The effect of urban heat island on groundwater located in shallow aquifers of Kutahya city center and shallow geothermal energy potential of the region

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Kentsel ısı adasının Kütahya şehir merkezi sığ akiferlerinde yer alan yeraltısuları üzerindeki etkisi ve bölgenin sığ jeotermal enerji potansiyeli

The effect of urban heat island on groundwater located in shallow aquifers of Kutahya city center and shallow geothermal energy potential of the region

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ÖZ

Kentleşme neticesinde doğal yüzeylerin yerini bina, kaldırım, asfalt gibi ısıyı hapseden yapay yüzeyler almakta, bunun sonucunda yerleşim yerleri çevrelerinde bulunan kırsal alanlara göre daha yüksek sıcaklık değerlerine sahip olmaktadır. Kentsel ısı adası olarak tanımlanan bu etki, sadece hava sıcaklığında değil, aynı zamanda yeraltı ve yeraltısuyunda da sıcaklık artışına neden olmaktadır. Bu çalışmada; kentsel ısı adasının Kütahya şehir merkezi yeraltı çevresindeki etkisinin tespiti için farklı tür yerleşim alanlarını, yeşil alanları ve tarım arazilerini kapsayan yaklaşık 53 km^2'lik bir alanda bir yıl boyunca yeraltısuyu sıcaklığı değerleri ölçülmüştür. Yapılan ölçümler neticesinde; kentsel ısı adası haritaları oluşturulmuş, yeraltısuyu sıcaklığı anomalilerinin kentsel/endüstriyel alanlara doğru artış gösterdiği gözlenmiş, kentsel ve kırsal alanlarda yeraltısuyu sıcaklığı farkının kuyu bazında 7 °C'ye kadar ulaştığı tespit edilmiştir. Kentsel ısı adası etkisiyle artan bu ısı enerjisi "sığ jeotermal enerji sistemleri" adı verilen sistemler aracılığı ile konutların/ticari binaların ısıtma işlemlerinde kullanılabilmektedir. Bu sebeple çalışma kapsamında Kütahya şehir merkezi altında yer alan alüvyon akiferin ısı potansiyeli hesaplanmıştır. Bu akiferin teorik ısı potansiyeli değerlerinin $3,50\times10^{13}$ kJ K^{-1} ortalama bir değer ile $1,64\times10^{13}$ kJ K^{-1}ile $5,55\times10^{13}$ kJ K^{-1}arasında değiştiği tespit edilmiştir. Kentsel ısı adası haritaları ve akiferlerin ısı potansiyeli hesaplarının, sığ jeotermal sistemlerin uygulanabilirliği açısından önemli parametreler olacakları düşünülmektedir.

Anahtar Sözcükler: Kentsel ısı adası, sığ jeotermal enerji, yenilenebilir enerji, yeraltısuyu, ısı potansiyeli

ABSTRACT

As a result of urbanization, natural surfaces are replaced by artificial surfaces that trap heat such as buildings, pavements and asphalt, so residential areas have higher temperature values than rural areas. This effect, defined as the urban heat island, causes an increase not only in air temperature but also in the subsurface and groundwater. Groundwater temperature values were measured during one year in an area approximately 53 km^2 consisting of different types of settlement areas to determine the urban heat island effect on the subsurface of Kutahya. As a result of the measurements, urban heat island maps were prepared. It was observed that the groundwater temperature anomalies increased towards the urban/industrial areas. The difference of groundwater temperature in urban/rural areas reached up to 7 °C by well. This heat energy increase with the effect of urban heat island can be used in the heating processes of buildings by utilizing systems called "shallow geothermal energy". For this reason, the heat potential of the alluvial aquifer under Kutahya was calculated. The theoretical heat potential values of this aquifer range between 1.64×10^{13} kJ K^{-1} and 5.55×10^{13} kJ K^{-1} with a mean value of 3.50×10^{13} kJ K^{-1}. It is thought that urban heat island maps and the heat potential calculations of the aquifers may be important parameters for applicability of shallow geothermal systems in the city center of Kutahya.

Keywords: Urban heat island, shallow geothermal energy, renewable energy, groundwater, heat capacity

1. Introduction

Due to economic, social and cultural factors, the human population in cities is increasing and city centers are getting more crowded. Urbanization in cities is rapidly increasing worldwide as a result of the need for shelter due to the increasing population. As a result of urbanization, artificial surfaces replace natural vegetation. As a result, city centers have higher air temperature values compared to the surrounding rural areas. This situation was first expressed by Howard (1983) and defined as "urban heat island". In another study (Oke, 1973), the highest air temperature difference in urban and rural areas was defined as the urban heat island intensity, and it was stated that the intensity of the urban heat island can reach up to 12 °C in open and windless summer evenings. As a result of the urban heat island effect, the air temperature in city centers can be up to 10 °C higher than in rural areas (Oke, 1987; Klysik & Fortuniak, 1999). According to Menberg (2013a), the difference between the city center and rural areas increases up to 20 K due to artificial structures.

The most important reason for the urban heat island effect is that natural surfaces are replaced by artificial surfaces. It has been stated in previous studies that green areas are cooler than urban areas around them (Gallo & Owen, 1999; Spronken-Smith & Oke, 1999). Artificial surfaces increasing due to urbanization in cities cause anthropogenic heat losses and changes in the radiation level in the atmosphere and the energy balance in cities. This situation causes change in the urban microclimate and increase in air temperature (Landsberg, 1956; Oke, 1988). Because during the day, plants emit the radiation coming from the sun back to the atmosphere through evaporation-transpiration (evapotranspiration). But; evapotranspiration decreases with the disappearance of natural surfaces, artificial surfaces such as buildings, asphalt, roads, sidewalks, bridges trap the sun's rays and cause the air temperature to increase during the day. As a result, the urban heat island effect emerges and higher air temperature values are observed in urban areas compared to rural areas with dense green areas. Filled areas, subway tunnels, electrical cables, district heating systems and sewage systems are other man-made structures that cause the urban heat island effect (Balke, 1977; Pollack et al., 1998; Menberg et al., 2013b).

It has been emphasized in previous studies (Oke, 1973) that the urban heat island effect is also a result of the city's size and population growth. Ezber et al. (2007) examined the effect of urban heat island in Istanbul and showed that the urban heat island factor is directly related to population and city size. However, according to some previous studies, it was stated that this effect was observed not only in big cities but also in medium-sized cities such as Granada (Spain) (Montavez et al. 2000) or in small cities such as Aveiro (Portugal) (Pinho and Manso Orgaz, 2000). According to Allen et al. (2003), the urban heat island effect may not be observed in every city. This effect depends on many factors such as regional weather, topography, density of streets, buildings and man-made structures, and the number of man-made areas such as parks and gardens. Landsberg (1981) pointed out that the urban heat island effect shows a heterogeneous distribution and is an area-specific concept, many microclimatic changes occur within the city, and the urban heat island is a summary of microclimatic changes in the city. In other words, the density of the urban heat island may vary within the city area depending on the urban characteristics.

Many studies and meteorological records show that in the last century there is a significant temperature increase trend in cities (Ferguson & Woodbury, 2007; Perrier et al., 2005; Taniguchi et al., 2007). This situation is a result of not only climatic factors, but also the urban heat island effect resulting from urbanization as mentioned above (Oke, 1973; Kataoka et al., 2009). For example, Karaca et al. (1995) examined the relationship between the population growth and the urban heat island effect in Istanbul and observed that the average temperature has decreased by 1.17 °C in the last 40 years in the northern part of Istanbul, where housing is less, and the average temperature has increased by 0.47 °C in the last 40 years in the southern part where housing is intense. This is a proof that the temperature increase in cities is not only a result of climatic factors but also of urbanization.

As in the previous studies mentioned above, the urban heat island effect that occurs in the atmosphere is widely known, and this change has been the focus of international studies for many years. However, the urban heat island effect causes an increase in temperature in and around the underground as well as in the atmosphere (Taniguchi et al., 2007). Underground temperature is controlled by the heat flux from the center of the earth and the surface temperature (Huang et al., 2009). Temperature changes that occur on the earth with the effect of urban heat island are transmitted underground by heat transfer and especially shallow aquifers located close to the surface are affected by atmospheric events occurring on the surface. Therefore, engineering structures such as buildings, parking lots, asphalt, subway tunnels that cause the urban heat island effect are responsible for the rise of the temperature of the ground and therefore the units located at shallow depths underground and the groundwater. It has been proven in various studies that the urban heat island effect has a strong effect on underground temperature and the urban heat island effect has been determined by many researchers using soil temperature and/or groundwater temperature values (Taniguchi et al., 1999; Changnon, 1999; Ferguson and Woodbury, 2004; Taniguchi, 2006; Taniguchi et al., 2007). Ferguson and Woodbury (2004) calculated heat loss from buildings in urban areas and stated that the underground environment is affected by previously ignored man-made activities such as subway networks or re-injected thermal waters. Ampofo et al. (2004) stated that 70% of the heat in the London subway can be vented out with ventilation, and the remaining 30% is transmitted to the underground. Kottmeir et al. (2007), using the Berlin example, established a relationship between the percentage of covered surfaces and groundwater temperature values. According to the researcher; there is a direct proportion between covered surfaces and percentage of urbanization and groundwater temperature. Groundwater temperature decreases in rural areas where closed surfaces and the percentage of construction are decreasing. Taniguchi (2006) established a direct relationship between population density and underground temperature values in Bangkok. Also, the increase in underground soil temperature in rapidly growing Asian cities has been researched by many studies (Taniguchi & Uemura, 2005; Taniguchi et al., 2009). In similar studies, it was observed that the soil temperature increased between 2 and 3 K in tropical and temperate regions as a result of the destruction of forest areas (Murtha & Williams, 1986; Nitoiu & Beltrami, 2005). In Turkey, Yalcin and Yetemen (2009) measured the soil temperatures at shallow depths at different points located on both sides of Istanbul and found that the underground temperature difference increased up to 3.5 K in settlement areas. It has been observed that the underground temperature measured in urban areas is 5 K warmer than the surrounding areas (Taniguchi et al., 1999; Ferguson & Woodbury, 2004; Reiter, 2006). In the study conducted in Cologne, Germany by Zhu et al. (2010), the areal distribution of groundwater temperature was examined and it was stated that the highest groundwater temperature values were found in aquifers under the city center where urbanization is intense. In many similar studies, groundwater temperature values increasing with the urban heat island effect have led to the idea of using aquifers located in the shallow depths of the city center as a geothermal energy source. With the increase in groundwater temperatures due to the urban heat island effect, these aquifers will become geothermal reservoirs and an environmentally friendly and renewable energy source will be provided as an alternative to fossil fuels. Because; aquifer with high temperature values means high amount of stored energy, high amount of stored energy means high geothermal potential. In this sense, high-temperature urban aquifers may allow the applicability of systems that are important for the national economy and environmental health like shallow geothermal systems. There are many studies assessing the applicability of shallow geothermal energy systems in rural and denser residential areas (Lee et al., 2017; Casasso et al., 2017; Francisco Pinto, 2018). The system in question has been installed more than half a million in countries such as France, Germany, Austria, the Netherlands and Sweden (EGEC, 2018). This number is about one million units worldwide (Pophillat et al., 2020). The number of these systems will increase as the installation costs decrease (Soltani, 2018).

As a result of the urban heat island effect arising due to the increasing population and urbanization, city centers become warmer than the surrounding rural areas. It has been predicted that the urban heat island effect can be observed in Kutahya, a city where the population and urbanization are constantly increasing. For this reason, within the scope of the study, it is planned to measure the groundwater temperatures and create urban heat island maps in order to determine the urban heat island effect in Kutahya city center. It has been proven in previous studies that the urban heat island effect has a strong effect not only on air but also underground and groundwater temperature. The idea of using these aquifers located in the shallow depths of the city center as a geothermal energy source was born with the increase in the temperatures of the underground environment and groundwater with the effect of the urban heat island. In Turkey where fossil fuel consumption and energy imports are high, it is thought that this environmentally friendly renewable energy source will be a very important alternative. Accordingly, in addition to determining the existence of the urban heat island effect in Kutahya city center, it was aimed to determine the heat potential of the alluvial aquifer. In summary, the main objectives of this study are to examine the effect of the urban heat island effect on the groundwater temperature in shallow aquifers in the city center of Kutahya, to assess the mentioned temperature values in terms of shallow geothermal systems and to calculate the heat potential in the alluvial aquifer.

2. Study site

Located in the Inner West Anatolia part of the Aegean Region, Kutahya was established at the foot of the Yellice Mountain, on the southern edge of the Kutahya Plain. It is located between 38° 70’ and 39° 80’ north latitudes and 29° 00’ and 30° 30’ east longitudes. Based on Turkish Statistical Institute (TURKSTAT) data the city constitutes approximately 1.5% of Turkey’s land with its 12.014 km^2 area.

Based on TURKSTAT 2019 data, the general population of Kutahya was determined as 579,257. Due to the stronger social and economic opportunities of the central district compared to other districts, approximately 50% of this population (272,367 people) live in the central district (Table 1). Therefore, population density and urbanization rate in the central district is higher than other districts. Again, based on TURKSTAT (2019) data, the annual population growth rate in Kutahya for 2019 is 2.3%, while this rate in the Central district is up to 20.7%. Depending on the increasing population, new areas are being opened to development, the rate of urbanization is increasing and the amount of agricultural lands and green areas is decreasing. This situation increases the potential for urban heat island effect to occur in the city center.

Table 1 - Statistical information about Kutahya city center.

Elevation (m)	Population (Person)[a]	Population density (km^2)[b]	Area (km^2)	T_{ort} (°C)[c]	Number of wells studied	Survey area (km^2)	Well/Area (well/km^2)
970	272.367	110,27	2470	10,81	41	52,44	0,78

a. Turkey Statistical Institute (TURKSTAT) (2019). b. General Directorate of Mapping c. Kutahya Meteorology Directorate (1970-2019), T_{ort}: Annual average air temperature

Kutahya Plain is a tectonic plain formed due to the Kutahya fault, and urbanization is intensely observed here. The plain has a generally flat topography and there are alluvial units in it. According to Ozburan (2009), the alluvium that overlies the units in the region inharmoniously is the product of the Porsuk and Felent rivers and their branches. The highest place in the study area is Yellice Mountain located in the southern part of the city. Paleozoic, Mesozoic and Cenozoic units crop out in the city. There are metamorphic units consisting of schist and marble at the base and ophiolitic rocks overlie them. Above these units there is a sequence standing with discordance, reflecting the lake/stream environment, intrusive with volcanics, clastic and carbonated. Younger fluvial sediments developed during and after the formation of the Kutahya Graben are found as graben filling (Ozburan, 2009). Quaternary aged Kirazpınar, Yakaca and Kutahya formations and alluvium are found as cover units in the region (Figure 1).

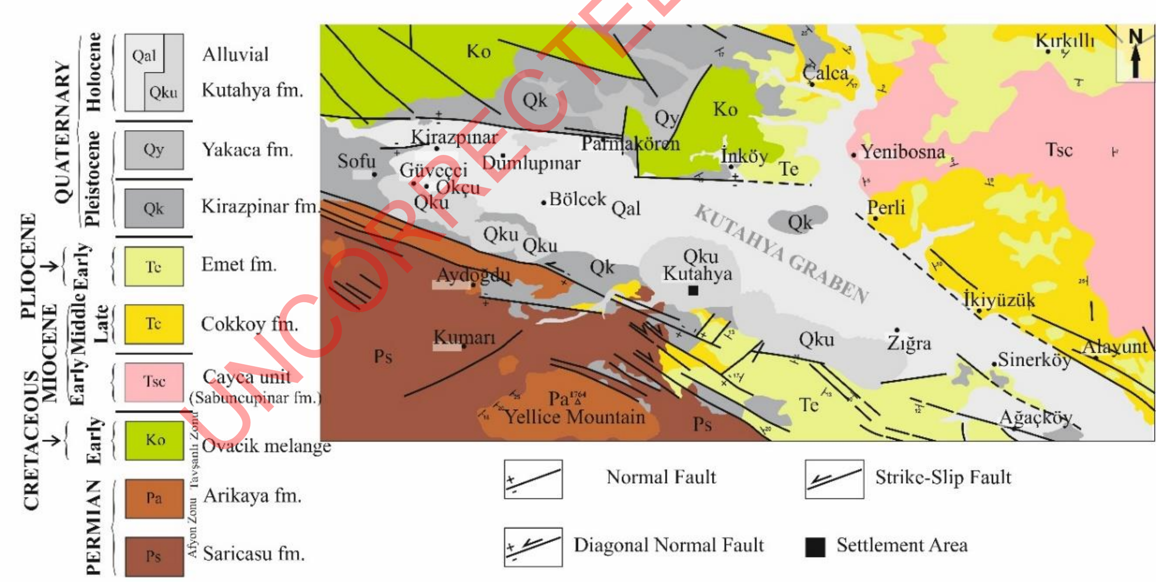


Figure 1 - General geological map of Kutahya and its surroundings (Ozburan, 2009).

The Alluvium unit, which spreads 145 m^2 in the region, is observed in the agricultural lands forming the plains along the Felent and Porsuk River. Groundwater is especially included in these Quaternary aged sediments. This water is used by the people of the region for purposes such as agricultural irrigation. Based on the results of the drilling in the alluvium unit, the drilling flows are between 2-12 l/s and the specific flow values are between 0.04-0.22 l/s/m. Quaternary aged aquifer located in the shallow depths of the city has an average hydraulic conductivity of 44.2 m/day and a transmissivity of 213.48 m^2/day (DSI, 2003). As a result of intense tectonic activity in the region, metamorphic rocks with high secondary permeability and sedimentary rocks with high porosity form permeable units. The streams with continuous flow in the study area are the Felent River, which runs from the northwest to the southeast, and the Porsuk Riverfrom the south to the north (DSI, 2003).

3. Material and Method

In order to determine the areal distribution of groundwater temperature in urban and rural areas in Kutahya Central district and to determine the urban heat island effect by using these values, water wells suitable for measurement in areas with dense urbanization and rural areas were required. In this direction, the field study started in the Kutahya plain in January 2019 and 42 water wells suitable for the measurement of groundwater level and groundwater temperature in rural and urban areas were determined (Figure 2). Due to the collapse in the well numbered L36 in February, this well was canceled and the work continued with 41 wells in total. In order to fully determine the urban heat island effect, care has been taken to distribute the well locations to be measured in urban, rural and industrial areas (Figure 2). Groundwater level and temperature were measured periodically every month for 12 months from January to December 2019 in an area of approximately 53 km^2 where residences, commercial buildings, public buildings, factories, green areas and agricultural lands are located, using level and temperature measurement tool (Heron Conductivity Plus). Groundwater temperatures were measured 1 meter below the groundwater table, considering the contact of the water surface with the atmosphere. Measurement depths in the wells vary between 1.20 and 25.40 meters. Maps showing the areal distribution of the data were created using Internal Distance Weighting (IDW) geostatistics method in the ArcMap 10.7 software (ESRI, 2019) in order to observe the areal distribution of the obtained temperature values and to determine the effect of the urban heat island based on the areas, and the effect of urbanization on groundwater and its environment was examined. In addition, groundwater temperature values obtained in field studies were compared with air temperature and 100 cm soil temperature values obtained from Kutahya Meteorology Station.

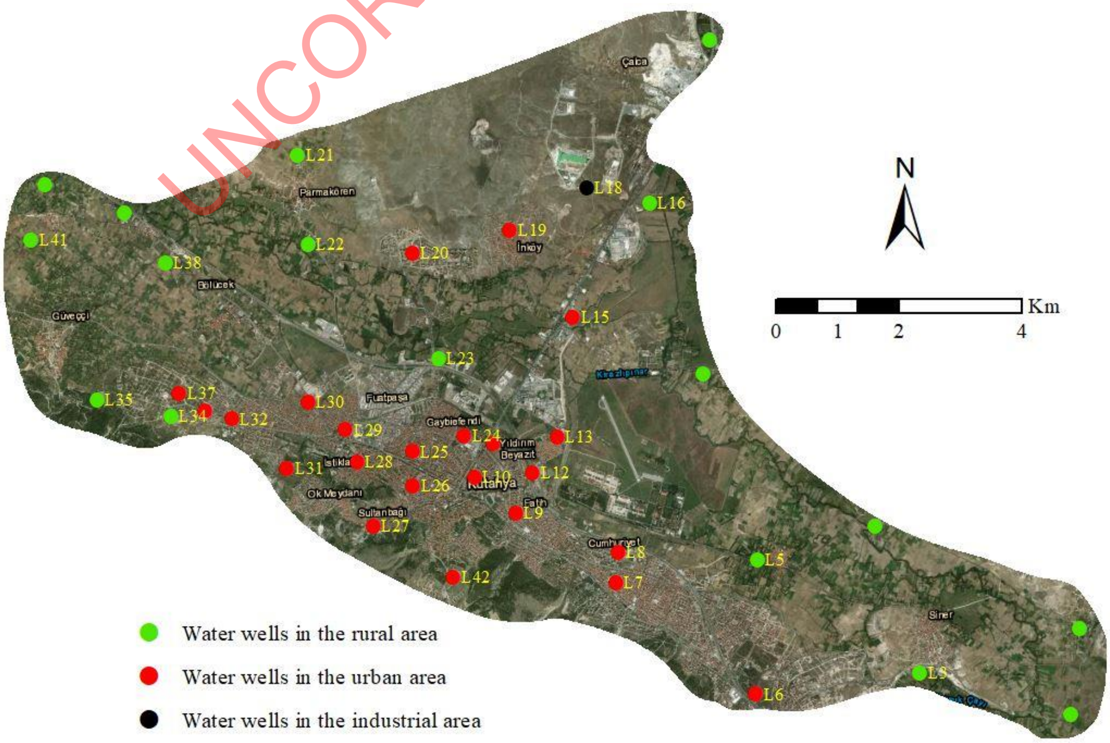


Figure 2- Locations of wells where measurements are made.

In order to determine the volumetric heat capacity C_s (kJ m^{-3} K^{-1}) of the soil, which is one of the parameters required to calculate the heat potential of the alluvial aquifer located in shallow depths under the city center, ground samples were taken from the well places where the measurement was made and then in November 2019, the volumetric heat capacities of the ground samples were determined using the ISOMET 2114 device in the laboratories of Torino Technical University (Politecnico di Torino) Department of Land, Environment and Infrastructure Engineering in Torino (Italy).

4. Observations and Obtained Data

4.1. Meteorological Data

In Kutahya, where the continental climate prevails, summers are hot and dry, winters are cold and rainy. According to the Köppen-Geiger (1954) climate classification, the city is in the CSB (hot and dry summer, cool and rainy winter) climate class. Rainfall is generally observed in spring, autumn and winter. In order to determine the effect of increasing urbanization on air temperature over time, 50 years of monthly/annual air temperature and 100 cm soil temperature data between 1970 and 2019 were obtained from Kutahya Meteorology Station. The location of the meteorology station in an area where urbanization is concentrated is seen as an important advantage in terms of understanding the effects of the urban heat island effect on the air and soil temperature. Based on meteorological data; annual average air temperature and soil temperature values were assessed in 10-year time intervals from 1970 to 2019 (Table 2). Accordingly, the annual average air temperature value, which was 10.26 °C between 1970-1979, has continuously increased over time, and this value reached 11.92 °C between 2010-2019. In other words, the average annual air temperature has increased by +1,66 °C in Kutahya city center in the last 50 years. Again, based on the data of the last 50 years, 100 cm soil temperature values have increased almost the same (+1.61 °C) since 1970. Based on TURKSTAT data; The population of Kutahya Central district, which was 129,056 people in 1970, increased by 111% in the last 50 years, reaching 272,367 people in 2019. This increase in the population caused the need for accommodation and urbanization in the city center increased from year to year. Based on the data obtained from the meteorology station located in the city center of Kutahya, between 1970 and 2019, the average air temperature increased by +1.66 °C and the average annual soil temperature increased by +1.61 °C. Since there is no meteorology station in rural areas in Kutahya, the average temperatures in urban and rural areas between these years cannot be compared. However, it is known that urbanization continuously increased depending on the population and green areas decreased between these years. Therefore, this increase in average air and soil temperatures between 1970 and 2019 is thought to be a result of not only climatic factors but also urbanization. Based on the data, the air temperature is the highest in July with an average of 21 °C and the lowest in January with 0.36 °C; soil temperature is highest in August with 20.27 °C and lowest in February with 6.19 °C.

Table 2 - Monthly and annual average air temperature and 100 cm soil temperature values between 1970 and 2019 in Kutahya city center.

Parameter	Month	Average	Diff.*

	Time interval (year)	1	2	3	4	5	6	7	8	9	10	11	12		
	1970-1979	0,34	2,38	5,65	9,92	14,09	17,73	20,19	19,35	15,96	11,25	6,11	0,79	10,26	
	1980-1989	0,64	0,76	4,32	10,21	13,90	17,89	20,21	20,26	16,80	10,95	5,53	2,24	10,31	
T_{air} (°C)	1990-1999	0,13	1,09	4,22	9,47	14,42	17,95	20,38	20,46	16,28	12,17	5,96	2,39	10,41	1,66
	2000-2009	0,19	1,53	6,12	10,07	14,85	19,06	21,97	21,86	16,91	12,41	6,69	1,97	11,14	
	2010-2019	1,17	3,93	6,86	11,07	15,57	19,23	22,25	22,19	18,39	12,19	7,57	2,57	11,92	
	1970-1979	5,56	5,03	6,26	9,12	12,35	15,46	18,45	19,72	18,42	15,32	11,21	7,89	12,07	
	1980-1989	6,21	5,35	5,99	9,23	12,38	15,34	18,33	19,91	18,98	15,82	11,75	8,52	12,37	
T_{earth} (°C)	1990-1999	7,54	6,28	7,11	9,74	13,18	16,2	18,67	19,92	19,15	16,59	13,01	9,85	13,10	1,61
	2000-2009	8,00	7,04	8,01	10,55	13,61	16,87	19,81	21,34	20,35	17,48	13,67	10,07	13,90	
	2010-2019	8,09	7,27	8,11	10,10	13,07	15,86	18,66	20,47	20,10	17,57	14,06	10,81	13,68	

T_{air}: Air temperature; T_{earth}: Earth temperature * Refers to the annual average temperature difference between 1970-2019.

4.2. Groundwater Temperature Distribution

Underground temperature is affected by physical factors such as ground type, thermal conductivity, specific heat capacity and density. In addition to these factors; climatic factors such as heat flux from underground, earth cover (natural/artificial) and air temperature, wind, sunlight and humidity are known as other factors affecting underground temperature (Landsberg, 1981; Krarti et al., 1995; Popiel et al., 2001). Popiel et al. (2001) divided the earth into three zones based on temperature distribution as surface zone, shallow zone and deep zone. Accordingly, the surface zone is the part of the ground up to a depth of 1 meter and this zone is affected by daily temperature changes. The zone in which the annual effect of the air temperature is observed is called the shallow zone. The shallow zone extends from 1 meter to 20 meters deep and depends on the type of ground and the water content. The deep zone is located under the shallow zone and is not affected by atmospheric changes. On the other hand, Oke (1987) defined the part up to 0.75 meter below ground as the surface zone, and the part up to 14 meters as shallow zone. Although researchers specify the depth limits for these zones, the depth of these zones depends on the type of cover of the surface. According to Landsberg (1981), daily and annual heat waves reach a depth of 4 to 8 meters on the grass-covered surface and deeper on concrete-covered surfaces and affect depths of 15-19 meters. Rybach and Sanner (2000) stated that this effect reaches a depth of 15 meters (Yalcin and Yetemen, 2009).

As stated in previous studies (Taniguchi et al., 1999; Ampofo et al., 2004; Ferguson and Woodbury, 2004; Taniguchi, 2006; Taniguchi, 2007; Yalcin and Yetemen, 2009; Zhu et al., 2010) urban heat island effect causes an increase not only in air temperature, but also in ground temperature through thermal diffusivity and in groundwater temperature as a result of heat transfer between ground and groundwater. In order to determine the effect of the urban heat island factor on the groundwater temperature in the city center of Kutahya, the annual average values of the groundwater temperature measurements made monthly in 41 water wells are presented in Table 3 and the graph of the change of groundwater temperature values by months within the year is presented in Figure 3.

Table 3- Annual average groundwater temperature (T_{sort}) values in wells in urban (U), rural (R) and industrial areas where the measurements were made.

Location	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14
T_{sort} (°C)	11,22	12,72	12,28	12,69	12,95	13,96	14,88	15,92	14,76	16,63	13,89	12,11	12,44	10,90
Area	R	R	R	R	R	U	U	U	U	U	U	U	U	R
Location	L15	L16	L17	L18	L19	L20	L21	L22	L23	L24	L25	L26	L27	L28
T_{sort} (°C)	11,82	13,80	11,64	14,15	14,01	14,59	13,56	11,05	11,71	12,76	15,71	15,93	11,58	13,15
Area	U	R	R	I	U	U	R	R	U	U	U	U	U	U
Location	L29	L30	L31	L32	L33	L34	L35	L37	L38	L39	L40	L41	L42	
T_{sort} (°C)	14,12	13,38	12,35	11,92	12,95	11,66	12,46	13,47	12,77	12,34	9,73	12,80	11,23	
Area	U	U	U	U	U	R	R	U	R	R	R	R	U	

T_{sort} (°C): Annual average groundwater temperature values R: Wells located in rural areas, U: Wells located in urban areas, I: Wells located in industrial areas

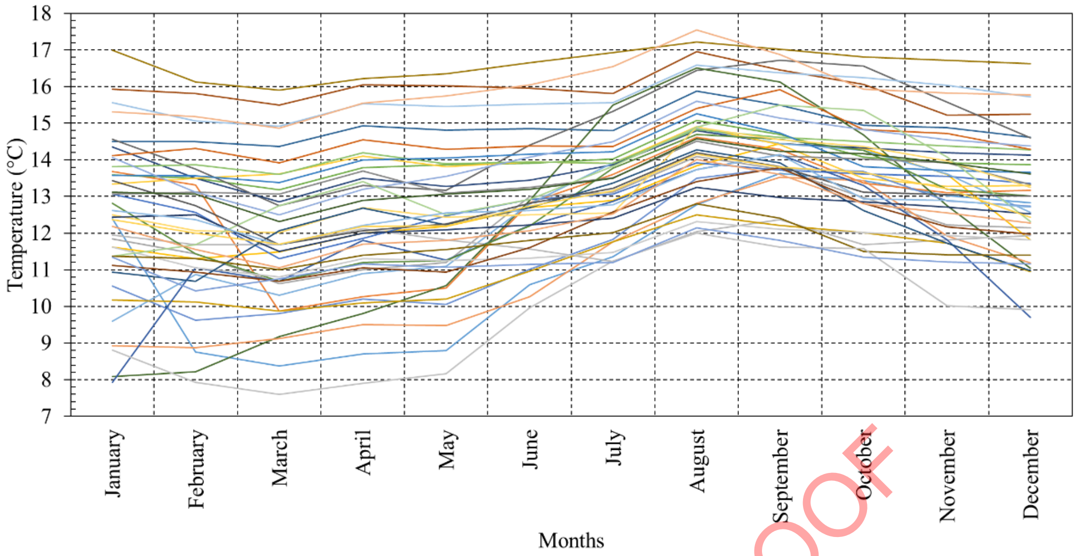
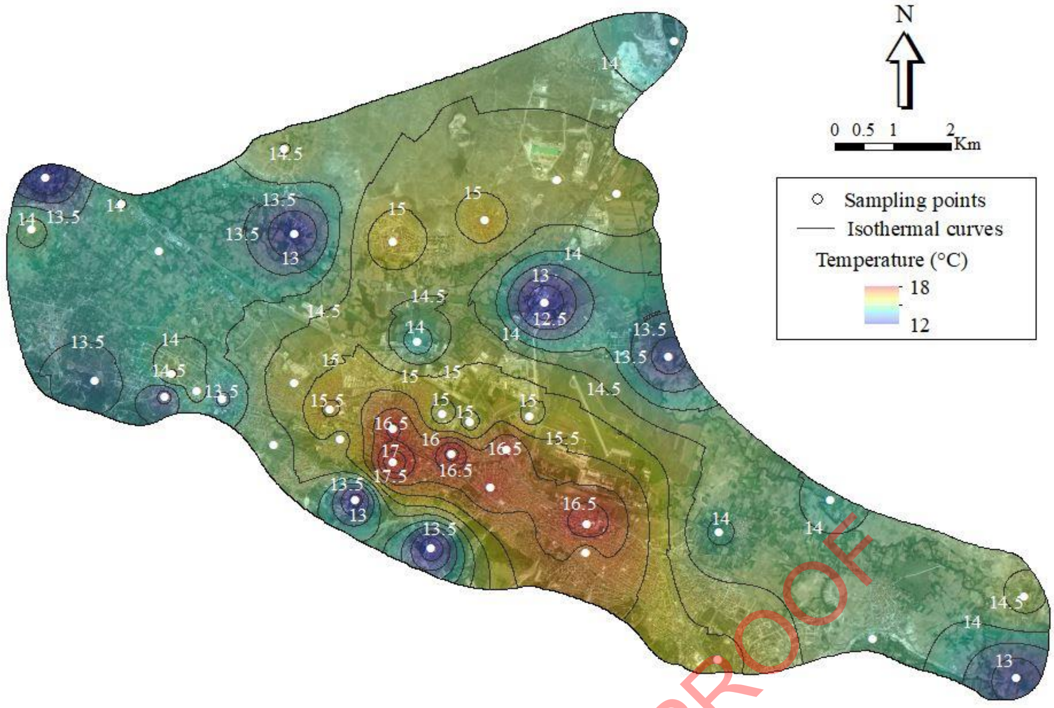


Figure 3- Groundwater temperature change by months in the wells measured in 2019.

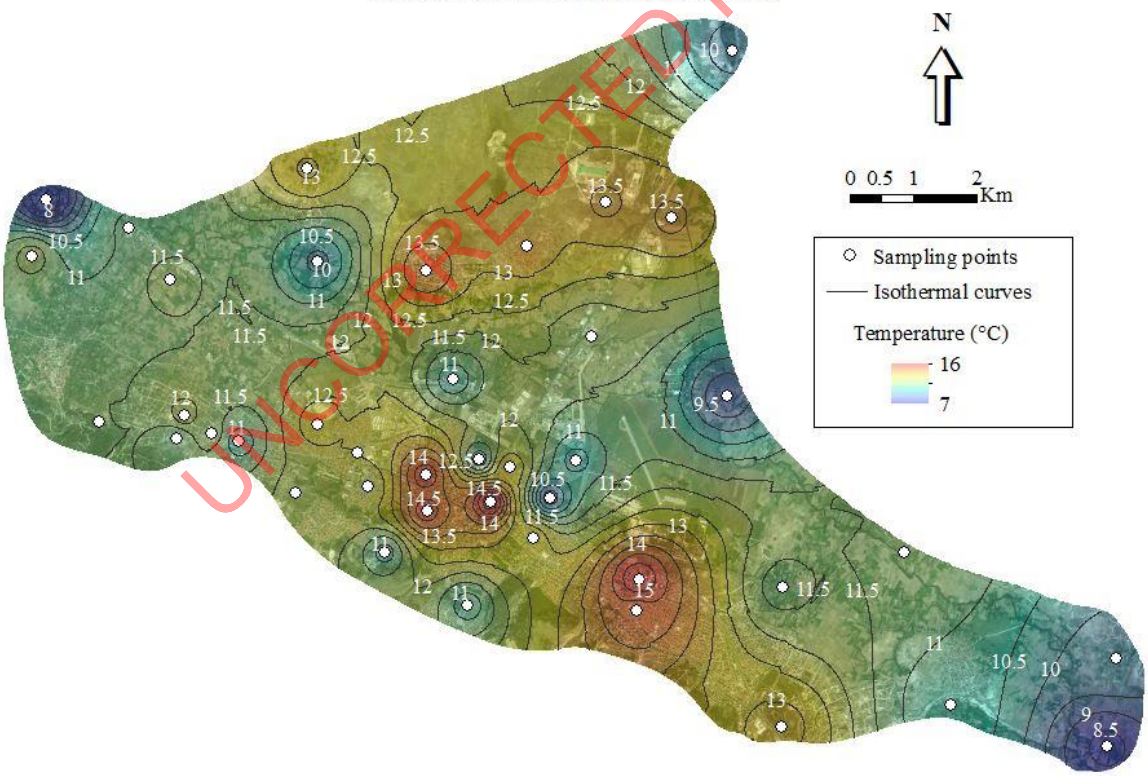
Based on the data obtained; the highest groundwater temperature was observed as 17.55 °C in August in location L26, which is in one of the regions where urbanization is most intense in the city center, while the lowest groundwater temperature was observed as 7.60 °C in March in location L40, where rural areas and cultivated agricultural lands are dense. The month when the groundwater temperature is the highest during the year is August with an average temperature of 14.43 °C, and the lowest month is March with an average temperature of 11.83 °C. Based on the data obtained from all wells examined; areal average annual temperature of groundwater in the city center of Kutahya is 13.02 °C. The difference in groundwater temperature in rural areas, mostly consisting of green areas and agricultural lands and in the city center, where urbanization is intense, varies from month to month, and this difference increases up to 1.63 °C.

As a result of the measurements made to observe the areal distribution of these groundwater temperature values and to determine the areal distribution of the urban heat island effect; urban heat island maps were created with the Internal Distance Weighting (IDW) method in the ArcMap 10.7 software (ESRI, 2019) based on August with the highest average groundwater temperature, March with the lowest average groundwater temperature and 12-month average groundwater temperature values and the effect of the urban heat island on groundwater and its environment has been studied (Figure 4).

Urban Heat Island Map for August (2019)



Urban Heat Island Map for March (2019)



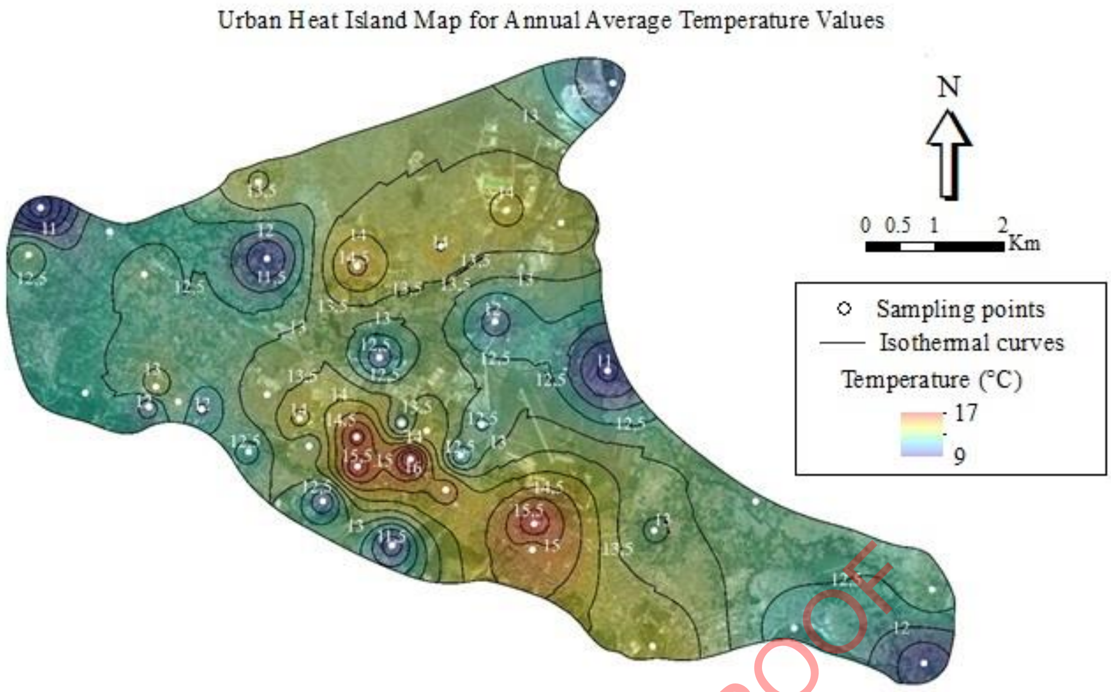


Figure 4. Urban heat island maps: a) August (2019) when the groundwater temperature values are the highest, b) March (2019) when the groundwater temperature values are the lowest, c) The annual average temperature values.

When the annual and monthly urban heat island maps are examined, it is clearly observed that the groundwater temperatures in the city center of Kutahya vary greatly from region to region and there is a tendency to increase the temperature towards the regions where urbanization is concentrated. The lowest temperatures were observed in rural areas, and the highest temperatures were observed in residential areas. In the city region, the groundwater temperature rises up to 16.93 °C in August. In rural areas, this value was measured as 11.20 °C in the same month. While the groundwater temperature is 11.95 °C on average annually in the measurements made from the wells in rural areas, the groundwater temperature in urban areas reaches 13.58 °C by increasing this average +1.63 °C. When the comparison is made on the basis of wells one by one, the difference between the two wells in urban and rural areas increases up to about 7 °C. For example, while the average annual groundwater temperature is 16.63 °C in a location on Ataturk Boulevard where urbanization is most intense in Kutahya, this value is 9. 73°C with a difference of 6.90 °C in the well in Kirazpınar Quarter, an old village dominated by agricultural lands and green areas. This situation is considered as an important indicator in terms of the direct effect of human-made structures on groundwater temperature. Based on the prepared maps (Figure 4), the groundwater temperature values in the city center of Kutahya show heterogeneous distribution within the study area, and these temperature values are directly related to human origin factors such as urbanization.

Considering the changing air, soil and groundwater temperatures throughout the year; soil and groundwater temperature increases/decreases parallel to air temperature (Figure 5). The soil temperature is significantly affected by the air temperature and large increases and decreases are observed throughout the year. This is due to the fact that the data used is based on the soil temperature at 100 cm depth. Because; soil temperature values measured at the meteorology station are the values taken from the surface zone, which Popiel et al. (2001) refers to up to a depth of 1 meter, and this zone is affected by daily temperature changes. Since the groundwater temperature measurements are made within the shallow zone, not from the surface zone, temperature fluctuations in groundwater are observed less.

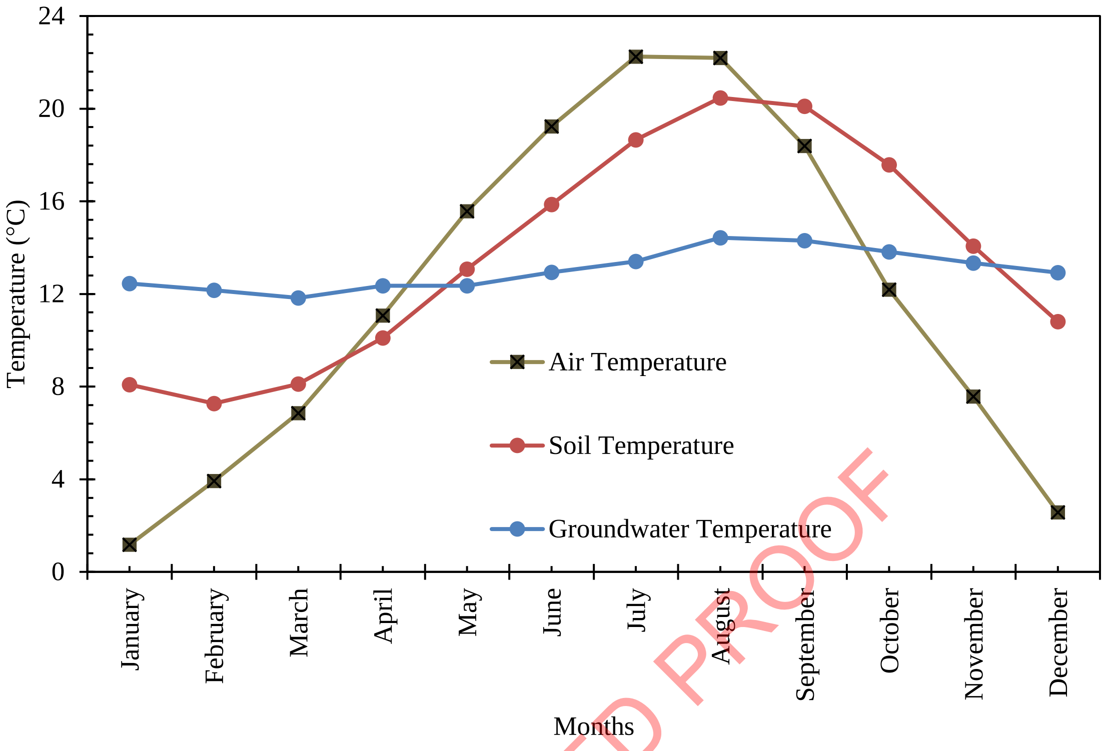


Figure 5- Temperature change graph of air, 100 cm soil and groundwater by months in 2019

5. Shallow Geothermal Energy

The increase in the energy need due to the population growth in recent years has led researchers to focus on renewable and reliable energy sources. In this sense, shallow geothermal energy has become one of the popular renewable energy sources especially in Europe in recent years. The temperature increase in groundwater due to the urban heat island effect caused the heat potential of these waters to increase, this situation led to the idea of using groundwater in shallow regions as a low-enthalpy energy source, and the concept of shallow geothermal energy has passed to the energy literature. With shallow geothermal energy systems, it has become possible to use these groundwaters for heating. Turkey is a country where the population is constantly increasing and urbanization is increasing rapidly accordingly. Today, Turkey provides its energy needs mostly from non-renewable energy sources and fossil fuels. Most of these resources are imported from abroad. The dissemination of renewable energy sources such as shallow geothermal energy is important for the national economy and environmental health. Both heating and cooling needs of buildings can be provided with shallow geothermal systems.

Due to the climate of Kutahya and its vicinity being hot and dry in summers and quite rainy in winters, shallow aquifers in the region have an important potential in terms of groundwater resources. Hot summer months cause some of the sun rays to be absorbed by natural and artificial grounds, as a result of this, it causes an increase in groundwater temperatures and therefore shallow geothermal energy potential. When the climatic conditions and urbanization rate are considered, it is predicted that the shallow geothermal system will be an important alternative to energy resources in Kutahya. The most important advantages of the system are that shallow geothermal energy is renewable, environmentally friendly and sustainable. Today, energy production based on fossil fuels causes a significant amount of CO_2 emission, as a result, serious environmental problems occur. However, the shallow geothermal system using heat pumps causes much less CO_2 emission than other systems, making it an environmentally friendly system.

While geothermal energy is defined as the energy stored in the form of heat in the depths of the earth, shallow geothermal energy is defined as the system that allows the use of the low temperature groundwater in the shallow depths by increasing the temperature by heat pumps in the heating and cooling systems of the houses. Many studies up to now (Allen et al., 2003; Kerl et al., 2012; Zhu et al., 2010) have shown that shallow aquifers under cities can be an important energy source with low enthalpy. The earth serves as a collector for the storage of energy received from the sun under the earth. Likewise, the heat from the earth's core is stored under the earth. These two sources are the two main factors affecting the shallow geothermal potential of a region. However, shallow geothermal energy is mostly derived from sun rays, and only a small proportion of the stored energy in shallow aquifers is due to the earth's internal heat or heat generated by plate tectonics (Banks, 2010). Shallow geothermal energy mostly covers the part of the ground up to 100 m depth. The system can be applied to deeper areas, but this increases the cost.

Heat pumps are tools that transfer heat from a heat source to a cooler (Aye and Charters, 2003). In shallow geothermal systems, heat pumps are essential as they are units where water/fluid enters and leaves and its temperature is increased/decreased. Shallow geothermal systems; based on the working principle and the way of establishment, are examined in two ways as open-loop and closed-loop (Figure 6) (Stauffer et al., 2013; Huang, 2012; Rees, 2016). Soil is used as heat source in the closed loop system, which has been used more widely until today. The soil temperature is taken from the ground with the help of fluid, and it is transmitted to the fluid named 'the thermal transfer fluid' circulated in the pipes. This fluid which is inside the pipes and consisting of water and antifreeze, circulates continuously in the closed loop system. The heat gained from the soil as a result of the heat exchange of the antifreeze fluid is increased by heat pumps and used in the heating processes of the buildings. In a closed loop system, the pipes are laid horizontally to a depth of 1-2 meters or vertically up to a depth of 100 meters, depending on the convenience of the application area and the purpose of heating/cooling. In the open loop system, which is observed to be less, the heat energy is taken directly from the groundwater, lake or river by means of pipes placed in the borehole, which is pumped and transferred to the heat exchanger and then to the heat pump. In other words; the open-loops are systems in which the water to be used in heating and cooling is drawn from groundwater or water bodies such as lakes/rivers by pumping through the borehole. In an open loop system, water circulates between two or more groundwater wells. After this water is drawn from underground and used for heating/cooling, it is injected back into the same aquifer or any water body (lake, river, etc.) on the surface through a second borehole. When the required amount of water is extracted in the open loop system, the aquifer must have high permeability in order to minimize the drawdown (Rafferty, 2000; Sanner, 2001).

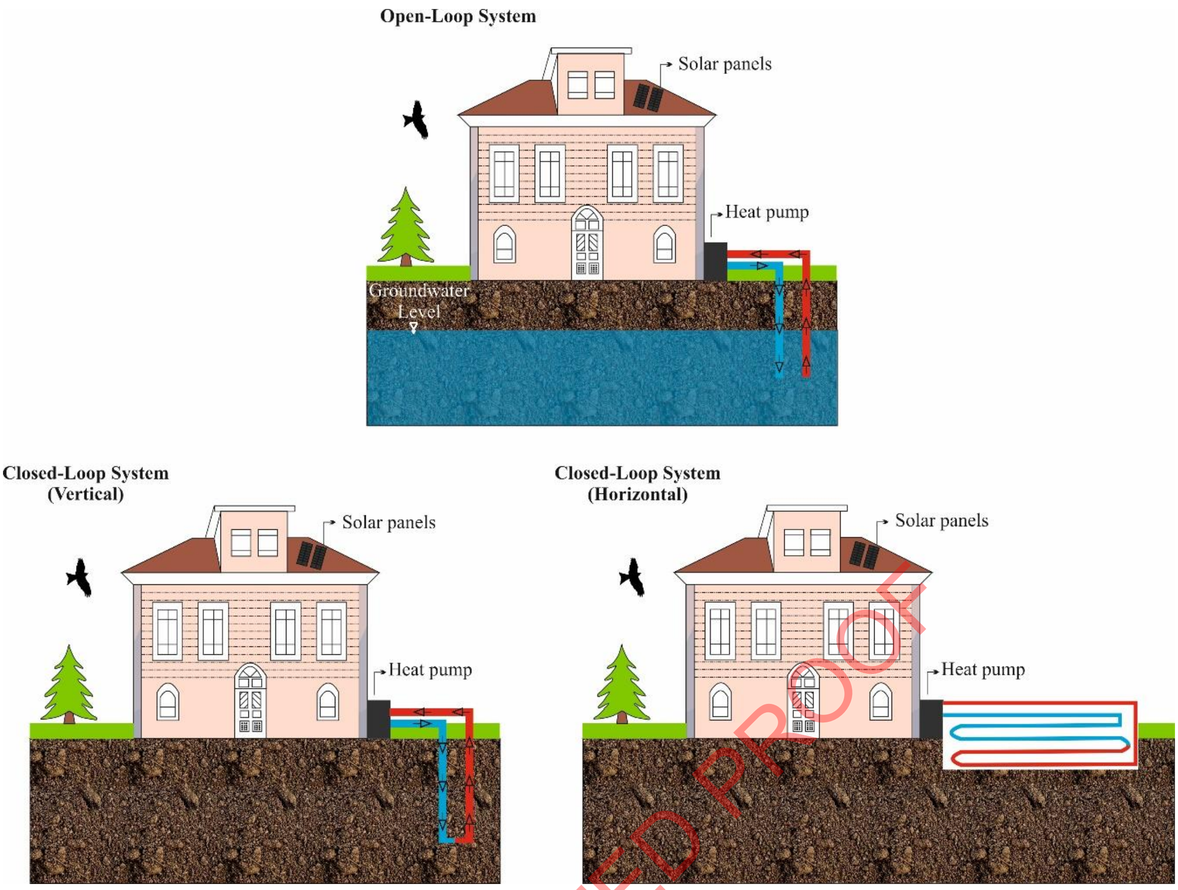


Figure 6- Schematic representation of shallow geothermal systems

Coefficient of performance (*COP*) of the heat pump, which is an important factor in the system cost, is defined as the ratio of the energy obtained at the output of a heat pump system to the consumed electrical energy (Curtis et al., 2005). COP is calculated with the equation stated below.

$$COP = \frac{Q}{W}$$

Here Q: is the heat supplied or removed from the reservoir; W: is the work consumed by the heat pump. More clearly; this coefficient expresses the ratio between the electrical energy consumed by the system and the amount of heat it can produce. High COP value is preferred in heat pumps in order to lower system cost. For example, in a system with a COP value of 4, 4 units of heat are obtained for one unit of electrical energy consumed. COP varies depending on the thermal load, building type, temperature to be supplied, input water temperature, climatic conditions, size, material and type of heat exchanger (Sanner et al., 2003; Yalcin and Yetemen, 2009). Also; COP of the heat pump increases according to the temperature of the input water (Boyd and Lineau, 1995; Sanner et al., 2003). Therefore; high reservoir temperature will increase the COP value, which will reduce the system cost.

According to Allen et al. (2003), if a shallow geothermal system is used in a 1-meter-thick gravel aquifer with 12 °C groundwater temperature, an annual energy saving of 2 GWh is ensured. According to this study; a heat pump operated with a COP value of 4.5:1 in a well having a groundwater temperature of 12 °C and an efficiency of 20 l/s can generate 865 kW of heat. It has been stated that in Finland, where the annual average groundwater temperature varies between 3.5 and 6.6 °C (Mälkki and Soveri 1986; Oikari 1981), 55 to 60 MW energy can be provided for the need for heating through water-source heat pumps with a COP value of 3.5 (Arola et al., 2014). As stated in the previous section, Kutahya city center is a region where the urban heat island effect with a groundwater temperature difference of +1.63 °C between rural areas and urban areas is observed. Increasing groundwater temperatures in the city center of Kutahya due to the effect of the urban heat island, an annual average groundwater temperature of 13.02 °C and soil temperature of 13.68 °C according to the last 10 years' data, groundwater-carrying aquifers being located in shallow depths and the groundwater level being close to the surface are the factors that increase the applicability of shallow geothermal systems in Kutahya city center. In this sense, when the data obtained within the scope of the study are compared with the results of previous studies (Allen et al., 2003; Arola et al., 2014; Zhu et al., 2010), a very promising picture emerges at the point of installation of both open and closed shallow geothermal systems in Kutahya.

6. Energy Potential of Alluvial Aquifer in Kutahya City Center

The use of heat energy in shallow aquifers in residential heating and/or cooling processes through shallow geothermal systems has become increasingly widespread especially in Europe in recent years. Increasing groundwater and soil temperatures due to urban heat island effect, enables the use of shallow aquifers as geothermal reservoirs, and this heat is used in residential heating through shallow geothermal systems. Therefore; the theoretical heat capacity of the alluvial aquifer carrying groundwater in the city center of Kutahya is calculated using the data in Table 4 through the following equation after Balke (1977).

$$Q = Qw + Qs = V\, n\, Cw\, \Delta T + V\, (1 - n) Cs\, \Delta T$$

Here Q (kJ) is the theoretical total heat content of the aquifer, V (m^3) is the aquifer volume, n is the porosity, C_w and C_s ($kJm^{-3}K^{-1}$) are the theoretical heat content stored in the groundwater and soil, Q_w and Q_s (kJ) are the heat stored in groundwater and in the ground. According to the VDI 4640/1 (2010) guide published by The Association of German Engineers (Verein Deutscher Ingenieure, VDI), the C_w value for water is 4.150 $kJm^{-3}K^{-1}$. C_s value changes depending on the sediment type, and according to the results obtained from the experiments carried out in the laboratories of Turin Technical University (POLITO); it varies between 1.934 and 2.216 $kJm^{-3}K^{-1}$ in Kutahya city center. ΔT is the temperature decrease observed throughout the aquifer, ranging between 2 and 6 °C. Care has been taken to ensure that the ΔT values selected here are within the limits specified in the VDI 4640/4 (2004) manual published by The Association of German Engineers (Verein Deutscher Ingenieure, VDI). The thickness of the alluvial aquifer has been determined by using many borehole data obtained until today by The State Hydraulic Works (DSI) and private engineering bureaus, and it varies between 10 and 64 m in Kutahya. Another parameter, the volume of the alluvial aquifer in the study area was calculated using the obtained borehole data using *Surfer 14 (Golden Software, LLC, 2017)* and *ArcMap 10.7 (ESRI, 2019)* software.

Table 4- Calculation of the heat content in alluvial aquifer in Kutahya province

Parameteres	Lowest	Highest	Average
Aquifer thickness (m)	10	64	28
Aquifer volume, V (m^3)		$2,87\times10^9$	
Porosity, n	0,42	0,52	0,47
Volumetric heat capacity of water, C_w ($kJ\, m^{-3}\, K^{-1}$)*		4.150	

Potential heat of groundwater, Q_w (kJ K^{-1})	1×10^{13}	$3,72\times10^{13}$	$2,24\times10^{13}$
Volumetric heat capacity of the ground, C_s (kJ m^{-3} K^{-1})	1.934	2.216	2.075
Potential heat of the ground, Q_s (kJ K^{-1})	$6,44\times10^{12}$	$1,83\times10^{13}$	$1,26\times10^{13}$
Temperature difference, ΔT (°C)	2	6	4
Heat potential underground (kJ)	$1,64\times10^{13}$	$5,55\times10^{13}$	$3,50\times10^{13}$

* Based on recommended value in VDI 4640/1 (2000) manual.

Based on the results obtained, alluvial aquifers in the city center of Kutahya theoretically have a serious heat potential between $1,64\times10^{13}$ kJ K^{-1} and $5,55\times10^{13}$ kJ K^{-1}, on average $3,50\times10^{13}$ kJ K^{-1}. It is predicted that the aquifer efficiency of this heat in the alluvium aquifer can be used in the heating processes of residential and/or commercial buildings after the factors such as hydraulic conductivity of the aquifer, annual groundwater budget, heat transfer models and its suitability in terms of shallow geothermal systems are fully revealed. It is predicted that a significant contribution to the environmental health can be made with reduction of fossil fuel consumption by uncovering this "hidden treasure", untouched until today, with the help of shallow geothermal systems, and to the national economy with the decrease in the amount of energy imported and returning to our renewable own resources.

7. Discussion

In various studies examining the effects of the urban heat island effect on the underground and its environment (Taniguchi et al., 1999; Changnon, 1999; Ferguson & Woodbury, 2004; Taniguchi, 2006; Taniguchi, 2007), it has been proven that this effect has a strong effect on the ground temperature. In this study, using the groundwater temperature values measured for a year, the urban heat island effect in the city center of Kutahya has been revealed. In the urban heat island maps created, it was clearly observed that the groundwater temperature values in Kutahya has increased towards urban and industrial areas.

The groundwater, whose temperature increases as a result of the urban heat island effect, can be used in the heating/cooling needs of the houses with shallow geothermal systems. These systems have been widespread in Europe since the early 2000s and have become increasingly popular. Based on the European Geothermal Congress report published by Sanner (2019) in 2019, there are approximately 1.9 million shallow geothermal systems currently in use in Europe. Based on the same report, shallow geothermal energy constitutes 66.5% of geothermal use in Europe and the energy obtained in European countries with these systems has reached a total capacity of 26,900 MWth (megawatt thermal) (Sanner, 2019). However, the fact that shallow geothermal energy systems are still not widespread in our country stands out as a serious deficiency in this area. For this reason, within the scope of the study, it was aimed to determine the existence of the urban heat island effect in the city center of Kutahya, and therefore the temperature increase in aquifers located at shallow depths. As a result of the heat island maps created based on groundwater temperature measurements, the existence of the urban heat island effect in Kutahya city center was determined. Then, the heat potential of the alluvial aquifer whose temperature increased with the effect of the urban heat island was obtained. Based on the results, it has been revealed that this aquifer theoretically has an average heat potential of 3.50×10^{13} kJ K^{-1}. This result shows that large amounts of thermal energy are stored in city centers with high population density. In the study carried out by Zhu et al. (2010) in Cologne (Germany) and Winnipeg (Canada), this value is 2.90×10^{13} kJ for Cologne and 4.10×10^{13} kJ for Winnipeg. The researcher pointed out that this energy is a large amount corresponding to 2.5 times the annual heating need of the city of Cologne. The potential energy calculated in the alluvial aquifer in Kutahya city center is 1.2 times the energy in the city of Cologne. Bayer et al. (2019) divided the shallow geothermal potential of a city/region into three categories: “theoretical potential”, “technical potential” and “economic potential”. According to the researcher, the total physically energy available underground refers to the “theoretical potential”. The next subcategory, the “technical potential”, is the poriton of the theoretical potential that can be harnessed by available technologies. As only part of the technically extractable energy is economically reasonable, this other fraction is defined as “economic potential”. The energy calculated within the scope of this study represents the theoretical potential.

Groundwater temperatures obtained within the scope of the study and soil temperature values obtained from Kutahya Meteorology Station are suitable values for the shallow geothermal system. Uncovering this hidden treasure located in the shallow depths of the ground is very important for both Kutahya and the economy of Turkey, where fossil fuel consumption and energy imports are high.

From now on, it is thought that the shallow geothermal energy potential of Kutahya should be determined theoretically and mapped on the basis of urban, industrial and rural regions by including other aquifers located at shallow depths under the alluvial aquifer. Urban heat island maps and heat potential calculations of aquifers can provide important data in assessing the applicability of shallow geothermal systems in the city center of Kutahya and/or throughout the country in the future. Depending on the geological, hydrogeological and areal conditions, open or closed systems may be preferred from shallow geothermal systems and some of the heating need of the city can be met with these systems. Thus, a contribution to the national economy by a national renewable energy resource and as well to environmental health by reducing fossil fuel consumption.

8. Results

In the city center of Kutahya, where the groundwater temperature distribution varies depending on the regions due to urbanization and industrialization, groundwater temperature anomalies show a clear increase towards the city center. In rural areas where the effect of man-made factors on groundwater temperature is minimal, groundwater temperature values are lower than in urban areas. In regions where urbanization and other man-made factors are intense, it has been observed that groundwater temperature values are 1.63 °C higher than rural areas. In this sense, the study results are consistent with previous studies focused on the urban heat island effect. The main reason for this situation is the intense construction in the city center, lack of green areas, underground car parks, closed surfaces that do not take air, sewage systems, thermal energy that has accumulated for years and still continues to accumulate due to the effects of the heat spread from the floor of the buildings to the underground. When the annual air temperature and the annual groundwater temperature values are compared, it was observed that these two parameters are related and that the air temperature controls the underground temperature.

The heat potential of the alluvial aquifer under the city center of Kutahya has been calculated numerically and it has been revealed that this aquifer theoretically has at least 1.64×10^{13} kJ K^{-1}, maximum 5.55×10^{13} kJ K^{-1}, average 3.50×10^{13} kJ K^{-1} heat potential.

When the temperature anomalies in the urban area are examined, it has been observed that the groundwater temperature in the urban area varies more than in the rural areas. In other words; while the groundwater temperature in a rural area does not vary much in a well compared to another well, in an urban area, these values vary more from well to well. It is thought that this situation is caused by the size of the spaces between the buildings in the city center. While some buildings are built very closely to each other in the city center, other buildings have much more space between them. In urban areas where sparse distribution is observed, empty spaces between buildings consist of green areas or natural areas with soil surfaces. This causes the groundwater temperature to vary by area. From this situation, it can be concluded that groundwater temperature shows a homogeneous distribution in rural areas and a heterogeneous distribution in urban areas.

Except for the city center, groundwater temperature values are higher in industrial areas than in rural areas. It is thought that there may be hot wastewater discharge into the aquifer by the factories and this discharge may increase the groundwater temperature in addition to the factory structuring.

It has been proven that the urban heat island effect has an effect not only on the air temperature values but also on the underground and its surroundings. As a result of the thermal energy that man-made structures confine and spread to the underground, the groundwater and soil temperature values change and the urban heat island effect emerges.

Groundwater temperature values measured in the city center of Kutahya vary between 7.60 °C and 17.55 °C throughout the year when all rural and urban areas are included, and the annual average groundwater temperature is 13.02 °C. These are very promising values regarding the shallow geothermal system in Kutahya. But; the temperature values alone are not sufficient for the applicability of the system. In order to fully reveal the suitability of the system, factors such as aquifer efficiency, hydraulic conductivity of the aquifer, annual groundwater budget must also be determined. In addition, in case the system is implemented, it is very important to create heat transfer models that will occur within and between aquifers, system health and observing the thermal effect/pollution that may occur in aquifers over time, thus assessing the sustainability of the system.

Considering the urbanization rate and accordingly increasing need for energy whether in Kutahya or in Turkey, the dissemination of renewable energy sources such as shallow geothermal energy is very important for the national economy and environmental health. It is expected that the use of such renewable resources will play an important role in increasing the domestic energy potential and reducing the foreign dependence on energy.

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