PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Tracer Testing at Kizildere Geothermal Field, Turkey, Using Naphtalene Sulfonates

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Keywords: Kizildere, tracer, naphthalene sulfonates, model

ABSTRACT

Kizildere Geothermal Field, Turkey is one of the oldest high enthalpy geothermal fields in Turkey is in third development stage. In order to optimize re-injection a tracer test where four tracers (Fluorescein and three different naphthalene sulfonates) were simultaneously injected into four different re-injection wells, was conducted. Quantitative and qualitative analysis of tracer concentrations measured using HPLC were used to identify connectivity between the re-injection and production wells. Flow – storage capacity plots were used to identify flow geometry. It has been concluded that tracer return patterns slightly changed in some production wells. The results showed that a single fracture model can be used to model tracer returns for most wells. Finally, a capacitance resistance model was used to confirm tracer results.

1. INTRODUCTION

The Kizildere geothermal field was discovered in 1968. It is located in the Denizli and Aydin provinces of western Turkey at the Western extreme of the Büyük Menderes graben. The Menderes massif was uplifted during late Pliocene and Quaternary times, and east-west grabens formed as a result of tensional forces. Magma rose under the massif and under the grabens where the earth's crust is thinner. Thus, the geothermal fields occur naturally along the grabens and the Kizildere field is an example (Simsek, 1985). The field lies on several main fault blocks, generated by two-step normal faults, running nearly parallel to the flank of the Menderes Valley. The area is rich with geothermal manifestations, including hot water springs at a temperature between 30 °C and 100 °C. Typical stratigraphic column of Kizildere reservoir consists of the three reservoirs, shallow Mesozoic limestones (Sazak formation), intermediate depth Paleozoic carbonates (Igdecik formation) and deep Menderes Paleozoic rocks. These rocks are overlain by continental and lacustrine Pliocene sediments that have been divided into four lithological units from bottom to top. The Kızılburun Formation (Tk) consists of alternating red and brown conglomerates, sandstone and claystone, and lignite seams. The Sazak formation (Ts) is a minor producing zone composed of intercalated gray limestone, marl and siltstone. The Kolonkaya formation (Tko) consists of yellowish green marls, siltstones and sandstones. The Tosunlar formation (Tt) is composed of alternating units of poorly consolidated conglomerates, sandstones and mudstones with fossiliferous claystone (Şimşek, 1985). The sediments with higher clay content or metamorphism dominated by mica form impermeable cap rocks above and between the permeable reservoir zones hosted in more brittle formations. In this regard, shallow Kizilburun, Kolonkaya and locally Sazak formation form the cap rock. The maximum temperatures of Sazak and Igdecik formations are 198 °C and 209.1 °C, respectively, whereas the metamorphic reservoir maximum is 236.5 °C. The Kizildere field was first investigated in the 1960's, and has been exploited to varying degrees since. The first well, KD-1, drilled in 1968 produced a mixture of water and steam with a temperature of 198 °C at a depth of 540 m indicating the existence of a water-dominated geothermal system. Since then, more than 30 wells have been drilled for phase I and II (Figure 1). The first geothermal power plant with a capacity of 20.4 MWe was commissioned in 1984. Well performance gradually declined that may be attributed to little or no reinjection relative to production and to calcite scaling in the production wells which was mitigated primarily by periodic mechanical removal from the wellbore. In 1998, a deep high temperature resource was discovered. After the privatization of the field in 2008 new re-injection and production wells have been drilled to mitigate pressure decline. Then a 60 MWe triple-flash power plant (Yamada et al, 2015) and 20 MWe binary plant started commercial operation in September 2013. Kizildere geothermal reservoir includes a high non-condensable gas (NCG) content, of which 99% is carbon dioxide (CO_2). CO_2 concentrations dissolved in the geothermal reservoir brine vary from 0.02-0.03 kg/kg of brine in the deep reservoir and 0.01 - 0.02 kg/kg of brine in the intermediate reservoir (Haizlip et al, 2011). The intermediate reservoir wells are producing to the Kizildere I and the deep reservoir wells are producing to the Kizildere II plant.

1.1. 2002 Tracer Test

A slug of 30 kg sodium fluorescein diluted in 3000 liters of water was injected to R-2 at an average rate of 230 ton/h fluid taken from the separators of four production wells 05/09/2002. Sample collection from the production wells stopped on 11.13.2003. During the tracer test, 81,313 tons of fluid and during long re-injection test 519,689 tons of fluid at a rate of 230 t/h was re-injected to R-2 well. In addition to these 715,308 tons of waste fluid was re-injected at an average rate of 106 t/h and at a temperature ranging between 114 °C and 144 °C from 12.10.2002 to 05.21.2004. It was observed that as a result of re-injection total production rate of the region where old production wells were found increased from 830 t/h up to 1000 t/h.

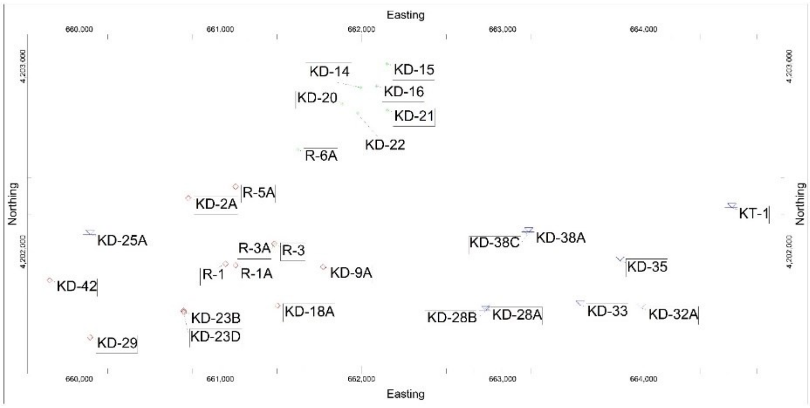

Figure 1: Kizildere location map (circles: Kizildere I production, diamonds: Kizildere II production, triangles: injection).

Throughout the test, there was a little change in the dynamic temperature at the reservoir level of KD-6 well for the aforementioned 101 day long re-injection test. This change was believed to be due to changes in production rate which was affected by calcite scaling in the well. But during and after the test, the temperature decline at the reservoir level was approximately 3.36°C. The temperature continued to decline for 160 days and then started to increase after reinjection stopped for 466 days. As a result, it was concluded that the re-injection reduced the reservoir temperature especially around KD-6 well and this negative effect was preserved for a long time.

When the first arrival time and the amount of tracer recovered from production wells were studied, it was seen that, tracer dispersed to KD-6 and KD-9 directions. Following that, it traveled to KD-13, KD-21, KD-20 and KD-22 wells. Finally, tracer reached to KD-16. The tracer flow path was in accord with the cold water mixing direction suggested by Simsek (1985). On the other hand, sodium fluorescein never reached at KD-14, KD-15 and R-1 wells during the test. R-1 is located near the southern fault zone whereas, KD-14 and KD-15 are at the north of the reservoir separated by a sloping spring from KD-16. Thus, compartmentalization at the north section of the reservoir is one possible reason for this behavior. On the other hand, production change at KD-15 affected the dynamic level of the observation well, KD-8. Likewise, production change at KD-14 affected the dynamic level of the observation well, KD-7. Thus the north region of the reservoir is partially sealed from the rest of the reservoir. Velocities calculated from mean tracer arrival times changed between 3,77 m/d to 5.85 m/d.

2. RESULTS AND DISCUSSIONS

2.1. 2015 Tracer Test

With the commissioning of Kizildere II power plant geothermal injectate has been re-injected using 11 wells (Fig 1). Four of these injection wells were selected to be used in the tracer test. KD-23C is located within the production zone of Kizildere II power plant. KD-27A is the closest of the injection wells located at the east of the field. KD-38C delivers most of the re-injection (775 t/h) and finally, KD-25A is located at the west of the field at the new production area of Kizildere III project. Naphtalene sulfonates were selected as tracer chemicals as they have been proven to work in high reservoir temperatures as conservative tracers (Rose et al., 2002). For the month prior to each test a steady injection rate is maintained at the injector of interest in order to establish a consistent injection flow path in the reservoir. Background samples are then collected from production wells for at least two weeks prior to tracer injection. The test started in 2 March 2015 by mixing 300 kg fluorescein in 4.5 tons of water. The resulting mixture was injected in less than half an hour into KD-38C using an additional 1.5 tons of cold water. Similarly, 50 kg of naphthalene sulfonate (1-ns, 1-5 nds or 1,3,6 nts) was injected in each aforementioned re-injection well by mixing with 1.5 tons of water. The amount of tracer chemicals injected and the corresponding well is reported in Table 1. Water samples were collected periodically at each production well three times a day using mini separators. After reaching peak tracer concentration the sampling period was reduced to two times a day. Finally, the sampling frequency was reduced to one sample per day when a plateau concentration is obtained. The sampling stopped in 1st of November due to a scheduled power plant shutdown. The HPLC method based on ion pair chromatography proposed by Rose et al. (2002) was modified to analyze Naphthalene sulfonates (1-ns, 1.5 nds, 1.3.6. nts). Fluorescein sodium salt concentration was analyzed using a fluorimeter.

Table 1. Tracer chemicals and injected amounts.

Well	Tracer	Amount, kg
KD-23C	1,3,6 nts	50
KD-25A	1,5 nds	50
KD-27A	1 ns	50
KD-38C	Fluorescein	300

2.2. Tracer Return Analysis

Tracer recovery observed in production wells are mapped as shown in Figure 2. All of the injected naphthalene sulfonate tracers have been observed in Kizildere Phase II production wells. The first and mean arrival times of naphthalene sulfonates provided information on the velocity of the injectate flowing on its path from the injector to the producers (Table 2). The mean residence time, or first temporal moment, is a useful property derived from a tracer test was obtained using a method proposed by Shook and Forsmann (2005). Note that tracer concentrations had not yet reached 0 ppm at the end of sample collection for both wells (See Figure 3, 4, and 5). That's why an extrapolation technique based on the slope of the final tracer concentrations was used. The flow velocities derived from mean arrival times and distances between reservoir levels of the injection and production wells were somewhat larger than those obtained during the 2002 tracer test, which could be either due to larger permeability and/or larger amount of re-injection due to increased capacity. Flow – storage capacity plots showed that reservoir was relatively homogeneous such that even at the most extreme case (KD-23B) 30% of the flow came from some 12% of the total pore volume. This indicates a few high permeability fractures are dominating the interwell flow. In addition to the information about the velocity, the tracer test also provided important information about the direction that injected fluids have traveled, both horizontally and vertically. The shallower Kizildere Phase I production wells did not show any tracer recovery during the test period. This implies a stratification to injectate flow, whereby deep injectate remains deep and is not recovered in relatively shallow producers. This could be due to permeability barriers that retard vertical flow, or simply caused by density contrast between the in situ reservoir fluid and the as-yet cooler injectate. Although a substantial amount of sodium fluorescein has been injected from KD-38C, it has not been observed in any production well. As discussed above this well injects the largest amount of injectate into the reservoir. Similar to aforementioned discussion, this could be due to a horizontal permeability barrier that retards the flow. It is also possible that there is no common path for injectate flowing between the two tagged injectors (KD-38C and KD-27A). On the other hand, 1.5 naphthalene di-sulfonate tracer injected from the west of the field has been recovered in the majority of Phase II wells. As a conclusion, flow mostly occurs in the direction of prevailing pressure gradients at both sections of the reservoir.

Using mean tracer arrival times, thermal breakthrough times and then the thermal velocities (Table 2 and Figure 2) were estimated using a method proposed by Shook (1999, 2001). Here t_T^{BT} is thermal breakthrough time, t_w^{BT} is tracer breakthrough time and D_t is the thermal retardation factor. The thermal velocities were somewhat smaller than the flow velocities due to retardation by thermal inertia of reservoir mass.

$$t_T^{BT} = t_w^{BT}(1 + D_t) \tag{1}$$

Table 2. Tracer mean arrival times and thermal velocity estimates.

Well	t_T^{BT}, 1,5 nds days	t_T^{BT}, 1,3,6 nts days	t_T^{BT}, 1 ns, days	Flow Velocity, m/d	Thermal velocity, 1 ns, m/d	Thermal velocity, 1.5 ns, m/d	Thermal velocity, 1.3.6. nts, m/d
KD-18A			266.34	9.01	7.71		
KD-23B	149.41	92.54		17.63		7.60	12.27
KD-23D	429.82			15.63		2.70	
KD-2A	297.5			13.05		2.73	
KD-9A			172.39	5.04	4.70		
R-1	176.56			12.02		5.82	
R-3A			205.09	7.43			
KD-42	144.28			4.49	5.27		
Mean	239.51	92.54	181.90	10.54	5.90	4.63	12.27

Several mathematical models (Homogeneous, fracture – matrix, single fracture, multi fracture and double porosity pseudo steady state) were used to model tracer returns observed in production wells. Similar to modelling results of 2002 tracer test two models' results were better than the others: multi-fracture and single fracture model (Fossum and Horne, 1982). Multi-fracture model assumes a multi fracture (more than 2) system joining the injection and observation wells. Dispersion is due to the high velocity profile across the fracture and molecular diffusion that moves tracer particles between streamlines (Taylor dispersion). On the contrary, in single fracture model, there is a large fracture connecting the production and injection wells. Tracer particles leave the main fracture and enter the micro fracture network (there is a small amount of fluid exchange), stay for a while, and then return to the main fracture. Longitudinal dispersion due to the velocity profile across the fracture is ignored in order to give a clear distinction from the single fracture model. A fracture with fluid velocity constant across the thickness and with diffusion perpendicular to the fracture into an infinite porous medium is used in this model. The details of the models are reported elsewhere (Akin, 2001). Tracer response curves were analyzed using a least squares approach. The matches were obtained by minimizing the sum of squares of the differences between the model and field data. A minimum of two fractures was enough to model tracer returns in most wells. Peclet number was larger than 15 and the mean arrival time of the main fracture was small in many instances. Small Peclet numbers (<1.5) were obtained for the majority of the wells in the slower fracture showing that dispersive transport was taking place. Contribution of this fracture was larger (e>0.9) than the faster fracture where advective transport was the dominant mechanism. As conclusion, it could be speculated that injected water travels through the Kizildere geothermal reservoir by paths (channels) along fractures and dispersion and mixing through a larger part of the reservoir confirming the observation obtained from the flow-storage capacity analyses. Unbalanced approach has been used to couple the effect of natural recharge.

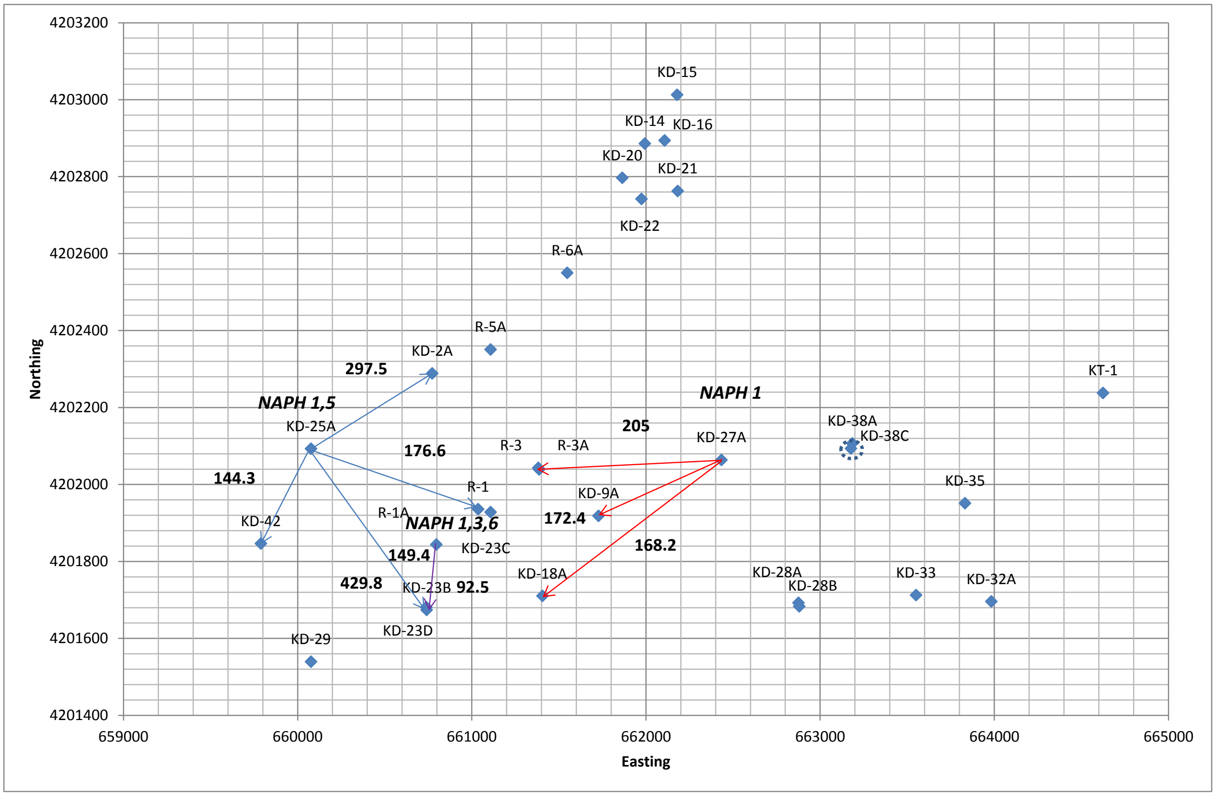

Figure 2: Tracer recovery and calculated thermal breakthrough times (days).

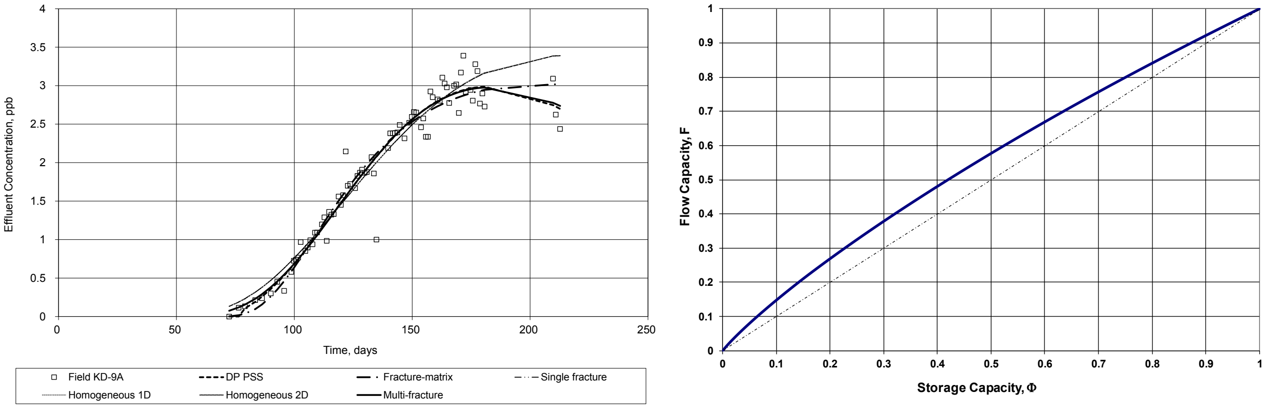

Figure 3: Tracer (1 ns) recovery curve (KD-9A) and model matches (left), flow-storage capacity plot (right).

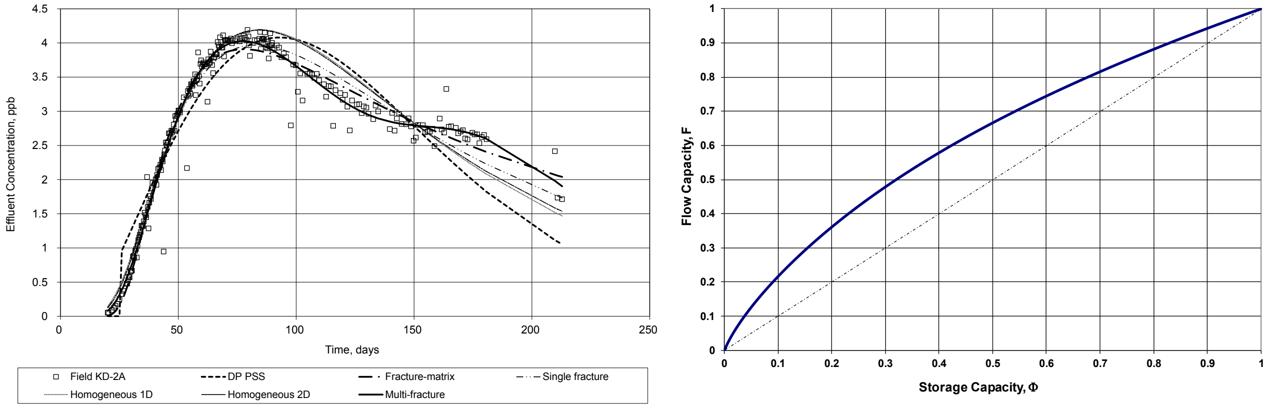

Figure 4: Tracer (1.5 nds) recovery curve (KD-2A) and model matches (left), flow-storage capacity plot (right).

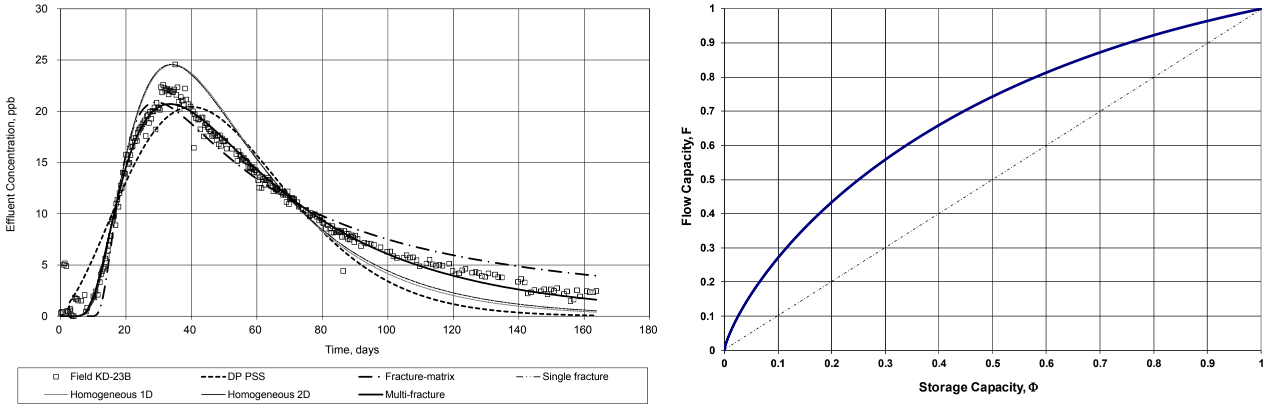

Figure 5: Tracer (1.3.6. nts) recovery curve (KD-23B) and model matches (left), flow-storage capacity plot (right).

2.3. Capacitance-Resistance Model

A simple capacitance-resistance model (CRM) model is developed for Kizildere geothermal reservoir to verify and support the findings obtained during the tracer test analysis. Details of this modeling approach is reported elsewhere Akin (2014). This model attempts to simulate a dynamic system with parameters that are not time dependent. The resulting analysis established producer-injector relationship (Figure 6). The model results were not used to interpret KD-25A and KD-23C as these wells did not have a long history to be matched using the CRM model. Contrary to findings of the tracer test analysis, CRM results showed KD-38C supported several producers to some extent. Similar results were obtained for KD-27A and other injectors. This could mean that although there is no direct flow path between an injector and a producer, but the injector still contributed to flow by means of pressure support. The resulting natural recharge analysis (Figure 7) showed that deeper Phase II wells had higher natural recharge support compared to shallower Phase I wells.

3. Conclusions

A tracer test was conducted in Kizildere Geothermal Field, Turkey where four tracers (Fluorescein and three different naphthalene sulfonates) were simultaneously injected into four different re-injection wells. The following conclusions were reached as result of quantitative and qualitative analysis of tracer concentrations.

- The flow velocities derived from mean arrival times and distances between reservoir levels of the injection and production wells were somewhat larger than those obtained during the 2002 tracer test, which could be either due to larger permeability and/or larger amount of re-injection due to increased capacity.
- Flow – storage capacity plots showed that reservoir was relatively homogeneous such that even at the most extreme case (KD-23B) 30% of the flow came from some 12% of the total pore volume. This indicates a few high permeability fractures are dominating the interwell flow.
- The shallower Kizildere Phase I production wells did not show any tracer recovery during the test period, which could be due to permeability barriers that retard vertical flow, or simply caused by density contrast between the in situ reservoir fluid and the as-yet cooler injectate.

- Although a substantial amount of sodium fluorescein has been injected from KD-38C, it has not been observed in any production well, which could be due to a horizontal permeability barrier that retards the flow
- Flow mostly occurs in the direction of prevailing pressure gradients at both sections of the reservoir.
- A multi fracture tracer model successfully modeled tracer return curves.
- A simple capacitance-resistance model (CRM) model developed for Kizildere geothermal reservoir verified some of the findings of the tracer test such that there is no direct flow path between an injector and a producer, but the injector still contributed to flow by means of pressure support.

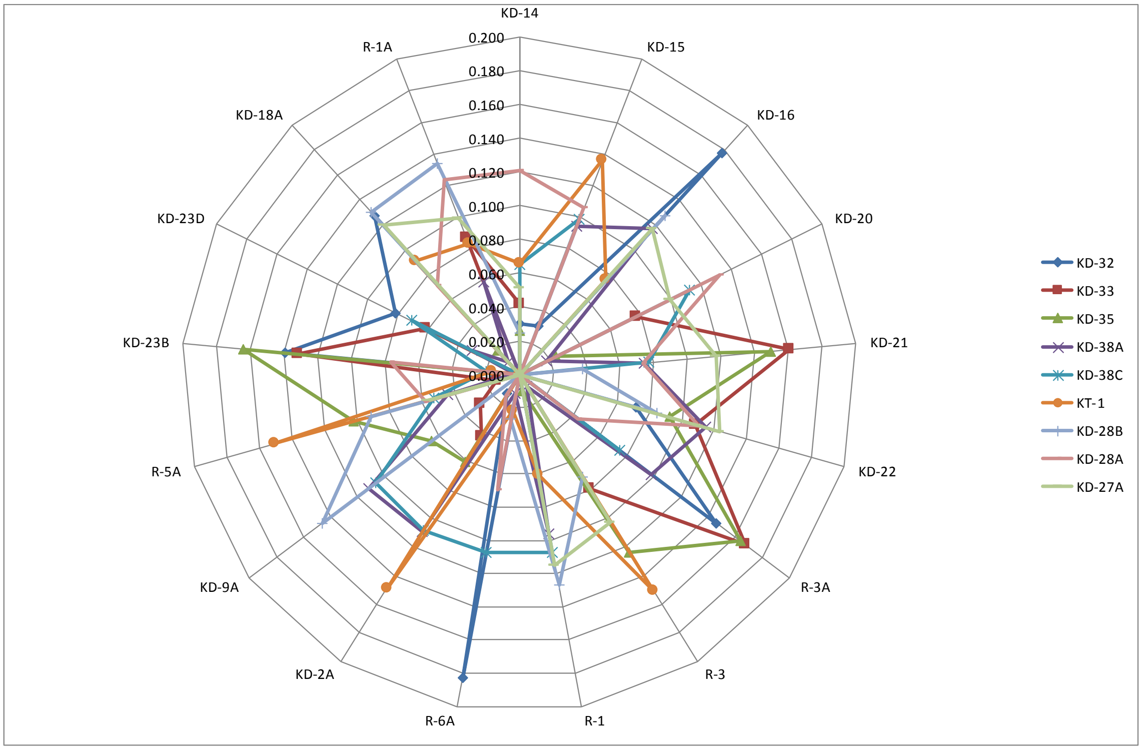

Figure 6: Tracer (1.3.6. nts) recovery curve (KD-23B) and model matches (left), flow-storage capacity plot (right).

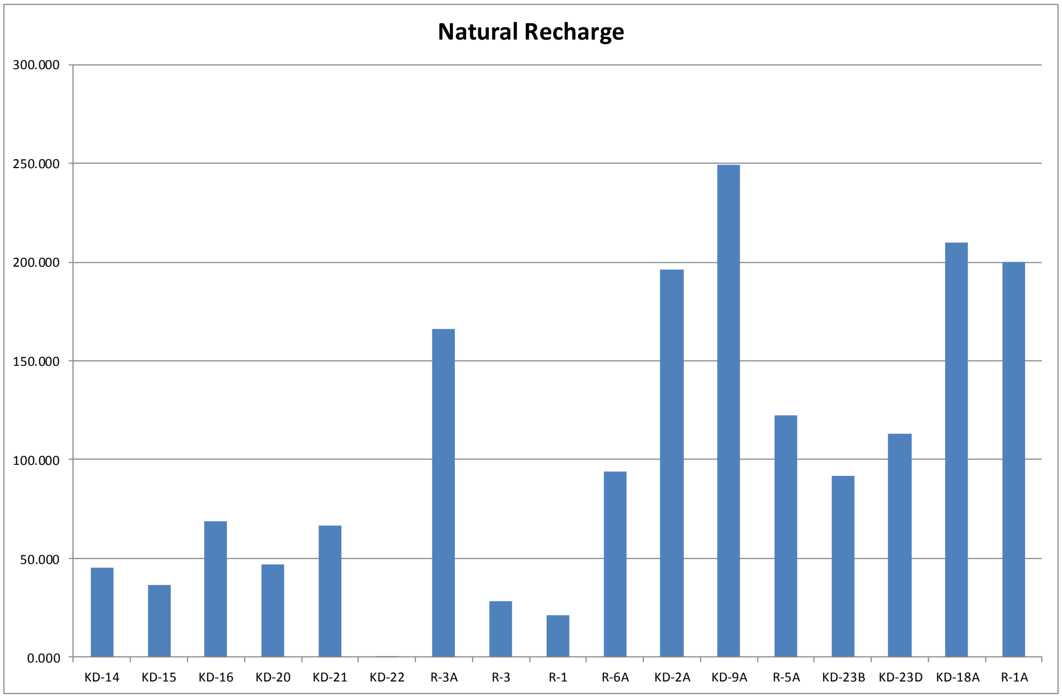

Figure 7: Natural recharge amounts obtained from CRM model.

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