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Environmental effects of geothermal energy utilizations: A case study of the Seferihisar geothermal system, İzmir, Türkiye

Jeotermal enerji kullanımının çevresel etkileri: Seferihisar jeotermal sistemi örneği, İzmir, Türkiye

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Abstract

Geothermal resources are often regarded as environmentally friendly and sustainable resources. They are utilized for different purposes, including energy generation, thermal tourism and greenhouse cultivation. The utilization type depends on the temperature, chemical characteristics and the flow rates of available geothermal resources. In long-term applications, there is a need for research and monitoring process to assess environmental consequences. Also, supervised use of the resource is crucial for both the geothermal system and its environment, as there is a possibility of unpleasant impacts on the environment, as chemical pollution, subsidence, and thermal effects in cases of improper use of geothermal resources. In Seferihisar, current consumption types of geothermal energy are consisting of a geothermal power plant with an installed capacity of 12 Mwe and a few primitive spas. In the Tuzla geothermal field, the geothermal waters ascending to the surface cause the deposition of travertine, where sea water interference to the geothermal system is clearly observed and supported by XRD analysis of the sample collected from the Tuzla travertine. Seismic activities as earthquakes, affect the surface manifestations of the SGS. The temperature measurement values obtained from Tuzla and Doğanbey are higher than the values recorded prior to the installation of the geothermal power plant. The operation of the geothermal power plant has caused the nearby hot springs to dry up and has ceased travertine deposition in the Cumalı geothermal field. The annual mean values of NO_2 and SO_2 for the region are lower than the National threshold value and European Union Countries' threshold value.

Keywords: Environment, Geothermal, Surface manifestations, Travertine

Öz

Jeotermal kaynaklar, genellikle çevre dostu ve sürdürülebilir kaynaklar olarak kabul edilmektedir. Enerji üretimi, termal turizm ve sera ısıtması dahil olmak üzere farklı kullanım türleri bulunmaktadır. Kullanım türü mevcut jeotermal kaynağın sıcaklığı, kimyasal özellikleri ve debisine bağlıdır. Uzun vadeli uygulamalarda, çevresel etkilerini ve sonuçlarını değerlendirmek için araştırma ve izleme süreçlerine ihtiyaç duyulmaktadır. Ayrıca, jeotermal kaynakların yanlış kullanılması halinde kimyasal kirlilik, çöküntüler ve termal etkiler gibi olumsuz çevresel etkilerin ortaya çıkma olasılığı da bulunduğundan, kaynağın denetimli kullanımı hem jeotermal sistem hem de kaynağın bulunduğu bölge açısından önem taşımaktadır. Seferihisar jeotermal sistemindeki jeotermal enerjinin mevcut kullanım alanları 12 MWe kurulu güce sahip jeotermal enerji santrali ve birkaç ilkel kaplıcadan ibarettir. Denizsuyu girişiminin net olarak gözlendiği Tuzla jeotermal sahasında yüzeye çıkan jeotermal sular traverten oluşumuna neden olmakta ve Tuzla travertenlerinden alınan numunenin XRD analizi ile desteklenmektedir. Deprem gibi sismik aktiviteler SJS'nin yüzeysel belirtilerini etkilemektedir. Tuzla ve Doğanbey'de elde edilen sıcaklık ölçüm değerleri, jeotermal enerji santralinin kurulmasından önceki değerlerden daha yüksektir. Jeotermal elektrik santralinin faaliyete geçmesi, yakınındaki sıcak su çıkışlarının kurumasına ve Cumalı jeotermal sahasındaki traverten oluşumunun durmasına neden olmuştur. Bölgedeki NO_2 ve SO_2'nin yıllık ortalama değerleri Ulusal limit değerinden ve Avrupa Birliği Ülkeleri limit değerinden düşüktür.

***Anahtar kelimeler**: Çevre, Jeotermal, Yüzey belirtileri, Traverten*

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1. Introduction

Geothermal resources are great sources for extracting heat energy and are abundant in the areas those take place on or near tectonically active zones. Turkey has a significant geothermal energy potential, with an installed capacity of 1691 Mwe as of year-end 2023. It ranks fourth among the top ten geothermal countries in the world, generating electricity (Figure 1) (ThinkGeoEnergy, 2023). Although these sources are meant to be a gift of the seismic activities, they also have some unpleasant impacts on the environment such as chemical pollution, subsidence and thermal effects in circumstances of improper use of geothermal resources. Regarding these global effects, numerous researchers focus on this issue in their studies (Kristmannsdo´ttir & A´rmannsson, 2003; Baba, 2004; Baba & A´rmannsson, 2006). To maintain the global balance, various international protocols and agreements, such as the Kyoto, Paris and the European Green Deal, have been established. The Kyoto Protocol was adopted in 1997 and entered into force in 2005, targeting to reduce emissions and greenhouse gases. The Paris Agreement was adopted in 2015 and entered into force in 2016, focused on limiting the global temperature rise to less than 2 °C which is a result of anthropogenic greenhouse gas emissions. The Green Deal Agreement, entered into force in 2019, courage utilization of clean energy supply with compare to fossil fuels. On the other hand, "Affordable and Clean Energy" is among the targets outlined in the Sustainable Development Goals Report-2023" prepared by the United Nations (United Nations, 2023). Despite these globally implementations, individuals residing in countries rich in geothermal energy potential respond negatively to these efforts with environmental concerns. Although geothermal energy has extra benefits for creatures such as extremophiles, still has to be assessed with care. In this sense, a thorough examination of geothermal fields and the geothermal systems in which they are situated, with regard to geothermal energy utilization and environmental effects, is crucial for achieving their optimal use and ensuring the sustainability of the system (Gerday & Berlemont, 2011; Rampelotto, 2013; Wahlund et al., 1991).

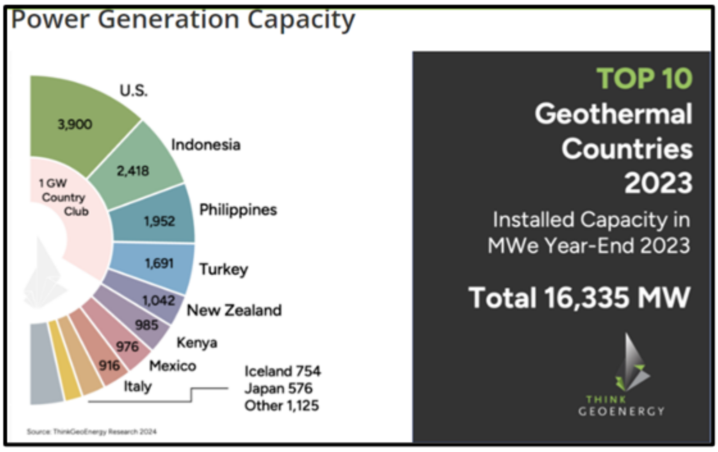

Figure 1. Top 10 geothermal countries in the world rank (www.thinkgeoenergy.com)

The commencement of geothermal energy research in Seferihisar region dates back to 1967 when the General Directorate of Mineral Research and Exploration (MTA) took the initiative. The region is located 70 km southwest of İzmir city, 54 km to the İzmir Adnan Menderes Airport (Figure 2). Numerous studies have been focused on the hydrogeochemical features of cold and hot waters in Seferihisar and its environments, potential of the Seferihisar geothermal system (SGS) in addition to geology, tectonic, hydrogeology features of the region (Eşder &Şimşek, 1975; Erdoğan, 1990; Baba & Sözbilir, 2012; Bakak et al., 2015; Özer & Polat, 2017; Alacali, 2023). There are many archaeological and natural sites in Seferihisar which makes the county more attractive. The 49 km-long coastline makes the region very attractive for both tourists and investors in the geothermal sector. From this point of view, a very delicate balance exists between the public and the people who are involved with geothermal energy all around the world and in Türkiye as well, thus prior to implementations of new geothermal projects in the SGS, it is important to examine the dynamic nature of geothermal and its effects on the environment.

With the aim of the sustainable utilization of geothermal energy, the goal of this paper is to examine geothermal energy applications and their environmental impacts, in terms of thermal effects, surface disturbances, protection of the natural feature and air pollution, specifically in the context of Seferihisar.

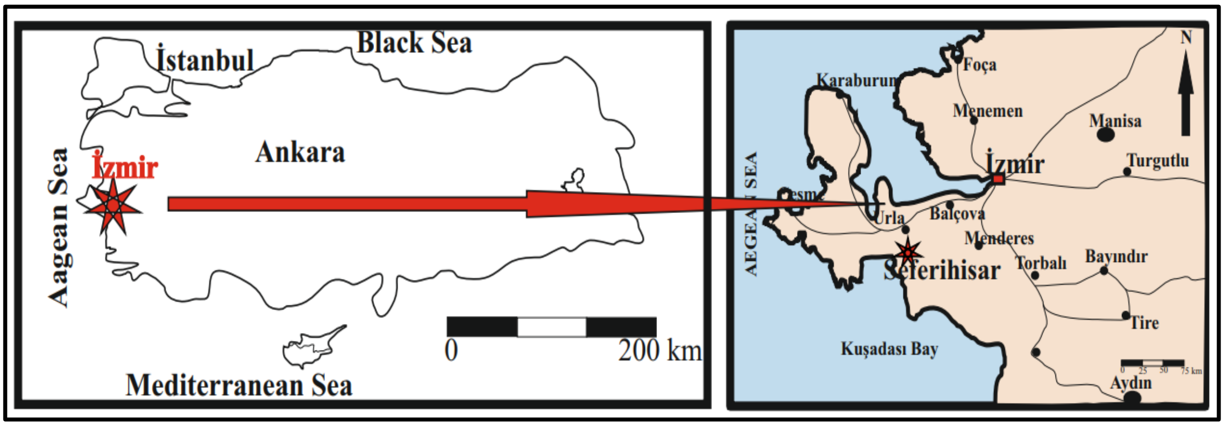

Figure 2. Location map of Seferihisar

2. Material and method

2.1. Field trips and sample collection

A series of field visits has been carried out to monitor the changes that occurred at the Tuzla geothermal field between 2019 and 2023. Changes in the most active points of the geothermal system have been observed and recorded. Photographs were taken during technical visits to the field on various dates and the temperatures of the geothermal water outlets were measured. At different times of the years 2021 and 2022, 9 sets of 66 temperature values in the Tuzla and Doğanbey geothermal fields have been measured with digital field thermometer and recorded. The temperatures of 6 hot water points, Tuzla spa, Tuzla travertines, Tuzla fault mirror, Doğanbey İmam Stream, Doğanbey spa-woman and Doğanbey spa-man are visited regularly, the temperatures of the rest of the hot water points are measured and recorded for monitoring the field. Additionally, travertine sampling has been conducted from travertines deposited in the downstream direction of geothermal water flow at the Tuzla geothermal field and were subjected to X-Ray Diffraction Analysis at the İzmir Institute of Technology.

2.2. Analysis

X-Ray Diffraction method is a well-known technique for analyzing both the composition and crystalline structure of a sample. In this approach, X-ray beams are directed through a sample, peculiarly chosen for its wavelength's resemblance to the spacing between atoms in the sample. Consequently, the angle of diffraction is influenced by the atomic spacing within the molecule, in contrast to employing significantly larger wavelengths that would remain unaffected by the spacing between atoms. This is according to the Bragg's Law given below as Equation (1) (Moore & Reynolds, 1989):

$$n\,\lambda = 2d\sin\Theta \quad (1)$$

Where d is the lattice spacing, Θ the angle between the wavevector of the incident plane wave, λ wave length, n order of the reflection.

3. Geothermal background of the SGS

The researches of the MTA in the region have started in 1967 and as a consequence, drilling studies began. Physical properties of the drills completed by MTA are given in Table 1 (Akkuş et al., 2005). The information of the geothermal wells drilled after 2005 are obtained from the wellhead plaquettes during the field trips. In the meantime, legal infrastructure studies regarding the geothermal resources located throughout the country and their management completed in 2007. Till then, MTA was the only institution authorized to carry out all the studies. As the drills completed, it was concluded that the region has high potential of geothermal energy.

Table 1. Physical properties of the first geothermal wells in SGS (Akkuş et al., 2005)

Well code	Drilling date	Depth (m)	Temperature (°C)	Flow rate (l/s)
SH-1	1971	442	107	---
SH-2	1975	1232	---	1
CM-1	1983	1417.45	140	Leaking
G-17A	1987	315	119	---
G-3A	1987	151.5	141	41.67
G-2A	1987	199.4	126	Leaking
CM-3	1987	341	153	55.56
G-12A	1987	299	74	---
TZ-1	1987	2009.5	99.88	---
DI-1	1995	350	78	12
CM-6	2008	284	146	51.27
CM-5	2008	666	120	10
CM-4	1995-2009	482	122	53.89
G-18A	2008	301	90.47	61.11
DI-IA	2011	590	78	78

The government tendered the fields with geothermal energy potential to private companies. Some of these fields are located in Seferihisar and presently, there are 11 different fields licensed either for searching or for operating the geothermal field. 28 geothermal wells in the region being used for production, re-injection and various purposes, temperatures changing from 41 °C to 207 °C.

4. Geology and geothermal features of the SGS

Tectonic features affect the SGS. Active faults host the geothermal springs, spas and numerous wells are drilled along these faults. The major faults are NE-SW trending Doğanbey, Tuzla, Cumalı faults (Eşder & Şimşek, 1975; Sözbilir et al., 2008; Uzel & Sözbilir, 2008) (Figure 3). Stratigraphically, Paleozoic Menderes Massif Metamorphics, is on the basement. This unit is overlaid by İzmir flysch. Izmir flysch consists of conglomerate, mafic volcanics, cherts and layers of stone-shale alternation. Continental sediments of Yeniköy formation of Neogene and rhyolitic volcanics overlie İzmir flysch. Quaternary alluvium units are listed to cover all these units (Eşder & Şimşek, 1975; Erdoğan, 1990; Tarcan & Gemici, 2003). Travertine deposits of Holocene around geothermal springs and clay alteration around the Doğanbey Burnu spring are observed. İzmir flysch functions as a reservoir for fluids, bearing secondary fractures and cracking systems within sandstone-shale alternations. Within the sedimentary layers, clayey zones play a pivotal role as the cape rock for the geothermal system. The heat source is attributed to the high geothermal gradient resulting from the crustal thinning. This is indicated by the Curie-depth point map of Türkiye (Eşder & Şimşek, 1975; Tarcan & Gemici, 2003; Aydın et al., 2005). The geothermal fluid in the SGS is of the NaCl type and has a tendency to cause scaling and corrosion due to its oversaturation in the means of the minerals as calcite, dolomite and aragonite (Tarcan & Gemici, 2003; Bulut, 2013; Alacalı, 2023). This statement is backed up by the field observations such as travertine deposits, mentioned in the following section. Doğanbey, Tuzla, Cumalı and Karakoç geothermal fields are the key geothermal locations in the region. The field distinctly exhibits hydrothermal alterations, especially in the vicinity of Tuzla, Karakoç, Cumalı and Doğanbey hot springs and spas. The type of hydrothermal alteration that occurs in aforementioned areas is direct precipitation. Also, seismic activities still affect geomorphology in the SGS. Following the earthquake, Samos, some of the existing hot water outlets in the region disappeared, new ones were formed, and even geysers were observed, often accompanied by surface fractures. Around Doğanbey hot springs, new boiling points surfaced along a small fracture system as well.

4.1. Doğanbey geothermal field

Doğanbey spa and the hot springs in the river of Hamam Stream are located on the Doğanbey Horst, in the southwest part of the region. The temperatures of the geothermal resources in the region vary between 48 °C and 77 °C. There are two old spas in the field serving in primitive conditions. Also, there are hot water points at 61 °C temperature in the sea around Doğanbey Bölme Cape, in the most southern part of the region.

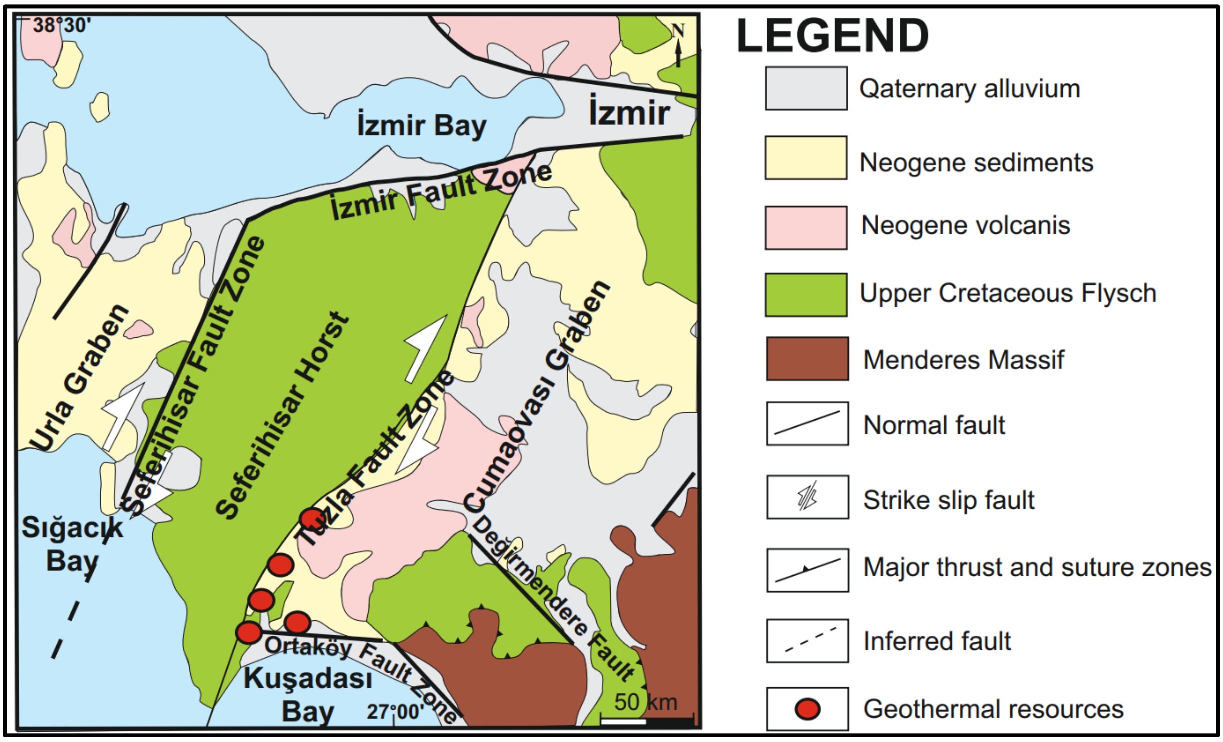

Figure 3. Geological map of the region including geothermal resources (modified after Eşder & Şimşek, 1975; Sözbilir et al., 2008; Uzel & Sözbilir, 2008)

4.2. Tuzla geothermal field

Hot water springs in Tuzla region are located along the intersection of two fault systems: Graben faults and strike-slip faults extending in NE-SW direction and diagonal faults extending in E-W direction (Eşder &Şimşek, 1975; Genç et al., 2001). There is an old spa with geothermal water at a temperature of 52 °C, which is being used in primitive conditions in the region. Holocene travertine is observed around the hot water springs (Figure 4).

Figure 4. Travertine deposition in Tuzla

4.3. Cumalı geothermal field

Geothermal resources in Cumalı region are located along the NE-SW trending Ilıca fault, on the descending block of Cumalı fault (Eşder &Şimşek, 1975). The spa in the region is dried up after the power plant. The installed capacity of the power plant is 12 Mwe and operating in order to generate electricity (Figure 5).

Figure 5. Geothermal well, geothermal power plant, travertine deposition and Cumalı Spa in the SGS

4.4 Karakoç geothermal field

In this region, hot springs are located at the intersection of two faults, trending in NE-SW directions and diagonal faults, in accordance with the general tectonic structure (Eşder &Şimşek, 1975). The recorded temperature of the geothermal water, being used in primitive conditions in the spa, is 64.5 °C.

Also, in Orhanlı-Ürkmez region, there are a few geothermal wells with temperatures varying from 48 °C to 141.18 °C.

5. Results and discussion

5.1 Analyze of the impact of geothermal energy at the region

Although geothermal resources provide environment-friendly energy, in some cases they can cause some effects on the environment. Monitoring the geothermal reservoir in long-term production processes, effect of natural hazards such as seismic activities on the geothermal systems and its' physical and hydrogeochemical features is crucial for the sustainability of the geothermal systems (Hunt, 2001; Kristmannsdo´ttir & A´rmannsson, 2003; Albertsson et al., 2010). In this section, geothermal applications and their impacts, in terms of thermal effects, surface disturbances, protection of the natural feature and air pollution on the SGS are discussed.

5.1.2 Geothermal applications

The temperature of the geothermal waters circulating in the SGS is high with respect to the neighboring geothermal fields such as Urla (33 °C), Balçova (141 °C), Çeşme (57 °C) and Menderes (33 °C) (Akkuş et al., 2005). The temperature range in the SGS is 44 °C - 207 °C.

A geothermal power plant (GPP) is currently in operation in the SGS with an installed capacity of 12 MWe. The temperatures of the wells vary from 118 °C to 207 °C. Although there are odor and noise complaints of the people living in the vicinity of the power plant, which started to provide electricity to the grid as of 01.01.2021, during the field work, it was observed that these complaints were caused by the tests performed by the power plant from time to time. Drilling work of the other private company which has operating license for electricity generation by using geothermal energy still continues. As direct use of geothermal energy, only two natural spas are being used in primitive conditions: Tuzla spa and Doğanbey spa. The spa located in Cumalı is dried up while the Karakoç spa is currently not being used. The only green house is located in the northeast part of the SGS and is owned by a private company. Trial production is carried out in a closed area of 1900 m², contributing to the employment in the local area but is currently inactive. The temperature range of these resources varies in between 43 °C – 99 °C.

5.1.3. Thermal effects: Temperature change of the geothermal points

Recorded temperatures of the geothermal springs and ponds are given in Table 2.

Table 2. Temperatures recorded in the Tuzla and Doğanbey geothermal fields

No	Point	Region	Date	Temperature (°C)	Set
1	Tuzla travertines-old hot spring	Tuzla	17.05.2021	66	1
2	**Tuzla spa**	**Tuzla**	**17.05.2021**	**46**	
3	Tuzla spa nearby- new hot spring	Tuzla	17.05.2021	75	
4	Tuzla travertines-1	Tuzla	17.05.2021	32	
5	Tuzla travertines-old hot spring	Tuzla	17.05.2021	69	
6	Tuzla old geyser	Tuzla	17.05.2021	87	
7	**In front of the Tuzla fault mirror**	**Tuzla**	**17.05.2021**	**89**	
8	**Tuzla spa**	**Tuzla**	**20.05.2021**	**49**	2
9	**Tuzla travertines**	**Tuzla**	**20.05.2021**	**66**	
10	Tuzla fault mirror	Tuzla	20.05.2021	86	
11	**In front of the Tuzla fault mirror**	**Tuzla**	**20.05.2021**	**87**	
12	**Doğanbey spa-woman**	**Doğanbey**	**20.05.2021**	**50**	
13	**Doğanbey spa-man**	**Doğanbey**	**20.05.2021**	**51**	
14	**Doğanbey-inside İmam Stream**	**Doğanbey**	**20.05.2021**	**74**	
15	Tuzla fault mirror	Tuzla	09.06.2021	69	3
16	**In front of the Tuzla fault mirror**	**Tuzla**	**09.06.2021**	**99**	
17	**Doğanbey spa-woman**	**Doğanbey**	**09.06.2021**	**48**	
18	**Doğanbey spa-man**	**Doğanbey**	**09.06.2021**	**47**	
19	Doğanbey İmam Stream-1	Doğanbey	09.06.2021	50	
20	Doğanbey İmam Stream-2	Doğanbey	09.06.2021	63	
21	**Doğanbey- inside İmam Stream**	**Doğanbey**	**09.06.2021**	**77**	
22	**Doğanbey spa-woman**	**Doğanbey**	**25.10.2021**	**46**	4
23	**Doğanbey spa-man**	**Doğanbey**	**20.10.2021**	**47**	
24	Tuzla fault mirror-old gayser-1	Tuzla	25.10.2021	66	
25	Tuzla fault mirror-old gayser-2	Tuzla	25.10.2021	72	
26	Tuzla spa-near travertines	Tuzla	25.10.2021	49	
27	**In front of the Tuzla fault mirror**	**Tuzla**	**25.10.2021**	**98**	
28	**Tuzla travertines**	**Tuzla**	**25.10.2021**	**89**	
29	**Tuzla spa**	**Tuzla**	**30.11.2021**	**46**	5
30	Tuzla travertines-west end	Tuzla	30.11.2021	66	
31	Travertines pond 1	Tuzla	30.11.2021	66	
32	Travertines pond 2	Tuzla	30.11.2021	61	
33	Travertines pond 3	Tuzla	30.11.2021	61	
34	In front of the Tuzla fault-soil	Tuzla	30.11.2021	37	
35	Tuzla fault geyser 1	Tuzla	30.11.2021	65	
36	Tuzla fault geyser 2	Tuzla	30.11.2021	69	
37	Displaced geyser- no outflow	Tuzla	30.11.2021	12	
38	**In front of the Tuzla fault mirror**	**Tuzla**	**30.11.2021**	**97**	
39	Doğanbey- inside İmam Stream	Doğanbey	30.11.2021	73	
40	**In front of the Tuzla fault mirror**	**Tuzla**	**17.01.2022**	**96**	6
41	**Tuzla travertines**	**Tuzla**	**17.01.2022**	**74**	
42	Tuzla travertines-west end	Tuzla	17.01.2022	64	
43	**Tuzla spa**	**Tuzla**	**20.04.2022**	**48**	7
44	Tuzla travertines-west end	Tuzla	20.04.2022	67	
45	Tuzla new hot pond	Tuzla	20.04.2022	83	
46	Travertines pond	Tuzla	20.04.2022	49	
47	In front of the fault mirror pond 1	Tuzla	20.04.2022	39	
48	**Doğanbey spa-woman**	**Doğanbey**	**21.04.2022**	**47**	
49	**Doğanbey spa-man**	**Doğanbey**	**21.04.2022**	**46**	
50	**Doğanbey- inside İmam Stream**	**Doğanbey**	**21.04.2022**	**76**	
51	**Tuzla spa**	**Tuzla**	**25.07.2022**	**52**	8
52	Tuzla travertines-west end	Tuzla	25.07.2022	66	
53	Travertines pond 1	Tuzla	25.07.2022	42	
54	Travertines pond 2	Tuzla	25.07.2022	64	

No	Point	Region	Date	Temperature (°C)	Set
55	Travertines rush bed	Tuzla	25.07.2022	84	
56	Travertines-north point 1	Tuzla	25.07.2022	32	
57	Travertines-north point 2	Tuzla	25.07.2022	52	
58	**Doğanbey- inside İmam Stream**	**Doğanbey**	**25.07.2022**	**76**	8
59	**Doğanbey spa-woman**	**Doğanbey**	**25.07.2022**	**50**	
60	**Doğanbey spa-man**	**Doğanbey**	**25.07.2022**	**51**	
61	SH-2 well head-leaking	Doğanbey	28.07.2022	29	
62	**Tuzla spa**	**Tuzla**	**17.08.2022**	**51**	
63	Tuzla travertines-west end	Tuzla	17.08.2022	56	
64	Travertines hot pond 1	Tuzla	17.08.2022	63	9
65	Travertines hot pond 2	Tuzla	17.08.2022	61	
66	Travertines hot pond 3	Tuzla	17.08.2022	72	

The old hot springs and geysers refer to the points existing before the earthquake occurred in 2020, new hot springs and geysers refer to the points appeared after the earthquake. The locations where measurement points are concentrated are indicated in Figure 6. The temperatures of 6 hot water points, Tuzla spa, Tuzla travertines, Tuzla fault mirror, Doğanbey İmam Stream, Doğanbey spa-woman and Doğanbey spa-man are visited regularly to assess the environmental impacts of the geothermal applications in the system. The rest of the temperature values are measured and recorded for monitoring the field. The temperature range of hot water ponds and outlets located at the Tuzla travertines is in between 32°C and 84°C. The measured temperature values of the small spa located in the Tuzla geothermal region range from a minimum of 46°C to a maximum of 52°C. The temperature measurements of two spas located in the Doğanbey geothermal field have provided values ranging between 46°C and 51°C. The temperature of the Doğanbey İmam Stream is measured as 77°C which was recorded as 68°C by Tarcan & Gemici in 2000 and 67°C in 2004 (Tarcan et al., 2004). The temperature of the hot spring feeding small spa located in the Cumalı geothermal field was recorded as 66°C by Tarcan & Gemici in 2000 and 61°C in 2003 (Tarcan et al., 2004). After the installation of the geothermal power plant, the hot springs dried up. The temperature of the hot water point located at the Tuzla fault mirror was recorded as 68°C (Tarcan et al., 2004) which is now ranging between 87 to 99°C.

The temperature measurements of the aforementioned 6 points show higher values with regard to the previous studies (Tarcan &Gemici, 2000; Tarcan et al., 2004). There is an increase in the temperature of the hot water points.

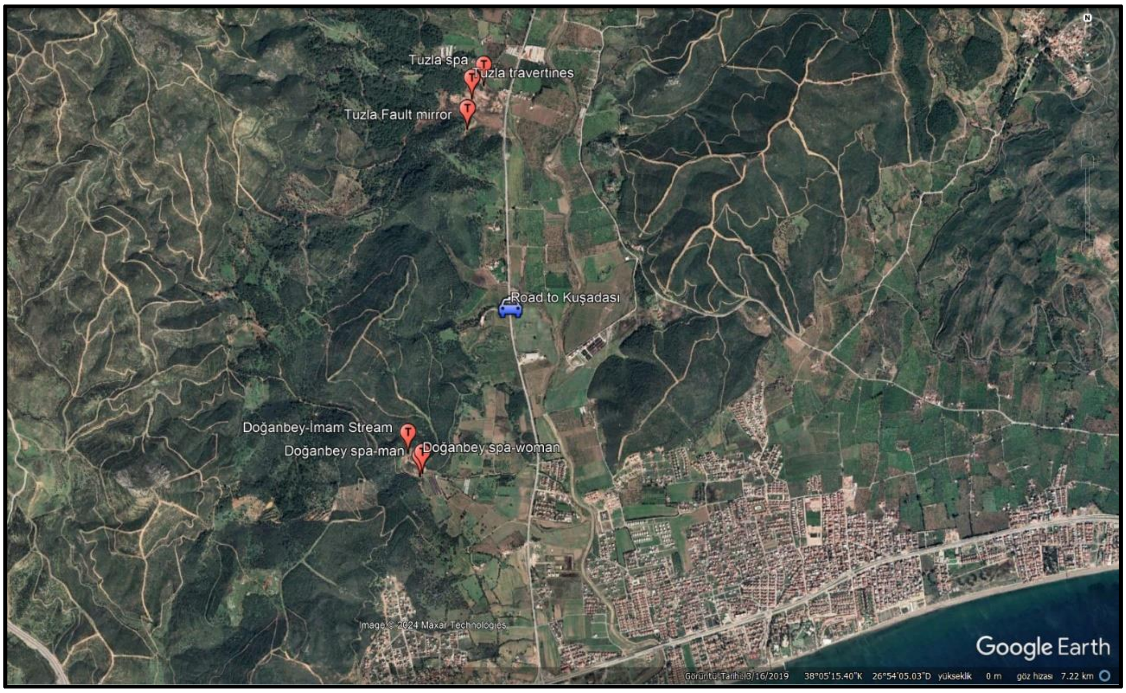

Figure 6. Google image of temperature measurement points (Google, 2014)

5.1.4. Surface disturbances: Cumalı geothermal region

Cumalı spa was being used for balneological purposes in the past. The geothermal springs located in the region was at 72°C with a flow rate of 5 l/s (Akkuş et al., 2005). In 01.01.2020, a geothermal power plant was installed nearby the geothermal springs. After the installation of the geothermal power plant, the hot springs located in the Cumalı region dried up, as a consequence, the Cumalı spa located in the region is presently not in use. Travertine formations in the Cumalı geothermal region have also ceased due to the drying up of hot water outlets.

5.1.5. Protection of natural features: Tuzla travertine

Travertine depositions provide enlightening information in various subjects within the field of earth sciences and serve as helpful tools for active tectonic and paleoclimate research, as well as a source of natural wealth (Hancock et al., 1999; Ayaz, 2002; Minissale et al., 2002; Erol, 2016). Hancock et al. (1999), added the term "travitonics" to the literature, meaning the studies of travertine tectonics from all aspects. Meteoric water undergoes heating processes, which can occur either around magma or during deep circulation along faults. As this circulation occurs, the water interacts with carbonate rocks, resulting in the release of CO_2 (Figure 7). The hot waters subsequently cool as they mix with cooler groundwater, achieving chemical equilibrium with the aquifer rocks at temperatures ~ 70°C (Bargar, 1978). Once the water reaches the surface, CO_2 is released, causing the water to become supersaturated with $CaCO_3$. This supersaturation, in turn, triggers the precipitation of carbonate minerals, often leading to the formation of travertine near or above the surface (Ellis, 1959; Wohletz & Heiken, 1992; Mazor, 2004; Duan & Li, 2008). In this case, for the SGS, travertine deposition is also affected by the increased NaCl concentration, halite, in the geothermal water resulting from the sea water interference to the SGS (2).

$$CaCO_3 + H_2O + CO_2 \leftrightarrow Ca(HCO_2)_2 \qquad (2)$$

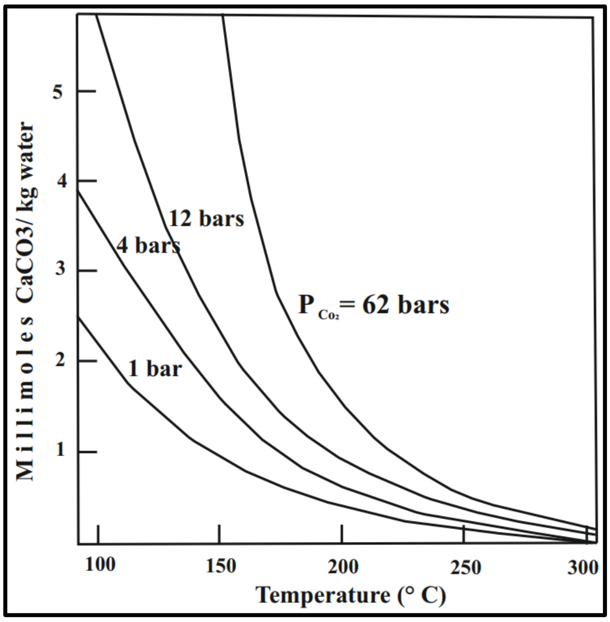

Figure 7. The effects of P and T on solubility of calcite (Ellis, 1959)

Although the reservoir below travertine deposits might not have significantly high temperatures, in some cases, it could be a marker for a hotter reservoir located nearby, in cases of Soda Dam, New Mexico (Goff & Shevenell, 1987). In the case of the Tuzla geothermal field, although the recorded temperature of the spa is 51 °C, there is a geothermal power plant within the field. The distance between the Tuzla travertines and the installed geothermal power plant is approximately 2.7 km to the north.

In Tuzla geothermal field, precipitation of the travertines is in accordance with the slope of the topography and spreads in an area of 1000 m² (Figure 8). Işıntek and Savaş, (2022) classified Tuzla travertine as "sinter-type" travertine due to the typical hot water effect. Travertines deposits in a virgin area and contain Na and Cl as a result of the sea water interference. The existence of Na and Cl is consistent with the earlier hydrogeochemical studies carried out in the region (Eşder & Şimşek, 1975; Bulut, 2013; Vengosh et al., 2002). The presence of the 4-methylpyridine-N-oxide is quite interesting and raise questions as this compound rarely exist naturally and generally used in laboratory conditions (Hariharasuthan et al., 2023). The compound named "Strontium barium titanium oxyhydride" may be resulted from the water-rock interactions. Celestine ($SrSO_4$) is the principal mineral source of strontium and mostly occurs in fissures and cavities of dolomites and dolomitic limestones. It also exists in evaporite deposits and in hydrothermal veins (Deer et al, 1966). The hydrothermal veins in the Tuzla travertines may have provided a suitable environment for the formation of this mineral through water-rock interactions (Figure 9).

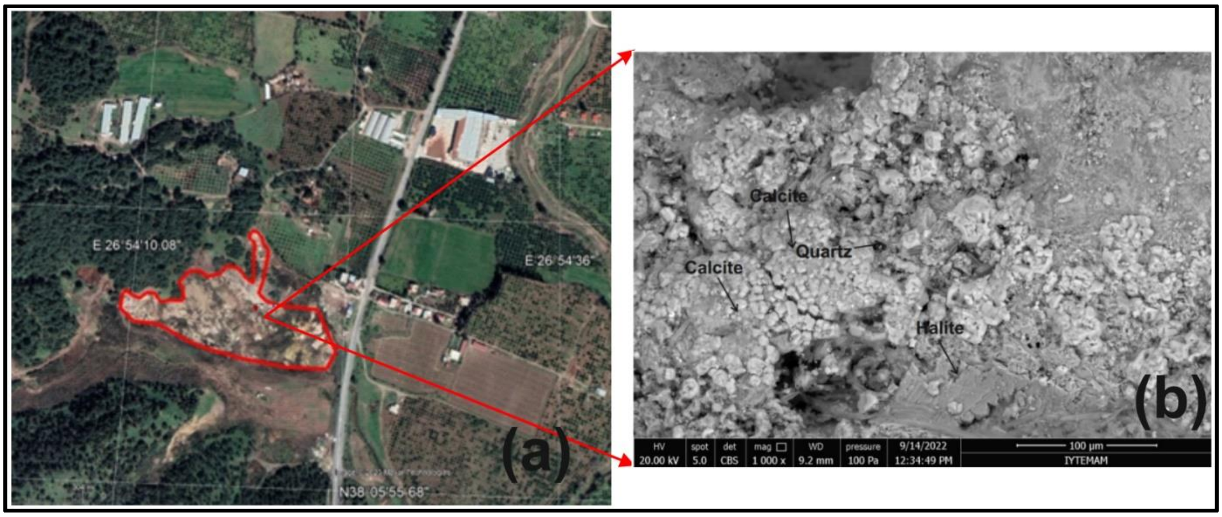

Figure 8. (a) Google image of the Tuzla travertine (Google Earth, 2014) (b) Electron image of the sample collected from the Tuzla travertine with calcite, quartz and halite minerals.

The current condition of travertines is given below (Figure 10). Due to the damage and pollution the travertines are exposed to, they should be protected to preserve their sustainability. Travertines contribute geological and natural richness to the areas they deposit and play a significant role in geotourism (Özkul et al., 2002; Valente et al., 2022). They are also used in industrial areas such as building material, souvenirs and cement manufacturing but has to be well-tested before deciding consumption type (Ayaz, 2002).

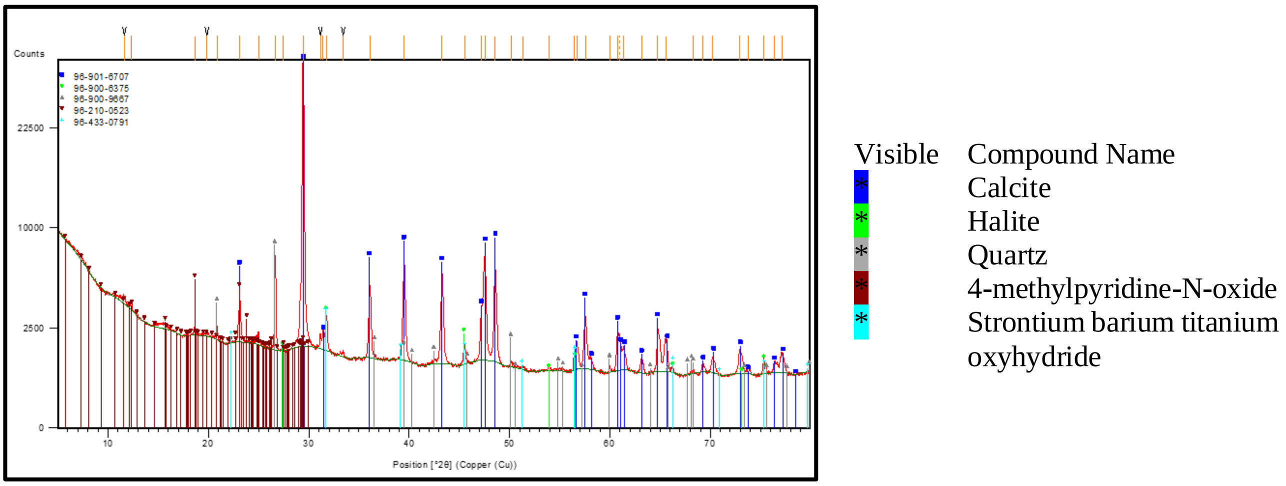

Figure 9. XRD analysis of the sample collected from the Tuzla travertines.

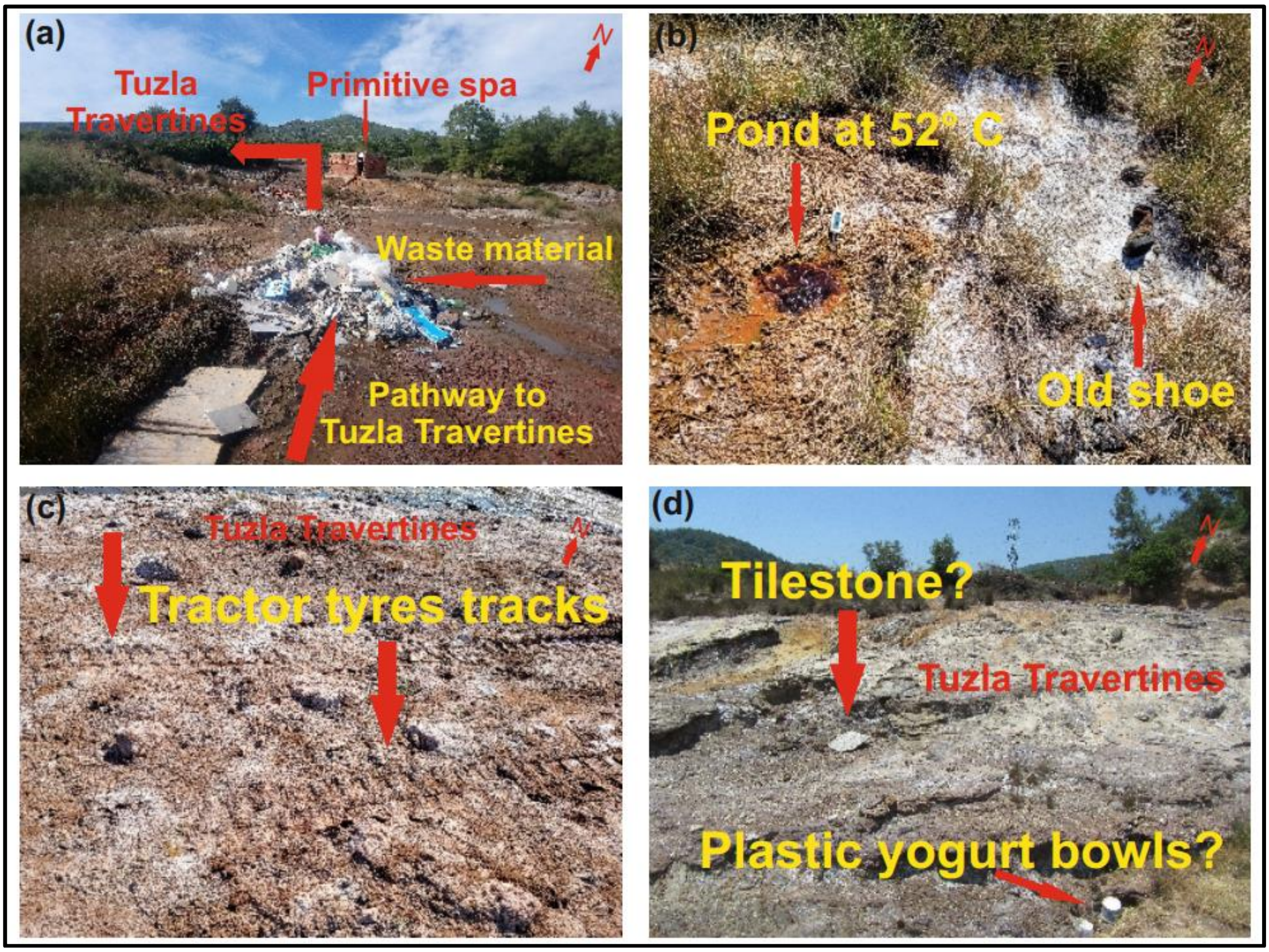

Figure 10. (a) Waste material on the pathway to the Tuzla Travertines (b) Hot water pond neighboured by an old shoe (c) Tractor tyre tracks on the Tuzla travertines (d) Plastic yogurt bowls and tile stone on the travertines.

5.1.6. Air pollution

Geothermal power plants are assumed as one of the environmental-friendly and sustainable type of energy production compared to fossil fuels. However, geothermal power plants may have environmental impacts as greenhouse gas emissions, including carbon dioxide (CO_2), hydrogen sulfide (SO_2) and these impacts can be site-specific due to the nature of the geothermal resources in use (Huang & Tian, 2006; Ferrara et al., 2019; Bošnjaković et al., 2019; Maione et al., 2022). The SGS is a highly significant geothermal region, with much of its geothermal potential drawing interest from the private sector, including one company involved in electricity generation. Since private companies are very sensitive about sharing their data, EMEP data was used in this case to make an approach and analyze the impact of geothermal power plants on air pollution. For Seferihisar distinct, in Figure 11 and Figure 12, NO_2 (Table 3) and SO_2 (Table 4) measured values, recorded every first day of each month, are given based on the 60-month National Air Quality Monitoring Network-Seferihisar-EMEP data belonging to Seferihisar district to address the most cited discussions of air pollution caused by the emission of non-condensable gases (NCG) during the electricity generation by using geothermal energy (Türkiye Ministry of Environment, Urbanization and Climate Change-National Air Quality Monitoring Network). EMEP is the abbreviation for "European Monitoring and Evaluation Programme" within the Cooperative Programme for Monitoring and Evaluation of Long Range Transmission of Air Pollutants in Europe (European Agency, 2023). Since geothermal power plants do not use conventional fossil fuels, the visible plumes observed above a geothermal power plant is water vapour emission, steam (Kagel et al., 2007). As shown in the Table 4, the measured amounts of NO_2 and SO_2 in the air during the year reach their highest values in July and December, despite the geothermal power plant operating throughout the year. The measured NO_2 and SO_2 values since 01.01.2021, when the geothermal power plant became operational, are close to the lowest values of the whole year. It can be predicted that the periods during which these values are high coincide with the periods when the population and, consequently, the traffic density of the city increased, such as in the summer months (July and August) and the coldest month of the year (December). Additionally, the increase in the population can be attributed to the global COVID-19 pandemic that began in 2019. Since Seferihisar is a district on the coast, this population increase is extremely common during the summer season. According to the measurements recorded at the Seferihisar Station of Türkiye Ministry of Environment, Urbanization and Climate Change-National Air Quality Monitoring Network, located 5 km to the north of the city center and 14 km north-northwest to the geothermal power plant, annual mean values of NO_2 and SO_2 are lower than the National threshold value and European Union Countries' threshold value (Table 5).

Table 3. NO_2 values based on EMEP for Seferihisar*

Date	**1.01.2019**	**1.02.2019**	**1.03.2019**	**1.04.2019**	**1.05.2019**	**1.06.2019**	**1.07.2019**	**1.08.2019**	**1.09.2019**	**1.10.2019**	**1.11.2019**	**1.12.2019**	**A. Mean**
NO_2	8	5	9	12	4	14	8	22	13	6	12	5	9
Date	**1.01.2020**	**5.02.2020**	**1.03.2020**	**1.04.2020**	**1.05.2020**	**1.06.2020**	**1.07.2020**	**1.08.2020**	**1.09.2020**	**1.10.2020**	**1.11.2020**	**1.12.2020**	
NO_2	14	3	9	11	4	3	23	15	11	4	8	16	10.1
Date	**1.01.2021**	**1.02.2021**	**1.03.2021**	**1.04.2021**	**1.05.2021**	**1.06.2021**	**1.07.2021**	**1.08.2021**	**1.09.2021**	**1.10.2021**	**1.11.2021**	**1.12.2021**	
NO_2	4	4	6	5	4	7	12	11	7	4	3	11	6.5
Date	**1.01.2022**	**1.02.2022**	**1.03.2022**	**1.04.2022**	**1.05.2022**	**1.06.2022**	**1.07.2022**	**1.08.2022**	**1.09.2022**	**1.10.2022**	**1.11.2022**	**1.12.2022**	
NO_2	25	9	13	9	13	27	17	17	24	6	9	6	14.6
Date	**1.01.2023**	**1.02.2023**	**1.03.2023**	**1.04.2023**	**1.05.2023**	**1.06.2023**	**1.07.2023**	**1.08.2023**	**1.09.2023**	**1.10.2023**	**1.11.2023**	**1.12.2023**	
NO_2	7	6	6	7	10	13	16	16	13	11	2	9	9.7

(*: Data obtained from Türkiye Ministry of Environment, Urbanization and Climate Change-National Air Quality Monitoring Network)

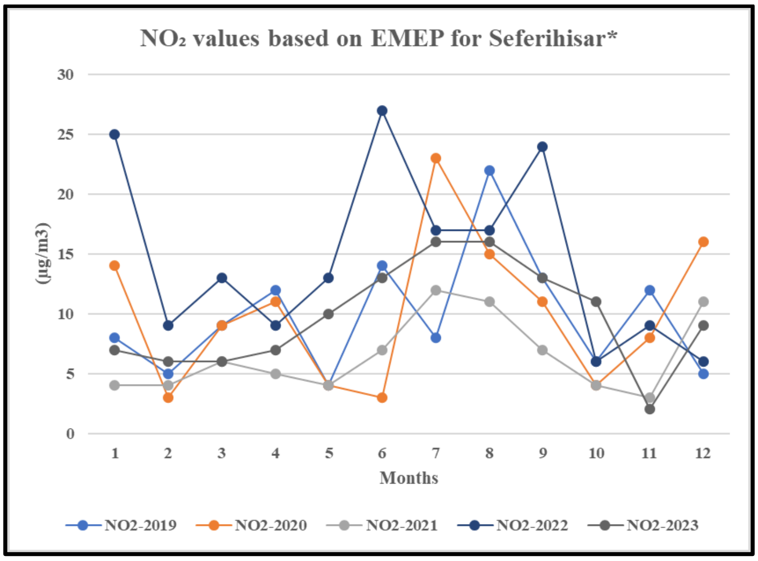

Figure 11. NO_2 values based on EMEP for Seferihisar

(*: Data obtained from Türkiye Ministry of Environment, Urbanization and Climate Change-National Air Quality Monitoring Network)

Table 4. SO_2 values based on EMEP for Seferihisar*

Date	**1.01.2019**	**1.02.2019**	**1.03.2019**	**1.04.2019**	**1.05.2019**	**1.06.2019**	**1.07.2019**	**1.08.2019**	**1.09.2019**	**1.10.2019**	**1.11.2019**	**1.12.2019**	**A. Mean**
SO_2	3	3	5	8	6	8	10	16	11	6	3	4	6.9
Date	**1.01.2020**	**5.02.2020**	**1.03.2020**	**1.04.2020**	**1.05.2020**	**1.06.2020**	**1.07.2020**	**1.08.2020**	**1.09.2020**	**1.10.2020**	**1.11.2020**	**1.12.2020**	
SO_2	7	6	7	6	5	4	4	4	4	8	10	12	6.4
Date	**1.01.2021**	**1.02.2021**	**1.03.2021**	**1.04.2021**	**1.05.2021**	**1.06.2021**	**1.07.2021**	**1.08.2021**	**1.09.2021**	**1.10.2021**	**1.11.2021**	**1.12.2021**	
SO_2	2	2	5	3	3	3	3	4	4	4	4	10	3.9
Date	**1.01.2022**	**1.02.2022**	**1.03.2022**	**1.04.2022**	**1.05.2022**	**1.06.2022**	**1.07.2022**	**1.08.2022**	**1.09.2022**	**1.10.2022**	**1.11.2022**	**1.12.2022**	
SO_2	9	7	6	9	4	11	11	9	7	15	12	11	9.3
Date	**1.01.2023**	**1.02.2023**	**1.03.2023**	**1.04.2023**	**1.05.2023**	**1.06.2023**	**1.07.2023**	**1.08.2023**	**1.09.2023**	**1.10.2023**	**1.11.2023**	**1.12.2023**	
SO_2	3	2	4	3	2	2	13	8	4	6	3	4	4.5

(*: Data obtained from Türkiye Ministry of Environment, Urbanization and Climate Change-National Air Quality Monitoring Network)

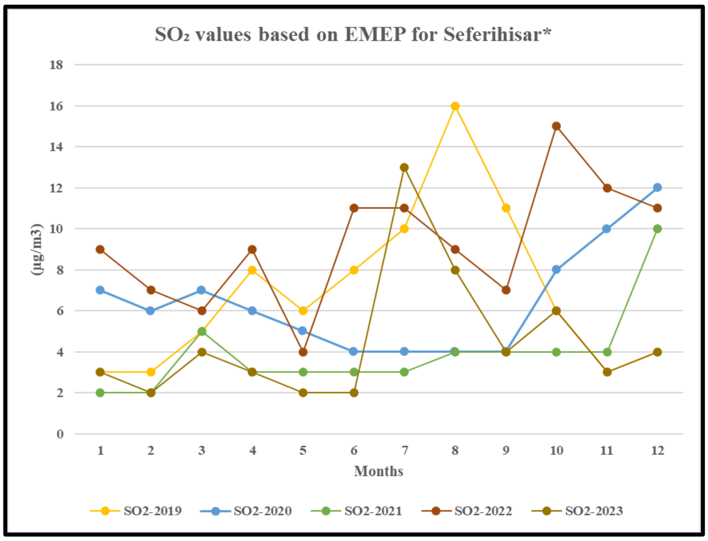

Figure 12. SO_2 values based on EMEP for Seferihisar
(*: Data obtained from Türkiye Ministry of Environment, Urbanization and Climate Change-National Air Quality Monitoring Network)

Table 5. Annual mean values of NO_2 ad SO_2 for Seferihisar*

Component (Pollutant)	Year	Annual mean value (µg/m³)	National threshold value (µg/m³)	EU Countries' threshold value (µg/m³)
NO_2	2019	9.8	250	200
	2020	10.1	250	200
	2021	6.5	250	200
	2022	14.6	250	200
	2023	9.7		
SO_2	2019	6.9	350	350
	2020	6.4	350	350
	2021	3.9	350	350
	2022	9.3	350	350
	2023	4.5		

(*: Data obtained from Türkiye Ministry of Environment, Urbanization and Climate Change-National Air Quality Monitoring Network)

6. Conclusion

In this research, the environmental effects of geothermal energy applications and their environmental impacts, in terms of thermal effects, surface disturbances, protection of the natural feature and air pollution, are discussed in outline. SGS is located in a region which is controlled by active faults. There are a few geothermal energy applications in the SGS, chiefly electricity generation and primitive spa usage. It is clearly observed throughout the surface manifestations that after the Samos earthquake, this system is an active geothermal system where seismic activities trigger the weak zones of the faults and fractures, resulting the occurrence of new hot water points or shifting the presents. The NaCl type geothermal waters are affected by the sea water interference, backed up by the XRD analysis of the sample collected from the Tuzla travertine. These pieces of evidences are consistent with previous hydrogeological studies. The temperature measurement values obtained from Tuzla and Doğanbey are higher than the values records prior to the installation of the geothermal power plant. Considering the re-injection process in the region and the fact that the region is seismically active, it would be a hasty approach to consider this increase as a direct effect of the power plant. Tracer tests to be performed in the region will provide insights into this matter. The formation of the Tuzla travertines is not presently affected by the GPP but this does not apply to the Cumalı geothermal field. Contrary to Tuzla, the hot springs have been affected due to the installation of the geothermal power plant and dried up. The spa in the field is also not in use and the deposition of travertine has ceased. Furthermore, the region where Tuzla travertine deposits exist must be protected to sustain its natural formations and should be preserved as a natural protected area. The measured NO_2 and SO_2 values since 1.01.2021, are close to the lowest values of the whole year. The periods during which these values are high as in the summer months (July and August) and the coldest month of the year (December), despite the geothermal power plant operating throughout the year. Air quality monitoring stations to be installed closer to the geothermal facilities in the future, will provide more detailed information in aspects of air pollution. A close monitoring will record the natural fluctuations induced by the harvesting of geothermal energy. With integrated use, the region can become economically stronger in terms of thermal facilities and greenhouse cultivation. Increase of awareness and improvement of the legal regulations is highly required in order to assess this geothermal potential, in general. In the case of new projects regarding geothermal utilizations, it is evident that the environmental impacts of geothermal resources can be minimized through technological innovations, monitoring and legal inspections.

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Author contribution

The manuscript was written by the corresponding author.

Declaration of ethical code

The authors declare that the materials and methods used in this study do not require ethical committee approval and/or legal-specific permission.

Conflicts of interest

The authors declare that they have no conflict of interest.

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