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Comparing Reinjection Strategies in Naturally Fractured Geothermal Reservoirs: A 3D Numerical Modeling Approach

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Doğal Kırıklı Jeotermal Rezervuarlarda Re-enjeksiyon Stratejilerinin 3 Boyutlu Sayısal Modelleme ile Karşılaştırılması

Hakkı AYDIN*

Zorlu Enerji, Jeotermal Kaynak Yönetimi Departmanı, Manisa, Türkiye

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Abstract
The strategic placement of re-injection wells within geothermal reservoirs is a pivotal determinant of sustainable and maximized thermal recovery. Minimizing temperature decline and maintaining effective pressure support over extended timescales are crucial objectives. This investigation comprehensively evaluates the implementation of diverse well injection patterns, including infield injection, dipole injection, and peripheral injection well configurations, within a heterogeneous geothermal reservoir characterized by the presence of faults in western Turkiye. The influence of these geological features and their associated properties on both field-scale performance and individual well productivity is rigorously assessed through a three-dimensional numerical reservoir simulation. By optimizing well configurations for various production-injection strategies, this study provides valuable insights into enhancing geothermal reservoir development in western Turkiye, ultimately maximizing thermal recovery for sustainable energy production.

Keywords: *Geothermal, Re-injection optimization, Numerical reservoir simulation, Fractured reservoir*

Öz
Re-enjeksiyon kuyularının jeotermal rezervuarlara stratejik olarak yerleştirilmesi, sürdürülebilir ve maksimum termal geri kazanımın önemli bir belirleyicisidir. Sıcaklık düşüşünü en aza indirmek ve uzun süreler boyunca etkili basınç desteğini sürdürmek çok önemli hedeflerdir. Bu araştırma, Türkiye'nin batısındaki fayların varlığı ile karakterize edilen heterojen bir jeotermal rezervuar içerisinde saha içi enjeksiyonu, dipol enjeksiyonu ve çevresel enjeksiyon kuyusu konfigürasyonları dahil olmak üzere çeşitli kuyu enjeksiyon modellerinin uygulanmasını kapsamlı bir şekilde değerlendirmektedir. Bu jeolojik özelliklerin ve bunlarla ilişkili özelliklerin hem saha ölçeğindeki performans hem de bireysel kuyu verimliliği üzerindeki etkisi, üç boyutlu sayısal rezervuar simülasyonu aracılığıyla titizlikle değerlendirilir. Bu çalışma, çeşitli üretim-enjeksiyon stratejileri için kuyu konfigürasyonlarını optimize ederek, Türkiye'nin batısındaki jeotermal rezervuar gelişiminin arttırılması ve sonuçta sürdürülebilir enerji üretimi için termal geri kazanımın en üst düzeye çıkarılması konusunda değerli bilgiler sunmaktadır.

Anahtar Kelimeler: *Jeotermal Re-enjeksiyon optimizasyonu; Sayısal modelleme, Kırıklı rezervuar*

1. Introduction

Geothermal reservoirs are complex systems that need sophisticated development strategies to maximize heat recovery over extended production periods. Typically, geothermal wells are strategically positioned along fault lines, providing their naturally high productivity and injection capacity. Wells with high temperatures are predominantly employed for production purposes, while those with low temperatures serve as re-injection wells. The sustainability of geothermal resources hinges upon the re-injection of waste brine, a process crucial for maintaining reservoir mass balance and providing efficient heat extraction. Neglecting this practice can lead to significant pressure decline, ultimately resulting in a steady decrease in production capacity.

Reinjected water flows through conductive pathways within the complex geological system, preferentially flowing from high to low pressure zones. Heat transfer between the injected fluid and the surrounding rock matrix plays a pivotal role in enabling efficient heat recovery from the geothermal system. Therefore, ensuring effective communication between injection and production wells stands as a cornerstone for the sustainable production of geothermal resources. This study investigates re-injection strategies in geothermal fields, with a particular focus on the geological structure of the Alaşehir geothermal field, one of the most active geothermal fields in western Turkey. The Alaşehir field is in the Alaşehir province of Manisa, within the Gediz Graben (Figure 1).

*Sorumlu Yazar/Corresponding Author: Hakkı AYDIN
e-posta/e-mail: hakki.aydin@zorlu.com

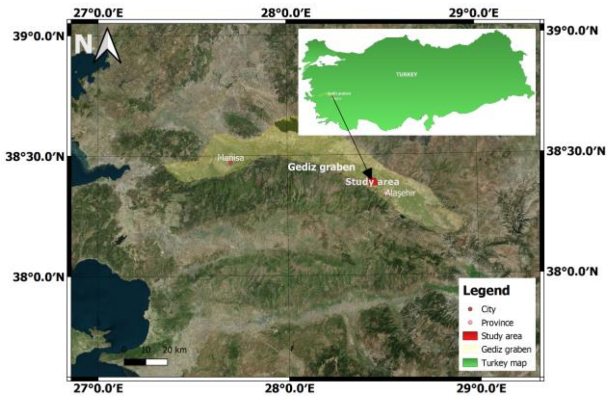

Figure 1. Study area: Alaşehir geothermal field.

The Alaşehir geothermal field is a highly conductive naturally fractured reservoir (Aydin et al. 2018). Such reservoirs exhibit double porosity and permeability characteristics. Tectonic activities and the circulation of meteoric water create fractures and vugs, which significantly enhance fluid flow within the reservoir (Figure 2).

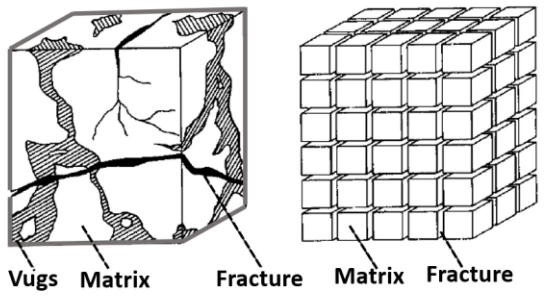

Figure 2. Heterogeneous porous medium (revised from Warren and Root, 1963)

Geologically complex and inherently heterogeneous, naturally fractured reservoirs pose significant challenges to conventional homogeneous modeling techniques, rendering them incapable of accurately capturing the fluid flow behavior within these systems (Bratton et al. 2006). Consequently, dual porosity models and Discrete Fracture Network (DFN) approaches have emerged as the most proper methodologies employed for simulating geothermal reservoirs. DFN modeling necessitates extensive fracture data, including fracture density, permeability, length, and aperture, among other parameters (Aydın 2018). However, acquiring all these data is challenging. Therefore, the double porosity model is more commonly employed to simulate naturally fractured geothermal reservoirs (Wang et al. 2023).

Re-injection optimization aids in maintaining reservoir pressure, preventing subsidence, and enhancing the sustainability of geothermal resources (Doğdu and Çelmen, 2023). Important factors impacting re-injection optimization are well location as well as injection rate. Widely employed reinjection optimization techniques include numerical modeling, machine learning, and real-time monitoring.

Numerical reservoir simulation plays a critical role in mimicking the dynamic behavior of geothermal reservoirs under diverse production-injection scenarios. This valuable tool empowers informed decision-making regarding field development and optimization. As exemplified by Ganefianto et al. (2010), reservoir simulation proved instrumental in optimizing production at the Salak geothermal field in Indonesia. Their study successfully characterized and identified novel injection areas, paving the way for optimal field development. Furthermore, Juliusson and Horne (2013) leveraged discrete fracture reservoir simulation models to optimize injection strategies in fractured geothermal reservoirs. Their investigation, guided by the objective of maximizing net present value (NPV), revealed a pivotal influence of the minimum design temperature for the power plant on the optimal injection schedule. Aydın (2018) applied a Discrete Fracture Network (DFN) model to the Alaşehir geothermal field to understand the connectivity between injection and production wells, observing a strong hydraulic connection. Kucuk et al. (2020) recommended deep reinjection for better pressure support of deep production wells in the Kızıldere field, using a 3D numerical reservoir simulation.

Machine learning (ML) emerges as a potential tool for re-injection optimization in geothermal systems, owing to its robust learning and predictive capabilities. This methodology integrates geological and wellbore data, enabling the generation of surrogate models that effectively address field-specific challenges (Schulte et al. 2020). Furthermore, by leveraging historical data, ML algorithms empower the anticipation of reservoir behavior under diverse injection scenarios, facilitating proactive and data-driven decision-making in re-injection strategies. Uraz and Akin (2003) optimized re-injection in geothermal reservoirs using artificial neural networks based on the dimensionless temperature and pressure drop. Similarly, Akin (2014) focused on the allocation of re-injection wells in West Anatolian geothermal fields, Turkey. Their approach utilized capacitance-resistance models to simulate reservoir behavior under various injection scenarios. This methodology generated hypothetical scenarios to identify the optimal injection scheme that maximized the long-term sustainability of the geothermal resource. Frota et al. (2022) used fuzzy logic to determine optimum injection rates for wells in sandstone reservoir. They found that higher injection rates caused severe injectivity losses.

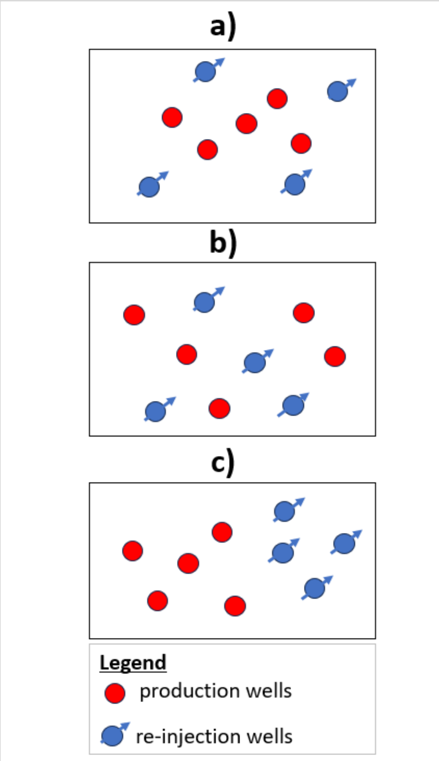

Figure 3. Production-injection scheme: a) peripheral injection b) infield injection c) dipole injection (revised from Mahmoodi, 2017)

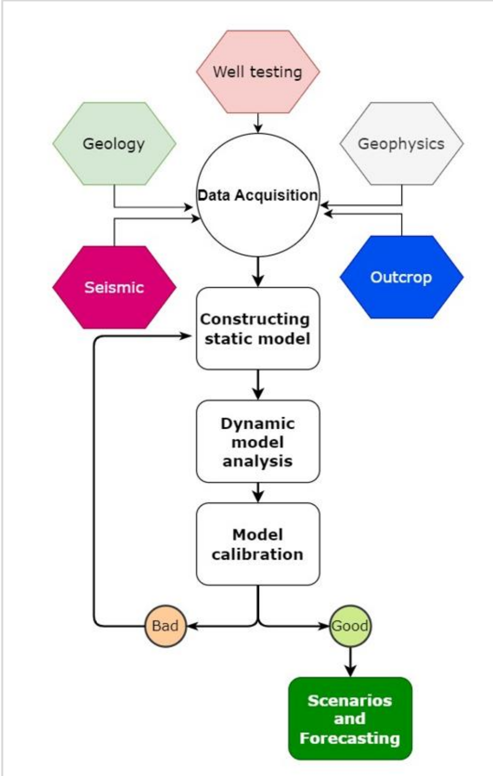

Figure 4. Workflow diagram of numerical reservoir simulation (revised from Aydın, 2018)

The Alaşehir field is characterized by a highly permeable metamorphic reservoir rock, predominantly influenced by normal faulting. Pressure transient tests analyzed by Aydin et al. (2024) indicated that the permeability-thickness product of the geothermal wells ranges between 0.8 and 96.5 Darcy-meters. Geothermal wells are strategically oriented towards highly permeable, naturally fractured zones to secure substantial flow rates. The structural characteristics of the geothermal system play a crucial role in dictating the optimal placement of these wells. Three primary re-injection strategies dominate current industrial practice: infield, dipole, and peripheral injection (Figure 3). The selection of injection and production wells is typically guided by factors such as fault orientation, reservoir permeability distribution, and temperature patterns within the reservoir itself. In high-permeability reservoirs, re-injection wells are typically placed at the periphery at a calculated distance ensuring large reservoir pore volume for heat transfer (Figure 3a). This approach minimizes early temperature breakthroughs while ensuring high thermal recovery from the reservoir with good pressure support. For example, Aydin et al. (2024) demonstrated through moment analysis of tracer tests in the Alaşehir field that wells with a large swept pore volume experienced less temperature decline. Conversely, in low-permeability reservoirs, re-injection wells are kept close to production wells to minimize local pressure drops caused by fluid withdrawal (Figure 3b). In a dipole injection system, production wells target upflow zones, while re-injection wells concentrate in the relatively lower temperature region (Figure 3c).

This study compares the effects of various reinjection strategies in naturally fractured geothermal reservoirs. Three distinct configurations are investigated: infield injection, dipole injection, and peripheral injection. A 3D numerical reservoir model, constructed to represent a specific region of the Alaşehir geothermal field, is employed to assess the combined influence of geological structure and well placement on field production performance under each re-injection scheme. Key performance indicators such as reservoir pressure, temperature, and CO_2 content of produced fluids are monitored to evaluate the effectiveness of each configuration.

2. Materials and Methods

Numerical models play a pivotal role in characterizing and predicting the dynamic behavior of geothermal reservoirs under long-term production-injection scenarios. This valuable tool empowers informed decision-making and sustainable resource management. This approach integrates data from diverse sources such as geological maps, seismic surveys, well testing, and outcrop data.

Using these data, a conceptual model is first constructed. This initial model serves as a basis for the subsequent dynamic model calibration phase. After that, production forecasts can be generated with the calibrated model (Figure 4).

A multitude of reservoir simulators exist for the numerical simulation of geothermal reservoirs. Karahanoglu (2019) provides a comprehensive list of reservoir simulation programs. These simulators solve coupled mass and energy transport equations, typically using the finite difference method (Chen et al. 2022). Among these, TOUGH2 is the most widely used for the numerical simulation of geothermal systems (Karahanoglu 2019). It numerically solves energy, mass, and momentum conservation equations under different conditions. Given that reservoir simulation solutions depend on both time and space, discretization techniques are essential. The main methods for discretization are the Finite Difference Method, Finite Element Method, and Finite Volume Method (Yuan et al. 2022). Space discretization involves dividing the reservoir into smaller sub-volumes or "grid blocks." TOUGH2 supports various grid shapes, including structured regular grids, structured irregular grids, and unstructured irregular grids (Pruess and Spycher, 2007). Smaller grid sizes yield more accurate and sensitive results, but they also increase the computational time required for numerical solutions (Wang et al. 2020, Bostanci et al. 2020). Once space discretization is complete, the grid blocks are prepared for numerical simulation. During numerical simulation, the total simulation time is divided into smaller time steps, which significantly reduces errors. In TOUGH2, numerical simulation is conducted using the solution of the linear equation system and the Jacobian matrix (An et al. 2021). There are two options for linear equation solvers: direct and iterative solutions. The iterative solver is preferable for simulating large reservoirs, as it requires less computational power and time. TOUGH2 primarily uses the concept of an equivalent porous medium. In fractured reservoirs, fracture properties are considered by assigning equivalent values to the grid blocks where fractures are present, thus treating the system as a matrix-porous system. Additionally, TOUGH2 can simulate a double porosity system using multiple interacting continua (MINC) methods (Pruess and Narasimhan 1985).

3. Numerical Model of the Studied Area

Reservoir modeling begins with the collection of data to construct a conceptual model. Following this, the gridding process is performed, and reservoir boundaries and sources are defined. Wells are specified, and their production intervals are identified based on well test and drilling data. The model is then run until steady-state temperature and pressure values are achieved throughout the reservoir. During the initial steady-state model calibration, key tuning parameters include heat flux, heat source area, enthalpy, non-condensable gas (NCG) content, permeability, and volume factor. Once a good match is obtained between the simulated and actual static temperature and pressure profiles, the initial steady-state model is considered calibrated. The dynamic model calibration involves matching the production and injection history of wells under dynamic conditions until a good correlation is achieved between simulated and actual values of pressure, temperature, and NCG production. During this stage, reservoir volume and permeability factors are the primary tuning parameters. Once the dynamic model calibration is complete, the next step is to evaluate reservoir behavior under different production scenarios.

3.1 Conceptual Model of Alaşehir Field

The Alaşehir geothermal field is one of the most actively producing fields in Turkiye. The stratigraphic units of the field are depicted in Figure 5. Paleozoic metamorphic rocks constitute the basement and the reservoir rock for geothermal wells. Tertiary fillings overlay the basement. Notably, high-angle normal faults identified at the surface play a dominant role in directing fluid flow within the reservoir, as illustrated in (Figure 6).

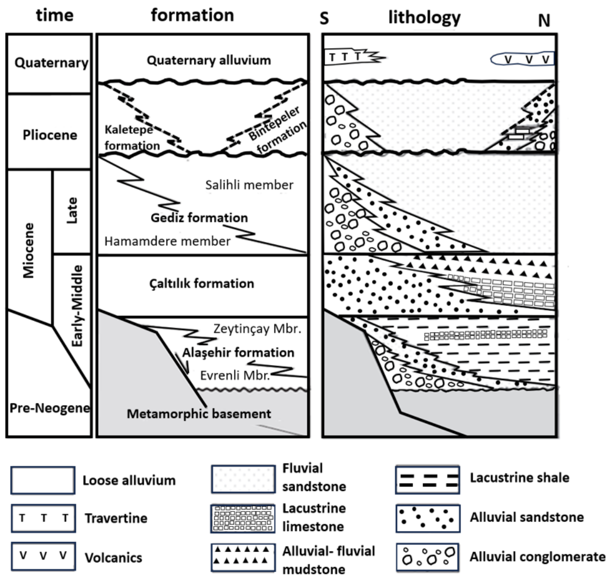

Figure 5. Stratigraphic Units of Alaşehir Geothermal Field (Çiftçi and Bozkurt 2009).

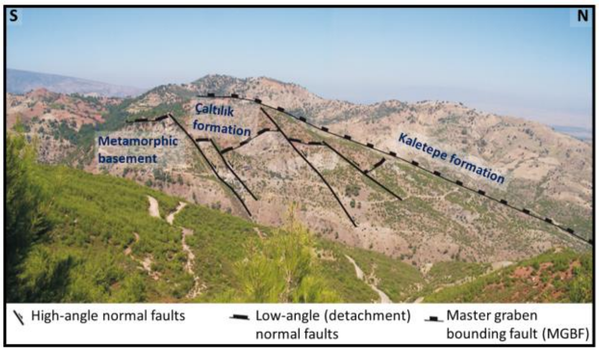

Figure 6. Fault Outcrops in Southern Gediz Graben (Revised from Ciftci 2007).

Ciftci & Bozkurt (2009) delineate the Alaşehir geothermal field's conceptual model (Figure 7). This model assumes a meteoric origin for the geothermal fluid, facilitated by conductive faults acting as conduits between the surface and subsurface. Meteoric and spring water migrate through these faults, accessing the reservoir rock. The acidic nature of this water promotes the dissolution of calcite minerals within the Paleozoic marble, potentially generating vugs along fractures. Notably, the Alaşehir field's Paleozoic metamorphic basement comprises marble, quartzite, mica schist, and calc-schist. The 3D static model of the field was constructed by (Aydin and Akin, 2021) as shown in Figure 8. This study uses a particular region of this model for delineating injection strategies.

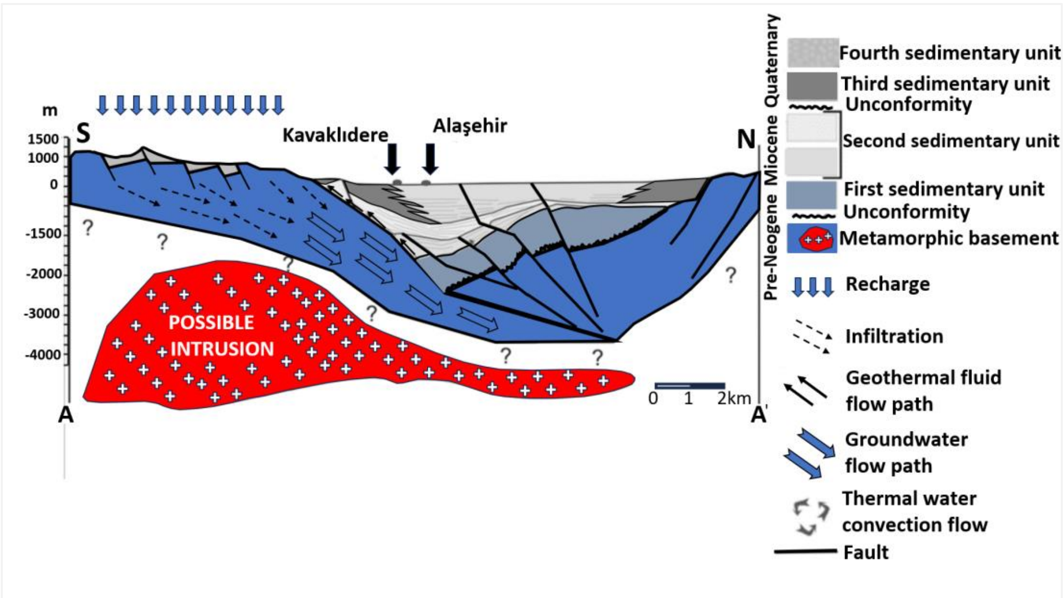

Figure 7. Conceptual Model of Alaşehir Geothermal Field (Çiftçi and Bozkurt 2009).

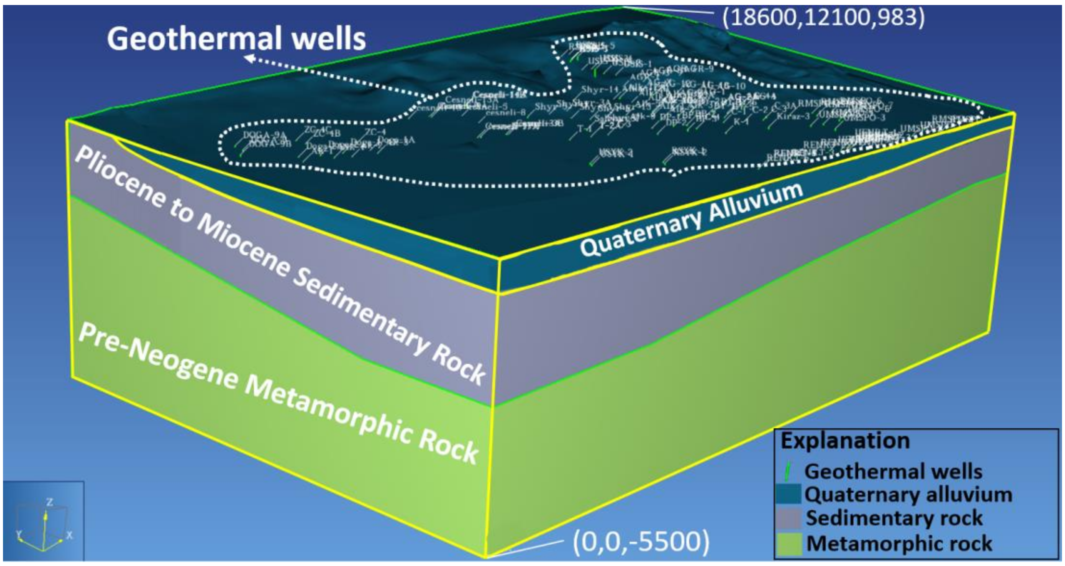

Figure 8. Conceptual model by using TOUGH2 (Revised from Aydin and Akin 2021).

3.2 Dynamic Model of the Selected Region in Alaşehir

Achieving a realistic representation of subsurface behavior using numerical models is essential, and dynamic model calibration is an iterative process that facilitates this by adjusting parameters to match observed field data. Calibration involves matching field temperature distribution and the evolution of reservoir pressure over production time. Accurately calibrated models can then forecast production under different development scenarios, such as varying well placement or pumping strategies. However, inherent heterogeneity in complex geothermal systems makes it challenging to have completely reliable models, and manual calibration and history matches remain typical methods in industry practice.

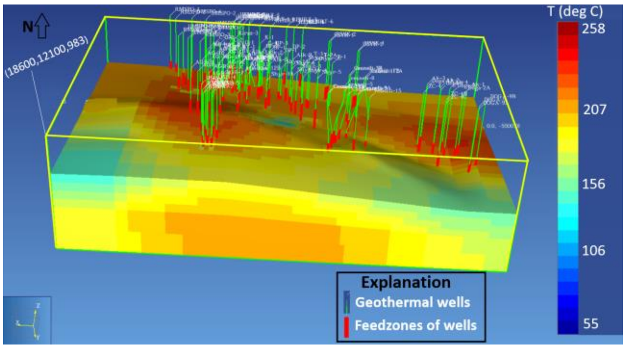

Figure 9. Temperature Distribution of the Model (revised from Aydin and Akin 2021).

For the Alaşehir geothermal field, dynamic model calibration employed changes in production parameters, including temperature, pressure, and non-condensable gas production, tracked over time (Aydin and Akin, 2021). Simulated temperature distribution in the field showed two up flow regions, consistent with field measurements (Figure 9). This study employs a numerical model encompassing an area of 35.6 km²with a vertical extent of 5.5 km. The model represents a reservoir temperature of 258°C at its base. Grid discretization utilizes 6720 blocks with variable sizes, ranging from 200x300 m rectangles near the wellbore to 1000x1050 m blocks at the model boundaries (Figure 10). To simulate impermeable boundaries, extremely low permeability values were assigned to the model's periphery. Based on field pressure transient test data, reservoir permeability was set to 300 mD in the horizontal (x-y) direction and 1 mD in the vertical direction. Metamorphic rock porosity was assumed to be 1%. Permeability and porosity within fault zones were increased using multiplication factors applied to fault-intersecting grid blocks. Normal faults are dominating the structure and geothermal activity of the Alaşehir geothermal reservoir. To represent the field's heterogeneity, the model incorporates NW-SE trending high angle normal faults (Rojay et al. 2019), which were further investigated through simulations with different well configurations.

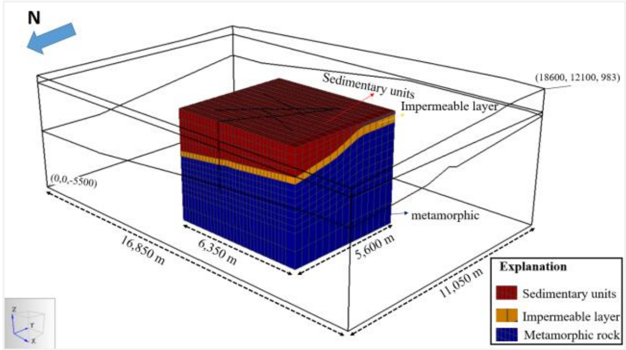

Figure 10. Studied region of the Alaşehir field.

3.3 Injection Strategies

A sector model developed within the numerical simulation of the Alaşehir field delineates diverse injection strategies, including peripheral injection (Figure 11), infield injection (Figure 12), and dipole injection (Figure 13), in the context of intersecting faults (both normal and transform). Production and injection rates are strategically modulated based on well location: wells situated within fault zones are designated for higher rates, whereas wells encountering zones of reduced permeability are assigned lower rates (Table 1, Table 2, and Table 3).

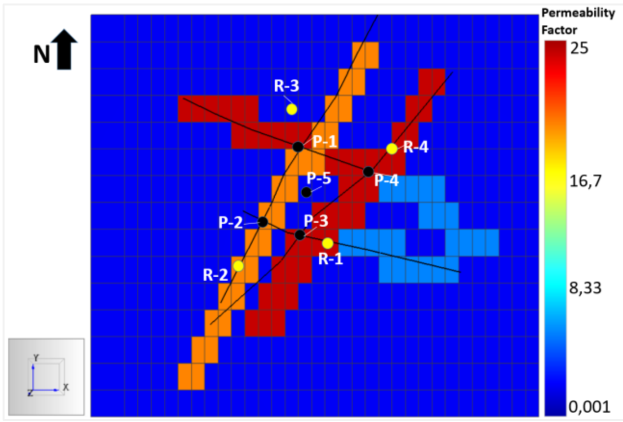

Figure 11. Peripheral injection scheme (yellow represents reinjection wells, black represents production wells).

Within various injection scenarios, well placement strategized the co-location of injection and production wells along identified fault lines. This strategy adhered to established industrial practice, maintaining a minimum well spacing of 500 meters. Wells positioned near faults were designated for higher production capacity, with an anticipated output of 250 tons per hour (Table 1). Conversely, wells situated outside of the fault zone were assigned a projected output of 100 tons per hour. The implementation of re-injection wells mirrored the placement methodology employed for production wells. Across various injection scenarios, our modeling assumed a re-injection ratio of 72%).

Table 1. Rates of geothermal wells in peripheral scenario

Well ID	Well type	Rate (ton/hour)
P-1	Production	250
P-2	Production	250
P-3	Production	250
P-4	Production	250
P-5	Production	100
R-1	Re-injection	250
R-2	Re-injection	250
R-3	Re-injection	150
R-4	Re-injection	150

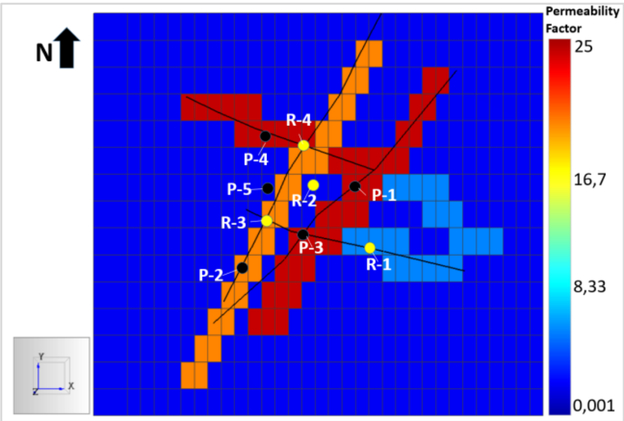

Figure 12. Infield injection scheme (yellow represents reinjection wells, black represents production wells).

Table 2. Rates of geothermal wells in infield scenario

Well ID	Well type	Rate (ton/hour)
P-1	Production	250
P-2	Production	250
P-3	Production	250
P-4	Production	250
P-5	Production	100
R-1	Re-injection	225
R-2	Re-injection	125
R-3	Re-injection	125
R-4	Re-injection	225

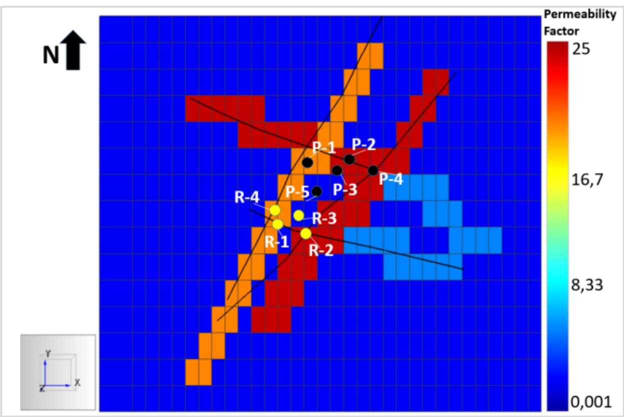

Figure 13. Dipole injection scheme (yellow represents re-injection wells, black represents production wells).

Table 3. Rates of geothermal wells in dipole scenario

Well ID	Well type	Rate (ton/hour)
P-1	Production	100
P-2	Production	250
P-3	Production	250
P-4	Production	250
P-5	Production	250
R-1	Re-injection	225
R-2	Re-injection	225
R-3	Re-injection	125
R-4	Re-injection	225

4. Results and Discussions

Numerical reservoir simulations revealed the criticality of strategic well placement within naturally fractured geothermal systems. This placement strategy aims to achieve concurrent objectives: maintaining high pressure support and minimizing temperature decline. However, due to the inherent site-specific nature of this optimization problem, directly applying the same methodology across diverse geothermal fields presents significant challenges. Therefore, these applications offer valuable insights, enabling the formulation of generic models rather than principles applicable to broader contexts.

The influence of field heterogeneity on key production parameters: Pressure, temperature, and non-condensable gas (NCG) content are critical factors influencing the sustainability of geothermal production. Numerical simulations highlight the significant impact of reservoir heterogeneity on the decline of these parameters.

Although infield injection enhances energy extraction by providing additional recharge as noted in Gunung Salak field (Libert 2017), Los Humeros field (Arellano et al. 2015a, Iglesias et al. 2015), and Bacman field (Espartinez 2015), and helps to minimize the rate of pressure decline (Olkaria field, Ouma et al. 2016), numerous studies have reported early temperature decline as a consequence Hellisheidi field (Kristjánsson et al. 2016), Gunung Salak field (Libert 2017), Uenotai field (Diaz et al. 2016). As illustrated in Figure 14, infield injection demonstrates the highest efficacy in maintaining reservoir pressure due to enhanced well connectivity and a minimized time lag between injection and production wells. However, Figures 15 and 16 indicate a potential risk of temperature and NCG decline associated with this scenario. Consequently, implementing infield injection within highly permeable metamorphic rocks found in western Turkey is not recommended.

Dipole injection is commonly employed in western Turkey, involves designating the high-temperature region for production and the low-temperature region for re-injection. While offering better temperature and NCG retention compared to infield injection, the extended distance between wells and the resulting time lag led to a local pressure drop, rendering it the least effective approach in terms of pressure support.

Based on the presented findings, peripheral re-injection emerges as the optimal approach for geothermal wells located in western Turkey. This strategy effectively balances pressure maintenance with minimized temperature and NCG decline. In the peripheral injection, the introduction of cold, gas-free brine facilitates mixing with reservoir fluids and interaction across a larger fracture pore volume. As aforementioned in the introduction section, Aydin et al. (2024) showed that geothermal wells with a higher swept pore volume in Alaşehir field, experienced less temperature decline. Kamila et al. (2020) reported a similar result, indicating that peripheral re-injection can be selected to maintain a sufficient distance between production and reinjection wells. Some fields have peripheral reinjection to avoid cooling (e.g. Lahendong field (Prabowo et al. 2015), Wayang Windu field (Diaz et al. 2016), Mokai field (Bromley et al., 2015), Rotokawa field (Hernandez et al. 2015). This configuration promotes enhanced heat transfer while mitigating NCG decline.

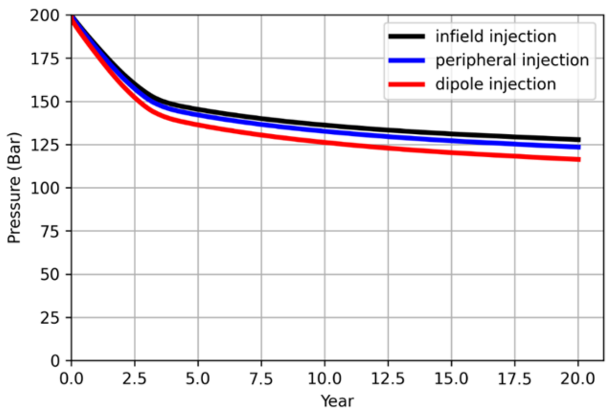

Figure 14. Average reservoir pressure changes in the studied injection scenarios.

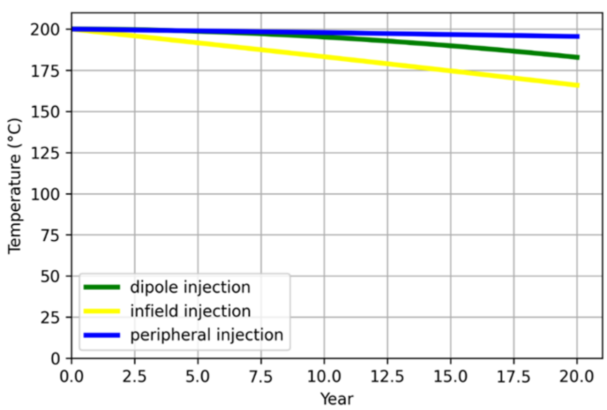

Figure 15. Average temperature changes in the studied injection scenarios.

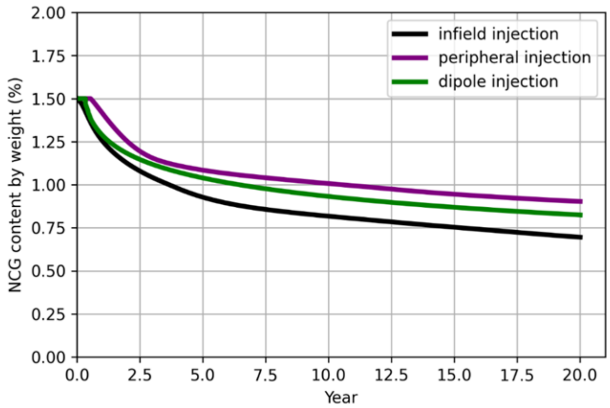

Figure 16. Average NCG changes in the studied injection scenarios.

The limitations of this study necessitate acknowledging the exclusion of vertical compartmentalization. Consequently, the presented findings are solely applicable to reservoir systems lacking impermeable barriers between production levels. The presence of such barriers would inevitably alter the performance of various re-injection scenarios, rendering the current results inapplicable to those scenarios.

To establish a comprehensive comparison with existing literature, a review of reports detailing to geothermal fields located in western Turkey was conducted. Hamendi (2009) simulated injection scenarios in Germencik geothermal field. The study showed that high permeability and connectivity of the geothermal wells caused a rapid pressure response to production and injection. Therefore, it is critical to optimize injection to not have sharp temperature decline. Notably, Aydin and Akin (2021) reported favorable reservoir pressure support at the Alaşehir geothermal field, with pressure changes ranging from 1 to 3 bar per year. However, they also identified high temperature and NCG decline as a significant challenge associated with the dipole injection scenario in this specific field. Building upon existing research, Senturk et al. (2020) reported the presence of impermeable layers within the Kızıldere geothermal field, functioning as barriers between distinct production zones. This finding necessitated the implementation of an injection rehabilitation program, transitioning the re-injection strategy from dipole and shallow injection to semi-peripheral and deep injection. This shift aimed to enhance the sustainability of production within the deeper reservoir section. Furthermore, Bayraktar et al. (2023) investigated the vertical connectivity between injection and production wells within the Kızıldere field. Their research underscored the significant influence of impermeable layer permeability on the behavior of crucial production parameters, including pressure and temperature.

5. Conclusion

This research investigated optimal re-injection strategies for highly conductive geothermal reservoirs in western Anatolia, Turkey. A 3D numerical reservoir simulator was employed to replicate the Alaşehir field and evaluate the efficacy of various injection scenarios, including infield, peripheral, and dipole injection. The study underscores the critical role of optimized re-injection strategies in managing geothermal reservoirs exhibiting high permeability-thickness products (ranging from 0.8 to 96.5 Darcy-meters) and significant heterogeneity. The key findings suggest that:

- Peripheral injection schemes deliver superior outcomes in highly conductive reservoirs, particularly when production and injection occur at the same reservoir level.
- The current model does not account for vertical compartmentalization within the reservoir, assuming no impermeable barriers exist between injection and production wells. Future studies should incorporate this aspect for a more comprehensive understanding.
- The optimal injection scenario achieved efficient pressure maintenance while minimizing temperature and non-condensable gas (NCG) decline. This success is attributed to the enhanced sweep efficiency within the reservoir.
- Geothermal wells targeting faults, which were modeled to exhibit high production rates, are consistent with field reports documented in the literature. However, these wells experienced an early temperature decline and a sharp reduction in non-condensable gas (NCG) levels due to high conductivity. Consequently, make-up wells may be required earlier than anticipated due to the decline in steam and gas production.
- The E-W and S-N trending normal faults in the Alaşehir field are highly conductive, offering significant pressure support but leading to premature temperature decline. Consequently, peripheral reinjection may be the optimal strategy to mitigate this temperature decline.
- The results align well with existing studies and reports on geothermal fields in western Anatolia, providing further validation for the implemented approach.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, methodology and software, visualization and writing, supervision, review and editing – original draft.

Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The authors declare that the main data supporting the findings of this work are available within the article.

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