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A Lingering Cold: Thermal Recharge of Geothermal Systems in Conduction-Dominated Aquifers

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Abstract

Direct use geothermal energy covers a growing share of the heat demand in many countries. When produced from porous sedimentary aquifers without significant fracture flow, thermal recharge occurs mainly through conduction from the layers above and below. The rate of heat extraction is usually two to three orders of magnitude higher than the rate of conductive recharge. Therefore, when cold water is re-injected, it remains colder than its surroundings for long times. The competition for hot undisturbed reservoirs will increase if geothermal exploitation continues and cold plumes accumulate over time. Recharge behavior will impact the degree to which the exploitation of geothermal energy is sustainable. We propose a definition of "thermal recharge", based on the replacement of the extracted energy, and propose that this is best measured at reservoir scale. Simulation results show that achieving 50 %, 75 % and 87.5 % recharge take decades, centuries and millennia (in our simulations about 50, 500 and 2000 years), respectively. Reservoir thickness is the most important factor because it controls the surface area of a cold plume. Thick reservoirs, often targeted for production, take many times longer to recover than thin ones. Placing multiple wells near each other does not affect recharge significantly. Natural groundwater flow has little impact in the first centuries, but accelerates the later stages when strong. Heterogeneous models recharge up to 18 % faster than homogeneous ones but their recharge benefits less from background flow.

Keywords: Direct Use; Renewability; Sustainability; Reservoir Management;
Resource Management; Recharge

1 Introduction

Direct-use geothermal systems (DUGS) have a vast potential to decarbonize heating worldwide [1, 2]. Suitable aquifers underlie about 16 % of the global land area [3] and could provide heating of the same order of magnitude as the world’s overall energy consumption Limberger et al. [3], Ren21 [4].

Despite this large potential, resources can be exhausted locally and temporarily when heat is extracted faster than it is naturally recharged [5]. In practice this is almost unavoidable [6], as many potential DUG aquifers are in conduction-dominated sedimentary settings where the natural heat flux into the system is far smaller than the extraction rates needed to make production economically viable [7] (natural heat flux is typically less than 100 mW/m² [8], while extraction is up to tens of MW [9–11]).

In DUGS with re-injection, over time, an expanding cold plume (a volume of cooled water and rock) forms around the injector well, eventually causing thermal breakthrough and a decline in production temperature. To manage this, several studies have monitored how the production temperature recovers when production is stopped [5, 12, 13]. They all find that significant rewarming - even 95 % according to Rybach and Mongillo [12] - occurs within decades after production stop. However, it is the temperature at the producer well that is being monitored. The extensive cooling around the injector well, which would impact the lifetime of future operations substantially, has not been considered. In contrast, Poulsen et al. [14] monitor the energy content of homogeneous low-enthalpy reservoirs over 300 years of constant production. They find that only 20 - 30 % of the extracted energy is effectively missing from the reservoir at the end of this period, because vertical conduction from the confining layers

provides significant recharge. Axelsson [15] states that the reason is that *the ‘volume of influence’ of the geothermal energy extraction is likely very large, and the renewal is supported by indirect energy extraction from the outer and deeper parts of the geothermal system.*

O’Sullivan et al. [7] generalize a formula for geothermal reservoirs with different degrees of naturally occurring convection and conduction. It is based on the rates of extraction and natural recharge. For conduction-dominated systems, these can be three orders of magnitude apart [16], which leads to predicted recovery times on the order of centuries. Management strategies that address this imbalance are based on limiting the rate of heat extraction, for example through cyclic [5, 17] or demand-controlled [18] operation where production is paused or reduced at regular intervals to allow for partial recovery. Mégel et al. [5] show that, in the long term, short on-off cycles allow for more energy production in the long term. They propose that infinitely short cycles should be equivalent to constant production at a halved rate and that at the studied site, a rate of 5 l/s would allow for 300 years of production under almost steady conditions. Similarly, Rybach [6] predicts that *Future production schemes are likely to be based on considerations of sustainability [...], adopting low production rates that can be sustained over long periods of time.* However, current commercial systems operate at (significantly) more than 5 l/s, typically ranging from ca 15 - 125 l/s [1, 9, 10, 19]. With the market share of geothermal energy increasing [20, 21], this trend is unlikely to reverse. Producers are moving from individual doublets to multiwell setups and in some areas, competition for license areas is increasing [10]. To our knowledge, there is no established definition of thermal recharge and no standard value for when to consider it complete. There is also no published research about the effect of more intense geothermal exploitation on recharge dynamics.

We begin this paper by proposing a definition for the thermal recharge of geothermal systems in conduction dominated, sedimentary settings. It is applicable equally

139 to a single doublet and to reservoir-scale exploitation with multiple wells. We then
140 identify the key factors that influence recharge behavior in a sensitivity analysis of
141 13 geological and operational parameters and use multi-well setups, natural ground-
142 water flow and different types of reservoir heterogeneity to provide a comprehensive,
143 systematic analysis of geothermal recharge.
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147 148 149 **2 Methods**

150
151 The operation and subsequent recharge of geothermal energy extraction from sedimen-
152 tary systems are modeled in 3D numerical simulation using the finite volume simulator
153 open-DARTS [22]. In this chapter, we introduce the definition of thermal recharge
154 (2.1), the setup of the numerical simulations (2.2), the models used for the sensitivity
155 analysis (2.3) and to study the effects of multiple wells (2.4, natural groundwater flow
156 (2.5) and heterogeneity (2.6).
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161 162 163 **2.1 Definition of Thermal Recharge**

164 By removing hot water and re-injecting cold water, geothermal production causes an
165 energy deficit in the subsurface. We define the thermal recharge of a reservoir as the
166 return of this energy:
167

$$168 \quad R(t) = 1 - \frac{\Delta E(t)}{E_{Ex}(t)} \quad (1)$$

169 where at any time t , $\Delta E(t)$ is the energy deficit in the reservoir compared to the
170 initial state and $E_{Ex}(t)$ is the cumulative amount of energy that has been produced
171 from the reservoir. This definition is similar to that by Poulsen et al. [14], who define
172 recharge as the absolute, rather than relative, amount of energy that has returned.
173

174 While not explicitly formulated, their analysis considers the ratio of that recharge to
175 the extracted energy as proposed here. R ranges from 0 (no recharge - not occurring
176 in practice because conductive recharge starts as soon as cold water is injected) to 1
177 (full recharge).
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The deficit ΔE is given by the temperature changes and fluid and rock properties,
integrated over the reservoir layer:

$$\Delta E(t) = \int_{V_{Res}} \Delta T(t) (\phi C_f \rho_f + (1 - \phi) C_r \rho_r) dV_{Res} \quad (2)$$

where at any time t , ΔT is the observed temperature change, ϕ is porosity and C and ρ are specific heat capacity and density of the rock (r) and fluid (f). All of them vary in space, and C_f and ρ_f are dependent on temperature. dV_{Res} denotes intergration over the volume of the reservoir. As long as the reservoir model is large enough to include all cooling, i. e. there are no boundary interactions, the size of the model does not affect ΔE since the contribution of outer cells to the sum is 0. Using the simulation output, we calculate

$$\Delta E(t) = \sum_{i=0}^{n_{Res}} dT_i(t) V_i (\phi_i C_{fi} \rho_f + (1 - \phi_i) C_r \rho_r) \quad (3)$$

where the sum includes all reservoir cells, V_i is the volume of cell i . In the temperature ranges of low enthalpy systems, C_f and ρ_f vary close to linearly with temperature. Therefore, we evaluate them at the midpoint between the initial and current temperature for each cell.

$E_{Ex}(t)$ can be calculated from the enthalpy of the fluid that is entering and exiting the reservoir through the wells:

$$E_{Ex}(t) = \sum_{p=1}^{n_P} \int_0^{t_{shut}} h_P Q_P dt - \sum_{p=1}^{n_I} \int_0^{t_{shut}} h_I Q_I dt \quad (4)$$

where n_P and n_I are the numbers of production and injection wells respectively, Q and h are the mass flow rate and specific in J/kg enthalpy of the fluid going through a

231 well, which is calculated from bottom hole pressure and temperature using IAPWS97
 232 properties for water [23].
 233

234 As we monitor the energy balance of the entire reservoir, heat transport within it
 235 does not contribute to recharge. This is in distinction from earlier studies, where the
 236 impacts of geothermal operations on the subsurface temperature are assessed inside or
 237 along the border of a license area (LA) ([24], [25]). To compare, we also calculate the
 238 recharge of the license area R_{LA} , which only considers the energy deficit inside the LA.
 239
 240

$$241 \quad R_{LA}(t) = 1 - \frac{\Delta E_{LA}(t)}{E_{ex}} \quad (5)$$

242
 243 The LA consists of two overlapping, simplified circles around the injector and producer
 244 with radii of 0.7 and 0.3 times the well spacing, respectively (Fig. 1). This droplet
 245 shape was developed to optimize the use of surface space and to reflect that the impact
 246 of the injector well on temperature and pressure tends to be larger than that of the
 247 producer [26] .
 248

249 If R_{LA} differs significantly from R , it indicates that the energy deficit has moved
 250 outside the LA polygon. This could be due to highly heterogeneous structures, strong
 251 anisotropy or a natural groundwater flow pushing a cold plume in a specific direction.
 252 Evaluating only the recharge within the LA could then give an incomplete picture of
 253 the subsurface state.
 254

255 In conduction-dominated reservoirs the recharge process is close to asymptotic
 256 because it is governed by Fourier's law
 257

$$258 \quad \mathbf{q} = -\lambda \nabla \mathbf{T} \quad (6)$$

259 where $\mathbf{q}$ is the local heat flux density in W/m^2 , λ the thermal conductivity of the
 260 material and $\nabla \mathbf{T}$ is the spatial temperature gradient. As full recharge takes close
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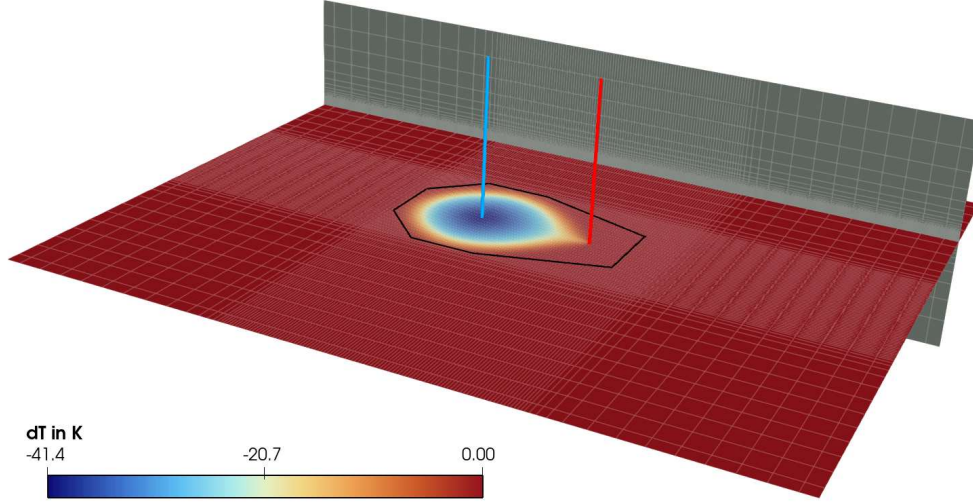


Fig. 1: Homogeneous base model at time of shutdown. ΔT illustrates the temperature change compared to initial temperature. License area outlined in black, wells as vertical lines (red for production, blue for injection).

to infinitely long when governed by conduction, we use thresholds to decide when a reservoir is "sufficiently recharged". For this study, we calculate the times until R reaches 50 %, 75 % and 87.5 %, which corresponds to the deficit being halved three times.

2.2 Numerical Simulation

All models consist of a reservoir layer that contains permeable sandstone, confined by impermeable claystone layers above and below. Large boundary volumes on the sides allow for flow into and out of the reservoir while keeping the pressure and temperature conditions constant. All wells perforate the entire reservoir thickness.

The grid (Fig. 1) has a high resolution in the central area of the reservoir that becomes coarser towards the model edges. The horizontal resolution in the center of the model, which includes all wells, all space between the wells and a buffer of 700 m around them, is 25 m in the models with one doublet, and 40 m in the larger models with multiple wells. The license area is entirely located inside this high resolution

323 area. From outside the buffer, the cell size gradually increases to 200 m. The vertical
324 resolution is 2 m throughout the reservoir layer and gradually increase toward 200 m
325 at the edge of the confining layers. The confining layers are each 1 km thick. This
326 ensures that no boundary interaction occurs during the long recharge phase.
327

328 The initial conditions represent a hydrostatic pressure gradient and an average
329 temperature gradient of 30 K/km (in the basecase). The latter was adjusted for the
330 confining and reservoir layers which have different heat conductivities, ensuring that
331 the vertical heat flow is constant with depth.
332

333 The wells are mass-rate controlled, representing the surface piping as a closed sys-
334 tem where 100 % of the produced fluid is re-injected. Flowrate Q is reported here in
335 units of m^3/h because it is more common, but for the simulations, it was converted
336 to mass rates under surface conditions (1 Bar, 10 °C). Heat loss along the wellbore is
337 neglected. The reservoir fluid is assumed to be pure water, as exact IAPWS formula-
338 tions for heat capacity and density under different pressure and temperature conditions
339 allow for a consistent calculation of the energy balance.
340

341 Thermal recharge is driven by conductive and advective heat transport. Conductive
342 recharge is always present, since the temperature gradient around the re-injected cold
343 water causes heat transfer towards it. Advective recharge is present when fluid moves,
344 for example due to a natural flow of groundwater or because neighboring wells induce a
345 horizontal pressure gradient. Dispersive heat transport and radiogenic recharge can be
346 neglected. Horizontal heat dispersion within the reservoir does not affect the reservoir's
347 energy balance, and vertical heat dispersion does not meaningfully impact simulated
348 recharge either. The reason is that the sum of vertical dispersion and conduction is
349 practically constant because heat dispersion decreases the thermal gradient [14]. In
350 the absence of dispersion, conduction takes over its share of heat transport, keeping
351 model results constant. Radiogenic heat production can be neglected because it is very
352 small in the typical porous reservoirs. Assuming an average value of $1\mu\text{W}/\text{m}^3$ [27] for
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sandstone and $1.6\mu W/m^3$ for claystone, it takes a period of 1000 years and 625 years, respectively, to produce $< 1\%$ of the typically extracted heat.

The models were run in three phases: An initial phase of 1000 years without well operation allows for the initial temperature and pressure fields to equilibrate around the very small, but existing, compressibility of water. This step is not typically necessary when simulating well response data, but because we sum changes in energy content over the whole reservoir, it is important that the production begins at a truly steady state, so that all observed changes can be attributed to production and recharge. The second phase is the operational phase of the doublet, which is 40 years in the basecase setup. The third phase is the passive recharge phase. For the first 60 years after shutdown, the pressure and temperature fields in the model and at the wells are recorded in 1 year steps. After this, changes in the model slow down and the timestep is increased to 10 years. Since the focus of this study is on the recharge, we refer to the time of shutdown as time 0. A recharge duration of 120 years, therefore refers to 120 years after production has ended.

2.3 Sensitivity Analysis on Single Doublets

The models for the parameter study all represent a porous reservoir with homogeneous, isotropic parameters and a single doublet placed in the center. We define a basecase, which is described by 13 parameters in the mid range of porous sandstone aquifers. They are porosity, permeability, heat capacity and thermal conductivity of the reservoir, heat capacity and thermal conductivity of the confining layers, reservoir thickness and depth, the vertical thermal gradient, time for which the doublet is operated, volumetric flowrate, initial extracted temperature difference, and well spacing. A one-at-a-time variation (values in Tab. 1) reveals how each one impacts recharge behavior. This results in a total of 27 homogeneous, single-doublet cases.

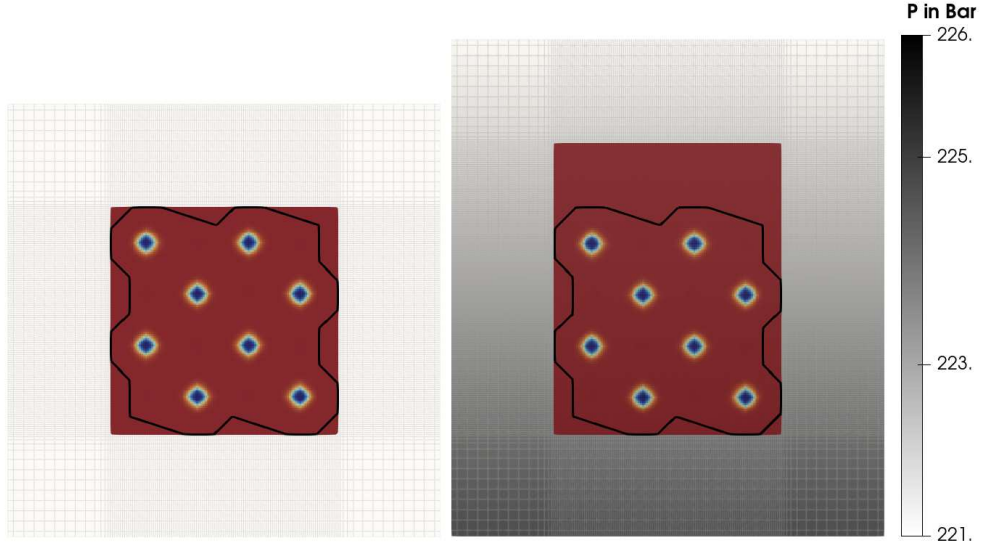


Fig. 2: Checkerboard setups with 16 wells. License area outlined in black. High-resolution area in the center shown with T-field at shutdown, outer areas shown as grid with initial pressure field. a) Basecase without groundwater flow. b) Basecase with a horizontal pressure gradient of 50 Pa/m to induce groundwater flow. The high resolution domain in the center is extended to allow for cold plume migration.

2.4 Multiwell Effects

If multiple injection wells operate near each other, their cold plumes can overlap and are likely to draw thermal recharge from the same parts of the confining layers [15]. To test this hypothesis, we run the models described in Section 2.3 with a larger domain and 16 wells arranged in a checkerboard pattern (Fig. 2a). The checkerboard pattern is chosen because it has been shown [25, 28] to limit negative interference between neighboring wells and even delay breakthrough compared to a single doublet. The spacing between wells is the same along both axes and the LAs, when drawn around pairs of wells, overlap to form one large area (black outline in Fig. 2).

2.5 Natural Groundwater Flow

Natural groundwater flow within an aquifer can be expected to affect the dynamics of thermal recharge. It separates the cold water from the cold rock, which spreads the

Table 1: Values of the varied parameters.

Variable	Param.	Min	Base	Max	Unit	Ref.
Porosity	ϕ	0.14	0.2	0.3		[29]
Permeability	k	50	225	400	mD	[29]
Heat cap. (conf.)	C_{Conf}	2000	2250	2500	kJ/(m ³ K)	[30]
Heat cap. (res.)	C_{Res}	2000	2250	2500	kJ/(m ³ K)	[30]
Th. cond. (conf.)	λ_{Res}	2.0	2.5	3.0	W/mK	[31]
Th. cond. (res.)	λ_{Res}	2.5	3.5	4.5	W/mK	[32]
Thickness	h	30	100	170	m	
Mid depth	D	1500	2250	3000	m	
Thermal gradient	dT/dz	0.02	0.03	0.04	K/m	
Operating time	t_{Op}	20	40	60	years	
Flowrate	Q	125	250	375	m ³ /h	
ΔT (initial)	ΔT	20	40	60	K	
Well spacing	L	500	1000	1500	m	

impact across a larger area. This reduces the thermal gradient, which is the driver of conductive recharge from the confining layers. On the other hand, a drifting cold plume is continuously exposed to new parts of the confining layers, which increases recharge.

To stimulate a flow of groundwater across the model domain, we implement a pressure gradient between two opposite sides of the model. It is maintained by the boundary volumes. We simulate three orders of magnitude (5 Pa/m, 50 Pa/m and 500 Pa/m), that represent weak, medium and strong background flow. They follow from an analysis of formation pressure data from wells in the Dutch cretaceous Schieland and Rijnland groups [33]. With a permeability of 225 mD and an in situ temperature of 73 °C, these gradients translate to darcy velocities of 0.09 m/year, 0.9 m/year and 9 m/year. With heterogeneous permeability fields (Section 2.6), flow will move faster along well-connected pathways and more slowly where areas of low permeability are in the way. To ensure that the energy deficit is monitored accurately throughout the simulation and does not leave the model domain, the grid is extended with a larger high-resolution zone downstream of the wells (Fig. 2b).

2.6 Heterogeneous Geology

Heterogeneous geological models have been generated to represent permeable channel structures surrounded by (nearly) impermeable claystone, which is a frequent setting in targeted reservoirs [34–36]. Channel structures introduce two mechanisms that are not reflected in homogeneous models: Irregular flow paths along preferential pathways and reserves of heat in impermeable parts of the reservoir which are only accessible through conduction. To define their impact on recharge, we define geological models with two variables: Net-to-gross ratio (N/G) and sinuosity. N/G controls the amount of pore space in the reservoir. Compared to a homogeneous model with only sand facies, the cold water will have to spread further when N/G is less than 100 %. At the same time, the amount of conduction-accessible heat in the clay facies increases. We use values of 40 % and 80 %, referred to as low and high N/G, respectively. Values outside this range occur, but below 40 % N/G, connectivity significantly declines which makes a reservoir less suitable for geothermal production [37]. Above 80 %, the characteristics of a reservoir begin approaching homogeneity [38]. Sinuosity controls the path length of channels [39], and therefore the surface area between the two facies through which conductive recharge can occur. It also changes flow patterns, which can be expected to impact the spread of cold water, as well as the interaction with natural groundwater flow. Combining high and low of both parameters results in four types of heterogeneity, referred to 80H, 80L, 40H and 40L for brevity. Fluvsim [40],

Table 2: Channel geometry parameters. Column labels describe the combination of N/G ratio (40 % or 80 %) and sinuosity (High or Low).

	40H	40L	80H	80L	Range
Thickness (m)	4	4	6	6	± 2
Wavelength (m)	1200	2000	1200	2000	± 400
Amplitude (m)	320	120	320	120	± 40
Width / Thickness	160	280	160	280	± 40
Orientation (°)	0	0	0	0	± 20

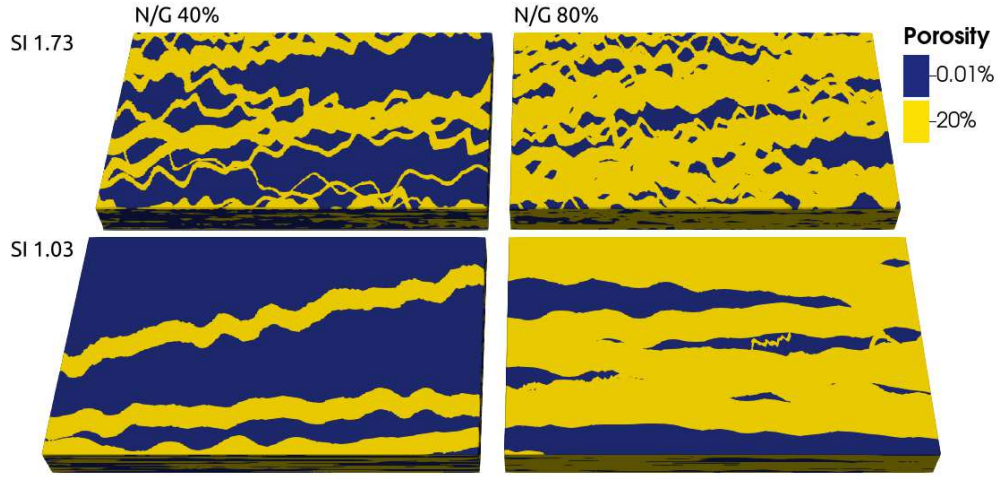


Fig. 3: Reservoir models with channelized subsurface. Constant properties per facies (sand and clay). Sinuosity index (SI) is an average.

a stochastic, object-based tool, is used to generate these models. Ten realizations per group account for variability. Additionally, we place 16 wells in the base checkerboard pattern, to minimize the impact of well placement and connectivity. An example of each heterogeneity type is shown in Fig. 3. Table 2 lists the channel geometry parameters used as input to Fluvsim. The widths, thicknesses and undulation lengths of channel structures reported in literature span multiple orders of magnitude ([41]). We focus on values in the middle of the ranges, which correspond to the size of geothermal doublets. Variability at a much smaller scale (e.g. channels of a few meters width and undulation length) would largely even out across a 1 km doublet and at a much larger scale, the wells would be placed in an effectively homogeneous part of the model. The channels have the same uniform properties as the reservoir in the homogeneous model. The surrounding rock has the same uniform properties as the confining layers. The models are run with and without background flow. We use the highest pressure gradient of 500 Pa/m (9 m/year) and apply it in two directions: Along and across the main channel axis (from left to right and from bottom to top in Fig. 3, respectively.)

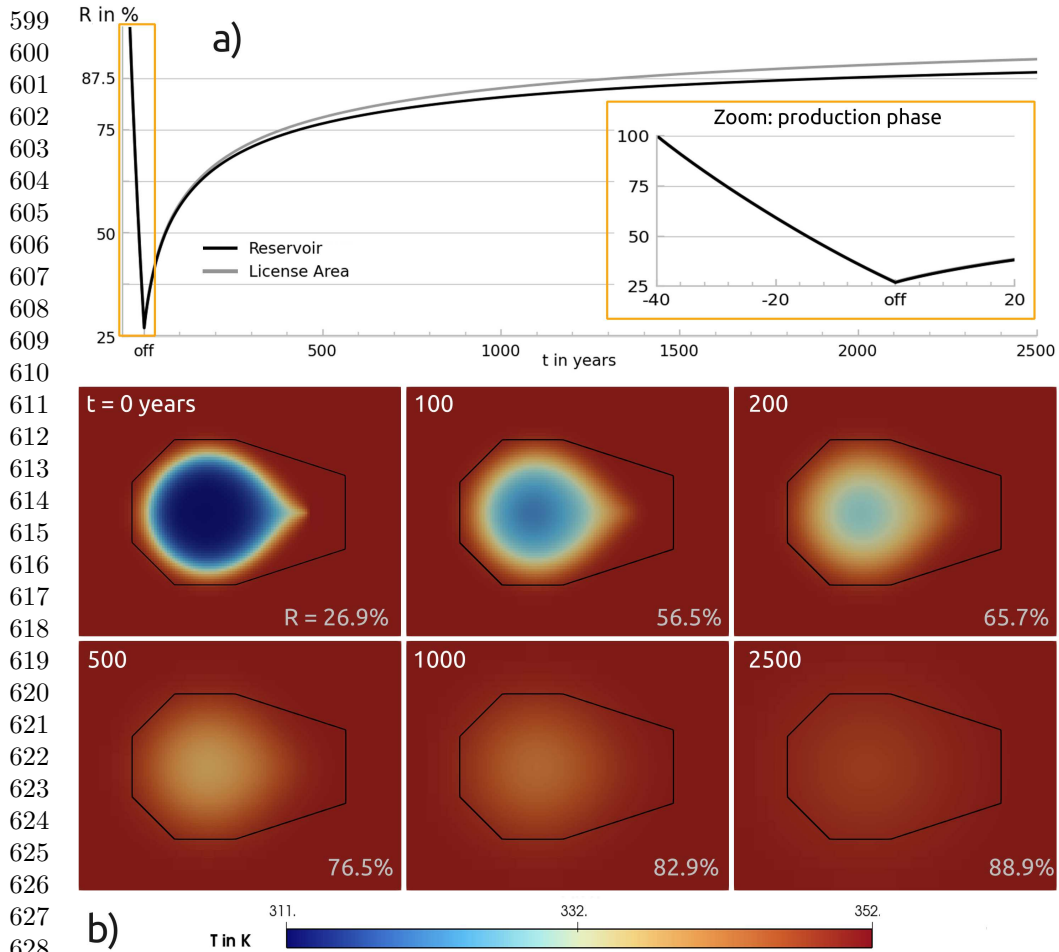


Fig. 4: a) Recharge (R and R_{LA}) over time for the basecase model. Inset shows the active production and first 20 years of recharge b) Horizontal slices through the reservoir center of the temperature field. LA marked in black, horizontal slices cropped to the center of the reservoir domain.

The flow should move along the channels more easily than across, given that the clay bodies restrict it. This changes the velocity and final distribution of the cold water.

3 Results

Fig. 4 shows the development of recharge levels (a) and temperature (b-c) in the base model over time. Initially, the reservoir is fully charged with heat. Over the course of

production, the energy content of the reservoir is reduced, but R only drops to 26.9 %. This means that more than a quarter of the produced energy is replaced through conduction from the confining layers into the cold plume while the system is still running. Most of the cold is contained in the LA, therefore R_{LA} is only marginally higher at 27.1 %. This is confirmed by the first time slice (Fig. 4b).

Both R and R_{LA} reach the 50 % threshold 60 years after shutdown. The strong vertical temperature gradient drives recharge, especially of the cold center of the plume (Fig. 4b). As this contrast weakens, it slows down the remaining recharge. Over longer time scales, horizontal conduction in the reservoir layer spreads the remaining heat deficit outside the LA. Fig. 4c shows how the cold front has widened into a broader zone. It causes the two definitions of recharge to diverge: R_{LA} crosses the 75 % threshold in year 390, R only in year 440. For the 87.5 % threshold, the time difference is between 1330 years for R_{LA} and 1940 years for R .

At the end of the simulated 2500 years, R is 88.9 % and R_{LA} is 92.1 %. This difference is small, given that a prediction about 2500 years into the future is too far for practical applications. For the homogeneous base model with purely conductive recharge, it could be concluded that the recharge of the LA is a good approximation for recharge across the reservoir.

3.1 Parameter study - Energy extraction

Fig. 5 illustrates the impacts of the 13 varied parameters on E_{Ex} . For the base model, the amount of energy E_{Ex} that is produced in 40 years is 14.1 PJ. This number logically varies most with the operational parameters that control the energy production (Fig. 5). Q and ΔT are proportional to the rate of produced energy, and t_{Op} controls the lifetime over which this rate accumulates. The changes in E_{Ex} are not quite proportional because after thermal breakthrough, the declining temperature results in reduced power output. Increasing t_{Op} or Q by 50 % therefore only results in 44 % more

691 E_{Ex} . On the other hand, increasing ΔT by 50 %, results in 52 % more E_{Ex} , as the
692 higher temperature contrast between the cold plume and the confining layers drives
693 stronger recharge. Well spacing L mainly has an effect when it is reduced, because this
694 makes thermal breakthrough, and therefore production of lower temperature water,
695 occur earlier.

699 The only geological parameter with significant impact on E_{Ex} is reservoir thickness
700 h . In a thin reservoir, the cold plume spreads more widely than in a thick reservoir
701 and therefore thermal breakthrough occurs earlier. This causes a stronger decline in
702 production temperature, decreasing overall E_{Ex} . Additionally, a small reduction of
703 E_{Ex} can be seen with low permeability. This is not due to thermal effects, but due
704 to Darcy flow. In a low-permeability reservoir, the water has to be re-injected with
705 higher pressure in order to maintain a desired flowrate. This additional energy offsets
706 the energy deficit in the reservoir, reducing E_{Ex} .

712 Orange horizontal lines show E_{Ex} for a checkerboard setup with 16 wells instead
713 of a single doublet. We use an average E_{Ex} per well to allow comparison. Interference
714 occurs with small values of h or L , both of which cause early thermal breakthrough: In
715 a checkerboard, this means that a larger share of the cold water is re-produced, since
716 the central production wells draw cooled water from all four sides rather than just
717 one, reducing average E_{Ex} . For the same reason, the less-than-proportional increase
718 of produced energy with Q or t_{Op} is more pronounced in the checkerboard. In most
719 other cases, the multiwell setup aligns with the single doublet, indicating that there is
720 no interference between neighboring wells in terms of energy production or recharge.

728 3.2 Parameter Study - Recharge times

731 Fig. 6 displays the times it takes for R to cross 50 %, 75 % and 87.5 %. For the basecase,
732 these times are 60, 390 and 1940 years. The largest variation is caused by reservoir
733 thickness. For a thin reservoir, over 50 % of recharge already occurs during production,

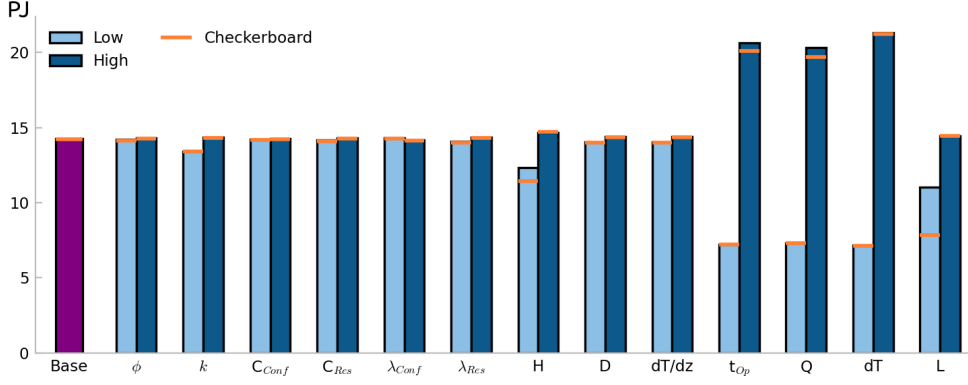


Fig. 5: E_{Ex} at time of shutdown for the 27 cases of the parameter study. Orange lines show equivalent results for the checkerboard setups.

and 87.5 % is reached after 160 years. Recharge is fast because a large surface area is in contact with the confining layers and the heat does not have to travel deep into the reservoir (Fig. 7a). The thick reservoir on the other hand takes 220 years to recharge by even 50 %, and 87.5 % is not observed within the simulated time. Recharge progresses much slower because the cold plume is compact with little surface area (Fig. 7b). Porosity has a similar effect, where the smaller pore volume of a low porosity reservoir forces the cold water to spread further. The operational parameters do not affect recharge times significantly. This is noteworthy because while they control the absolute amount of E_{Ex} , the relative recharge progression is the same. Heat capacity and thermal conductivity of the confining layers control how much heat is available and how fast it is transported. They have little impact on the first 50 % of recharge, which are reached between 50 and 80 years with all geological variations. In the later stages, they become more relevant and can shift 87.5 % recharge by several centuries. The heat capacity of the reservoir layer acts the opposite way. A higher value means that the energy deficit is concentrated in a smaller value, slowing recharge.

White triangles in Fig. 6 indicate the recharge times according to R_{LA} . As in the basecase, the first 50 % of recharge occurs at the same time when measured across the whole reservoir. This shows that the cold plume is close to fully contained by the LA.

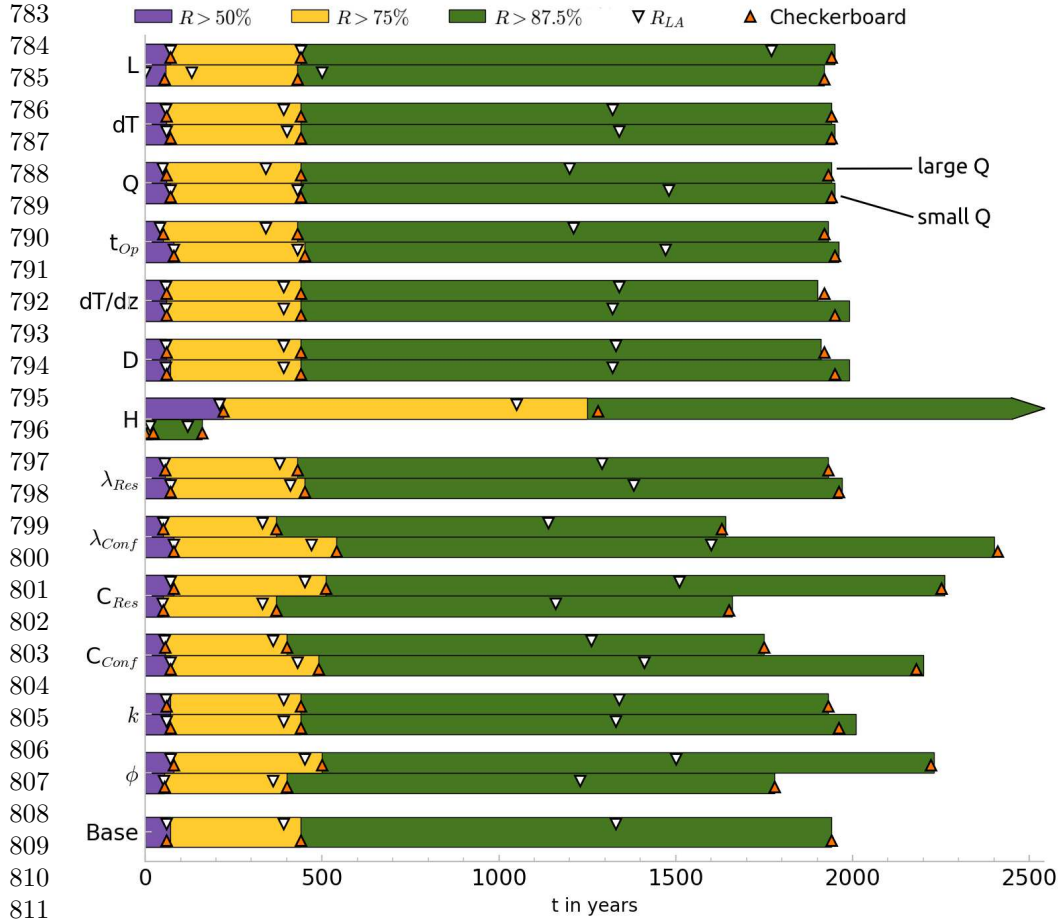


Fig. 6: Recharge durations for the parameter study. Bars indicate time until R reaches 50 %, 75 %, or 87.5 %. Of the two bars drawn for each parameter, the top and bottom bar describe the higher and lower values from the sensitivity analysis, respectively. White triangles mark R_{LA} , which is reached earlier than R . Orange triangles mark R for the checkerboard scenarios with 16 wells and matches R closely.).

75 % recharge are reached some decades earlier in the LA, as horizontal conduction redistributes the heat deficit. With a small well spacing, it is reached several centuries earlier, as the license area is defined via L and a small LA excludes a significant portion of the injected cold water. This trend remains the same for 87.5 % recharge, with the gap between R and R_{LA} widening to several centuries.

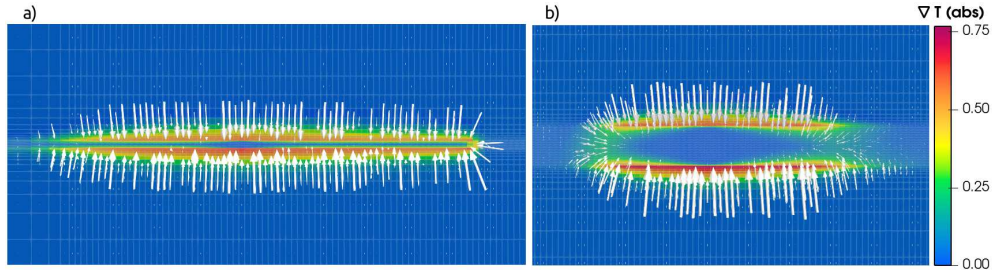


Fig. 7: Vertical slice through the thin (a) and thick (b) reservoir at time of shutdown. Color and arrows represent the magnitude and direction of the temperature gradient, along which heat conduction takes place.

Orange triangles in Fig. 6 indicate recharge durations for the checkerboard cases. The results are almost identical to those for single doublets, indicating that the definition of R is robust for systems of different sizes. The largest difference is observed for 87.5% recharge, where a small D , small dT/dz or small k accelerate recharge by 80 years. However, with absolute durations around 2000 years, this equals 4% and can be considered negligible.

While most of the geological properties clearly impact thermal recharge, reservoir thickness clearly has an outsized effect. Especially in the first decades and centuries, it is the most relevant parameter by far. For the remaining parts of the study, we therefore use the basecase along with variants for high and low h , as the other parameters are unlikely to significantly change the results.

3.3 Natural Background Flow

Fig. 8 shows horizontal slices through the basecase reservoir at different points in time, with background flows of 0.09, 0.9 and 9 m/year (induced by 5, 50 and 500 Pa/m). Significant migration of the cold water is only visible under strong background flow. Here, the cold plumes are already drifting at the time of shutdown. The flow distributes the energy deficit across a larger volume by separating cold water from cold rock. As a result, after 100 years, the plumes have increased in size but also warmed by 20 K, while with no, little or medium flow, they have only warmed by 13.4 K. After 1000

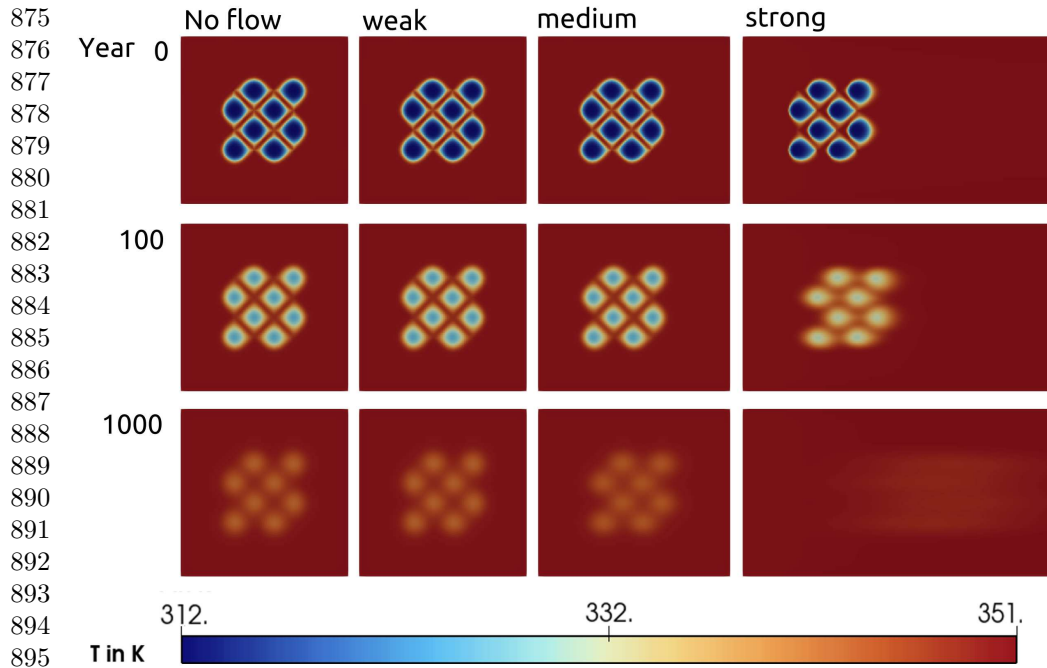


Fig. 8: Time slices (rows) through the basecase reservoir with no, weak, medium and strong background flow (columns). Under strong flow, the cold plumes are visibly migrating and warming.

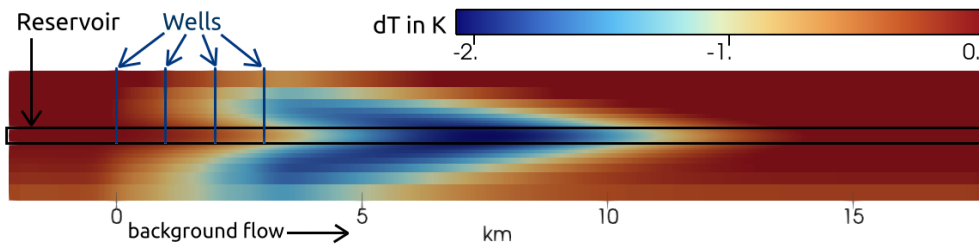


Fig. 9: Cooled confining layer after 1000 years, for the multiwell basecase with strong background flow. Wells indicate where water was originally injected (only 4 wells visible because the 4-by-4 grid is viewed from the side.) The cold plume has traveled ca. 10 km to the right.

years, the plumes have smeared into one weakly cool area with strong flow, while still being individually discernible in the other cases. The medium flow causes light smearing of the temperature fronts and visible displacement, but no significant changes in temperature. The weak background flow does not visibly affect position, shape or

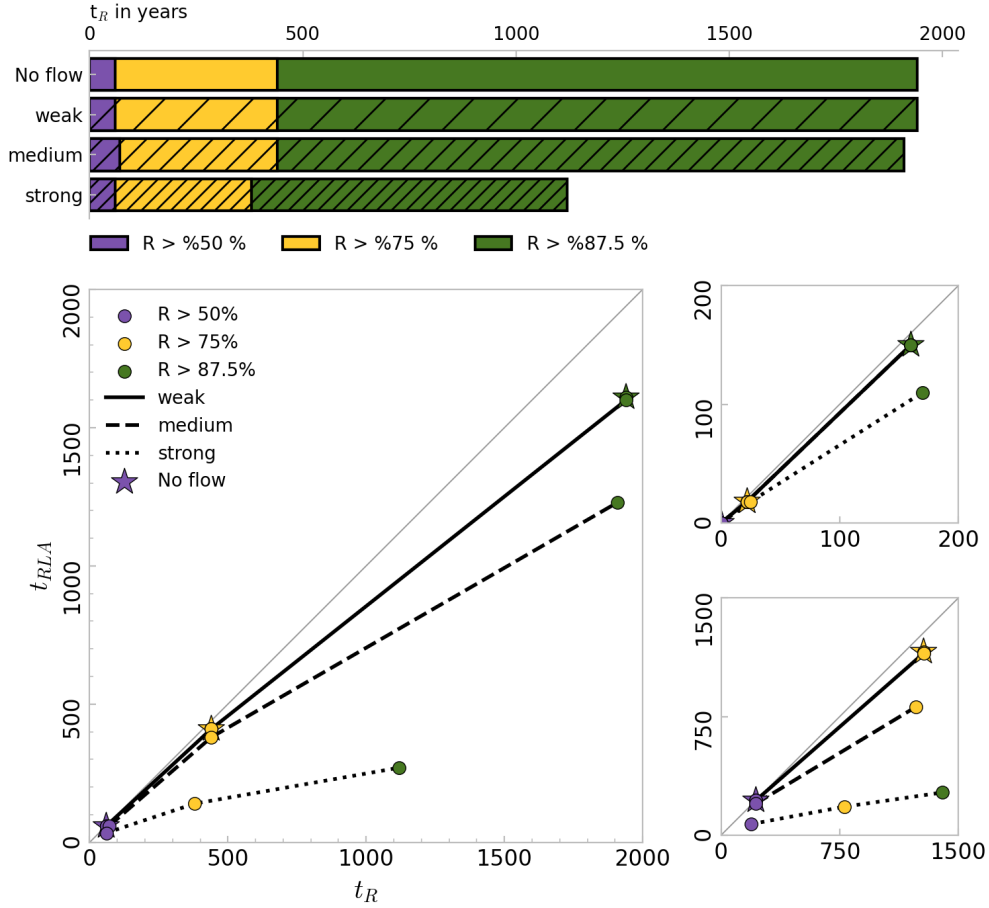


Fig. 10: a) Time for R of the basecase under different levels of background flow. b) time for R_{LA} vs R for the basecase under different levels of background flow. c-d) same as b for a thin and a thick reservoir.

temperature of the cold plumes. This is expected, given that it takes 450 years for the water to cross the 40 m of a single model cell.

Fig. 9 depicts a vertical slice through the simulation with strong flow, 1000 years after shutdown. The coldest part of the reservoir is located 8 km downstream of the wells, showing how far the cold has migrated. At the wells, the reservoir has reheated almost completely since the background flow pushes warm water through the cooled

rock matrix continuously. However, an impact remains, visible as two diagonal streaks going deeper into the confining layers where there is no advection.

Fig. 10a illustrates the recharge times for the basecase under the three flow scenarios. There is no meaningful difference between no flow and weak flow for any of the thresholds. With medium background flow, 87.5 % recharge is reached 30 years earlier, which is near-negligible at total times of over 1900 years. Under strong background flow however, 75 % and 87.5 % are reached significantly earlier, the time to the latter is almost halved from 1940 to 1120 years, due to the access to heat from different parts of the confining layers (9).

When the cold water is transported outside the LA, the difference between R and R_{LA} , which was small in the results without background flow, can be expected to increase. The durations calculated from both definitions are plotted against each other in Fig. 10b. Without background flow, recharge times calculated from R_{LA} are already about 10 % shorter than those from R because some cooling of rock outside the LA always occurs. A weak background flow does not significantly change this. With medium flow, R_{LA} speeds up as some of the cooled water leaves the LA, while the total energy deficit, and therefore R , remains the same. Strong background shortens R_{LA} further due to the large amount of warm water passing through the LA. But it also shortens R , due to the increased exposure to confining rock. Because reservoir thickness h is the most influential factor for recharge duration, we repeat this analysis for the two thickness variations (30 and 170 m). The migration velocity of the cold water is the same in all cases. But in a thin reservoir (Fig. 10b), recharge is so much faster that there is less time for the water to exit the LA. All recharge thresholds are reached in less than 200 years, and the difference between R and R_{LA} is relatively small. With a thick reservoir (Fig. 10c), the migration effect is active over a much longer time. While 87.5 % recharge were not observed in the basecase parameter study,

the strong flow makes it occur after 1400 years using R , and after only 270 years using R_{LA} .

3.4 Heterogeneous Geology

Geological heterogeneity controls flow paths and velocities, as well as the pore volume that the injected cold water can take up. The effect of this is shown in Fig. 11. For one realization of 80L, 80H, 40L and 40H each, it shows the temperature difference between the homogeneous and the heterogeneous case on a slice through the reservoir, at time of shutdown. In all cases, the plumes are warmer (less cold) than in the homogeneous model, and the spaces between wells are colder. This effect is stronger with 40 % N/G than with 80 % N/G, because there is less pore space available, forcing the re-injected water to spread further, including into the areas in between wells. The 40H case has some particularly warm locations, up to 22.7K warmer than they the would be in a homogeneous case. In the geological model, these locations correspond to clay bodies which are only cooled through conduction from the channels surrounding them. The 40L case, with broader and straighter channels, shows plumes that are more regularly shaped and visibly elongated along the mean axis of the channels. With 80 % N/G, the maximum temperature deviation is $\pm 10K$, since the reservoir is much more similar to the homogeneous case. The temperature deviations are more regular in the 80L case, again reflecting the broader, straighter channels.

In all heterogeneous scenarios, recharge progresses faster than in the homogeneous case. The 40H cases show the strongest shortening of recharge times (Fig. 12a), reaching 75 % and 87.5 % 70 and 315 years earlier than the basecase. For 40L, these numbers are 40 and 200 years, respectively. Notably, the recharge is not only faster in 40H but also more consistent across realizations. The standard deviation is 7 % for 40H compared to 9 % for 40L. This is in contrast to the irregular plume shapes, but is explained by the fact that there are more, narrower channels compared to fewer wide

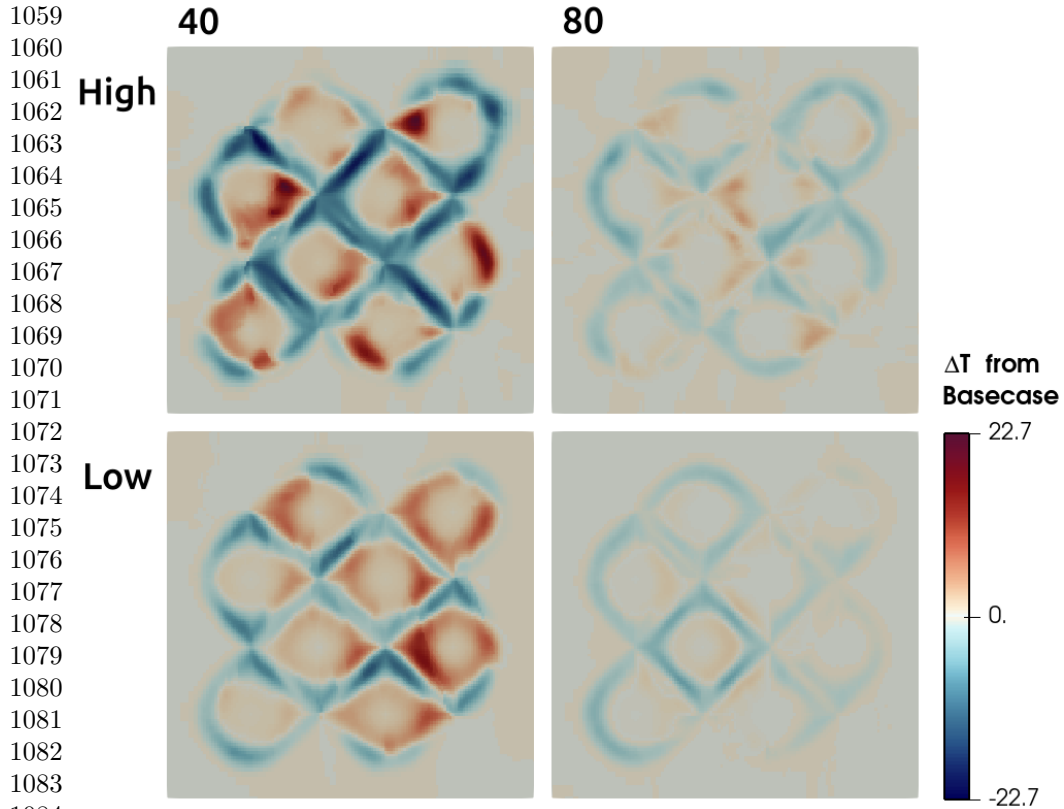


Fig. 11: Temperature differences between the cold plumes in heterogeneous and homogeneous model. 'High' and 'Low' refer to sinuosity, 40 and 80 to N/G. The plumes are warmer than in the homogeneous models, and the space in between the wells is colder.

ones. Therefore, the well connectivity, and thus the way the cold water spreads, is more consistent across realization.

The 80L and 80H cases reach the 75 % and 87.5 % thresholds only ca. 20 and 90 years earlier than the basecase, with no significant difference between high and low sinuosity. The standard deviation between realizations is less than 2 %. This suggests that at N/G ratios of 80 % or more, a homogeneous model that neglects the clay facies could be an acceptable approximation of recharge behavior.

Background flow accelerates recharge in all geology types, but not to the same extent. With strong flow, (Fig. 12d-e), the order in which the cases reach the recharge

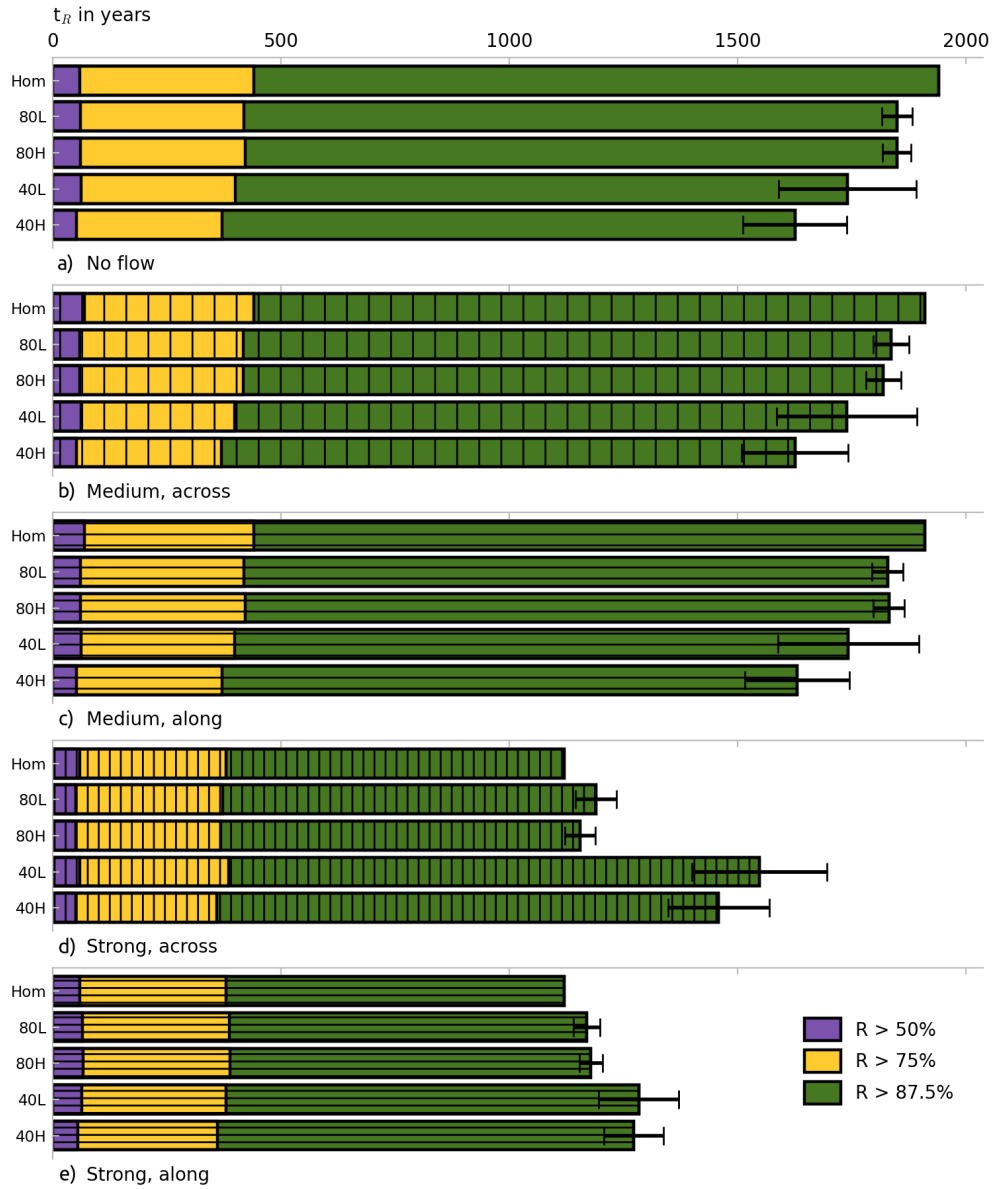


Fig. 12: Durations for R for heterogeneous geologies, averaged per group. Black lines mark standard deviation for reaching 87.5 % recharge. a) - e) represent different background flow scenarios.

thresholds is reversed, so that the homogeneous case is fastest, followed by the high N/G cases, and the low N/G cases slowest. This observation is explained by two effects contrasting effects of impermeable zones in a reservoir. On the one hand, with a smaller N/G, the cold water occupies a larger horizontal area and it has contact with a greater part of the confining layers. Without background flow, this allows the 40H and 40L cases to recharge faster. On the other hand, when there is background flow, the impermeable zones act as barriers. This limits cold plume migration (Section 3.3), so that the positive effect on recharge is much smaller than for 80 % N/G or homogeneous cases.

The flow direction only impacts the recharge durations of the low N/G cases. They reach 80 % recharge about 200 years faster when the flow is along the channels compared to across. This matches the barrier effect, which is of course less pronounced along the main channel axis.

The medium flow only reduces recharge time slightly compared to no-flow. There is no significant difference between the flow directions. Across flow scenarios, 40H consistently recharges faster than 40L, while 80H and 80L still perform nearly identically. The standard deviations are also consistent, being small for 80H and 80L, larger but still below 10 % for 40H and most pronounced for 40L.

4 Discussion

We define the thermal recharge R of a geothermal reservoir as the return of the extracted energy over time, evaluated across the entire reservoir. The results illustrate the asymptotic nature of conductive heating, with the first half of the energy deficit returning within decades, and the second half over centuries and millennia. Reservoir thickness is by far the most important parameter, as the amount of heat entering the reservoir from the confining layers mainly depends on the horizontal extent of the cold plume. This result is in line with the study by Poulsen et al. [14] who also determine

thickness as the most important factor. With a basecase of 50 m and a maximum thickness of 100 m, they focus on thinner reservoirs, which explains the higher degree of recharge (70-80 %) they observe during 300 years of ongoing production. Background flow was shown to accelerate recharge by up to a factor of 2, but only in the later stages and for homogeneous models. For more realistic heterogeneous models and the more practically relevant earlier stages of recharge, the impact is more limited. Heterogeneity itself tends to accelerate recharge by increasing the plume surface.

4.1 Comparison of R with other Quantifications of Recharge

The long time scales on which the higher recharge thresholds of 75 or 87.5 % are reached in our results contrast studies focused on the production well, which have repeatedly found near-complete recharge within a century [5, 12]. It should be pointed out that these results are not in disagreement, but highlight different aspects of recharge physics. For practical applications where the goal is to determine the length of a production break after which a system will deliver the original temperature for some additional years or decades, the producer-well approaches are appropriate. While thermal breakthrough is likely to occur faster in a second or third production cycle [5], significant additional production can be achieved from an existing well. The remaining energy deficit around the injector well that is considered here is important from a larger-scale sustainability perspective, where the focus is on the resource as a whole.

Poulsen et al. [14] presented a definition similar to R , defining recharge as the absolute amount of energy that had returned to the reservoir but analyzing it, as done here, in relation to the deficit. With a thinner basecase reservoir of 50 m and continuous operation over 300 years, they highlight the return of 70-80 % of the extracted energy during those 300 years. While the absolute energy difference of course increases as long as production continues, continuous operation would indeed benefit relative recharge, since the temperature gradient between the cold plume and its surroundings would be

1243 kept strong. After eventual shutdown, the remaining deficit would still take centuries
1244 or millennia to recharge.

1246 The energy balance approach by O’Sullivan et al. [7] results in timescales compa-
1247 rable to our results. They suggest that the recharge time t_R can be estimated from
1248 the production ratio PR which describes the imbalance between the heat extraction
1249 rate and the natural heat flow. Assuming a typical heat flow of 70 mW/m^2 for sed-
1250 imentary basins [42, 43] and our basecase scenario which operates at 11.6 MW , it is
1251 approximately $PR = 51$. The expected recharge time is given by $t_R = (PR - 1) * t_{Op} =$
1252 2000 years, which closely matches our result of 1940 years.

1258 Applying the definition of recharge to the entire reservoir and the LA highlights
1259 how, over long time scales, the energy deficit is smeared across the reservoir. When
1260 strong background flow is present, the cold water moves with the current and quickly
1261 leaves the LA. In this case, the difference between R and R_{LA} is considerable and
1262 evaluating only the LA means disregarding a significant portion of the energy deficit.
1263 In most other cases, particularly when the focus is on the earlier stages of recharge,
1264 the results of both methods will be similar.

1269 While our definition of R provides a way to describe recharge, it does not define
1270 when the process can be considered complete. This again depends on the use case and
1271 requires choosing a threshold. As the recharge curves flatten so much in the later stages
1272 of recharge, the chosen threshold is equally or even more important in determining
1273 recharge duration than the parameters of the system being evaluated.

1279 4.2 Implications for Geothermal Energy as a Sustainable 1280 Resource

1283 The Brundtland report from 1987 [44] defines sustainable development as *meeting*
1284 *the needs of the present without compromising the ability of future generations to*
1285 *meet their own needs*. Our result show that in conduction-dominated settings, a single
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geothermal project can never be truly sustainable. While wells may produce sufficient temperatures for decades even after thermal breakthrough, it is clear that the resource declines and stays affected for long times. The later stages of recharge approaching "full" recharge take centuries to millennia, because conduction slows down as the temperature gradient weakens.

A recurring suggestion to achieve practical sustainability has been to limit flowrates such that production can be maintained for 100 years or more [5, 45, 46]. While this may work physically, the current trend in a growing industry [20, 21] is towards higher flowrates and denser placement to achieve higher shares of heat-in-place recovery [10] and better economic performance [25]. Another suggestion has been to approach the sustainable use of geothermal resources at a basin scale rather than at a project scale [47]. This approach acknowledges that locally, geothermal production can diminish the resource for a long time but at a larger scale, a balance of exploitation and long term recovery could be achieved. It also allows to assign value to unused subsurface space, leaving resources intact for unknown future uses.

Our results show that intense local production is not in the way of sustainability. Clusters of wells with dense spacing or high flowrates recharge at the same speed as individual doublets (Fig. 6). This was not expected since it had been pointed out, and was motivation for the study, that a cold plume draws heat from a bigger volume of the confining layers [15], and that the overlapping of several of these volumes may slow down recharge. That does not appear to be the case because recharge occurs mainly vertically. Intense production may therefore be beneficial for economic returns as well as sustainability.

4.3 Limitations

In this study, we have calculated R for scenarios with multiple wells operating at the same time, but not for wells operating at different times or restarting after a break.

1335 At the reservoir scale, our definition of recharge could be applied to these setups
1336 easily, by measuring the restoration of the cumulative energy deficit. At the scale of an
1337 individual project which begins in an already disturbed subsurface, it would require
1338 a decision about what state to consider as the baseline. The new operation would re-
1339 establish and deepen an existing energy deficit and the conduction into existing cold
1340 plumes would overlap with that into the new cold plume. Simulations of the long-term
1341 effects of repeated reservoir use could illuminate the impacts of such repeated use.

1342 A challenge separate from evaluating recharge progress in simulations is evaluat-
1343 ing it in practice. This is not possible with any definition that relies on more than
1344 well temperature, which could conceivably be monitored after wells have been aban-
1345 doned. However, given that reservoir models are often made before operations begin,
1346 they could also be used to predict recharge behavior. The fact that most geological
1347 parameters were shown to not impact recharge behavior much, particularly in the
1348 first decades and centuries after shutdown, supports this and makes predictions robust
1349 to simplifications and deviations. The present study shows that reservoir thickness,
1350 strong background flow and N/G are the factors that determine recharge behavior
1351 most strongly. A prediction method based directly on these factors, all of which are
1352 important in the planning and operating of geothermal systems, could help to estab-
1353 lish recharge behavior as a factor that should be considered from the start, as it would
1354 not require additional geological insight or simulations.

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1356

1357 5 Conclusion

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1359 We propose unity minus the ratio of energy deficit to energy extracted (R as defined
1360 in Eq. 1) to define the degree of thermal recharge of a geothermal system. Expressing
1361 recharge in proportion to the total extracted energy is compatible with a resource-wide
1362 or basin-wide approach to subsurface management because the replacement of heat
1363 from outside the reservoir, not redistribution within it, is counted. As a result, R is

applicable across license areas, well configurations, production patterns and geological settings. In the context of sustainable subsurface development, it ensures that the cumulative long-term impacts of multiple geothermal installations are accounted for.

In almost all evaluated scenarios, thermal recharge occurs on timescales of centuries to millennia. This is due to the asymptotic nature of heat conduction. Typical recharge durations from our simulations are 60 years for reaching 50 %, 500 years to reaching 75 % and 2000 years to reaching 87.5 %. Out of 13 geological and operational parameters we test, only reservoir thickness dramatically changes this, because heat transfer into the reservoir occurs through the contact area between the cold water and confining layers. A thin reservoir (30 m) achieved 87.5 % recharge ten times faster than the 100 m basecase, while for a thick reservoir, this threshold was not observed in the simulated time.

Natural groundwater flow affects recharge by transporting cold water through a reservoir. But when assessing at a reservoir-scale, the horizontal displacement of an energy deficit alone does not qualify as recharge. However, we show that strong background flow (meters per year) continuously exposes cold water to new parts of the confining layers, drawing heat more quickly. Heterogeneity has two opposing effects. On the one hand, lower N/G ratios recharge faster because the cold water fills a larger area. While reservoirs with 80 % N/G behave similarly to homogeneous reservoirs, reservoirs with 40 % N/G recharged up to 18 % faster. On the other hand, internal clay bodies, particularly in the 40 % N/G cases, inhibit background flow and displacement of the cold water. The benefit of strong flow on thermal recharge is therefore less pronounced.

1427 **Declarations**

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1429 **Availability of Data and Materials**

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1432 The datasets used and/or analysed during the current study are available from the
1433 corresponding author on reasonable request.

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1436 **Competing Interests**

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1438 The authors declare that they have no competing interests.

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1447 **Authors' Contributions**

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1449 **C. Wallmeier:** Conceptualization, Methodology, Validation, Writing - Original Draft,
1450 Writing - Review & Editing, Visualization, **P. J. Vardon:** Conceptualization, Writing

1451

1452 - Review & Editing, Supervision, **A. Daniilidis:** Conceptualization, Writing - Review

1453

1454 & Editing, Supervision, Funding acquisition

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