the spacing between doublets as recommended from the multi-doublet analyses. Following the approach outlined in this study, there would be room for 15 to maximum 20 licenses. Unused areas in between could be granted in a second generation of licenses.

Current exploration licenses were granted conservatively large in order to account for the high initial uncertainties and in line with the proposed work programs. They will be redefined for the exploitation phase based on the exploration results.



Example of production license positioning and spacing for doublets in the Carboniferous Limestone Group across the entire geothermal field in the western part of the Campine Basin (concept 1 area), according to the approach outlined in the current study. The spacing parallel to the main faults is 4000 m.

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Can we monitor pressure and temperature changes in the subsurface, and how should monitoring be done?

Reservoir monitoring plays a fundamental role in optimization and safety of exploitation of geothermal resources.

Monitoring can provide additional information giving insights into multiple questions:
Migration of the cold water front
Hydraulic interaction between projects
Occurrence of mechanical deformation
Occurrence of induced seismicity

Deriving pressure and temperature fields in the deep subsurface remains challenging without the use of monitoring wells. The pressure field can be measured with a relatively low number of wells, as pressure changes are communicated over long distances. The temperature field is the most difficult to map, as local measurements cannot easily be extrapolated laterally.

Field to be monitored	What information can be retrieved?	Monitoring techniques
Pressure	• Interaction between licenses. • Depleted areas and over-pressurized areas detection. Important for understanding the level of geological risks. • Validation of numerical models used for reservoir management.	Observer wells dedicated to monitoring. Pressure build-up and fall-off tests in producer and injector wells.
Temperature	• Actual cold flooded area that would indicate whether the license area size is sufficient for containing. • Validation of numerical models use for reservoir management. (Ayling & Rose, 2013)	Observer wells dedicated to monitoring Resistivity-sensitive surveys (ERT, MT and CSEM)

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Where to find more information?

This brochure is based on the following report:

Broothaers, M., Hernandez-Acevedo, E., Pogacnik, J., Rombaut, B. (2025). Prospective dynamic modelling for an optimal definition of volume areas in the deep subsurface of Flanders. Studie uitgevoerd in opdracht van Vlaams Planbureau voor Omgeving (Departement Omgeving).

The full report of this study is available at FRIS (https://researchportal.be/nl)

Decreet Diepe Ondergrond: https://navigator.emis.vito.be/detail?woId=40089&woLang=nl

Besluit Diepe Ondergrond:
https://navigator.emis.vito.be/detail?woId=40324&woLang=nl

More information on the deep subsurface of Flanders is available at www.dov.vlaanderen.be

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