Prospective dynamic modelling for an optimal definition of volume areas in the deep subsurface of Flanders

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Vlaanderen moet de komende jaren grote stappen vooruit zetten om het energiesysteem koolstofarmer en duurzamer te maken. Een deel van de energieoplossingen van de toekomst kan gevonden worden in bronnen en opslagcapaciteit in eigen ondergrond. Het doel van deze studie is om via dynamische modellering van verschillende concepten en scenario's een scherper inzicht te verwerven in de te verwachten druk- en temperatuurinvloeden rond toepassingen in de Vlaamse diepe ondergrond (i.e. dieper dan -500m TAW) om zo de nodige 3D-volumegebieden voor opsporing en winning efficiënter te kunnen afbakenen.

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PARTNERS

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SUMMARY

Introduction & Objectives

One of the ways to achieve a more sustainable energy supply and system is the use of geothermal heat from the deep subsurface. Standard deep geothermal applications operate a doublet system, with one well for production of hot water and another well for injection of the water after the heat has been extracted. These systems target subsurface hydrothermal reservoirs, which in Flanders are almost exclusively present in the Campine Basin. 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. With additional future developments expected in the same subsurface reservoirs, 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.

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 volume areas.

Approach abroad

Although dynamic modelling is at the core of this study, the results of the reservoir modelling should be complemented by insights from other countries or regions. An examination of how license boundaries are established elsewhere, and based on which parameters, puts the current results into perspective. Three regions have been investigated: the Paris Basin, Zuid-Holland, and Bavaria.

The subsurface of the Paris Basin presents the longest history of exploitation of deep geothermal heat in the neighboring countries. The area includes over 50 deep geothermal projects spread over an area of over 500 km^2, targeting Middle Jurassic and Lower Cretaceous aquifers. According to the *Code Minier*, licensing distinguishes between an exploration and a production phase. The exploitation permit is defined as a volume, with the lateral extent delineated in a purely geometrical way, considering the spacing between the production and injection wells. Projects should not have a hydraulic impact exceeding 1 bar on another project, with the thermal impact limited to 1°C. However, these values are not defined by law.

The Netherlands present a case with 14 active projects in Zuid-Holland, in the area between Rotterdam and The Hague (an area less than 300 km^2). These projects target Triassic to Cretaceous reservoirs and operate in an area with active oil and gas extraction from the same layers. The definition of license boundaries to avoid negative interference has already been studied in the Netherlands. In the current Dutch system for geothermal licenses, the boundaries of a follow-up license for production are defined in a geometrical way, based on the approach used in France (the "French method"), but in a slightly modified way. In the Netherlands, the license boundary is a rectangle encompassing the circles around the wells (each having half the well spacing as radius). The assumption is that when the license area is defined in this way, a temperature decrease of 1°C will occur at the boundary simultaneously with a 1°C temperature decline in the production well. Hence, the license boundary is related to the project lifetime (thermal breakthrough). Licenses are also limited in the vertical dimension and therefore defined as a volume. TNO is currently working on a possible modification and improvement of the current way of defining the limits of the permit.

Finally, the Munich area in Bavaria presents another region where multiple geothermal doublets are concentrated (18 projects over 850 km^2), all targeting the Malm limestone. The *Federal Mining Act* defines exploration and production licenses, with more detailed guidelines published at state level. The extent of the exploration license is related to the spatial scope of the proposed work program. In contrast to France and the Netherlands, the extent of the production permit is defined based on the results of reservoir simulations. The guidelines mention a maximum pressure drawdown at the license boundary of 1 bar, and a maximum temperature decrease of 1°C.

Reservoir concepts

Static models form the basis on which (dynamic) reservoir simulations can be run. The static models incorporate a geological or structural model and are populated with reservoir properties. Apart from the parameter values used, the model also outlines how these reservoir characteristics are spatially distributed: their geometry and their relationship to the geology. Thereby capturing the main reservoir's heterogeneity, which will ultimately determine the movement of water within the aquifer. These reservoir concepts need to be defined first.
Based on our knowledge of the geology and characteristics of the (Lower) Carboniferous Limestone Group in the Campine Basin, we combined different structural settings with a typical occurrence of porosity and permeability in the reservoir to come up with reservoir concepts. In a first approximation, three concepts can be distinguished:

1. An area in the western part of the Campine Basin, where the Carboniferous Limestone Group is present at relatively shallow depth (roughly between 1000 and 2000 m below TAW), has been exposed before the deposition of Namurian sediments, and those overlying strata are limited in thickness. A single reservoir layer is recognized in addition to permeable fault zones. Porosity and permeability of the reservoir layer decrease away from the faults.
2. An area along the southern margin of the Campine Basin, where the Carboniferous Limestone Group is present at shallow depth (less than 1000 m below TAW) and is present directly below the base Cretaceous unconformity. In addition to the reservoir layer and permeable fault zone from concept 1, another reservoir layer is identified at the top of the sequence, directly below the base-Cretaceous unconformity.
3. A large area in the central and eastern part of the Campine Basin where the Carboniferous Limestone Group is present at greater depth (between 1000 and more than 6000 m below TAW) and is covered by a thick interval of Namurian sediments. Here the reservoir layer presents lower porosity and permeability and is confined to a narrow zone along the fault zones.

Definition of scenarios and parameters

After defining the structural and reservoir concept, relevant parameters need to be identified. In a second step they must be quantified. Petrophysical, thermal and geometrical reservoir characteristics for the 3 reservoir concepts were defined based on the current knowledge of the Carboniferous Limestone Group in Flanders, including the 3D model of the Dinantian in the Campine Basin (G3Dv3), the wells drilled in the Campine basin and the performance of current geothermal projects (Beerse and Mol).
A minimum, base case and maximum value were defined for the various parameters for each of the defined reservoir settings. A selection of parameters was chosen for further sensitivity analysis and reservoir modelling.
In addition to the parameters, three well configurations were defined for each reservoir setting. Each configuration has different positions of the wells with respect to the main reservoir

heterogeneities. The different well configurations were used to evaluate the effect of well locations on the thermally and hydraulically disturbed areas

Sensitivity

The sensitivity study consists in evaluating the uncertainty of the output of the simulation model with respect to a given set of input parameters (rock properties, initial conditions or well conditions). To accomplish this, simulations are run considering the maximum or the minimum values of every selected input parameter while leaving the remaining properties fixed as the base case.

The sensitivity analysis was done via numerical reservoir simulation in DARTS. The simulation consists of a hydro-thermo-monophasic model of liquid water at medium enthalpy flowing through porous media and faults.

The results were visualized and analyzed in terms of:

1. the disturbed temperature area (where the temperature has changed by more than 1°C),
2. the disturbed pressure area (where the pressure has changed more than 1 bar),
3. the thermal breakthrough time (arrival of the cold front leading to a temperature decline of 3.5°C or more),
4. the final flow rate,
5. temperature and pressure maps in the reservoir layers,
6. fluid rates and temperature evolution at injection and production well.

Based on tornado plots of results 1-4, the following parameters were considered to have the biggest impact and to be most relevant for further simulations:

- karst extension, porosity and permeability of the second set of faults, the permeability anisotropy ky/kx, karst porosity and permeability, and reservoir layer thickness (for reservoir concept 1)
- porosity and permeability of the main fault set, the permeability anisotropy ky/kx, the permeability of the top layer, and the porosity and permeability of the second set of faults (for reservoir concept 2)
- the porosity and permeability of the second set of faults, the minimum reservoir permeability, the distance how far the enhanced permeability extends from the faults and the fault height (for reservoir concept 3).

Single-doublet scenarios

After selection of the most relevant parameters from the sensitivity analysis, single-doublet scenarios were simulated with varying parameter values. All possible combinations of parameter values were evaluated, effectively combining medium and/or extreme values.

For concept 1, different values for 5 parameters were applied, leading to 243 combinations. The well configuration with the injector between two faults and the production well in one of the faults in a 'L-shape' was the base case. The results reveal a bimodal distribution, with an increased number of cases with an area the size of 0.1 to 1 km^2, as well as cases with a size ranging from 2 to 3.7 km^2. the parameters impacting the bimodal distribution are mainly the karst extension away from the faults and its permeability. Minimum values for these parameters lead to small thermally influenced areas, as they result in low injectivity around the well (and eventually a reduced flow rate). If only cases with high flow rate are considered (> 80 m^3/h), the average size of the thermally impacted area ranges between 1 and 3.5 km^2. The hydraulically influenced area (where pressure is affected) varies from 1 km^2 to 60 km^2 depending on the combination of reservoir properties. For instance, the area is small (< 30 km^2) when there is good hydraulic communication between the injector and producer well (high karst extension, high permeability of faults) or when injection rate is low due to poor well injectivity. Large hydraulic areas are

expected when there are restrictions (short karst extension and low permeability of the faults located between the wells) between the wells and injection flow rates are high.
Only 4 parameters were selected for concept 2, leading to 81 combinations. These cases again reveal a bimodal distribution for the thermal area, with the permeability anisotropy ky/kx playing a significant role. In general, the size of the thermal area is smaller (0.5-3.4 km^2) compared to concept 1 as injection takes place in two layers. For concept 2, a large number of cases have lower flow rate, even below 80 m^3/h, resulting from a combination of the no-flow boundary at the subcrop limit of the formation, low permeability for fault set 2 and the top layer, and matrix anisotropy. As in concept 1, the area undergoing hydraulic impact varies considerably in size from below 20 km^2 to around 40 km^2.
81 cases were analyzed for concept 3. The results indicate a small area where the temperature is disturbed as the volume of karst and fault zones are limited. Thermal breakthrough occurs early in a lot of cases. Therefore, the time period of the simulations is shorter and the injected volume is lower. The area is usually smaller than 2 km^2 and often elongated along the faults. In some cases, it is above 4 km^2. The pressure area is greater, in most cases more than 40 km^2.

Multiple doublets
As more geothermal projects are planned and commissioned in Flanders, interference between projects may become a challenge. Therefore, a next step was to simulate the impact of and interference between multiple doublets. This task focused on concept 1. There is less data available for concepts 2 and 3, and geological uncertainty is higher. Most data are available for the area of concept 1. There is also already one operational project in this area (in Beerse) and further interest is anticipated (e.g. exploration license in Turnhout). Hence this area is where the issue of interference may arise first.
For this task, a reservoir models include 9 doublets with the same L-shaped well configuration, but with different emplacement patterns. Three cases were evaluated: the base case, a case with high permeability in the fault set 2, and a case with properties according to the P90 case for thermal area for concept 1 (single doublet cases).

In general, when doublet spacing length and width are reduced, areal sweep efficiency improves and cumulative heat production per doublet deteriorates. The line drive pattern has higher sweep efficiency compared to the off-line pattern but is more prone to generate thermal and pressure interference. If there is good hydraulic communication between the wells, a spacing length of approximately 4000 m and a spacing width equal to or higher than 2500 m are required to avoid marked deterioration of cumulative heat extraction. If transmissivity between wells is low (ky/kx is low), then higher spacing lengths are required. Large spacing lengths will have lower field efficiency but would leave the possibility of exploiting the unused areas in between later in the future.

Monitoring
Reservoir monitoring plays a fundamental role in optimization and safety of exploitation. Monitoring during the operational phase is required to reveal additional reservoir information relevant to the management of a project (or projects). At this stage, multiple questions may arise, e.g. on the migration of the cold waterfront, on the hydraulic interaction between projects, or the occurrence of mechanical deformations. In addition to pressure, temperature and fluid flow fields in the reservoir, mechanical deformations, changes in water composition or seismic monitoring are relevant here.
Instrumented monitoring wells (in static and dynamic flow conditions) and geophysical methods are the main proven methods for monitoring. Pressure fields can be measured with a relatively low number of wells as pressure changes travel a long distance. The temperature field is the most

difficult variable for mapping. It can be measured directly in the monitoring well but remains challenging elsewhere in deep reservoirs. Fluid flow can be better understood by means of tracer testing.

Recommendations

The extent of the thermally influenced area around the wells is dependent on the concept, well configuration and reservoir properties. The hydraulically impacted area is a lot larger in size. Keeping an efficient use of the subsurface in mind, the extent of the thermal area should be leading.

A geometrical approach is used in France and the Netherlands for the definition of the license boundaries (French method). When comparing this method with the results from the three reservoir concepts, it works for most of the tested scenarios in concept 2. However, it falls short in adequately covering the disturbed thermal area for concepts 1 and 3. This discrepancy arises due to reservoir heterogeneity. Therefore, an alternative approach or improvement of the French method is required for spatial license definition in these concepts.

A procedure for defining the boundaries of the production license is proposed. It is recommended to combine the results of the permutation analysis with the French method, resulting in a rectangular area. For concept 1, in case of long permeable faults (set 1) and a production well near the fault zone, a first set of boundaries should be parallel to these faults. The length of the license area in the direction parallel to these faults should be based on the permutation analysis, using high percentile values from the length distribution. In the direction perpendicular to these faults, the boundaries are comparable to the French method, with a width of twice the well spacing.

In order to maximize the exploitation of the geothermal resources located in the Carboniferous Limestone Group of the Campine Basin in a sustainable way, field strategies are required for spatial and temporal organization of the geothermal doublets.

Ideally, for maximizing the energy extraction, relatively simultaneous geothermal doublets could be organized in patterns. The off-line or staggered pattern is recommended because this pattern reduces both the pressure and thermal interference and pressure gradient between upstream and downstream doublets when compared to the linear pattern. This pattern could be organized following the fault strike and using the L-shaped well configuration, where the producer well is drilled close to one permeable fault and the injector is located off-center from the neighboring horst structure. Nevertheless, this kind of organization may not be easy to implement in practice as the real location of the doublet is constrained by the location of the final user and heat demand and by local geological conditions.

Another important point to consider in the development strategy is the sustainability of the geothermal exploitation so that future generations can also rely on this source of energy. Based on the worst-case estimation made in this report, assuming conduction only and no advection or convection, the reservoir (concept 1) could be recharged to levels equal or higher than 90 % of the original heat in place after resting 60 years to 200 years, depending on the production conditions. Considering the time needed to restore most of the extracted energy and the fact that the location of the end user is unlikely to change over generations, a sequential or rotational exploitation strategy can be proposed. A rotational scheme could involve two or more areas depending on the resting or recharging time selected.

SAMENVATTING

Inleiding en doelstellingen

Een van de manieren om een duurzamere energievoorziening en -systeem te bereiken, is het gebruik van geothermische warmte uit de diepe ondergrond. Standaard diepe geothermische toepassingen werken met een doubletsysteem, met één put voor de productie van warm water en een andere put voor de injectie van het water nadat de warmte is onttrokken. Deze systemen richten zich op ondergrondse reservoirs, die in Vlaanderen bijna uitsluitend aanwezig zijn in het bekken van de Kempen. De projecten in Mol en Beerse onttrekken beide warmte aan de kalksteenlagen in de Kolenkalk Groep van het Onder Carboon. Nieuwe opsporingsvergunningen in het gebied zijn gericht op hetzelfde reservoir of op het zandsteenreservoir van de Trias Buntsandstein Formatie. Aangezien in de toekomst meerdere bijkomende ontwikkelingen in hetzelfde ondergrondse reservoir worden verwacht, is het belangrijk om vergunningsgebieden of volumes optimaal af te bakenen om negatieve interferentie tussen projecten te voorkomen en een efficiënt gebruik van de diepe ondergrond te garanderen, nu en in de toekomst.

De huidige studie heeft tot doel om inzichten te verbeteren voor de definitie van vergunningsgrenzen door middel van dynamische reservoirsimulaties. Het doel is om verschillende concepten en scenario's te simuleren en de resultaten te gebruiken om inzicht te krijgen in de aspecten en randvoorwaarden van typische toepassingen. Ook kunnen er aanbevelingen worden gedaan voor de efficiënte afbakening van 3D-volumegebieden.

Aanpak in het buitenland

Hoewel dynamische modelleringen de hoofdmoot uitmaken van deze studie, is het nuttig de resultaten van de reservoirmodellering aan te vullen met inzichten uit andere landen of regio's. Een onderzoek naar hoe vergunningsgrenzen elders worden vastgesteld en op basis van welke parameters, plaatst de huidige resultaten in perspectief. Er zijn immers andere regio's waar meerdere geothermische projecten op relatief korte afstand van elkaar zijn gelegen.

Er is informatie verzameld over drie regio's buiten Vlaanderen. In omringende landen vertoont de ondergrond van het Bekken van Parijs de langste geschiedenis van exploitatie van diepe geothermische warmte. Het gebied omvat meer dan 50 diepe geothermische projecten verspreid over een gebied van meer dan 500 km^2, gericht op aquifers uit het Midden-Jura en het Onder-Krijt. Volgens de Code Minier maakt de vergunningverlening onderscheid tussen een exploratie- en een productiefase. De exploitatievergunning wordt gedefinieerd als een volume, waarbij de laterale omvang op een puur geometrische manier wordt afgebakend, rekening houdend met de afstand tussen de productie- en injectieputten. Projecten mogen geen hydraulische impact hebben die groter is dan 1 bar op een ander project, waarbij de thermische impact beperkt is tot 1°C. Deze waarden zijn echter niet bij wet vastgelegd.

Nederland presenteert een casus met 14 actieve projecten in Zuid-Holland, in het gebied tussen Rotterdam en Den Haag (een gebied van minder dan 300 km^2). Deze projecten richten zich op reservoirs van het Trias tot het Krijt en opereren in een gebied met actieve olie- en gaswinning uit dezelfde lagen. De definitie van vergunningsgrenzen om negatieve interferentie te voorkomen, is al in Nederland bestudeerd. In het huidige Nederlandse systeem voor geothermische vergunningen worden de grenzen van de vervolgvergunning voor productie op een geometrische manier gedefinieerd, gebaseerd op de aanpak in Frankrijk (de "Franse methode"), maar met een kleine aanpassing. In Nederland is de vergunningsgrens een rechthoek die de cirkels rond de putten omvat (elk met de helft van de putafstand als straal). De veronderstelling is dat wanneer het vergunningsgebied op deze manier wordt gedefinieerd, er een temperatuurdaling van 1°C zal optreden aan de grens, min of meer gelijktijdig met een temperatuurdaling van 1°C in de productieput. De vergunningsgrens is dus gerelateerd aan de levensduur van het project (thermische doorbraak). Vergunningen zijn ook beperkt in de verticale dimensie en daarom gedefinieerd als een volume. TNO werkt momenteel aan een mogelijke aanpassing en verbetering van de huidige manier om de grenzen van de vergunning te definiëren.

In Beieren zijn in het gebied rond München ook meerdere geothermische doubletten geconcentreerd (18 projecten over 850 km^2), die allemaal gericht zijn op de Malm-kalksteen. De federale mijnbouwwet definieert exploratie- en productievergunningen, met meer gedetailleerde richtlijnen die op staatsniveau worden gepubliceerd. De omvang van de exploratievergunning is gerelateerd aan de ruimtelijke reikwijdte van het voorgestelde werkprogramma. In tegenstelling tot Frankrijk en Nederland wordt de omvang van de productievergunning gedefinieerd op basis van de resultaten van reservoirsimulaties, vergelijkbaar met Vlaanderen. De richtlijnen vermelden een maximale drukverlaging aan de vergunningsgrens van 1 bar en een maximale temperatuur-daling van 1°C.

Reservoirconcepten

Statische modellen vormen de basis waarop (dynamische) reservoirsimulaties kunnen worden uitgevoerd. De statische modellen hebben een geologisch of structureel model als basis en worden aangevuld met reservoireigenschappen. Naast de gebruikte parameterwaarden schetst het model ook het ruimtelijk voorkomen van deze reservoirkarakteristieken, hun geometrie en in welke relatie tot de geologie. Op deze wijze wordt de heterogeniteit in het reservoir gevat, die uiteindelijk de stroming van het water zal bepalen.
Op basis van onze kennis van de geologie en kenmerken van de (Onder-)Carboon Kolenkalk Groep in het Kempenbekken, hebben we verschillende structurele situaties gecombineerd met een typisch voorkomen van porositeit en permeabiliteit in het reservoir om reservoirconcepten te definiëren. In een eerste benadering kunnen drie concepten worden onderscheiden:

1. Een gebied in het westelijke deel van het bekken van de Kempen, waar de Carboon Kolenkalk Groep op relatief geringe diepte aanwezig is (ruwweg tussen 1000 en 2000 m onder TAW), is blootgelegd vóór de afzetting van Namuriaan sedimenten, en de bovenliggende lagen beperkt zijn in dikte. Er wordt een enkele reservoirlaag herkend naast permeabele breukzones. Porositeit en permeabiliteit van de reservoirlaag nemen af naarmate de afstand tot de breuken toeneemt.
2. Een gebied langs de zuidelijke rand van het bekken van de Kempen, waar de Kolenkalk Groep aanwezig is op geringe diepte (minder dan 1000 m onder TAW) en direct onder de basis Krijt discordantie. Naast de reservoirlaag en de permeabele breukzone van concept 1, wordt een bijkomende reservoirlaag geïdentificeerd aan de top van de sequentie, direct onder de basis Krijt discordantie.
3. Een groot gebied in het centrale en oostelijke deel van het bekken van de Kempen waar de Kolenkalk Groep aanwezig is op grotere diepte (tussen 1000 en meer dan 6000 m onder TAW) en bedekt is door een redelijk dik interval van Namuriaan sedimenten. Hier vertoont de reservoirlaag een lagere porositeit en permeabiliteit en is beperkt tot een smalle zone langs de breukzones.

Definitie van scenario's en parameters

Na het definiëren van het structurele raamwerk en het reservoirconcept, moeten relevante parameters worden geïdentificeerd. In een tweede stap moeten ze worden gekwantificeerd en moeten geschikte waarden worden gekozen. Petrofysische, thermische en geometrische reservoir-

karakteristieken voor de 3 reservoirconcepten werden gedefinieerd op basis van de huidige kennis van de Kolenkalk Groep in Vlaanderen, inclusief het 3D-model van het Dinantiaan in het bekken van de Kempen (G3Dv3), de geboorde putten in het bekken en de resultaten van de huidige geothermische projecten (Beerse en Mol).
Een minimum-, basis- en maximumwaarde werden gedefinieerd voor de verschillende parameters voor elk van de gedefinieerde reservoirconcepten. Er werden parameters geselecteerd voor verdere gevoeligheidsanalyse en reservoirmodellering.

Naast de parameters werden drie putconfiguraties gedefinieerd voor elk reservoirconcept. Bij elke configuratie zijn de putten anders gepositioneerd ten opzichte van de heterogeniteiten in het reservoir. De verschillende putconfiguraties zijn gebruikt om de impact te evalueren van de plaatsing van de putten op de thermisch en hydraulisch beïnvloedde gebieden.

Sensitiviteit

De gevoeligheids- of sensitiviteitsanalyse bestaat uit het evalueren van de onzekerheid van de output van het simulatiemodel met betrekking tot een gegeven set invoerparameters (gesteente-eigenschappen, omstandigheden bij aanvang of putomstandigheden). Om dit te bereiken, worden simulaties uitgevoerd met inachtneming van de maximum- of minimumwaarden van elke geselecteerde invoerparameter, terwijl de voor resterende eigenschappen de referentiewaarde wordt aangehouden.
De gevoeligheidsanalyse werd uitgevoerd via numerieke reservoirsimulaties in DARTS. De simulatie bestaat uit een hydraulisch-thermisch model van vloeibaar water (één fase) met gemiddelde enthalpie dat door poreuze media en breuken stroomt.

De resultaten werden gevisualiseerd en geanalyseerd in termen van:

1. de thermische invloedssfeer (waar de temperatuur met meer dan 1°C is veranderd),
2. de hydraulische invloedssfeer (waar de druk met meer dan 1 bar is veranderd),
3. de thermische doorbraaktijd (aankomst van het koudefront dat leidt tot een temperatuur-daling van 3,5°C of meer),
4. het uiteindelijke debiet,
5. kaarten met druk en temperatuur in de reservoirlagen,
6. debiet en evolutie van de temperatuur bij injectie- en productieput.

Op basis van tornadoplots van resultaten 1-4 werden de volgende parameters beschouwd als degene met de grootste impact en meest relevant voor verdere simulaties:

- extensie van de karst, porositeit en permeabiliteit van de tweede set breuken, de permeabiliteitsanisotropie ky/kx, de karstporositeit en -permeabiliteit en de dikte van de reservoirlaag (voor reservoirconcept 1)
- porositeit en permeabiliteit van de belangrijkste reeks breuken, de permeabiliteits-anisotropie ky/kx, de permeabiliteit van de bovenste laag en de porositeit en permeabiliteit van de tweede set breuken (voor reservoirconcept 2)
- de porositeit en permeabiliteit van de tweede set breuken, de minimale permeabiliteit van het reservoir, de afstand waarover de verhoogde permeabiliteit zich uitstrekt vanaf de breuken en de breukhoogte (voor reservoirconcept 3).

Scenario's met een enkel doublet

Na selectie van de meest relevante parameters uit de gevoeligheidsanalyse werden scenario's gesimuleerd met één doublet met variërende parameterwaarden. Alle mogelijke combinaties van parameterwaarden werden geëvalueerd, waarbij gemiddelde (referentie) en/of extreme waarden werden gecombineerd.

Voor concept 1 werden verschillende waarden voor 5 parameters toegepast, wat leidde tot 243 combinaties. De putten werden geplaatst in een L-vorm met de injectieput tussen twee breuken in en de productieput in een breuk (de referentie putconfiguratie). De resultaten laten een bimodale verdeling zien, met een toegenomen aantal gevallen met een oppervlakte van 0,1 tot 1 km^2, evenals gevallen met een oppervlakte variërend van 2 tot 3,7 km^2. De parameters die de bimodale verdeling beïnvloeden, zijn voornamelijk de extensie van de karst weg van de breuken en de permeabiliteit ervan. Minimale waarden hiervoor leiden tot kleine thermisch beïnvloede gebieden, omdat ze resulteren in een lage injectiviteit rond de put (en uiteindelijk een verlaagd debiet). Als alleen gevallen met een hoog debiet worden beschouwd (> 80 m^3/h), varieert de gemiddelde grootte van het thermisch beïnvloede gebied tussen 1 en 3,5 km^2. Het hydraulisch beïnvloedde gebied varieert tussen 1 en 60 km^2 afhankelijk van de reservoirkarakteristieken. Het gebied is klein (< 30 km^2) indien er een goede hydraulische communicatie is tussen de putten (grotere verbreiding van de karst, hoge permeabiliteit in de breukzone) of wanneer het debiet laag is omwille van beperkte injectiviteit. Grotere gebieden worden verwacht wanneer er restricties zijn in de connectiviteit tussen de putten (beperkte verbreiding van de karst, lage permeabiliteit in de tussenliggende breuken) en wanneer het debiet hoog is.
Slechts 4 parameters werden geselecteerd voor concept 2, wat leidde tot 81 combinaties. Deze gevallen laten opnieuw een bimodale verdeling zien voor de thermische invloedssfeer, waarbij de permeabiliteitsanisotropie ky/kx een belangrijke rol speelt. Over het algemeen is de grootte van het gebied kleiner (0,5-3,4 km^2) vergeleken met concept 1, aangezien de injectie in twee lagen plaatsvindt. Voor concept 2 heeft een groot aantal gevallen een lager debiet, zelfs onder de 80 m^3/h, als gevolg van een combinatie van de subcropgrens van de formatie (geen stroming), de lage permeabiliteit voor de secundaire breuken en de bovenste laag, en de matrixanisotropie. Net als in concept 1 varieert het gebied dat hydraulische impact ondergaat aanzienlijk in grootte van minder dan 20 km^2 tot ongeveer 40 km^2.
81 gevallen werden geanalyseerd voor concept 3. De resultaten geven een klein gebied aan waar de temperatuur verstoord wordt omdat het volume van permeabele zones beperkt is. Thermische doorbraak treedt in veel gevallen vroeg op. Daarom is de tijdsperiode van de simulaties korter en is het geïnjecteerde volume lager. Het gebied is meestal kleiner dan 2 km^2 en vaak uitgerekt langs de breuken. In sommige gevallen is het groter dan 4 km^2. De hydraulische invloedssfeer is groter, in de meeste gevallen meer dan 40 km^2.

Scenario's met meerdere doubletten

Naarmate er meer geothermische projecten in Vlaanderen worden gepland en in gebruik worden genomen, zal interferentie tussen projecten een grotere uitdaging worden. Daarom was een volgende stap om de impact van en interferentie tussen meerdere doubletten te simuleren. Deze taak richtte zich op concept 1. Er zijn minder gegevens beschikbaar voor concepten 2 en 3 en de geologische onzekerheid is daar hoger. De meeste gegevens zijn beschikbaar voor het gebied van concept 1. Er is ook al één operationeel project in dit gebied (in Beerse) en er wordt verdere interesse verwacht (bijvoorbeeld de explorativergunning in Turnhout). Daarom is de verwachting dat het probleem van interferentie zich als eerste kan voordoen in dit gebied.
Voor deze taak zijn reservoirmodellen opgesteld met 9 doubletten met dezelfde L-vormige putconfiguratie, maar volgens verschillende plaatsingspatronen. Drie gevallen werden geëvalueerd: het referentiescenario, een situatie met hoge permeabiliteit in de secundaire set breuken en een situatie met eigenschappen volgens het P90-geval voor de thermische invloedssfeer voor concept 1 (met een enkel doublet).

Over het algemeen geldt dat wanneer de afstand tussen de doubletten (in lengte en breedte) wordt verkleind, er op een efficiëntere wijze warmte wordt geëxtraheerd over het ganse veld, maar dat de cumulatieve warmteproductie per doublet verslechtert. Met het line-drive patroon wordt een hogere efficiëntie bereikt in vergelijking met het off-line patroon, maar het is gevoeliger voor thermische en drukinterferentie. Als er een goede hydraulische communicatie is tussen de putten, is een afstand in de lengterichting van ongeveer 4000 m en van minstens 2500 m in de breedte vereist om een duidelijke verslechtering van de cumulatieve warmte-extractie te voorkomen. Als de transmissiviteit tussen de putten laag is (ky/kx is laag), zijn grotere afstanden vereist (in lengte). Een grotere afstand leidt tot een lagere veldefficiëntie, maar laat wel de mogelijkheid om de tussenliggende niet gebruikte gebieden later in de toekomst te exploiteren.

Monitoring

Reservoirmonitoring speelt een fundamentele rol bij de optimalisatie en veiligheid van de exploitatie. Monitoring tijdens de operationele fase is vereist om aanvullende reservoirinformatie te bekomen die relevant is voor het beheer van een project (of projecten). In deze fase kunnen er zich meerdere vragen stellen, bijvoorbeeld over de migratie van het koudwaterfront, over de hydraulische interactie tussen projecten of het optreden van mechanische vervormingen. Naast druk-, temperatuur- en stromingsvelden in het reservoir zijn mechanische vervormingen, veranderingen in de samenstelling van het water of seismische monitoring hier relevant.
Monitoringsputten uitgerust met meetinstrumenten (in statische en dynamische stromingsomstandigheden) en geofysische technieken zijn de belangrijkste bewezen methoden voor monitoring. Drukvelden kunnen worden gemeten met een relatief laag aantal putten, aangezien drukveranderingen zich over een lange afstand doorzetten. Het temperatuurveld is de moeilijkste variabele om in kaart te brengen. Het kan direct worden gemeten in een monitoringsput, maar blijft elders in diepe reservoirs een uitdaging. De stroming van het water kan beter worden begrepen door middel van tracertesten.

Aanbevelingen

De omvang van de thermische invloedssfeer rond de putten is afhankelijk van het concept, de putconfiguratie en de eigenschappen van het reservoir. De hydraulische invloedssfeer is veel groter. Met het oog op een efficiënt gebruik van de ondergrond moet de omvang van de thermische invloedssfeer leidend zijn.

In Frankrijk en Nederland wordt een geometrische benadering gebruikt voor het definiëren van de vergunningsgrenzen (Franse methode). Bij vergelijking van deze methode met de resultaten van de drie reservoirconcepten, blijkt dat het volstaat voor de meeste geteste scenario's in concept 2. Deze aanpak slaagt er echter niet in om op adequate wijze het verstoorde thermische gebied voor concepten 1 en 3 af te lijnen. Dit heeft te maken met de heterogeniteit van het reservoir. Daarom is voor deze concepten een alternatieve benadering of verbetering van de Franse methode vereist voor de ruimtelijke definitie van de vergunningsgrenzen.

We stellen een procedure voor om de grenzen van de winningsvergunning te definiëren. Het wordt aanbevolen om de resultaten van de permutatieanalyse te combineren met de Franse methode, wat resulteert in een rechthoekig gebied. Voor concept 1, in het geval van lange permeabele breuken (set 1) en een productieput nabij de breukzone, moet een eerste set grenzen parallel aan deze breuken zijn. De lengte van het licentiegebied in de richting parallel aan deze breuken moet gebaseerd zijn op de permutatieanalyse, met behulp van hoge percentielwaarden uit de lengteverdeling. In de richting loodrecht op deze breuken zijn de grenzen vergelijkbaar met de Franse methode, met een breedte van tweemaal de afstand tussen de putten.

Om de exploitatie van het geothermisch potentieel in de Carboon Kolenkalk Groep van het bekken van de Kempen op een duurzame manier te maximaliseren, zijn strategieën vereist voor de ruimtelijke en temporele organisatie van de geothermische doubletten in het veld.

Idealiter zouden relatief gelijktijdige geothermische doubletten in patronen kunnen worden ontwikkeld om de extractie van warmte te maximaliseren. Het off-line of gestaffelde patroon wordt aanbevolen omdat dit patroon zowel de hydraulische als thermische interferentie en de drukgradiënt tussen stroomopwaartse en stroomafwaartse doubletten vermindert in vergelijking met het lineaire patroon. Dit patroon zou kunnen worden gevolgd parallel aan de breuken en met volgens de L-vormige putconfiguratie, waarbij de producerende put dicht bij een permeabele breuk wordt geboord en de injectieput zich niet in de aangrenzende horststructuur bevindt. Zulke organisatie is in de praktijk mogelijk niet eenvoudig te implementeren, omdat de werkelijke locatie van het doublet wordt in belangrijke mate wordt bepaald door de ligging van de eindgebruiker en de warmtevraag en door lokale geologische omstandigheden die kunnen afwijken van het hier gevolgde concept.

Een ander belangrijk punt om te overwegen in de ontwikkelingsstrategie is de duurzaamheid van de geothermische exploitatie, zodat ook toekomstige generaties deze bron van warmte kunnen aanspreken. Gebaseerd op de slechts mogelijke inschatting die in dit rapport is gemaakt, waarbij alleen warmtegeleiding en geen advectie of convectie wordt verondersteld, zou het reservoir (concept 1) terug kunnen opwarmen tot een niveau van minstens 90% van de oorspronkelijke situatie na een rustperiode van 60 tot 200 jaar, afhankelijk van de productieomstandigheden. Gezien de tijd die nodig is voor de regeneratie van het grootste deel van de gewonnen warmte en het feit dat de locatie van de eindgebruikers waarschijnlijk niet snel zal veranderen over enkele generaties, kan een sequentiële of roterende exploitatiestrategie worden voorgesteld. Een rotatieschema kan twee of meer gebieden omvatten, afhankelijk van de geselecteerde rust- of regeneratietijd.

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1 INTRODUCTION

1.1 CONTEXT

Flanders is working on making the energy supply and the entire energy system more sustainable, including increasing the share of renewable energy sources (Flemish Energy and Climate Plan or Vlaams Energie- en KlimaatPlan – VEKP). One of the ways to achieve this is to extract heat from, or store heat in, underground aquifers.
The geothermal potential of the subsurface in Flanders and Belgium has been discussed by Vandenberghe & Bouckaert (1981) and Berckmans & Vandenberghe (1998). Four potential reservoirs are considered by the latter, including limestone layers of the Carboniferous Limestone Group (Lower Carboniferous), sandstone layers in the Coal Measures Group (Upper Carboniferous) and in the Buntsandstein Formation (Lower Triassic), and chalks of the Upper Cretaceous. So far, geothermal developments in Flanders have focused on Cretaceaous chalks (Gysen, 2000) and the Carboniferous Limestone Group in the Campine Basin (Bos & Laenen, 2017; Broothaers et al., 2021).

Licensing of geothermal projects is currently regulated by the *Decreet Diepe Ondergrond of 8 May 2009* (last updated by the Decree of 29 March 2019) and the decision of the Flemish Government of 15 July 2011 (*Besluit van de Vlaamse Regering van 5 juli 2011 tot uitvoering van het decreet van 8 mei 2009 betreffende de diepe ondergrond en tot wijziging van diverse besluiten*), last updated on 7 June 2024. A distinction is made between an exploration license and a production license. The regulations specify for which activities a license is required, what the procedure is for applying for a license, the duration of the procedure, the required content of the license application, and the criteria used for evaluation. Among these criteria, the Flemish Government assesses whether the operator intends and is able to carry out the planned activities and operations in a safe way. The operator needs to provide a description of how the activities will be carried out, how much heat is in place and how much geothermal heat will be extracted. This information is crucial to assess whether (and to what extent) the geothermal resources are exploited in an efficient and sustainable manner and how it contributes to (or allows) an organized management of geothermal and other resources in the deep subsurface. The operator also needs to delimit an adequate 3D volume based on dynamic modelling, while searching an equilibrium between “large enough” to encompass relevant impacts and “small enough” to avoid jeopardizing other subsurface potential.
The latter assessment adds to the structure vision for the deep subsurface (*Structuurvisie Diepe Ondergrond*) drafted by the Flemish Government which has the objective of achieving an organized and sustainable management of the deep subsurface resources in Flanders. It will provide a framework giving insight in the potential and boundary conditions for different subsurface activities.

Five permits have currently (December 2024) been granted for the exploration of geothermal energy in Flanders. Three of these permits are in the Campine Basin and focus on the Carboniferous Limestone Group. If multiple additional permit applications in the future also concentrate on the same layer, it is important to optimally delineate the license areas or volumes. The boundaries of the volume areas are determined by the size of the zone where the pressure and temperature in the subsurface around the application are affected. This depends on the geological properties of the subsurface. In the Carboniferous Limestone Group, the reservoir properties are highly variable and there is considerable local uncertainty about the exact parameter values.

The placement of the wells also plays a role. Finally, safe operation must be taken into account, which means that the pressure changes must remain within certain limit values in order to guarantee the stability of the subsurface and the wells, and that the pressure and temperature change on fracture surfaces must not be so great that seismicity can be induced. Optimal delineation of the permitted volume areas therefore requires better insights into the pressure and temperature impact around applications in the subsurface.

1.2 OBJECTIVES

The aim of the assignment is to obtain a more efficient delineation of 3D volume areas for subsurface applications in Flanders (in the Carboniferous Limestone Group). An optimal delineation must allow to define the permitted volume areas in such a way that:

1. They are large enough so that different applications can safely coexist without negative interference (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.

The direct objectives of the study consist of the following three components:

1. To simulate various concepts and scenarios using dynamic reservoir models;
2. To use the models to gain insights into the aspects and boundary conditions of typical applications in the subsurface of Flanders;
3. To make recommendations based on the above for efficient delineation of 3D volume areas for evaluation and approval of licenses or permits.

1.3 APPROACH

Considering the context and the objectives of the study, VITO proposed a methodology based on multiple dynamic reservoir models or simulations. The approach can be summarized into eight tasks, which are described and presented in each of the chapters of the report:

1. Approach abroad
2. Definition of reservoir settings
3. Definition of possible scenarios & variables
4. Modelling: Parameter space evaluation (sensitivity analysis)
5. Modelling: Single doublet scenarios
6. Modelling multiple doublets
7. Monitoring
8. Integration of results and conclusions

Although dynamic modelling is at the core of this study, the results of the reservoir modelling should be complemented by insights from other countries or regions. An examination of how license boundaries are established elsewhere, and based on which parameters, puts the current results into perspective. After all, there are other regions where multiple geothermal projects are located at a relatively short distance from each other, such as the Paris Basin or the region around Munich. The approaches applied abroad can be useful and informative for formulating recommendations for Flanders based on the current study. Looking at the concentration of geothermal projects, the Paris Basin, the Munich area, and the western part of the Netherlands (Zuid-Holland) were considered as comparable in scope and therefore the applicable regulations in France, Germany (Bavaria) and the Netherlands were examined. The concentration of projects and rules followed to define licenses for these three regions are presented in Chapter 2 Approach Abroad.

Before starting the modelling, it is necessary to define and quantify the parameters that control heat, mass flow and pressure diffusion in the geothermal reservoir. These parameters include permeability/transmissivity and porosity, thermal properties, heterogeneity, anisotropy, and fracture density and characteristics. In addition, it is important to make a representative choice of the structural framework. Therefore, the first task was to establish a structural framework and define typical reservoir settings, and then to quantify the properties of the different rocks in the model, such as the matrix, karst levels, or fracture zones. The structural framework is based on the regional G3Dv3 geologic model of Flanders (Deckers et al., 2019). Based on the characterization of the structural settings, three reservoir concepts typical for the Lower Carboniferous in the Campine Basin are distinguished. These are presented in Chapter 3 Definition of Reservoir Settings.

Based on the structural framework and reservoir characteristics, different parameters are defined and quantified, based on properties derived from geophysical exploration, drilling and well testing in the basin. These parameters and the choice of the values to be used (in function of the defined reservoir settings) are presented in Chapter 4 Definition of Scenarios and Parameters.

The bulk of the work involves setting up static and dynamic models and running reservoir simulations. The models are used to evaluate the magnitude and extent of pressure and temperature changes in the reservoir around the production and injection wells.

In a first phase, the models and simulations are used to check the sensitivity for an initial selection of parameters and to determine which parameters are more relevant than others. The approach followed is to simulate a base case for each of the reservoir concepts with average values, which is then used as a reference. Next, simulations are run using the base case values for all parameters but one, where a minimum or maximum value is applied. This is done for each of the selected parameters. The results are compared to the base case result to evaluate which parameters have the highest impact on pressure and temperature changes in the reservoir. This sensitivity analysis is important to make a final selection in the scenarios and parameters that will be included in subsequent step. This allows us to limit the number of scenarios and to increase focus on a specific series of scenarios. By varying the parameters and seeing how their impact varies (range, average, parameters with the greatest influence on the sphere of influence), we can also determine which scenarios are the most relevant to simulate. The setup of the models, the simulation results and the sensitivity analysis for each of the three concepts defined in Chapter 2 are presented in Chapter 5 Sensitivity. This chapter also includes a section on the recharge or recovery of temperature and heat in a geothermal field after the exploitation period of a geothermal doublet.

After the relevant parameters have been selected for each concept, they can be applied to dynamic models used to investigate the pressure and temperature impact of certain scenarios (combinations of parameters) for a single doublet, and subsequently also for multiple doublets.

Simulations of single doublet systems make up the subject of Chapter 6 Modelling: Single Doublet Scenarios. Here, combinations of minimum, average and maximum parameter values are combined, for each reservoir setting. This means extreme values (either minimum or maximum) of several parameters can be combined. The results of these simulations are presented in terms of the size (length and width) of the disturbed temperature and pressure areas. These results will provide insights into the impact of reservoir properties in combination with the structural framework on a single project and on the reservoir pressure and temperature.

Chapter 7 Modelling: Multiple Doublet Scenarios presents the setup of the models and the results concerning a combination of doublets in the geothermal field. Such simulations are required to evaluate the interference between them (pressure, temperature, fluid front). This has a greater relevance to extracting as much heat as possible, making optimal use of the subsurface, and long-term developments. Neighboring projects do not usually start at the same time, but it is very likely (or even certain) that several projects will be developed in the same area in the long term. It is therefore important to evaluate potential interference in order to stimulate the responsible development of activities in the subsurface, rather than restricting them. Which type of front (pressure, temperature, injected water) causes interference between projects and what is acceptable in terms of influence can be related to the type of project and application. For example, it may be acceptable for two neighboring geothermal projects that pressure communication occurs if they make a positive contribution to production and/or injection, while the breakthrough of colder water is not desirable. For other projects, such as gas storage, it may be that even the slightest pressure communication is unacceptable.
When simulating multiple doublets and investigating the interference between them, we also look at the positioning and orientation of the doublets (and of the individual production and injection wells) and their mutual distance. This can provide interesting insights into the role of the placement of the wells, which is informative for evaluating which criteria or limit values should be used when setting boundaries. However, care must be taken here as in practice, each doublet will be started at a different time and according to the requirements and expectations of each individual permit holder.
It should be noted that the analysis presented in this chapter focuses on doublets in reservoir concept 1. This is because most wells drilled so far are located in this area, hence the amount of data available is higher. It is also in this area and concept that multiple projects are being developed: one is operational (in Beerse), another one is in the exploration stage (in Turnhout). The area of concept 3 offers geothermal potential, but due to the lower amount of data, the uncertainty and therefore the risks are currently higher. For the moment, reservoir concept 3 is the least understood. So far, only VITO's geothermal project in Mol is developed in this area. There are currently no geothermal projects in the concept 2 area.

Models provide insights into the pressure and temperature changes in the reservoir. However, monitoring is required to know the actual changes. Chapter 8 Monitoring describes the reasons why monitoring is relevant or needed, what can be monitored and how.

Chapter 9 Conclusions & Recommendations bring together the lessons learned from the different steps (sensitivity, single doublet modelling, multiple doublet modelling) and proposes some conclusions and recommendations for licensing. These include not only spatial aspects and dimensions of the licenses, but also temporal aspects related to the long-term use of the reservoir for the extraction of geothermal heat.

2 APPROACH ABROAD

2.1 INTRODUCTION

As mentioned in the previous chapter, the *Decreet Diepe Ondergrond* and the *Besluit Diepe Ondergrond* define how licensing for geothermal projects is regulated in Flanders. License applications are evaluated considering the safe execution of the activities, and the efficient and sustainable extraction and use of heat. The extent to which they contribute to a well-thought of management of deep subsurface resources is also taken into account.

According to article 63/7 §3 of *Decreet Diepe Ondergrond*, license volumes should be delimited in such a way (and its size large enough) that it encompasses the entire area where the activities will have a relevant impact. Its boundaries should be chosen such that the activities can be carried out as good as possible from a technical and economical point of view. On the other hand, the license volume should not be larger than required for an efficient execution of the operations.
In case the execution of the activities covered by the license interferes negatively with other previously permitted activities in the deep subsurface, the Flemish Government can impose measures and collaboration with neighbouring permit holders and, where needed, may decide to suspend or revoke the license (articles 63/8 and 63/19 of *Decreet Diepe Ondergrond*.

According to Article 14/30 of the *Besluit Diepe Ondergrond*, the license application should contain, among others:

- 4° a digital plan indicating the boundaries of the license volume;
- 10° an overview of all the other licenses that have been granted within a perimeter of 10 km (geothermal, hydrocarbons, gas storage, subsurface disposal of nuclear waste), including the results of dynamic modelling assessing the impact of the activities in the subsurface and with respect to potential interference between the planned and already existing activities;
- 11° a document providing a description of how efficiently and sustainable the heat will be extracted and used.

The above attest to the requirement of applying the results of dynamic reservoir models to define the limits of the requested license volume. In practice, the extent of the impact of the activities may be set at 1 bar for pressure changes and 1°C for temperature changes. However, these values are not defined by law. A case by case evaluation of the relevant impacts is needed in order to avoid unnecessary and inefficient fragmentation of subsurface resources.

Five permits have currently (December 2024) been granted for the exploration of geothermal energy in Flanders. Three of these permits are in the Campine Basin (Figure 1) and focus on the limestone-bearing sequence of the Carboniferous Limestone Group for the extraction of geothermal heat.

To provide context and guidance for this study, and to assist in formulating recommendations, it is useful to look at legislation in other countries to evaluate how license boundaries are defined outside of Flanders.
Ideally, regulations and best practice are analyzed from countries with a comparable situation where multiple geothermal projects (doublets) are clustered. If projects are located within limited distance of each other, the same challenge arises in terms of defining their boundaries and making

sure they can be operated safely and without significant negative impact from one project to another.

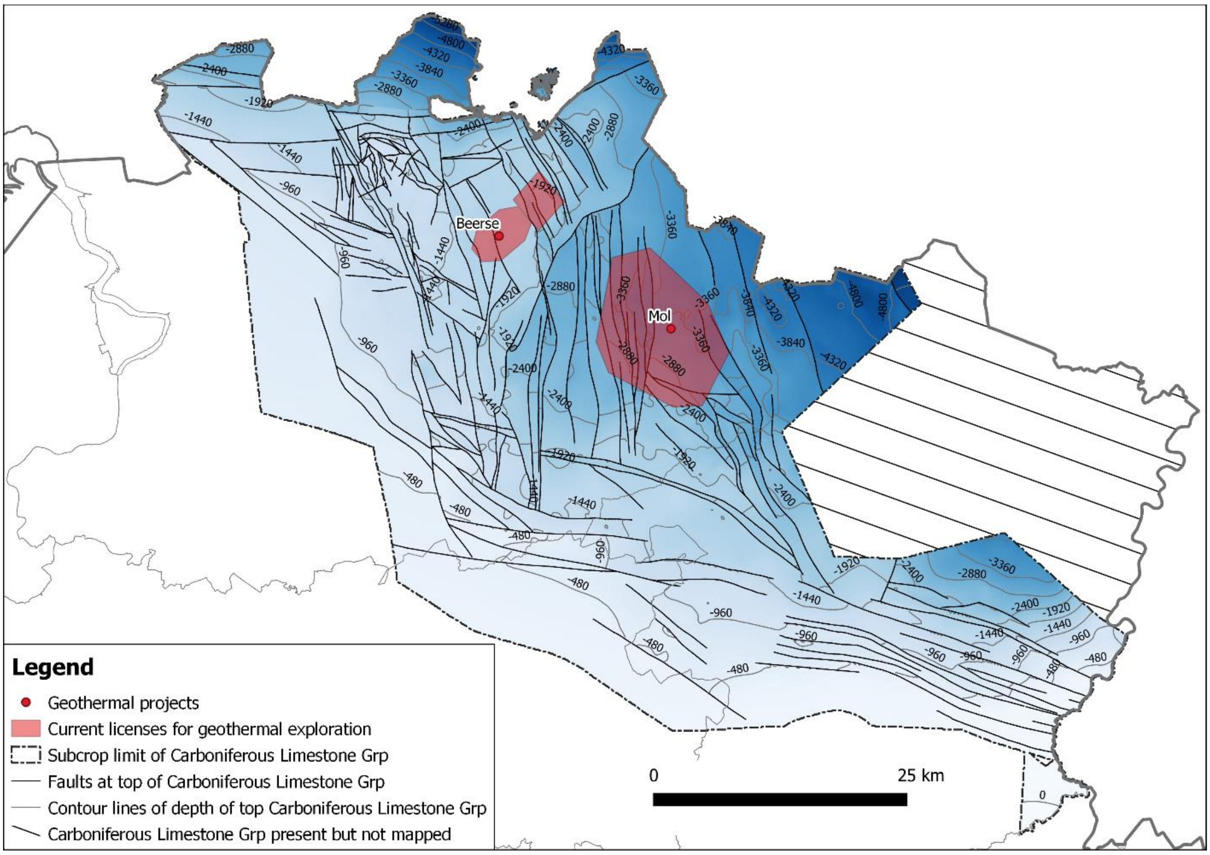


Figure 1: Map showing the location and extent of current licenses for the exploration of deep geothermal energy in the Campine Basin (December 2024).

For this study, regulations on (deep) geothermal licenses were screened for the Netherlands, France and Germany. All three countries have regions where numerous deep geothermal projects are situated close to each other: the area between The Hague and Rotterdam in the Netherlands, the Paris Basin in France, and the Munich area in Germany.

2.2 THE NETHERLANDS

2.2.1 Why the Netherlands?

The Netherlands present an interesting case to compare to as according to www.nlog.nl there are already 123 geothermal licenses approved (as of January 1st 2024), 65 of which are located in the southern and central part of the province of Zuid-Holland. Of the more than 20 operational geothermal projects (with several of them comprising multiple doublets), 14 are located in this part of Zuid-Holland. These projects are located within a radius of roughly 15 km, South of The Hague and West of Rotterdam, across an area with a size of less than 300 km^2.
The target reservoirs are siliciclastic and more homogeneous in nature (Cretaceous or Triassic sandstone), with flow occurring through matrix porosity and permeability. Faults or fault zones are not considered targets as permeability may be lower. In fact, they are rather seen as risks. Even though these projects do not all target the exact same reservoir layers, this region does highlight the case for potential interference between adjacent geothermal projects. In addition,

it should be noted that (active) oil and gas fields are also present in the same area, targeting the same intervals.

2.2.2 How are geothermal licenses regulated in the Netherlands?

Deep geothermal activities are regulated by the Mining Law (*Mijnbouwwet*). Artikel 1 of the Mining Law defines three types of license for geothermal (below 500 m depth):

- a geothermal exploration area ("*zoekgebied*") grants the exclusive right to apply for a starting license in a specific area (Artikel 24k 1: 4 year)
- a geothermal starting license ("*startvergunning*") is a license allowing to explore for geothermal heat and to extract the heat during the validity of the permit (Artikel 24v 1: 2 year)
- a geothermal follow-up license ("*vervolgvergunning*") grants a permit for extraction or production of the geothermal heat as long as the license is valid.

Either a geothermal starting license or geothermal follow-up license is required to be allowed to explore (by means of drilling) and/or extract geothermal resources.

Artikel 1 also defines the area of influence as the area of the subsurface where, because of the production of geothermal heat, a decrease in temperature occurs.

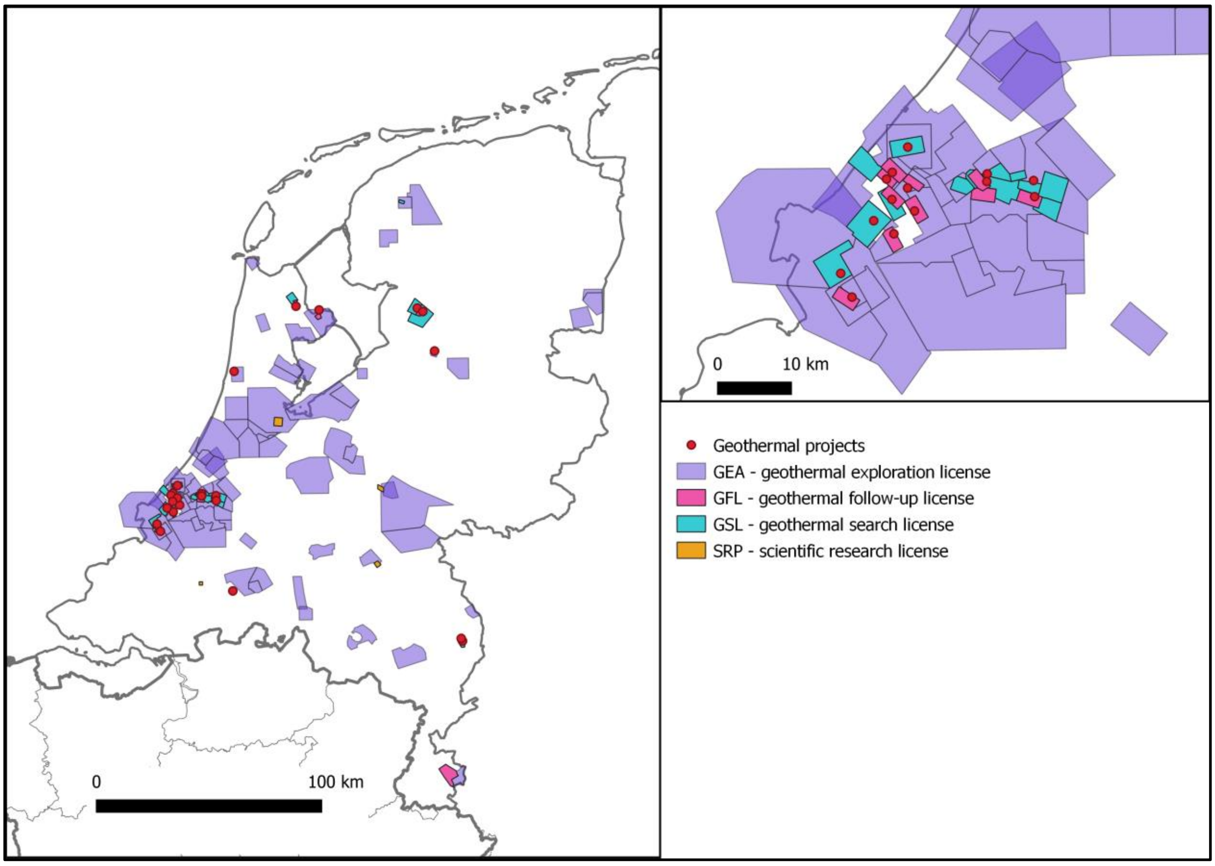


Figure 2: Location of approved geothermal licenses and operational projects in the Netherlands (left) and more specifically in Zuid-Holland (Westland) area (top right). The license areas are taken from www.nlog.nl, the list of geothermal projects is available on www.geothermie.nl.

2.2.3 How are boundaries defined?

In 2014 TNO published a report on how the boundaries of operational geothermal licenses are defined. The report builds on and replaces a previous report by TNO on spatial planning of geothermal doublets (Mijnlieff & van Wees, 2009). The study has some starting assumptions, some of which are:

- The operational license area should be entirely enclosed within the previously existing license area for exploration.
- The license is granted for a maximum period of 35 year.
- During the validity period of the license, the calculated temperature decline at the license boundary may not exceed 1°C to prevent the extraction of heat from outside the license area.
- If the maximum allowable temperature decrease is expected prior to the period of 35 year, the validity of the license will be shortened.
- It is preferable to have a license area which is slightly larger than strictly required.

The analysis of TNO starts with what they call the "French method". This method involves a rectangular license area around the doublet, based on two circles centered on both wells with a radius which is equal to half the spacing between the wells at reservoir level (Figure 3). The well position is defined in the middle of the well trajectory within the reservoir (the middle of the reservoir is preferred). The assumption is that when the license area is defined in this way, a temperature decrease of 1°C will occur at the boundary simultaneously with a 1°C temperature decline in the production well. However, the method ignores variations in operational parameters and geological aspects such as the presence of multiple permeable layers or heterogeneities (TNO, 2014).

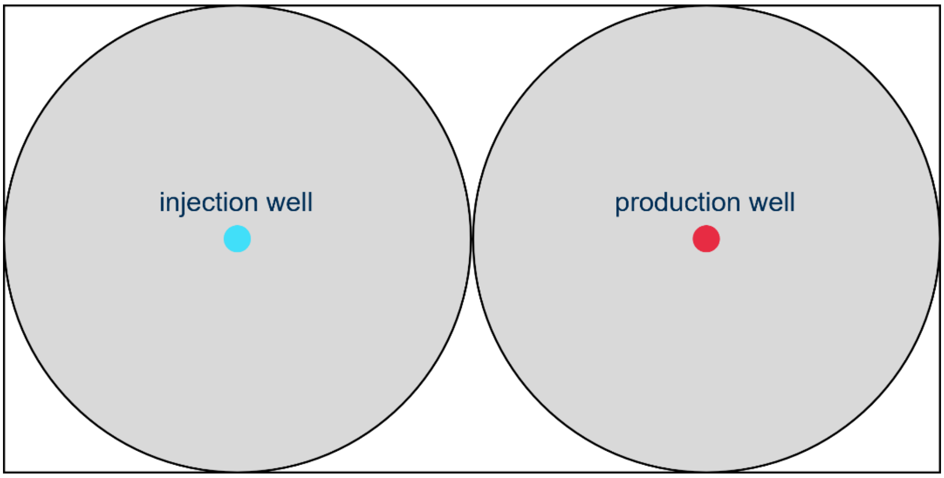


Figure 3: French method presented by TNO (2014) to define operational license boundaries, with the license area comprising the entire rectangle around the wells.

The simulations by TNO showed that, in case of a homogeneous aquifer, a temperature drop of 1°C occurs at the license boundary prior to a 1°C production temperature decline. The main parameters are the production flow rate, the distance between the wells and the reservoir volume (related to thickness and porosity of the reservoir layer). The method is also conservative in case of heterogeneous reservoirs. Heterogeneities parallel to the wells lead to faster breakthrough.

In case of overlap between two applications, there is an evaluation of the overlap area in terms of the most efficient production of heat. Adjustments to the French method are possible in case this would be better to avoid or decrease e.g. seismic risk.

TNO recommended to add information on flow rate and hours, or to add as a condition that production should be suspended when the cumulative produced volume equals or exceeds the calculated cumulative volume for the time when temperature starts declining at the license boundary or when there is a long-term production temperature decline of 1°C. Both could be indicative for temperature impact outside of the license area.

Vertical boundaries of the license volume should preferably be defined along aquitards (impermeable, present across large area), thick enough to prevent communication to over- and underlying aquifers.

2.2.4 Current insights

There are some deviations from the general agreement in timing between thermal breakthrough at the production well and the arrival of the cold waterfront at the license boundary. This could be solved by a adding a buffer to the existing geometry based on the French method or by defining an alternative geometry for the license boundaries (TNO, pers. comm.).
However, overall, the approach allows for an elegant, simple, clear, and fast solution which is good enough for the majority of cases. Regulations provide flexibility to use detailed reservoir models to define different license boundaries, whenever required.

Altogether the authorities are reluctant to provide too strict guiding or directions. It is up to the operator to design and plan the project and apply for a license volume. The authorities prefer to have limited restrictions (conditions) which must be met, without interfering with the operators plans.

In the case of a homogeneous reservoir TNO found that the temperature and pressure influence were not that different in extent. Even if there are some deviations, applying the French method ensures that pressure impact will not get out of hand. This is relevant as elevated pressure differences could pose additional seismic risk.
Despite the general approach followed, applicants submit results of reservoir simulations as these provide information of pressure and temperature changes for the entire intended lifetime of the project (projects usually apply for a 35 year period).
Currently, temperature is leading in the defining the license boundaries and pressure changes are not mentioned (also refer to Artikel 1 of the Mining Law). Changes in temperature or pressure are also not specified or quantified in regulations. In the application stage, the impact of a new project on existing adjacent projects should be addressed (in terms of temperature and pressure). This forms part of the evaluation, but in the end it is up to the operators to come to some sort of agreement.

2.3 FRANCE

2.3.1 Why France?

France has a long history of geothermal projects, with the first doublet in the Paris Basin initiated in 1969. There are over 50 active deep geothermal sites in the Paris Basin alone, over an area of over 500 km^2 (Figure 4). Most projects are operated by local authorities (often using public service delegation for the realization of the project. They usually feed into district heating networks. Some projects are operated by private operators (usually for industrial use).
These geothermal wells target reservoir layers in the Dogger (Middle Jurassic) and in the Lower Cretaceous, at a depth of 1500 to 2000 m (temperature 57-85°C). The target reservoirs are

siliciclastic and more homogeneous in nature, with flow occurring through matrix porosity and permeability. Hydrocarbon fields are present but are not in exactly the same formation.
As in the western part of the Netherlands, the high concentration of projects requires thought about how to operate multiple projects in close vicinity and how to prevent (or deal with) potential interference between projects with regards to temperature and/or pressure impact.

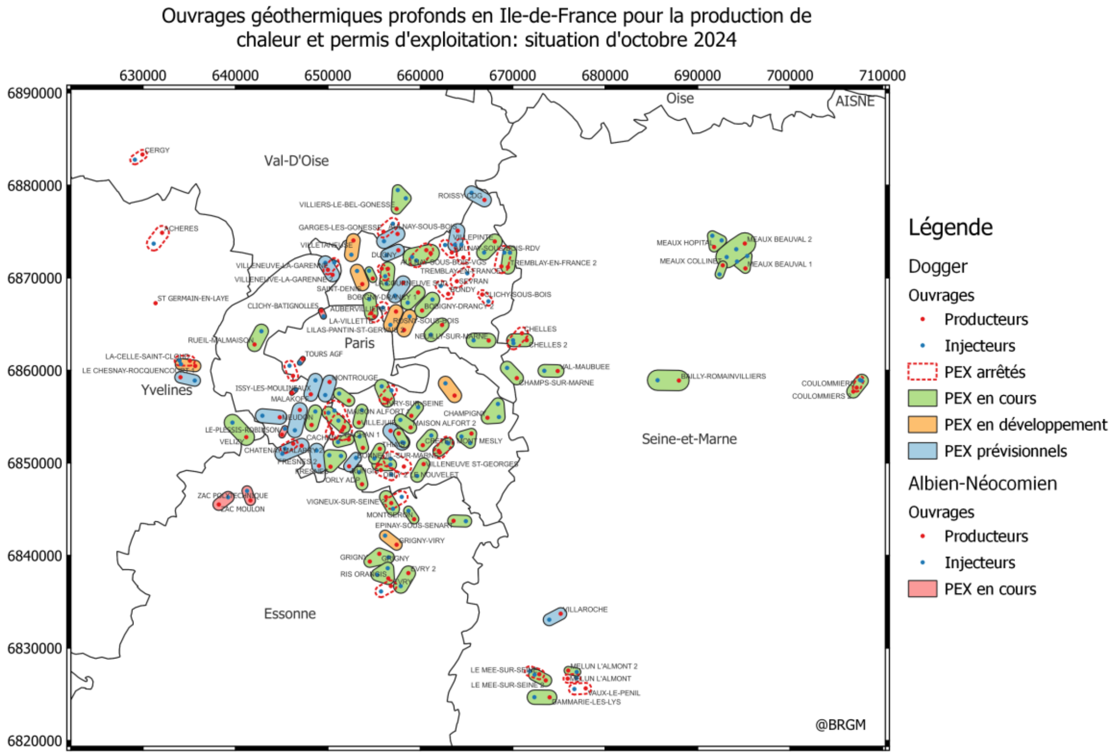


Figure 4: Overview of abandoned, active and planned geothermal projects (wells and licenses) in the Paris area (source: BRGM).

2.3.2 How are boundaries defined?

In France, geothermal licenses are regulated through the *Code Minier*. A distinction is made between the exploration phase and the exploitation phase.

Regarding the exploitation phase, projects with a thermal output below 20 MW have to obtain an exploitation permit (*permis d'exploitation*). In case thermal output reaches 20 MW or exceeds this value, a concession is required. Most projects in the Paris Basin belong to the former category.

The exploitation perimeter is defined in a purely geometrical way. The exploitation volume is defined in the horizontal plane by an envelope encircling the wells (at top reservoir). It contains two circles, one around each well, with half of the distance between the wells as radius (Figure 5). In a vertical direction, these two circles are extended as vertical cylinders. The top of the volume is defined by the shallowest casing shoe at the top of the reservoir, the base of the volume by the deepest well.

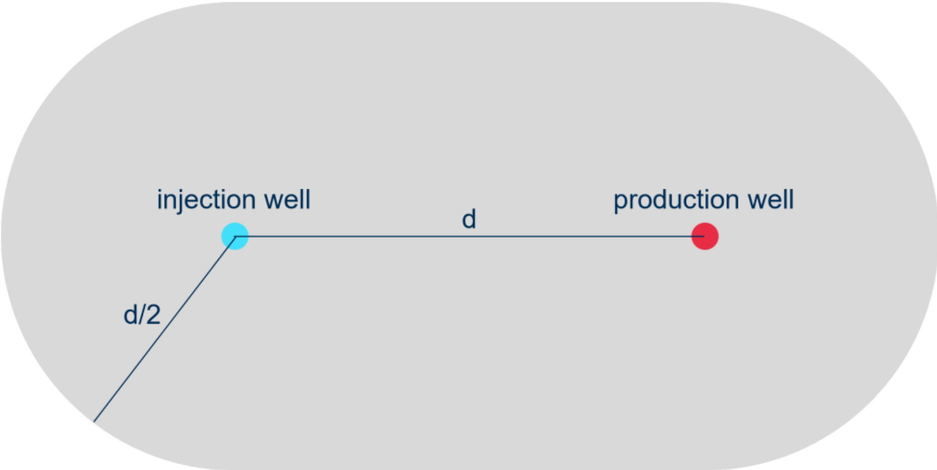


Figure 5: Horizontal projection of geometrical definition of a geothermal license volume in France.

In the application, however, hydraulic and thermal impact of the project are analyzed, in particular on existing projects and operations. Permits should not overlap. In general, hydraulic impact of one project on another should not exceed 1 bar, whereas thermal impact should not exceed 1°C. However, these values are not defined explicitly in the regulations. In specific cases, authorities may intervene and define specific rules.

The project lifetime is usually about 45 years, with the initial permit for 30 years being extended by another 15 years. Considering the long history of extracting geothermal heat in the Paris Basin, cooling was already expected in some places. However, the initial estimates turned out to be on the pessimistic side, as cooling has not set in yet. With the exception of the project in Alfortville where a drop of 3°C was observed, the thermal decrease should not be felt before 2028 or even 2040 according to the simulations (BRGM). Early estimates were based on models considering more pessimistic assumptions and properties (Lopez et al., 2010). In addition, these authors mention the difficulty of detecting small temperature changes due to the reliability of the measurements (usually at surface), the precision of the instruments and measurements, and the impact of the strong seasonal variations in flow rate and injection temperature (in contrast to the stable operational conditions assumed in the models).

2.4 GERMANY

2.4.1 Why Germany and Bavaria?

Similar to the western part of the Netherlands and the Paris Basin, there is a significant number of deep geothermal projects in the Munich area, at short distance from each other. Eighteen projects are present within an area of roughly 850 km^2. Although several projects are operated by Stadtwerke München, there are increasingly more developments from other operators. Hence, estimating and avoiding potential interference between geothermal doublets is therefore essential for an optimal operation and heat production.
Geothermal wells target the Malm reservoir (Upper Jurassic), made up of carbonate strata. Reservoir characteristics may be quite comparable to the Carboniferous Limestone Group in Flanders, with flow occurring through zones of increased permeability in karst and/or fault zones (Hörbrand et al., 2024).
There are active licenses for hydrocarbons in the same area, for example for large-scale exploration. However, there is no practice of having multiple licenses in the same area but

covering different depth ranges (in contrast to Flanders, licenses are defined as areas, not volumes).

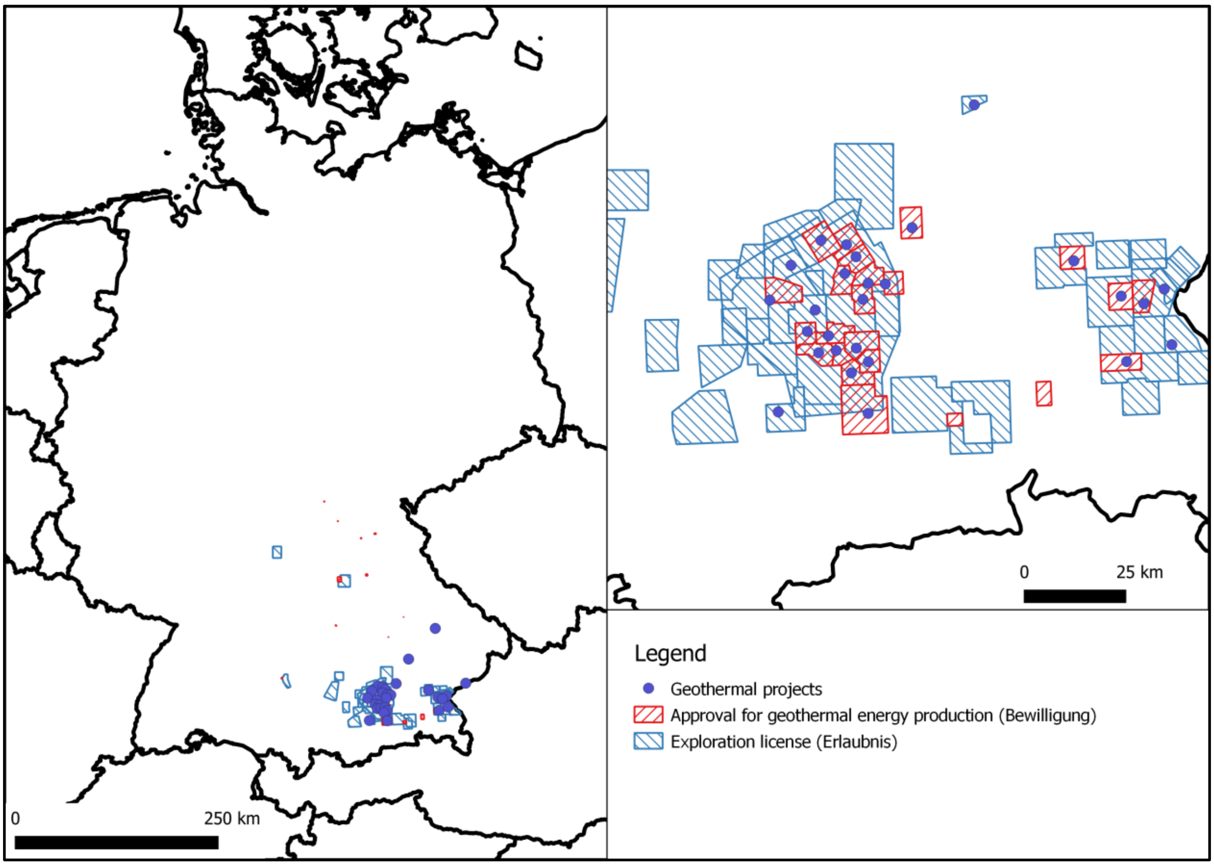


Figure 6: Location of approved geothermal exploration licenses, geothermal energy production licenses and operational projects in the state of Bavaria. A zoom of the Munich area is shown in the top right map. The license areas are taken from https://www.stmwi.bayern.de/energie/bodenschaetze, the geothermal projects are taken from https://geothermie-allianz.de/en/geothermal-plants-in-bavaria. Not all project locations have been identified and shown here.

2.4.2 How are boundaries defined?

All mining activities in Germany are regulated through the *Federal Mining Act*. Here, geothermal resources are defined as freely mineable (Part I Section 3 Freely mineable and freehold mineral resources). Part II Chapter 1 Subchapter 1 Section 6 Principle defines the principle that an exploration license and an extraction license are required to explore for and extract freely mineable resources, respectively. The *Federal Mining Act* does not specify any rules for the determination of license boundaries.
Individual states are responsible for the execution of the regulations, therefore there are different possible interpretations of these regulations due to e.g. regional geological conditions. In Bavaria, practical guidelines are issued at state level to specify how geothermal licenses should be applied for, what information should be submitted and what criteria are used for evaluation.

In Bavaria, applications for an exploration permit for commercial purposes must be submitted in writing to the State Ministry of Economic Affairs, Regional Development, and Energy. The application should contain the following items:

- The resource to be explored
- Identification of the applicant
- An exploration map

- A work program with proposed exploration program, suited in terms of scope and timeline
- The requested duration of the permit (usually 5 years)
- Proof of complete financing
- A declaration according to §11 No. 4 of the *Federal Mining Act* (BBergG.)

The extent of the exploration field is based on the spatial scope of the work program, which should be chosen in such a way that favorable geological conditions are encountered (such as e.g., karstified areas, fault zones). At this stage, no reliable statements can be made on the extent and magnitude of the hydraulic and thermal impact.

Applications for an approval of geothermal energy production must be submitted in writing to the State Ministry of Economic Affairs, Regional Development, and Energy. The application should contain the following items:

- Identification of the applicant
- Identification of the mineral resource to be extracted
- A plan of the site, with specific locations (XYZ) of where the resources were discovered
- Proof of technical recoverability, including results of circulation tests, production temperature, water chemistry, etc.
- A technical work program
- The utilization concept (e.g. heat, electricity)
- A geothermal heat mining report with a site-specific structural-geologic model and simulation results showing pressure and temperature changes around the wells; specifically the hydraulic drawdown line of 10 m (1 bar) and the thermal cooling line of 1°C have to be indicated
- The requested approval period, with a maximum of 50 years
- Proof of financing

The boundaries of the license field are based on results of reservoir models and simulations, taking into account the hydraulic and geologic conditions, and using recognized software. The following criteria are used to define the boundaries:

- A maximum thermal impact at the field boundary of 1°C
- A maximum hydraulic impact at the field boundary of 1 bar
- A maximum hydraulic drawdown of 1 bar on existing geothermal wells in neighboring fields

In some cases, exploration and production license areas overlap. This may occur when the same operator holds both licenses and exploration continues while a first project with production license has been developed. This can also happen when there is shared ownership. In some cases, different operators have overlapping licenses if their activities (e.g. production vs. large-scale exploration) do not interfere directly.

There are plans in Germany to change licensing and regulations for deep geothermal projects (*Geothermal and Heat Pump Act*, GeoWG). These focus on prioritizing geothermal projects, moving to digital procedures and shortening the time required to process and approve license applications.

3 DEFINITION OF RESERVOIR SETTINGS

In this study, dynamic reservoir models are used to analyze the pressure and temperature impact around geothermal doublets. The results are used to evaluate the potential license area (or volume) required. Before being able to run these reservoir simulations, a static model of the reservoir needs to be constructed. The static model incorporates the geological structure(s) with the depth and position of different permeable and impermeable layers, and faults, as well as the interrelationship these features. In addition, the static model includes the properties of the various rocks (porosity, permeability, thermal conductivity, heat capacity, etc.).
The geological structure and the rock properties are not constant in the Campine Basin. They vary from one location to another. Setting up numerous location-specific models is not within the scope of this study. In this project we set up a limited number of representative static models. For this, three concepts were proposed, each representing a different reservoir setting with its own structural context and reservoir properties. The structural setting for the Carboniferous Limestone Group was defined based on the G3Dv3 regional geological model of Flanders and its latest update (Deckers et al., 2019; Rombaut et al., in review). Further variation of the reservoir properties was done as part of subsequent tasks and chapters.

In a first approximation, three settings can be distinguished for the Carboniferous Limestone Group in the Campine Basin.

1. An area in the western part of the Campine Basin, where the Carboniferous Limestone Group is present at relatively shallow depth (roughly between 1000 and 2000 m below TAW), has been exposed before the deposition of Namurian sediments, and those overlying strata are limited in thickness.
2. An area along the southern margin of the Campine Basin, where the Carboniferous Limestone Group is present at shallow depth (less than 1000 m below TAW) and is present directly below the base Cretaceous unconformity.
3. A large area in the central and eastern part of the Campine Basin where the Carboniferous Limestone Group is present at greater depth (between around 1000-2000 and more than 6000 m below TAW) and is covered by a rather thick interval of Namurian sediments.

3.1 RESERVOIR CONCEPT 1

3.1.1 Occurrence

The area in the western part of the Campine Basin is almost triangular (Figure 7). The vertices of the triangle are located just Northeast of Turnhout, just South of Herentals, and the western side of Wuustwezel. The area is bounded by:

- the roughly E-W oriented Hoogstraten fault structure to the North, where the Carboniferous Limestone Group deepens rapidly;
- the (mainly fault-related) rapid deepening of the Carboniferous Limestone Group to the East to Southeast;
- the decrease in depth of the Carboniferous Limestone Group and the pinching out of the overlying Upper Carboniferous strata to the Southwest, where it eventually occurs directly below the base Cretaceous unconformity.

The presence of reservoir concept 1 in the area further Southeast, in the depth range of 1000 to 1500 m, is speculative.

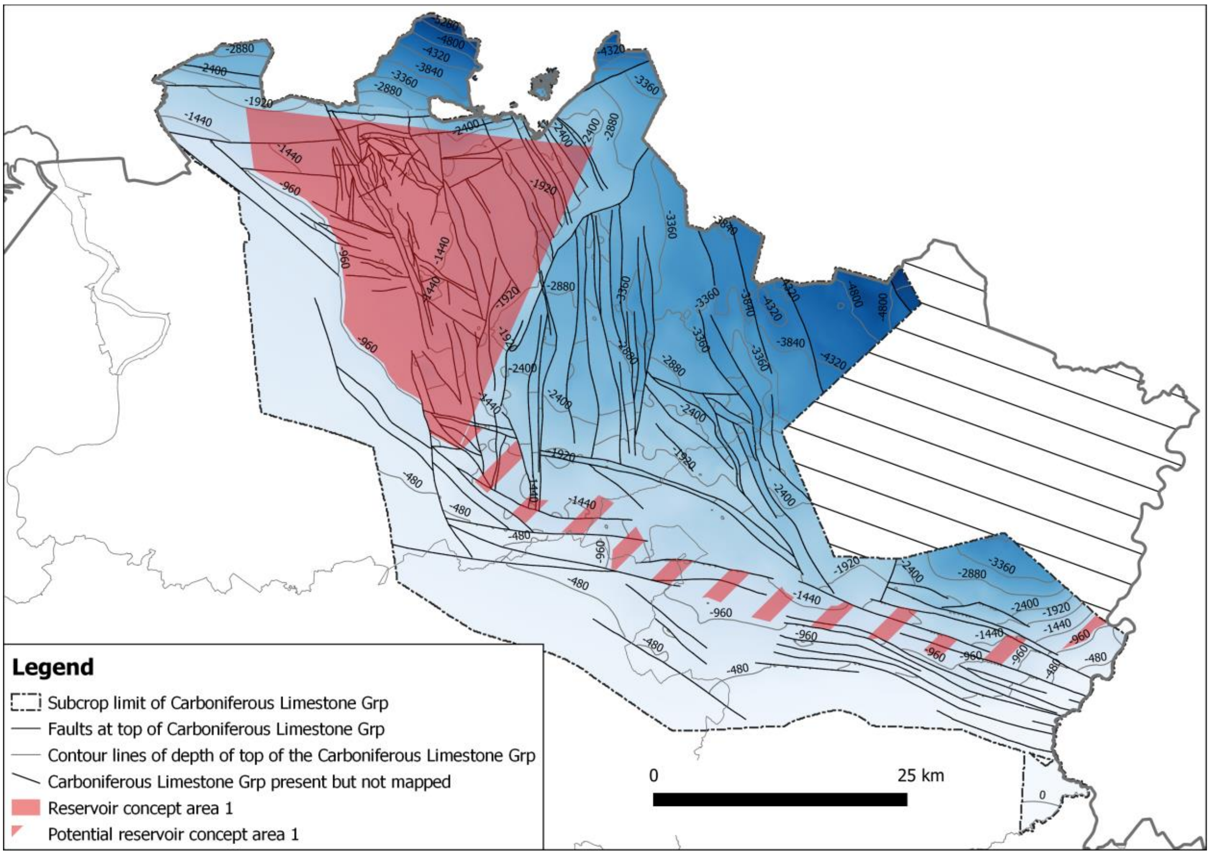


Figure 7: Location of reservoir setting 1 in the western part of the Campine Basin. Depth of the top of the Carboniferous Limestone Group and fault traces according to the latest update to the G3Dv3 regional geological model of Flanders (Rombaut et al., in review)

3.1.2 Description

This area is characterized by the relatively shallow depth of the top of the Carboniferous Limestone Group (between 1000 and 2000 m below TAW) and by the rather thin cover of overlying Namurian and Westphalian strata. Before the deposition of these overlying sediments, the area was elevated and emersion has caused karstification in the upper levels of the carbonate rocks.
During later burial and associated diagenetic processes, the original karst porosity has been reduced just about completely. However, additional secondary porosity (and permeability) has been created at a later stage, not necessarily coinciding with the previous karst. This secondary porosity has been encountered in various wells in the area such as in Loenhout, Merksplas, Turnhout and Beerse.

Wells usually encounter permeable intervals in the top 100 to 200 m within the Carboniferous Limestone Group, like e.g. in Turnhout (Gulinck, 1956) or Merksplas (Vandenberghe et al., 2000). These do not necessarily occur along the same stratigraphic layers, although the creation of secondary porosity is considered to be influenced by the lithology and mineralogy of the rocks. Faults (or fault zones) are considered to have played a role in fluid migration leading to the creation and enhancement of secondary porosity. Therefore, the reservoir concept includes porous and permeable zones both along the faults as well as along layers in between the faults (Figure 8). Porosity and permeability are expected to decrease gradually away from the fault zones.

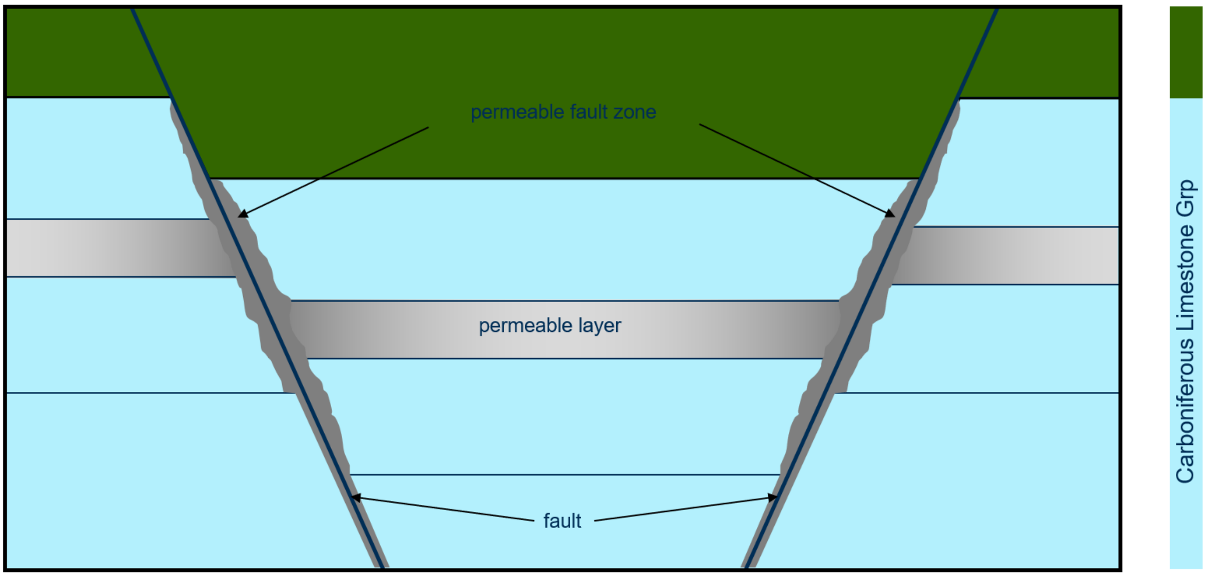


Figure 8: Reservoir concept 1 with secondary porosity (and permeability) occurring along fault zones and along layers within the fault blocks. Porosity and permeability are expected to decrease away from the fault zones (as indicated by shading).

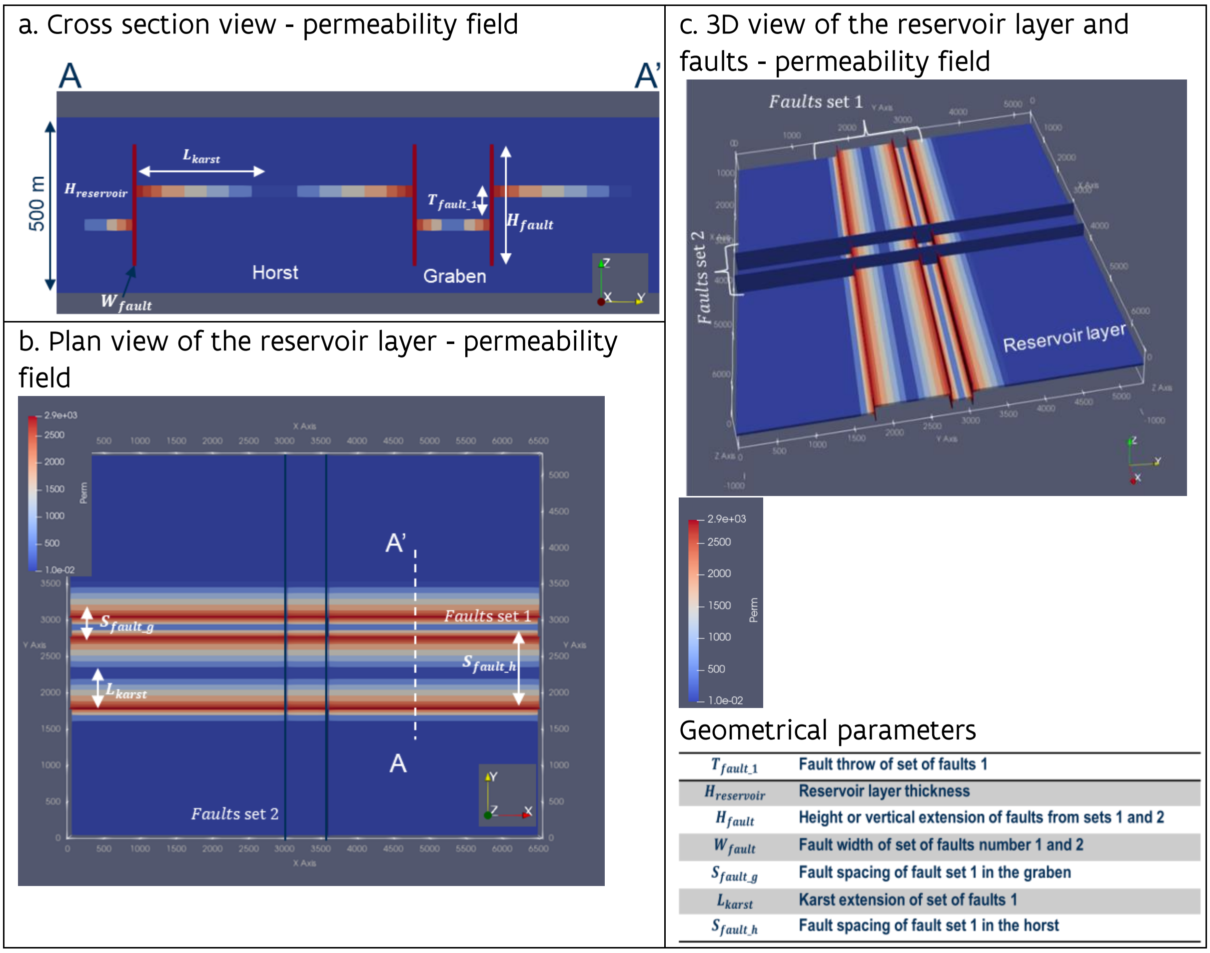
3.1.3 3D model representation of concept 1

A general conceptual 3-dimensional geological model was built for concept 1 (see Figure 9) following the characteristics that were previously mentioned and indicated in Figure 8. This model will be used as a basis for the definition of the optimum area and volume for open-loop geothermal applications (doublets) in the Carboniferous limestone reservoirs.

The model considers structural features like graben and horst structures delimited by their corresponding faults, defined here as set of faults 1. The possibility was also considered to have a second set of faults orthogonal to fault set 1. Both fault sets are vertical and intersect the reservoir layer.

The reservoir layer is the target for the geothermal production in this model, it is embedded within an ultra-low permeability rock. Its permeability and porosity are heterogeneous, being higher next to the first set of faults and decreasing linearly towards the center of the structures until a certain distance called here ‘karst extension’. This was done to mimic the presence of karst.

Regarding the dimensions, the total thickness of the model is 500 meter while the length (x direction) and the width (y direction) are 6.5 km and 5.5 km respectively.



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

Figure 9: Geological model of Concept 1 for geothermal reservoir simulation displaying the permeability field [mD]. The main geometrical characteristics are indicated in every view. a. cross-section indicating the non-reservoir and reservoir regions (low and high permeability respectively), b. plan view of the reservoir layer, c. 3D view of the reservoir layer.

3.2 RESERVOIR CONCEPT 2

3.2.1 Occurrence

Reservoir setting 2 is situated along the southern (to southwestern) margin of the Campine Basin (Figure 10). It runs from Northwest, in the vicinity of Kalmthout, to Southeast, near Maastricht. The southern boundary of the area is defined by the pinching out of the Carboniferous Limestone Group. The northern boundary is taken slightly North of the subcrop limit of the overlying Namurian sediments (South of this line the Carboniferous Limestone Group covered directly by Cretaceous sediments, further North it is covered by Namurian strata), at a depth of roughly 1000 m below TAW.

3.2.2 Description

Here, the Carboniferous Limestone Group is present directly below the base Cretaceous unconformity. The depth of the top of the interval usually amounts to less than 1000 m below TAW. The emergence and exposure of the carbonate rocks prior to the Late Cretaceous may have caused karstification in the top of the sequence (Figure 11). Similar to reservoir concept 1, fluid migration along faults may have played a role in the creation of secondary porosity. This may have occurred at deeper levels within the Carboniferous Limestone Group. Karstification may also have occurred slightly basinward as fluid migration may have continued for some distance. The presence of permeable zones in the fault blocks is envisaged comparable to reservoir setting 1.

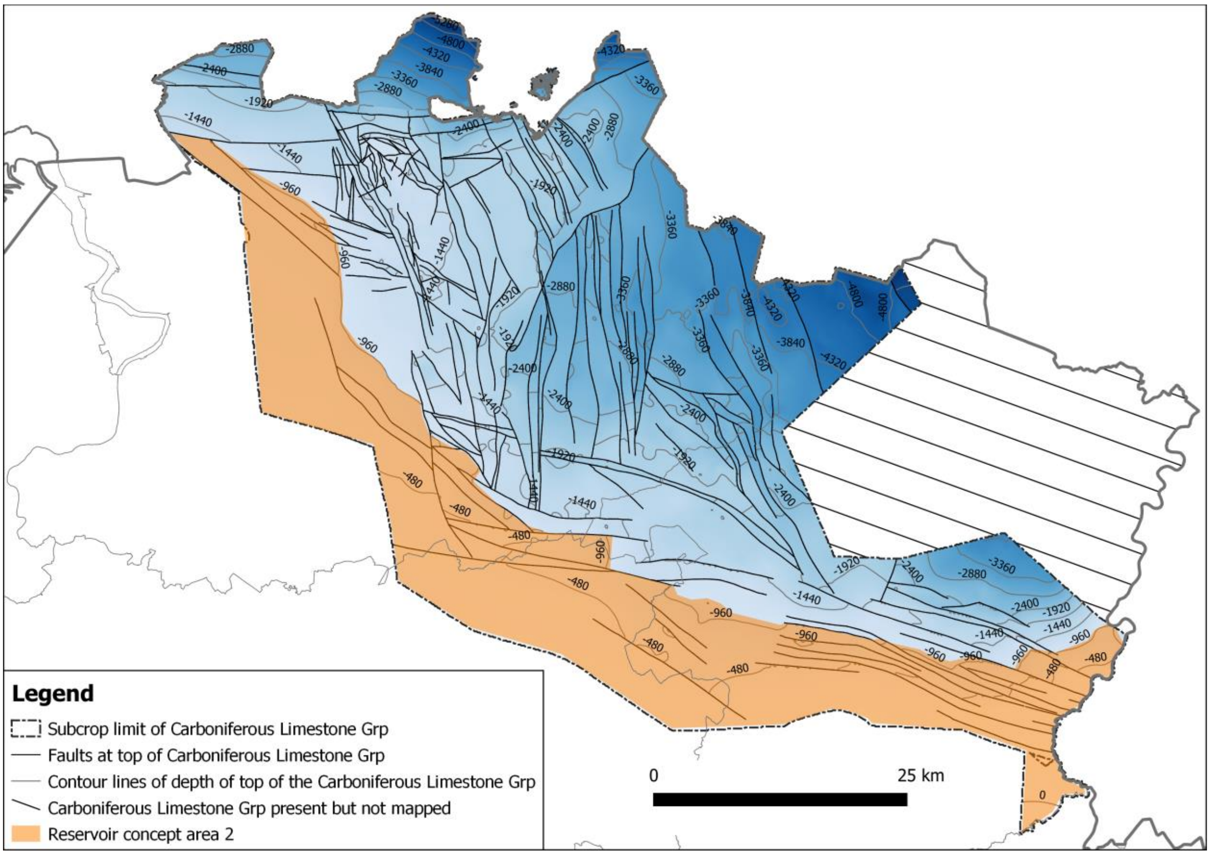


Figure 10: Location of reservoir setting 2 along the southern margin of the Campine Basin. Depth of the top of the Carboniferous Limestone Group and fault traces according to the latest update to the G3Dv3 regional geological model of Flanders (Rombaut et al., in review).

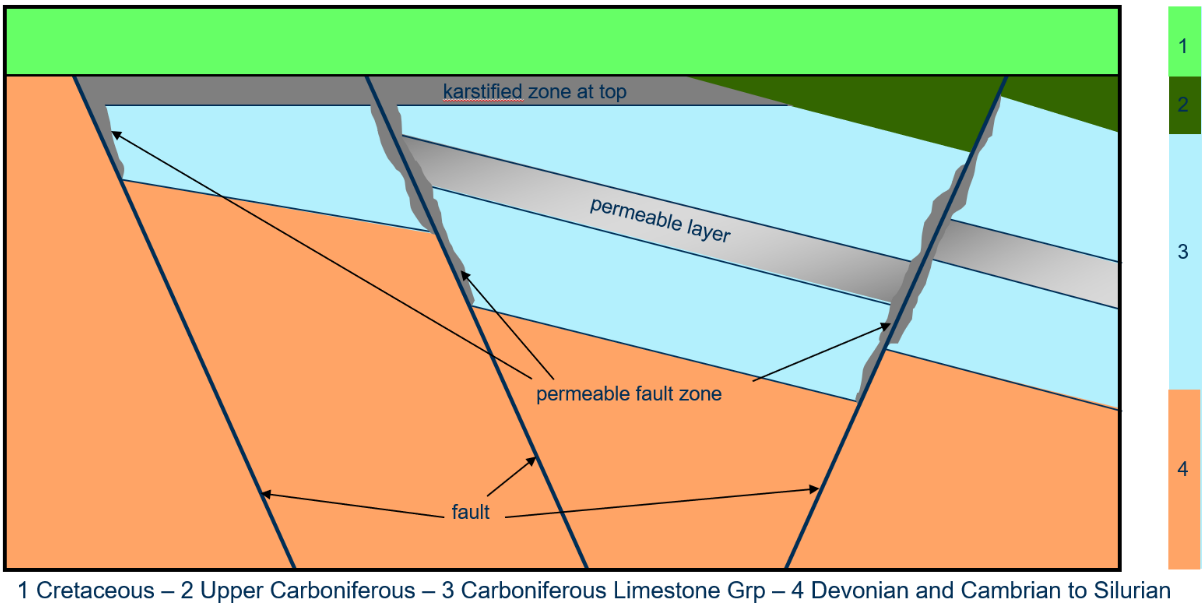
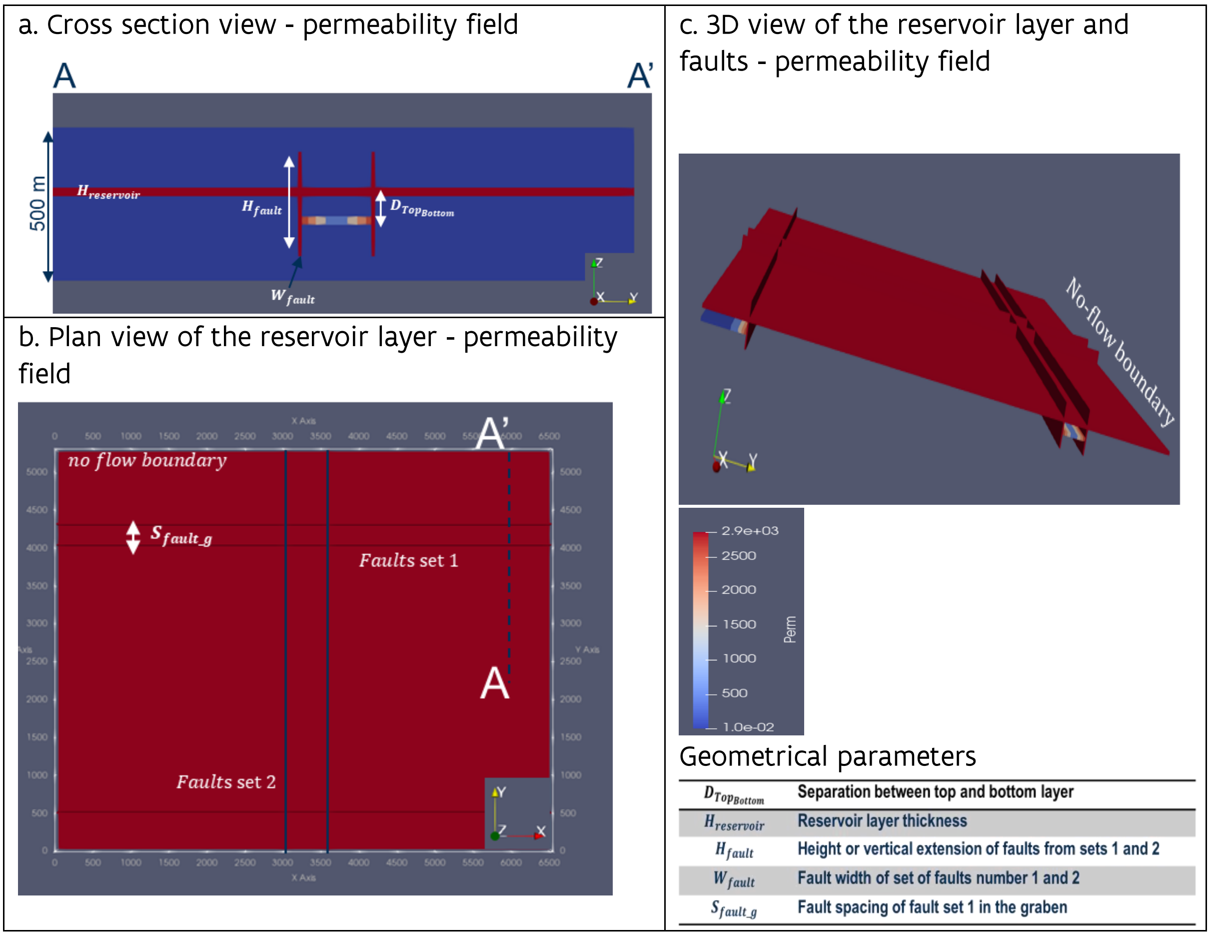


Figure 11: Reservoir concept 2 with secondary porosity (and permeability) occurring at the top of the Carboniferous Limestone Group (directly below the base Cretaceous), as well as along fault zones and along layers within the fault blocks. For the permeable zones in between the fault zones, porosity and permeability are expected to decrease away from the fault zones (as indicated by shading).

3.2.3 3D model representation of Concept 2

The 3D geological model of Concept 2 is like Concept 1 in terms of geological structural features. Nevertheless, a continuous reservoir layer at the top was additionally considered, which represents a karst layer that is expected to be near to the unconformity between the Cretaceous and the Lower Carboniferous (still to be proven).

Figure 12 describes the final representation of Concept 2 in 3 dimensions. The geothermal simulation analysis will be carried out in between the graben structure and the no-flow boundary of the model.



$D_{TopBottom}$	Separation between top and bottom layer
$H_{reservoir}$	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

Figure 12: Geological model of Concept 2 for geothermal reservoir simulation displaying the permeability field [mD]. The main geometrical characteristics are indicated in every view. a. cross-section indicating the non-reservoir and the 2 reservoir layers. The top reservoir layer (red) is continuous and its petrophysical properties homogeneous while the bottom layer is limited to the graben, b. plan view of the reservoir layer, c. 3D view of the reservoir layer.

3.3 RESERVOIR CONCEPT 3

3.3.1 Occurrence

The large central, eastern and northern part of the Belgian Campine Basin can be attributed to concept 3. It runs from the area Northeast of Turnhout (Ravels and Poppel) to the South of Herentals. To the East it runs until the border with the Netherlands near Lanaken. The boundaries are defined on the western side by the rapid deepening (from West to East) of the top of the Carboniferous Limestone Group below 2000 m (and thickening of the overlying Namurian sediments); on the southern side the area is adjacent to the area of concept 2 (or potentially an intermediate area of concept 1), again where depth increases northwards. The presence of a zone where concept 1 occurs in between both concepts 2 and 3 is uncertain. It would shift the southern limit of concept 3 further to the North by 5-10 km.

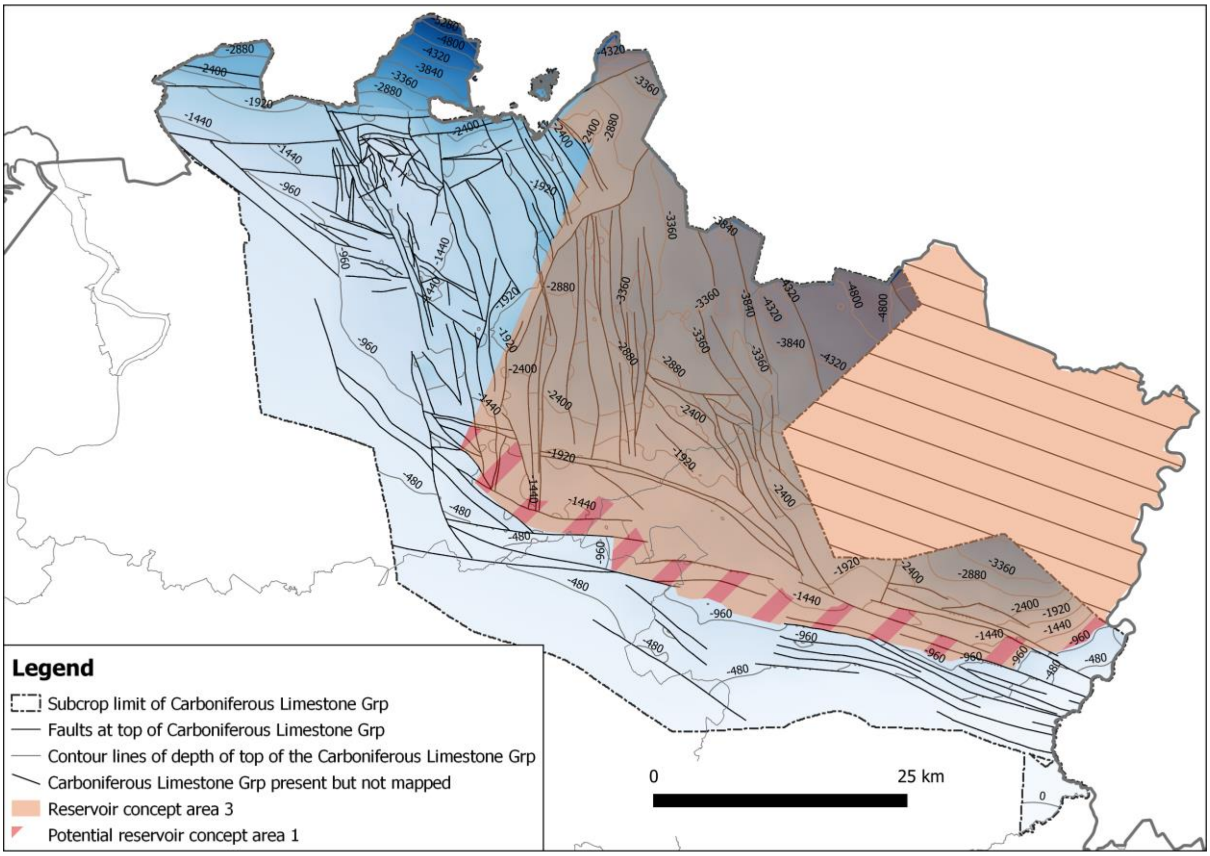


Figure 13: Location of reservoir setting 3 in the central, northern and eastern part of the Belgian Campine Basin. Depth of the top of the Carboniferous Limestone Group and fault traces according to the latest update to the G3Dv3 regional geological model of Flanders (Rombaut et al., in review).

3.3.2 Description

In the area of concept 3, the Carboniferous Limestone Group is covered by a thick sequence of Namurian sediments. The top of the interval is present at a depth of around 2000 m below TAW along the western and southern margins of the area. Further North and East, depth increases to 3000 to 5000 m. Within the Roer Valley Graben in the Northeast, depth may increase further to 6000-8000 m. The creation of secondary porosity in this area was probably limited, it may only occur in relatively narrow zones along fault zones and over small distances away from the faults. Its overall occurrence remains poorly understood (Broothaers, Bos, et al., 2020). Continuous layers with increased porosity and permeability occurring over larger areas are not expected. Permeable zones along more or less parallel fault zones (NW-SE to N-S) may be connected to each other by another set of faults with different orientation (E-W to WNW-ESE).

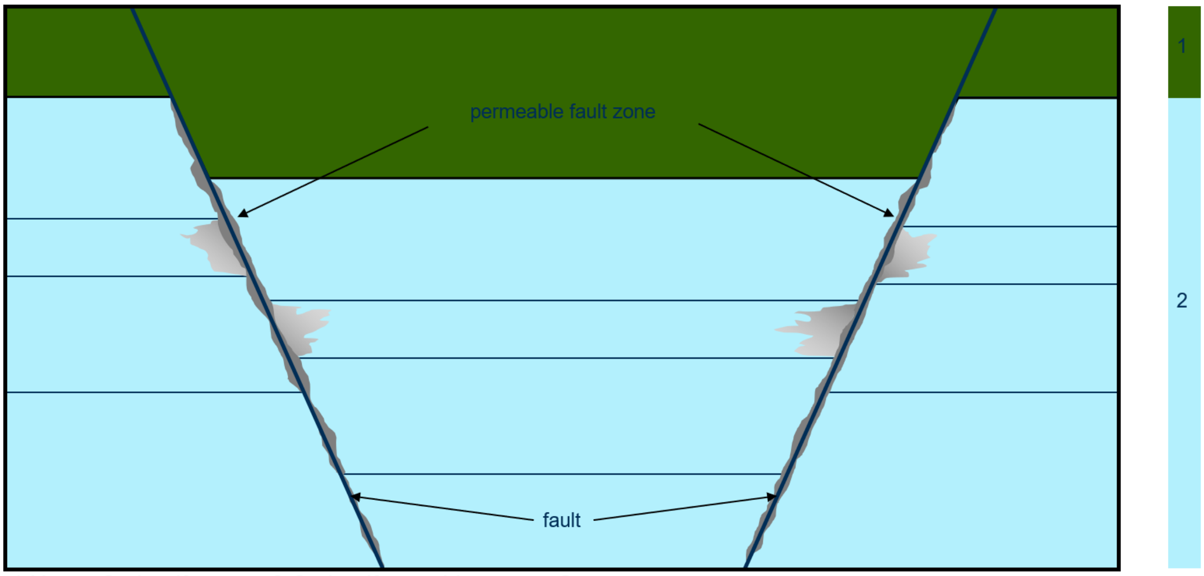


Figure 14: Reservoir concept 3 with secondary porosity (and permeability) occurring along thin zones in and around fault zones. Depending on the mineralogy of the adjacent strata, secondary porosity and permeability may extend a short distance away from the faults. Cross-cutting faults with different orientation may connect the parallel fault zones shown.

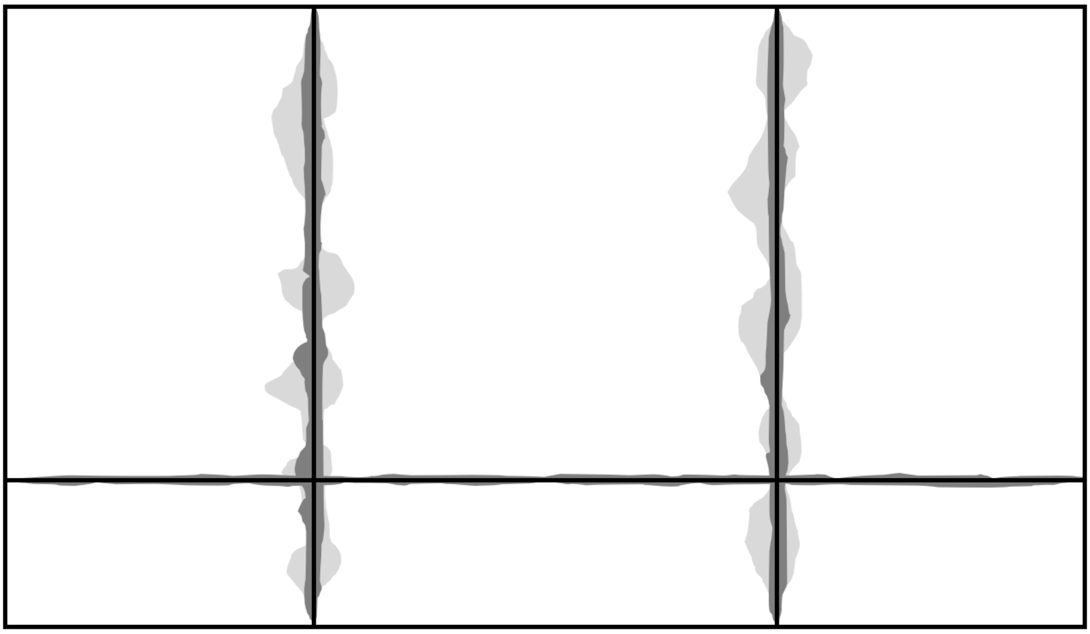


Figure 15: Map view of reservoir concept 3 with secondary porosity and permeability occurring along thin zones around faults. Parallel faults may be connected by cross-cutting faults of different orientation.

3.3.3 3D model representation of Concept 3

The model of Concept 3 has the same structural, stratigraphic and petrophysical elements as Concept 1 as shown in Figure 14. Nevertheless, instead of having a karstified region next to the faults it has an enhanced reservoir region instead (‘$L_{Enhanced}$’). This region is assumed to be created by diagenetic and mechanical (fracturing) processes. The length of the enhanced reservoir region is assumed shorter than the karst length in Concept 1 as shown in Figure 16, which makes this concept low in both transmissivity and porous volume. This consideration leads to the faults playing an important role in the flow during geothermal operations.

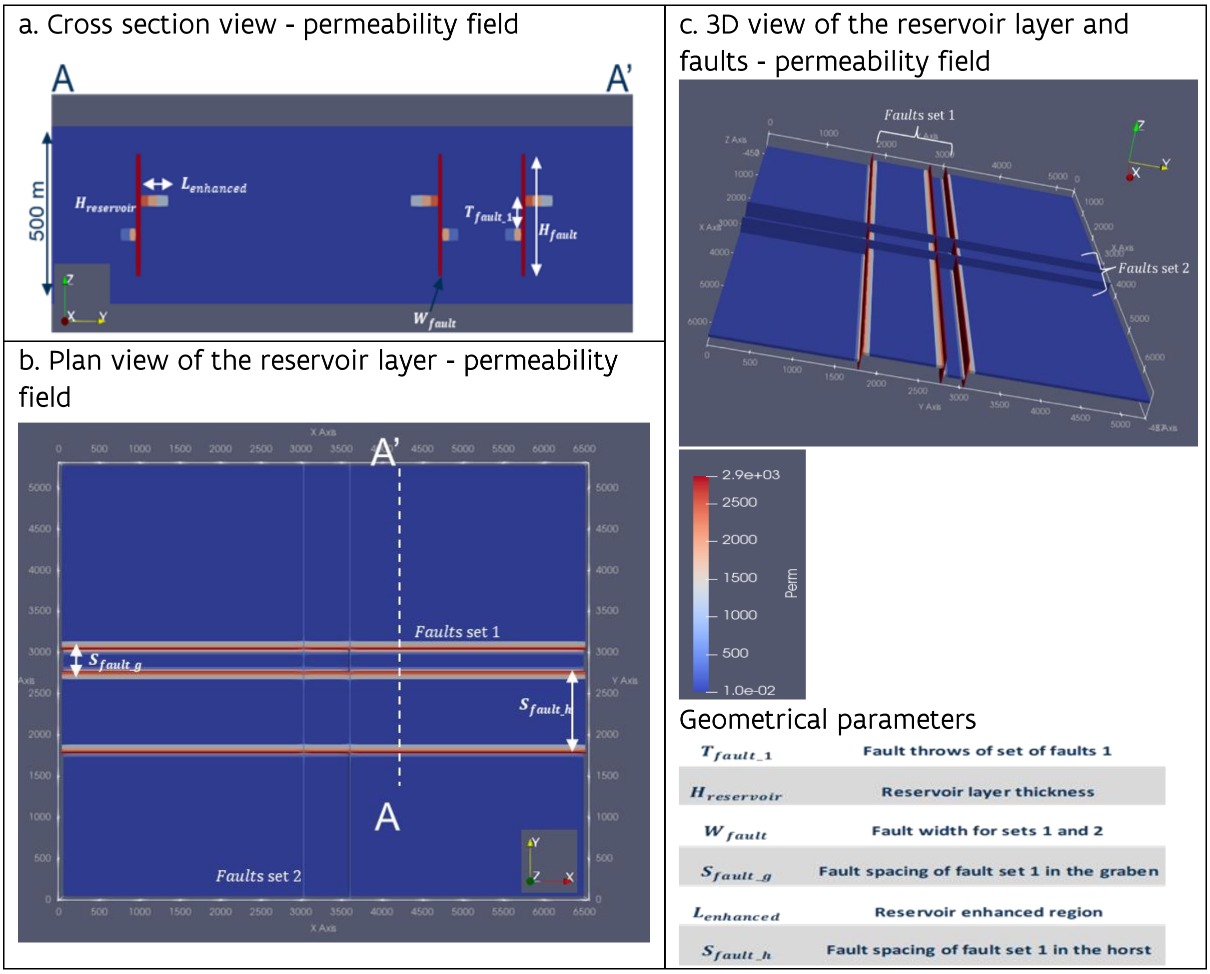


Figure 16: Geological model of Concept 3 for geothermal reservoir simulation displaying the permeability field [mD]. The main geometrical characteristics are indicated in every view. The length of the enhanced reservoir region is shorter than the karts length in Concept 1. a. cross-section indicating the non-reservoir and reservoir regions (low and high permeability respectively), b. plan view of the reservoir layer, c. 3D view of the reservoir layer.

4 DEFINITION OF SCENARIOS AND PARAMETERS

After defining the structural framework, setting and reservoir concept, it is time to look at what parameters and scenarios are to be included in the evaluation. First, relevant parameters need to be identified. In a second step they must be quantified and appropriate values chosen.
Petrophysical, thermal and geometrical reservoir characteristics for the 3 reservoir concepts were defined based on the current knowledge of the Carboniferous Limestone Group in Flanders. Thus, the 3D model of the Dinantian in the Campine (Deckers et al., 2019), the wells drilled in this basin and the performance of current geothermal projects (Beerse and Mol) were used for defining their values. The values of these parameters for the base case are shown in the Table 1.

4.1 PETROPHYSICAL PARAMETERS

The porosity and permeability of non-reservoir layers was set according to values from well log analysis and core samples. These indicate very low values for the matrix porosity: 0.5-2% in Poederlee (Laenen et al., 2006) and very low permeability even below the 1 mD range. Hence, 1.5% and 0.01 mD were chosen as values for all three concepts. Slightly higher values were chosen as the background value for the reservoir layers (3% and 10 mD respectively). Porosity for permeable zones in the reservoir appear to be in the order of 10-20%, as reported by Vandenberghe et al. (2000) for the Merksplas-Beerse well. Permeability in these zones, both in the fault zones as well as the maximum value in the reservoir layer (karst), was set at 2857 mD for an average reservoir layer thickness of 35 m. This value was chosen towards the high values derived from well tests.
The value for thermal conductivity of 2.41 W/m.K was taken as the mean value listed for the Carboniferous Limestone Group by Broothaers et al. (2020).

Table 1: Petrophysical parameters considered for the base case of the 3 reservoir concepts.

		Base case			
Parameter	Description	Concept 1	Concept 2	Concept 3	Unit
$\check{k}_{reservoir}$	Minimum reservoir layer permeability	10	10	10	mD
$\check{\phi}_{reservoir}$	Minimum reservoir layer porosity	3	3	3	%
$k_{top\_reservoir}$	Homogeneous permeability of top layer (only for concept 2)	-	2857	-	mD
k_y / k_x	Horizontal permeability anisotropy in the rock's matrix	1	1	1	-
$\check{k}_{non\_reservoir}$	Minimum non-reservoir layer permeability	0.01	0.01	0.01	mD
$\check{\phi}_{non\_reservoir}$	Minimum non-reservoir layer porosity	1.5	1.5	1.5	%
$\check{\lambda}_{reservoir}$	Reservoir layer thermal conductivity	2.41	2.41	2.41	W/m/°K
$\check{C}_{reservoir}$	Reservoir rock heat capacity	2200	2200	2200	kJ/m3/°K
$\check{\lambda}_{non\_reservoir}$	Non-reservoir layer thermal conductivity	2.41	2.41	2.41	W/m/°K
$\check{C}_{non\_reservoir}$	Non-reservoir rock heat capacity	2200	2200	2200	kJ/m3/°K
$\widehat{k}_{karst}$	Maximum karst permeability in reservoir layers next to the faults	2857	2857	2857	mD
$\widehat{\phi}_{karst}$	Maximum karst porosity in reservoir layers next to the faults	10	10	10	%
k_{fault_1}	Permeability of fault set 1	2857	2857	2857	mD
ϕ_{fault_1}	Porosity of fault set 1	10	10	10	%
T_{fault_1}	Fault throws of fault set 1	100	100	100	[m]
k_{fault_2}	Permeability of fault set 2	No fault set	No fault set	500	mD
ϕ_{fault_2}	Fault porosity of fault set 2	No fault set	No fault set	5	%

4.2 GEOMETRICAL PARAMETERS

The main geometrical parameters were the reservoir layer thickness, the lateral extension of the secondary porosity and permeability (karst) away from the faults, the fault throw, the dimensions of the faults (height and width), and their spacing. For concept 2, the vertical separation between the upper and lower permeable layer was also considered.

The reservoir layer thickness was set at 35 m based on observations reported from wells in Merksplas-Beerse, Turnhout and Oostmalle, where values appear to be in the range of 30 to 50 m. The geometrical parameters related to the faults were defined based on the fault characteristics at the top of the Carboniferous Limestone Group as included in the G3Dv3 model (Deckers et al., 2019). An average fault throw of 100 m was considered. The average fault spacing was set at 1000 m for the graben structures and 300 m for the horst structures. The maximum extension of the karst was defined accordingly.

Table 2: Geometrical parameters considered in the base case of the 3 reservoir concepts. Fault height is the vertical extension of the fault and the associated permeability.

		Base case			
Parameter	Description	Concept 1	Concept 2	Concept 3	Unit
$D_{Top_{Bottom}}$	Separation between top and bottom layer (only for concept 2)	-	100	-	[m]
k_y / k_x	Horizontal permeability anisotropy ratio in the rock's matrix	1	1	1	-
$H_{reservoir}$	Reservoir layer thickness	35	35	35	[m]
L_{karst}	Karst extension fault set 1	500	500	--	[m]
$L_{enhanced}$		--	--	150	
T_{fault_1}	Fault throw of fault set 1	100	100	100	[m]
H_{fault}	Fault height for sets 1 and 2	352	352	352	[m]
W_{fault}	Fault width for sets 1 and 2	15	15	15	[m]
S_{fault_g}	Fault spacing of fault set 1 in the graben	300	300	300	[m]
S_{fault_h}	Fault spacing of fault set 1 in the horst	1000	Not apply	1000	[m]
$S_{fault\_set\_2}$	Fault spacing of fault set 2	600	600	600	
$k_{fault\_1} * W_{fault}$	Fault set 1 flow capacity	42.8	42.8	42.8	[Darcy*m]
$k_{fault\_2} * W_{fault}$	Fault set 2 flow capacity	No fault set (equal to rock flow capacity)	No fault set (equal to rock flow capacity)	7.5	[Darcy*m]

4.3 PARAMETER SELECTION

After evaluation of all the parameters, the following selection was made for further analysis in the sensitivity study (presented in the next chapter). Other parameters were considered to have lower impact and/or have smaller uncertainty on the values.

Table 3: List of parameters selected for the sensitivity analysis

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

4.4 WELL CONFIGURATIONS

In addition to the petrophysical and geometrical parameters, different well configurations were defined and tested (in the sensitivity analysis) for the three reservoir concepts. Three configurations were defined for each concept.

4.4.1 Concept 1

For concept 1, the base case configuration has a production well in the fault zone, while the injection well is positioned on the horst, roughly halfway between the middle of the horst and the next parallel fault. The reason for this setup is that having the production well in the fault zone maximizes productivity as permeability is higher in the fault zone and the karst zone adjacent to it. In addition, an injection well on the horst allows to reduce the depth of that well (and hence save costs). The injection well is not situated in the middle of the horst, as according to the reservoir concept the middle of the fault block has the lowest permeability (permeability decreasing with distance from the faults). The injection well is not located in a fault zone, because of the impact of increased fluid pressure on seismic risk. Because of the resemblance, this base case will sometimes be referred to as the L-shaped configuration.
It is worth noticing that existing doublets targeting the Carboniferous Limestone Group in the Campine Basin and adjacent areas have well configurations comparable to this base case. Both in Beerse and in Horst a/d Maas in the Netherlands, the production wells target a fault zone, whereas the injection well is drilled away from the fault on a shallower fault block. The production well in Mol also targets a fault zone, with the injection well drilled away from the fault, however not in the horst.

An alternative well configuration combines a production well in the center of the graben with an injection well in the horst (as in the base case). This configuration is referred to as the minimum case (or 1).
A third configuration (maximum case or 2) has the production well in the fault zone, as in the base case, but combined with an injection well in the center of the graben.

The well configurations for concept 1 are illustrated in Figure 17. All three configurations were included in the sensitivity analysis, only the base case has been used in subsequent modelling.

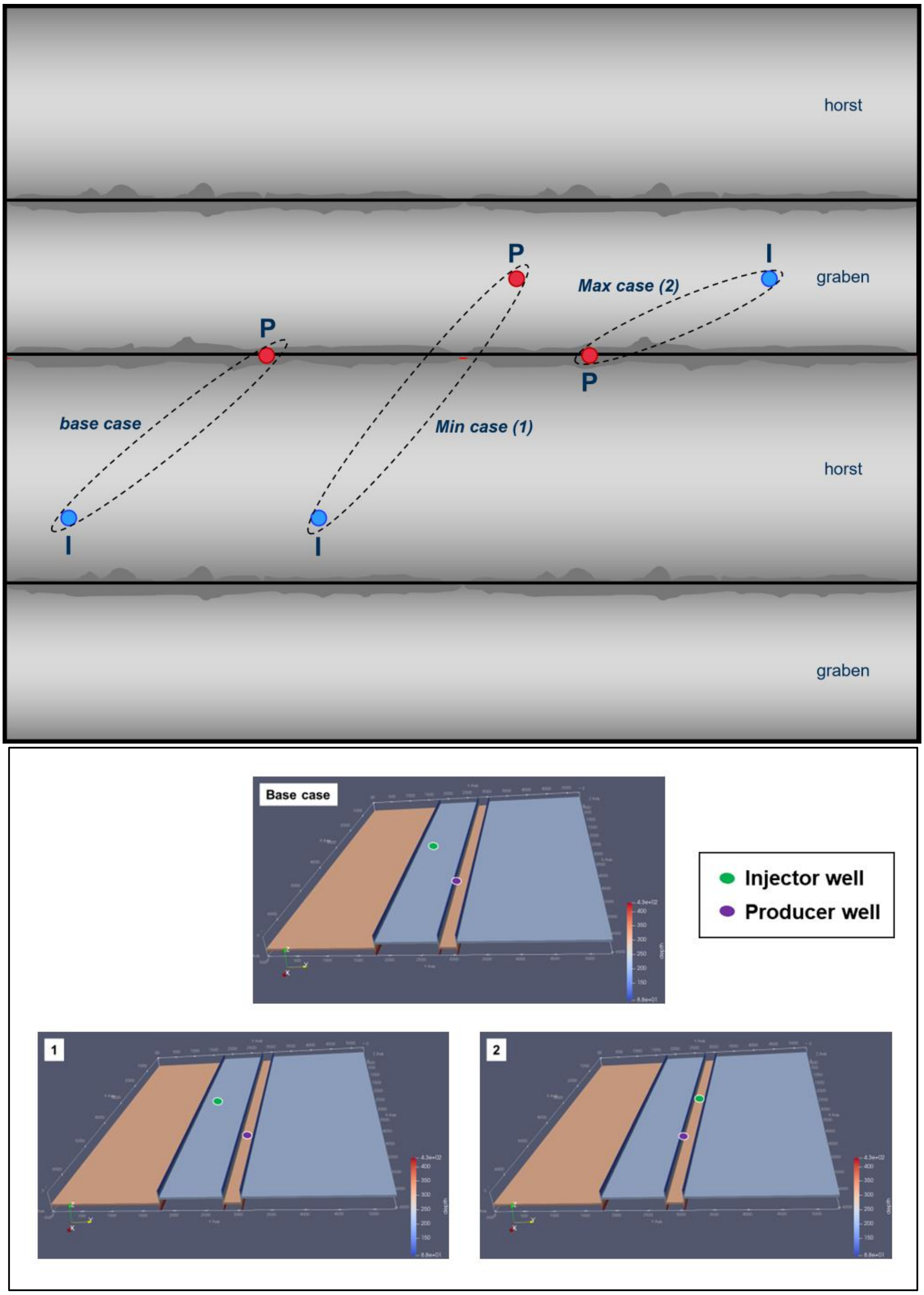


Figure 17: Map view (top) and 3D view (bottom) of well configurations and tagging used during sensitivity analysis on reservoir concept 1.

4.4.2 Concept 2

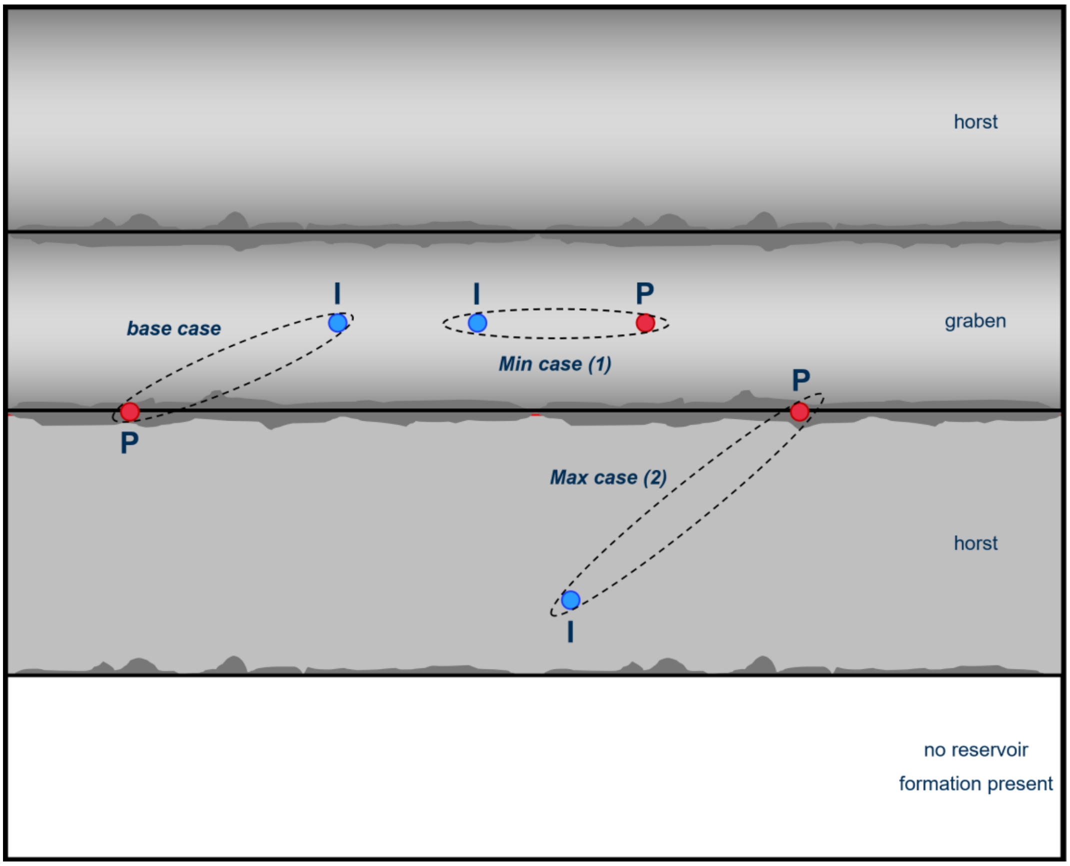
The reference or base case for concept 2 has the production well in the fault zone and the injection well in the center of the graben. The producer targets enhanced permeability in the fault zone and is completed in the lower depth range where the deeper permeable layer in the graben is situated. This allows to increase production temperature, although some permeability in the shallower permeable layer is left unused. In addition to the deeper layer, the injection well also targets the shallower reservoir layer at the top (distinguishing this concept from concept 1). This allows the injected fluid to be distributed in two permeable layers (increasing injectivity of the well).

In the minimum case (or 1), the well configuration has both wells positioned in the middle of the graben. Production takes place in the deeper permeable layer, whereas injection occurs in the top permeable layer. Both layers are connected through the permeable fault zone.

The configuration in the maximum case (or 2) has the same position for the production well as in the reference case. However, the injector is placed in the horst towards the subcrop limit of the formation, where it targets only the permeable layer at the top. This setup has lower injectivity compared to the base case as only a single layer is used, but a shallower injection well reduces drilling costs.

There is currently no geothermal doublet in the reservoir concept 2 area.

The well configurations for concept 2 are illustrated in Figure 18. All three configurations were included in the sensitivity analysis, only the base case has been used in subsequent modelling.



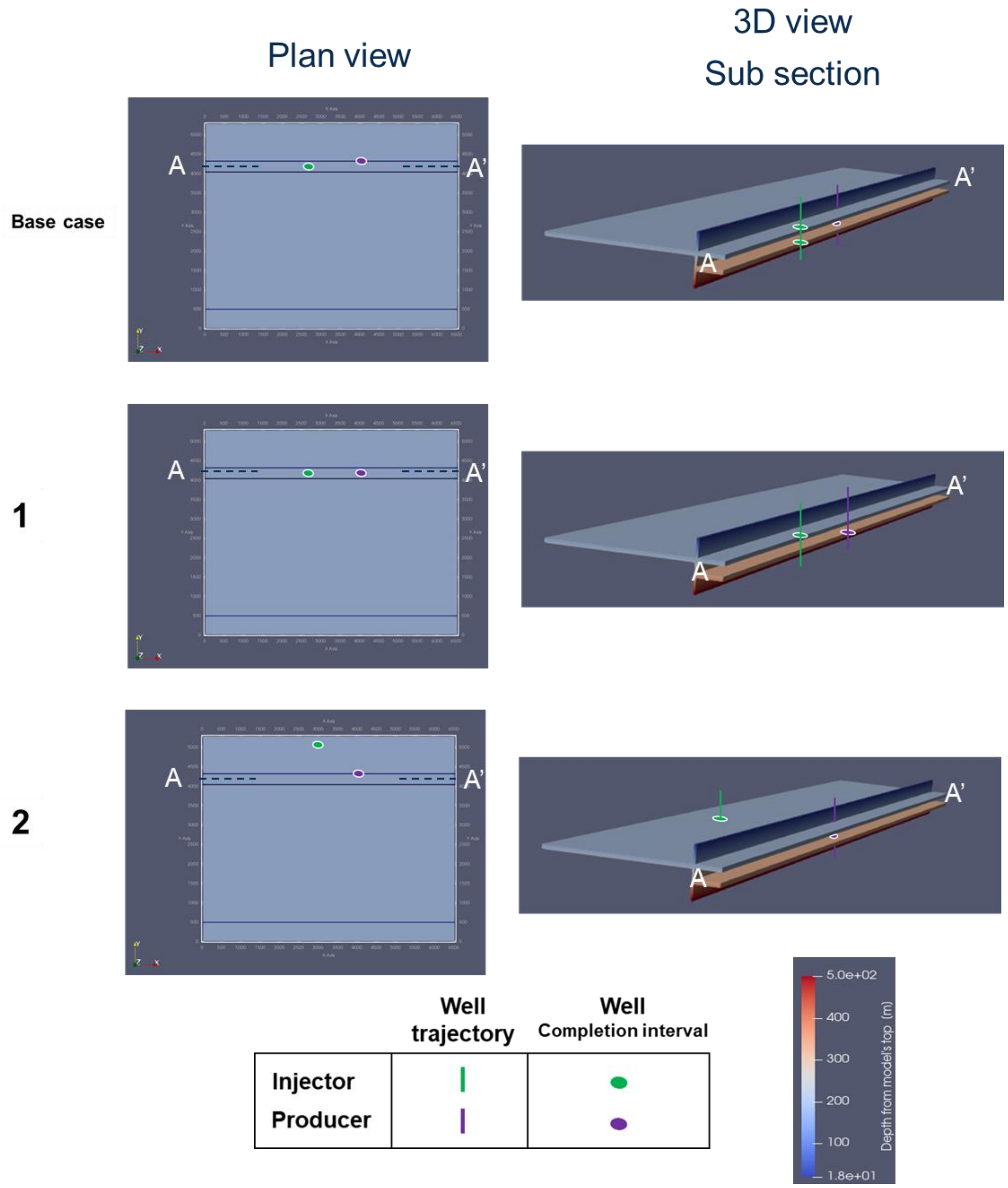


Figure 18: Map view (top) and 3D view (bottom) of well configurations and tagging used during sensitivity analysis on reservoir concept 2.

4.4.3 Concept 3

In concept 3, the base case combines a production well in the fault zone with an injector completed in the enhanced permeability layer close to the adjacent parallel fault on the opposite side of the horst. This setup optimizes productivity and production temperature, while reducing drilling costs by placing the injection well in the horst. The injector is close to the fault (where layer permeability is higher), but not in the fault. The latter situation would not be allowed due to seismic risk. However, considering the proximity of the injector to the fault and keeping in mind the reservoir concept 3 which has no enhanced permeability at large distance from the faults, the risk of induced seismicity should be assessed in all cases.

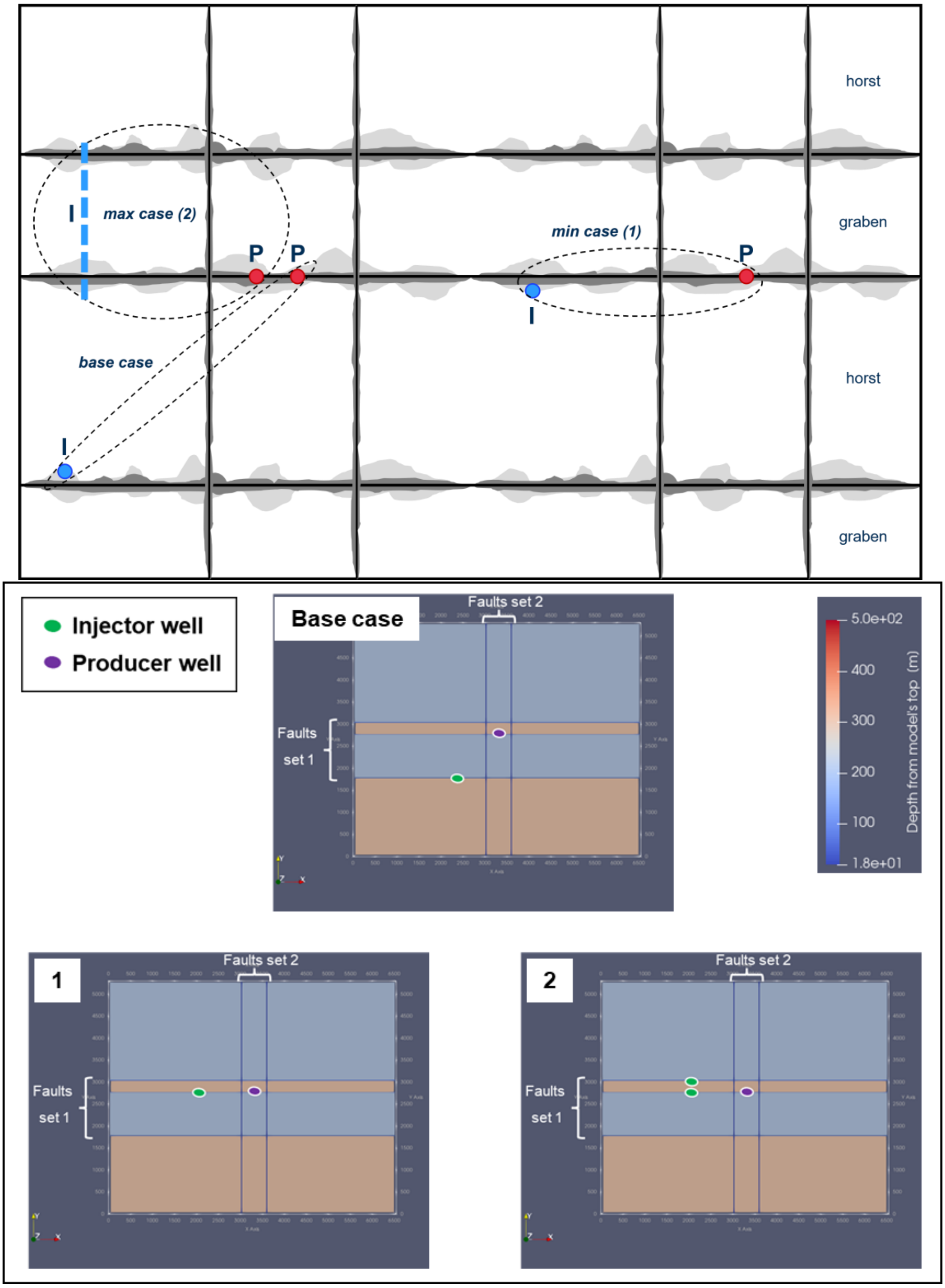


Figure 19: *Map view (top) and 3D view (bottom) of well configurations and tagging used during sensibility analysis on reservoir concept 3.*

As an alternative, the injection well can be positioned in the enhanced permeability layer on the horst side of the same fault as the producer, improving communication between the wells. This is the minimum case (or 1).

Finally, the configuration in the maximum case (or 2) has the same producer position as the other cases, but has a long horizontal injection well crossing the entire graben system and both faults. This case maximizes injectivity as the well connects to both fault zones and the layer with increased permeability on both sides of the graben.

Only a single deep geothermal project has been developed so far within the reservoir concept 3 area. The project in Mol has three wells, including one non-productive well. The production well targets a fault zone, whereas the injector was deviated away from the (known) faults to reduce seismic risk. However, injection tests and long-term circulation tests in Mol reveal lower permeability than anticipated, and the project faces the challenge of induced seismicity. Observations so far indicate permeability is related to fractures, fracture zones and fault zones, and also point to the presence of smaller faults, previously undetected, not too far away from the injection well. The setup does not match with any of the configurations described above. Considering the latest insights, it would be somehow comparable to the base case, but the actual structural geological framework is more complex.

The well configurations for concept 3 are illustrated in Figure 19. All three configurations were included in the sensitivity analysis, only the base case has been used in subsequent modelling.

4.5 INITIAL STATE AND BOUNDARY CONDITIONS

This section presents how the initial and boundary conditions were set for the different simulation studies: sensitivity analysis, permutation of single doublet scenarios and multiple doublet scenarios.

The initial temperature and pressure at the top of the reservoir 'Depth referential' were estimated based on the referential depths defined for every reservoir concept (see Table 4), using a temperature gradient of 0.0325 °C/m and a pressure gradient of 0.103 bar/m (ratio of pressure and depth in the Mol geothermal project), a surface temperature of 11°C and following equations 1 and 2.

$$\boldsymbol{T}_{\boldsymbol{reservoir}_{top}} = T_{gradient} * Depth_{referential} + T_{surface} \quad \text{Equation 1}$$

$$\boldsymbol{P}_{\boldsymbol{reservoir}_{top}} = P_{gradient} * Depth_{referential} \quad \text{Equation 2}$$

The boundary conditions considered constant temperature and zero fluid flow at the base and top of the model (hydraulic confined aquifer – no vertical leakage). The bottom temperature is computed based on a heat flux of 0.055 W/m^2 and the thermal rock conductivity. Regarding the lateral boundaries, the temperature is held constant and the aquifer is considered semi-infinite with two edges open and two edges closed for flow. To achieve this, a volume multiplier (order 10^3) was used for the cells located in the borders with open conditions.

The final "initial conditions" are defined after running the natural state phase (simulation period without wells aimed for defining the equilibrium conditions) during thousands of years of simulation time. The initial conditions used for running the natural state are shown in Table 4.

Table 4: Initial conditions.

		Base case			
Parameter	Description	Concept 1	Concept 2	Concept 3	Unit
$T_{reservoir}$	Reservoir temperature at top	51.6 - *324.7*	19.1 - *292.2*	100 – *373.5*	[°C] - *[K]*
$P_{reservoir}$	Reservoir pressure at top	129.7	25.9	285.4	[bar]
$Depth_{referential}$	Referential depth at the top of the model	1250	250	2750	[m]
Q_{heat}	Heat flux	0.055	0.055	0.055	[W/m2]

4.6 WELL'S OPERATIONAL CONSTRAINTS

In all the performed studies, the conditions for the injection and production wells of the doublets are as follows:

- Wells are vertical and completed in all cells that form the thickness of the reservoir.
- Water is injected and produced at constant temperature at a maximum flow rate of 4800 tons/day, equivalent to 200 m^3/h for a water density of 1000 kg/m^3.
- Injection temperature is held constant during simulations and depends on the reservoir concept. Thus, the injection temperatures are 10℃, 30℃ and 60℃ for the reservoir concepts 1, 2 and 3 respectively.
- During simulation, the mass flow rate is reduced to 70% of the previous flow rate (old) if the maximum pressure at the bottom of the injector well is reached following the equation below, where maximum injection pressure is directly proportional to initial reservoir pressure by a parameter sigma 'σ'. For this study the sigma value is 1.27 coming from experience in VITO's geothermal project, around which induced seismicity takes place. This is a bulk number that needs to be defined according to every project conditions.

$$If\ P_{inj} > \boldsymbol{P_{inj\_max}}\ then\ \dot{\boldsymbol{m}}_{\boldsymbol{inj\_new}} = 0.7 * \dot{\boldsymbol{m}}_{\boldsymbol{inj}_{old}}\ , where\ \boldsymbol{P_{inj\_max}} = \sigma * Pi \quad \text{Equation 3}$$

Where:
P_{inj}: $Bottomhole\ well\ injection\ pressure$
$\boldsymbol{P_{inj\_max}}$: $Maximum\ injection\ pressure\ at\ the\ reservoir\ for\ \sigma$=1.27 .
Pi: $Initial\ pressure\ in\ the\ well\ at\ reservoir\ level$
$\dot{\boldsymbol{m}}_{\boldsymbol{inj}}$: $Mass\ injection - production\ fluid\ rate$

5 SENSITIVITY

The sensitivity study consists in evaluating the uncertainty of the output of the simulation model with respect to a given set of input parameters (rock properties, initial conditions or well conditions). To accomplish this, simulations are run considering the maximum or the minimum values of every selected input parameter while leaving the remaining properties fixed as the base case. This approach allows to identify what inputs have the largest effects on the results, especially on those related with license definition (affected thermal and pressure areas). These results indicate which parameters must be considered for the next studies (permutation and multiple wells). It will also indicate general shapes and dimensions of the affected areas.

5.1 SIMULATION MODEL DESCRIPTION

The sensitivity analysis was done via numerical reservoir simulation. The simulation consists of a hydro-thermo monophasic model of liquid water at medium enthalpy flowing through porous media and faults. Faults are represented as vertical planes with constant petrophysical properties. Permeability and porosity fields were populated in accordance with the description of every reservoir concept.

To conduct the geothermal reservoir simulations, the DARTS simulator was used (Wang et al., 2020). It is a Multiphysics finite-volume simulator that takes advantage of the operator-based linearization 'OBL' concept to speed up simulation problems with non-linear physics (Voskov, 2017). In this study, the DARTS's geothermal module and the IAPWS-IF97 water properties (Kretzchmar & Wagner, 2019) were used. The simulator can be utilized via python scripting which provides flexibility for pre-processing, simulation, and post-processing.

Table 5: Model dimension and mesh size for reservoir concepts 1, 2 and 3 during the sensitivity study.

Length in x direction [m]	Length in y direction [m]	Length in z direction [m]
6302	5265	518
Number of cells in x	Number of cells in y	Number of cells in z
66	80	48
Total number of cells	253440	
Average Cell size x direction [m]	Average Cell size y direction [m]	Average Cell size z direction [m]
80	80	8

5.1.1 Mesh

For the sensitivity simulation a structured mesh with mesh refinement orthogonal to the fault planes was used. The description of the base grid, used in the three concepts, is given in *Table 5*. The refinement was done to account for gradual changes in permeability from the fault towards the center of both the grabens and horsts and for improving accuracy in flow calculation as significant flow is expected to be orthogonal to the faults due to well locations. It consisted in gradual decreasing of cell size from 80 m to 15 m in 'y' direction from the center of both graben and horst toward the faults that strike in 'x' direction as shown in Figure 20. Mesh coarsening was used at the lateral ('x' direction) and vertical limits ('z' direction) of the model to consider sufficient volume. For instance, cell size in x direction increases from 80 m to 480 m in the x limits of the model as shown in Figure 20.

The mesh and population of the properties is generated within the simulation script, which eases the consideration of the geometrical aspects during sensitivities and permutation tasks.

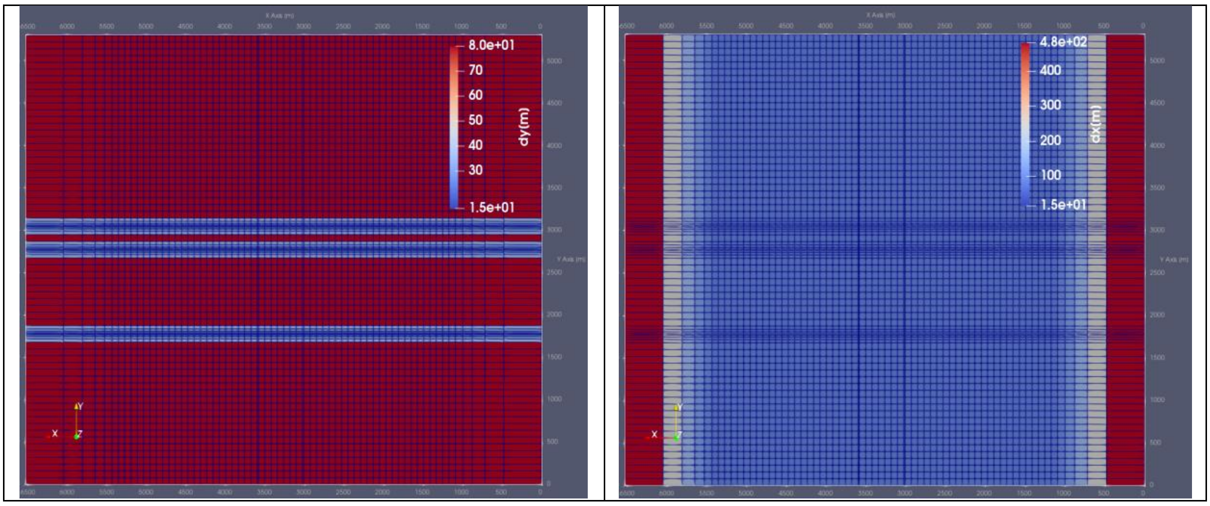


Figure 20: Mesh elements sizes in 'y' (left) and 'x' (direction) directions for the base mesh used in sensibilities studies.

5.1.2 Well operational constraints

Injection and production well conditions used in the sensitivity analysis are shown in Table 6. Water is injected at constant temperature at a maximum flow rate of 4800 tons/day. Injection temperature depends on the reservoir concept. For instance, it is set 10℃ lower than initial temperature in concept 2 and 40℃ lower than initial temperature in Concept 3.

If the maximum injection pressure is reached due to reservoir tight petrophysical conditions, the flow rate is reduced according to equation 3. Maximum injection temperature is considered to be proportional to the initial reservoir pressure. The constant of proportionality depends on project conditions. For this study a value of 1.27 was chosen. In the sensitivity analysis simulations are finished if a temperature drop of 3.5 ℃ is reached in the produced water (considered as thermal breakthrough).

Table 6: Well operational constraints considered during sensitivity task

		Base case			
Parameter	Description	Concept 1	Concept 2	Concept 3	Unit
$T_{reservoir}$	Reservoir temperature at top	51.6 - *324.7*	19.1 - *292.2*	100 – *373.5*	[°C] - *[K]*
$P_{reservoir}$	Reservoir pressure at top	129.7	25.9	285.4	[bar]
T_{inj}	Injection temperature at the reservoir level	30	10	60	[°C]
$\dot{m}_{inj}$	Initial injection mass rate	4800	4800	4800	[tons/day]
P_{inj_max}	Maximum allowable pressure at the injector	191	58	404	[bar]
dP_{inj_max}	Maximum allowable delta pressure at the injection well:	61.3	32.1	118.6	[bar]
$dTemp_{threshold}$	Temperature drop threshold at the producer well for stopping simulations during sensitivity tasks	3.5	3.5	3.5	[°C]

5.1.3 Steps in the sensitivity study

Two simulations steps were carried out in the sensitivity study for every reservoir concept:

- Modeling the base case of geothermal production with a single doublet until a temperature drop of 3.5°C is reached in the production temperature. This moment is defined as cold water breakthrough time. These results allow establishing the point of comparison with the sensitivity simulations. Input data for the base case of the 3 reservoir concepts is shown in *Table 6*, *Table 7*, *Table 10 and Table 13*.

- Modeling the impact of considering the minimum or the maximum value of the selected parameters while keeping the rest of the parameters constant. The parameters selected for the sensitivity study are shown in *Table 7*.

5.1.4 Outputs for analysis

The following results or indicators will be analyzed, which are considered useful for defining a license area for geothermal production:

- Affected temperature area: Area where changes in temperature between the initial and final simulation time are higher than 1°C. Computation is done after estimating the average temperature in every column of cells (cells in z direction) that belong to the reservoir layer or fault.
- Affected pressure area: Area where changes in pressure between the initial and final simulation time are higher than 1 bar. Computation is done after estimating the average pressure in every column of cells (cells in z direction) that belong to the reservoir layer or fault.
- Cold breakthrough time: Time at which a reduction of 3.5 °C in production temperature is reached.
- Final flow rate: All simulations are started with an injection rate of 200 m^3/h (4800 Tons/day). If pressure at the injector is higher than the maximum allowable pressure, then the flow rate is reduced until maximum pressure is not reached. This is the final flow rate that is reported.
- Temperature and pressure maps in the reservoir layers.
- Fluid rates and temperature profiles for injector and producer well.

All these outputs are stored in dedicated folders and files as indicated in ANNEX G. Tornado plots will be used for defining the impact of every reservoir parameter or well configuration considered during the sensitivity study.

5.2 SENSITIVITY ON CONCEPT 1

5.2.1 Simulation results of the base case for Concept 1

The base case for concept 1 was modeled following the reservoir properties and conditions described in *Table 1* and *Table 2*. The results of this simulation will be used as comparison points in the present sensitivity study. The forecasted production temperature profile and corresponding cold-water distribution the permeable layers by the end of the simulation for the base case is shown in Figure 21.

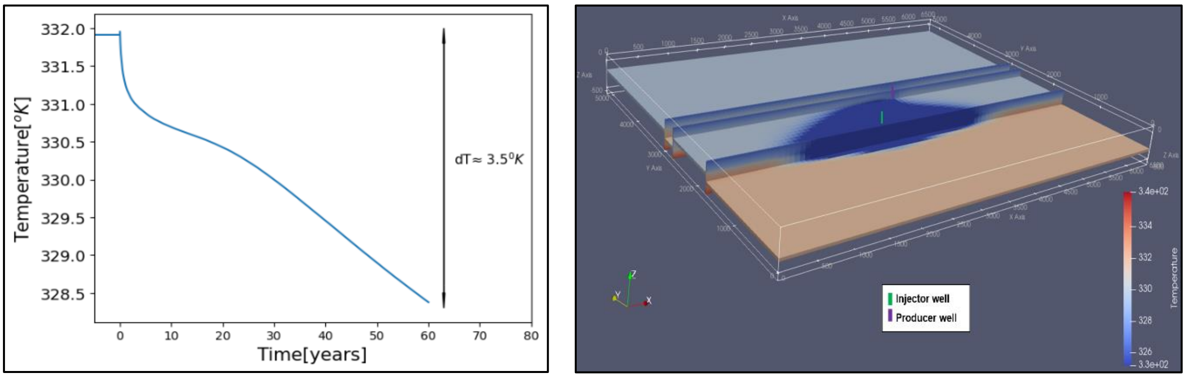


Figure 21: *Base case - Concept 1: Production temperature profile (left). The simulation is stopped when the production temperature change 'dT' is more than 3.5°C (60 years). The sharp early temperature decline is due to the injector and production well completion locations in the horst (colder) and graben (hotter) respectively. 3D temperature distribution [°C] in the reservoir layer and faults (right). Cold injected water flows along the nearest fault to the injection well and the reservoir layer.*

The referential results of the base case are presented below:

- The cold-water breakthrough (production temperature drops 3.5°C) is forecasted at 60 years of continuous injection at 200 m^3/h.
- The affected thermal area reaches a value of 4.47 km^2 at the moment of water breakthrough (60 years). The shape of this area is elongated following the faults and the karst permeability distribution (Figure 22-left).
- The affected pressure area (pressurized and depleted) covers 20 km^2. This area develops around the injector and producer wells (Figure 22-right). There is a high-pressure gradient (pressure drop) at the center of the horst (between the wells) due to the assumed karst permeability distribution as shown in Figure 23. This distribution is responsible of the size of the disturbed pressure area. Figure 23. also shows flow directions (arrow direction) indicating that some flow is coming in and out of the domain (open boundaries).

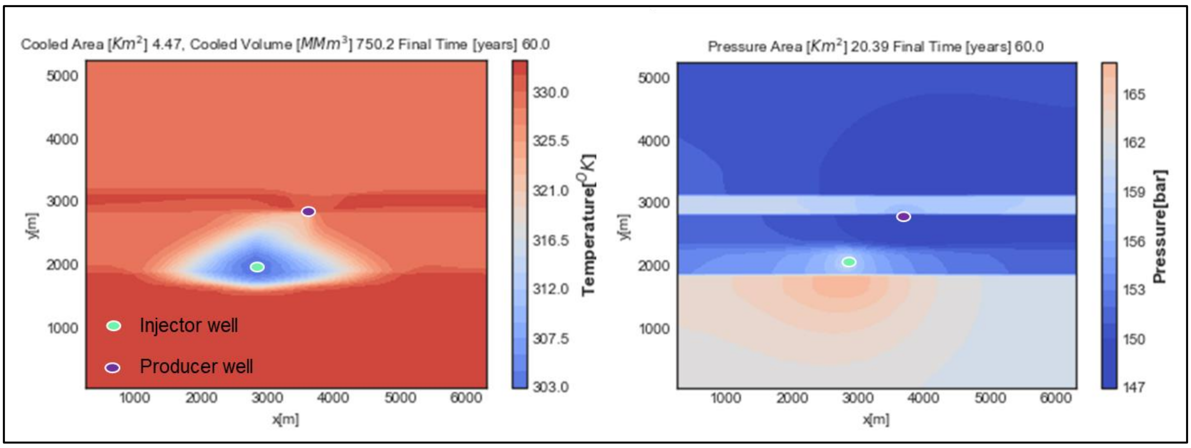


Figure 22: Plan views of the reservoir layer showing final temperature distribution (left) and pressure distribution (right) for the base case.

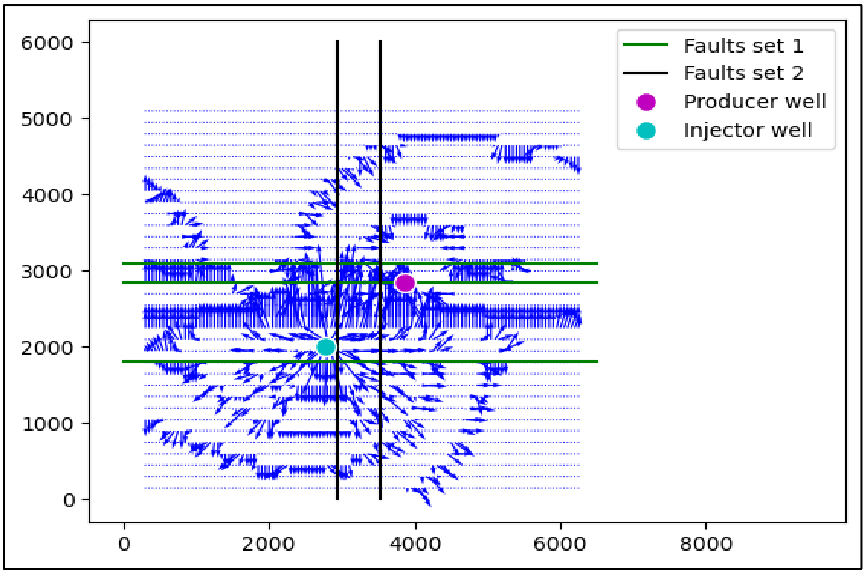


Figure 23: Flow vector field in the reservoir layer representing the base case properties for Concept 1. The arrows indicate the direction of flow, with their lengths proportional to the magnitude of the pressure gradient. The highest pressure gradients occur in the central region of the horst (between the wells), where most of the flow is concentrated. This area also exhibits the lowest permeability values, further influencing the pressure gradient.

Table 7: List of parameters selected for the sensitivity analysis and their corresponding minimum, maximum and base value - Concept 1.

	Minimum [1]	Base	Maximum [2]
Porosity and permeability fault set 1 *	5% (500 mD)	10% (2857 mD)	20% (5000 mD)
Throw of fault set 1 [m]	0	100	150
Faults spacing for set 1 at graben [m]	100	300	500
Max. Karst porosity -permeability	5% (500 mD)	10% (2857 mD)	25% (5000 mD)
Min. reservoir permeability [mD]	1	10	100
Karst extension from fault horst [m]	300	500	700
Permeability anisotropy ky/kx [-]	0.1	1	10
Porosity and permeability fault set 2 *	3% (10 mD)	No second fault set	10% (2857 mD)
Well configuration	1	Base 'L shape'	2
Reservoir layer thickness [m]	20	35	50
Fault height [m]	100	352	440

* Fault thickness is 15 m

5.2.2 Sensitivity results for Concept 1

The parameters listed in Table 7 were selected for the sensitivity study in concept 1 as they are found to be the most relevant for geothermal performance and license area definition. This table also indicates the minimum, maximum and base values defined for these parameters.

After running the sensitivity study, tornado plots were built for the next outputs: disturbed thermal area, pressure thermal area, cold water breakthrough time and final flow rate. The tornado plots with respect to the base case are shown in Figure 24. The reservoir parameters that have the largest impact on the affected temperature and pressure area are: karst extension, maximum karst porosity - permeability, porosity and permeability of fault set 2, matrix permeability anisotropy, reservoir layer thickness and well configuration. The thermal and pressure affected area is the largest if karst extension from the faults has the minimum value [1]. Thus, this is an important reservoir characteristic for defining the license area in Concept 1. Comments on the tested parameters are shown in Table 8.

These parameters (Table 9), except the well configuration, will be considered during the permutation study. The well configuration is a condition of design, the results suggest that injector and production wells should not be drilled along or near the same fault trend because early water breakthrough can take place (Figure 24-bottom left).

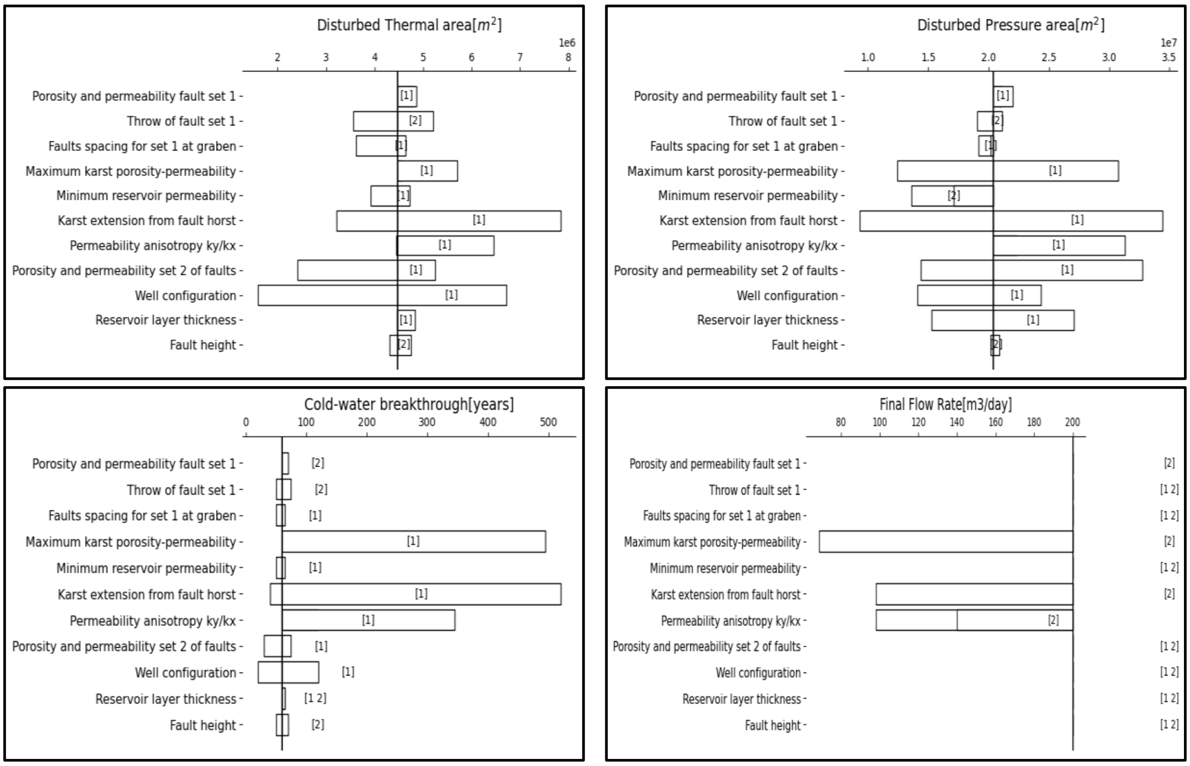


Figure 24: Sensitivity results represented on tornado plots for different variables in Concept 1. Results are reported at cold-water breakthrough time. On the left-top, the affected thermal area for the base case is in between 4 to 5 km^2. On the left-bottom, the cold-water breakthrough time defined when well production temperature decreases 3.5°C. On the right, the corresponding pressure affected area (top) and final well doublet flow rate (bottom). It is shown that the extreme values of some parameters induced long cold-water breakthrough (more than 100 years). This is due to both poor petrophysical properties around the wells and low hydraulic communication between wells. The vertical line indicates the value of the base case for every variable. The number in brackets indicates whether the minimum [1] or the maximum [2] value of a parameter is responsible for the maximum response of a variable (thermal or pressure areas for instances).

Table 8: Comments on tested parameters on affected thermal and pressure areas in Concept 1.

	Thermal and Pressure disturbed areas comments
Porosity and permeability fault set 1	In general, it has low impact on disturbed thermal and pressure area.
Throw of fault set 1 [m]	Low impact on thermal area. Shorter breakthrough time when the throw is 0 m and larger when the throw is 150 m. In the sensibility analysis, the cold breakthrough time is calculated when the produced temperature drops below a threshold of 3.5°C. Nevertheless, this threshold was adapted depending if the fault throw is the minimum (threshold: 1.2°C) or maximum (threshold: 4.6 °C) acknowledging that temperature in the injection block (horst) increases when the throw is '0 m' and decreases when the throw is 100 m respectively.
Fault set 1 spacing at graben [m]	Wide grabens are likely to have low permeability in its center while narrow graben are highly permeable. This causes that narrow grabens create a wider permeable area making the fluid to flow more orthogonal to the faults, pronting the elongation of the thermal area.
Karst porosity -permeability	The lower the permeability of the karts the lower the permeability in the center which causes more enlongated and wider thermal area.
Reservoir permeability	The lower the background permeability of the reservoir layer reduces the permeability in the center of the horst which causes more enlongated and wider thermal area. Disturbed pressure area will be small if background reservoir permeability is high or low. If it is high pressure disturbed propagates wider than with small permeability but pressure changes are small. For this case the maximum pressure disturbed area is found at the center due to this interaction of pressure difusion and and pressure change.
Karst_extension_from_fault_horst'	If karst extension is long, high permeability across the horst is created which hydraulic connect injector and producer wells, which generate low affected thermal area. Conversely, if the karst extension is short, low permeability rock is left in the center of the horst which causes the injected cold water to flow along the nearest fault befor flwing towards the producer well. This generate wide thermal disturbed area but also high pressure in the injection side and low pressure in the producer side.
Karst extension from fault horst	The anisotropy in horizontal permeability, defined by the ratio of ky (ortogonal to faults) and kx (paralell to faults), causes elongated thermal area along the fault when its value is the minimum (low ky) due to flow restriction and small rounded area when its value is maximum (ky >> kx). These are similar behaviours as the one obtained with karts extension. Low ky/kx causes pressurization and depletion araound the injector and producer well respectively, which lead to wider pressure disturbed area.
Permeability anisotropy ky/kx	The present of a second set of fault orthogonal to the main fault set and in between injector and producer wells affects the thermal area because it creates heterogeniety in the permeability field, leading to results similar the ky/ky anisotropy. For instance, high permeability faults lead to water short circuit whcih causes relative early breakthrough and small disturbed area.
Porosity and permeability fault set 2	By far the parameter that affects the most, luckly well configuration can be manipulated. For the case the producer wells are driled in the center of the graben or in a fault and the injector is drilles relatively close to the opposite fault in the horst block, wide thermal disturbed areas are created, which mean good performance in thermal output. On the other hand, if both injector and producer wells are drilled in the same graben, water short circuit is likely to occurr along the faults, leading to small disturbed areas.
Well configuration	Thickness (porous volume) sligthly affects the disturbed thermal area but it does affect the disturbed pressure area. Low thickness implies low transmissiblity and porous media which causes wider and higher pressure drops.
Reservoir layer thickness	Pressure nor thermal disturbed areas are significantly affected. Thermal area slightly increases when thickness increases because transmissiblity improves, which improve the flow along the faults.

Table 9: Selected parameters for single doublet permutation study Concept 1

Count	Parameters
1	Karst extension
2	Porosity and permeabilty. 2nd set of faults
3	Permeability anisotropy ky/kx
4	Karst porosity & permeability
5	Reservoir layer thickness

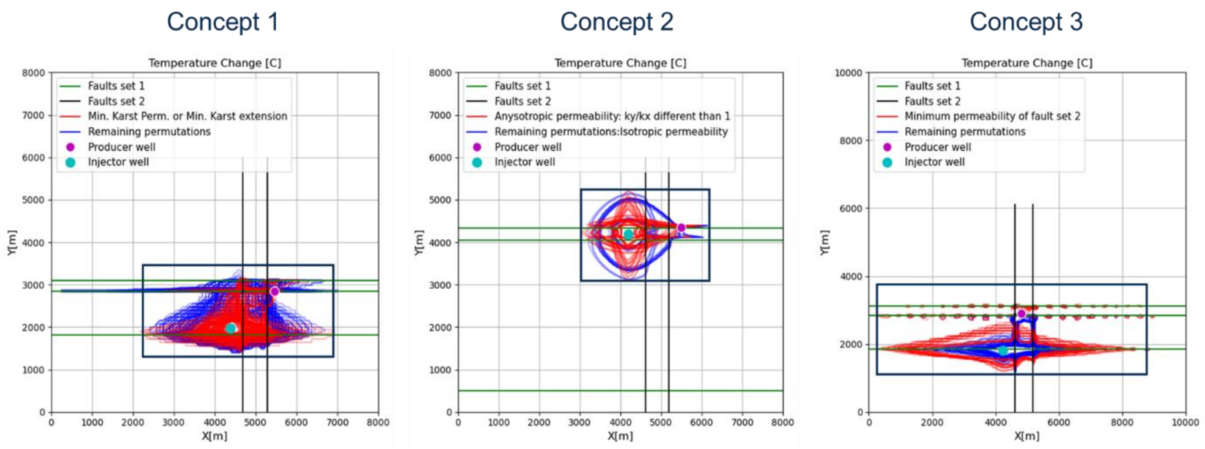


Figure 25: Delineation of thermal area with rectangular shape for the three studied reservoir concepts.

5.3 SENSITIVITY ON CONCEPT 2

5.3.1 Simulation results of the base case for Concept 2

Concept 2 has 3 distinctive reservoir conditions: shallow depth, 2 reservoir layers in the target graben and a no-flow boundary close to the wells. These conditions lead to different results of the base case of concept 2 if compared to Concept 1, these are:

- A smaller and more rounded affected thermal area of 3.27 km^2 (Figure 28-left).
- A longer cold breakthrough time of 70 years (Figure 26).
- A smaller affected pressure area of 7 km^2 (Figure 28-right).

The final flow rate of 200 m^3/h could also be reached with the conditions of the base case of concept 2. The presence of two permeable layers distributes the injected cold water (Figure 27), leading to the smaller affected thermal and pressure area and longer cold breakthrough time than for concept 1. These results will be used as reference in the tornados plots.

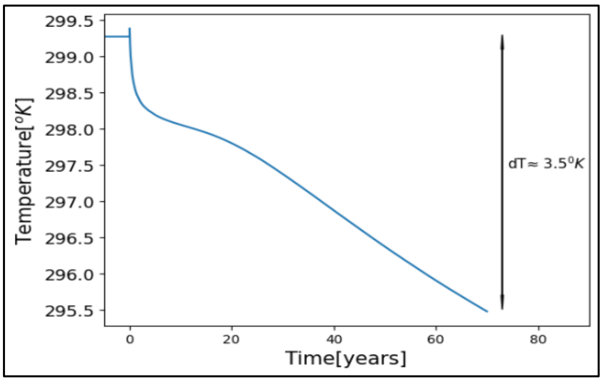


Figure 26: Base case - Concept 1: Production temperature profile, the simulation is stopped when the production temperature decreases more than 3.5°C (60 years). The sharp early temperature decline is due to colder water flowing from the top layer toward the producer well completed at the fault in the hotter bottom layer.

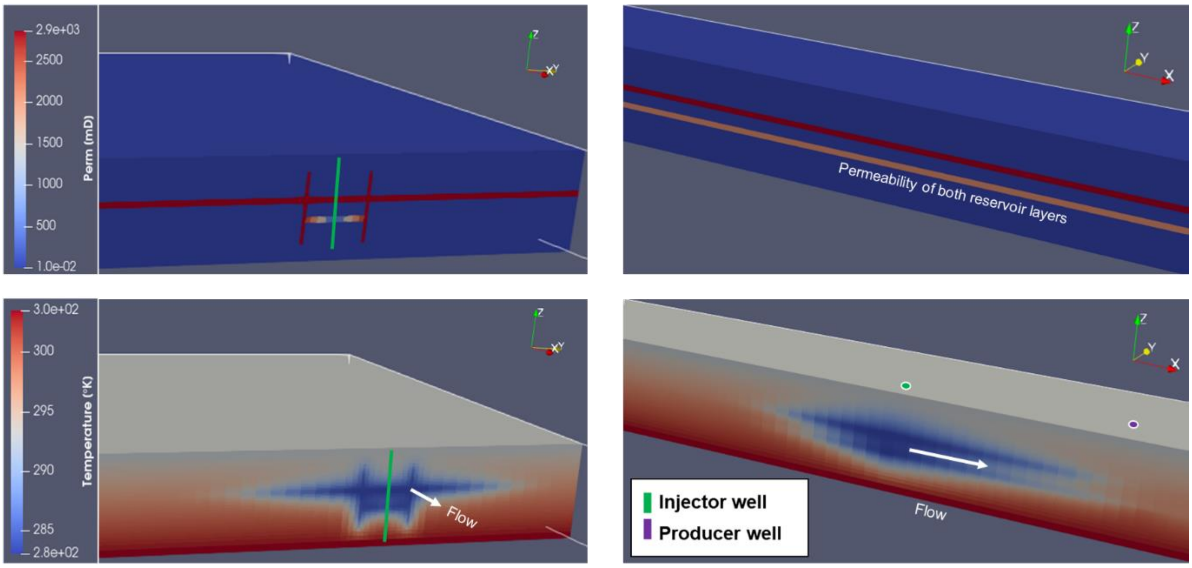


Figure 27: Permeability and temperature at the end of the simulation (70 years) for the base case – Concept 2. Slice of the model orthogonal to the flow at the injection well (left) and parallel to the flow (right). The injected cold-water flows through both layers towards the producer well.

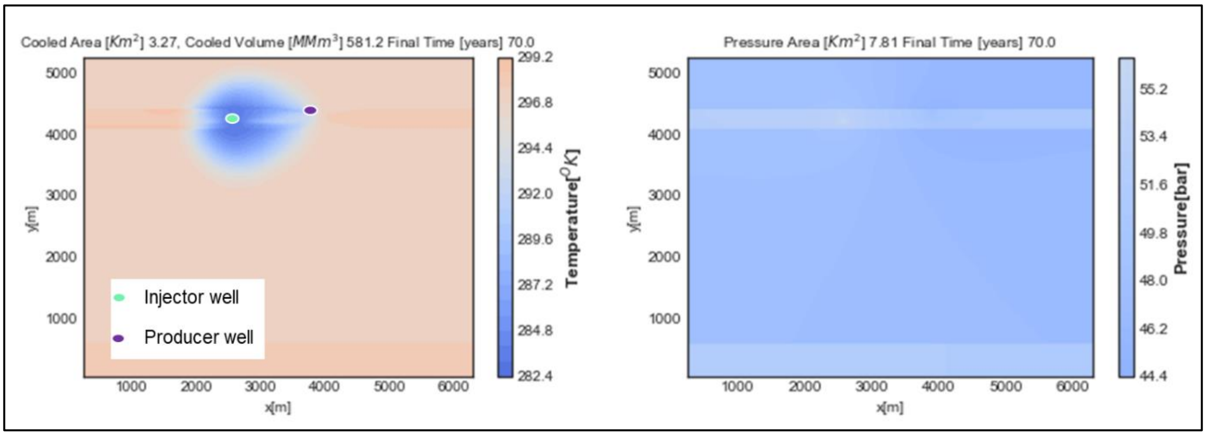


Figure 28: Plan views of the reservoir layer showing final temperature distribution (left) and pressure distribution (right) for the base case Concept 2.

5.3.2 Sensitivity Concept 2

The selected parameters for the sensitivity analysis are shown in Table 10, comprising e.g. layer permeability (for both layers), fault permeability (for both sets), permeability anisotropy and well configurations.

Figure 29 shows the results of the sensitivity analysis in tornado plots. Low permeability of fault set 2 leads to wider affected thermal and pressure areas. In addition, high ky/kx ratio also leads to a wider affected pressure areas. Thus, these are important parameters to consider during license area definition.

Table 10: Reservoir parameters and well configuration considered during sensitivity analysis on Concept 2.

	Minimum [1]	Base	Maximum [2]
Porosity and permeability fault set 1 ⁎	5% - 500 mD	10% - 2857 mD	20% - 5000 mD
Top & bottom layer separation [m]	8	100	150
Faults spacing for set 1 at graben [m]	100	300	500
Maximum karst porosity and permeability	5%-500 mD	10%-2857 mD	25%-5000 mD
Minimum reservoir permeability [mD]	1	10	100
Karst extension from fault horst [m]	300	500	700
Permeability anisotropy ky/kx	0.1	1	10
Porosity and permeability fault set 2	3% - 10 mD	No fault set	10%-2857mD
Well configuration	1	base	2
Reservoir layer thickness [m]	20	35	50
Top layer permeability	500 mD	2857 mD	5000 mD
Fault height [m]	100	352	440

⁎ Fault thickness is 15 m

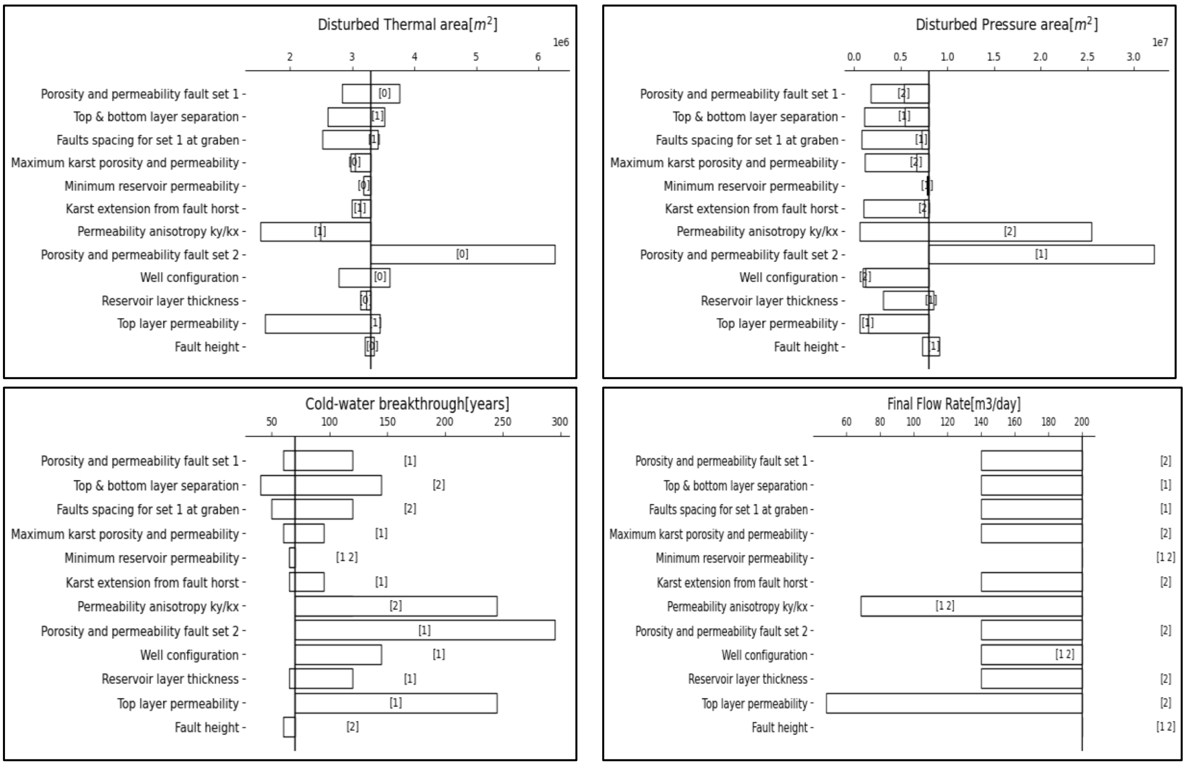


Figure 29: Sensitivity results represented on tornado plots for different variables in Concept 2. Results are reported at cold-water breakthrough time. On the left-top, the affected thermal area for which the base case is in between 3 to 4 km^2. On the left-bottom, the cold-water breakthrough time defined when well production temperature decreases 3.5 K. On the right, the corresponding pressure affected area (top) and final well doublet flow rate (bottom). It is shown that the extreme values of some parameters induced long cold-water breakthrough (more than 100 years). This is due to both low petrophysical properties around the wells and low hydraulic communication between wells. The vertical line indicates the value of the base case. The number in brackets indicates whether the minimum [1] or the maximum [2] value of a parameter is responsible for the maximum response of a variable (thermal or pressure areas for instances).

Table 11: Comments on tested parameters on disturbed thermal and pressure areas in Concept 2

Porosity and permeability fault set 1	The higher the fault set 1 permeability the lower the thermal affected area. Because cold water channelized from the injector toward the producer when fault permeability is high.
Top & bottom layer separation	The lower the separation the lower the thermal area. This promotes the flow in the layers than in the faults.
Faults spacing for set 1 at graben [m]	The smaller the fault spacing the lower the disturbed thermal area because it creates narrow and highly permeable grabens that channelize the flow.
Maximum karst porosity and permeability	No impact on both disturbed thermal. The low Karst permeability leads lower flow rate than 200 m^2/hr due to maximum pressure restriction which cause small pressure areas.
Minimum reservoir permeability [mD]	No impact on both disturbed thermal and pressure area.
Karst extension from fault horst [m]	No major impact on disturbed thermal area. If value is low injectivity and final flow rate are affected.
Permeability anisotropy ky/kx	Ky/kx = 1 creates more homogeneous thermal areas while ky/kx different than 1 creates smaller thermal areas and affects injectivity.
Porosity and permeability fault set 2	The presence of second set of faults with low permeability between the wells makes the thermal area to incresea and pressure to build up in the injector well side and deplete in the producer well side.
Well configuration	The tested well configurations do not have major impact of disturbed thermal area but has an impact on well injectivity
Reservoir layer thickness [m]	No impact on both disturbed thermal and pressure area.
Top layer permeability	The higher the top layer permeability the lower the disturbed thermal area and small pressure area. If top layer permeability is low well and final flow rate reduces affecting also disturbed pressure area.
Fault height [m]	No impact on both disturbed thermal and pressure area.

The parameters that have the largest impact on disturbed thermal and pressure area and selected for the permutation study are shown in Table 12.

Table 12. Selected parameters for single doublet permutation study Concept 2.

Count	Parameters
1	Porosity and permeability fault set 1
2	Permeability anisotropy ky/kx
3	Top layer permeability
4	Porosity and permeability fault set 2

5.4 SENSTIVITY ON CONCEPT 3

5.4.1 Simulation results of the base case from Concept 3

The results corresponding to the base case of Concept 3 indicates a reservoir fully dominated by faults. This can be seen in the shape of the affected thermal area, which follows mainly the faults while the nearby rock is almost undisturbed in terms of temperature (Figure 30-right and Figure 31-left). This leads to a very small affected thermal area of 0.77 km^2 and very short cold-water breakthrough (10 years). Nevertheless, the low permeability of the rock induces a affected pressure area of 34 km^2. These values will be used as reference for the tornado plots.

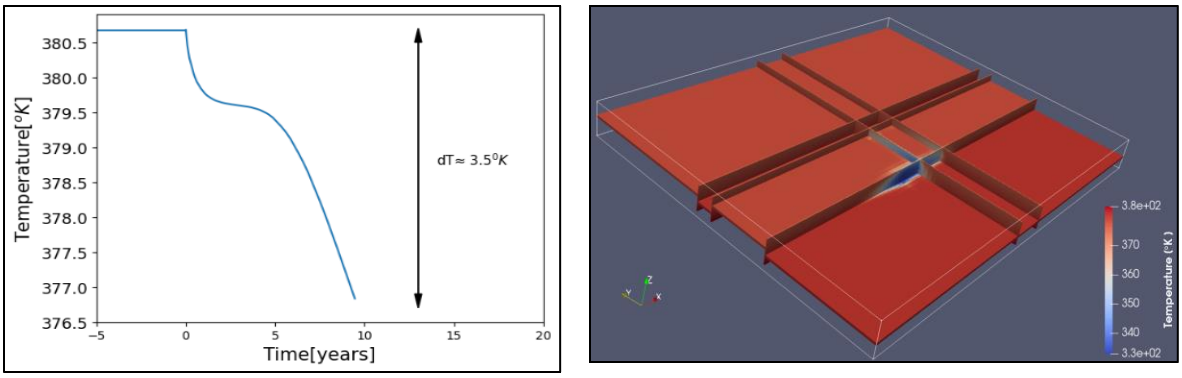


Figure 30: Base case - Concept 3: Production temperature profile (left), the simulation is stopped when the production temperature decreases more than 3.5 K (9.5 years). The sharp early temperature decline is due to water coming from shallower depth. 3D temperature distribution [K] in the reservoir layer and faults (right). Cold injected water flows along the nearest fault to the injection well and the reservoir layer.

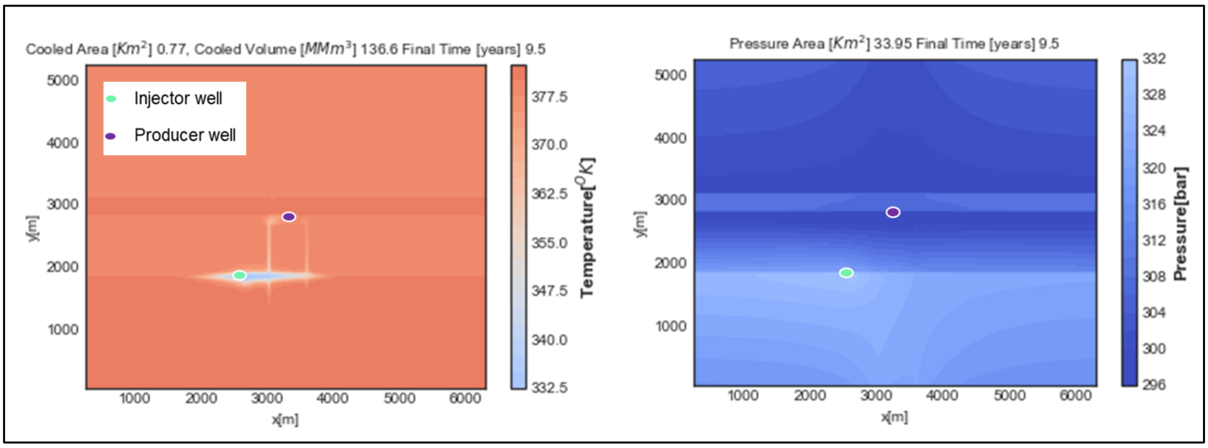


Figure 31: Plan view of the reservoir layer showing final temperature distribution (left) and pressure distribution (right) for the base case Concept 3.

5.4.2 Sensitivity Concept 3

For this reservoir concept, fault permeability and host rock permeability (Minimum reservoir permeability) were selected for the sensitivity study among different reservoir parameters (Table 13). In addition, three different well configurations, shown in Figure 19, were tested. It considers in addition to wells in different faults of the horst (base case), injector and producer wells in the same fault (case 1) and the injector drilled through the 2 faults of the graben (case 2).

The affected thermal and pressure areas are not sensitive to most tested reservoir parameters. Only low permeability of fault set 2 and well configuration significantly affect the reservoir response (Figure 32). When the permeability of this fault-set is low, a wide thermally affected area is generated. In addition, a small affected pressure area and short cold-water breakthrough times are expected if injector and production wells are drilled in the same fault. The comments of the effect of every parameter in reservoir response are detailed in Table 15.

It is important to mention that the simulated cases were able to inject and produce 200 m^3/h because the assumed maximum bottom pressure at the injector (404 bar), which is approximately 85 bar at the wellhead, was not reached in any case. This value of pressure is in the same order of magnitude to the conditions where seismicity started to be important in VITO's deep geothermal project in Mol. This pressure threshold was never reached because the tested case has lower flow restrictions that the mentioned project. For instance, multiple low permeability faults and probable lower matrix permeability is presented in the mentioned project.

Table 13: Reservoir parameters and well configuration considered during sensitivity analysis on Concept 3

	Minimum [1]	Base	Maximum [2]
Porosity and permeability set 1 of faults*	5%-500 mD	10%-2857 mD	20%-5000 mD
Set 1 of faults throw [m]	0	100	150
Faults spacing for set 1 / set 2 at graben [m]	100/400	300/600	500/800
Maximum porosity permeability of enhanced reservoir region	5%-500 mD	10%-2857 mD	25%-5000 mD
Minimum reservoir permeability [mD]	1	10	25
Extension of enhanced reservoir region from fault horst [m]	100	150	200
Permeability anisotropy ky/kx	0.1	1	10
Porosity and permeability set 2 of faults	3%-10 mD	5%-500 mD	10%-2857 mD
Well configuration	1	base	2
Reservoir layer thickness [m]	20	35	50
Fault height [m]	100	352	440

* Fault thickness is 15 m

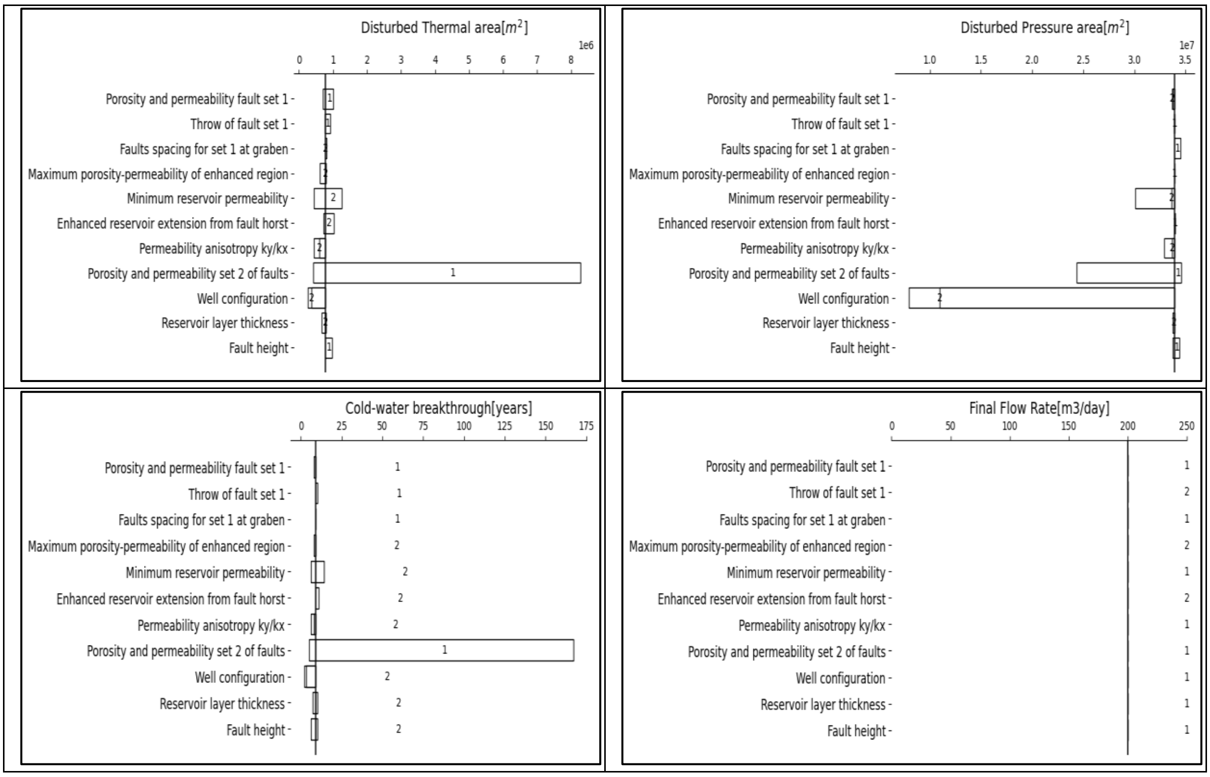


Figure 32: Sensitivity results represented on tornado plots for different variables in *Concept 3*. Results are reported at cold-water breakthrough time. On the left-top, the disturbed thermal area for which the base case is in between 4 to 5 km^2. On the left-bottom, the cold-water breakthrough time defined when well production temperature decreases 3.5 K. On the right, the corresponding pressure disturbed area (top) and final well doublet flow rate (bottom). It is shown that the extreme values of some parameters induced long cold-water breakthrough (more than 100 years). This is due to both low petrophysical properties around the wells and low hydraulic communication between wells. The vertical line indicates the value of the base case for every variable. The number in brackets indicates whether the minimum [1] or the maximum [2] value of a parameter is responsible for the maximum response of a variable (thermal or pressure areas for instances).

Table 14: Selected parameters for single doublet permutation study *Concept 3*

Count	Parameters
1	Porosity and permeability set 2 of faults
2	Minimum reservoir permeability
3	Enhanced reservoir region extension from fault horst [m]
4	Fault height

Table 15: Comments on tested parameters on disturbed thermal and pressure areas in Concept 3

Fault_poro' and Permeability of 1st set	No major impact on pressure and temperature within the tested values.
Fault throw in set 1 [m]	No major impact on pressure and temperature within the tested values.
Fault spacing graben both sets [m]	No major impact on pressure and temperature within the tested values.
Max. Karst poro and Permbeality	No major impact on pressure and temperature within the tested values.
Minimum reservoir permeability' [mD]	When its values are high, the disturbed thermal area increases because water can flow into the matrix. Contrary, the disturbed thermal area reduces because most of the flow is restricted to the faults.
Karst extension from fault horst' [m]	No major impact on pressure and temperature within the tested values.
ky/kx in the matrix' [dimensionless]	No major impact on pressure and temperature within the tested values because the rock matrix permeability is low for this scenario.
Fault poro and Permeability of 2nd set	When its permeability is low, then wider disturbed thermal areas are induced because the injected fluid is forced into the rock. This also leads to high injection pressures and wider disturbed pressure areas.
Well_conf	When injector and producer well are completed in the same fault system (Well configuration 1 and 2), injection pressure and disturbed pressure area decreases, which is good for pressure-induced risks but this comes at the expense of an earlier influx of cold water and therefore an earlier decrease in production temperature.
Thickness' [m]	No major impact on pressure and temperature within the tested values.
Fault_height' [m]	No major impact on pressure and temperature within the tested values.

5.5 SENSITIVITY ON RECHARGE TIME

The license limits are not only spatial but also temporal, as a license is granted for a specific period. In view of a long-term sustainable management of the subsurface, VPO wants to get a view on thermal recharge of license areas after abandonment. Although geothermal energy is a renewable energy source, temporal overexploitation to meet the required output for a project may result in a cooled area that needs some time to recover thermally before it can be used for a new project. Optimal limiting of license volumes is therefore not only a strive for efficient heat sweeping realizing maximum benefit for the next decades, but also a strive for long term renewable energy production. The concept 1 base model (description in Table 5 and Table 6) was used to analyze the sustainable exploitation on the long term, and to analyze the sensitivity for differences in total production time and shut in time of the geothermal projects.

5.5.1 Renewable geothermal doublet

An ideal sustainable exploitation system is the one that extracts the resource at the same rate as it is recovered by nature. Geothermal energy, by definition, is considered renewable as the Earth's heat is essentially infinite on a human timescale. Therefore, a renewable resource like geothermal energy can be exploited sustainably, ensuring that its use today does not compromise the ability of future generations to meet their energy needs while aligning with the available energy supply. The recharge mechanisms of a geothermal source include (radiogenic) heat generation, conductive heat flow and convective heat flow. The recharge rate depends on the dominant mechanism, with convective heat flow accelerating the process compared to pure conduction and heat generation. One important question in the sustainability of this resource is at what time scale the geothermal energy is renewable, a point which has been addressed previously (Rybach et al., 2000). They highlight that 100 % recovery will take almost infinite time for a limestone fractured reservoir when only heat flow via conduction is considered. Nevertheless, recovery to

90% to 95% of the original energy could be in the range of hundreds of years (100 - 200). The asymptotic approach to 100% recovery at infinity time is inherent to the pure diffusion model used. When convective heat flow is present, lateral natural water flow in the layers or through the faults, a shorter recharge time is expected.

Simulations were done for reservoir concept 1 to study the energy recovery behavior after ceasing geothermal exploitation. The boundary conditions assumed the reservoir is recharged via conductive heat only. Therefore, this is the more pessimistic scenario. The boundary conditions considered constant temperature at the base and top of the model. The temperature at the top of the model is defined by the general temperature gradient (0.0325°C/m) and temperature at the surface (11°C) while the bottom temperature is computed based on a heat flux of 0.055 W/m^2 and the thermal rock conductivity. Then, the model is run with these boundary conditions during thousands of years so that equilibrium is achieved (natural stage phase). The simulations considered a doublet produced at 200 m^3/h, cold injection temperature of 30°C, initial temperature 51.6°C - 56°C under different exploitation times: 20 y, 30 y, 40 y, 60 y and 80 y. The ratio of useful heat available and original heat, both having as reference the injection temperature, was used to monitor the heat recovery after exploitation.

$$Useful\ heat\ ratio[\%] = \frac{Useful\ heat\ available\ after\ exploitation}{Initial\ useful\ heat} * 100 = \frac{(S[p,T,t_{recharge}] - S[p,T_{inj}])}{(S[p,T,t_{initial}] - S[p,T_{inj}])} * 100 \quad \text{Equation 4}$$

Where:
$Useful\ Heat\ in\ place$: $The\ amount\ of\ heat\ having\ as\ reference\ the\ injection\ temperature$
S: $Heat\ in\ the\ reservoir\ at\ specific\ pressure, temperature\ and\ time$
$S[p, T_{inj}]$: *Referential heat when considering the temperature of the reservoir equal to* T_{inj}
p: $Reservoir\ Pressure$
T: $Reservoir\ Temperature$
T_{inj}: $Injection\ temperature$
$t_{recharge}$: $Time\ after\ stopping\ exploitation$
$t_{initial}$: $Time\ at\ the\ start\ of\ exploitation$

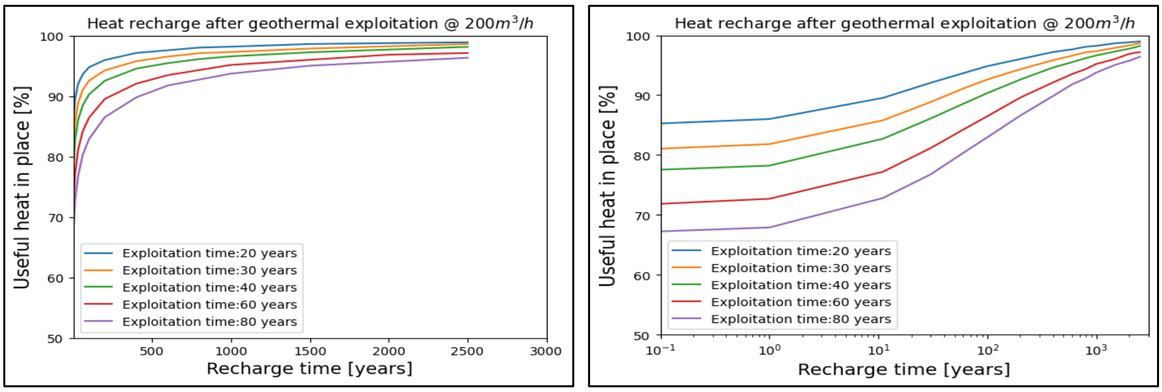


Figure 33: Evolution of the percentage of heat available with respect to the original heat after ceasing geothermal operations for different exploitation times. Results are presented in linear (left) and logarithmic (right) time scales. Heat recharge due to only heat diffusion is considered. An area of 3800 m long and 1350 m width (affected thermal area after 80 y of exploitation) considering the reservoir rock was used as reference for the estimations.

The Figure 33 shows the results of the simulation when considering recharge under conductive heat flow. Next, the main observations are described:

- The depletion of the resource is proportional to the exploitation time. For instance, for a time of 20 y, the available heat after production is 85% while for a time of 80 y it reduces to 67 %. Even at long exploitation time a lot of useful heat remains in place, meaning that the reservoir is not severely depleted.

- The recharge rate is higher at early times (lower than 500 y) than at late times as can be seen in Figure 33-left. The log graph (Figure 33-right) allows to see the details at early times. The decrease of the recharge rate at late times is because the heat flow is proportional not only to the rock conductivity but also to the temperature difference between the reservoir and surrounding rock, which reduces as the reservoir is recharged.
- Recovering the initial energy levels of the resource via conductive heat transfer is a slow process as the recovery rate slows down when the temperature difference becomes smaller. Nevertheless, the reservoirs could be recharged to 90% of its initial useful energy during resting periods of 10 year and 200 years for production times of 20 years and 60 years respectively. Which could allow to establish sustainable exploitation strategies.

5.5.2 Sustainable exploitation

Although full recovery by conductive heat flow can take thousands of years, Figure 33 also shows that heat is recovered faster at early times. In fact, heat is replenished to levels higher than 90 % after 100 y of rest for exploitation times lower or equal to 40 years. This is a time frame feasible in society scale which could provide an energetic outcome still sufficient to satisfy the energy demand of future generations.

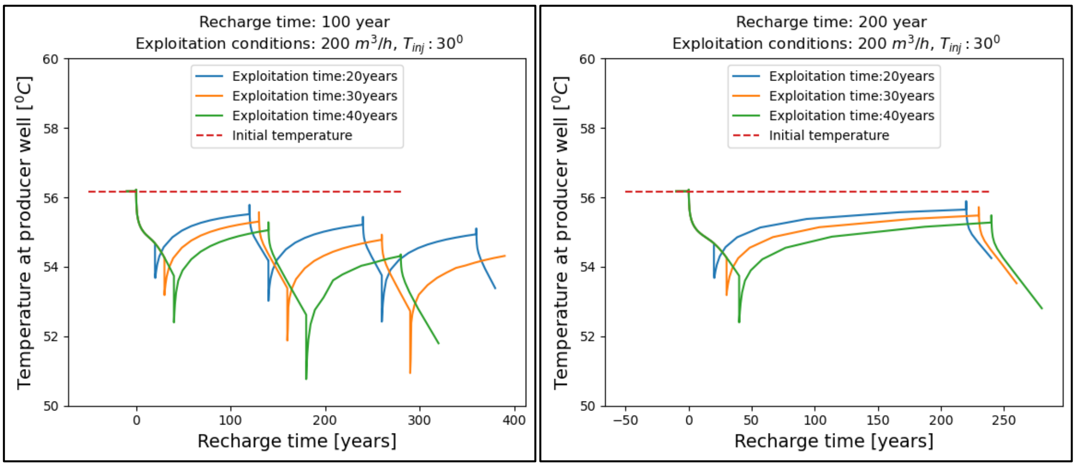


Figure 34: Forecast of temperature recovery and production during and after recharging 100 years (left) and 200 years (right). Sharp reduction of temperature after ceasing production is due to convection effects presented in the fault where the production well is completed.

The temperature behavior at the producer well during production before and after recharging heat is shown in Figure 34 for 2 recharging times: 100 years and 200 years. The temperature at the producer is recovered up to 0.5°C for a license time of 20 years and 1°C for 40 years of production considering 200 years resting. Temperature recovery is lower for 100 years recharge time. The second production periods show a sharper decline than the first production period as not all the heat has been recovered.

Practical experience in areas that have been producing for a very long time, such as the Paris Basin and Mons Basin, does not confirm the modelling results with no clear cooling effects after more than 40-50 years. The longer recharge times predicted result partly from the model assumptions and boundary conditions chosen (like e.g. conduction only, simplifications of the reservoir), which inherently leads to more pessimistic results. As in the Paris Basin, the initial approach may be on the conservative side as there is not yet a good understanding of the basin. As experience and knowledge increase, uncertainty reduces and more accurate models and results can be obtained. A good monitoring of temperature over time is crucial to improve the understanding of the reservoirs.

6 MODELLING – SINGLE DOUBLET SCENARIOS

6.1 INTRODUCTION

A permutation parameter study on geothermal energy extraction via a single doublet was run to estimate the range of the affected thermal and pressure area for the three reservoir concepts. This information will be used for recommending the license size guidelines for geothermal projects in the Carboniferous limestone reservoirs of the Campine Basin. The permutation study consists of modelling multiples cases for geothermal heat production via a single doublet by considering as input data the combination or permutation of the minimum, mean and maximum values of the selected parameters. In this study, the selected parameters were defined based on the sensitivity study.

The results of the simulated cases, in terms of affected thermal and pressure areas (including length and width thermal dimensions shown in Figure 35-b), will be presented in a quantitative way by histograms and/or cumulative frequency plots. Contours and density plots of changes in temperature and pressure respectively will be used for presenting the results in a qualitative manner.

The simulation model considers the properties and reservoir concepts described in the previous chapters. Nevertheless, model size was increased to 10 km in 'x' and 6 km in 'y' directions for minimizing the influence of the boundaries and consequently improving estimation of the areas.

The single doublet considers the well configuration named as base or 'L shape' in the sensitivity analysis of every concept (Figure 17, Figure 18, Figure 19). It comprises a producer well completed in a fault and an injector well completed in a horst. Well spacing is fixed to 1250 m.

In addition, the cases were run for a fixed time of 35 years. If cold water breakthrough occurs earlier in time (production temperature drops more than 3.5℃), simulation was stopped, and the affected areas were calculated at the breakthrough time. In addition, injection/production flow rates were reduced if pressure at the injector became higher than the defined maximum pressure at the injector as it was done in the previous simulations (sensitivity analysis). Table 16 describes the well control conditions used during the simulation for the 3 cases. Affected thermal and pressure areas are calculated based on a minimum variation of 1℃ and 1 bar absolute respectively.

Table 16: Simulation and well conditions for permutation study.

	Concept 1	Concept 2	Concept 3
Well doublets	1	1	1
Initial injection rate [m^3/h]	200	200	200
Initial pressure at injector well [bar]	150	46	315
Maximum pressure at the injector [bar]	190	58.42	400
Injection temperature [℃ / K]	30 / 303.15	10 / 283.15	60 / 333.15
Completed interval [m]	Equal to reservoir thickness	Equal to reservoir thickness	Equal to reservoir thickness
Simulation time [years]	35	35	35

6.2 CONCEPT 1

A total of 5 parameters were selected for the permutation study. These parameters are shown in Table 17 as well as their corresponding minimum, mean and maximum values. The number of parameters and the three different values mean that the permutation study considers at total of 243 simulations ($values^{parameters} = 3^5 = 243$ cases). The used well configuration corresponds to the base case (Figure 17)

Table 17: Parameter considered for the permutation study in Concept 1

Parameter	Minimum value	Base value	Maximum value
Karst extension in the horst [m]	300	500	700
Porosity and permeability fault set 2	3% (10 mD)	No faults	10% (2857 mD)
Matrix permeability anisotropy ky/kx	0.1	1	10
Maximum karst porosity -permeability	5% (500 mD)	10% (2857 mD)	25% (5000 mD)
Reservoir thickness [m]	20	35	50

6.2.1 Affected thermal area

The frequency distribution of the affected thermal area from the permutation study is shown in Figure 35-a. It shows 2 sub-distributions: one with small thermal areas, high frequency, and narrow range (from 0.1 to 1 km^2) and a second distribution with larger thermal areas and range going from 1 km^2 to 3.7 km^2.

The thermal area in reservoir concept 1 can be characterized in terms of length (parallel to fault set 1) and width (sub-parallel to well spacing and parallel to fault set 2) as shown in Figure 35-b. These topological characteristics can be helpful delineating the license area. The estimated maximum length from the permutation study ranges from 300 m to 7000 m (Figure 35-c). On the other hand, the width ranges from 200 m to 1800 m (Figure 35-d). It presents 2 sub-distributions: one from 200 m to 800 m and a second one from 1000 m to 1800m. In addition, not all the cases presented the same injection fluid rate due to the maximum pressure limitation at the injector well. Thus, disturbed thermal area is also a function of cumulative injected water volume (Figure 35-e).

In addition, the effect of the tested parameters was investigated, it was found that certain reservoir characteristics have an impact on the thermal area size and shape distributions. For instance, the parameters behind the dual or bi-modal thermal area distributions (small and large thermal areas in Figure 35-a) are mainly the karst permeability and its extension away from the faults (towards the middle of the horst and graben). Figure 36-a and b show that the minimum values of the karst permeability and/or its extension are responsible for most of the small thermal areas (lower than 1 km^2) and smaller length (Figure 36-e) while the width is hardly affected by these properties (Figure 36-f). Conversely, higher values of these parameters will lead to large thermal areas (remaining permutations). The reason behind the small areas is that the low permeability and/or short extension of the karst system leads to low well injectivity and finally low flow rates (flow rates are reduced from 200 m^3/h). Under low flow rates the thermal area is small (Figure 35 -c) because a lower amount of water is injected during the 35 years of operation than in the cases with high flow rate. This points out that the thermal area is a function of the rock properties and the corresponding flow rate as shown in Figure 36. The independent effect of the maximum and minimum value of every permutated parameter can be found in Annex A.

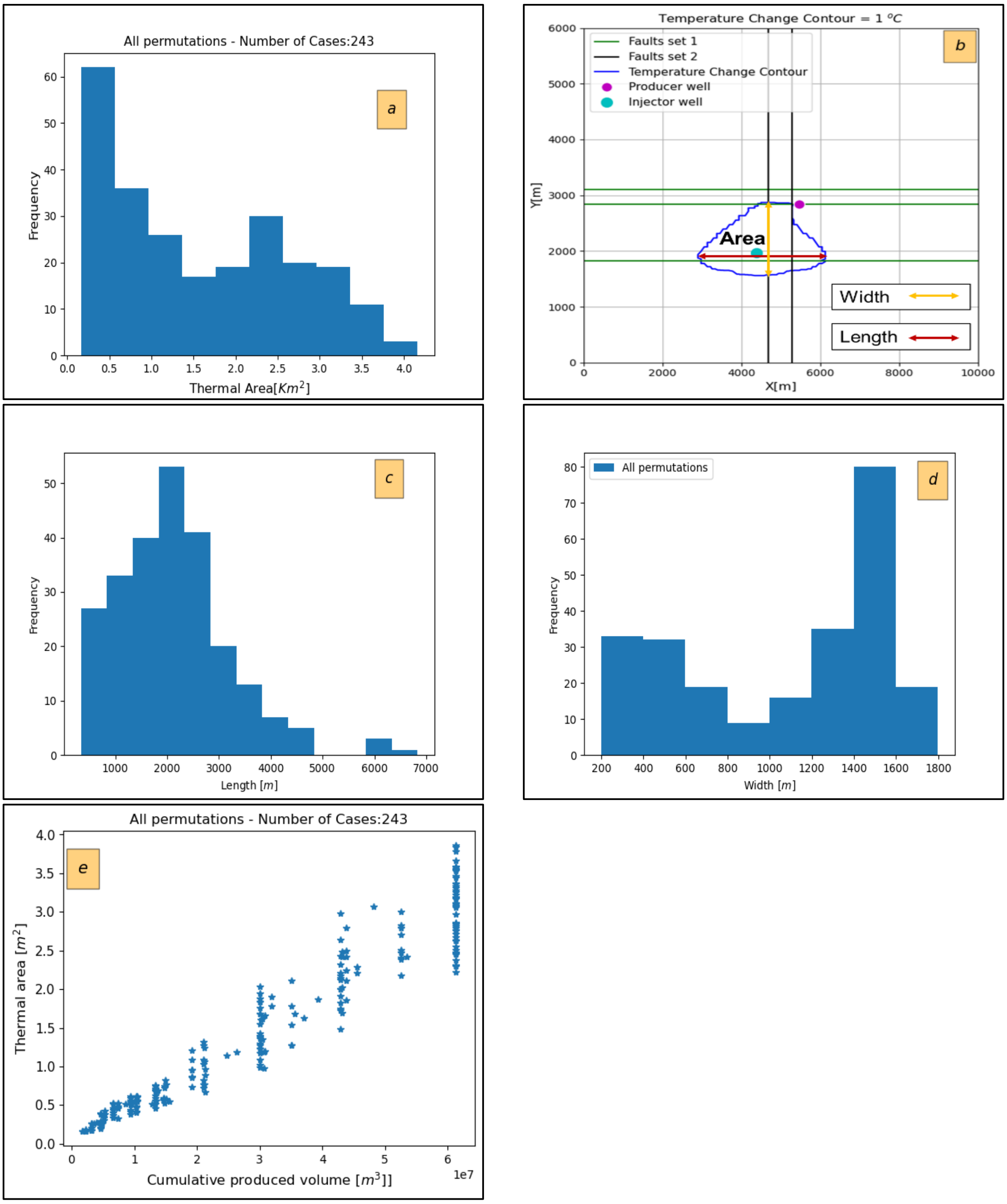


Figure 35: General results for all the permutations in terms of affected thermal area forecasted at year 35 considering a temperature change threshold of 1°C for Concept 1. Frequency distribution of the affected thermal area (a). Illustration of the characteristic dimensions of the affected thermal area: Length and width (b). Distribution of the corresponding length (c) and width of the affected thermal area (d). Thermal flow area is also a function of injection rate and time 'cumulative produced or injected volume' (e)

If only the cases or permutations with a flow rate equal or higher than 80 m^3/h are plotted (Figure 36-b) then the disturbed thermal area distribution indicates a range of 1 km^2 to 3.7 km^2 with an average value of 2.5 km^2 approximately while the values of length and width for a percentile 50% correspond to 2500 m and 1450 m respectively as can be read in Figure 38. Alternative distributions considering flow rates thresholds of 50 m^3/h and 100 m^3/h are presented in Annex A.

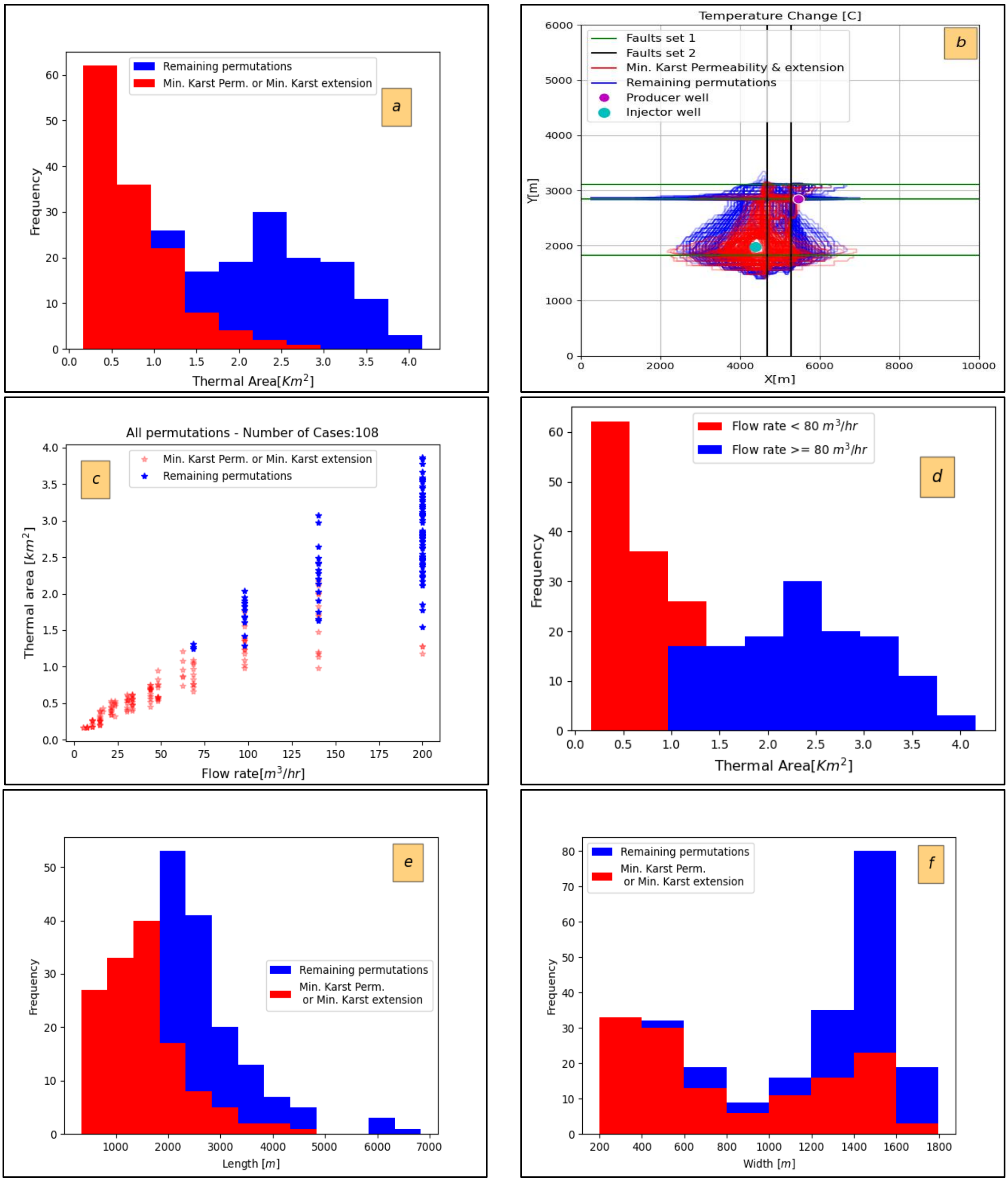


Figure 36: Effect of karst permeability and karst extension on the affected thermal area (a and b). The minimum values of these parameters and the corresponding low flow rates are responsible of the small thermal areas (c). Disturbed thermal area distribution for reservoir conditions that can sustain injection/production fluid rates >= 80 m^3/h (d). Length (e) and width (f) of the affected thermal areas. Results of Concept 1 reported at 35 years and considering 1℃ minimum temperature change for disturbed thermal area estimation.

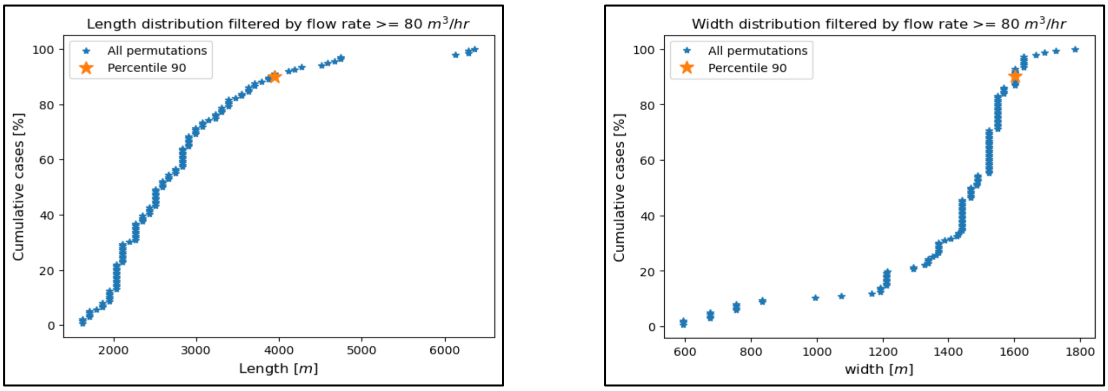


Figure 37: Cumulative distribution of thermal length and width of the disturbed thermal area coming from permutation analysis. The Percentile 90 for length, width is indicated for each of them.

In addition, the permutations also indicate the possible presence of outliers (terms out of the distribution) in the distribution of length (Figure 36-e). These are represented by the highest values of length (higher than 6000 m). These values are the result of cooling along the fault where the producer well is located as shown in Figure 36-b. This cooling is caused by preferential flow from the horst (cold water) towards this fault in cases where the ky/kx is the lowest (low permeability in y direction), the thickness is the highest and karst permeability is high (high injection flow rates). These outliers are a total of 4 cases out of 243 if cases with lengths equal or higher than 6000 m are considered.

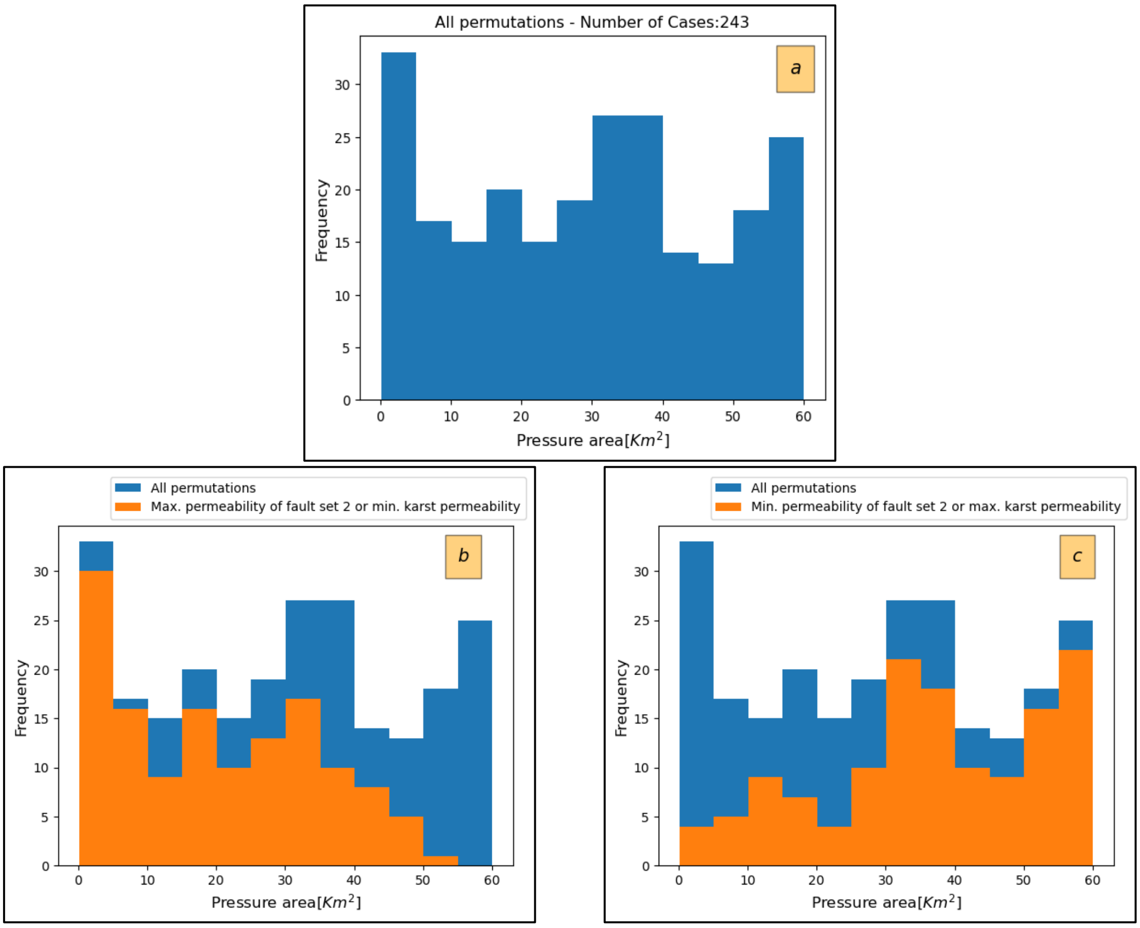


Figure 38: Frequency distribution of affected pressure area considering all the permutations for Concept 1 (a). Distribution considering: maximum permeability of the fault set 2 and minimum permeability of the karst (b) and minimum permeability of the fault set 2 and maximum permeability of the karst.

6.2.2 Affected pressure area

The affected pressure area, which is defined as the area that experienced a change of absolute pressure 'dP' of 1 bar after exploitation, has a wider distribution than the affected thermal area. It goes from values lower than 1 km^2 to values equal to the area of the simulation model, which is 60 km^2 as shown in Figure 38-a. In general, wide pressure areas (> 30 km^2) are prone to develop when there is poor hydraulic communication between producer and injector well and high injection flow rates are still possible. For instance, when the permeability of fault set 2, which is located between the wells is low or/and permeability of the karst is high (high flow rates) as shown in Figure 38-c. On the other hand, smaller pressure areas (< 30 km^2) will preferentially develop if permeability of the fault set 2 is high or if the karst permeability is low (Figure 38-b). Under the former characteristics there is good hydraulic communication between the wells and under the latter characteristics the corresponding injection flow rates are the lowest (pressure at the injector reaches the maximum) which reduces the distribution of high values of pressure.

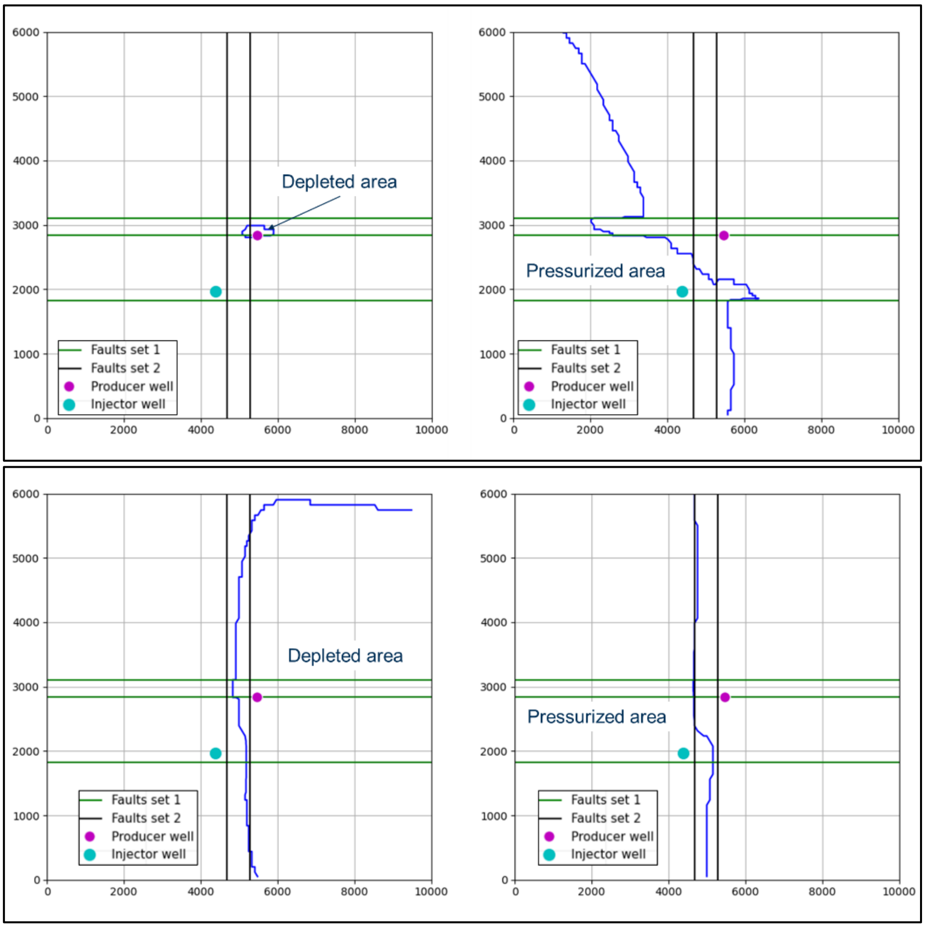


Figure 39: Examples of affected pressure area shapes from the permutation in Concept 1. The case on top considered high permeability in Faults set 2 and low karst permeability while the one at the bottom considered low permeability of the fault set 2 and high permeability of the karst.

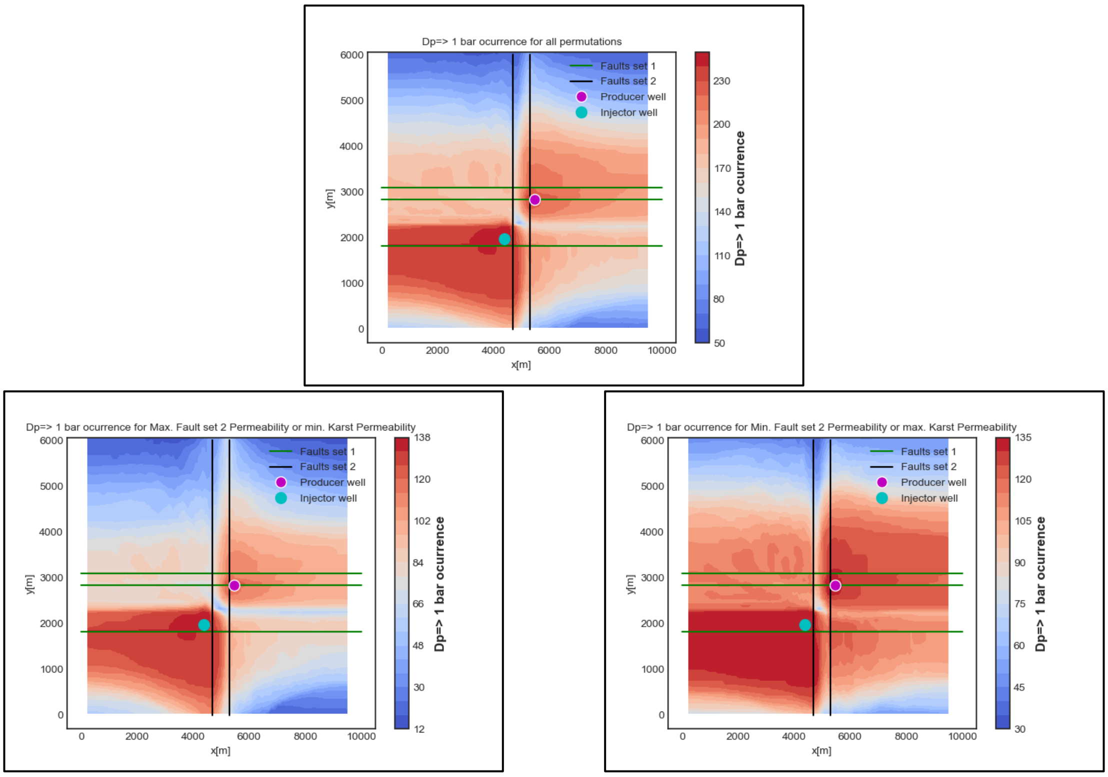


Figure 40: Visualization of the number of simulated cases per position that reached an absolute change of pressure above 1 bar 'dP ocurrence'. The figure at top shows all the cases from the permutation. The cases only considering maximum permeability of fault set 2 or minimum karst permeability are shown in the figure at the bottom left and the cases with the inverse condition of fault set 2 (low values) and karst permeability (high values) are shown at the bottom right. The faults and the low permeability area in the horst (area between the wells) define the boundaries of pressurized and depleted areas in quadrants. The quadrants where the wells are located are usually pressurized (around the injector well) and depleted (around the producer well) while the remaining the other 2 quadrants are likely to experience lower changes in pressure.

The shapes of the affected pressure areas are more variable than the affected thermal areas because pressure diffusion is more sensitive to reservoir parameters (permeability). Figure 39 shows how a change in fault and karst permeability could generate different shapes of the disturbed pressure areas (depleted and pressurized). To provide a comprehensive analysis of the pressure affected area, occurrence or density maps, which plot the number of simulated cases per position where pressure has changed more than 1 bar (either increase or decrease), were used. Figure 40-top shows the absolute dP occurrence map considering all the permutations. As expected, the higher occurrence happens in an around the wells due to injection (pressurization) and production (depletion) and it is displayed in quadrants delimited by the faults and low permeability reservoir areas. The lower occurrence takes place in the quadrants where there are no wells. This could provide indication on where to place neighboring doublets to diminish over pressurization in case this condition brings technical and economic issues.

Figure 40-bottom-left and Figure 40-bottom-right show the effect of permeability of both the karst and fault set 2. High permeability of these faults or low permeability of the karst (low injection rates) generates affected pressure areas that extend along the faults from set 1 (Figure 40-bottom-left) while the inverse conditions generates disturbed pressure area that propagates into the reservoir (Figure 40-bottom-right).

In addition, pressure effects reach the open boundaries of the model in most of the cases. This is due to the heterogeneity assumed between the injector and producer well (usually low permeability between them) and the fault permeabilities. This indicates that pressure disturbance could really travel a long distance and some water could go and come to/from far regions. In these simulations the boundaries are between 2 km to 4.5 km from the wells. It should be noted that long-distance effects are partly a result of model assumptions, including a perfectly confined reservoir layer (at top and base).

6.3 CONCEPT 2

The permutation analysis for reservoir concept 2 considered 4 parameters: porosity and permeability of fault set 2, matrix permeability anisotropy ky/kx, top layer permeability, and porosity and permeability of fault set 1. The minimum, maximum and base values used in the permutation are indicated in Table 18.

Table 18: Parameter considered for the permutation study in Concept 2.

Parameter	Minimum value	Base value	Maximum value
Porosity and permeability fault set 2	3% - 10 mD	No fault set	10%-2857mD
Matrix permeability anisotropy ky/kx	0.1	1	10
Top layer permeability	500 mD	2857 mD	5000 mD
Porosity and permeability fault set 1	5% - 500 mD	10% - 2857 mD	20% - 5000 mD

6.3.1 Affected temperature area

The main observations from the permutation results (Figure 41) are described below:

- Dual distribution for thermal area (Figure 41-a), mainly ruled by rock anisotropy (ky/kx) which induces low injection flow rates and/or preferential paths (Figure 42). Its values range from lower than 0.5 km^2 to 3.4 km^2.
- Rounded thermal areas due to homogeneous permeability in the top layer (Figure 41-b).
- The width and length (Figure 41-c and d) have similar values (2000 m approx.), in contrast to results obtained from concept 1 where length is much larger than width. This is due to the permeability in the continuous top layer.
- An important number of the permutations lead to injection and production flow rates lower than 80 m^3/h (Figure 41-f). This is the result of the combination of the no-flow boundary condition, the minimum permeability for fault set 2 and the top layer, matrix anisotropy, and a relatively low value of maximum pressure at the injector (58.42 bar).

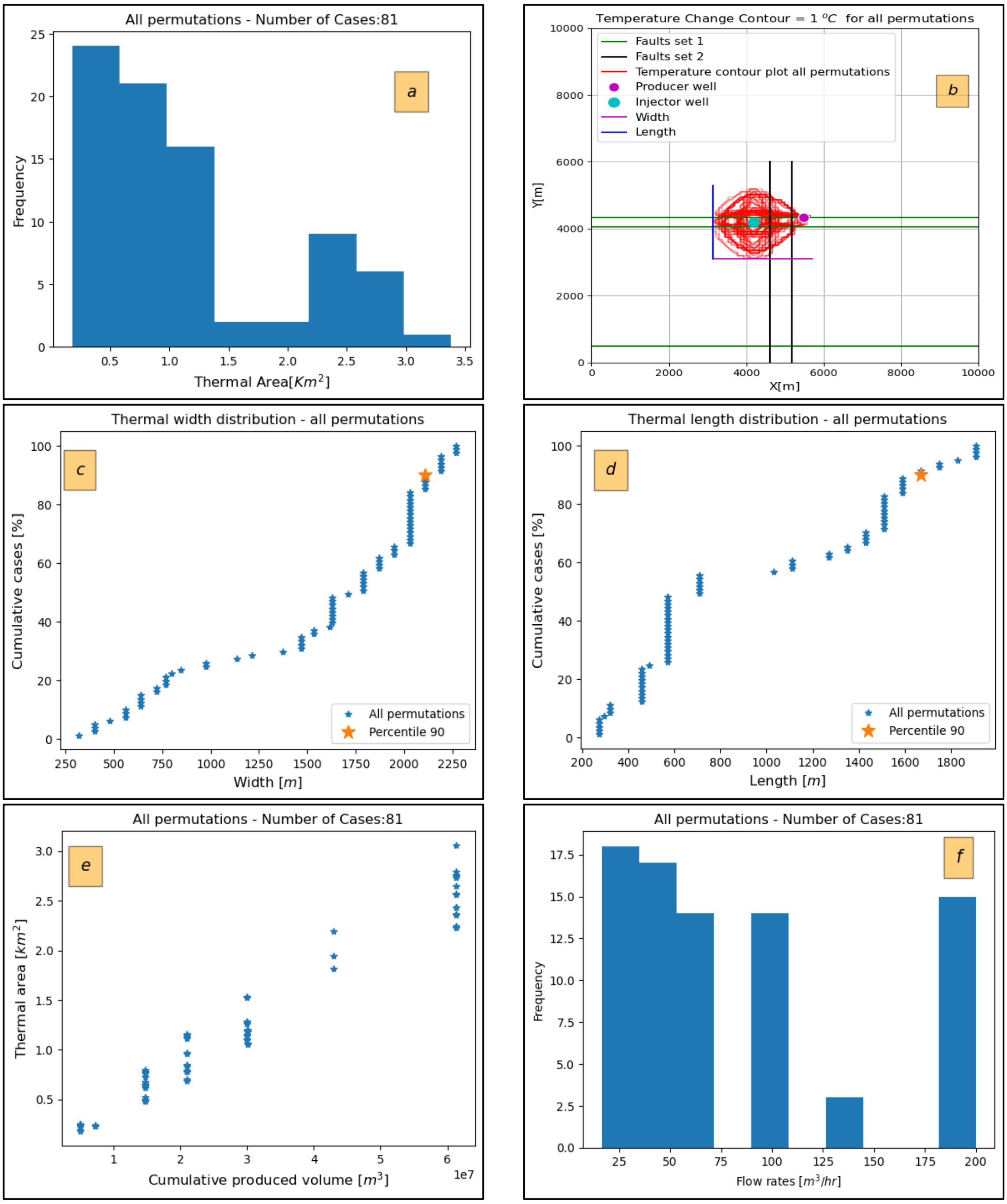


Figure 41: General results for all the permutations in terms of disturbed thermal area forecasted at year 35 considering a temperature change threshold of 1°C for Concept 2. Frequency distribution of the affected thermal area (a). Illustration of the characteristic dimensions for thermal area (b). Distribution of the corresponding length (c) and width (d). Thermal flow area is also a function of injection rate and time 'cumulative produced or injected volume' (e). Final injection/production flow rates (f)

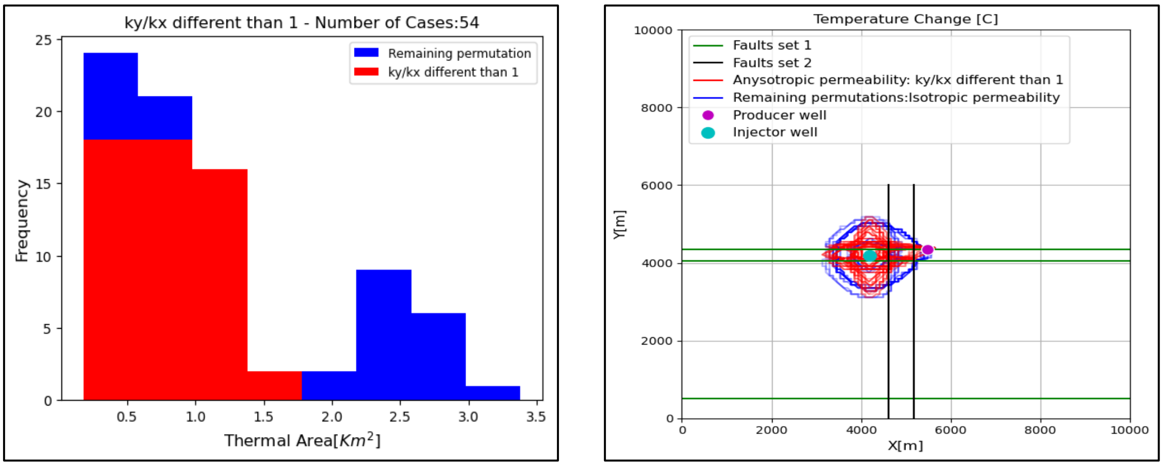


Figure 42: Effect of permeability anisotropy 'ky/kx' on thermal area. When 'ky/kx' is different than 1, It induces low flow rates or/and preferential flow paths in the x direction which result in small and not rounded thermal areas.

6.3.2 Affected pressure area

Disturbed pressure area or 'Pressure area' ranges from values as low as 0.09 km^2 to as high as 43 km^2 as shown in Figure 43. Low permeability of fault set 2 is responsible for the largest-pressure area. Thus, if these faults are found with low permeability (equal or lower than 10 mD), an important pressure interference between areas is expected. In that case, fluid injection rates must be adapted to honor possible pressure constraints.

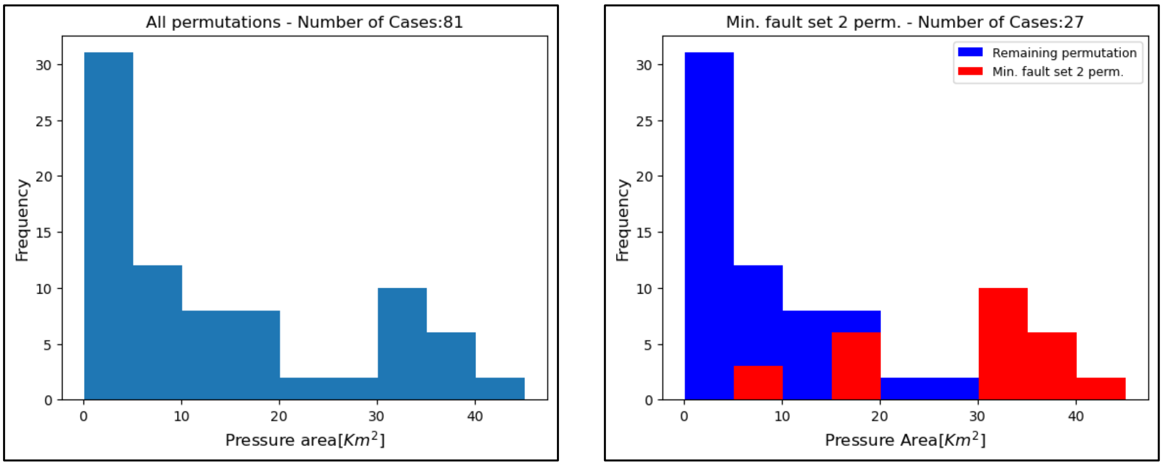


Figure 43: Distribution of disturbed pressure area size for all permutations (left) and impact of minimum low permeability of fault set 2 on the distribution of all cases.

From a spatial point of view, most of the cases experience a depletion higher than 1 bar around the producer well and towards the boundary of the model located at y=6000 m (Figure 44). The latter due to the no-flow boundary condition imposed at this boundary that tries to mimic the lateral discontinuity between the rocks of the London-Brabant Massif (low permeability) and the Lower Carboniferous limestones.

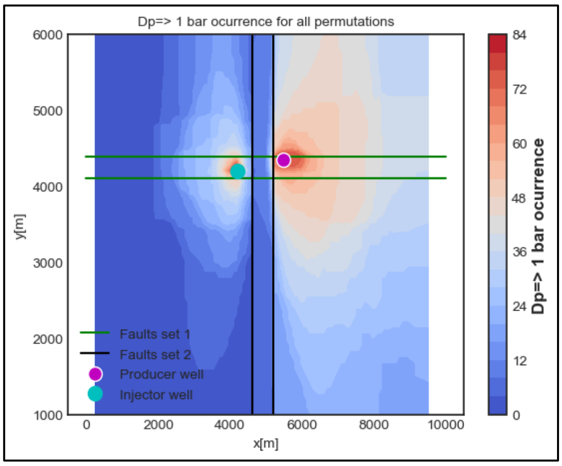


Figure 44: Map of pressure change occurrence of 1 bar for the permutation analysis on concept 2.

6.4 CONCEPT 3

The permutation analysis for reservoir concept 3 considered 4 parameters: porosity and permeability of fault sets 1 2, minimum permeability of the reservoir rock or background permeability and the fault height. The minimum, maximum and base values used in the permutation are indicated in Table 19.

Table 19: Parameters considered for the permutation study in Concept 3.

Parameter	Minimum value	Base value	Maximum value
Porosity and permeability fault set 1	5%-500 mD	10%-2857 mD	20%-5000 mD
Porosity and permeability fault set 2	3%-10 mD	5%-500 mD	10%-2857 mD
Minimum reservoir permeability	1 mD	10 mD	25 mD
Fault height	100 m	352 m	440 m

6.4.1 Affected temperature area

The general response of the permutation analysis in terms of thermal area, shape and corresponding length and width are shown in Figure 45. The thermal area frequency distribution has an exponential shape (Figure 45-a), with most simulated cases yielding thermal areas smaller than 2 km^2. Permeable faults, low permeability of the matrix and low extension of the enhanced reservoir region are the responsible characteristics of these small areas. The shape is in general elongated (Figure 45-b), along the nearest permeable fault to the injector. In general, wells in this reservoir concept must be relatively close to the fault zones or/and fractured areas to have sufficient permeability for injection and production (the reservoir rock has almost no matrix permeability). Nevertheless, this situation implies geological risks related with fault reactivation and possible induced seismicity. Thus, the injection conditions must be engineered and faults not prone to reactivation must be identified so that stress changes on the fault planes are below that the threshold for reactivation.

Some parameter combinations can lead to very elongated shapes of the thermal area (Figure 45-b). The corresponding thermal length could reach up to 8000 m (Figure 45-c and Figure 48), which is twice what is expected for concept 1 and almost 4 times the length for concept 2. Thus, a much larger production area could be required for concept 3 than for the other concepts. These very

elongated shapes are expected to occur when the permeability of fault set 2, which hydraulically connects injector and producer wells, is in the order of 10 mD as shown in Figure 46.
Also, it is important to mention that approximately two thirds of the simulated cases yield breakthrough times shorter than 20 years. Breakthrough times are measured when produced water temperature drops 3.5 °C. These short times are also the result of fault zones being the only or main reservoir in this concept.

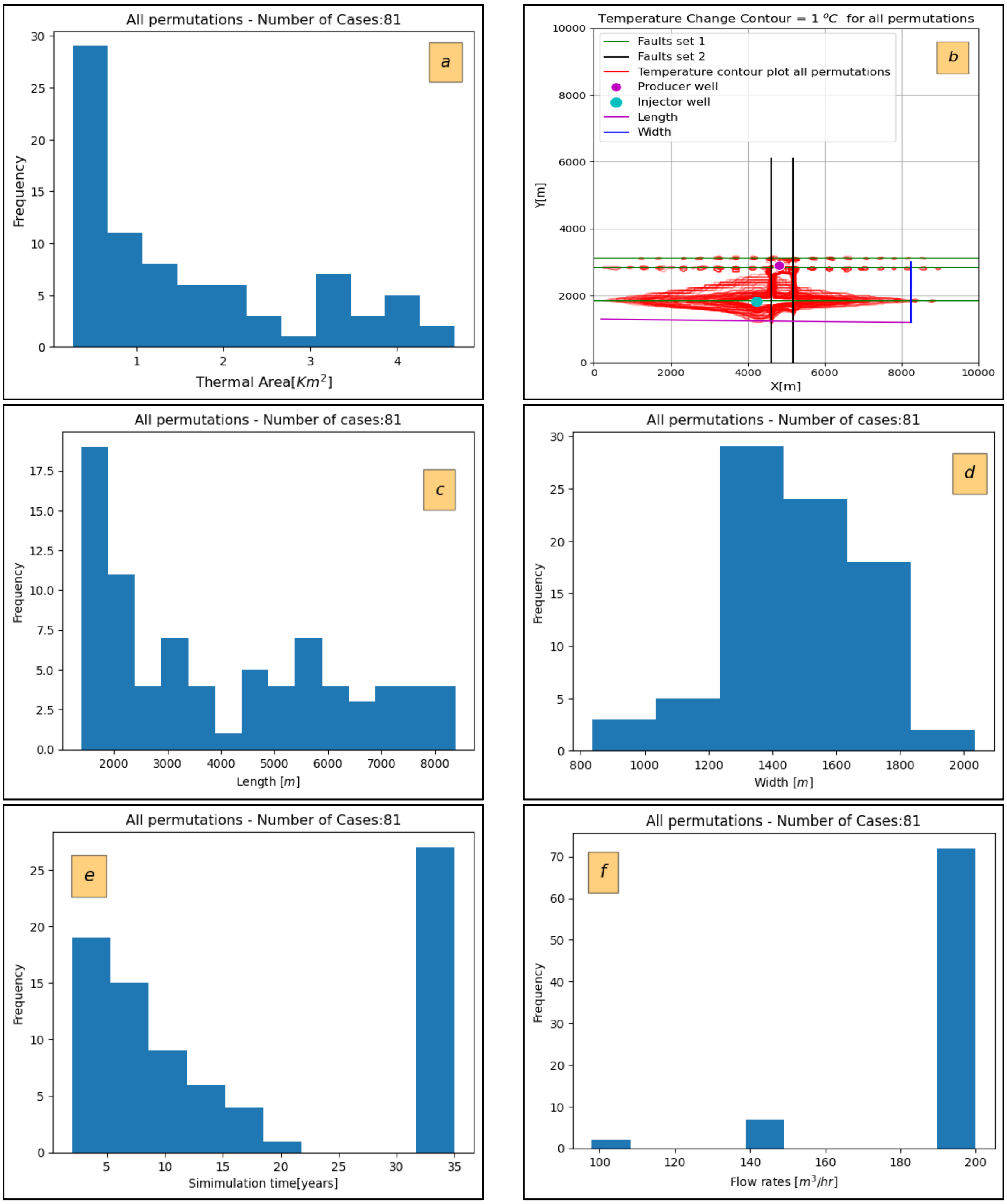


Figure 45: General results for all the permutations in terms of disturbed thermal area forecasted at year 35 considering a temperature change threshold of 1°C for Concept 3. Frequency distribution of affected thermal area (a). Illustration of the characteristic dimensions for thermal area: Length and width with all temperature change contours (b). The circles shown in b are due to the presence of convection cells when permeability of fault set 1 is too high. Distribution of the corresponding length (c) and width of the disturbed thermal area (d). Thermal flow area is also a function of injection rate and time 'cumulative produced or injected volume' (e). Final injection/production flow rates (f).

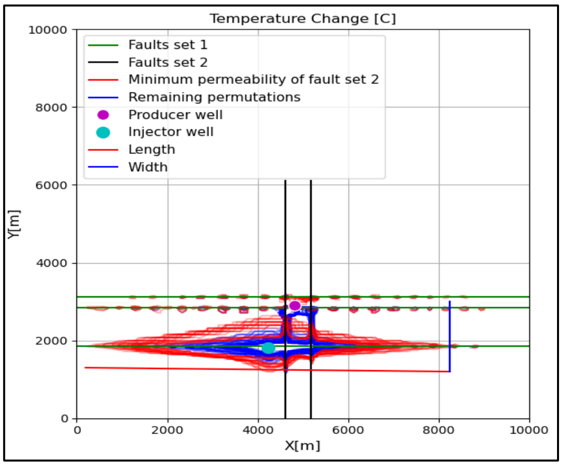
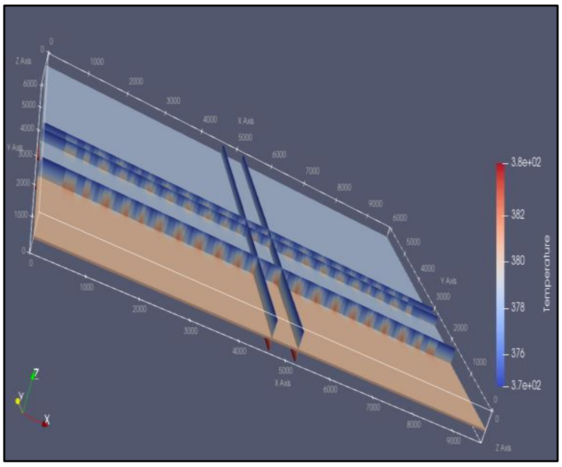


Figure 46: Temperature change contours of 1 C° at the end of the simulation, indicating the thermal areas generated by the cases of low values of permeability of fault set 2 and all the cases.



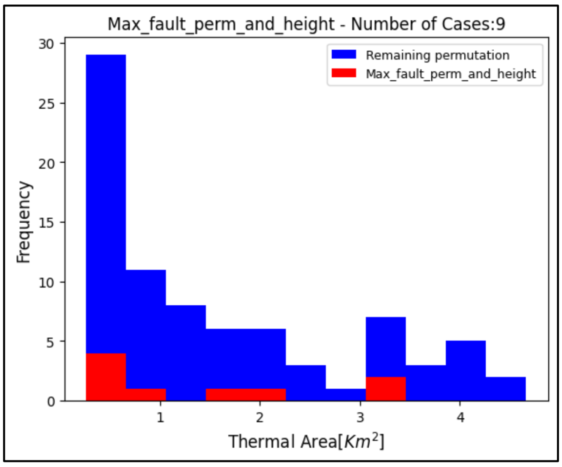


Figure 47: Forecasted convection cells when fault set 1 permeability and height are high (left) and their impact on thermal area estimation (right).

The circles of the temperature contours shown in Figure 45-b, Figure 46 and Figure 47 along the fault set 1 are due to the presence of convection cells. These cells take place when simulated cases have a high permeability in fault set 1 (5000 mD) and when the height of the fault is also high (440 m). It is important to mention that these values are not likely to be present in the current setting but were considered for understanding the limits. Their impact in the distribution of the thermal area is shown in Figure 47-right. These cases have in general the tendency to have small thermal areas.

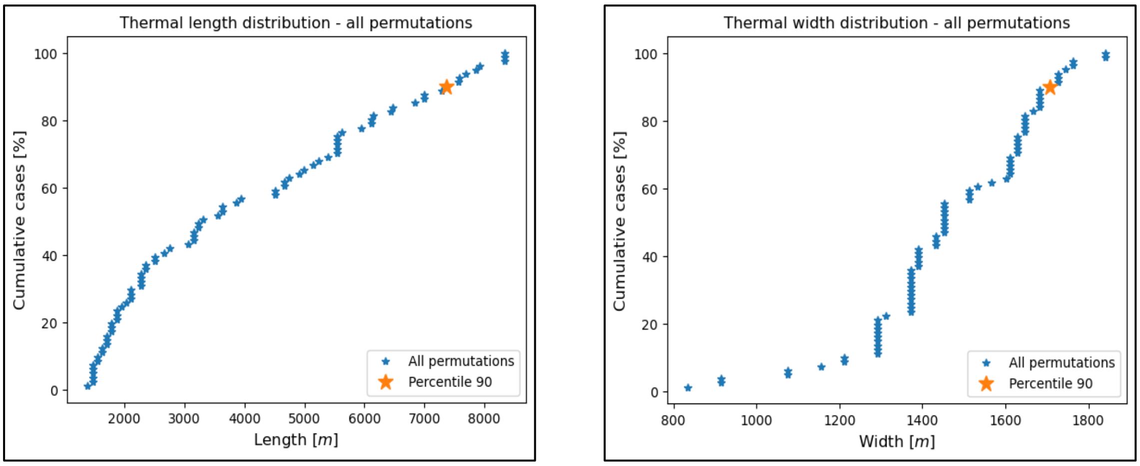


Figure 48: Cumulative distribution of the results obtained in the permutation analysis in terms of length and width of the disturbed thermal area for concept 3.

6.4.2 Affected pressure area

Graphs of the affected pressure area in Figure 49 (when considering 1 bar pressure change) reveal that half of the cases yield a wide area (50 km^2 to 60 km^2). These wide areas are mainly due to low permeability of fault set 2 (Figure 50-left). On the other hand, when permeability of these faults is high, affected pressure area tends to be small (Figure 50-right).

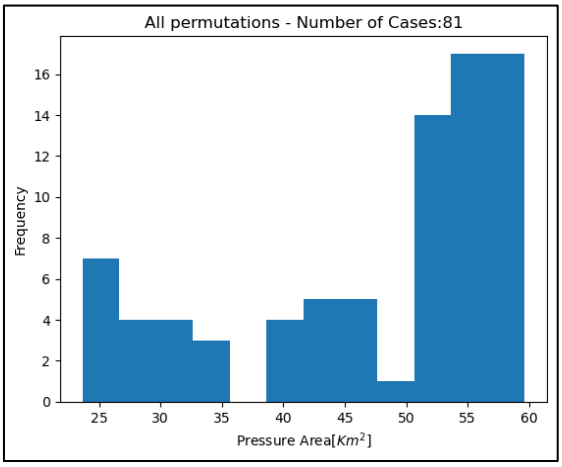


Figure 49: Frequency distribution of the pressure area considering all permutations.

The pressure changes ‘dP’ of 1 bar or higher are forecasted to take place along the faults (set 1 and set 2) as shown in Figure 51. Then, the affected pressure area could spread from these faults significantly or not depending on fault and matrix permeability. In addition, most of the permutated cases show that high pressure changes (|dP| >= 10 bars) are forecasted around the injector well along the faults zones (Figure 51 - right). For avoiding that fault reactivation and induced seismicity in this kind of setting, the flow rate must be engineered, i.e. the flow rate has to be defined so that pressure and temperatures are below the reactivation thresholds and well locations have to be far from those faults that are prone to reactivation, preferable in those areas where fracture permeability is more laterally continuous. Thus, proper reservoir characterization via 3D reflective seismic could be needed in this setting.

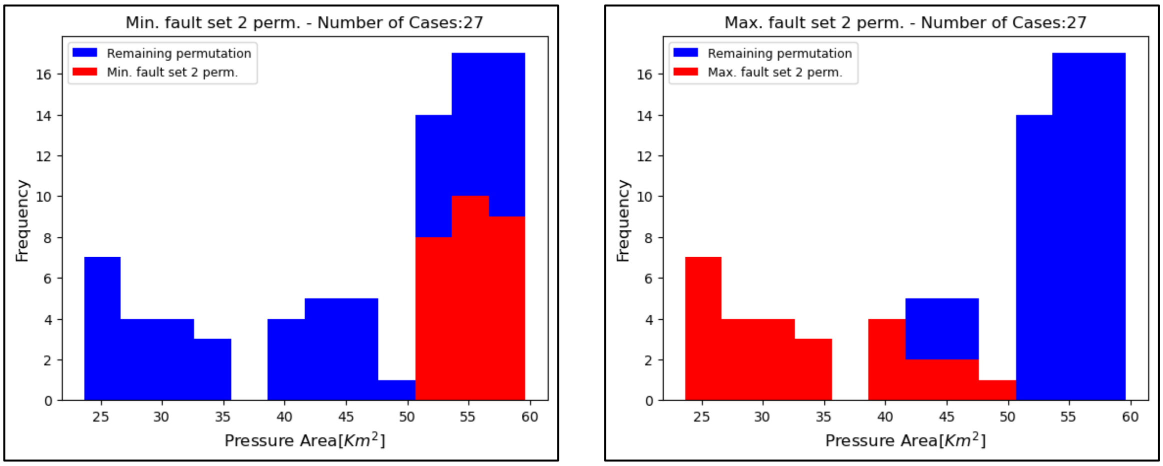


Figure 50: Frequency distribution of the pressure area highlighting the effect of minimum (left) and maximum (right) permeability of fault set 2.

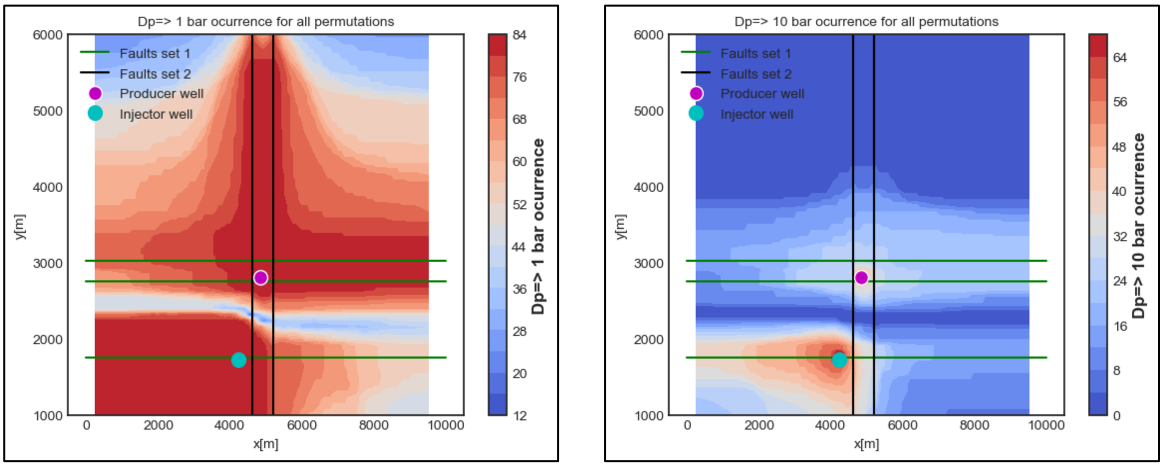


Figure 51: Pressure change occurrence maps from the permutation study for 1 bar (left) and 10 bars (right) for Concept 3.

6.5 Summary and analysis

- Concept 1

The disturbed thermal and pressure areas induced by geothermal operations in reservoir concept 1 could range between 1 to 3.7 km^2 and from 1 to 60 km^2 respectively. The reservoir parameters influencing the size and shape of these areas are:

Disturbed thermal area:

- Karst permeability.
- Karst extension from the fault.
- Fault orientation.

Disturbed Pressure area

- Permeability of the faults between the wells (Fault set 2).
- Karst extension from the faults and assumed minimum permeability in the center of the graben (10 mD).

Large disturbed thermal areas, that may lead to better thermal performance, are prone to form when it is possible to inject high volumes of water (High permeability of karst) and there are certain restrictions to flow between the injector and production well (low permeability of fault set 2, permeability anisotropy and heterogeneity). Nevertheless, these conditions could also lead to extended disturbed pressure areas (>30 km^2) if the restriction for flow between injector and producer wells is important.
Contrary, small thermal areas are expected to form when petrophysical or business conditions lead to low flow rates or/and when there is short circuiting between injector and producer wells (high permeability of fault set 2). Regarding disturbed pressure areas, they will have small sizes when there is good hydraulic communication between injector and producer well (karst permeability is high and its extension from the faults is long, high permeability of faults).

- Concept 2

The thermal affected area shows a dual distribution for this concept due to matrix permeability anisotropy that controls flow rate magnitude and permeability of the fault set 1 that could lead to short circuiting if its values are high. The average values of disturbed thermal area for every sub-distribution are 0.75 km^2 and 2.5 km^2. These values are smaller than in concept 1 because 2 layers are available for injection.

The disturbed thermal areas for concept 2 show two topological patterns:

- Elongated, corresponding to the cases where the karst along the faults presents the higher permeability compared to the rest of system (Figure 52-left) or when there is strong permeability anisotropy.
- Elliptical or rounded shapes corresponding to the cases where the permeability of the upper layer (second layer) is high (> 500 mD in either direction) and isotropic (Figure 52-right).

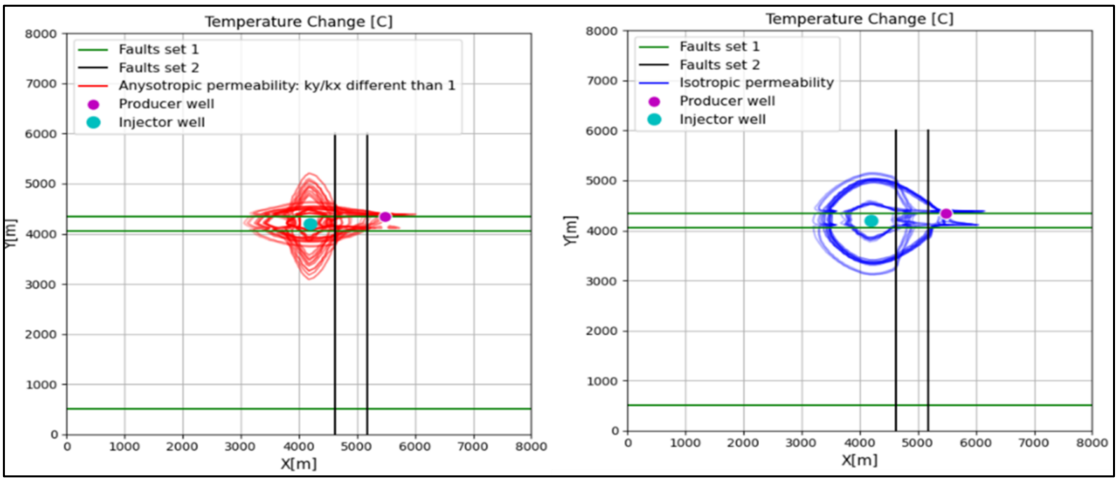


Figure 52: Effect of anisotropic permeability (left) and isotropic permeability in the reservoir layers on disturbed thermal areas, indicated by delta temperature of 1°C contour, for Concept 2.

As in concept 1, disturbed pressure area varies considerably (wide range). There are cases with values smaller than 10 km^2 corresponding to cases of high permeability of the matrix, karst and faults or low injection flow rates due to pressure constraints at the injector well. The large areas can reach values of 30 to 40 km^2 when the faults between the wells have low permeability. As mentioned in Concept 1, pressure area will depend on the injection and production flow rates.

- Concept 3

For concept 3, the affected thermal area is expected to be small (< 2 km^2) but elongated because it mainly covers the fractured zones along the faults. In fact, it could reach a thermal length of up to 8 km for certain reservoir parameter combinations. The main parameters leading to these results are:

- Permeable faults regions with low extension of the enhanced reservoir region around the faults.
- Low permeability of the matrix.

Pressure changes spread along the fractured zones and faults preferentially in this concept. The size of the disturbed pressure area for most of the tested cases is higher than 40 km^2. The main reason is the expected small permeability of the matrix and low permeability of faults. As flow will be preferentially through fault and related fractured zones, flow rates and well design must be engineered for avoiding fault reactivation so that seismic risk is minimized.

- Analysis

The multiple reservoirs scenarios that were studied via the permutation analysis have allowed to understand the possible shapes and sizes of both the disturbed temperature and pressure areas for the different reservoir concepts. These spatial fields are commonly used as criteria for defining the production license area of geothermal projects as mentioned in section 2 'Approach Abroad'. One of the most common approaches for defining the production license area is the *French method*. This approach aims to define a license area that covers the temperature changes in homogeneous reservoirs. It proposes a rectangular production license with a length of two times the well spacing and a width of one time the well spacing. When this method is compared with the disturbed thermal areas (Figure 53) and with the disturbed pressure areas (Figure 54), it is evident that this approach cannot properly frame them for reservoir concepts 1 and 3. Nevertheless, this approach seems to work better for concept 2, this is because the top layer of this concept is considered homogeneous.

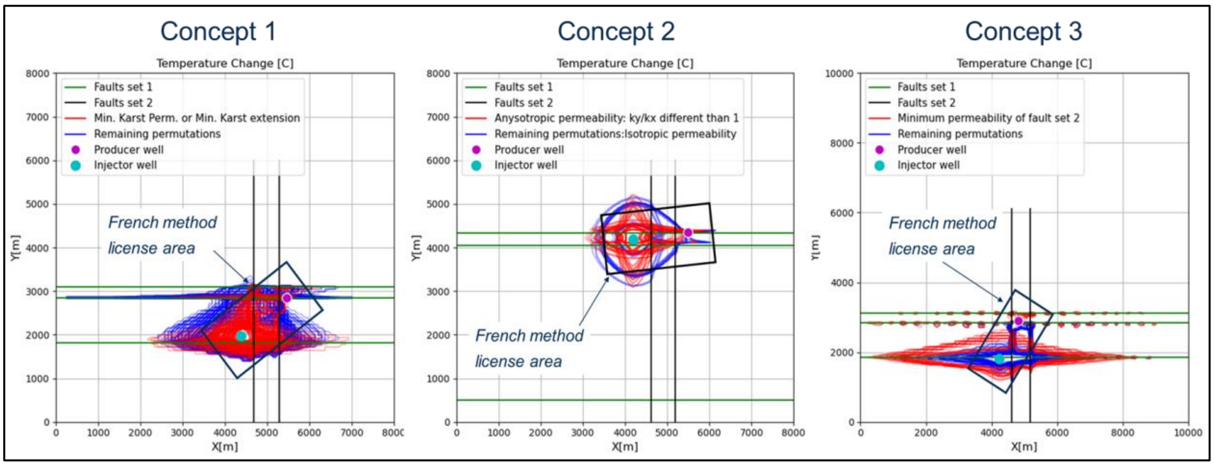


Figure 53: Comparison of disturbed thermal area from the permutation analysis (blue and red contours) with French method for the three tested concepts. Temperature change contour correspond to 1 °C.

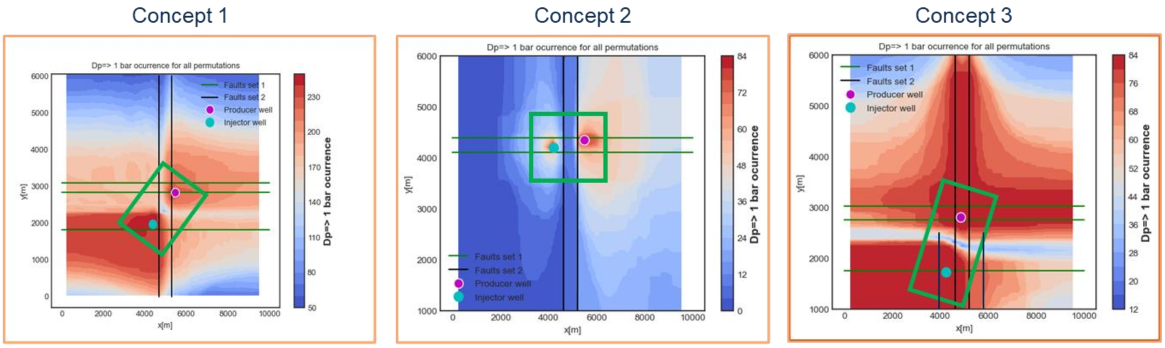


Figure 54: Occurrence of absolute change of pressure ‘dP’ equal or higher than 1 bar from the permutation study results of the different concepts. Maximum flow rate was 200 m^3/h. It shows that for concept 1 and 3, there are numerous simulations where results indicate pressure changes of more than 1 bar outside the French method license area (green rectangle)

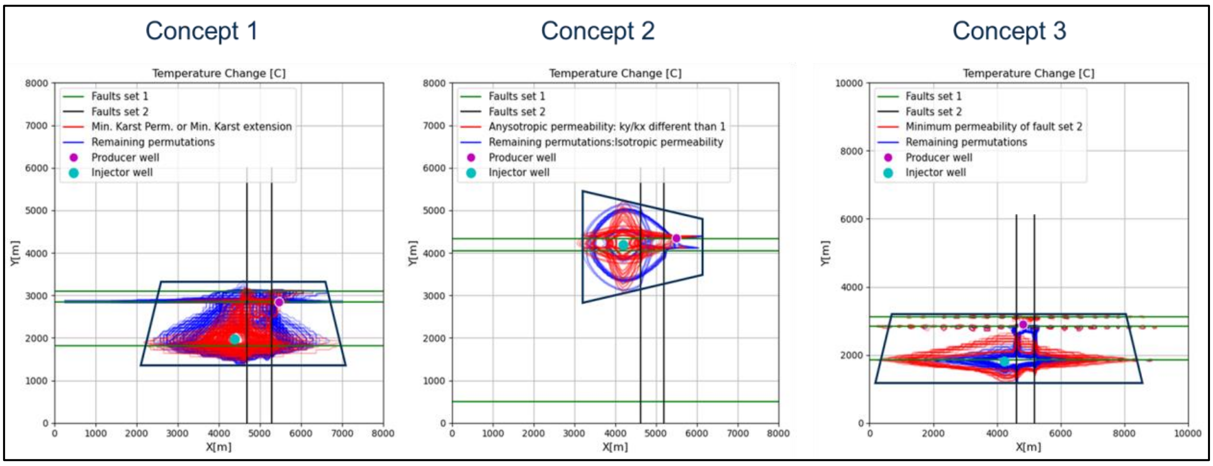


Figure 55: Delineation of thermal area with trapezoidal shape for the three studied reservoir concepts.

Heterogeneous reservoirs, such as those found in the limestones of the Campine Basin, demand a tailored approach to ensure that the disturbed thermal zone remains confined within the production license boundaries, thereby preventing interference with neighboring projects. One initial approach is defining a license with trapezoidal shape following the possible shapes of the temperature contours as shown in Figure 55. Nevertheless, this approach will lead to irregular shapes of the license that could complicate its organization and might not leave room for additional reservoir uncertainties. Thus, an alternative approach is to use a rectangular license that frames the possible disturbed thermal areas and guarantees that the well spacing between nearby projects is equivalent to the well spacing within projects as shown in Figure 56. A more detailed description of this recommended method is given in section 9 ‘Conclusions and recommendations’.

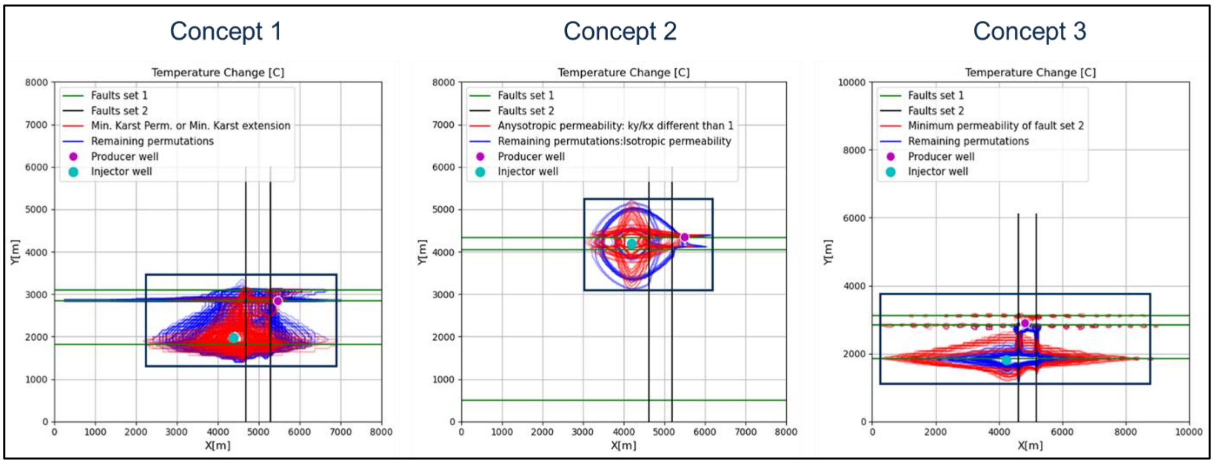


Figure 56: Delineation of thermal area with a rectangular shape for the three studied reservoir concepts.

7 MODELLING – MULTIPLE DOUBLET SCENARIOS

As more geothermal projects are planned and commissioned in Flanders, interference between projects will become a challenge. In addition to the structural/petrophysical parameter spaces tested in the previous section, it is also possible to test different production scenarios where additional projects operate in the same model. In this way, it is possible to predict the impact of interacting projects and determine licensing boundaries and doublet placement in a better way. For this task, only Reservoir Concept 1 was considered, as it is the one with the best conditions for geothermal development (good temperature and permeability values) in the Carboniferous limestone in the Campine Basin in Flanders.

7.1 MODEL DIMENSIONS AND WELL PATTERNS

A total of 9 doublets were tested under two well patterns: line drive and off-line drive as shown in Figure 57. The base case well configuration for Concept 1 was used (see section 4). To accommodate these doublets and allow for different doublet spacing, a large numerical model was required. For this task a model of 20 km in 'x' direction (direction of fault set 1) and 17 km in 'y' direction (direction of fault set 2) was defined. The number of cells 'n' in x, y and z direction is nx=165, ny=160, nz=56 respectively, corresponding to a total number of 1,478,400 cells. Thus, simulation takes longer which eventually puts a limit on the number of simulations that can be carried out.

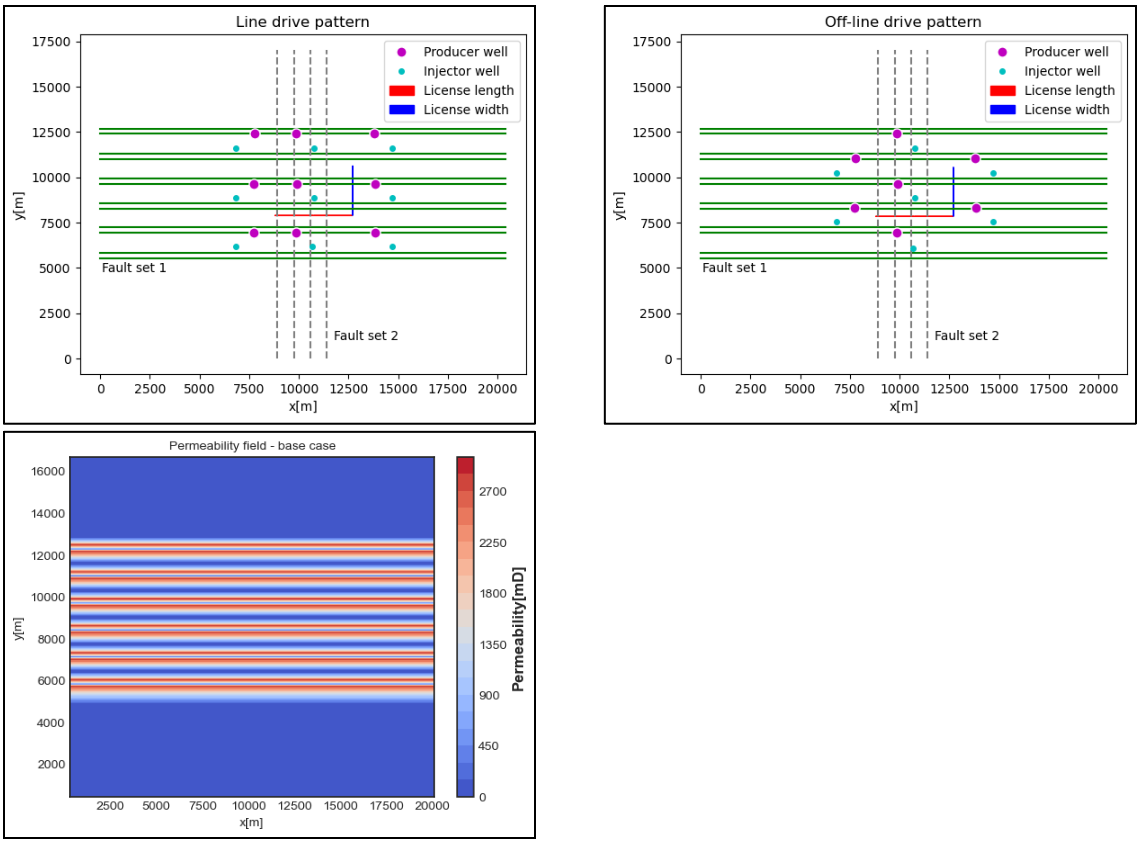


Figure 57: Illustration of multiple well doublets considering two well patterns: line drive (top-left) and offset line drive (top-right). The permeability field for the base case is shown in the bottom for better correlation of the results. The limits of the boundary or license are also indicated for the doublet located in the center.

7.2 SIMULATION SENSITIVITIES AND WELL CONTROL CONDITIONS FOR CONCEPT 1

Three cases of reservoir scenarios of reservoir concept 1 were considered for multiple doublet modeling as shown below. Their corresponding properties are shown in Table 20:

- Base case .
- Base case with high permeability of fault set 2.
- Properties of the conservative thermal length scenario.

The conservative thermal length scenario of reservoir concept 1 corresponds to the percentile 90% of the estimated thermal length in the permutation analysis (Figure 37). This case allows the evaluation of doublet interference in the most critical condition. It is compared with 2 referential cases: the base case and a variation of the base case with high permeability of fault set 2.

Table 20: Input parameters corresponding to base case, high permeability fault set 2 and an extreme case (Percentile > percentile 90) of disturbed thermal length obtained from the permutation study. In bold the parameters that differ from the base case of concept 1

Input parameters	Base	Base with high permeability of Fault set 2	Conservative thermal length scenario
Porosity and permeability fault set 1	10% (2857 mD)	10% (2857 mD)	10% (2857 mD)
Throw of fault set 1 [m]	100	100	100
Karst extension in the horst [m]	300	300	300
Maximum karst porosity -permeability	10% (2857 mD)	10% (2857 mD)	10% (2857 mD)
Minimum reservoir permeability [mD]	10	10	10
Karst extension from fault horst [m]	500	500	500
Permeability anisotropy ky/kx	1	1	0.1
Porosity and permeability fault set 2	No faults	10% (2857 mD)	No faults
Well configuration	base	base	base
Reservoir layer thickness [m]	35	35	50
Fault height [m]	352	352	352

The well configuration was the one named 'base' or 'L shape' (Figure 17) while two doublet patterns were tested (Figure 57):

- Line drive where the injectors are in the same line and the production wells are also in the same line.
- Offset line drive, where injector and producer are in the same x direction line.

Well constraints, completion interval and injection temperature were the same used during the permutation task (Table 16). Flow rate was reduced by a multiplier factor of 0.7 (30% reduction) if maximum pressure at the injector is reached. The simulation was run for 35 years.

Different distance between injector wells of neighboring projects in x direction 'Spacing length' and y direction 'Spacing width' (see Figure 57) were considered to study the interference. A total of 6 spacing lengths and 2 spacing widths were considered. The corresponding values are in Table 21.

Table 21: Sensitivity on length and width of the license area considered during multi-well study.

Length [m]	Width [m]
2000, 3000, 4000, 5500,6500, 20000	1350, 2700, 17000

7.3 MAPS AND INDICATORS

For evaluation of the multiple doublet performance, pressure and temperature maps were used to illustrate the topological shapes of the disturbed areas. In addition, three indicators were monitored so that conclusions can be drawn about the size of the license area:

- Areal thermal sweep efficiency. This is the ratio between the area that has been cooled down at least 1°C ('Affected thermal area') and the total rectangular area defined by the minimum and maximum 'x' and 'y' coordinates reached by the affected thermal area induced by all doublets (Figure 58). Both areas are calculated at the end of the simulation time. This will help to understand how efficiently the geothermal reservoir is being used.

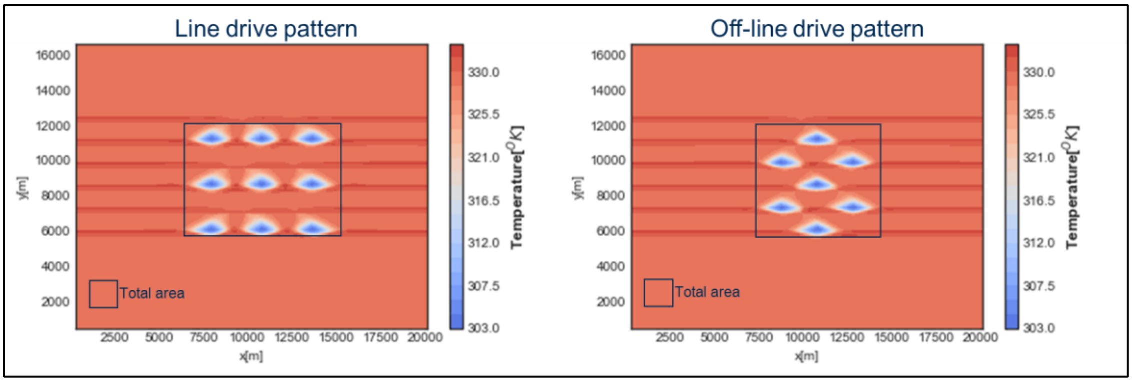


Figure 58: Illustration of the total area and affected thermal area (lighter colors) used as a reference for areal sweep efficiency estimation: Line drive doublet pattern (left) and off-line doublet pattern (right). Case: spacing length 2000 m, properties from the base case.

$$Areal\ sweep\ efficiency[\%] = \frac{Disturbed\ thermal\ area}{Total\ area} * 100 \quad \text{Equation 5}$$

- The coefficient of performance 'COP' for the doublet located in the center of the well pattern is computed. This doublet will be the one experiencing the most interference as it is surrounded by doublets on all sides. The COP is defined as the ratio of the gross thermal energy produced from the doublet and the expended pumping energy indicated by equations 6 and 7.. A pump efficiency of 50% is assumed (which is on the low side).

- Maximum and minimum delta pressure in all the faults. This will allow to understand to what extend doublet spacing and multiple doublets increase/decrease the pressure in the faults.

$$COP = \frac{Gross\ thermal\ energy}{Pumping\ energy} \qquad Equation\ 6$$

$$Pumping_{energy} = \frac{q*(\Delta P_{injection} + \Delta P_{production})}{\eta} \qquad Equation\ 7$$

$\Delta P_{injection}$: Absolute reservoir delta pressure at the injection point [Pa]
$\Delta P_{production}$: Absolute reservoir delta pressure at the production point [Pa]
q: Volumetric flow rate [$\frac{m^3}{sec}$]
η: Pump efficiency [fraction, dimensionless]

Only pressure losses in the reservoir are considered: delta pressure = |Pressure well – Pressure reservoir @ static conditions|

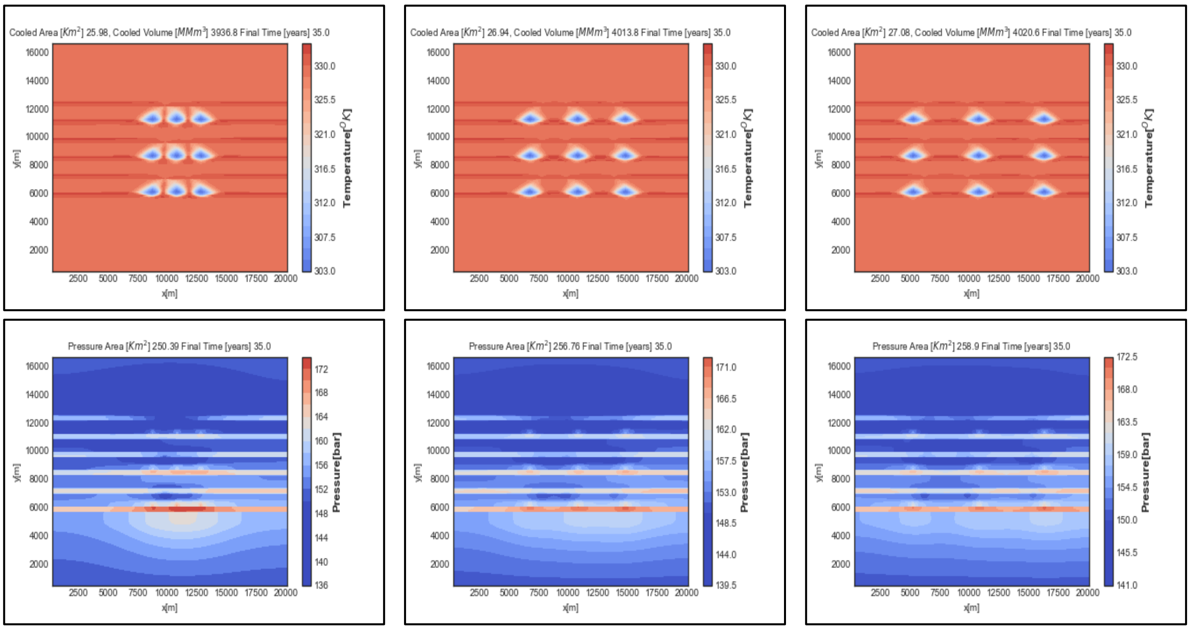
7.4 .

7.5 0RESULTS FOR MULTIPLE DOUBLETS (CONCEPT 1)

7.5.1 Line drive pattern

Base case properties – Spacing length evaluation

The effect of different spacing length (distance between injector wells in x direction) on cold thermal areas shapes and the performance quantitative parameters like: areal sweep efficiency, cumulative heat production and well production and injection pressures are shown in Figure 59 and Figure 60 respectively.



Spacing Length = 2000m   Spacing Length = 4000m   Spacing Length = 5500m

Figure 59: Temperature (top) and pressure (bottom) fields after 35 years of geothermal operations considering line drive doublets patterns, three doublet spacing lengths, constant doublet spacing width of 2700 m and properties from the base case of concept 1.

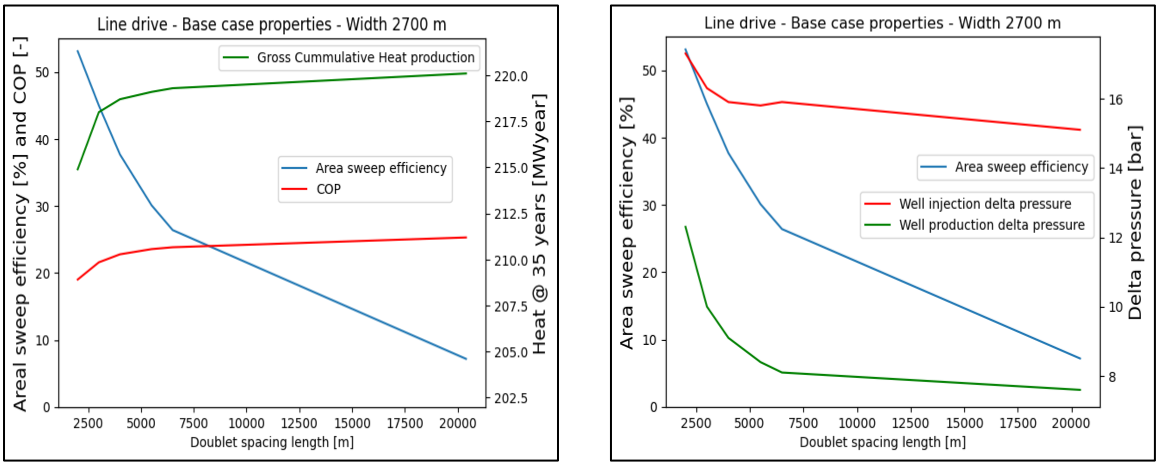


Figure 60: Effect of spacing length on the performance of the doublet located at the center. Areal sweep efficiency, gross produced heat and COP as a function of doublet spacing length (left) and corresponding well delta pressure (right) for the doublet in the center. Line drive doublet pattern, width 2700 m and base case properties.

The main observations and analysis of the effect of different spacing lengths are:

- Cold flooded areas are mainly distorted due to pressure interference when doublet spacing length is 2000 m (Figure 59 - Top left). Spacing lengths equal or higher than 4000 m do not affect the shapes of cold flooded areas. It is not seen major thermal interference, i.e. cold water from one doublet going to a neighbor doublet.
- Delta pressure in the wells of the central doublet (Figure 60-right) start to increase more than 2 bars with respect with the case of single doublet when spacing lengths are equal or lower than 3000 m. This indicates pressure interference.
- The gross heat production and COP of the central doublet slightly decline when reducing spacing length as shown in Figure 60-left. In fact, the gross cumulative heat reduces 3.7% (from 212 MWyear to 204 MWyear) when reducing spacing length from 20000 m to 2000 m. Thus, pressure interference, which is the most important in this reservoir case, is not causing important changes in energy production.
- Contrary to the decrease of heat production, the decrease in spacing length leads to important increment in areal sweep efficiency from lower than 10% when projects are spaced 17000 m to 50% when their spacing length is 2000m. Which means, that the heat extraction of the area tends to be maximized as the spacing length is reduced because more area and volume of the reservoir is contacted.
- The line doublet pattern induces a pressure gradient parallel to the 'y axis' with the development of high and low pressure areas in the doublets located upstream ('y' = 6000 m in Figure 59) and downstream ('y' = 12000 m in Figure 59) respectively.

Base case properties – Spacing width evaluation

In this point, the comparison of 3 different spacing width (distance between injector wells in 'y' directions): 1350 m, 2700 m and 17000 m is explored. Figure 61 – top right shows that when spacing width is 1350 m, there is thermal interference between projects, i.e. the producer well is receiving cold water not only from its corresponding injector well but also from the neighboring project. This causes a reduction of 4% in heat production when width spacing is reduced from 2700 m to 1350 m (Figure 61 – bottom), which can be considered significant for this change of well spacing.

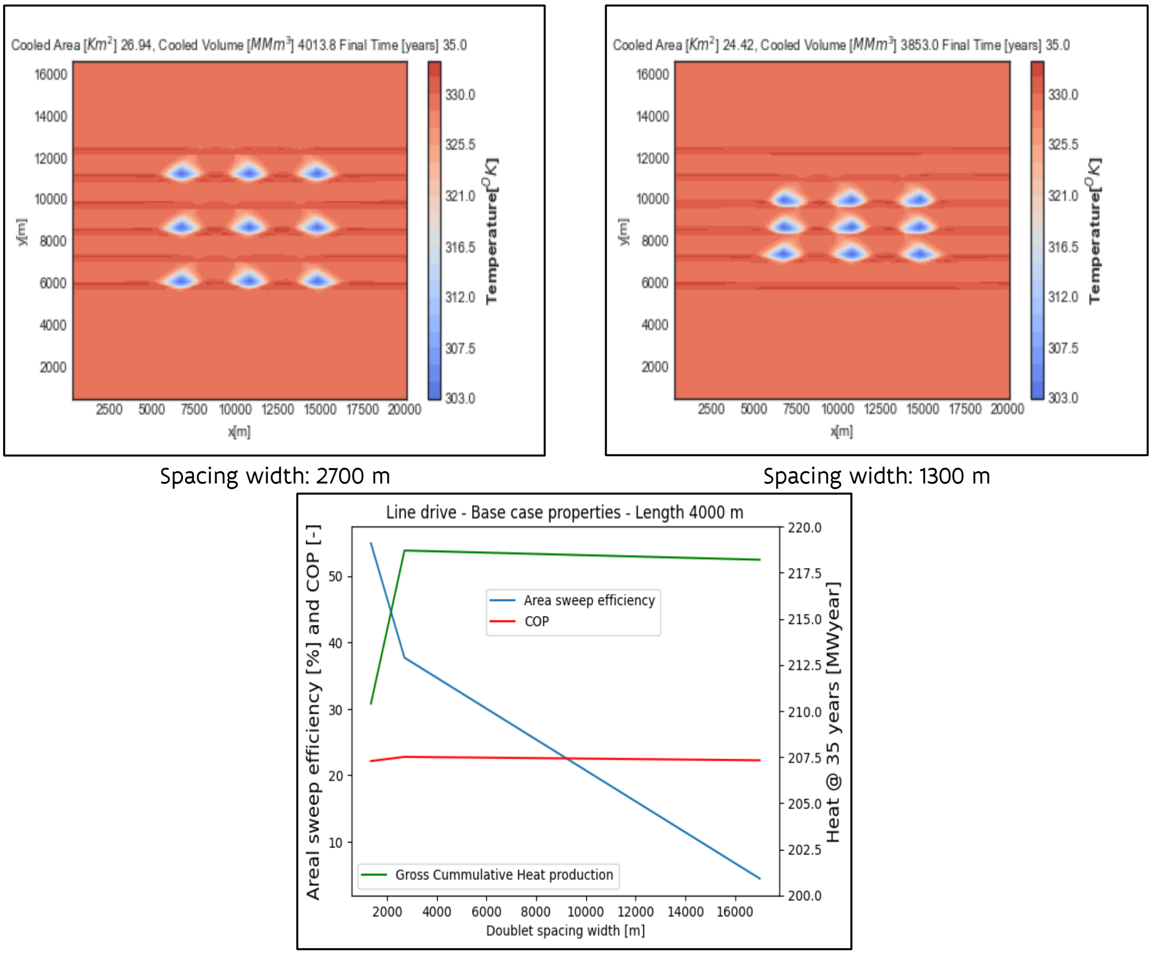
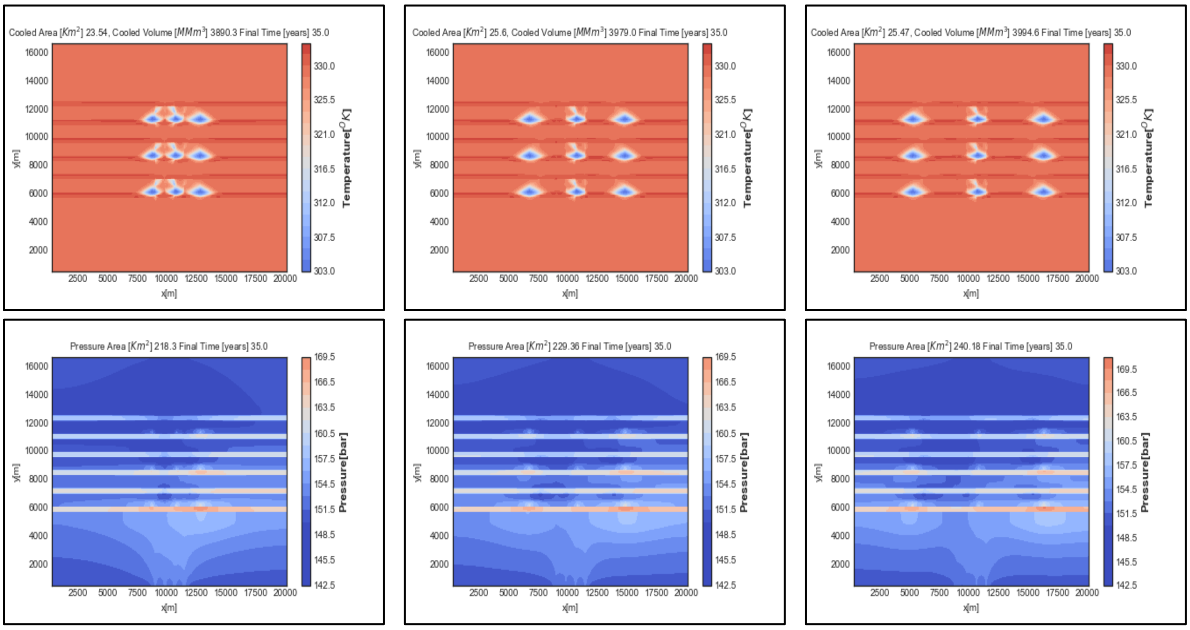


Figure 61: Effect of spacing width on the performance of the doublet located at the center. Areal sweep efficiency, gross produced heat and COP as a function of doublet spacing width (left). The case with doublet spacing equal to 17000 m corresponds to a single doublet line. Temperature field for a doublet spacing width of 1350 m (right). Line drive doublet pattern, constant doublet spacing length of 4000 m and base case properties.

Base case with high permeability of fault set 2 - spacing length evaluation

The impact of having permeable faults that connect projects in the ‘y’ direction (fault set 2 in this report) on the interaction of multiple projects is presented in Figure 62. From the thermal point of view, the shape of the cold flooded areas gets distorted when the spacing length is 2000 m (Figure 62-Top left). This causes reduction of the gross cumulative heat production of 4% between the case the doublet is alone and the case the doublet has neighboring injector wells at 2000 m. On the other hand, the sweep efficiency of the area increases 50% at this 2000 m spacing length.

In term of delta pressures in the wells (Figure 63) and the reservoir pressure (Figure 62), the presence of the permeable faults reduces their maximum magnitude but the changes travel more far in the ‘y’ direction (Figure 62-bottom).



Length = 2000 m Length = 4000 m Length = 5500 m

Figure 62: Temperature (top) and pressure (bottom) fields after 35 years of geothermal operations considering line drive doublets patterns, three doublet spacing lengths, constant doublet spacing width of 2700 m and properties from the base case of concept 1 – except permeability of fault set 2 is high: 2857 md.

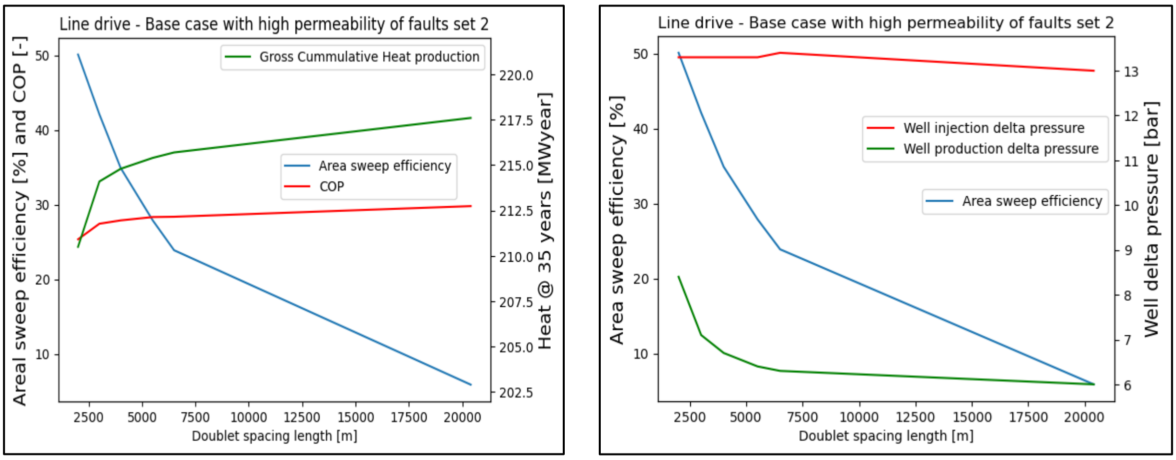
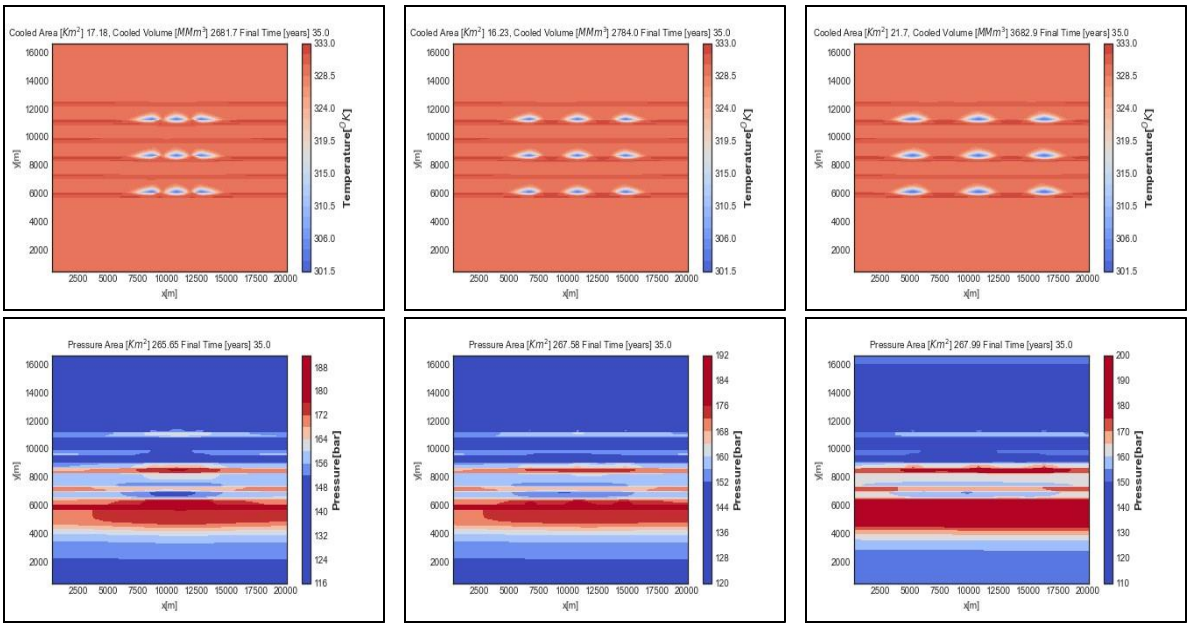


Figure 63: Areal sweep efficiency, gross produced heat and COP as a function of doublet spacing length (left) and corresponding well delta pressure (right) for the doublet in the center. Line drive doublet pattern, width 2700 m and properties from the base case of concept 1 – except permeability of fault set 2 is high: 2857 md.

Properties of the conservative thermal length scenario – spacing length evaluation

From the thermal point of view, no major interaction between projects is seen. Again, shapes of the cold flooded areas are only distorted when the spacing is 2000 m (Figure 64 Top-left).
In terms of reservoir pressure, this reservoir condition results in a higher pressure upstream and lower downstream than in in the base case. This is due to low permeability in the Y direction. The same happens with the pressure changes in the wells, in this case they are more severe.
With respect to heat production, the changes are severe when spacing length is reduced 5000 m. A reduction of 30% in gross cumulative heat is forecasted as a result of pressure interference that makes prohibited keeping the flow rates at the initial condition of 200 m^3/h as shown in Figure 65-right.



Spacing Length = 2000 m   Spacing Length = 4000 m   Spacing Length = 5500m

Figure 64: Temperature (top) and pressure (bottom) fields after 35 years of geothermal operations considering line drive doublets patterns, three doublet spacing lengths, constant doublet spacing width of 2700 m and properties from the conservative case (long length).

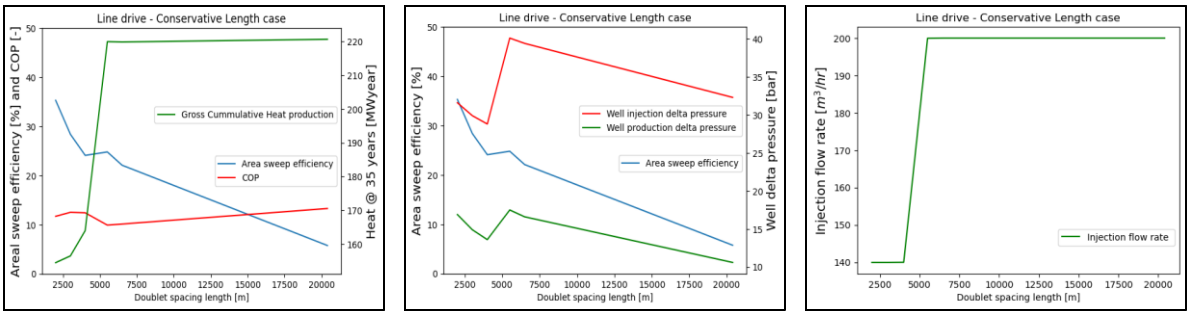


Figure 65: Areal sweep efficiency, gross produced heat and COP as a function of doublet spacing length (left), corresponding well delta pressure (center) and injection flow rate (right) for the doublet in the center. Line drive doublet pattern, width 2700 m and properties from percentile 90 case. Areal sweep efficiency changes its trend when the doublet spacing length is below 4000 m because injection flow rate is reduced (right) as maximum pressure at the injector is exceeded.

Line drive main analysis

- Cold flooded areas are mainly distorted due to pressure interference when doublet spacing length is 2000 m for the three reservoir scenarios (Figure 59, Figure 62, Figure 64). Spacing lengths equal or higher than 4000 m do not affect the shapes of cold flooded areas in any of the cases. Cold flooded areas of the central doublet have irregular shapes when the permeability of fault set 2 is high (Figure 62).
- Due to the tested doublet pattern (line drive), there is an induced pressure gradient parallel to the ‘y axis’ with high pressure in the doublets located at ‘y’ equal to 6000 m and low pressure at ‘y’ equal and higher than 12000 m. The presence of permeable faults in this direction makes this gradient to extend further.
- High- and low-pressure areas concentrate around producer and injector well respectively when the spacing length is short because these wells are closer. This becomes sever when the permeability anisotropy ‘ky/kx’ is 0.1, resulting in wells reaching the maximum

injection pressure which induces reduction in the flow rate and consequently in the cumulative heat.

- Areal sweep efficiency '*ASE*' increases as spacing length decreases while energy production decreases as spacing length decreases in the reservoir scenarios considered (Figure 60, Figure 63, Figure 65). The ASE reaches around 50% when the spacing length is 2000 m for reservoir properties similar to the base case.
- Reductions in cumulative energy production happen when spacing length is lower than 4000 m. Nevertheless, this decrease is not severe when reservoir conditions are similar to the base case. For example, when doublet spacing is 2000 m a reduction 3.7% reduction with respect to the performance of a single doublet is forecasted (Figure 60). Nevertheless, if reservoir conditions were like the ones considered in the conservative thermal length scenario, a severe reduction in cumulative production could take place due to pressure build up when projects are too close due to bad properties.
- When properties of the reservoir are like the base case, a spacing length of 4000 m will minimize pressure interference between projects. If the reservoir has low permeability across the graben and horst structure a spacing length of minimum 5000 m is recommended.
- The decrease of spacing width reduces cumulative heat produced by the central doublet (Figure 61).

7.5.2 Off-line drive pattern

The effect of the off-line drive doublet pattern (Figure 57) on doublet interference was tested. The gross cumulative heat production and COP of the central doublet for the three reservoir cases is shown in Figure 66. The next observations can be made based on the performance of the central doublet:

- Gross heat production and COP are not a strong function of doublet spacing length. In addition, COP in the off-line patterns is higher than in the line patterns, specially at small doublet spacing. Thus, this doublet pattern is less prone to cause thermal and pressure inference than the line drive pattern.
- Gross heat production and COP are not increasing monotonically with spacing length, there are peak values related with the interaction between the central doublet and the doublets around it. For instance, the heat production reaches a peak at spacing length of 4000 m for the base case and the case with high permeability of the fault (Figure 66). The reason for that is that at relatively small spacing, the injectors located at the left and right of the central doublet push the hot water located *in the graben* towards the producer well while when the spacing is long, the doublet at the top of the central doublet becomes dominant and pushes cold water *from the horst* toward the graben where the producer well is located.
- Regarding pressure distribution, the off-line doublet pattern does not induce localized low- or high-pressure areas as happens in the line drive patterns because neighbor doublets are not either injecting or producing in the same faults as shown in Figure 67.
- Figure 68The induced pressure gradient in the y direction persists but with lower magnitude than the line drive pattern (Figure 68).

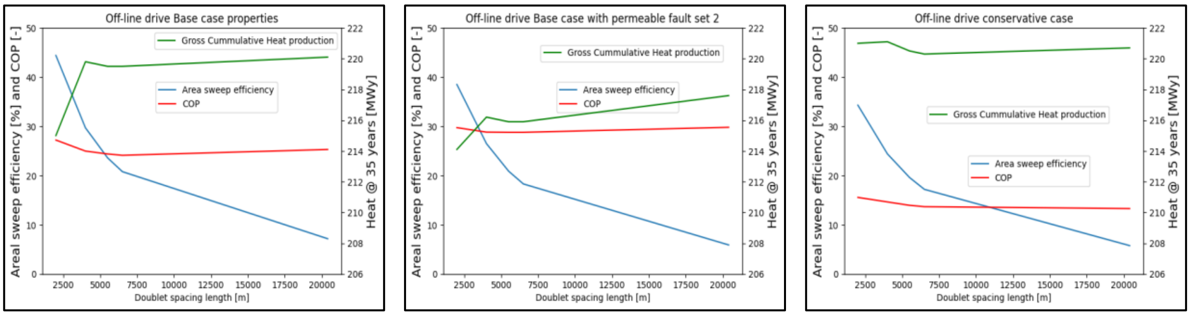


Figure 66: Areal sweep efficiency, gross produced heat and COP from the central doublet as a function of doublet spacing length for the three reservoir scenarios: base case (left), base case (center) with permeable fault set 2 (right) and case percentile 90 'conservative case' of disturbed thermal area.

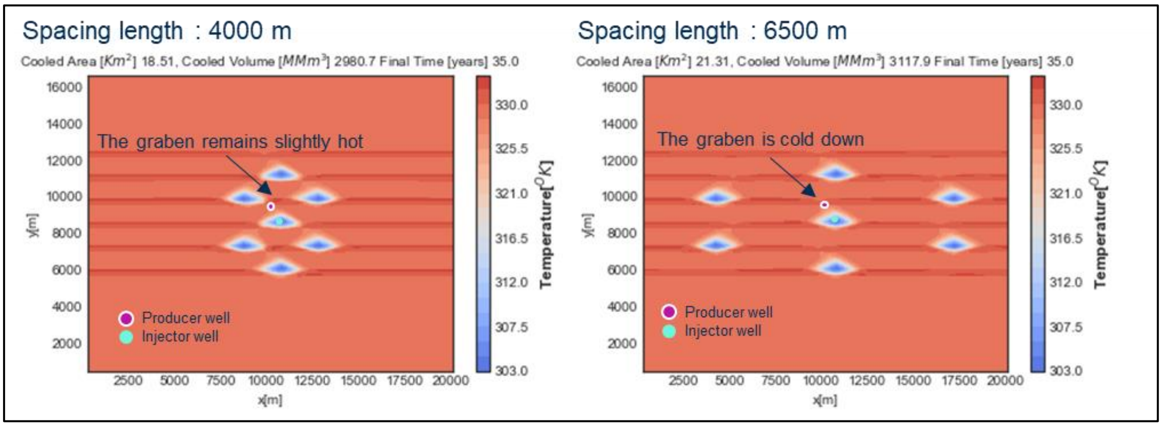
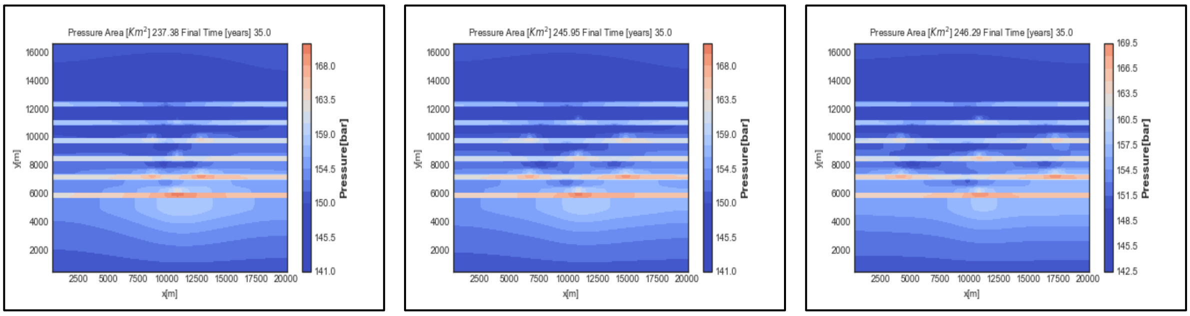


Figure 67: Temperature field after 35 years when an off-line well pattern is used for two spacing length and base case properties. The effect of spacing length on the final temperature distribution around the producer well is indicated.



Spacing Length = 2000 m   Spacing Length = 4000 m   Spacing Length = 5500m

Figure 68: Pressure field after 35 years of operation for different spacing lengths considering off-line doublet pattern. Properties are from the base case of concept 1.

7.5.3 Analysis of multi-well study

- In general, when doublet spacing length and width are reduced, areal sweep efficiency improves and cumulative heat production per doublet is reduced.
- Line drive pattern has higher sweep efficiency compared to the off-line pattern but is more prone to generate thermal and pressure interference.
- Cold flooded areas (low values in the temperature fields) are mainly distorted due to interference when doublet spacing length is 2000 m for the three tested reservoir

properties. Spacing length equal to or higher than 4000 m does not affect the shapes of cold flooded areas.

- If good hydraulic communication between injector and producer wells is given, a spacing length of approximately 4000 m and a spacing width equal to or higher than 2500 m between affected thermal areas are required to avoid marked reduction of cumulative heat and still have relatively high sweep efficiency. These lengths are in accordance with the permutation studies while larger widths than those estimated in the permutation studies are recommended.
- Large spacing lengths will form un-flooded or undrained areas (areas that remain at initial temperature). These areas could be exploited after the exploitation in the initial produced areas is finished, which could provide continuity in the exploitation and while the already flooded areas are recharging.
- Contrary, if transmissivity between wells is low (ky/kx is low), then high spacing lengths of at least 5000 m are required to avoid pressure interference that could lead to reduction of projects fluid rates, and consequently reduction of heat production.

8 MONITORING

Reservoir monitoring plays a fundamental role in optimization and safety of exploitation a geothermal site. Exploration and well appraisal phases provide important ingredients for reservoir characterization and project design, but the geological uncertainty will remain. Thus, monitoring during the operational phase is required for revealing additional reservoir information important for the management of a single or multiple projects. This information must be measured and collected via specific plans and goals.

8.1 WHY DO WE HAVE TO MONITOR?

Concerning the case of multiple geothermal projects both the supervisory authorities and the operators have an interest in understanding the impact of the operations on the subsurface. Multiple questions may arise like:

- Is the injected cold fluid from one license flowing towards the neighbors?
- Is the granted production license volume or area too small or too large?
- Is the hydraulic interaction between multiple license volumes extremely depleting or over-pressurizing certain reservoir areas?
- Are severe mechanical deformations in the underground taking place?

These and more questions may arise during the exploitation of a reservoir like the Carboniferous limestones in the Campine Basin. Thus, monitoring techniques must be considered and screened based on their cost and effectiveness, and clear responsibilities on who does what must be defined.

8.2 WHAT DO WE HAVE TO MONITOR?

The above results indicate that is important to measure or infer pressure, temperature and fluid flow fields in the reservoir because they will indicate not only the status of the project but also its future. This information is an important tool for management of the resource (adjustment of flow rates, spotting new well locations, optimizing spatial and temporal spacing between projects etc.).

In addition, it is recommended to monitor mechanical deformations and changes in water composition because they could work as proxies for the mentioned pressure, temperature and flow fields, and more importantly because of safety and environmental reasons. For instance, detection of micro-seismicity can provide warnings about the safe operation of the system (Maurer et al., 2020). In fact, in countries like France, the guide of good practices for deep geothermal includes the use of seismic monitoring networks during drilling, testing and exploitation phases (Maury et al., 2023). These networks must be installed if the anticipated level of induced seismicity risk is classified as 1 or 2 on the scale developed by INERIS and BRGM, which ranges from 0 (no risk) to 3 (high risk, requiring project re-evaluation) (Maury et al., 2023). The level of risk is related with reservoir characteristics: flow medium porous, flow in fractures and faults and whether the faults are prone to reactivation. These recommendations follow the updated *Code Minier* issued in 2021. As an action from this monitoring, flow rates can be adjusted or more wells could be drilled for minimizing or avoiding this risk (pressure damping by distribution of injection or/and production rates).

8.3 WHAT ARE THE MEANS FOR PERFORMING THIS MONITORING?

Instrumented monitoring wells (in static and dynamic flow conditions) and geophysical methods are the main proven methods for performing monitoring. These monitoring wells could be former injection and production wells but also wells drilled specifically for this purpose. Reusing geothermal wells for monitoring reduces the price of drilling and well completion but the abandonment expenses might be fully or partially absorbed by the institution performing the monitoring. Nevertheless, they provide direct information of not only pressure but about the temperature recovery, which could allow to improve the estimations heat recharge mechanism and temporal license spacing.

Proven geophysical methods (indirect methods) for monitoring areal and vertical geothermal reservoir performance are related with following rock deformations. The imaging of pressure and temperature fields in deep reservoirs remains a challenge in reservoir surveillance. Injection of tracers constitutes the better way for understanding fluid flow field and forms an indirect means for temperature variations.

The temperature field is the most difficult variable for mapping. A resistivity-based method has been tested successfully in the field for evaluating the cold plume of geothermal operations in shallow aquifers (Hermans et al., 2014) as resistivity is a function of temperature. In theory, electrical resistivity tomography (ERT), magneto telluric (MT) and controlled-source electromagnetic method are sensible to resistivity changes at deep depths. Nevertheless, ERT will require spacing many times larger than the targeted depth which could make it impractical depending on the depth and MT might not be able to capture small resistivity changes (CSEM) are sensible to resistivity changes (Eltayieb et al., 2023). CSEM has been tested for hydrocarbon exploration, reaching deep depths of thousands of meters (Constable & Srnka, 2007). Nevertheless, as with all imaging technologies its resolution is a function of depth. For improving this, surface to borehole acquisition has been proposed for the TUDelft geothermal project but it has not been tested (Eltayieb et al., 2023). Thus, resistivity-sensitive imaging for characterizing cold plume of deep geothermal projects is a technique in evolution that has to be monitored for potential future applications.

On the other hand, pressure fields can be measured with a relatively low number of wells as pressure changes travel long distances in systems with low total compressibility (water and rock) and/or high permeabilities, which is the case in the Dinantian limestones of the Campine Basin. The table below provides the main recommended monitoring methods for the most important reservoir fields, what could be the intention for monitoring and the main advantages, disadvantages, and challenges.

Table 22: Possible monitoring techniques for geothermal field management.

Field to be monitored	What information can be retrieved?	Monitoring techniques	Advantages and disadvantages/Challenges
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.	Reliable and continuous technique as it provides hard data over time. Only one value of pressure per time in one position can be obtained. Thus, multiple wells are required for deriving the pressure field of an area. Nevertheless, not many wells because pressure changes are expected to cover wide areas. Expenditures for drilling, data acquisition, maintenance and abandonment must be considered.
		Pressure build-up and fall-off tests in producer and injector wells.	Provides current static pressure of a specific project but it does not say about the dynamic pressure. Compromise of the operator for stopping the wells is required.
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	One point per well. Too many wells within the production area are required because temperature changes are mainly local. Thus, it is not viable for temperature field definition.
		Resistivity-sensitive surveys (ERT, MT and CSEM)	Resistivity fields can be a proxy for temperature changes due to geothermal operations. Nevertheless, under current state of the art it has been proven only for shallow projects (hundred meters depth (Hermans et al., 2014). Research for deep reservoirs is taking place (Eltayieb et al., 2023)
Fluid flow directions	Map flow pathways. Interference between licenses. Swept volumes etc. Residence time. Validation of numerical models used for reservoir management. Areal mapping of highly porous regions like Karst systems	Injection of tracers and sampling in production and observer wells (Ayling & Rose, 2013)	Direct indicator of flow path and communication between licenses. No need for stopping operations on wells. Implies the involvement of the operators and a coordinated or continuous sampling. The challenge is having sufficient different tracers as running projects.
		Reflective seismic acquisition and application of the Amplitude versus Offset 'AVO'	The technique can allow areal mapping of highly porous regions like Karst systems. Even though this technique does not track the fluid flow directions it can provide good starting point for guessing via simulation what could be the main fluid directions.
Rock deformations	Detection of subsidence or uplifting. Induced seismicity	Seismic monitoring network (Kinscher et al., 2023) and (Maurer et al., 2020)	Continuous monitoring of possible location and magnitude of seismic events. This monitoring allows to determine whether these possible events are caused by geothermal operations and to take actions. It can be done at surface or using shallow wells. It may require involving third institutions for interpretation and validation of the data.
		Satellite radar interferometry (Raspini et al., 2022)	Wide areas can be monitored for subsidence and uplifting. It is a relative standard technique. It provides snapshots i.e of surface elevation.

8.4 ACQUISITION STRATEGY AND DATA INTEGRATION

A program for data acquisition (whether pressure, temperature, water composition, tracers or/and rock deformation) must be stablished and the corresponding hardware and software (pressure and temperature sensors in the wellbore, servers for storing data, seismicity surveillance networks etc.) must be considered in the design of each specific geothermal project.

The acquisition programs or strategies that are developed for each project could be enriched by considering their neighboring licenses. This will help for improving the knowledge of the resources and for optimizing the exploitation scheme. Interference pressure tests—where one well is producing while another remains shut-in—and tracer tests are tools primarily designed to acquire data within a specific license area. However, they can also provide valuable information across license boundaries, offering insights that extend beyond their initial purpose. This kind of activity requires the establishment of good communication between license owners for coordinating these activities. This role could be played by an association of owners or/and the regulating authorities.

One important point is that the analysis of pressure, temperature and fluid flow patterns could be extended further than a specific license via mapping these variables at field scale, so that monitoring and optimization can be done at a large scale. This once again highlights the need for an organized approach to integrate the data and establish agreements among license owners. Such activities could, for instance, help prevent negative impacts from new developments on existing operations.

9 CONCLUSIONS & RECOMMENDATIONS

9.1 CONCLUSIONS

In this study, dynamic reservoir simulations were carried out to evaluate the impact of various subsurface parameters on pressure and temperature changes around the injection and production wells in a heterogeneous reservoir like the Carboniferous Limestone Group. Fault permeability, permeability anisotropy, and the well doublet configuration are the main elements that control the performance of a geothermal doublet system. The preferred well configuration in such a faulted system has the producer well near or crossing a permeable fault while the injector well can be placed near the center of the corresponding graben or horst structure. This is possible when the permeability is expected to be sufficient at the center of these structures otherwise wells must be placed offsetting this center. Wells drilled in line with the faults could have lower performance than the L-shape due to short-circuiting.
If faults, fractures, or matrix with low permeability are found between the injector and production wells (equal or lower than 10 mD), considerable pressure interference between areas is expected. In this case, fluid injection rates must be adapted to honor possible pressure constraints related with geological risks (e.g. induced seismicity).

The extent of the affected temperature area is the main criterion for definition of the production license area of geothermal doublet projects because its modification, due to interference with neighboring geothermal doublets, leads to reduction of the energy produced by the doublet(s) as shown in the multi-well study.

On the other hand, the affected pressure area is not seen as a primary criterion for production license definition because it does not have a direct implication on heat production. In addition, its size is very sensitive to the permeability field which also makes it difficult to define. Nevertheless, the pressure and temperature effects of neighboring projects must be considered to define the spacing between simultaneous production licenses so that individual production performance is maximized, and the technical and safety thresholds are respected.

Neighboring projects affect the size and shape of the affected thermal areas when the distance between the projects is too small. This translates into reduction of the production power capacity of individual projects as the affected thermal areas get squeezed. On the other hand, having the projects close to each other improves the areal flooding efficiency at field scale (more area of the whole reservoir is contacted by cold water). Thus, a balance must be found. For the condition tested in concept 1, a lateral spacing between injector wells of 4000 m in the direction of the length of the affected thermal area (parallel to the main faults) is already sufficient to avoid influence on affected thermal areas. Shorter spacing could be used for maximizing reservoir exploitation but impacts on heat production could be felt by the projects.

The licenses to be produced simultaneously should be ordered in a staggered or off-line well pattern with a lateral spacing between licenses of 3500 m to 4000 m.

One approach to defining the geothermal production area is the French method (TNO, 2014). However, when comparing this method with the results from the three reservoir concepts, it falls short in adequately covering the disturbed thermal area for concepts 1 and 3. This discrepancy arises due to reservoir heterogeneity. For concept 2, the French method works for most of the tested scenarios, largely because one of the layers exhibits homogeneous permeability—an assumption inherent in this method.

Therefore, an alternative approach or an improvement to the French method is necessary for spatial license definition. A potential solution is to base the dimensions of geothermal production licenses on both the thermal length and width of the disturbed thermal area. These boundaries, which would limit thermal interference, can be estimated using permutation or uncertainty analyses, so that the uncertainty in the main reservoir parameters is considered. However, the thermal width alone does not account for sufficient drainage area around the producer well, as the affected thermal area does not extend far enough from this well.

For sorting the previous limitations for defining the production license area of a geothermal doublet, it is recommended to combine the results of the permutation or uncertainty analysis with the French method as follows: One of the boundaries of the rectangular license area is equivalent to the thermal length estimated at the expected end of the license (for example, after 35 years of exploitation). This value can be obtained from an uncertainty simulation analysis on the reservoir properties, so that geological uncertainties are considered. For this case, it is recommended to use the length value corresponding to high percentiles of the resulting distribution of the uncertainty analysis. The remaining lateral boundary of the square license is proposed to be equivalent to two times the well spacing between injector and producer well as done in the French method. The procedure for this proposed modification to the French method is detailed in Section 9.3.

9.2 PARAMETER SENSITIVITY

The sensitivity study allowed to understand which are the main geological characteristics that affect the disturbed pressure and thermal area during geothermal operations in the Carboniferous Limestone Group of the Campine Basin. These areas are essential for defining the size of the license area. The main geological characteristics of this limestone and the methods for accessing them are shown in the table below.

Table 23: Most important reservoir characteristics impacting pressure and thermal disturbed area and the size of the production license.

Parameters			
Concept 1	Concept 2	Concept 3	How to acquire it
Karst extension from faults. Reservoir layer thickness.		Karst/fractured zone extension from faults	Seismic exploration for detecting the faults and thickness
Porosity and permeability of fault set 2. Permeability anisotropy ky/kx. Karst porosity & permeability.	Porosity and permeability of fault set 1 and set 2. Top layer permeability. Permeability anisotropy ky/kx.	Minimum reservoir permeability Porosity and permeability of fault set 2.	Seismic exploration for detecting the faults and production/injection well testing for permeability, well logging
		Fault height	Seismic exploration for detecting the faults

9.3 RECOMMENDED PROCEDURE FOR THE DEFINITION OF PRODUCTION LICENSE BOUNDARIES

A general procedure for defining the area and boundaries of the production license is proposed to mitigate thermal interference between neighboring geothermal projects. The goal is to ensure that each project can deliver its expected heat output. While this procedure serves as a starting point, it is not intended to be rigid and will likely evolve as more experience and insights are gained in the basin. Special cases, such as interference with underground gas storage, are outside the scope of this procedure and will require separate analysis.

9.3.1 Key Criteria for the Procedure:

Containment of Affected Thermal Area:
The expected thermally affected area must be fully enclosed within the boundaries of the production license. This prevents wells from being drilled in zones that are, or are expected to be, thermally impacted by neighboring projects.

Minimum Distance Between Wells:
The minimum distance between wells from different neighboring projects should be at least equal to the well spacing between injectors and producers within a single project. Shorter distances increase the risk of early thermal breakthrough of injected cold water between projects due to reduced hydraulic resistance.

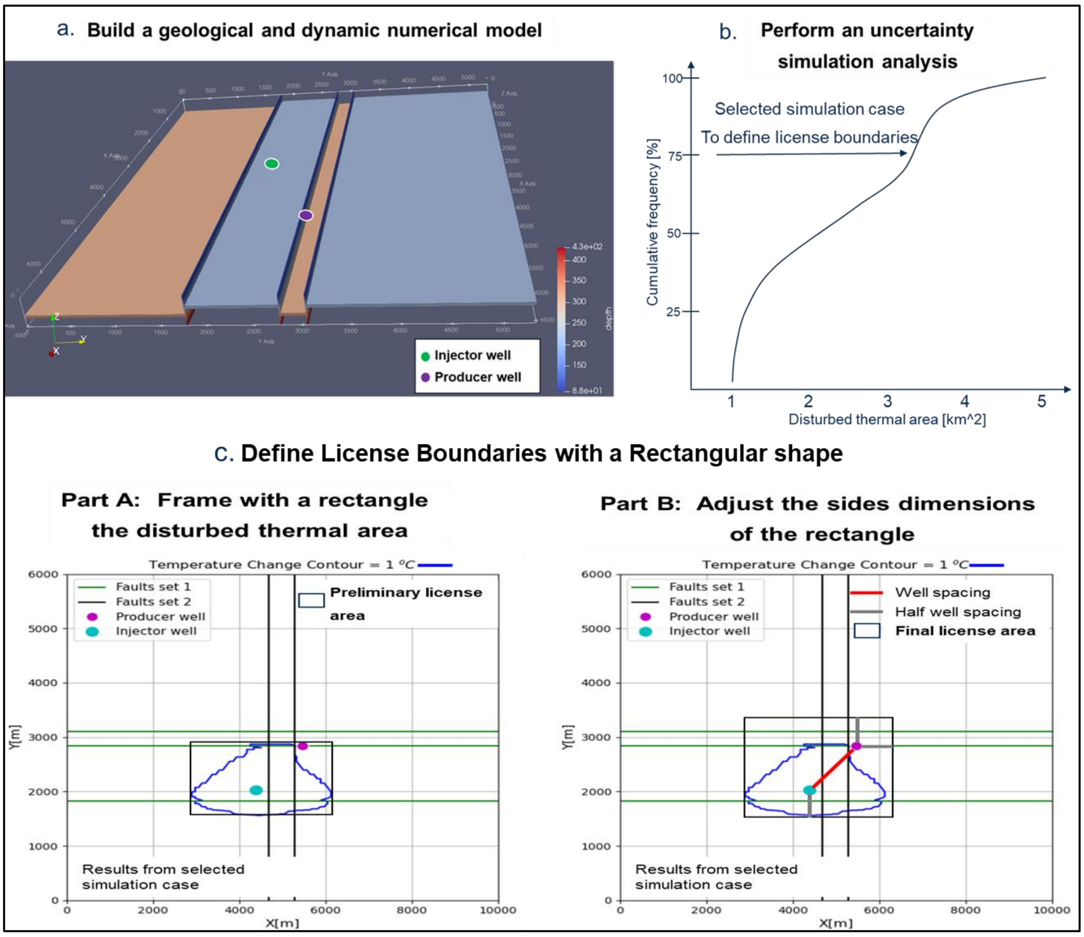


Figure 69: Illustration of the recommended procedure for production license definition of geothermal projects.

9.3.2 Procedure main steps

The recommended steps with their respective justification are shown sequentially in Table 24. These steps are also illustrated in Figure 69. This procedure is independent of the well's arrangement with respected to the reservoir heterogeneities (petrophysical and structural).

Table 24: Recommended procedure for the definition of geothermal production license boundaries.

Step	Justification	Sub-steps
Build a geological and dynamic numerical reservoir model	The petrophysical and structural characteristics of the geothermal aquifer (e.g., permeability and porosity distribution, orientation and permeability of faults) dictate water flow patterns, affecting the thermal and pressure disturbance areas. These characteristics directly influence the size of the required license area	Data Gathering: Acquire geophysical and petrophysical data, such as reflective seismic and well logs. Geological Model Development: Interpret and integrate the data into a simple 3D numerical model. Identify key uncertainties. Model Initialization: Define initial pressure, temperature, and boundary conditions. Set initial injection/production flow rates based on heat and temperature demand.
Define flow rates	Thermal disturbance is directly related to flow rate, which influences the size of the disturbed thermal area.	Evaluate heat and temperature demand. Define desired flow rate and injection temperature
Perform a permutation or uncertainty simulation analysis for the selected well locations	Geothermal reservoirs are inherently uncertain due to variability in petrophysical and structural properties and limited characterization. A range of simulation models considering the wells of the single project or, if possible, also the wells of the neighboring projects is needed to account for the uncertainties and understand possible outcomes (e.g., disturbed thermal area, cumulative heat production).	Identify parameter uncertainty with its ranges or probability distributions. For example, permeability of the matrix and faults. Define well locations. Run the different simulation models for the desired license duration. Build a cumulative frequency plot in terms of disturbed thermal area. During simulation, consider maximum well injection pressure and minimum production pressure. This will indicate whether the desired flow rate is feasible.
Define License Boundaries with a Rectangular shape	A rectangular shape is preferred for simplicity and to minimize small areas that are difficult to claim by others.	Part A Part B.
Part A: Frame the disturbed thermal area with a rectangle	The license must encompass the expected disturbed thermal area to prevent interference with neighboring projects. The use of simulation cases that resulted in high percentile of disturbed thermal areas is recommended because most of the estimated areas would be within the defined thermal area.	Select simulation cases with high cumulative frequency or high percentiles (e.g., 75%-90%) from the uncertainty analysis. Generate an average map, based on the selected simulation case, of the disturbed thermal area (defined as areas with at least a 1ºC temperature change). Frame this area with a rectangle.
Part B: Adjust the sides (dimensions) of the rectangle if the distance of the wells to the boundaries is not equal to or higher than half the well spacing	By ensuring that the distance between the wells and the boundaries of the rectangle is at least half the well spacing (half distance between injector and producer well), the preferential flow toward neighboring projects would be avoided. Otherwise, it is possible that much lower hydraulic resistance is presented between wells of neighboring projects.	Ensure wells have a distance to the boundaries at least equal to half the well spacing. Update rectangle dimensions accordingly.

9.4 FIELD DEVELOPMENT MANAGEMENT

To maximize the exploitation of the geothermal resource located in the Carboniferous Limestone Group of the Campine Basin in a sustainable way, field strategies are required for spatial and temporal organization of the geothermal doublets. The possible strategies and their limitations will be discussed next.

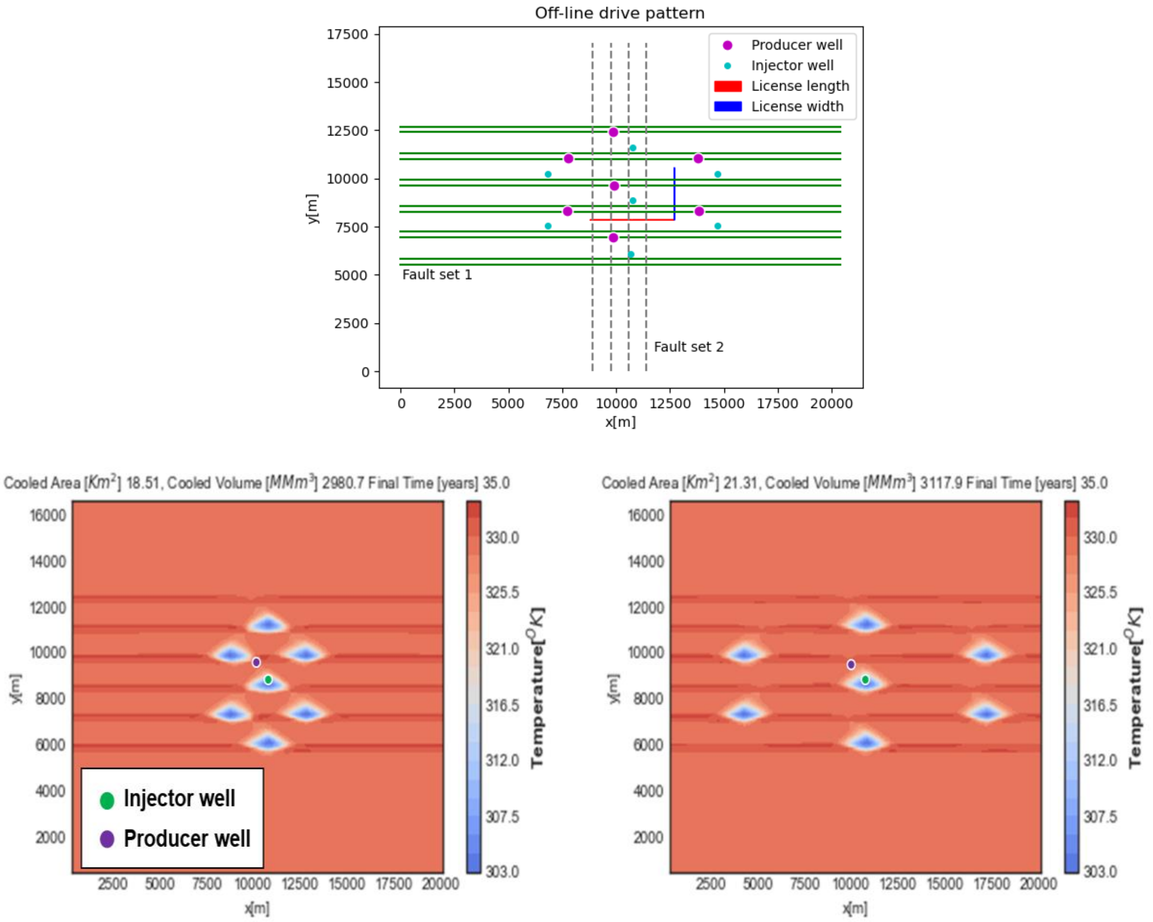


Figure 70: Off-line pattern recommended for the development of the carboniferous limestone reservoir in the Campine Basin (top). Temperature distribution after 35 years of exploitation for 2 well spacing (bottom). The low temperature areas represent the cold flooded area of every geothermal doublet (total 7 doublets). Dark red are the grabens while light red are the horsts.

9.4.1 Doublet organization

To maximize the energy extraction, relatively simultaneous geothermal doublets could be organized in different patterns: line or off-line drive pattern. The Off-line or Staggered pattern (as shown in Figure 70) is recommended because this pattern reduces both the pressure and thermal interference and pressure gradient between upstream and downstream doublets when compared to the linear pattern. This pattern could be organized following the fault strike and using the well configuration named here as 'base' or L-shape, where the producer well is drilled close to one permeable fault and the injector is located near the center of the corresponding graben or horst structure. It is important to mention that as the spacing between projects is reduced more energy can be extracted from the global point of view but if projects are positioned too close to each other the potential production of individual projects may decrease. Thus, it is recommended to respect the license area defined with the proposed procedure. An example on how the off-line pattern could be organized in concept 1 area of the Campine Basin is shown in Figure 71. The lateral spacing (main fault direction) between licenses is 4000 m in this example. Undrained areas (areas that remain with the initial temperature) can be produced when the already exploited areas are recharging. This will provide a more sustainable usage of the resource as it will be discussed in the next point.

Nevertheless, this kind of organization may not be easy to implement in practice as the real location of the doublet is constrained by the location of the final user and heat demand (company, town etc.). But with the use of inclined wells, it could be approximated at least.

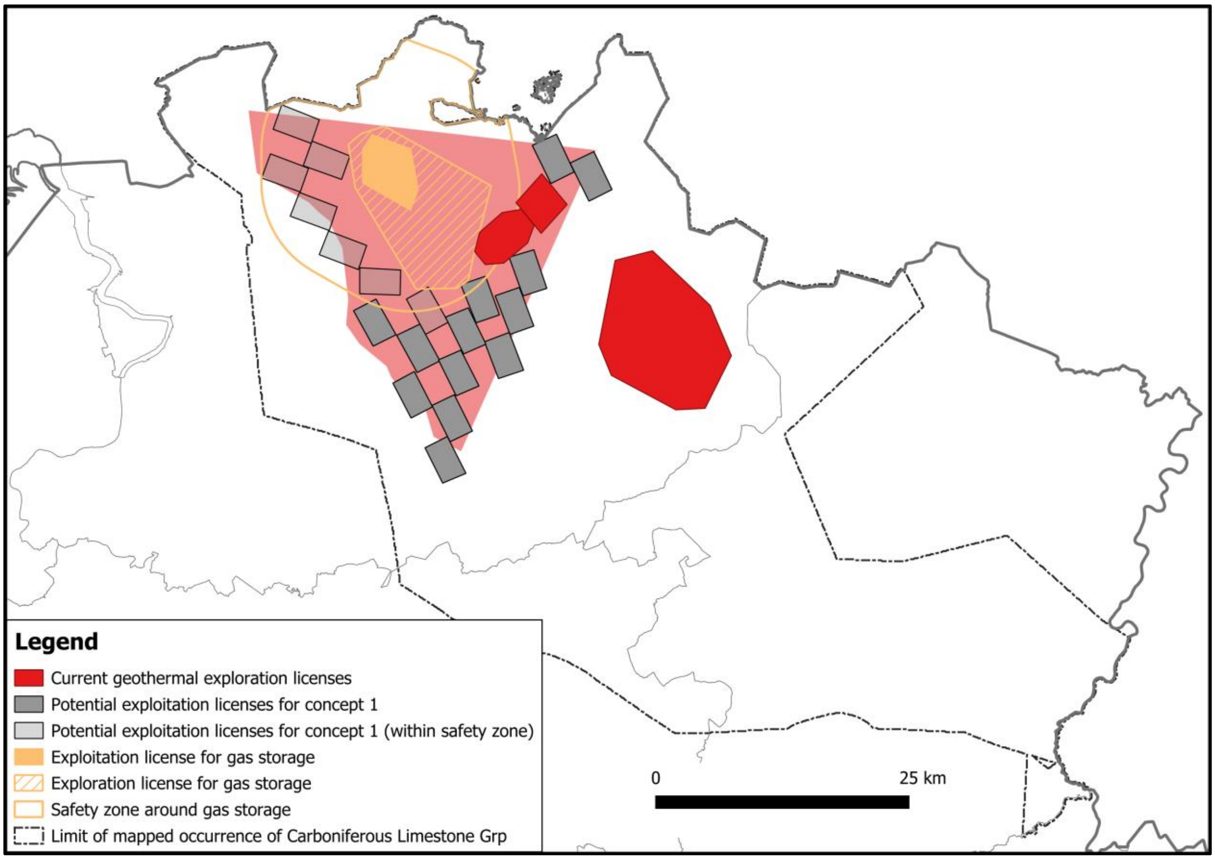


Figure 71: Possible arrangement of production license areas under off-line or staggered pattern for concept 1. The size of the production area was derived from the modified French method using the percentile 90 result from the permutation analysis. Patterns are oriented following the dominant strike of faults.

9.4.2 Long-term perspective and sustainability

Another important point to consider in the development strategy is the sustainability of the geothermal exploitation so that future generations can also rely on this source of energy. Strictly speaking, sustainability implies that a resource is exploited at the same rate that it is restored by the system. Geothermal energy is regenerated naturally once it is extracted by thermal conduction, convection and/or advection, and heat generation. Thermal conduction is a slow process driven by thermal rock conductivity and temperature differences, while convection and/or advection involve vertical or lateral flows that transport heat towards the produced reservoir area. Currently, the recharge mechanism is not well established in the Campine Basin.

When considering the worst-case scenario for recharge (thermal conduction only), the reservoirs could be recharged to levels equal or higher than 90 % of the original heat in place after resting between 60 years to 200 years, provided the production time is lower than 60 years and the flow rates are equal or lower than 200 m^3/h. Thus, it is possible to restore part of the heat in relatively reasonable time which makes the process quasi-sustainable.

Considering the time needed to restore most of the extracted energy and the fact that the location of the end user (such as a city or neighborhood) is unlikely to change over generations, a sequential or rotational exploitation strategy is recommended. When utilizing multiple sections of the reservoir sequentially, the sustainability of exploiting the limestone reservoir could be enhanced. This approach is like the rotational grazing method used in livestock management. In this case, heat is extracted from a specific area using a well doublet for a set period, after which extraction shifts to a new area, allowing the initial exploited area to recover heat for future use.

This rotational scheme could involve two or more areas depending on the resting or recharging time selected. Figure 72 illustrates this concept with 4 areas, each exploited for 35 years, providing a 105-year rest period, which should be sufficient for restoring around 90% of the original heat in place at least. Nevertheless, this scheme requires the existence of exploitable nearby areas that could be preferable reachable from the same surface location to reduce surface investments.

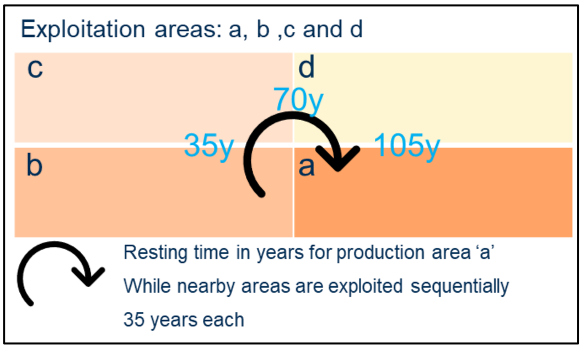


Figure 72. Rotational scheme for a more sustainable exploitation of the rotational resources. For this example, a production time of 35 years for each production area is used. To have a resting or recharging time of 105 years 4 nearby production areas are required.

A scheme like this will imply securing an area 4 times greater than the license production area If this were applied in concept 1 area only 4 additional projects could be launched. This rotational scheme can be also compatible with the off-line pattern of production license (Figure 71), where one area can be left resting while the neighboring one is recharging. Nevertheless, this could imply shorter recharging times if heat production needs to be provided continuously, thus lower energy recovered but more projects running simultaneously.

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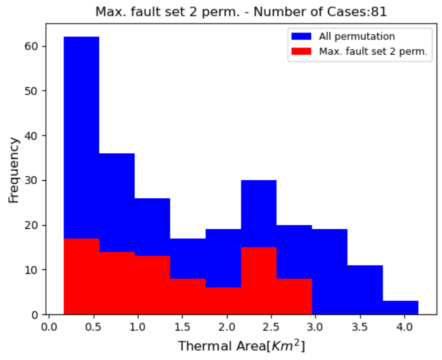
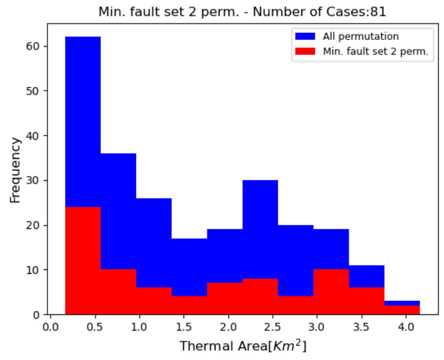
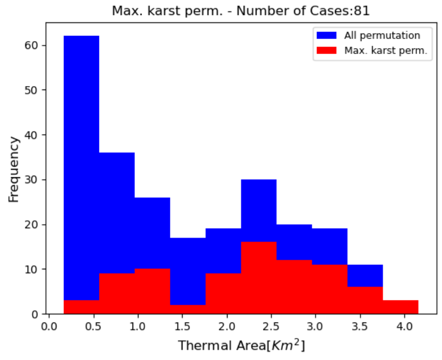
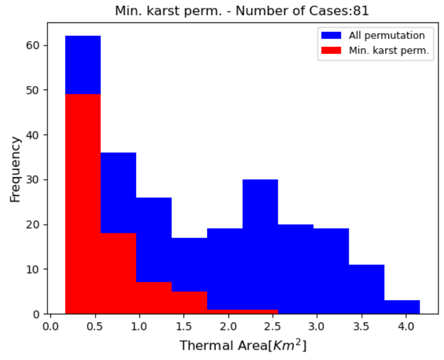
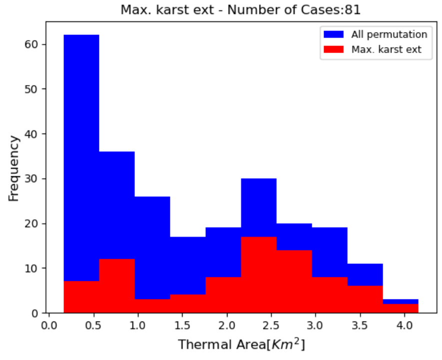
ANNEX A: IMPACT OF THE PERMUTATED PARAMETERS ON AFFECTED THERMAL AREA FOR CONCEPT 1

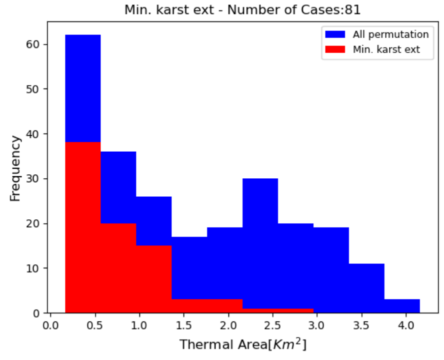


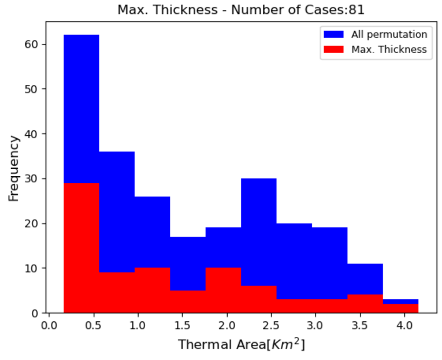


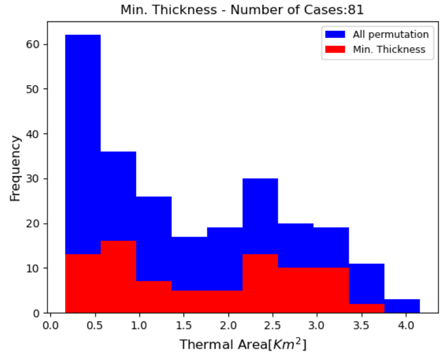


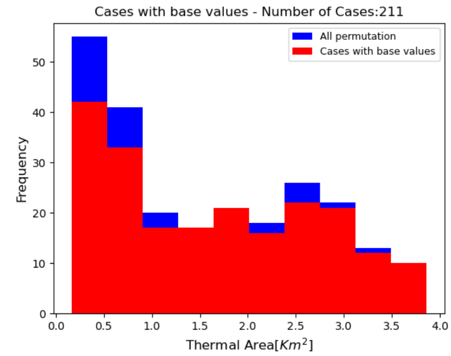








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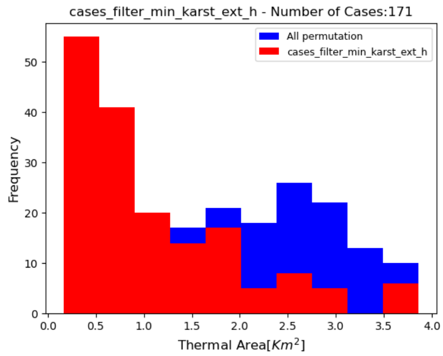
All permutation
Cases with base values
Frequency
Thermal Area[Km^2]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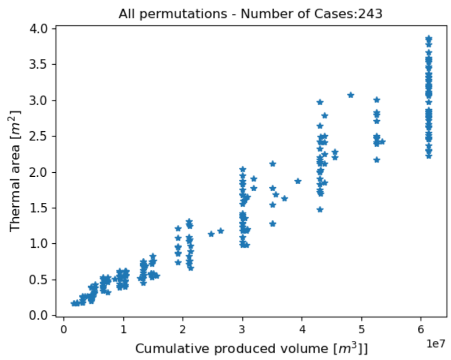
All permutation
cases_filter_min_karst_ext_h
Frequency
Thermal Area[Km^2]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Thermal area [m^2]
Cumulative produced volume [m^3]]
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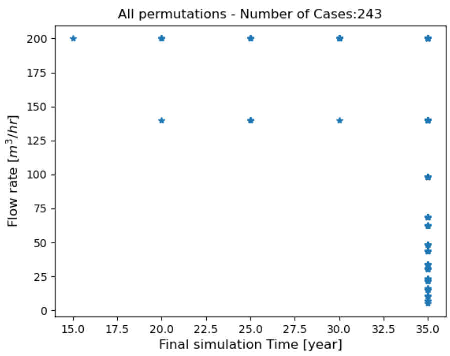
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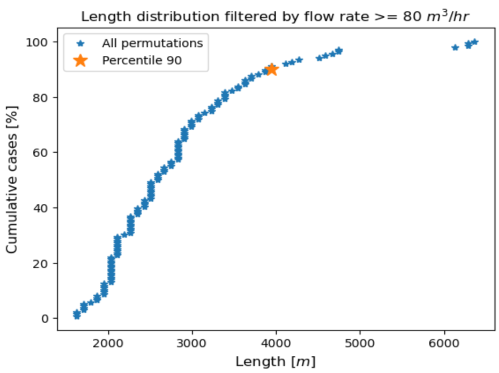
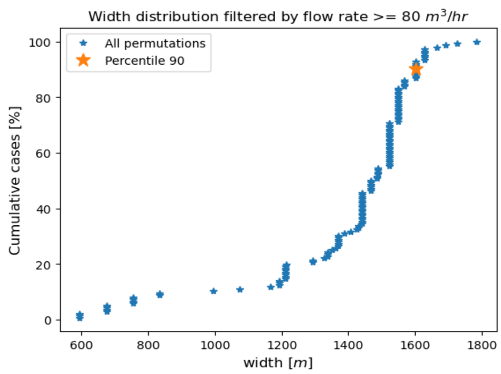
Flow rate [m^3/hr]
Final simulation Time [year]


Length distribution filtered by flow rate >= 80 m^3/hr
All permutations
Percentile 90
Cumulative cases [%]
Length [m]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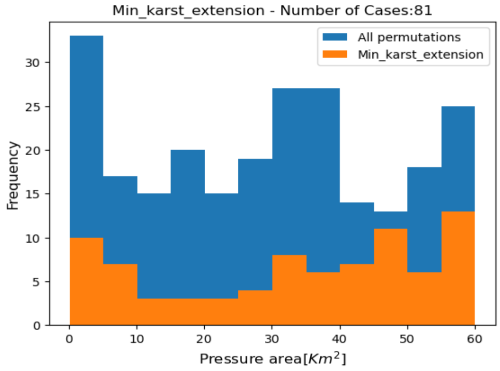
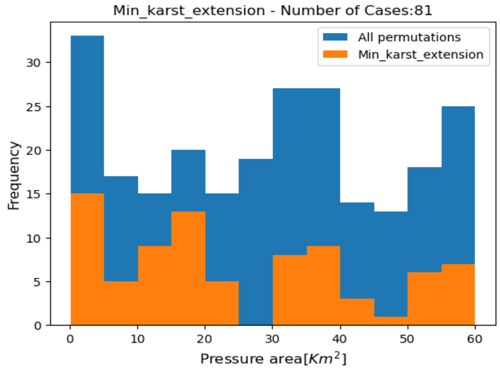
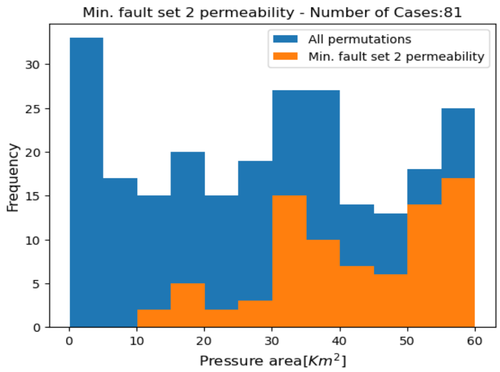
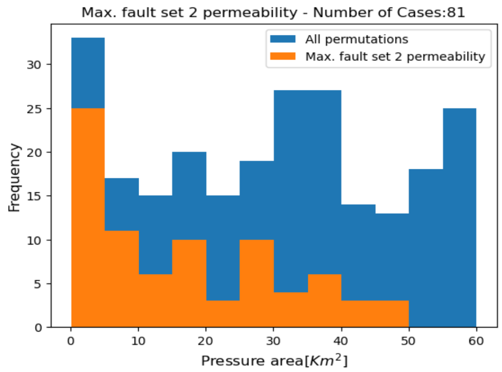
All permutations
Percentile 90
Cumulative cases [%]
width [m]

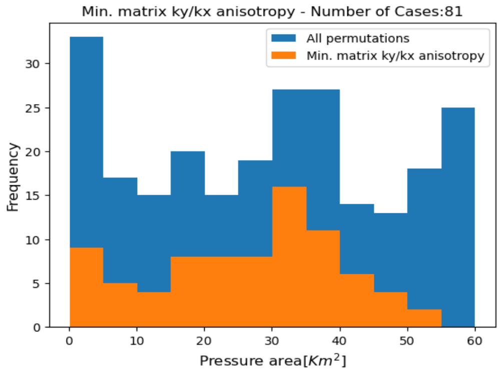
ANNEX B: IMPACT OF THE PERMUTATED PARAMETERS ON AFFECTED PRESSURE AREA FOR CONCEPT 1

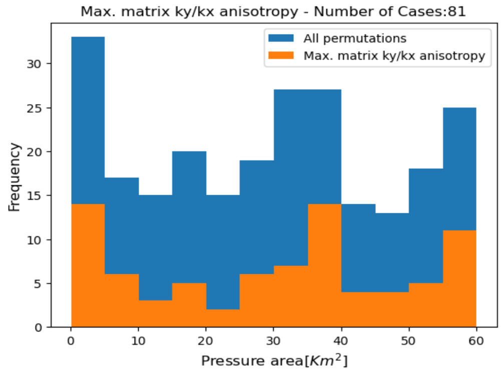


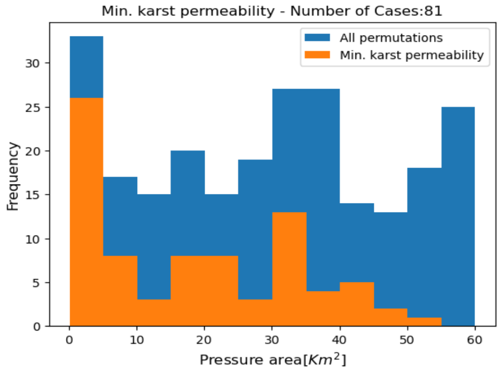


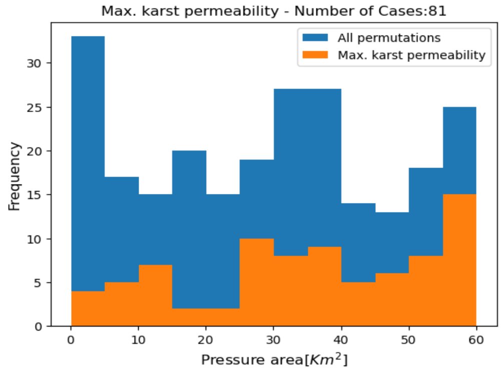


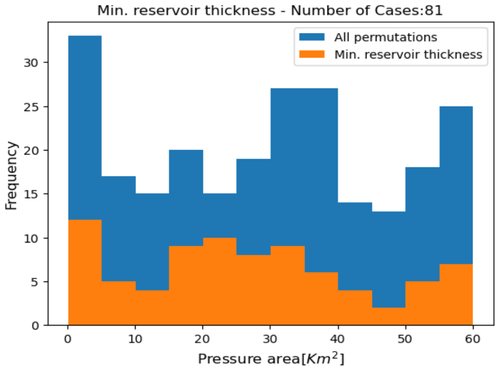


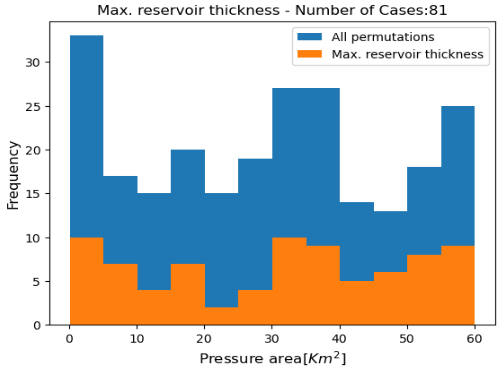




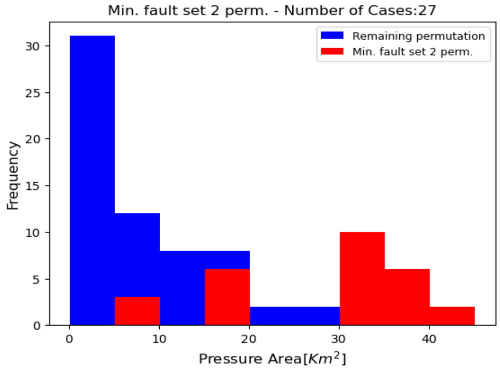


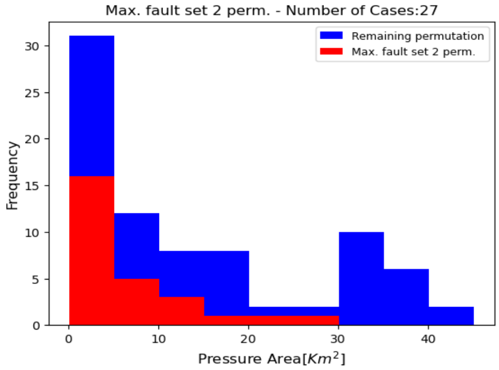


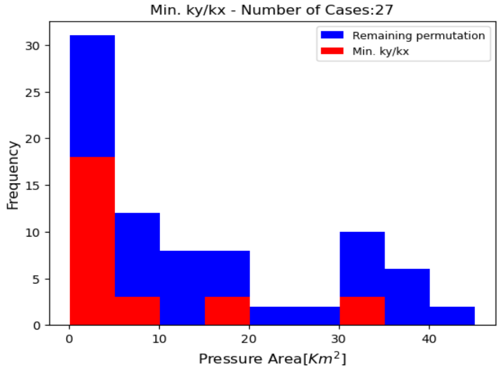

Min. reservoir thickness - Number of Cases:81
All permutations
Min. reservoir thickness
Frequency
Pressure area[Km^2]

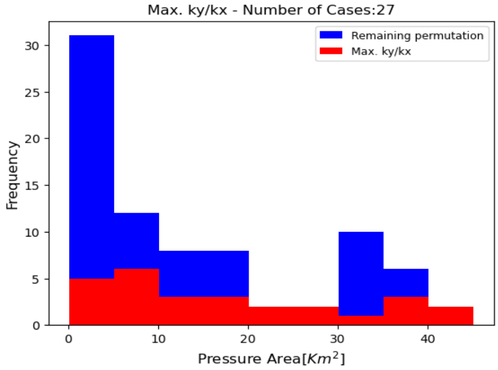

Max. reservoir thickness - Number of Cases:81
All permutations
Max. reservoir thickness
Frequency
Pressure area[Km^2]

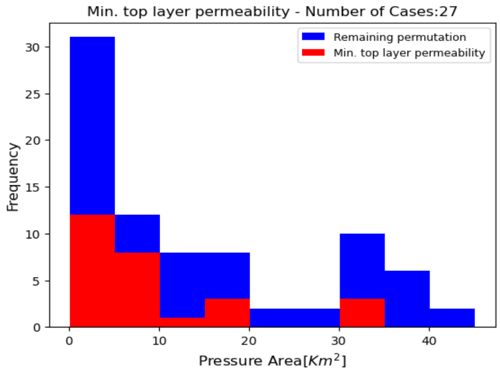
ANNEX C: IMPACT OF THE PERMUTATED PARAMETERS ON AFFECTED PRESSURE AREA FOR CONCEPT 2

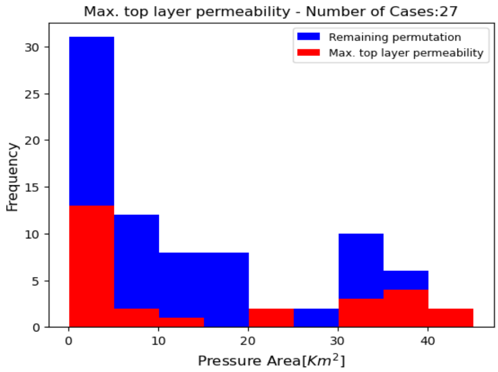


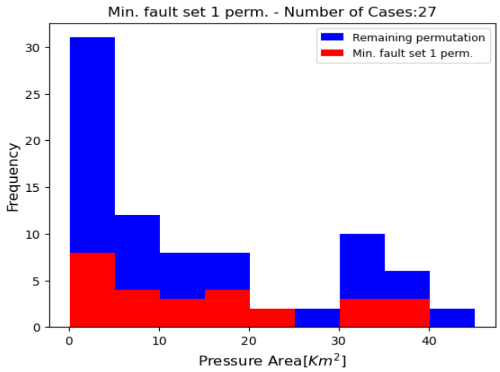


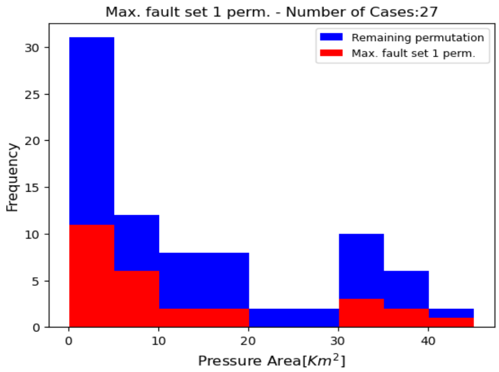




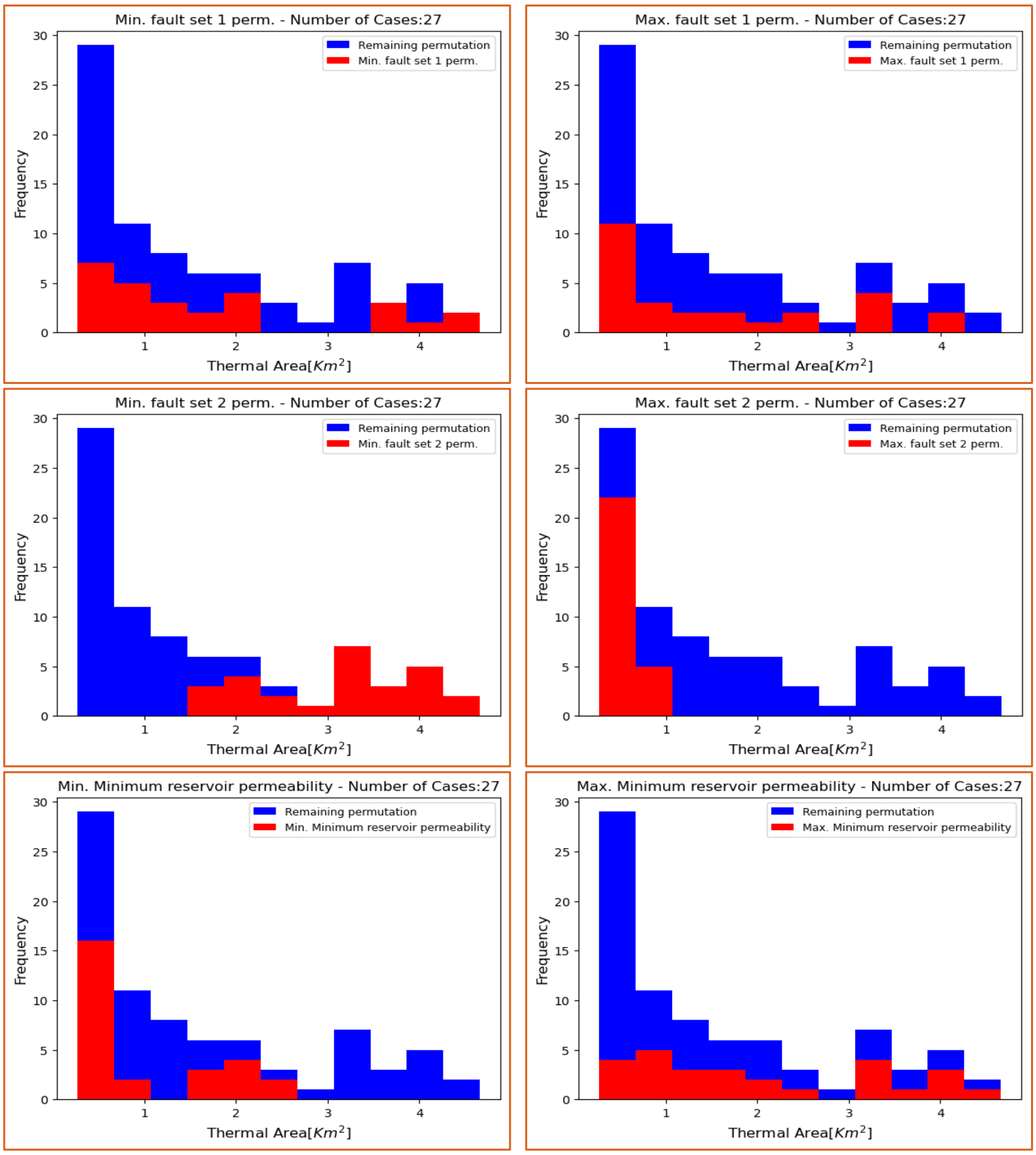






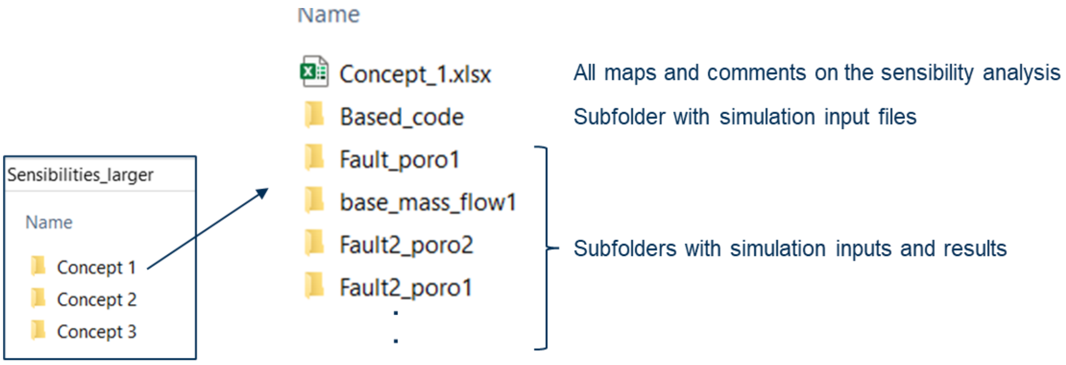


ANNEX D: IMPACT OF THE PERMUTATED PARAMETERS ON AFFECTED THERMAL AREA FOR CONCEPT 3

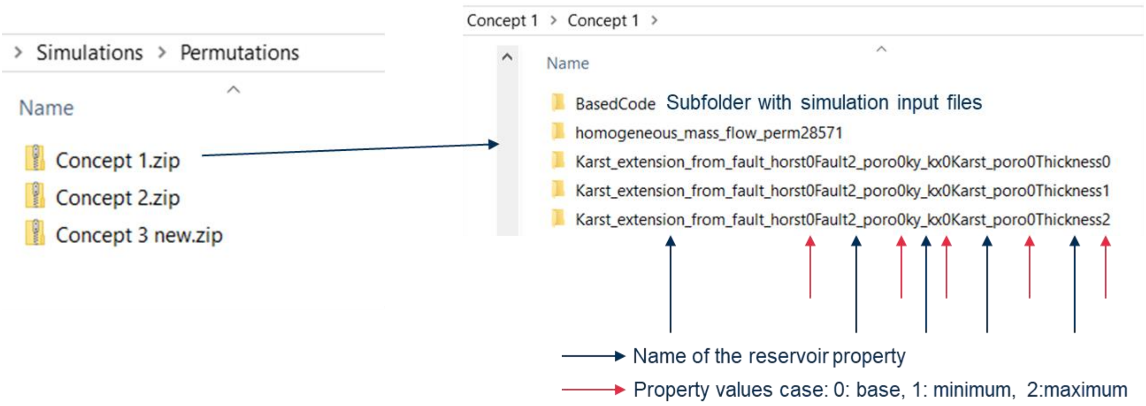


ANNEX E: FOLDER AND FILES DESCRIPTION FOR SENSITIVITY AND PERMUTATION ANALYSIS RESULTS

Sensitivity and permutation analysis results were deliverable in 3 separated folders corresponding to every reservoir concept as shown in the figure below:



Structure of sensibility folder



Structure of permutation folder

For sensibility and permutation studies, each reservoir concept folder contains a group of subfolders where the results of every modeled case are stored. These results folders are named following the name and case (nase,minimum, maximum) of the tested property in the sensibility study while in the permutation case the name is formed by the permuted properties and the cases tested. For the sensibility study, an excel file that compiles all the forecasted temperature and pressure maps for the different sensitivities is located each folder concept, this file is named Concept_n.xlsx (n=1,2,3). Each reservoir concept folder also have a subfolder that contains the input files of the simulation (python format 'py' for DARTS 1.02 version), the 3D results (vtk format) of every modeled case that can be open with a program called Paraview.

Description of subfolders

The subfolder for sensibility cases are name following the next logic: property_namez, where z=1 is minimum value, z=2 is maximum value. For example, for minimum fault throw the folder is called Fault_throw1.

For permutation study, the name of the cases is similar, but all permuted parameters are part of the name and the base value of the property is indicated with z=0 ''. For example, for 2 permutated properties the name of the folder could be: property_name1z1property_name2z2, where z1 and z2 could be 0,1 and 2 for base case, minimum and maximum respectively. The correspondence between the property names used in the subfolders and those provided in the report is shown in the table below.

Inputs and results are written in these subfolders for every case as mentioned before. Table bG shows the meaning of every written file.

Table aG. Correspondence between name of the property and name in the subfolders.

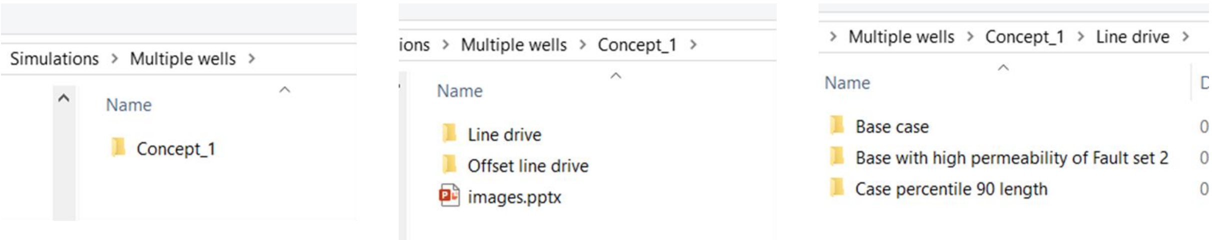
Porosity and permeability fault set 1	Fault_poro
Throw of fault set 1	Fault_throw
Faults spacing for set 1 at graben [m]	Fault_spacing_graben
Karst porosity -permeability	Karst_poro
Reservoir permeability [mD]	Minimum_reservoir_permeability
Karst extension from fault horst [m]	Karst_extension_from_fault_horst
Permeability anisotropy ky/kx	ky_kx
Porosity and permeability fault set 2	Fault2_poro
Well configuration	Well_conf
Reservoir layer thickness [m]	Thickness
Fault height [m]	Fault_height
Top & bottom layer separation	Layer_separation
Top layer permeability	perm_top

Table bG. Description of the files written in the subfolders.

Input Files names	Description	Ouput Files names	Description	Ouput figures names	Description
DX.txt, DY.txt, DZ.txt	3D meshes of Cells sizes in direction 'x', 'y', 'z'	enthalphy_init.txt enthalphy_final.txt	Initial enthalpy Final enthalpy (end of simulation)	INJ_pres.png	pressure at the injector
perm.txt, por.txt	Permeability in x direction and porosity 3D meshes	pressure_init.txt pressure_final.txt	Initial pressure Final pressure (end of simulation)	PRD_pres.png PRD_temp.png PRD_water.png	Well pressure, temperature an water flow rate
RType.txt	Rock type 3D mesh (reservoir (0),non-reservoir (1))	temperature_field_initial.txt temperature_field_final.txt	Initial temperature Final temperature (end of simulation)	press.png press_init.png	Initial and final pressure map at the level of the reservoir
		Indicator.txt	Main results of the simulations at the end of the simulation time	temp.png temp_init.png	Initial and final pressure map at the level of the reservoir
				well_profiles.xlsx	Well production injector vectors

ANNEX G: FOLDER AND FILES DESCRIPTION FOR SENSITIVITY AND PERMUTATION ANALYSIS RESULTS

Multiple wells are found in 'Multiple wells folder' and split in a Line drive and an offset line drive folder. In each of them, counts with 3 sub-folders where results are stored for the base case, base case high permeability and case percentile 90 respectively. The content and organization of these folder is also the same that is shown in Table aG.



Structure of Multiple wells folder