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Reinjection Optimization of Kızıldere Geothermal Field for Sustainable Reservoir Pressure Management

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ABSTRACT

Pressure decline with respect to time is one of the main concerns in geothermal field management. In order to maintain the reservoir pressure, a sustainable reinjection strategy is needed. In this study, a numerical model of Kızıldere Geothermal Field is constructed, which is then used to assess the current shallow reinjection/deep production strategy. According to the output of the numerical simulation, a new reinjection strategy is proposed. It has shown that more sustainable and reliable reinjection strategy can be applied by diverting the reinjection water from the shallow wells to the existing deep wells.

1. INTRODUCTION

Geothermal energy is always attributed as a reliable source of clean energy. Among other renewable energy sources, it provides more continuous base load power, meaning that it produces energy with lesser intermittency. But, maintaining the reservoir pressures while producing the geothermal fluid can be an issue in geothermal fields. As the primary solution, a good reinjection strategy can help to mitigate the reservoir pressure declines.

Kızıldere Geothermal Field is one of the largest geothermal power sources of the world with a total installed capacity of 260 MW as of June 2019. Currently, more than 80 production and injection wells are operational that are used to feed the geothermal power plants in the field and to reinject the geothermal fluid into the reservoir after its heat is harvested. Currently, the field is experiencing reservoir pressure decline as observed in several observation wells. In order to assess and to optimize the current reinjection strategy, a three-dimensional, non-isothermal, multiphase and multicomponent numerical model of the field is constructed. The areal extent of the numerical model covers all existing and prospective operation areas. Additionally, the model includes the effects of non-condensable gases, especially the carbon dioxide, since the geothermal fluid of Kızıldere reservoir contains high CO_2 content. As an average, geothermal fluid from the shallower reservoir section has 1.5wt% of dissolved CO_2, and that value increases to 3wt% at deeper metamorphic section (Haizlip et al., 2012).

1.1. Kızıldere Geothermal Field

Kızıldere geothermal field is the first geothermal energy field of Turkey. It was discovered by Directorate of Mineral Research & Exploration (MTA) after a broad range of geological, geophysical, hydrogeological, and geochemical studies. After the initial evaluations, the first commercial scale geothermal power plant of Turkey was constructed in Kızıldere by government's electricity authority Electricity Generation Co. Inc. (EÜAŞ) in 1984, with a capacity of 17.8 MW. After being operated for 24 years by Turkish Electricity Generation Co. Inc. (EÜAŞ), Kızıldere Geothermal Field had undergone privatization in September 1, 2008. Zorlu Energy had acquired the operational rights of the license area (64.375 km²) including the power plant, for 30 years (Şimşek et al., 2009).

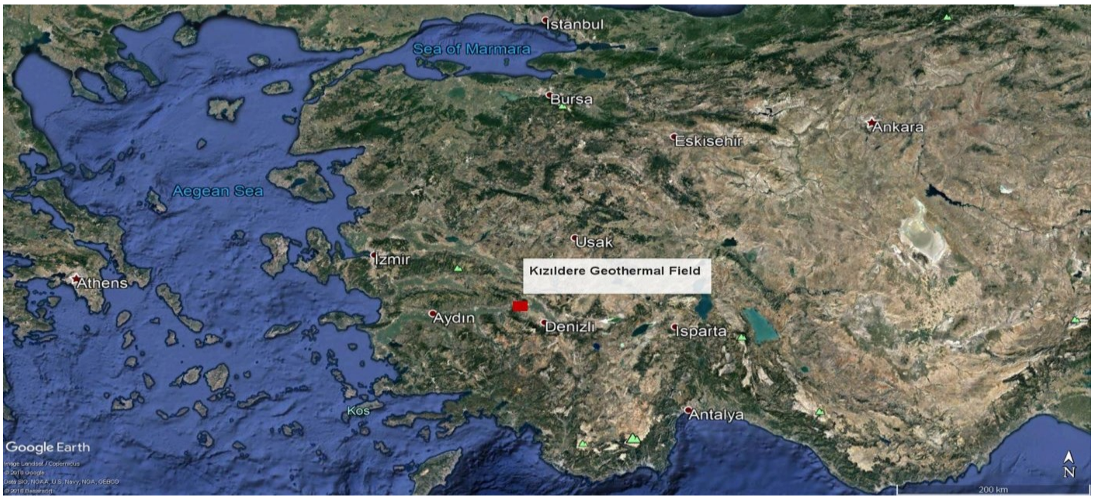

Figure 1. Location of Kızıldere Geothermal Field

1.1.1. Geographical Setting

Kızıldere geothermal field is located between Denizli and Aydın provinces, at the eastern part of the Büyük Menderes Graben, between the Buldan and Babadağ Horsts. The field is at the southern part of the Menderes Massifs, which is one of the largest (300x200 km) metamorphic massifs in Turkey (Bozkurt & Oberhänsli, 2001). The meandering Büyük Menderes River is in the vicinity of the Kızıldere Geothermal Field.

1.1.2. Geology

Kızıldere Geothermal Field is in the eastern part of the Büyük Menderes Graben. Paleozoic metamorphics of Menderes Massifs and Pliocene and Quaternary sedimentary rocks form the general stratigraphy of the field (Şimşek et al., 2009). Menderes metamorphics form the basement rocks, which mainly consist of augen gneisses, schists, quartzite, micaschists and marbles (Karamanderesi, 2013). The upper Pliocene and Quaternary sedimentary rocks have been divided into four lithological units (Şimşek, 1985a). These units, from bottom to top, are Kızılburun Formation, Sazak Formation, Kolankaya Formation, and Tosunlar Formation. The Kızılburun Formation consists of well-consolidated 200 m thick red-brownish conglomerates, sandstones, and claystones. It behaves as a caprock due to its impermeability and forms the boundary between the Paleozoic metamorphics and Pliocene sediments. Sazak Formation is the shallow reservoir section of the field and mainly consist of 100 - 250 m thick limestones, but gradations into marls and sandstones were observed, laterally and vertically, which makes a restriction for a continuous reservoir aspect. Most of the first wells of the Kızıldere Field produced from the Pliocene limestones of the Sazak Formation. The 350 – 500 m thick intercalated yellowish green marls, siltstones, and sandstones which overlie the Sazak Formation is named as Kolankaya Formation. This impermeable formation forms the cap rock of the shallow reservoir section. The Tosunlar Formation forms the upper unit of the Pliocene and Quaternary sedimentary rocks. It consists of poorly consolidated conglomerates, mudstones, and sandstones and have a thickness of about 500 m (Şimşek et al., 2009).

The interbedded marble-quartzite-schist section of the upper unit of the Menderes metamorphics are called İğdecik Formation, and forms the intermediate level reservoir of the Kızıldere geothermal field, with a varying thickness of 100 m to 300 m. This formation is reached for the first time in 1969 and temperature values as high as 212°C were observed (Şimşek, 1985b) . İğdecik Formation has better reservoir characteristics compared to the Sazak Formation. Secondary porosity and permeability values are higher than that of the Sazak Formation. A deeper, third reservoir section, which mainly consists of metamorphic schist and marble, was discovered in 1998, with a drilling depth of 2261 m. The general stratigraphy of the Kızıldere Geothermal Field is shown below (Şimşek et al., 2009).

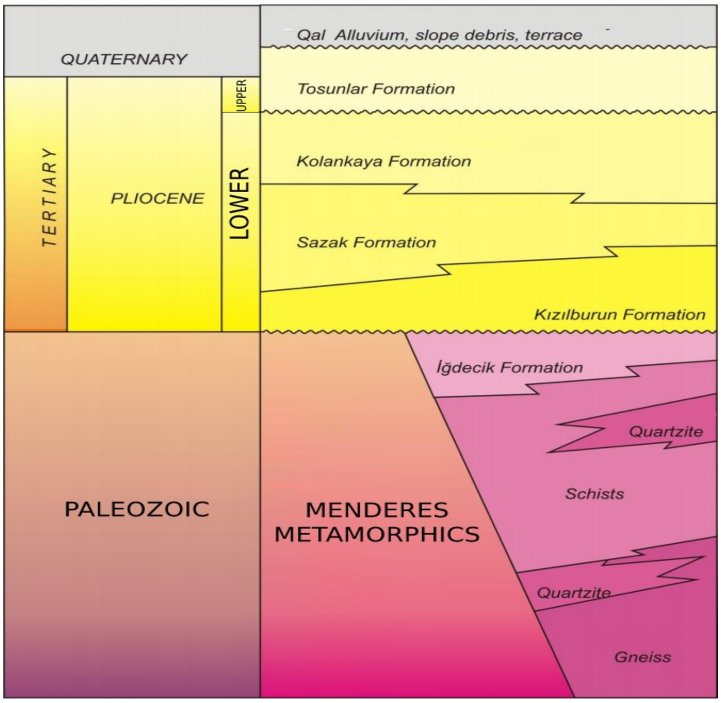

Figure 2. General Stratigraphy of the Kızıldere Geothermal Field (Şimşek et al., 2009)

1.2. Previous Modeling Studies of Kızıldere Geothermal Field

Many modeling studies of the Kızıldere Geothermal Field can be found in the literature. Özkaya (2007) used SUTRA (Saturated-Unsaturated TRAnsport) numerical simulator, which uses a hybrid finite element method and integrated finite difference method with two-dimensional (2D) quadrilateral finite elements for the discretization of the continuous space. Due to the fact that there were only 8 production wells when the model was constructed, the areal extent of the model was limited compared to the current operational area. Since the model was two-dimensional, producing zone was fixed to a level equal to a representative depth of İğdecik Formation. Therefore, two deep wells of that time were considered as shallow wells with high productions by modifying their actual pressures with the subtraction of the hydrostatic pressures below the İğdecik Formation. Additionally, both pressure and temperature responses of the reservoir was modeled separately throughout the modeling studies.

Similarly, the areal extent of the Kızıldere model developed by Yeltekin (2001) was only limited with Phase-I wells, and the area was divided into only 480 grid blocks (8x12x5). Production history of the field for the period of 1984 – 2000 with 8 production wells was used for history matching. A three-phase multi-component thermal and steam additive simulator, STARS (Computer Modeling Group) was used throughout the study. Although, the software is capable of handling non-isothermal flow, in most cases the reservoir was assumed as isothermal because of the numerical instabilities occurred during the simulations. The reservoir temperature was taken as 200 °C throughout the study. The main explanation for assuming an isothermal reservoir was that the temperature decline was small enough within the production period (i.e. 1984 to 2000). The most important deficiency of both of the above-mentioned studies is that effects of CO_2 on production and pressure behavior was not considered.

A recently published numerical model of the Kızıldere Geothermal Field (Garg et al., 2015), modeled a larger area while using the available production and injection data for the period between January 1984 and March 2013, including both the Phase-I and Phase-II wells. STAR geothermal reservoir simulator (Leidos) was used to construct a 3D numerical model of the field. In their study, CO_2 (3%) and NaCl (0.5%) were included in the simulation. The computed pressure and temperature data were compared with the available observation data at several computational times. It was decided to use the computed natural state at 100,000 years for history matching. However, it can be observed in the pressure vs. time plots that the simulation pressures were still increasing at the beginning of the history matching, indicating that the natural state conditions had not been reached, yet. So, it can be deduced that although good matches were obtained, 100,000 years were not enough for the model to reach the stabilized conditions (natural state conditions). Or, another possible explanation for this situation can be related with the amount of the water flux entering to the model from the heat source located at the bottom of the model. High amount of water flux into a limited area model might be increasing the pressures even at the natural state conditions.

2. MODELING OF KIZILDERE GEOTHERMAL FIELD

2.1. Conceptual Model

The first step of a geothermal field modeling is to construct the conceptual model of the study area. For Kızıldere Geothermal Field and Büyük Menders Graben, many geological, hydrogeological, geochemical, and geophysical studies can be found in the literature (Bozkurt & Oberhänsli, 2001; Gokgoz, 1998; Karamanderesi, 2013; Özgüler et al., 1983; Serpen & Uğur, 1998; Şimşek, 1985a, 1985b; Şimşek et al., 2009).

The conceptual model of the Kızıldere Geothermal Field (Şimşek et al., 2009) shows the main features of the geothermal system (Figure 3). The model states that rain water is collected at the highs of the Buldan and Babadağ Horsts, then recharged into the deeper sections of the field through the flow conduits provided by faults and fractures. Since the temperature is high at these depths, water is heated up and rises toward upper sections due to buoyancy through these faults and fractures, until its flow is restricted by an impermeable section – cap rock. A conceptual heat source is placed below the bottom of the reservoir, which provides the heat into the geothermal system.

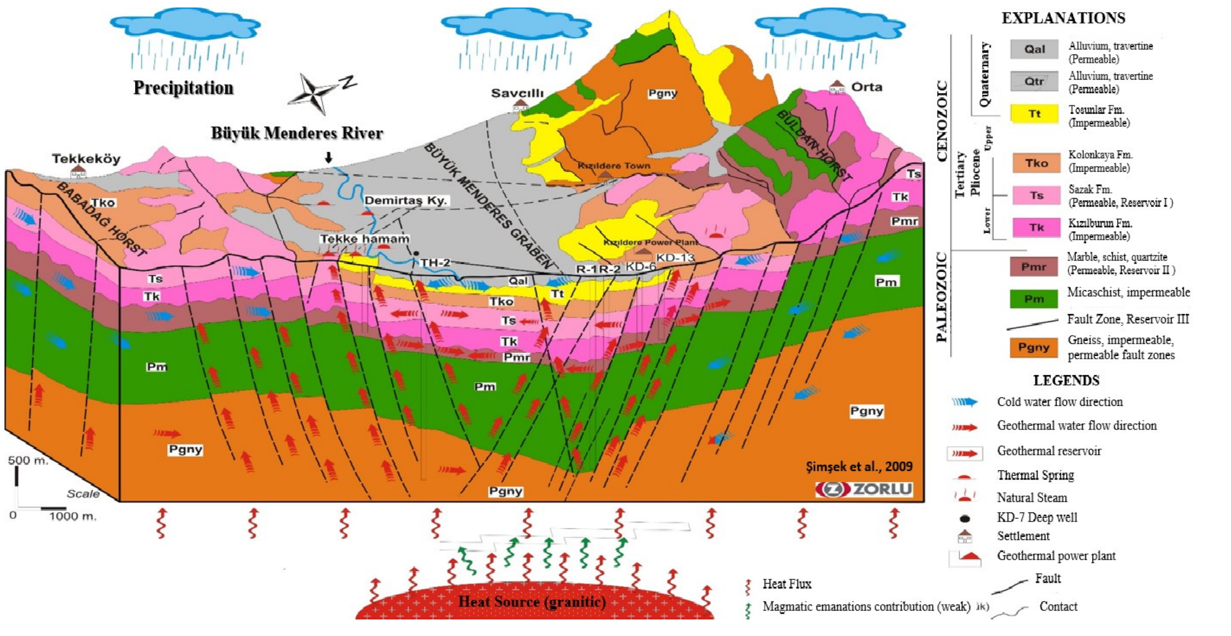

Figure 3. Conceptual Model of the Kızıldere Geothermal Field (Şimşek et al., 2009)

2.2. Numerical Simulation Codes and The Interface

In the numerical simulation of Kızıldere Geothermal Field, TOUGH2 version 2.0 code has been used. The TOUGH family codes allow the numerical simulation of non-isothermal flows of multiphase, multi-component fluids in one, two, and three dimensional porous and fractured media (Pruess, 1991; Pruess et al., 1999). The acronym TOUGH stands for "Transport Of Unsaturated Groundwater and Heat". There are many fluid property modules contained in the TOUGH2 codes. They are represented as different equation-of-state (EOS) modules and extensions. For the numerical simulation of Kızıldere Geothermal Field, EOS2 module of TOUGH2 (which is developed for water-CO_2 mixtures) is used, since the field contains significant amount of CO_2, which has considerable effects on the reservoir performance.

Petrasim is used as the graphical interface to TOUGH2 numerical simulator. It is a helpful tool for preparing the input data and visualizing the output data of simulations. The software enables to select the appropriate EOS module and solver properties. Creating meshes, defining different material properties, setting up initial and boundary conditions, and adjusting output options are made simpler by Petrasim.

2.3. Geological Model

The geological setting is described in section 1.1.2. Seismic showed that metamorphics (second and third reservoir sections) are getting shallower in the western and north-western sections of the field. Gathering all the information from geophysical surveys and correlating them with the data obtained from drilled wells, a basic representation of the formation distribution of the Kızıldere geothermal field has been constructed in the Petrasim interface.

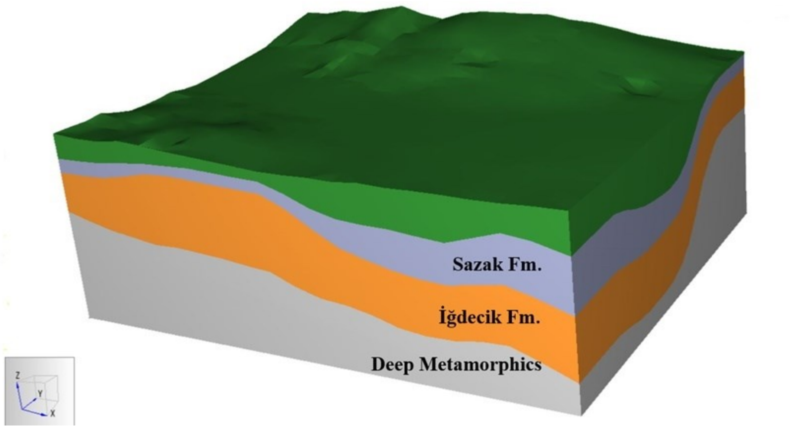

Figure 4. Formation Distribution of Kızıldere Geothermal Field

Note that below the surface rocks (green), only the reservoir formations are displayed on the model (Sazak, İğdecik, and deep metamorphics, from top to bottom, respectively), and cap rocks are incorporated into the corresponding reservoir formation. The cap rock features of the Kolankaya Formation (above the Sazak Formation), the Kızılburun Formation (above the İğdecik Formation), and impermeable Paleozoic rocks (above the deep metamorphic rocks) are controlled by using the "permeability factor" option of the simulator, and adjusted locally according to data obtained from the wells.

Faults, fractures, and rock fissures provide the necessary conduits for the flow of the geothermal fluid. Fluid is heated up at the deeper parts of the field, and rises towards upper sections through these conduits, as a result of buoyancy. The fluid circulation is dominated by NE-SW trending faults, especially the strike-slip Gebeler Fault. There are also some E-W trending normal faults, correlated with the drilled wells. Depth, direction, angle, and hydraulic properties (permeability) of these faults have been reevaluated and tested during the calibration-validation studies (history matching) of the model. It should be noted that the faults, fractures, and fissures have not been represented as discrete, individual formations in the simulation. So, properties of these formations should be approximated until a verified fluid circulation network is obtained (matching static and dynamic pressure, temperature, and production/injection histories of wells, with an acceptable accuracy). Figure 5 shows the distribution of the main faults and formation borders. Note that, some formations are also divided within themselves in order to better represent the heterogeneities and cap rock during the calibration of the model.

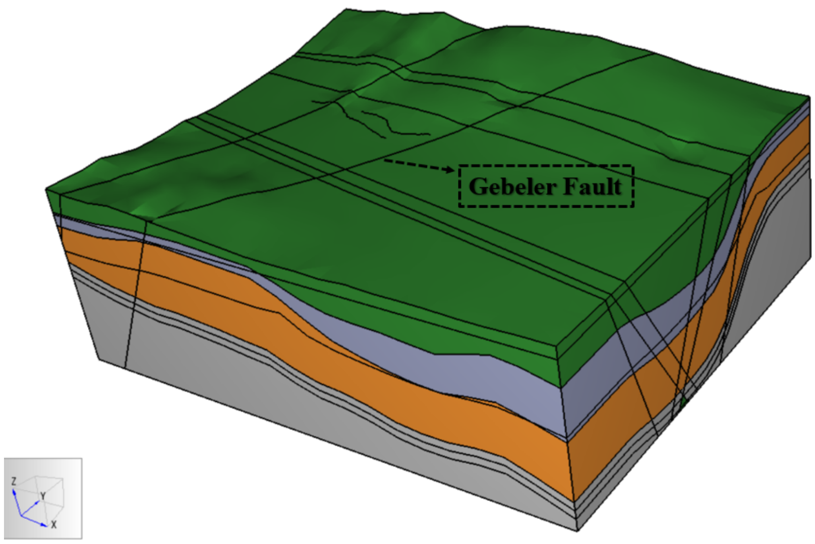

Figure 5. Faults and Formation Borders

2.4. Model Dimensions

The areal extent of the model is 15.9 km in E-W direction, and 12.9 km in N-S direction, approximately 200 km^2. The highest point on the surface is 1,114 meters above the sea level, and the total depth is taken to be 5,000 meters below the sea level. The coverage of the model is much bigger than the areal extent of the drilled wells, since there are other geothermal power plants run by some other energy companies in the vicinity of the Zorlu Energy's license area, and it is intended to include their possible effects into the Kızıldere model. Having a bigger model area than the drilling area also enables to predict the consequences of potential future operations on the undrilled regions of the field. Additionally, setting the boundaries of the model away from the study area is a good choice for the sake of the success of the simulation results, which would otherwise be required to deal with the complicated effects of the outer boundaries.

2.5. Gridding

The Kızıldere model was divided into approximately 24,000 simple, three-dimensional rectangular grids, with varying sizes. The outer boundary grids were kept relatively larger compared to inner sections, since these cells are actually away from the main study area. Yet another reason for using larger blocks near the borders is that it was desired to minimize the interactions between outer boundary cells and the cells in the main study area. Conversely, the grid sizes were kept as small as possible in the main study area (around the wells and faults), in order to better represent pressure and temperature variations and also to make necessary changes more elaborately according to the results of the simulation throughout the study. The following table shows the dimensions and distributions of the grid blocks in x-y directions (x is in the E-W direction; y is in the N-S direction).

Table 1. Grid size distribution along the model area

X, East to West		Y, North to South	
Number of Grids	Grid Size, m	Number of Grids	Grid Size, m
2	750	2	970
30	354.7	30	265
2	750	1	1000
1	2250	1	2000
Total: 15890m		Total: 12890m	

In the z-direction, the model was divided into two major layers: The first layer covers the area between surface and -100 meters (according to the sea level), and the second layer extents from -100 meters to the bottom of the model (-5,000 meters). The reason behind this is to set an upper reference depth below the sea level, and avoid from dealing with above or below the sea level depth related complications. The lower major layer was further divided into 18 sublayers, of which the first 16 layers (to the depth of -3000 meters) are relatively thinner and the bottom 2 layers are relatively thicker. Since most of the production wells reach out to the depth of -3000 meters, this section (-100 meters to -3000 meters) has been further divided into layers to realistically represent pressure variation as a function of depth. The figure given below shows Kızıldere geothermal field after the implementation of above-mentioned grid system.

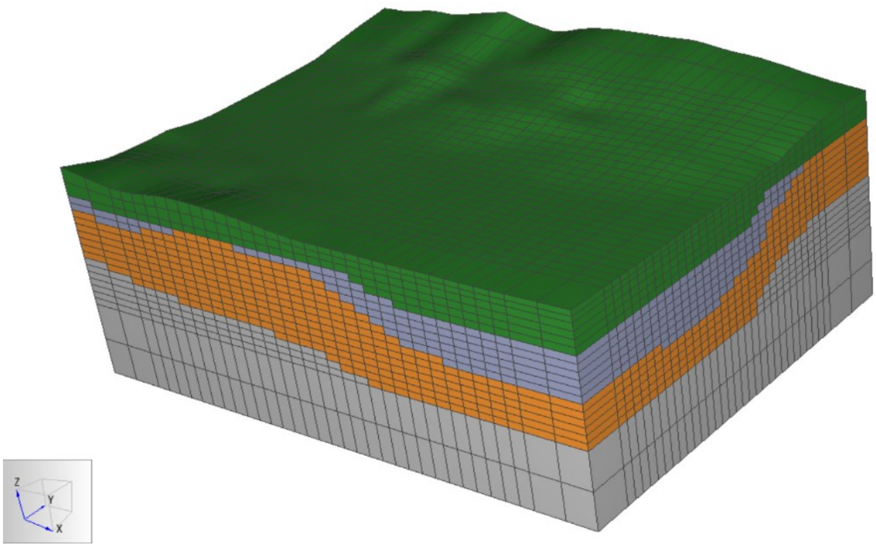

Figure 6. Grid system of the model

2.6. Formation Properties

In Table 2, initially assigned porosity and permeability values of the formations are given. These values were adjusted locally and globally during the calibration of the model. In Table 3, several rock properties, which were used throughout the simulation of the model is given.

Table 2. Porosity and permeability values of the formations

Formation Name	Porosity	Permeability in x-direction (milli Darcy)	Permeability in y-direction (milli Darcy)	Permeability in z-direction (milli Darcy)
Sazak	0.10	50	50	5
İğdecik	0.05	50	50	5
Deep Metamorphics	0.02	60	60	6

Table 3. Some other rock properties of the model

Formation Name	Rock Density (kg/m3)	Rock Specific Heat (J/kg °C)	Wet Heat Conductivity (W/m °C)
Sazak	2600	1000	1.0
İğdecik	2600	1000	1.0
Deep Metamorphics	2600	1000	1.0

As mentioned before, permeability factor option has been used in order to assign fault, fracture, and cap rock permeabilities to appropriate grid blocks, which were also adjusted during the calibration of the model. As high as 10 times and as low as 1/1000th of the initial permeability values were used in the model. Permeability factor of the faults were generally assigned twice more of regular grid blocks meaning that grid blocks, which represent the fractured region along the faults, have permeabilities twice the initially assigned formation permeability. On the other hand, cap rock blocks have been represented with a permeability factor of 1/1000. For example, the cap rock, which overlies the İğdecik Formation has a lateral permeability of 0.05 mD (50 mD x 1/1000) and vertical permeability of 0.005 mD. Porosity, permeability, and permeability factor distribution of the model is illustrated in Figure 7.

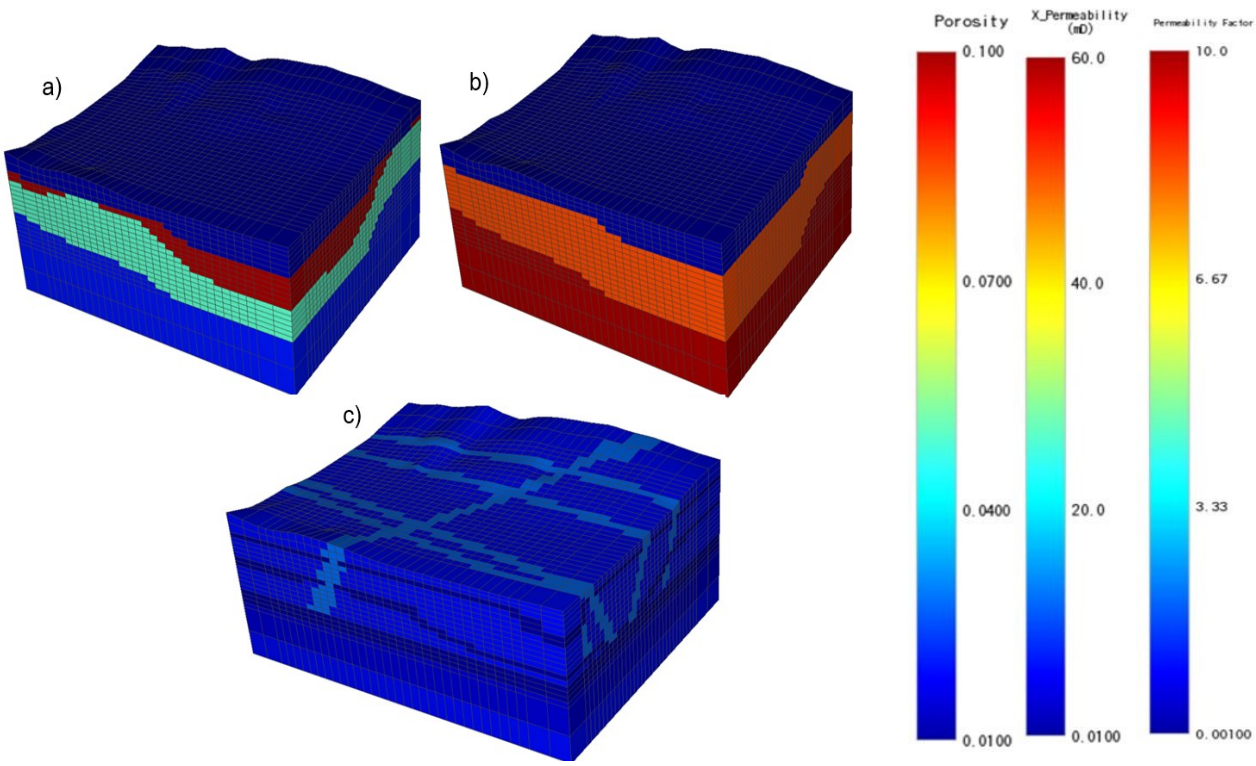

Figure 7. (a) Porosity (b) Permeability (lateral) (c) Permeability Factor distribution in the model

2.7. Heat Sources

There are two heat sources in the model, both of them are also providing meteoric water influx to the system. The first source is at the bottom, covering an area of approximately 13 km^2, at a depth of -5,000 meters. The water flux through this source is 27.5 kg/s, with an enthalpy of 1000 kJ/kg and with 4 wt.% dissolved CO_2 corresponding to 1.1 kilogram of CO_2 entering to the system per second. The conductive heat flux from the source is 0.7 J/s/m^2.

Another source was placed into the northern, shallower İğdecik Formation (below the Buldan Horst), to simulate the cooling effects of the rain waters entering to the system from the highs of the horst. It covers an area of 4.2 km^2, at a depth of -740 meters. The amount of water flux is 7.4 kg/s with an enthalpy of 400 kJ/kg. No CO_2 is associated with the water from this source.

2.8. Initial and Boundary Conditions

The uppermost layer of the model has been set as fixed-state, meaning that no changes occur in the properties of this layer, and pressure/temperature values stays constant throughout the simulation. In other words, the top layer of the model acts as a constant pressure and constant temperature boundary. The outer side layers are no flow boundaries. The bottom layer of the model is also a no flow boundary, except for the grids representing the heat source.

The natural state conditions (pre-production conditions) must be obtained and used as the initial conditions before the field is put on production. It means that the distributions of temperature, pressure, CO_2, and fluid flow prior to human intervention should be determined. For that purpose, the data from the first wells drilled in the field in 1960's and 1970's, as well as the deep wells drilled after the acquisition of the field by Zorlu Energy in 2008 are analyzed. Initial values of static pressure, static temperature and CO_2 distribution are estimated. The estimated values were used as the starting point for the numerical simulation of the model.

3. NUMERICAL SIMULATION AND HISTROY MATCHING

The model of the Kızıldere Geothermal Field was numerically simulated until the reservoir parameters stabilize (natural state conditions are reached). Then, based on the obtained natural state conditions the production-injection history of the field (1984-2018 in our case) is simulated. By comparing the simulation results with the real data coming from more than 50 wells, the model was modified by calibrating the initial and boundary conditions, as well as the conceptual model parameters. As a result, the static/dynamic pressure and temperature profiles obtained from the simulation were matched with a great accuracy with the real data. The confidence interval for the comparisons was less than 10% for each well. For illustration, the static pressure and temperature matches of four wells have been shown in Figure 8 and 9.

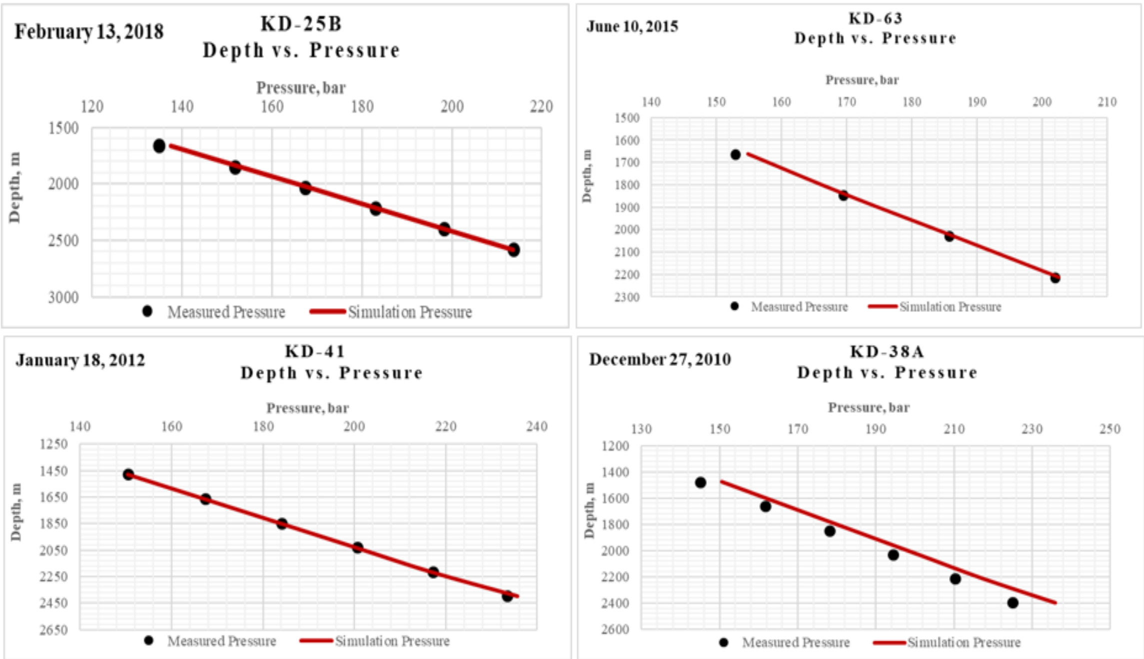

Figure 8. Static pressure matches

To validate the model in representing the actual conditions of the Kızıldere Geothermal Field, the goodness of fit of several wells were tested by comparing the dynamic pressure profiles of 15 observation wells with the simulation results. Since operations such as injection, production and shut-downs are supposed to be observed in the observation wells, matching the dynamic pressure profiles is a strong test of the model. Consequently, the dynamic pressure difference between the simulation and observation wells were less than 5% (Figure 10 and 11). Note that, these matches were carried out at different observation periods and observation depths.

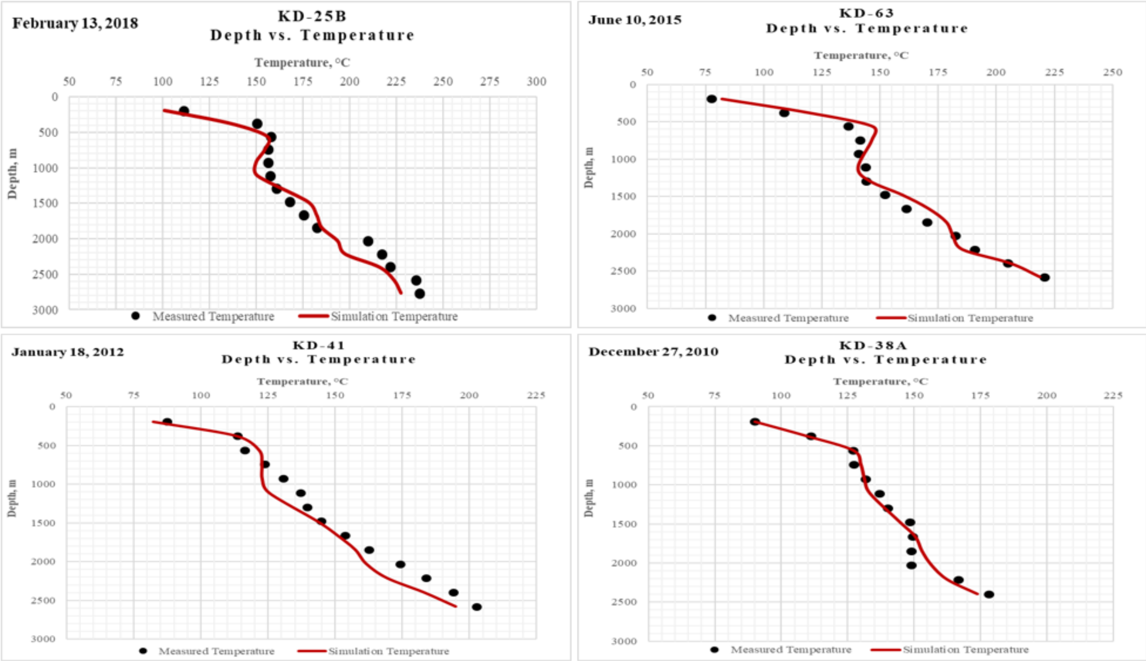

Figure 9. Static temperature matches

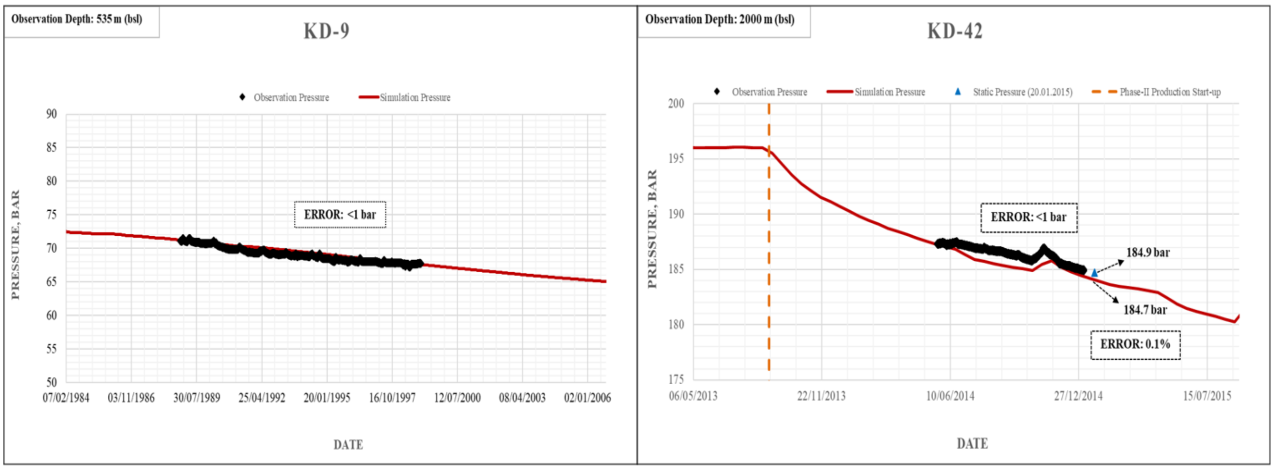

Figure 10. Observation wells KD-9 and KD-42

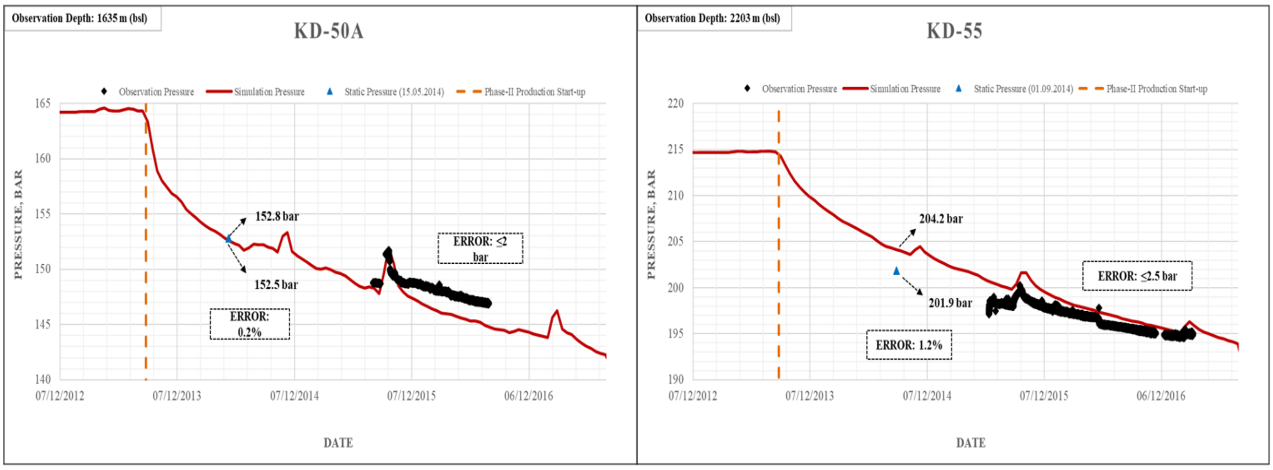

Figure 11. Observation wells KD-50A and KD-55

All in all, static pressure/temperature profiles of more than fifty wells and dynamic pressure histories of 15 observation wells have been compared with the simulation results and excellent results have been obtained. The average dissolved CO_2 content of the Kızıldere field (which is 1.5wt% and 3wt% for shallow and deep reservoirs, respectively) was also matched. It was concluded that the Kızıldere numerical model is a good representation of the actual field and it can be used for reinjection optimization purposes.

4. REINJECTION OPTIMIZATION AND RESULTS

There are more than 70 wells operational (both production and injection) in Kızıldere Geothermal Field to feed the power plants and to reinject the geothermal fluid into the reservoir after its heat is harvested. The depths of these wells vary from several hundred meters to more than 3500 meters deep. Before studying the optimum production/injection strategy for the Kızıldere field, the wells were classed into groups. The production wells were grouped according to the power plant which they are feeding; namely Phase-1, Phase-2, Phase-3A, and Phase-3B. Production and injection wells are illustrated in Figure 12.

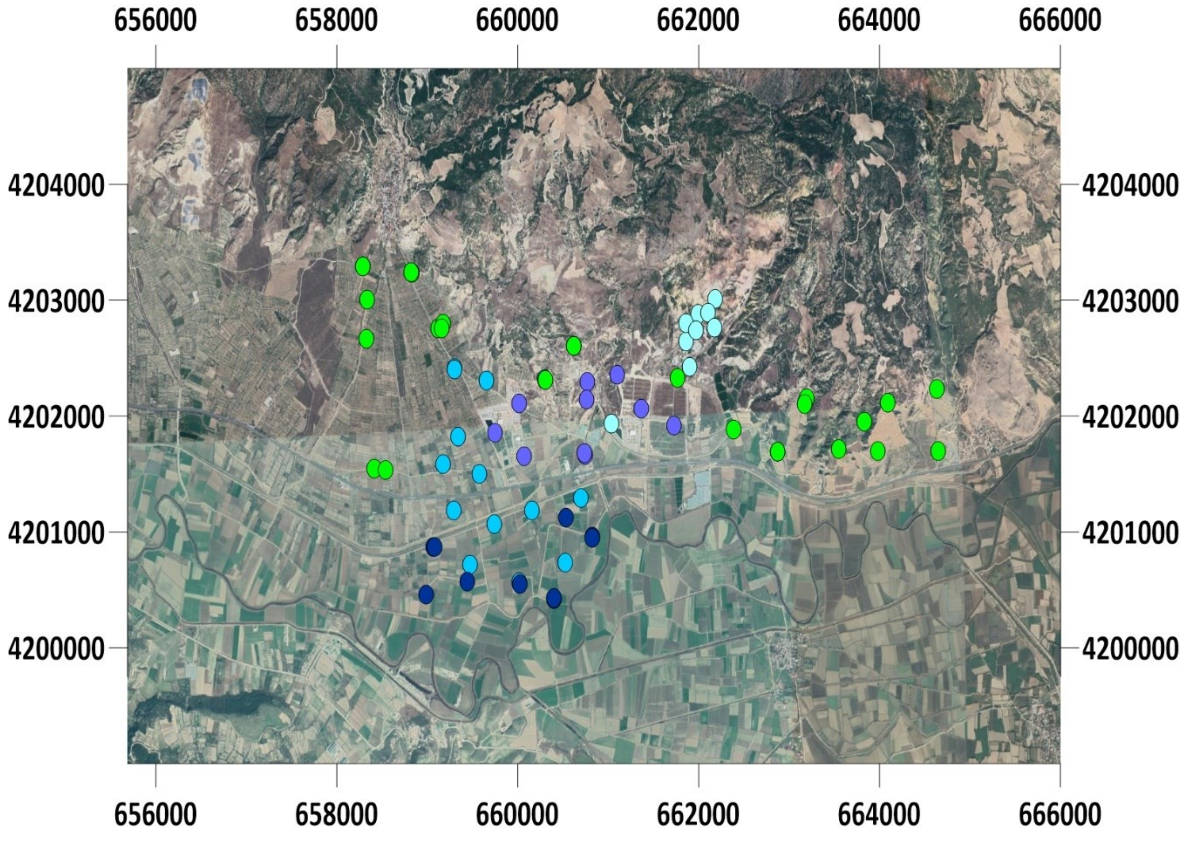

Figure 12. Green dots: Reinjection Wells, Blue Dots: Production Wells - different shades of blue represent different power plants

The reinjection wells were also grouped according to their depths and geographic locations. It is observed that most of the reinjection wells at the eastern and north-western parts of the field reinject into the shallower formations at several hundred meters deep. On the other hand, there is a large water withdrawal from the deeper metamorphic formations (mainly marble) through the deep production wells.

Many different production/reinjection scenarios were generated based on the formed groups of the wells. The natural desire for the management of the field, which is producing as much high enthalpy fluid as possible while maintaining the reservoir pressures and temperatures as high as possible, was tried to be satisfied with the generated scenarios. Through a labored and time consuming process, which includes preparing the input files, running the simulations, and analyzing the simulation results, a wide range of production and reinjection scenarios for Kızıldere field were obtained.

During the evaluation of the production/reinjection rates of the wells, it was observed that almost forty percent of the total reinjection was through 5 shallow injection wells located at the eastern and north-western parts of the field. In order to assess the effects of reinjection through these wells, two different conditions were compared by simulations: (1) shallow injection wells shut in instantly, (2) nothing has been changed in the model. The average pressure decline of all production wells were plotted with respect to time (Figure 13). The simulation time was set as 20 years.

Figure 13. Illustrating the effects of 5 shallow wells

Although, shallow reinjection wells comprise approximately 40% of the total reinjection rate, their pressure support to the production wells was found to be around 4%. It can be deduced that the reinjection through these wells could be considered as water-disposal instead of a good reinjection strategy.

In order to optimize the reinjection efficiency, different scenarios were simulated on the model. Since the reach of these injection wells were too shallow compared to the deep production wells, it was eventually decided to divert most of their water to some other deep injection wells. These new wells were selected among the existing deep production and observation wells. In Figure 14, the locations of these wells are illustrated.

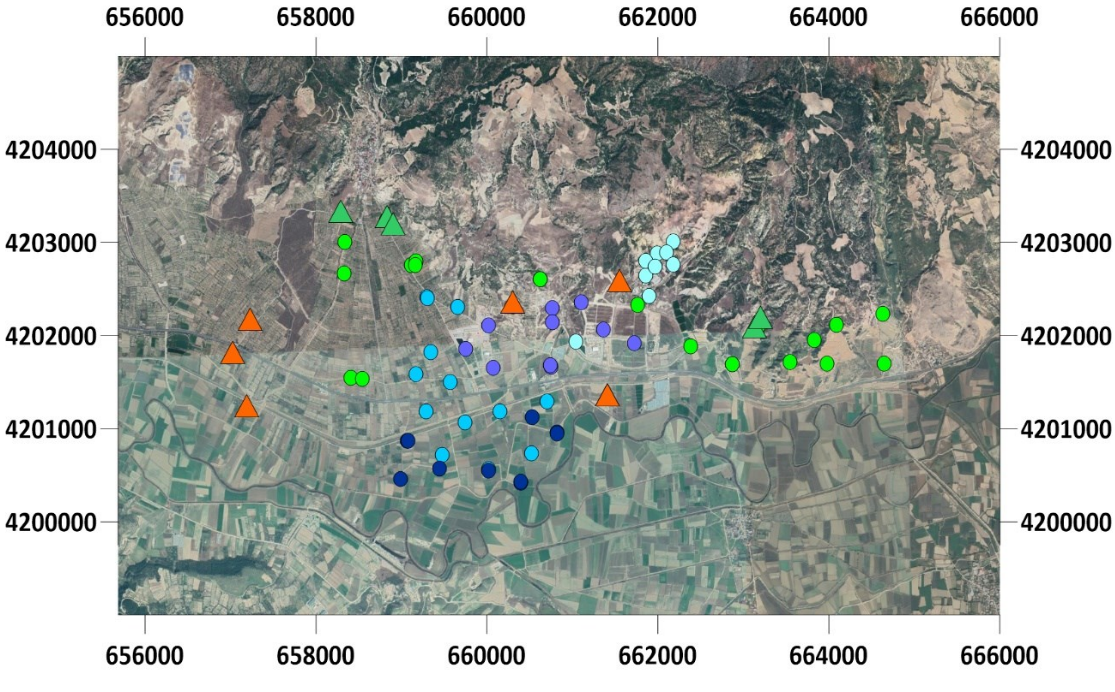

Figure 14. Green triangles: Shallow reinjection wells which comprise the forty percent of the total reinjection rate
Orange triangles: New deeper reinjection wells
Blue circles: Production wells
Green circles: Remaining reinjection wells

The proposed reinjection scenario was simulated on the TOUGH2 model for 20 years. In the simulation, production rates were kept constant with respect to changing reservoir pressures. The successfulness of the scenario was determined by comparing the total pressure drop occurred in the production wells in the initial and the proposed reinjection scenario. The plot of the average pressure drops of the production wells at $9^{5/8}$ casing setting level with respect to time for both of the scenarios are given in the Figure 15.

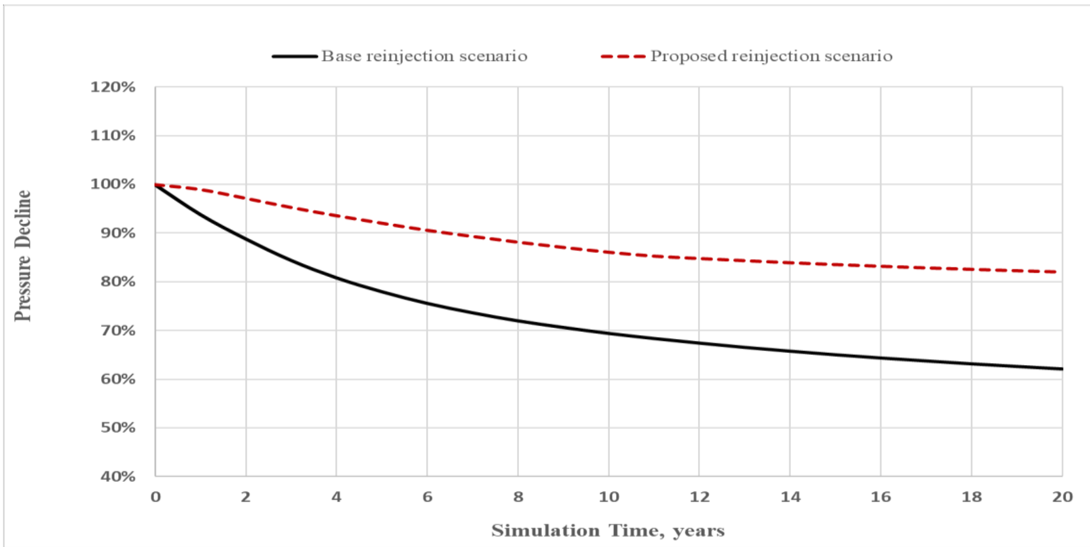

Figure 15. Significant pressure support with the proposed reinjection strategy

The proposed strategy has already been tested in the field. The proposed existing wells converted into reinjection wells became operational in the late 2018. The water of these new wells had been diverted from the 5 selected shallow reinjection wells. The successfulness of the new reinjection strategy can be assessed by looking at the pressure profiles of observation wells. Figure 16 shows how the sharp pressure decline stabilizes towards the end of 2018 in one of the observation wells. Temperature and CO_2 changes were not significant in the aforementioned simulations, where the declines were less than 1%.

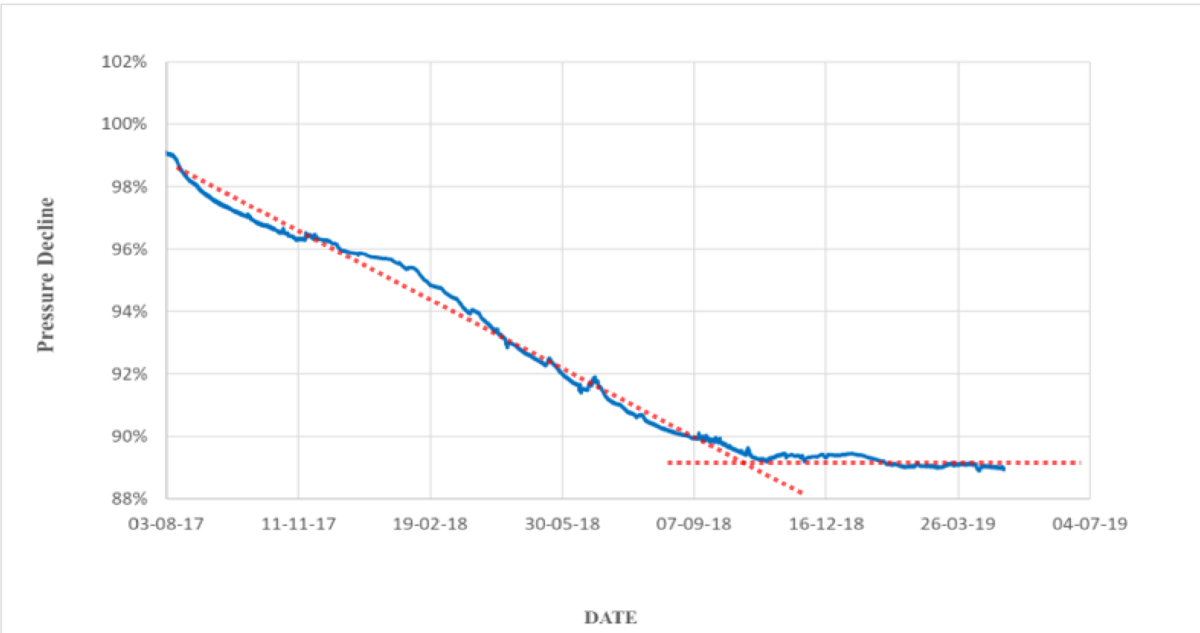

Figure 16. Response to the new reinjection strategy in an observation well

CONCLUSION

A numerical model of Kızıldere reservoir has been developed. Using the calibrated model, reinjection optimization has been conducted. In this regard, deeper injection rather than shallow injection has been preferred. It has been observed that the effectiveness of the new reinjection strategy is significantly better compared to “do not change injection” strategy. When the total reinjection rate stays unchanged, the average pressure decline in the production wells decreases more than 20%. The main reason behind this situation is the depth of the new reinjection wells. Compared to the 5 selected wells, whose reinjection rates comprise approximately 40% of the total reinjection rate, the proposed reinjection wells reach to the deep metamorphics where most of the current wells are producing. These results imply that shallow injection/deep production strategy fails in Kızıldere Geothermal Field. Instead, deeper wells should be selected for reinjection. This study also proves the successfulness of converting low pressure production wells into reinjection wells, depending on the depth and location of the well.

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