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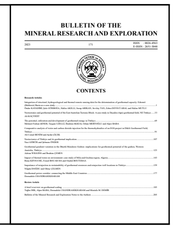

Importance of reinjection in sustainability of geothermal resources and reinjection well locations in Türkiye

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ABSTRACT

Sustainability of geothermal energy is related with the type of geothermal resources (natural springs, well), usage situations (thermal, residential-greenhouse heating, energy, etc.), amount of use (optimal flow, appropriate pressure-temperature changes), conservation of resources, and is mostly achieved by reinjection of the geothermal fluid returning from usage. It is important to take measures to prevent adverse changes in temperature and pressure conditions in the reservoir to properly remove the fluid returning from use in geothermal areas from the environment and recharge the reservoir. Reinjection should be carried out under appropriate conditions for the protection of resources. In the operation of geothermal resources, reinjection/discharge conditions and obligations are also specified in the provisions of the Law No. 5686 and the implementing regulation. Various studies within the scope of exploration activities in geothermal fields, determining the production-reinjection areas and determination the location of the reinjection wells in conditions that will not adversely affect the production pressure-temperature conditions are of great importance for the sustainability of the geothermal reservoir.

1. Introduction

Ideal geothermal systems constitute four parameters, namely, (1) the heat source within the crust of a size and age that can form a geothermal system at an economical depth, (2) porous and permeable reservoir that are related with faults and fracture networks that have hydraulic channels for the transport of hot fluids in the reservoir zone, (3) the impermeable cap rock that keeps the heated fluid in the reservoir and maintain its heat, and (4) a suitable recharge area that naturally recharge the geothermal reservoir (Figure 1).

The heat source in a geothermal system is the heat originating from the mantle of the earth and this heat can be transported either conductively (radiation of heat) or convectively (with the movement of a substance, where it is carried by water). As a result of the solid crust (lithosphere) folding and fracturing along tectonic lines caused by movements of the earth's crust and magma differentiation in the upper mantle, the heat in the depths of the earth can reach shallow depths in the crust as a result of magmatic intrusions and volcanic activities. Lithological units formed by these folding and fractures forms reservoir zones within fractures. In that systems, water infiltrates the earth through faults and fractures, where it warms up in contact with magmatic intrusions and rises through faults or by the pressure force between descending cold water and rising hot water temperature. However,

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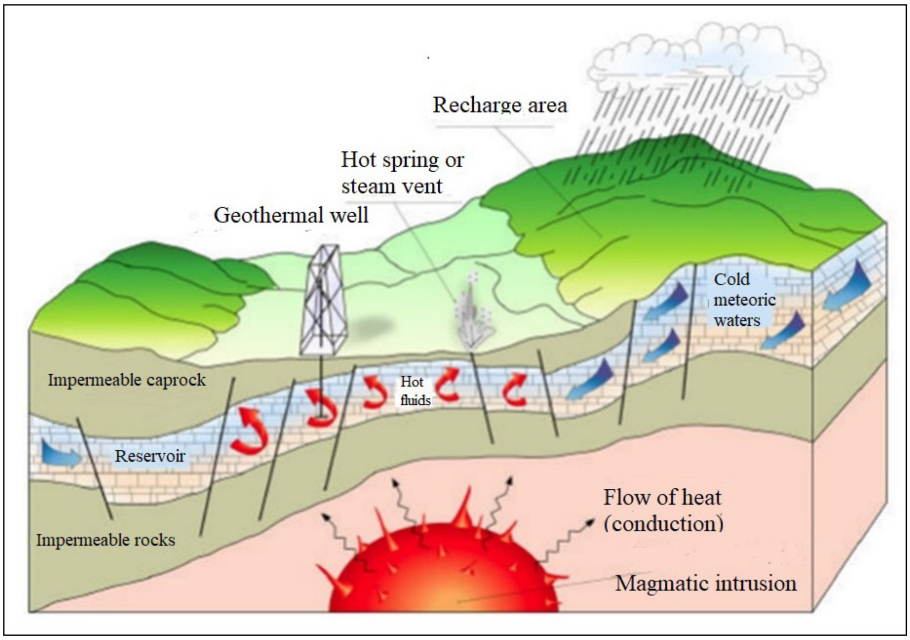

Figure 1- Schematic representation of a geothermal system (Barbier, 2002).

most of the time, in geothermal systems, the heat transport is not by the water circulation in contact with the magma, but also by the heat transfer from the mantle and crust to the earth. Meteoric waters infiltrate deep through fissures and fractures in the ground, and, after being heated in the above-mentioned heat anomaly areas, rise again towards the surface to economically shallow depths. The heated fluid carried upwards that can be stored in the crust economically at shallow depth in porous and permeable lithological units and/or zones. The geothermal reservoir must be connected to a recharge area over long distances so that it can be recharge continuously. In order for geothermal reservoir to remain protected without losing its energy, there must be an impermeable cover rock to prevent heat and fluid loss (Figure 2).

The concept of sustainability in geothermal systems covers the operation of the fluid obtained from the geothermal reservoir without changing its

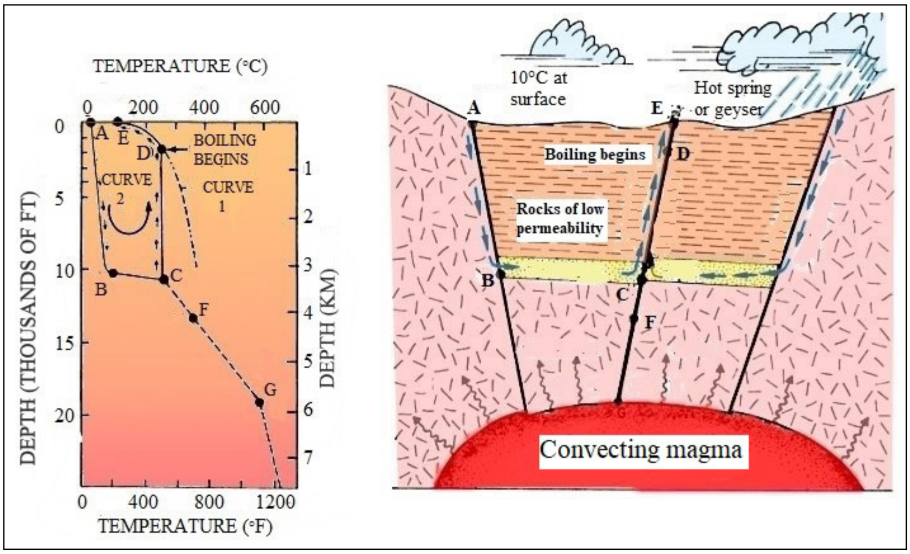

Figure 2- Conceptual model of a high-temperature geothermal system (White, 1973).

physical properties such as temperature, pressure and chemical structure negatively and, also, the protection of the geothermal resource from pollution effects. In order to ensure sustainability, geothermal fluids should be produced at optimum production rates and reinjected properly to ensure production-reinjection balance (Figure 3).

2. Reinjection in Geothermal Reservoirs

The first reinjection applications started in high-temperature, electricity-generating areas such as The Geysers, U.S.A. (1969), Otake, Japan (1972), Larderello, Italy (1974), Hatchobaru, Japan (1977), Kakkonda, Japan (1980) and Onuma, Japan (1981). Reinjection was primarily carried out to dispose of waste water from geothermal use. Later, reinjection became a “science” in the form of monitoring the reinjection process, and determining the reinjection strategy specific to each geothermal area due to its impact on the reservoir and the environmental (Kamila et al., 2021). Geothermal reinjection involves injecting energy-depleted fluid back into geothermal systems, providing an effective mode of waste-water disposal as well as supplementary fluid recharge (Axelsson, 2013). In heating and energy projects where geothermal water is used, reinjection of the water returning from use is necessary in order to keep high temperature and pressure conditions in balance and to prevent a decrease in flow rate.

In geothermal reservoirs where the liquid phase is dominant, the water temperature is lower than the evaporation temperature and stays in the liquid water phase. In terms of protection of the system and phase transition, it should be considered that a decrease in the amount of fluid has a risk of adversely affecting the reservoir pressure, and reinjection will have a positive effect in this case. However, in a high enthalpy geothermal reservoir used for electricity generation, a reservoir pressure decline can result to the reservoir temperature to be higher than the evaporation temperature that leads to more steam generation.

In two-phase geothermal reservoirs, there is a combination of liquid water and steam. High permeability and secondary porosity due to fractures, are important reservoir characteristics for this type of reservoir. The risk of pressure decline may affect

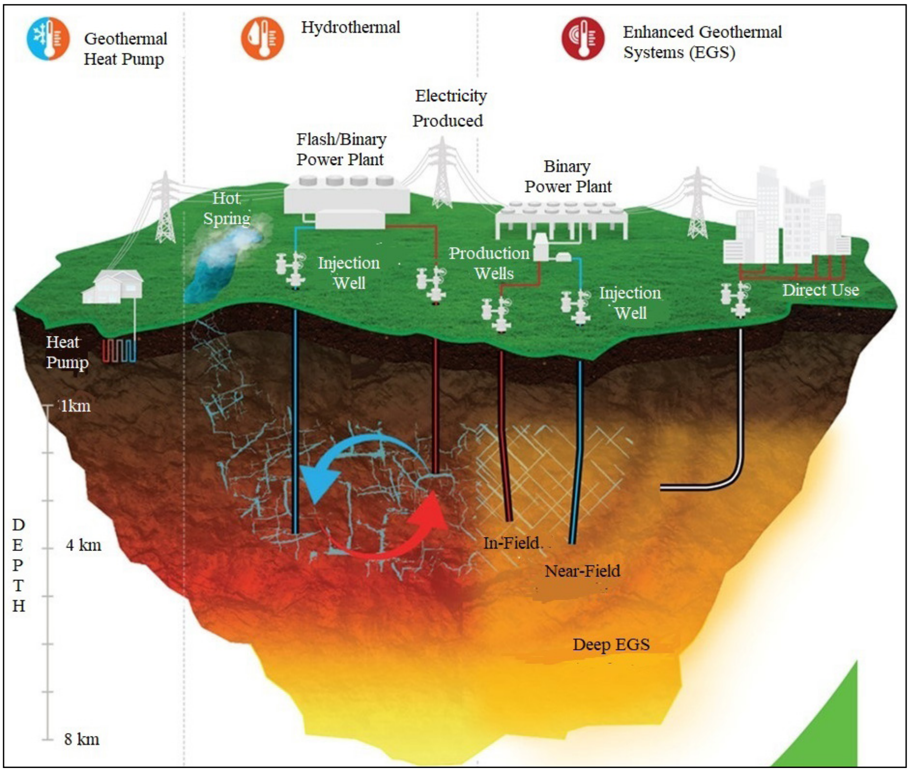

Figure 3- Operation conditions in different geothermal systems (Roberts, 2020).

reservoir very quickly. In such systems, as long as the production-reinjection balance is maintained, only short-term changes in pressure and temperature may be observed. In both relatively-low enthalpy areas with temperatures below 150°C and high enthalpy areas with temperatures above 150°C, the reinjection policy varies according to the purpose of use.

In geothermal reservoirs where steam phase is dominant, the fluid temperature is higher than the vapour pressure and the steam phase is dominant. In these reservoirs, it is important that the reinjection operation recharge the reservoir system continuously.

Below are the following reasons for conducting reinjection studies in geothermal fields are;

- Reduce pressure decline due to production and slow recharge,
- Prevent environmental pollution,
- Recover thermal energy after usage,
- Sustain energy in the reservoir to ensure the sustainability of the area, and
- Prevent subsidence and any surface movement on the surface due to mass extraction.

Reinjection also sustains pressure sustainability of the reservoir, reduce ground subsidence risk and be used to maintain significant surface thermal activity (Figure 4).

The amount of energy taken from the reservoir can be increased by recovering the mass and energy loss that occurs with production. Due to reservoir pressure decline, production from the geothermal wells may decrease. Since the liquid dominant phase controls reservoir pressure, protecting the amount of liquid phase will also protect the reservoir pressure.

In Türkiye, 90-100% reinjection of used thermal fluids is one of the indispensable reservoir management activities in curently operating geothermal power plants. In space heating (housing or greenhouse), approximately 70% of the used fluid is reinjected although sometimes geothermal fluid that used for direct heating may also used for thermal facilites and other integrated purposes.

If reinjection is not done properly in geothermal areas, the reservoir pressure may decrease and sometimes collapses may occur due to the decrease in the water level. On the other hand, geothermal

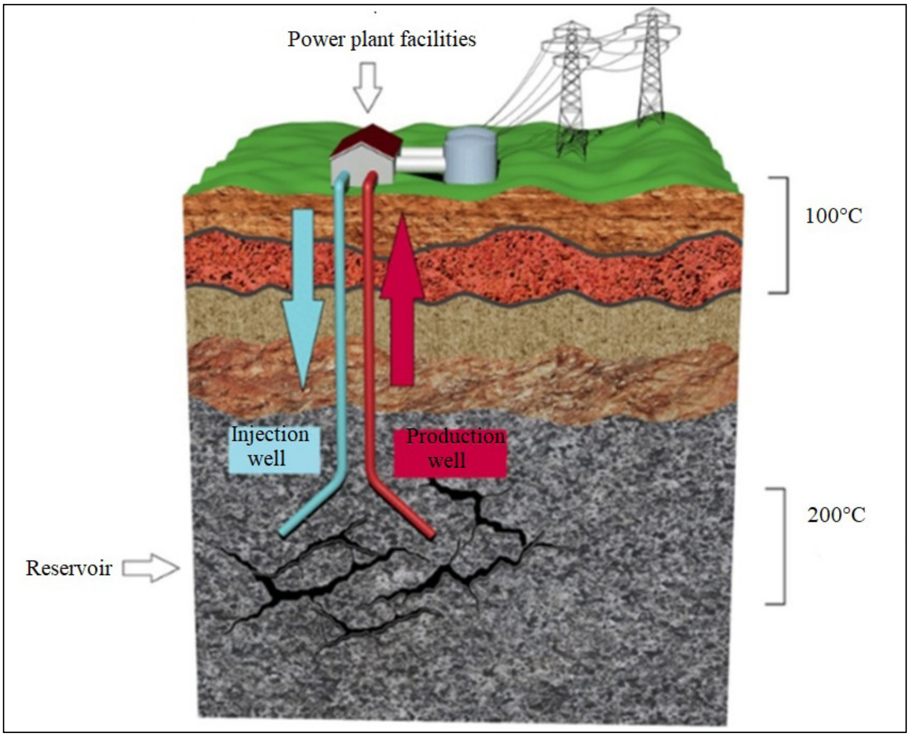

Figure 4- Scheme of deep geothermal system, production and injection wells (Vitaller et al., 2019).

resources that classified as renewable energy sources, cannot be renewed with the lack of reinjection and may be short-lived and run out. If reinjection is not performed under suitable conditions, it may cool and cause scaling, corrosion, etc. in the reservoir and also may adversely affect the surface waters.

The reinjection system, such as, distance to other wells (production/reinjection), amount of reinjected fluid, temperature, chemical properties, evaluation of short-term and long-term effects of thermal fluids, play an important role in the sustainable operation and development of the geothermal reservoir. The use of different and appropriate reinjection strategies in different geothermal areas requires examination and knowledge of all the technical characteristics of the geothermal area.

For this purpose, geothermal reservoir systems are classified for different purposes according to the active fluid (steam or liquid phase dominant) state in the reservoir, to form the model of the system according to its chemical composition.

Reinjection on the main fault zones of a fault-controlled geothermal system may cause negative results as the reinjected fluid would reach the production wells quickly (e.g.Nevşehir-Kozaklı geothermal field). When the previous surveys are examined in Turkey and the world, it is seen that reinjection strategies varies a lot. The process of reinjection varies in different geothermal fields: location of the recharge area, infield injection in the center of the production area, at the edge and outside of the production area, and either above, at the same level, or below the production zones. It is clear that reinjection can be done from different depths and locations in different reservoir systems in different areas, either by pumping or gravity. The important thing in all these applications is to ensure the sustainability of the field. The chemical properties of the produced fluid play an important role in designing the appropriate reinjection strategy for a geothermal field. To increase the performance of the reservoir, the geological structure of the area should be known in detail considering that the rapid routes from reinjection to reservoir, such as faults and fractures to avoid shallow circulation.

In the case of overproduction, reservoir collapse may occur due to pressure loss, water level decline and, consequently, the weight of the rocks/sediments above the reservoir may subside. Reinjection of the used fluid is a best practice for reservoir management that sustains reservoir pressure and prevent any reservoir collapse.

After the reinjection well is drilled, well tests (including injectivity, tracer, pressure fall-off and build-up, etc.) should be carried out to determine the optimal production-reinjection amount balance and prevent anomalous temperature and pressure declines in the reservoir. Chemical analyses should be performed on the water samples collected at least every 3 months in the reinjection wells and ~6 months in the production wells to better understand the parameters and conditions that will cause scaling and, corrosion problems. Chemical analyses also give some clues about whether sustainable production-reinjection process exist or not.

As it is known, both for the regulations of the Law No. 5686 and for the sustainable operation of the geothermal reservoirs, it is obligatory to reinject the used brine from operational activities, especially for space heating and electircity generation purposes. In such activities, reinjection at a suitable locations and conditions not only prevents long-term pressure and temperature drops in the reservoir, but also ensures that the geothermal brine not to harm environment physicochemically. In addition to this, due to geological characteristics or geometric shape of the licensed geothermal area, reinjection activity may not be carried out without causing temperature and pressure declines in the reservoir. In such cases, sometimes, the geothermal fluid can be operated without recharging the reservoir and/or reinjection may occur in the opposite direction out of the system. In this case, it is necessary to ensure the long-term sustainability of the reservoir by not using large-volume pumps, limiting mass extractionof thermal fluid to balance natural recharge of the geothermal system. If surveys shows that reinjection is technically impossible to perform, then, licensed owner should apply for MTA over Governorship to get permission for other possibilites and reservoir management policy under the Law No: 5686.

In the above cases, the used geothermal brine is reinjected underground to the appropriate formation without significantly affecting the environment especially surface waters and near-surface aquifers while maintaining the pressure recharge process that is critical for the sustainability of the geothermal resource. It should be noted that disposing used geothermal fluid underground should be applied only in technically imperative situations. The main objective in geothermal reservoir management is to reinject the used geothermal fluid into the appropriate formation at a suitable distance (so that the injected brine gets heated up by the hot rocks as it travels back into the reservoir) to ensure the resource long-term sustainability. Mineral scaling due to the inherent chemical properties of the geothermal fluid is one of the most important problems encountered in the operation of geothermal fields. In cases where no precautions are taken, scaling affects the well production, production-reinjection line and other surface facilities, including the power plants, and the chemical properties of the produced fluid that will be reinjcted back. Of course, precautions must be taken to prevent mineral scaling.

In some cases, the first thing that comes to mind for reinjection strategy is to reinject geothermal fluid to some unused geothermal production wells. However, such application may cause cooling of the geothermal reservoir and production wells. Another thought is to recharge the thermal fluids by drilling a deeper well in the same area. Another application is to carry out this operation by drilling a little further away from that field (Atılgan, 1994). In recharging the geothermal fluid to the reservoir by reinjection wells, vertical and lateral wells should be chosen at a distance that will not adversely affect the wells or the reservoir by means of temperature and pressure.

2.1. Legal Regulations

Many regulations have been made in the Geothermal Resources and Natural Mineral Waters Law and Implementation Regulation No. 5686 for the reinjection and discharge-disposal of the produced thermal fluid after the use of geothermal resources. First of all, it is stated in the 3rd Article-Definitions section of the Law and in the 4th Article-Definitions section of the Implementation Regulation that "Reinjection: After the produced geothermal fluids used by artificial methods, all or the remaining part is sent back to the geological formations where they were produced".

In Article 14 of the Law: Regarding discharge in case the reinjection conditions cannot be met, there is a provision that "(4) The licensee may discharge the surplus fluid after usage, taking into consideration the environmental limits. If the contents of fluid does not enable the discharge of the fluid according to environmental limits, the licensee is required to reinject it. However, if General Directorate of Mineral Research and Exploration (MTA) confirms that reinjection is not possible due to the physical and chemical characteristics of the formation, the discharge shall be done by taking measures to prevent environmental pollution" provisions are included.

Article 23 of the Implementation Regulation: Protection of resource reservoirs section; " (2) Measures to protect the reservoir in the resource protection zone area survey; According to the reservoir parameters determined as a result of the production tests carried out before the source is put into operation, the total production amount that can be taken from and on the basis of the well, the amount of the fluid returning from use and the suitable locations for the underground reinjection of this fluid and the number of wells with appropriate capacity, It includes necessary practices to ensure sustainable production in case of detection of compounds that will cause partial or complete blockage of zones and production wells" provisions are included.

Article 24 of the Implementation Regulation: In the discharge and reinjection section, it contains provisions on reinjection application conditions, environmental legislation and its physical and chemical effects. (1) The license holder has done the chemical analysis of the fluid returned from use, by an accredited laboratory. If the chemical composition of the fluid exceeds the environmental limits, it is first purified by appropriate methods and reduced to the limits of the relevant environmental legislation. Then, the appropriate receiving environment is determined. The fluid returning from use is duly discharged to the determined receiving environment. Chemical analysis of the fluid obtained after treatment is performed every three months and it is checked whether it exceeds the environmental limits. (2) The license holder is obliged to reinject if the content of the fluid returning from use is not suitable for discharge according to the environmental limits specified in the environmental legislation. If there is an existing well that has been dug in the area determined for reinjection and meets the reinjection conditions, it is evaluated. It is determined by making a preliminary assessment whether the fluid will have negative effects on the reservoir where it will be reinjected. If there is no adverse effect, reinjection can be done. If there is a negative effect, reinjection is performed after this effect is eliminated. Observations are continued as long as reinjection is made. In case of negative effects of reinjection on the reservoir and production values, the reinjection process is stopped and a search is made for a new location. (3) If the studies carried out give the result that reinjection is not possible, this situation is forwarded to MTA by the Administration together with all the information and documents, and it is examined, and if necessary, an on-site inspection is carried out by MTA, at the expense of the license holder. If MTA approves that reinjection cannot be performed in the operation license area due to the physical and chemical characteristics of the formation, the discharge is carried out by taking measures to prevent environmental pollution. (4) Reinjection and injection conditions may not be required in detached spa and natural mineral water enterprises outside the integrated geothermal resource usage area. In such cases, the fluid can be duly discharged to the appropriate receiving environment, by taking the opinion of the relevant ministry in terms of environmental legislation.

Articles 25 and 26 of the Implementation Regulation contain provisions regarding the integrated and optimum usage conditions of the geothermal fluid. “25-(4) Except for geothermal fluids suitable for energy generation and heating applications, the fluid is primarily used for health and thermal tourism purposes in areas where other fluids are present. For this purpose, after the exploration, research and development studies related to the fluid, the evaluation regarding whether it is suitable for use for health and thermal tourism purposes is made by the relevant Administration according to its physical, chemical or indication characteristics. In these areas, the part of the geothermal fluid subject to energy production and heating applications, at the temperature and flow rate in the range allowed by the reinjection conditions after these uses, is integrated for health and thermal tourism purposes. In areas where there is geothermal fluid suitable for energy and heating, the use of this fluid for health and thermal tourism purposes is allowed in cases where there is no demand or demand for energy and heating purposes or there is no potential for use.” “26-(4) (Changed: OG (Official Gazette))-24/9/2013-28775) Real or legal persons, who have a geothermal fluid operation license suitable for integrated use, must first use the geothermal fluid in greenhouse and organic agriculture heating at the temperature and flow rate allowed by the reinjection conditions. In case the license holder does not establish a greenhouse himself, it is rented to third parties with the approval of the administration, primarily to the existing greenhouses. The administration is required to ensure that the matters specified in this paragraph are provided in the operation projects. The lower and upper limits of the rental price are determined by the administration. While determining the rental price, the prices determined in the nearest cultural and tourism protection and development regions are taken into account”.

2.2. The Selection of the Reinjection Area and the Well Locations

Considering all the characteristics of the geothermal area and the reinjection under appropriate conditions ensure the sustainability of the geothermal resources. In particular, geological data (stratigraphy, lithology, tectonism, hydrogeology), borehole data (litostratigraphy, definitions, changed temperature in depth), geophysical data, well logs, flow rates, hydrogeochemical datas (temperatures of springs and wells, chemical compositions) are very important in addresing this issue. The additional factors affecting the selection of the reinjection well locations may be the foresight of the temperature changes of geothermal fluid that reach to the production zone.

2.2.1. Using Groundwater Flow Maps for Determining Reinjection Well Locations

By interpreting the geology, stratigraphic units, tectonic structures (fault, graben), well datas, hydrogeological characteristics of the geological units, the reservoir, cap rock and tectonic structure parameters, the flow conditions the reinjection area possible reinjection areas are determined. In this case, the determination of the flowstream paths, fracture network and hydrochemical parameters between the recharge and discharge zones in the area plays an important role in the determination of the reinjection zone. We can use groundwater flow maps and tracer tests to determine the circulation time, direction and movement of water from the recharge zone to the discharge zone in the geothermal field (Figure 5). Hydrogeologic mapping requires the geology, hydrogeology (hydrologic, topographic, well data), geomorphology and hydrogeochemistry of groundwater as they affect the occurrence, flow and quality of groundwater (Figures 6 and 7).

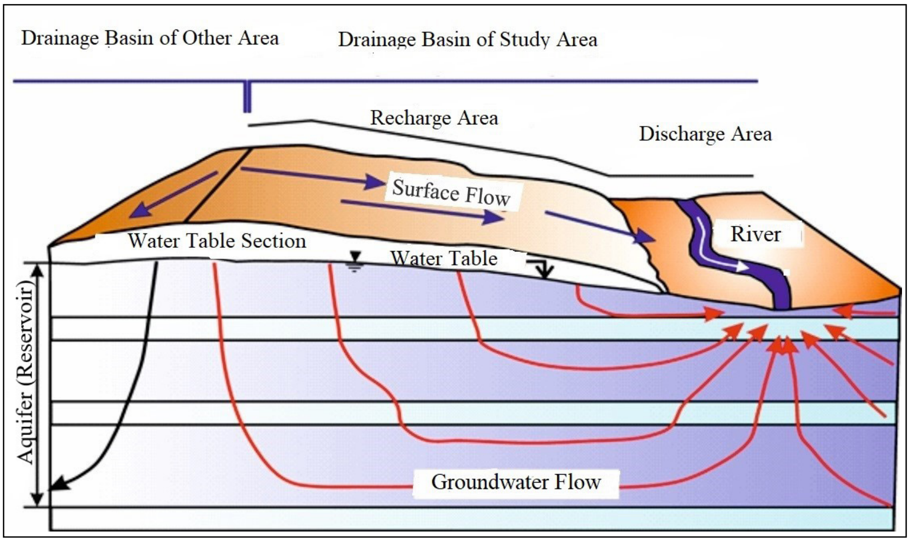

Figure 5- Groundwater drainage basin and flow paths (Tezcan, 2000).

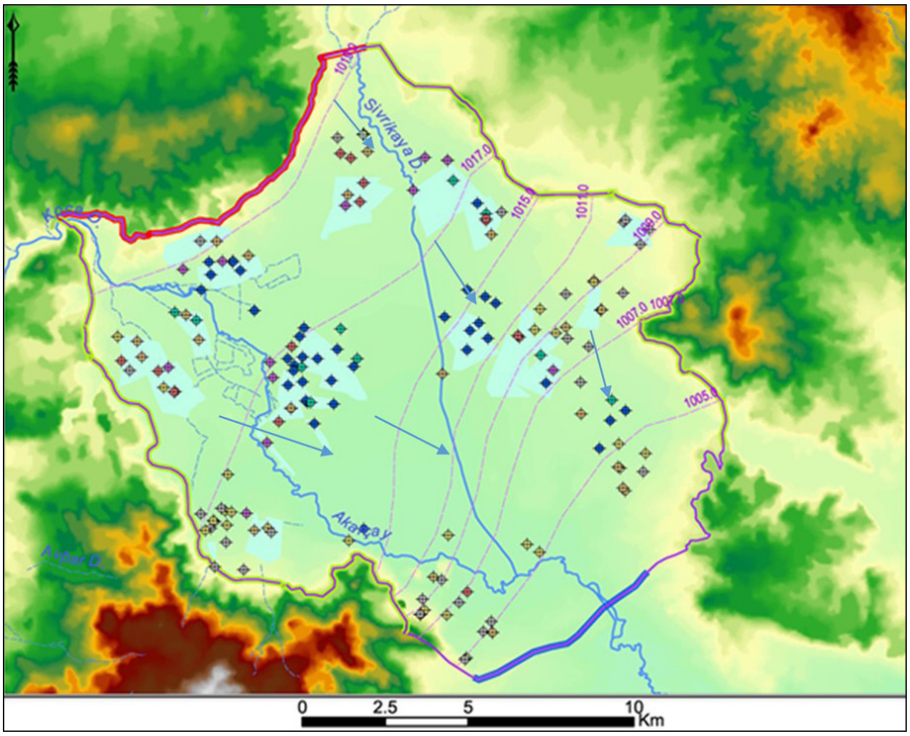

Figure 6- Groundwater flow, flow paths hydrogeological map of Afyon Plain (Doğdu, 2004).

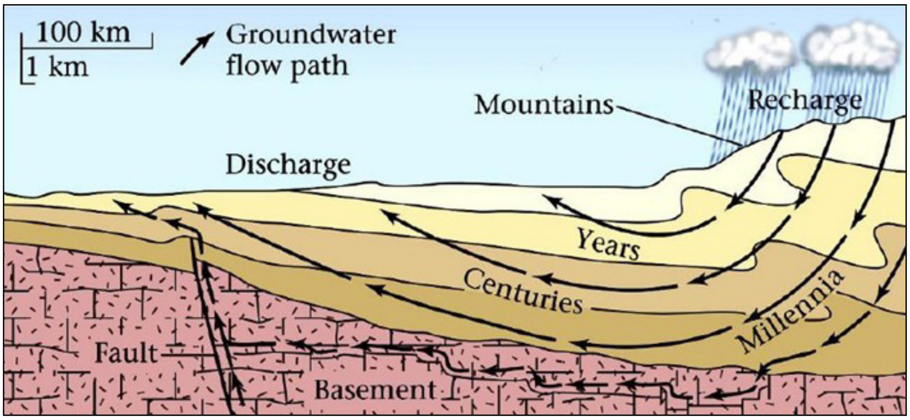

Figure 7- Groundwater flow paths (Şirin, 2019).

2.2.2. Using Tracer Tests for Determining Reinjection Well Locations

Tracer tests are widely used in hydrological and hydrogeological studies such as the determination of groundwater flow rate and direction and source of pollutants in groundwater. In some cases, the exact evaluation of the geothermal field to determine the circulation of production-reinjection system balance is tracer tests.

Tracer testing has become a highly important tool in geothermal research, development and resource management. Its purpose is mainly threefold: (1) general hydrological studies of subsurface flow, (2) reinjection research and management and (3) flow rate measurements in pipelines carrying two-phase geothermal fluids. Their role has, in fact, been more significant in reinjection studies. This ihis is because tracer tests provide information on the nature and properties of connections, or flow-paths, between reinjection and production boreholes. Additionally, it controls the possibility and rate of cooling of the production wells during prolonged re-injection of colder fluid. Enabling such cooling predictions is actually what distinguishes tracer tests in geothermal applications (studies and management) from tracer tests in groundwater hydrology and related disciplines (Axelsson, 2013).

Another important role that tracer testing plays is in geothermal research and management, in particular, concerning heat-transfer efficiency in reinjection operations and EGS development. Advances have been made in the introduction of new tracers, which both add to the multiplicity of available high-sensitivity tracers as well as being increasingly more temperature tolerant. However, the geothermal industry needs to follow advances in other disciplines and adopt those which are useful. In particular, advances in modelling of tracer return data, which has been limited so far, especially modelling of reactive tracer data, which can yield information on flow-channel surface areas in addition to their volumes (Axelsson, 2013).

2.2.3. Using Stable Isotopes for Determining Reinjection Well Locations

In geothermal fields, one of the most important criteria in the determination of the reinjection locations is to identify the recharge zone of the geothermal reservoir in the region. This determination is very important in terms of re-heating the reinjected hot water in the medium- to long-term circulation so that the reinjected fluid is heated by the reservoir rocks before it reaches the production area.

One of the methods used to find the recharge zone is to determine the recharge elevation If the recharge altitude is determined, the geology of the region and the hydrochemical properties of the water can be evaluated together, and the recharge area can be easily found with other geological and hydrogeolocial data.

Stable isotopes are used to determine the recharge elevation of geothermal water (Figure 8). As it is known, the main stable isotopes used in hydrology are the isotopes of oxygen and hydrogen in the structure of water. The ^{1}H-hydrogen isotope with mass number 1 of the element hydrogen has the highest abundance in nature with 99.985%. The heavy isotope ^{2}H-deuterium, which has a mass number of 2, is less common. The stable isotopes of oxygen and hydrogen are generally used in geothermal waters to enlighten the circulation of water, reveal the extent of water-rock interaction and determine the recharge altitude of the geothermal resource.

Oxygen-18 and deuterium isotopes of precipitation can be used to determine the recharge area of the hot water resources of the regions from precipitation (Mazor, 1991). As the isotopic ratio of atmospheric water vapor rises above sea level, it becomes poorer in heavy isotopes. At the same time, there is a decrease in isotope content with altitude. Although it varies regionally, the δ^{18}O isotope value of the precipitation water may decrease between 0.15-0.5 per thousand despite every 100 metres of elevation increase. Based on this information, if the oxygen-18 isotope content of any water is known, it is possible to determine the recharge elevation of that water (Figure 8).

To determine the recharge altitude of a geothermal reservoir, first of all, the oxygen-18 and/or deuterium content of the precipitation in the region must be known. However, this data is notknown or has not been measured in some areas. In this case, the oxygen-18 data of cold water sources, which are formed as a result of short-term infiltration of precipitation, can also be used as analog. Thus, the elevation and stable isotope value of cold water, which is formed as a result of short-term infiltration of precipitation, is compared with the elevation and stable isotope value of hot waters.

Three cold water springs were used by Çelmen (2008) to determine the recharge altitude of some hot water springs (BT-1, BT-2, BT-3, BT-5) located in the Ankara-Beypazarı region. The water samples used in the study were BS-3 from Ilıcakpınar spring, BS-4 from Dikmen spring and BS-5 from Tahirler brackish water spring. In the study, the hot water sources of the Beypazarı region is found to have a recharge altitude

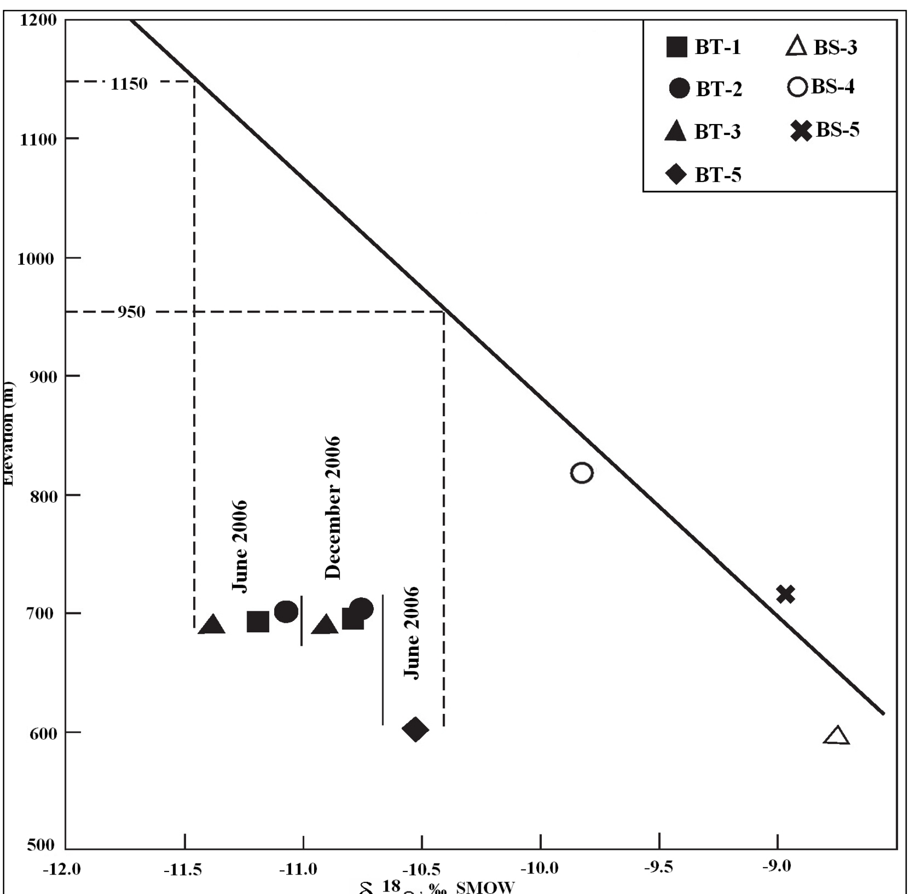

Figure 8- Oxygen-18 (δ^{18}O) versus elevation diagram of the waters in the Beypazarı region (Çelmen, 2008).

of 950-1150 meters. After determining the recharge elevation of the geothermal resource in the study area, the recharge area of the geothermal resource can be found by evaluating the hydrochemical characteristics of the water, the hydrogeological cycle in the region and also the tectonic and geological structures of the region.

After the determination of the recharge area, a suitable reinjection location should be selected where the geothermal fluid can be reheated as it reaches the reservoir again in the medium- to long-term time periods. If the reinjected geothermal fluid reaches the production wells in a very short time, it will cause a decline in temperature in the reservoir. There are examples of this negative situation that seen in some geothermal fields.

2.3. Reinjection Wells and Locations Determined By MTA Studies

Geothermal energy research studies in Türkiye were initiated by the MTA in 1962. Distrubition of geothermal resources in Türkiye that prepared by MTA shown in Figure 9. With these studies, many geothermal fields with different temperatures were discovered and tendered for investment in accordance with the provisions of the Geothermal Resources and Natural Mineral Waters Law No. 5686 and its Implementation Regulation. Reinjection trials and applications continue in many geothermal fields where geothermal energy is used for electricity generation, greenhouse heating and residential heating by municipalities and a lot of companies.

2.3.1. Denizli-Kızıldere Geothermal Field

The geothermal exploration surveys in Denizli-Kızıldere geothermal field were initiated by MTA in 1968 with the geological, geophysical, geochemical, drilling and testing studies in the area; this geothermal field is currently in operation for energy production. With the studies carried out by MTA, 10 production and 9 reinjection wells were drilled.

The operating license area was purchased by Zorlu Energy through a tender from the Prime Ministry Privatization Administration, and a total of 89 wells were drilled for geothermal energy production in the licensed area. The fluid obtained from these drillings is used in Kızıldere I Geothermal Power Plant (GPP) with an installed power of 17.5 MWe, Kızıldere-II GPP with an installed power of 80 MWe and Kızıldere GPP-III with an installed power of 165 MWe (Figure 10).

All produced geothermal fluids are reinjected back into the reservoir with the reinjection system located at the edge of the production area.

2.3.2. Kütahya-Simav-Eynal-Çitgöl-Nasa Geothermal Field

In the Simav-Eynal-Çitgöl-Naşa geothermal field, drilling works have been carried out by the General Directorate of MTA and the Municipality since 1985 and the geothermal fluid obtained from the drillings is used for residential heating, greenhouse heating and thermal purposes. There are 40 production and 2 reinjection wells in the area. The production

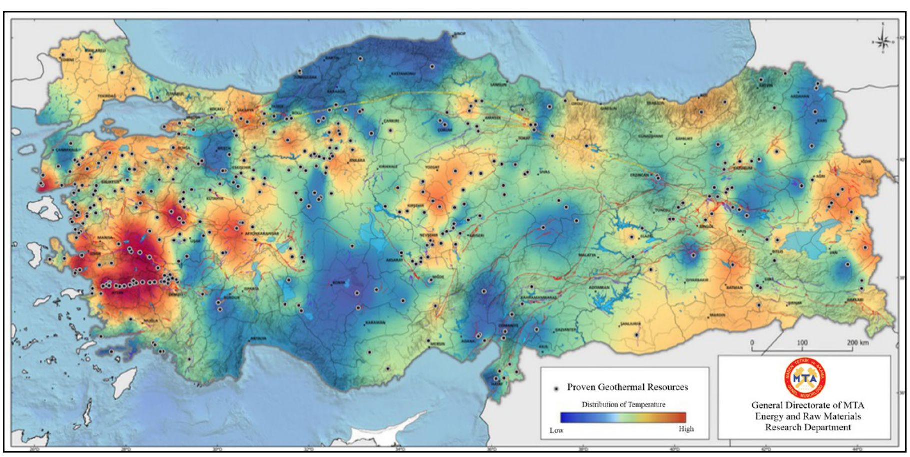

Figure 9- Distrubition of geothermal resources in Türkiye.

Figure 10- Kızıldere-3 Geothermal Power Plant by Zorlu Enerji Inc. in Denizli-Kızıldere geothermal field.

temperatures of the wells vary between approximately 45°C -136°C and the reinjected temperatures vary between 60°C-75°C (Doğdu et al., 2019). In Simav district, geothermal energy is used for 13.400 Re (residential equivalence) and also 265 decares of greenhouse heating as well as for thermal purposes. In the Simav-Eynal geothermal field Y-1 well is used for reinjection purposes. The geothermal wells in Çitgöl area are used for heating of 1,200 Re houses, and also for 130 decares of greenhouse heating as well as for thermal purposes. It has been determined that the wells in Naşa are used for thermal purposes in the spa facilities. It was observed that the geothermal fluid was reinjected into the existing Y-1 well during the periods of geothermal use in the winter months, but this was not sufficient for the sustainability of the geothermal reservoir. In this context, the reinjection area was determined as a result of the multidisciplinary evaluation of the geological, geophysical and other data of the MTA, and then for the purpose for the reinjection of water returned from Simav and Eynal residential and greenhouse heating uses, the reinjection well EJR-1 was drilled in 2022 by MTA (Figure 11) (Doğdu et al., 2022). But according to the observations and geothermal usage of the geothermal field, it has seen that at least 2-3 reinjection wells are needed for the long-term sustainability of geothermal resource in that region (Figure 11) (Doğdu et al., 2022).

2.3.3. Nevşehir-Kozaklı Geothermal Field

Nevşehir-Kozaklı geothermal field is considered as a medium enthalpy geothermal system based on available data and interpretations. In this geothermal area, drilling works have been carried out by the General Directorate of MTA and the Municipality since 1965. The geothermal fluid obtained from the drillings is used for residential heating, greenhouse heating and thermal purposes in the Nevşehir-Kozakli geothermal area. In the area, 2.294 residential heating, 67.000 m^2 greenhouse heating and 28 thermal facilities are used for thermal purposes. There are 25 production and 1 reinjection wells in the field (Figure 12). The production temperatures of the wells vary between approximately 36°C-92°C and the reinjected temperatures vary between 50°C-55°C. Thermal fluid is distributed by NEVJET AŞ to subscribers for residential heating and thermal use from the collection/distribution tank with a capacity of 1,500 tones, and fluid sent back to the reinjection well from the reinjection tank with a capacity of 500 tones. With surveys of MTA, 2 reinjection well locations have been determined by MTA in Nevşehir-Kozaklı geothermal area. Upon this survey, 1 reinjection well has drilled by authorities and currently used for reinjection purposes. According to long time surveys in Nevşehir – Kozaklı geothermal fields, it is suggested by MTA that, in order to ensure the sustainability of the geothermal field, the geothermal wells that are constantly used in the field should not be operated at full capacity before getting full production-reinjection balance of the reservoir. In terms of integrated use, distribution and used thermal water should be utilised for thermal purposes after residential heating and greenhouse heating applications. Finally, to ensure the sustainability of the geothermal field, reinjection of used brine should not be done at temperatures below 55°C-60°C.

In the Nevşehir-Kozaklı geothermal field, two sinkholes (Kozaklı-1 and Kozaklı-2) with a diameter of 90 x 70 meters and 22.3 x 21 meters were formed in 2007 and 2019 (Figure 13). It is thought that this situation is due to the inability to implement a suitable reinjection strategy and the lack of optimum production from geothermal wells. In addition to the existing wells, requested new wells will generate more thermal fluid from the geothermal reservoir and it would be

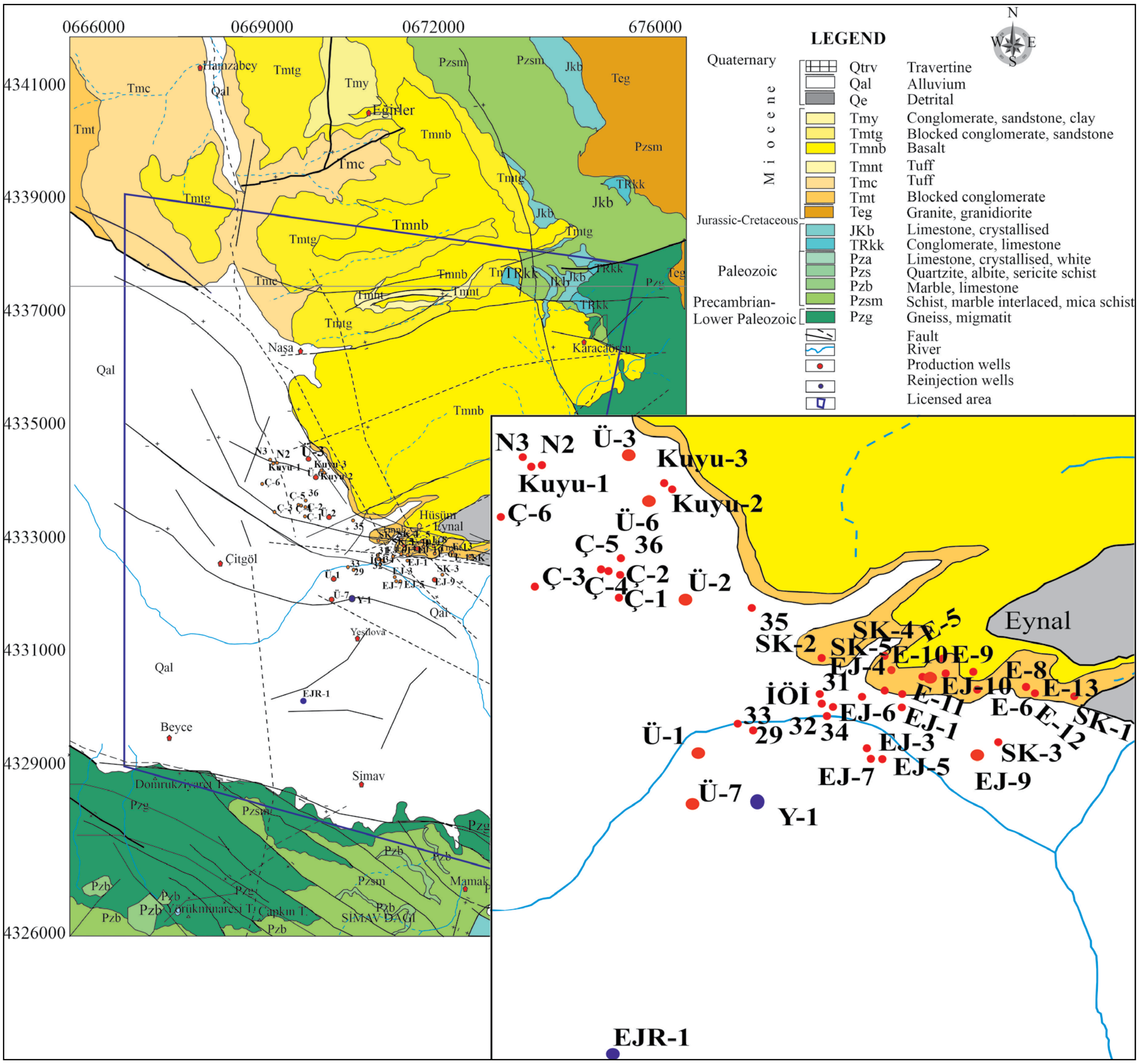

Figure 11- Kütahya-Simav-Eynal-Çitgöl-Naşa Geothermal Field (Doğdu et.al., 2022).

appropriate to ensure more controlled use of all wells, including conducting another round of interference testing to ensure the sustainability of the geothermal field. It would be appropriate to drill a new reinjection well in the reinjection area determined by the MTA. However, it would also be a good strategy to monitor existing reinjection and production wells for at least two periods to ensure that the reinjection volume does not adversely affect the geothermal reservoir.

It is clear that production-reinjection balance is very critical in some areaa to ensure the sustainability of the geothermal reservoir. If this geothermal balance is provided with good production-reinjection policy, new sinkholes that result from sudden water level changes due to the mass withdrawal from the production wells may be prevented.

2.3.4. Afyon-Sandıklı Geothermal Field

In the Sandıklı geothermal field, as a result of geophysical, geological studies and hydrogeological evaluations carried out within the framework of consultancy works carried out by MTA, a reinjection area was determined and a reinjection well (AFS-188) was drilled. In current time, Afyon-Sandıklı geothermal resource operation licensed area is used by SANJET Inc. According to the conversations with the authorities, 19,200 Re houses (equivalent to 33.000

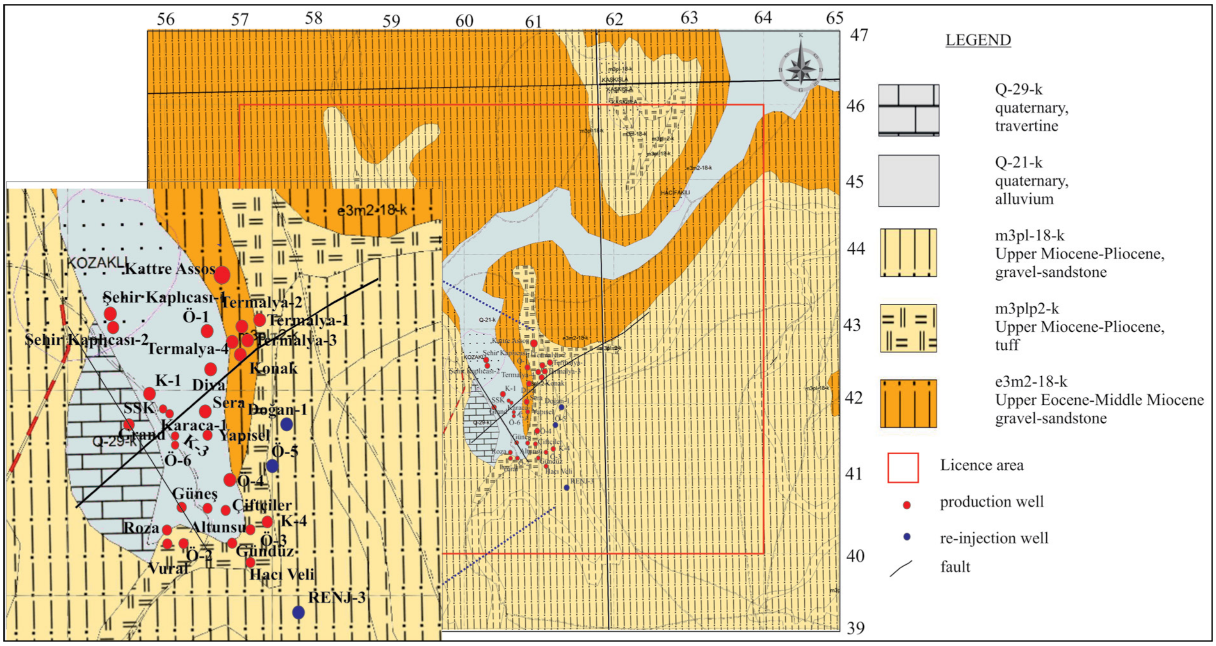

Figure 12- Nevşehir-Kozaklı Geothermal Field (Doğdu et al., 2018).

Figure 13- a) Kozaklı-1 sinkhole (2007) and b) Kozaklı-2 sinkhole (2019).

houses) and 24 greenhouses (1.500.000 m^2) were heated by geıthermal energy and 1.200 m^3-1.500 m^3 of geothermal fluid at a temperature of about 70°C-75°C in the current situation came to the heat center storage. It was learned that 1.200-1.500 m3 of geothermal fluid was reinjected at temperature approximately 40°C-45°C. According to the well information received from Afyon Special Provincial Administration, there are 33 production and 4 reinjection wells in the Afyon-Sandıklı geothermal resource operation licensed area.

The geothermal fluid in the field is used for both thermal tourism and space heating purposes. Geothermal operations should carried out by a plan as a result of the production and interference tests and reinject the fluid after heating purposes under suitable conditions to make sure the sustainability of the source. The effect of reinjection on the geothermal system should be monitored with the well tests and also should taking into account the measures and activites mentioned in the Geothermal Resources and Natural Mineral Waters Law No. 5686 and the Implementation Regulations.

In addition, as stated in the technical opinions given by MTA in previous Resource Conservation Area reports, no new wells should be drilled especially in the corridor extending from Hüdai thermal springs to İnpınarı location to ensure sustainability in the field, (Tamgaç et al., 2012). Also, that MTA study suggests that new production wells should be drilled at the north of Tozkoparan Tepe, Şaban well location, Savurmaz Harmanları, Gülbahçe location line, and south of the Sipsin Damları, Koruçayırı location, and Cinsigüzel locality line. It is strongly recommend to monitoring geothermal field with production wells according to reinjection strategy in the field to ensure sustainability of the geothermal field.

2.3.5. Afyon-Merkez-Ömer-Gecek Geothermal Field

Afyon Merkez-Ömer-Gecek geothermal field is operated by AFJET Inc. for electricity generation, residential heating, greenhouse heating and other thermal purposes. This geothermal field is operated with a production-reinjection system.

In the Ömer-Gecek geothmeral area, AFJET Inc. used some closely spaced reinjection wells near production wells as observed by the MTA. A new reinjection area was determined by the MTA that would not affect the production wells according to a request of the Afyon Governship in 2016. To determine the new reinjection area, previous geological, geophysical and hydrogeological studies should be evaluated.

2.3.6. Afyon-Çobanlar Geothermal Field

There are six wells registered under the Çobanlar Municipality in the Afyon-Çobanlar geothermal area. In this area, geothermal wells are used for greenhouse heating and thermal tourism purposes. It was learned from the greenhouse authorities that the geothermal fluid used for heating the greenhouse, after being transported approximately 3.5 km, has an inlet temperature of 57°C-58°C and an outlet temperature of 32°C-35°C.

According to request of Afyon Government in 2016, a new renjection area was determined by MTA considering the location of reservoir, production wells and groundwater flow direction, etc.

2.3.7. Elazığ-Cipköy Geothermal Field

According to the request of the Elazığ Municipality in 2020, on-site investigations were carried out in the Elazığ-Cipköy geothermal area by MTA. Considering the studies carried out in the previous years, a new geothermal reinjection area was determined to ensure the sustainability and integrity of the reservoir. Also, the MTA suggested to produce geothermal fluids to use in optimum flow rates and to reinject after usage in greenhouse heating.

By evaluating all the geological, geophysical, hydrogeological and isotopic studies carried out, it is suggested that, the possible recharge elevation of the geothermal reservoir could be between 1300 meters - 1500 meters. At this elevation, the possible recharge of the system may be from marble-limestone units lithologically that located north-northwest of the geothermal area. Thus, it was suggested to consider drilling new geothermal reinjection wells from licence border (currently) to the Poyraz and Pelteköy locations.

3. Conclusions

Reinjection plays a crucial role in maximizing the efficiency and sustainability of geothermal energy production. From this point of view, ensuring the sustainability of geothermal resources depends on the protection of these resources to sustain production-reinjection balance policy.

Firstly, reinjection helps maintain reservoir pressure, ensuring a long-term and sustainable energy resource. Geothermal reservoirs are naturally pressurized and the extraction of fluids for energy production can lead to a decline in pressure over time. This can result in a reduced efficiency of energy extraction or even the complete depletion of the reservoir. However by reinjecting the used thermal fluids in the right conditions and locations, the pressure is maintained, allowing for continuous and reliable geothermal energy production.

Geothermal fluids may contain economical valuable minerals and dissolved substances that can be extracted and utilized for various industrial and agricultural purposes that may be not economical in todays technology. By reinjecting the fluids, these valuable resources can be preserved and potentially extracted in the future as technology advances.

Reinjection also helps to mitigate environmental impacts. Geothermal fluids often contains heavy metals and dissolved gases that can have negative impacts for the nature. If these fluids are not properly managed and disposed of, they can pose a risk to ecosystems and groundwater quality. However, by reinjecting the thermal fluids into the reservoir, the potential for contamination is minimized, and get ensure the protection of surrounding ecosystems and water sources.

In details, reinjection locations determinations should be surveyed with geological data (stratigraphy, lithology, tectonism, hydrogeology), borehole data (litostratigraphy, definitions, changed temperature in depth), geophysical data, well logs, flow rates, hydrogeochemical data (temperatures of springs and wells, chemical compositions) and also with flow maps, tracer tests and stable isotope studies. These datas should be examined together to ensure the recharge area of the geothermal system, to get rid of possible negative effects of reinjection such as scaling problems in the wells or cooling geothermal reservoir by short circulating of reinjected thermal fluid.

In some cases, because of the geographical shape of the licenced area (ununiformed or small sized), reinjection locations determinations may be difficult even impossible to determine. In this situation reinjection or discharge policy of the used thermal fluid should be evaluated by General Directorate of Mineral Research and Exploration under the Geothermal Law.

Finally, although the determination of a reinjection well in a geothermal system is very important for sustainable energy production, continuous monitoring of the production and reinjection balance is very crucial. With this monitoring and continous surveys, possible changes in the reservoir parameters (pressure, temperature, hydrochemical etc.) and also in the production and reinjection wells should be carried out to get long term green energy sustainability.

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References

Atılgan, M. 1994. Jeotermal Kaynaklarda Re-enjeksiyonun Önemi. Jeotermal Uygulamalar Sempozyumu, 27-30 Eylül 1994, Pamukkale Üniversitesi, Denizli, Turkey, 56-60.

Axelsson, G. 2013. Tracer tests in geothermal resource management. In EPJ Web of Conferences (Vol. 50).

Barbier, E.2002. Geothermal energy technology and current status: An overview. Renewable and Sustainable Energy Reviews. 6(1–2):3-65.

Çelmen, O. 2008. Hydrogeochemical and isotopic investigation of the thermal and mineralized springs between Sivrihisar and Beypazarı region (in Turkish). Ankara University. Graduate School of Natural and Applied Sciences. Ph.D. Thesis, 239, Ankara, Turkey.

Doğdu, N. 2004. Determination of Hydraulic Properties of Afyon Plain by Indicator Geostatistics and Inverted Modeling Techniques. Hacettepe University. Graduate School of Natural and Applied Sciences. Ph.D. Thesis, 66, Ankara, Turkey.

Doğdu, N., Orakcı, A., Atmaca, İ., Akar, M., Duran, Y. 2018. Kozaklı (Nevşehir) 2007/18 numaralı işletme ruhsatına ilişkin Kaynak Koruma Alanı Etüt Raporu, General Directorate of Mineral Research and Exploration. Report No: 13746. 122, Ankara, Turkey (unpublished).

Doğdu, N. Aydoğdu, Ö. Akar, A. Şahan, M. Akar, M. Duran, Y. Bilgiç, Ö. 2019. Simav-Eynal-Çitgöl-Naşa (Kütahya) 105 numaralı işletme ruhsatına ilişkin kaynak koruma alanı etüt raporu. General Directorate of Mineral Research and Exploration. Report No: 13813, 244, Ankara, Turkey (unpublished).

Doğdu, N., Şahan. M., Tamgaç, Ö. F., Öztel, İ., Akar, A., Güven, A., Toy, E., Atmaca, İ. 2022. Kütahya İl Özel İdaresi adına tescilli 105 nolu jeotermal kaynak işletme ruhsat sahası Ü-1, Ü-2, Ü-3, Ü-6 jeotermal araştırma sondajları kuyu bitirme raporu. General Directorate of Mineral Research and Exploration. Report No: 14076. 122, Ankara, Turkey (unpublished).

Kamila, Z., Kaya, E., Zarrouk, S.J. 2021. Reinjection in geothermal fields: An updated worldwide review 2020. Geothermics. Volume 89.

Mazor, E. 1991. Applied Chemical and Isotopic Groundwater Hydrology. Open University Press, Suffolk, 274.

Roberts, D. 2020. Geothermal energy is poised for a big breakout, www.vox.com.

Şirin, Ö. 2019. Yeraltısuyu akışı, yeraltısuyu boşalımı ve Darcy Kanunu, https://docplayer.biz.tr.

Tamgaç, Ö.F., Doğdu, N., İncegil, F., Ünal H., Akar, M 2012. Sandıklı (Afyonkarahisar) jeotermal alanına ait kaynak koruma alanları etüt raporu. General Directorate of Mineral Research and Exploration. Report No: 11526, 74, Ankara, Turkey (unpublished).

Tezcan, L. 2000. Groundwater Models. Lecture Notes. Hacettepe University, Geological Engineering Department. Ankara, Turkey (unpublished).

Vitaller, A. V., Angst, U., Elsener, B. 2019. Corrosion Behaviour of L80 Steel Grade in Geothermal Power Plants in Switzerland, Metals - Open Access Metallurgy Journal 9 (3), 331.

White, D. E. 1973. Characteristics of Geothermal Resources. in P. Kruger and C. Otte, eds., “Geothermal Energy: Resources, Production, Stimulation” (Stanford University Press, Stanford, 69 - 94.