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Assessment of water pollution in a waste storage drainage area (a case study in Eskişehir, Türkiye)

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Abstract: Before 2016, the Eskişehir city landfill was an irregular landfill. Since then, it has been transformed into a regulated landfill. This study aimed to investigate the presence of pollution in the landfill drainage area. For this purpose, water samples were collected from the landfill drainage area and the Kadirbey Farm Spring, upstream of the landfill area, during the rainy and dry seasons of 2021. Analyses of the heavy metal content, total dissolved soil (TDS), chemical oxygen demand, biochemical oxygen demand, pH, phenol material content, ammonia nitrogen content, and conductivity were conducted on the samples. Electrical resistivity tomography (ERT) measurements were also performed along the stream bed. According to Turkish Soil Water Quality regulations, the TDS concentrations of all the samples, except one, were lower than the limits for class 3 water quality. The conductivity limits were within the acceptable range for class 3 water quality. The pH of the water samples was alkaline. The calculated leachate pollution index values indicated a pollution risk. The heavy metal pollution index values for the water samples were under 100. Additionally, 75% of the samples were in the very pure category according to the heavy metal evaluation index, with the remaining samples classified as slightly affected. According to the ERT measurements, soils with low resistivity near the landfill were notably laterally wider. The conductivity decreased with the increasing distance from the landfill site. Low resistivity zones, such as plumes, were disconnected from each other. The shape and volume of highly contaminated plumes decreased toward BH1. Based on the study outcomes, it is recommended to measure the water pollution parameters at periodic intervals within the landfill drainage area.

Key words: Eskişehir, ERT, heavy metal pollution, landfill, leachate pollution index

1. Introduction

The global annual municipal soil waste production is approaching 2.2 billion tons due to economic development, urbanization, changing lifestyles, and population growth (Cetin et al., 2018; Ucun Ozel et al., 2019; Cetin, 2020; Sevik et al., 2020a, 2020b; Cetin and Jawed, 2021; Koç, 2021; Varol et al., 2022). While developed countries manage their waste with regulated programs, underdeveloped and developing countries often use wild storage methods, which lead to environmental pollution, groundwater contamination, and health problems for the population (Daniel, 1993; Han et al., 2016; Kamaruddin et al., 2017; Sharma et al., 2019). However, efforts to create sanitary landfills continue worldwide to eliminate the negative effects of unregulated landfills, such as landfill sliding, explosions, soil pollution, surface and groundwater pollution, and odor (Baccini et al., 1987; Niininen and Kalliokoski, 1993; Muttamara and Leong, 1997; Celik et al., 2007). Kumar and Alappat (2005a, 2005b, 2005c) suggested the leachate pollution index (LPI) as a quantitative method for assessing leachate pollution material.

Eskişehir sanitary waste storage, once a wild waste landfill area, was rehabilitated and used as a sanitary landfill in 2017 (İlbank, 2016). The waste deposited in the landfill primarily includes household residues, construction debris, and ash. Additionaly, as of 2017, medical waste has also been hygienically stored at this site.

The current study investigated the potential for water pollution in the area affected by landfill leachate. Two boreholes were drilled to a depth of 30 m. Surface water and groundwater samples were collected during the wet and dry seasons of 2021. Heavy metal content, pH, total dissolved soil (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), phenolic material concentration, conductivity, and ammonium nitrogen concentration analyses were performed on the surface and groundwater samples. Electrical resistivity tomography (ERT) measurements were taken along the line between the boreholes to determine probable contamination along the Takahasan Stream bed in the landfill drainage area. The results obtained from the analyses were discussed in detail regarding contamination.

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2. Study area

The study area is located on the border of the Gülpınar neighborhood in the Odunpazarı district of Eskişehir City, Türkiye. The corner coordinates of the area defined in the universal transverse mercator (UTM) projection system Zone 36 is 4,398,000–4,401,000 (North) and 288,000–294,000 (East). The landfill is near the Eskişehir-Seyitgazi D665 State Highway, approximately 7.6 km from the city center of Eskişehir (Figure 1). Settlement areas are located in Gülpınar, approximately 4.2 km east of the landfill; Kayapınar, 6.2 km west; and Sultandere, 9 km west. The Takahasan Stream, which flows seasonally, used to pass through the region before it was converted into a landfill. The bed of the Takahasan Stream was filled in after garbage deposition began. The bed of the Takahasan Stream extends northward for approximately 1.7 km before joining the Ayrıklı Stream, which flows eastward for about 2.5 km and eventually merges with Sarısungur Creek. From there, it continues for an additional distance until it reaches the drying channel of the Eskişehir Waste Water Treatment Plant. Afterward, it continues for about 3 km until it meets the Porsuk River. These streams exhibit a sparse dendritic drainage pattern, with both seasonal and continuous flows directed toward the Porsuk River.

The dominant climate in the region is continental. The maximum temperature was recorded in June (21.7

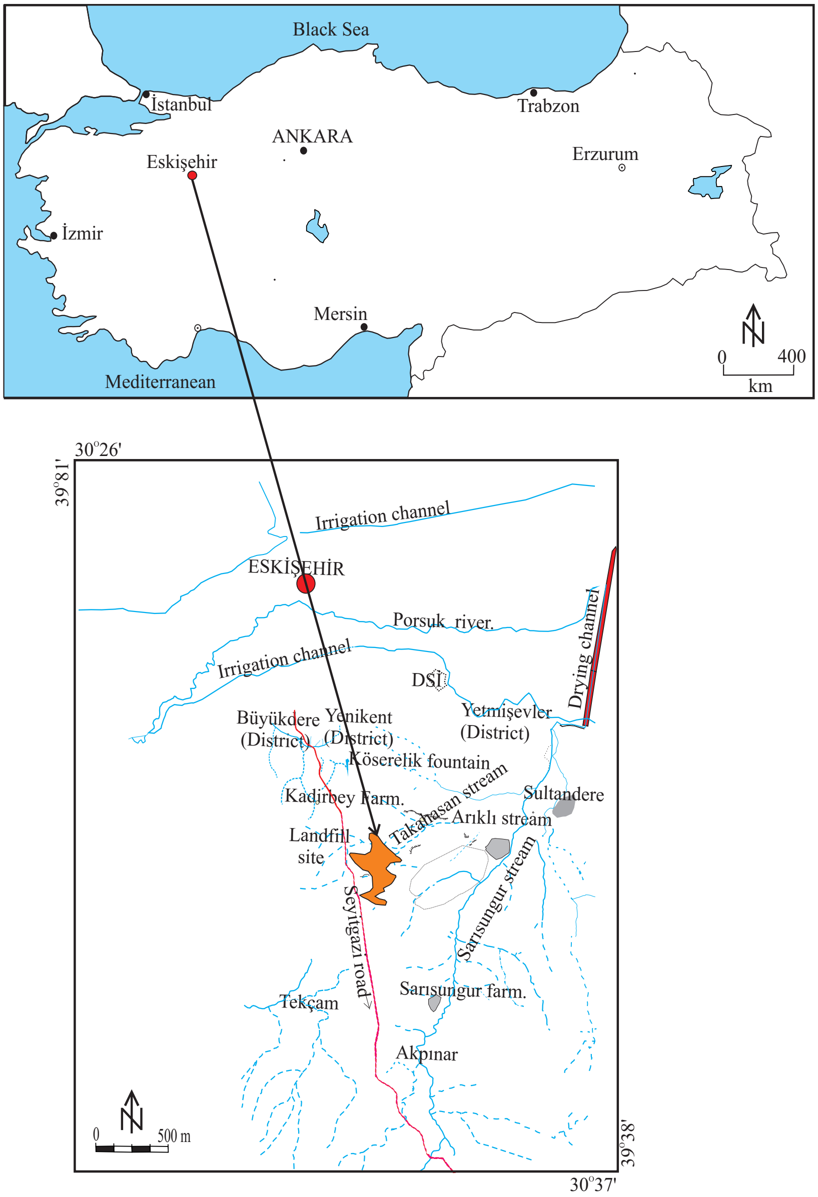

Figure 1. Location map of the Eskişehir landfill site.

°C), while the minimum temperature was recorded in January (0.1 °C).[1] Considering the geological perspective, the groundwater and topography map in Figure 2a and the SW–NE oriented geological section in Figure 2b, it is evident that the landfill areas, cemetery areas, Takahasan Stream, and Ayrıklı Stream are situated within deposits of conglomerate, sandstone (Em1), clay, and marl (Em2) from the Eocene-aged Mamuca Formation, Porsuk Formation limestones (Np5), as well as alluvial deposits. Possible faults exist close to both the landfill and the cemetery (Gözler et al., 1985). A groundwater map was prepared by determining the static water levels from 13 wells drilled by the General Directorate of State Hydraulic Works (DSİ, Devlet Su İşleri in Turkish). As can be seen in Figure 2a, groundwater flows in a northeast (NE) direction along the Takahasan Stream. Takahasan Stream flows during the rainy seasons but is generally dry during other seasons. It merges with its tributaries in the NE direction and is named Ayrıklı Stream. The areas surrounding the Ayrıklı and Takahasan streams are primarily used for agricultural purposes. The highest altitude in the area is 997 m, while the lowest is 806 m.

The Eskişehir landfill area, previously a wild landfill before 2016, was rehabilitated by the Eskişehir municipality (İlbank, 2016) and is now used as a regular landfill storage area. Figure 3 shows views of the wild landfill storage area. The thickness of the waste material in the landfill ranges between 7 and 37 m. The waste layer in the area was stored irregularly. While the excavation material content was relatively high toward the edges of the valley, most domestic waste was observed at the center. First, drainage ditches were excavated at the base of the

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[1] MGM (2018). Turkish State Meteorological Service [online]. Website https://www.mgm.gov.tr/eng/forecast-cities.aspx?m=ESKISEHIR [accessed 01 February 2022].

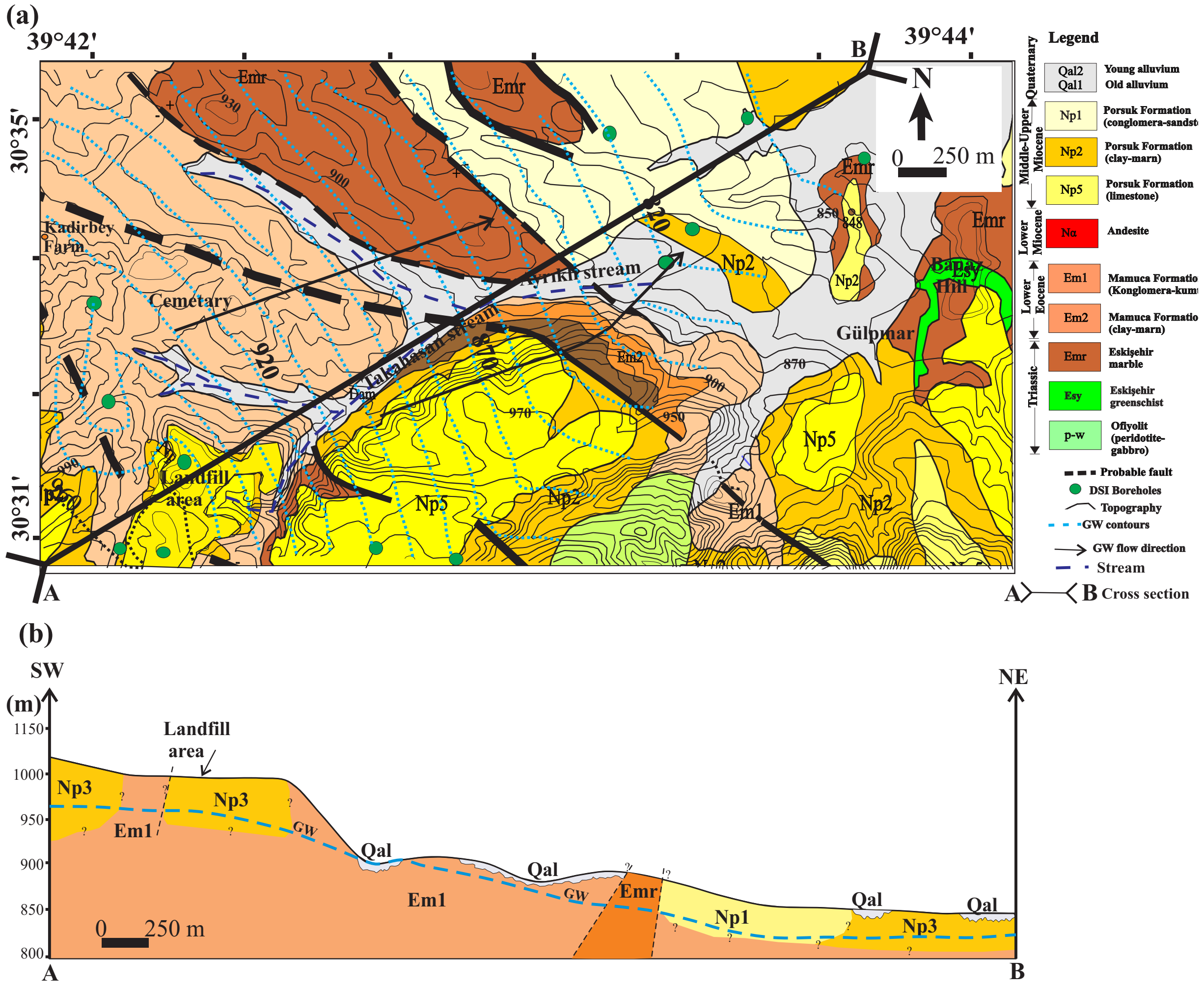

Figure 2. (a) Study area geology, topography, and groundwater flow map vicinity (geology map modified from Gözler et al., 1985); and (b) SW–NE oriented geological section of the area.

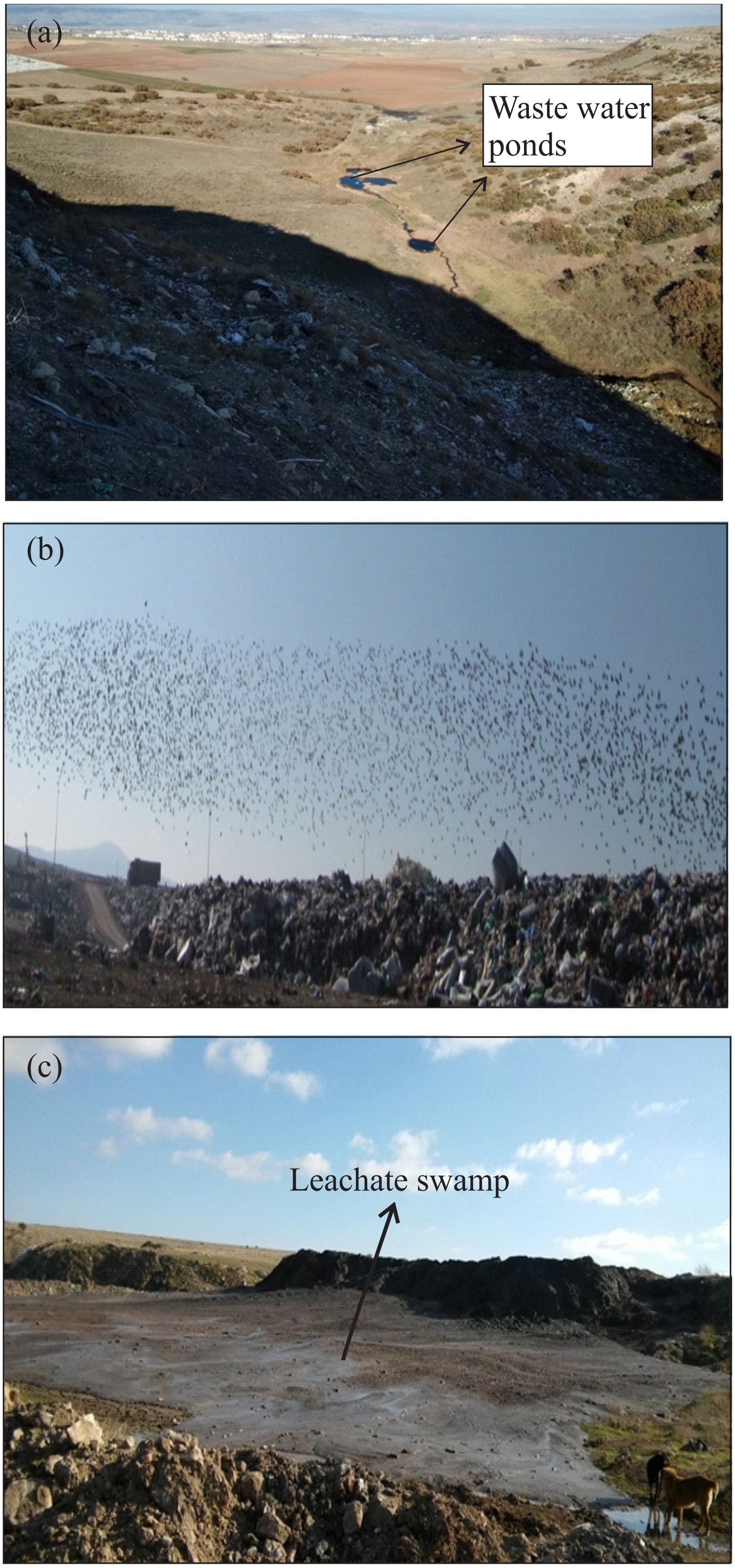

Figure 3. Views from previous irregular landfill (a) waste water ponds along the Takahasan Stream bed, (b) garbage disposal and wildlife, and (c) leachate swamp.

landfill slopes to discharge the accumulated leachate from the existing landfill body. Perforated drainage pipes were installed, and the leachate water was collected in pools at the pumping station. The landfill was irrigated using return pumps to evaporate some of the leachate in the pools. Regulatory work was carried out in the landfill area, reducing the slopes of the hills and waste to the minimum possible angle. A balancing layer was applied with a 3% inclination. The landfill rehabilitation was completed by repeating a 50-cm-thick drainage layer with geotextile and clay impermeable covers. A reinforced retaining wall, varying in height and approximately 800 m in length, was constructed to ensure stability (Figure 4a).

Then, 31 methane gas collection chimneys were systematically placed in the landfills for energy production. The energy production facility was completed in 2017 and commenced the production of electrical energy. The installed capacity of the facility is 11.32 MW, with a current production of 10 MW of energy. The Eskişehir integrated facility accepts 800 t of domestic solid waste daily (Figures 4b and 5).

3. Materials and methods

3.1. Water and heavy metal analyses

The most important problems in solid waste landfills are the pollution of the surrounding soil, surface water, and groundwater by the leachate generated during the storage of the waste. Leachate is water containing organic and inorganic pollutants that are likely to interact with other factors. For this reason, leachate is considered important due to the potential damage it may cause. As a result, landfills pose threats to groundwater, surface water, and soil quality. At a depth of 30 m, two boreholes (BH1, BH2) were drilled to assess lithological properties and collect groundwater samples. BH1 and BH2 are located 715 m

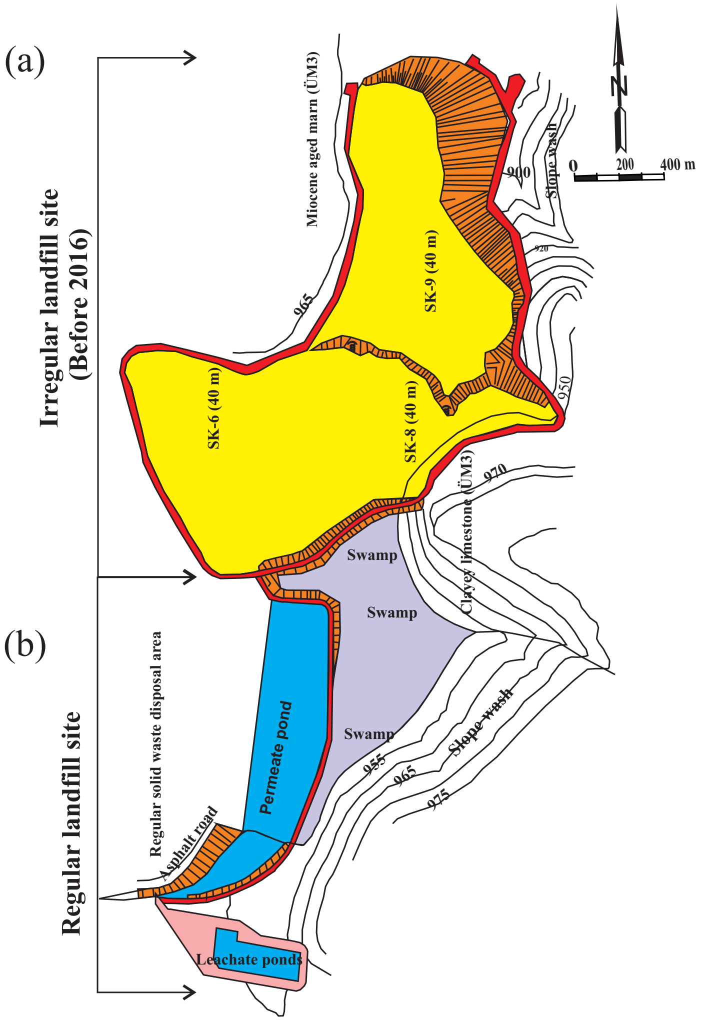

Figure 4. Plan map of the regular and irregular landfill sites (İlbank, 2016). (a) Rehabilitated irregular landfill area and (b) regular landfill area.

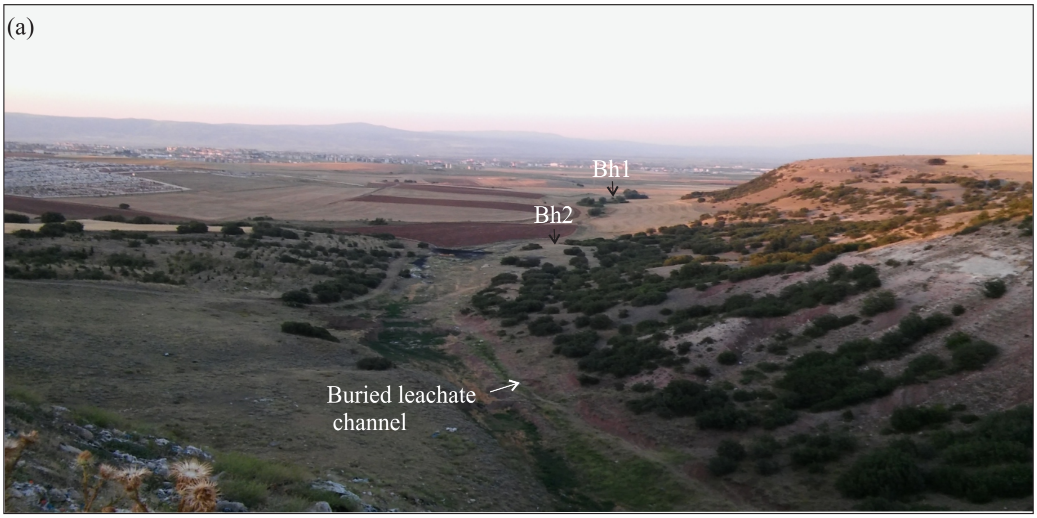

Figure 5. View of the Eskişehir regular landfill from (a) west to east, (b) south to north, and (c) north to south.

apart, with BH2 being closer to the waste disposal area. The soil cover was drilled to a depth of 0.5 m, followed by gravelly, sandy, and silty clay layers extending to depths of 10–15 m in both boreholes. Beyond this depth, brownish claystone was encountered and drilled down to 30 m. Average soil compositions for BH1 and BH2 were 9% gravel, 64.5% sand, 17.5% silt, and 9% clay and 4% gravel, 49% sand, 30.5% silt, and 16.5% clay, respectively. The groundwater levels in the boreholes were measured at one-month intervals.

Groundwater samples were collected from BH1, BH2, as well as surface water near BH1 and the Kadirbey Farm Spring (KFS). The KFS is located upstream of the landfill site, and therefore, it is not affected by landfill drainage pollution. Water samples were collected on May 13th, 2021, during the wet period, and on September 22nd, 2021, during the dry period in the study area (Table 1).

Water samples were stored in 1-L polyethylene plastic bottles and transferred to the laboratory. Water sample analysis was conducted by the Eskişehir Osmangazi University, Central Research Laboratory Application and Research Center (ARUM, Merkezi Araştırma Laboratuvarı Uygulama ve Araştırma Merkezi in Turkish), and the Eskişehir Technical University, Environmental Problems Application and Research Center Laboratory (ÇEVMER, Çevre Sorunları Uygulama ve Araştırma Merkezi in Turkish). The pH, conductivity, COD, and BOD analysis standards, respectively, are TS EN ISO 10523 (2012), TS 2789+T1 (2011), and SM 2510-B (2021). The samples were collected and preserved following the procedure suggested by TS ISO 5667-10 (2021).

This study used the LPI to calculate leachate pollution, as proposed by Kumar and Alappat (2005a, 2005b, 2005c). The LPI serves as an informational tool for identifying the top priority landfills that may contribute to environmental pollution (Tamru and Chakma, 2015). The LPI quantifies pollution data between 5 and 100. It consists of three subscripts, such as the inorganic material LPI (LPI_{inor}), organic material (LPI_{or}), and heavy metal LPI (LPI_{hm}). The sum of these subscripts gives the total LPI.

Different indices were proposed in the literature for the evaluation of heavy metal pollution, such as the heavy metal pollution index (HPI) (Horton, 1965; Mohan et al., 1996; Prasad and Bose, 2001; Kara et al., 2021) and heavy metal evaluation index (HEI) (Edet and Offiong, 2002; Kara et al., 2021). The HPI is used to calculate the contribution of molten metal concentration to groundwater pollution (Sirajudeen et al., 2014). Rizwan et al. (2011) stated that an HPI value under 100 is safe for human consumption. The HPI is calculated using

$$\mathrm{HPI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

Eq (1).

$$\mathrm{Q_i} = \sum_{i=1}^{n} \frac{|M_i - L_i|}{S_i - L_i} \tag{2}$$

Here, M_i is the concentration of the i-*th* heavy metal, I_i is the maximum limit of the i-*th* heavy metal, and S_i is the standard permissible concentration value (Mohan et al., 1996). Q_i is subindex of the i-*th* parameter, W_i is the unit weight of the i-*th* parameter, and n is the number of parameters considered.

The HEI, also known as the metal index (Edet and Offiong, 2002; Tamasi and Cini, 2003), assesses the heavy metal risk in water concentration. It is calculated using Eq. (3):

$$HEI = \sum_{i=1}^{n} \frac{H_c}{H_{MAC}} \tag{3}$$

Here, H_c is the measured value of the heavy metals, and H_{MAC} is the maximum permissible concentration of heavy metal (MAC) of the i-*th* parameter (Edet and Offiong, 2002).

3.2 Geophysical measurements

The objective of using the ERT in this study was to detect groundwater pollution resulting from the possible flow of leachate from the landfills and assesses its impact on the groundwater quality in the area. The ERT were measured along the profile between BH1 and BH2 (Figure 6) with a length of 715 m. A Lippmann 4-point light device (Lippmann Geophysical Instruments, Schaufling,

Table 1. Water sample locations and sampling dates.

Location	Coordinate	Water sample	Sampling date
Kadirbey farm	39°42’56.5”N	SW1M	May 2021
	30°31’48.5”E	SW1S	September 2021
BH1	39°42’52.6”N	SW3M	May 2021
	t30°33’01.6”E	SW3S	September 2021
BH2	39°35’51.5”N	SW2M	May 2021
	27°10’42.1”E	SW2S	September 2021
Surface water	39°42’52.6”N	SW4M	May 2021
	30°33’01.6”E	SW4S	September 2021

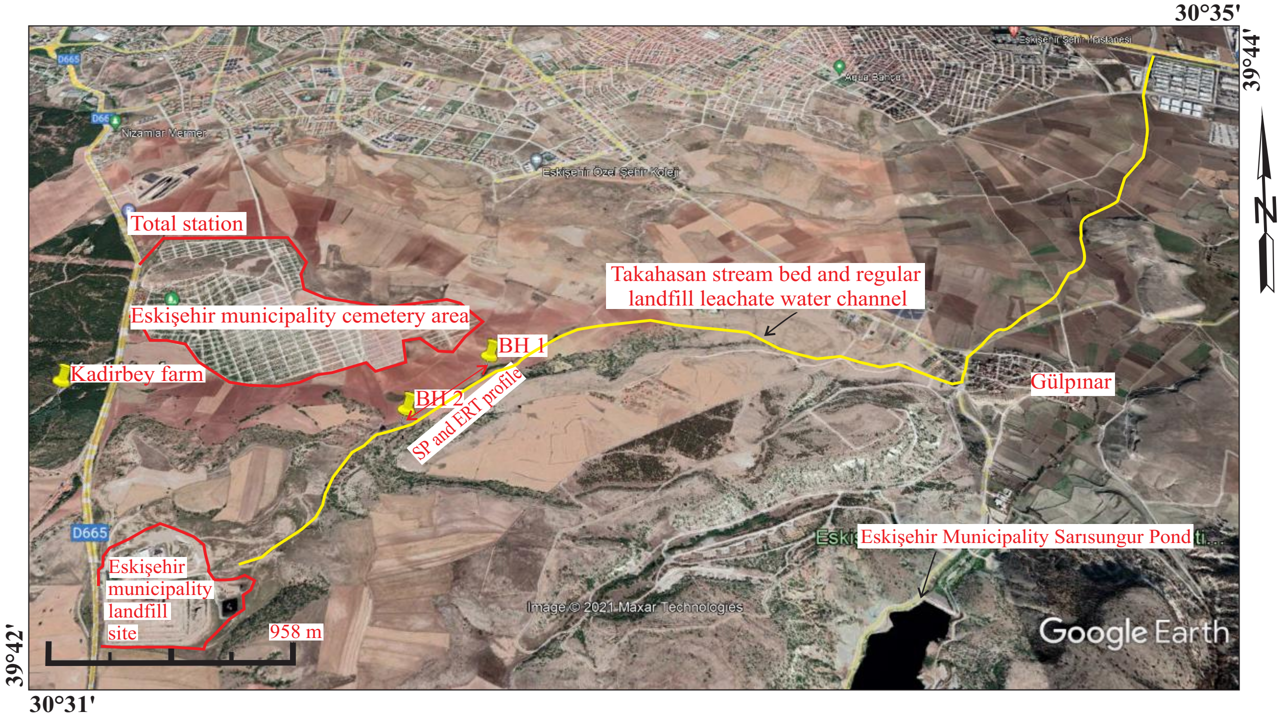

Figure 6. ERT profile on a Google Earth image.

Germany) was used for the ERT measurements. The geophysical measurements were conducted on April 29th, 2021, along the right and left sides of the Takahasan Stream bed.

ERT is a popular method in geophysics that has been used for a long time (Warner, 1969; Stierman, 1984; Adepelumi et al., 2005; Ayolabi and Daniel, 2005; Bayowa et al., 2012). However, when identifying anomalies, the characteristics of the embedded structure are not the only factors to consider; the electrode arrays used also play a crucial role. Therefore, the calculated apparent resistivity (ρ_a) values of any ground model may vary depending on the chosen electrode arrays. For this reason, selecting an appropriate electrode array for the research was crucial for its success. The ERT measurements were carried out on a 715-m-long profile, with an electrode spacing of 5 m, using the dipole measurement technique in six stages. The ρ_a values measured by the dipole-dipole electrode array were placed at the intersection point of the lines descending at an angle of 45 ° from the A, B current, and M, N voltage electrode pairs. In Figure 7, the distance between the current and voltage electrodes (AB-MN) remains constant. The ratio of the distance between the B and M electrodes (a current and an electrode) to the distance between the two current and two voltage electrodes is denoted as n. The disadvantage of this array is that as the value of n increases, strong signals cannot be obtained. For instance, when the n value is increased from 1 to 6 while keeping the current constant, the measured potential value becomes 56 times greater.[2]

4. Results

4.1 Water analysis

The groundwater levels and monthly precipitation (mm) are illustrated in Figure 8a.[3] The highest groundwater level change was 33 cm in BH1 and 116 cm in BH2. The groundwater recharge area of BH1 is larger than that of BH2. For this reason, the groundwater level in BH1 is closer to the surface. Simple regression analyses were performed between the monthly precipitation (mm) and groundwater depth in the borehole. As can be seen in Figure 8b, there was a significant relationship between the groundwater level records in BH1 and monthly precipitation, with a correlation coefficient of $R^2 = 0.68$. Figure 8c shows the simple regression analysis between the groundwater level records in BH2 and monthly precipitation, with a correlation coefficient $R^2 = 0.42$. The low correlation coefficient in BH2 is due to the small size of the feeding

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[2] Loke MH (2000). Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys [online]. Website https://pages.mtu.edu/~ctyoung/LOKENOTE.PDF [accessed 12 January 2021].

[3] MGM (2022). Turkish State Meteorological Service [online]. Website https://www.mgm.gov.tr/eng/forecast-cities.aspx?m=ESKISEHIR [accessed 01 February 2022].

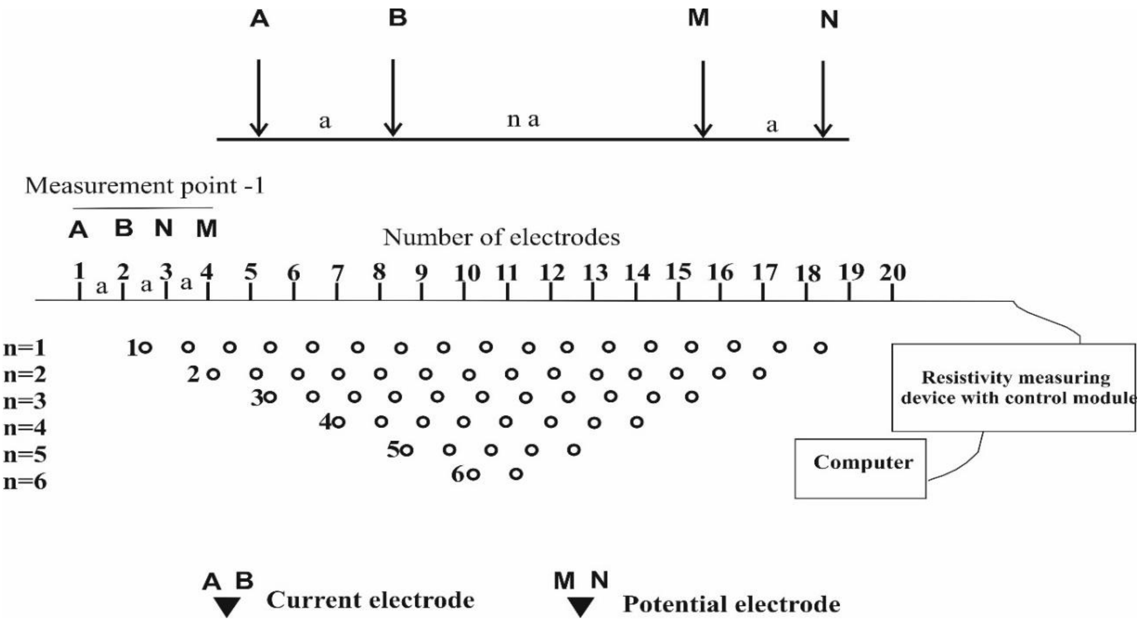

Figure 7. Schematic representation of the dipole-dipole array (after Loke, 2000)[2].

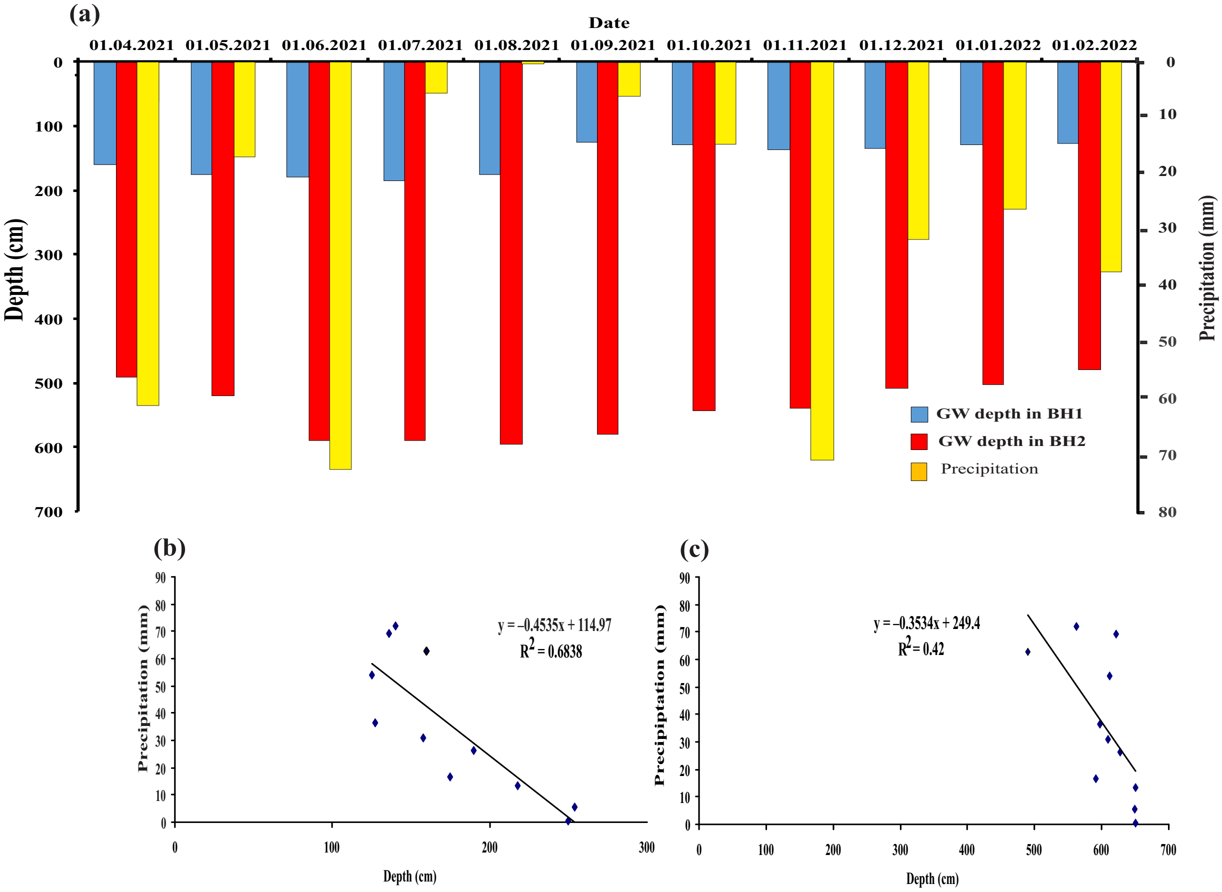

Figure 8. Graph showing (a) groundwater level records in the boreholes and monthly precipitation, (b) simple regression analysis between the montly precipitation and groundwater depth records from BH1, and (c) simple regression analysis between the montly precipitation and groundwater level records from BH2.

basin and measures taken to prevent permeability in the wastage area.

Groundwater in the boreholes was drained to determine hydraulic conductivity. After the drainage process was completed, the rise of the groundwater level was measured at certain time intervals. Using the Houghoudt equation (Houghoudt, 1936), hydraulic conductivity (K) was determined as 0.194 m/day for BH1 and 0.076 m/day for BH2.

The TDS is formed by inorganic salts and small amounts of organic substances. TDS concentrations below 1000 mg/L are recommended; however, very low TDS concentrations give water a flat taste. An excessive TDS concentration increases water hardness (World Health Organization (WHO), 2022). The TDS results obtained in the study are given in Table 2. The highest TDS concentration was measured in the SW4S sample and did not pose any risk according to WHO standards (2022). The Türkiye Surface Water Quality Regulation (TSWQR, 2021), published in the Turkish Official Gazette on June 16, 2021 and numbered 31513, categorizes water classes into 4 groups based on their intended use, such as high-quality (class 1), less polluted (class 2), contaminated (class 3), and very polluted (class 4). The tests from İlbank (2016), the TSWQR (2021) limits, and the findings of the current study are illustrated in Figure 9. As can be seen in Figure 9a, except for the SW4S sample, the TDS concentrations of all the samples were below the limit for class 3 water according to the TSWQR (2021).

The degree of transmission of electricity by water is called electrical conductivity. Pure water is devoid of minerals and has no conductivity. High electrical conductivity means high ion and TDS contents. However, the contribution of each dissolved substance to the conductivity of the water is different. Resistivity of the ground, geological factors, porosity, permeability, saturation with water, distribution of water in soil, salinity, and temperature increase also determine conductivity (Johansen and Carlson, 1976; Divya and Belagali, 2012; Demirbilek et al., 2013; Meride and Ayenew, 2016; Ozel et al., 2017; Khatib et al., 2023). High electrical conductivity causes high corrosion, and low electrical conductivity increases the ability to dissolve surrounding materials. Conductivity shows the status of major ions in inorganic pollution and measures the total dissolved solids and ionized species in the water. The conductivity test results of the current study were all higher than the maximum limit (400 µs/cm) of WHO standards (WHO, 2022). The results of the analyses performed on the water samples are given in Table 2. The conductivity of the samples is shown in Figure 9b. It was observed that the conductivity of the water samples exceeded the conductivity limit set for class 3 water in the TSWQR (2021).

The COD measures the oxygen required to oxidize organic substances in water or waste water (Ziyang et al., 2009). The COD values of the samples were higher than the limits defined in the TSWQR (2021). The COD values of the samples taken from the KFS outside the study area were below the COD and BOD limits defined in the TSWQR (Figure 9c). The BOD is the amount of oxygen that bacteria need to break down organic substances under aerobic conditions and is used to index the degree of organic pollution in water. While some of the organic substances are oxidized in BOD, they are all oxidized in COD. The measured BOD value of the SW2 samples in the dry period was lower than the BOD value measured in the wet period (Table 2). The COD and BOD were under the limit of detection (LOD) in the SW3 samples. The COD and BOD measured in the wet period were lower than those in the dry period in the SW4 samples. High COD values indicate that more organic materials were hydrolyzed due to increased water input. The BOD value is equal to half of the COD value in uncontaminated or lightly polluted waters. A low BOD/COD ratio indicates an excessive amount of nonbiodegrable material (Demirbilek et al., 2013). The BOD/COD ratio also shows the age of a landfill. In general, aerobic, acetogenic, and metanogenic phases occur in the decomposition of solid wastes (Pfeffer, 1992). A BOD/COD ratio >40% is seen in the acetonic phase, <40% in the methanogenic phase, and

Table 2. Water sample test results.

Sample no.	TDS (mg/L)	pH	Phenol (mg/L)	Conductivity (µs/cm)	COD (mg/L)	BOD (mg/L)	Ammonia nitrogen (mg/L)	BOD/COD
SW1M	100	7.99	0.0018	449	<LOD*	<LOD**	12	-
SW1S	175	8.05	0.0019	435	<LOD*	<LOD**	8	
SW2M	750	7.05	0.0938	853	92.744	56.53	968	0.61
SW2S	830	7.89	0.0867	1543	88.740	9.49	1150	0.11
SW3M	678	7.90	0.192	958	91.759	<LOD**	1387	-
SW3S	750	7.82	0.136	960	<LOD*	<LOD**	398	-
SW4M	989	7.85	0.203	1228	88.500	67.87	258	0.77
SW4S	1189	8.00	0.168	1356	97.500	86.92	367	0.89

LOD: Limit of detection,*LOD = 20.55, **LOD = 4.85.

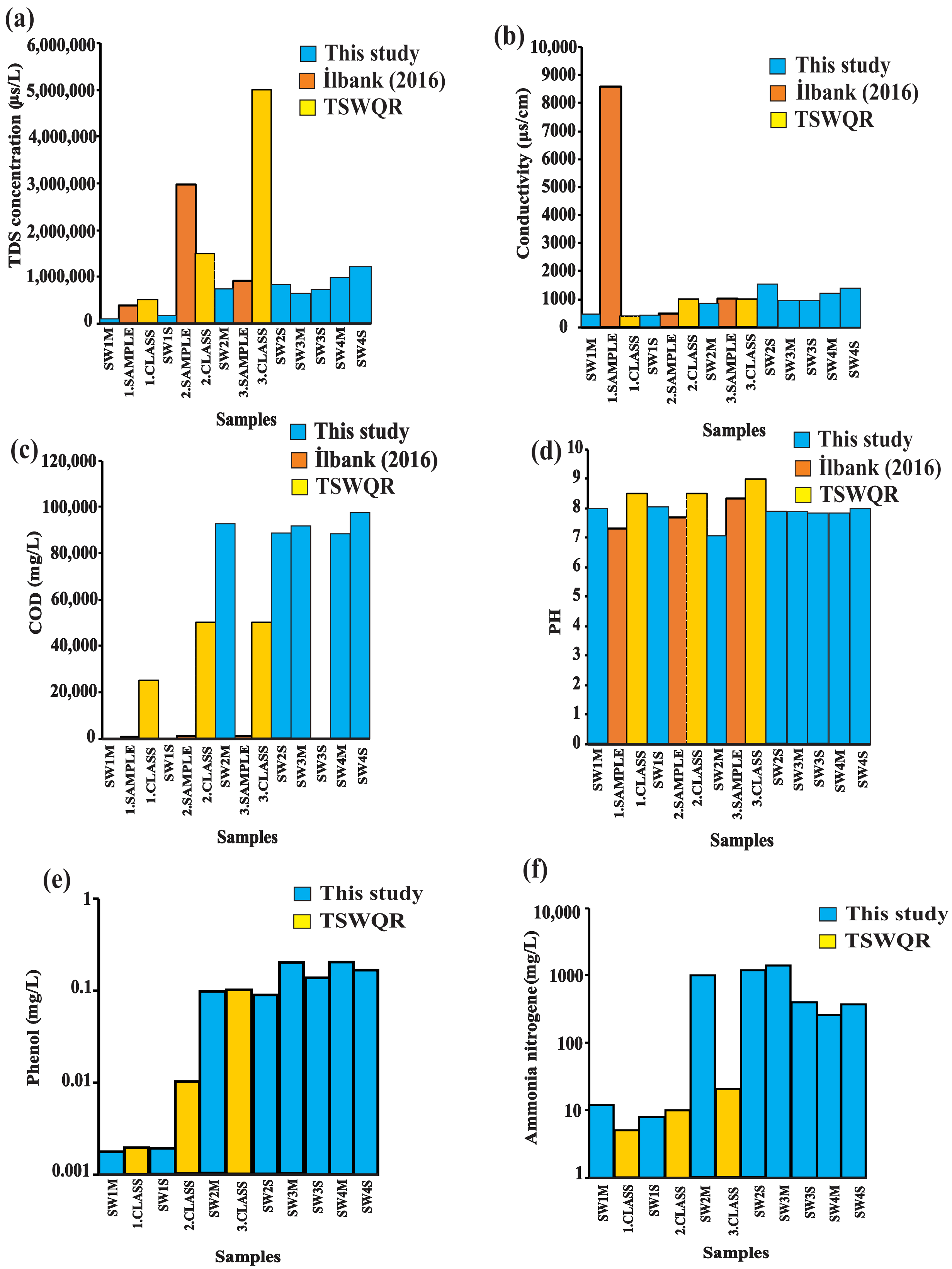

Figure 9. Histograms: this study, İlbank (2016), and the TSWQR limits for the (a) TDS concentration, (b) conductivity, (c) COD concentration, (d) pH test, (e) phenolic material concentration, and (f) ammonia nitrogen concentration.

<20 during the methanogenic phase. In the current study, the BOD/COD ratio was <20%, indicating that the landfill is in the methanogenic phase (Lo, 1996). Chain (1977) stated that when the BOD/COD ratio is greater than 0.5, biological treatment is more suitable. In the present study, the lowest BOD/COD ratio was 0.11, while the highest was 0.89. These values indicate that the acetogenic and methanogenic phases continue simultaneously due to ongoing deposition.

The pH is a logarithmic measure of the acidity or basicity of water. Variation in the pH is influenced by the biological structure and diversity of wastes, as well as their dilution effects (Johansen and Carlson, 1976). As the waste site ages, the pH value tends to shift from acidic to basic.

If hydrogen ions increase, the pH of the water decreases, and the water becomes acidic. Conversely, the pH value increases when hydrogen ions increase and the water becomes alkaline. The pH of the aquatic system is an important indicator of the water quality and the extent of pollution in landfill areas and the environment. The pH concentration of water is measured on a scale ranging from 1 to 14. The pH value of pure water is equal to 7. If the pH value is <7, the water is acidic. If the pH value is >7, the water is basic. Carbonates and bicarbonates increase the basicity of water. It should be determined whether chemicals causing high pH are harmful. Low-pH waters are corrosive and can be hazardous, as they have the potential to dissolve toxic materials in their environment. The water in the region is slightly alkaline. A pH range of 6.5–8.5 is normally acceptable according to WHO (2022) and Turkish Standards Institution (TSE, Türk Standardları Enstitüsü in Turkish) (2005) guidelines. The pH of all the water samples was >7 (Table 2). The highest pH value was 8.00, while the lowest was 7.05 (Figure 9d). The slightly alkaline character of water samples indicated the methanogenic phase (Lo, 1996). The pH test results were within the TSWQR limits.

Phenolic materials are among the chemical pollutants in waste water. Phenol pollutants derive from the iron, steel, petrochemical, and medicine industries (Doğan, 2014). The United States Environmental Protection Agency (USEPA, 1992) and the European Union classified phenols as primary pollutants affecting human health. The number of phenolic substances in potable water should be <0.002 mg/L according to TSE 266 (2005) and WHO (2022) standards. The phenolic substance content in the water samples taken from the Eskişehir landfill drainage area was a minimum of 0.0867 mg/L and maximum of 0.203 mg/L. The phenolic material and ammonia nitrogen concentrations in the waste water were not investigated in the study of İlbank (2016). In Figure 9e, the phenolic material concentration limits of the TSWQR water classes are provided, along with histogram graphs illustrating the phenolic material concentrations determined in the water samples in the current study. Except for the SW1 samples, the phenolic material concentration of the other water samples contained more phenolic material than the class 3 water quality according to the TSWQR limits.

The ammonia nitrogen concentration in leachate is a significant factor influencing environmental pollution and human health. In addition, ammonia nitrogen also affects leachate treatment processes (Haslina et al., 2021). Ammonia nitrogen is the long term stable component in leachate (Christensen et al., 2001). As shown in Figure 9f, the ammonia nitrogen concentration of the water samples in this study was greater than that for class 3 water defined in the TSWQR (2021).

Table 3 shows the LPI_{or}, LPI_{inor}, LPI_{hm}, and overall LPI values calculated in the SW1-May sample, which are shown in histograms in Figure 10. The lowest total LPI value was calculated in the SW1 sample taken from the KFS located at the upstream part of the drainage basin of the landfill. The highest LPI values were obtained from the SW2 sample. This was likely because the BH2 borehole, from which the SW2 sample was taken, is in close proximity to the landfill.

The LPI values of the TSWQR (2021) were calculated for correlation with the LPI values of the current study. As shown in Table 4, the total LPI value of the water samples was within the limits of class 4 (very polluted). The overall LPI value of the SW2 sample was 4.9 times greater than that of class 4 in the TSWQR, while that for the SW3 sample was 3.1 times greater, and that for the SW4 sample was 2.68 times greater.

4.2 Heavy metal analysis

The concentration of heavy metal elements determined in the water samples of the KFS was accepted as the concentration of heavy metal elements related to the lithological structure. As can be seen in Appendix, an increase in the concentration of Mn, Ti, Mo, B, Mg, W, Al, Fe, V, Co, Ni, Cu, Sr, Pb, Zn, Cr, Mo, Sn, and Sb was observed during the measurement. Figure 11a shows the heavy metal concentration trendline graph for all the water samples. The Cu and Se concentrations were below the limit of detection in the SW1 May sample. The Ag concentration was below the limit of detection in the SW4 May sample. The Se, Pb, and Zn concentrations were below the limit of detection in the SW1 September sample, SW3 September sample, and SW1–SW3 September samples, respectively. Figure 11b shows the ratio of the heavy metal concentrations of the water samples taken from the KFS to those of the samples from the study area. According to Figure 11b, the Mn, Se, Ti, Mo, Sn, Sb, B, Mg, V, Fe, Co, Ni, Cu, Sr, Pb, Bi, Zn, and Cr concentrations of the water samples taken from the study area were higher than those in the samples taken from the KFS in both the wet and

Table 3. Sub-LPIs and overall LPI of the Eskişehir landfill drainage area waters (SW1-May).

Index	Parameter	Pollutant conc	Subindex value (pi)	Weight factor (wi)	wiPi
LPI organic LPI$_{or}$	COD	20.55	5	0.344444	1.72222
	BOD	4.85	5	0.338888	1.69444
	Phenolic compounds	0.0015	5	0.316666	1.58333
	LPI$_{or}$				4.999
LPI inorganic LPI$_{in}$	PH	7.99	3	0.214008	0.642023
	TKN	0.89	5	0.206226	1.031128
	Ammonia nitrogen	12	5	0.198444	0.992218
	TDS	100,000	20	0.194553	3.891051
	Chlorides	58	5	0.18677	0.933852
	LPI$_{inor}$				7.4902
LPI heavy metals LPI$_{hm}$	Total chrominium	2.144	10	0.14128	1.412804
	Lead	0.163	6	0.139073	0.834437
	Mercury	0.002	5	0.136865	0.684327
	Arsenic	3.667	10	0.134658	1.346578
	Zinc	0.383	5	0.12362	0.618102
	Nickel	1.63	7	0.11479	0.803532
	Copper	0.001	5	0.110375	0.551876
	Iron	231.67	10	0.099338	0.993377
	LPI$_{hm}$				7.245
Overall LPI	0.232LPI$_{or}$ + 0.257LPIin + 0.511LPI$_{hm}$				6.78

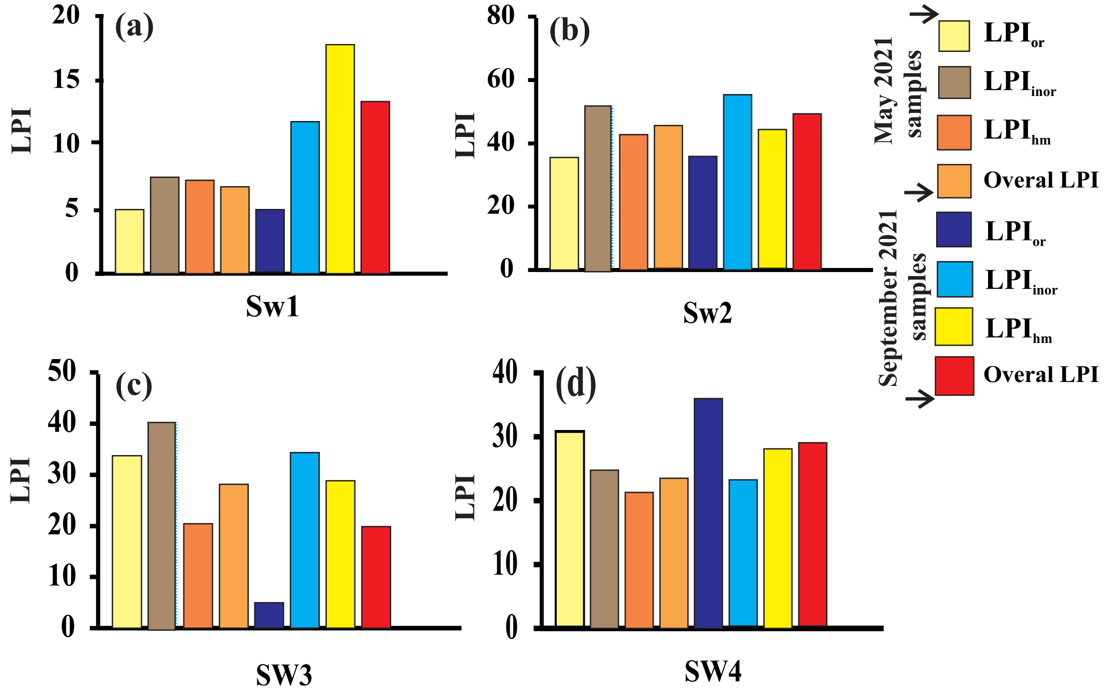

Figure 10. Histograms showing the LPI values: a) SW1 sample, b) SW2 sample, c) SW3 sample, and d) SW4 sample.

Table 4. LPI values determined in this study and those calculated according to the TSWQR (2021).

	SW1		SW2		SW3		SW4		TSWQR (2021)			
	May	Sept	May	Sept	May	Sept	May	Sept	Class 1	Class 2	Class 3	Class 4
LPI_{or}	4.99	4.99	35.58	35.58	33.68	4.99	30.83	35.99	5.0	15.05	26.06	20.37
LPI_{inor}	7.49	11.809	51.77	55.33	40.23	34.35	27.74	23.27	5.0	5.0	7.04	7.04
LPI_{hm}	7.24	17.78	42.72	44.41	20.41	28.80	21.28	28.06	5.0	5.0	5.23	5.23
Overall LPI	6.78	13.28	43.39	45.17	28.58	24.70	24.64	24.65	5.0	7.4	9.20	9.20

dry periods. The Ru, Rh, Ir, Be, Ga, Tb, Tl, Th, W, Al, Ag, and Hg concentrations increased in the wet period and decreased in the dry period. The Cs and As concentrations decreased in both the wet and dry periods.

The correlation with water quality is given in Table 5. The metal concentrations determined from the water samples belonging to the study area were in good agreement with the limits established in the TSWQR (2021).

According to the metal limits defined by the WHO (2022) for potable and usable water given in Table 6, the highest Ni concentration determined in this study was higher than the acceptable level.

Herein, the HPI and HEI were calculated using the ratios of measured heavy metal concentrations to the limits established in the TSWQR (2021). Figure 12a indicates that the calculated HPI values were under 100 in this study. The HEI gives the general evaluation of heavy metal risk in water concentration. Figure 12b shows that the SW1, SW3 and SW4 samples were in "very pure-pure" zone, where as SW2 sample was in "slightly affected zone."

As shown in Figure 12a, all the samples were under the upper level of the low risk zone for both periods. The TSWQR values (for S_i values class 4, for I_i values class 1) were based on the calculations. The SW2 sample showed the highest degree in the dry period. The others yielded similar results. The HEI values were similar to the HPI values; however, the SW2 sample was in the slightly affected zone (class 3, Caeiro et al., 2005). The SW1, SW3, and SW4 samples were in the very pure zone in the wet period (class 1). These samples were in the pure zone in the dry period (class 2). These results showed consistency in terms of the TSWQR.

Figure 13 shows the relationship between the total metal content and pH. All the samples were close to the near neutral, high metal location, except the SW3 sample, which was between the near neutral-high metal and acid-high metal locations. A high metal content in water samples can pose serious health risks for consumers (Ficklin et al., 1992; Caboi et al., 1999).

4.3 Geophysical measurements

Dissolved waste material is directly related to electrical conductivity and resistivity. Given that leachate contains a high concentration of ions, water pollution may be to blame for the low electrical resistivity and high conductivity (Bernstone et al., 2000; Meju, 2000; Kjeldsen et al., 2002; Rosqvist et al., 2003). However, geophysical methods alone are not always sufficient in this regard. Geophysical methods can be used together with chemical and hydrogeological methods to investigate groundwater pollution. There are many geophysical studies on this subject (Meju, 2000; Karlık and Kaya, 2001; Baba et al., 2004; Kaya et al., 2007; Boudreault et al., 2010; Vaudelet et al., 2011; Haile and Abiye, 2012; Ayolabi et al., 2013; De Carlo et al., 2013; Kaya et al., 2014; Tsourlos et al., 2014; Wijesekara et al., 2014; Oliva et al., 2015; Konstantaki et al., 2015; Çınar et al., 2016; Ganiyu et al., 2016; Gómez-Puentes et al., 2016; Soupios and Ntarlagiannis, 2017; Di Maio et al., 2018; Kayode et al., 2018; Akintorinwa and Okoro, 2019).

The right- and left-side ERT measurement profiles are given Figure 14. It was observed that the resistivity records taken on the right-side ERT measurements were slightly different, especially at near-surface levels. The ERT measurements emphasize a slight difference between the right- and left-side records regarding contamination. The measurements can be grouped as low resistivity values (<5 Ω m) significantly observed in the region close to the landfill area, moderate resistivity values (10–20 Ω m), and relatively high resistivity values as a thin layer close to the surface (>20 Ω m). Soils with low resistivity are notably laterally wider, particularly in the regions close to the landfill area, up to 130 m. Intensive contamination was remarkable between 40 and 80 m horizontally. The contamination was thought to be caused by the accumulation of leachate water. Highly contaminated zones like a plume which disconnected with each other. The shapes and volumes of the highly contaminated zones got smaller toward the BH1. The presence of sandy, silty litology observed at surface in the region caused the leachate water to flow to deep levels due to their high permeability. Low resistivity values were rarely observed in the continuation of the measurement zone away from the landfill area. Conversely, areas with high resistivity were monitored at a narrow depth, for almost the entire measurement line at near-surface levels. The recording of high resistivity values near the surface may be related to surface water flow throughout the landfill to

Table 5. Correlation of the quality criteria of water resources (TSWQR, 2021) and highest data determined at the study site.

Water quality parameters	Water class				Study site	
Inorganic pollution parameters (ppb)	1	2	3	4	KFS	Landfill drainage area
Hg	0.1	0.5	2	>2	0.046	0.051
Cd	5	5	10	>10	0.468	1.058
Pb	10	20	50	>50	1.063	6.189
As	20	50	100	>100	6.037	4.323
Cu	20	50	200	>200	4.169	17.53
Cr	20	50	200	>200	3.385	87.35
Co	10	20	200	>200	0.764	9.64
Ni	20	50	200	>200	5.67	147.36
Zn	200	500	2000	>2000	0.383	13.64
Fe	300	1000	5000	>5000	666.372	1118.79
Mn	100	500	3000	>3000	20.807	224.823
B	1000	1000	1000	>1000	55.338	725.04
Se	10	10	20	>20	0.001	3.981
Ba	1000	2000	2000	>2000	292.515	288.16
Al	300	300	1000	>1000	791.94	435.19

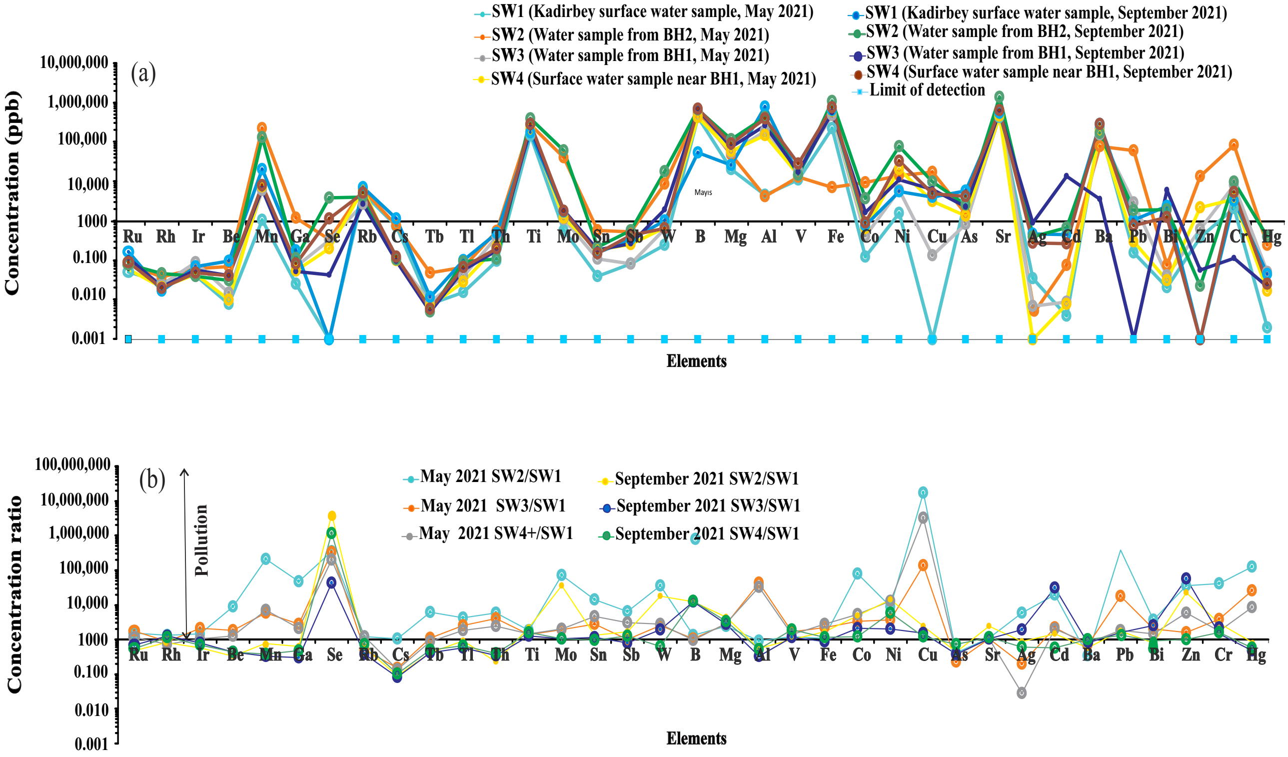

Figure 11. (a) The trendline of heavy metal concentrations in water samples, and (b) the trendline of the ratio of heavy metal concentrations determined in water samples taken from the study area to the heavy metal concentrations in water samples taken from the KFS.

BH1 (Ganiyu et al., 2016). Left-side records show the high contamination observed at the deeper levels near the landfill area. The levels are considered to be saturated with leachate water, distinguished by low resistivity values, and are still remarkable but spread up to 95 m horizontally from the landfill area.

Table 6. Comparison of the heavy metal concentrations in the water determined in this study with the limits of the WHO (2022).

WHO standards 1996 (µg/L)		This study (µg/L)	
Metal	Limit	Lowest limit	Highest limit
Al	1170	149.982	435.019
Sb	4	0.085	0.580
As	12,000	0.018	0.093
Ba	300	80.80	288.16
Be	1.2	0.01	0.071
Cd	3	0.008	1.07
Cr	50	2.144	9.883
Cu	2000	0.138	17.53
Fe	2000	505.02	1118.379
Pb	10	0.01	6.189
Mn	500	1.078	224.823
Hg	5	0.017	0.412
Mo	70	0.594	63.308
Ni	20	5.656	147.36
Se	10	0.200	3.981
Ag	100	0.001	0.415
Zn	3000	0.001	13.64

A total of four profiles with various depths of the Takahasan Stream bed were obtained in Surfer 8 to analyze the contamination change. Near-surface heterogeneity was also evident at a depth of 1.2 m, as shown in Figure 15. The increase in contaminated areas with low resistivity is highlighted more prominently. It was determined that locations near the landfill area were significantly affected by leachate water. A remarkable decrease was observed in the resistivity values from a depth of 12.76 m and continued slightly down to 31.80 m (Figures 15b–15d).

5. Conclusion

This study investigated possible surface water and groundwater pollution in the Eskişehir city landfill drainage area. This area was used as a wild storage area before 2016. After 2016, it was converted to a regular waste storage area. Two boreholes at a depth of 30 m were drilled in the Eskişehir landfill drainage basin. Groundwater and surface water samples were collected in 2021, during both the wet and dry periods. In addition, water samples were taken from the water source of the KFS area, which is at the upstream part of the landfill area drainage basin.

The TDS concentration of all the water samples, except one, was lower than the class 3 water TDS concentration limits defined by the TSWQR (2021). The conductivity limits were within the boundaries of class 3 water quality according to the TSWQR (2021). In addition, the conductivity values of the water samples were higher than the conductivity limits of the WHO (2022). The COD values of the water samples taken in the landfill basin area were higher than the COD limits of the TSWQR (2021). A high BOD/COD ratio indicates the presence of excessive organic pollution in water samples. The highest pH of the water samples taken from the study area was 8.73, while the lowest was 8.00. According to the TSWQR on pH limits, the pH test results of the water samples were alkaline in nature. The quality of spring water in the Kadirbey area was determined to be a class 1 water source, according to the TSWQR (2021). The analysis results on the samples taken from the KFS represent that the region is not affected by the landfill pollution.

The Mn, Se, Ti, Mo, Sn, Sb, B, Mg, V, Fe, Co, Ni, Cu, Sr, Pb, Bi, Zn, and Cr concentrations in the water samples taken from the study area were increased during the testing periods. However, according to the TSWQR (2021) and heavy metal concentration limits defined by the WHO (2022), the heavy metal concentration values determined in the water samples were within the limits, except for the Ni concentration.

The LPI_{inor}, LPI_{or}, LPI_{hm}, and overall LPI were calculated. The overall LPI value of the SW2 sample was 4.9 times greater than that of class 4 water in the TSWQR, while that for the SW3 sample was 3.1 times greater, and that for the SW4 sample was 2.68 times greater.

According to the HPI and HEI indices, which provide an overall evaluation, the results of the heavy metal analyses did not appear to indicate significant risks.

The ERT records showed a decrease in resistivity with depth. This may have resulted from the pollution formed during wild storage along the Takahasan Stream and

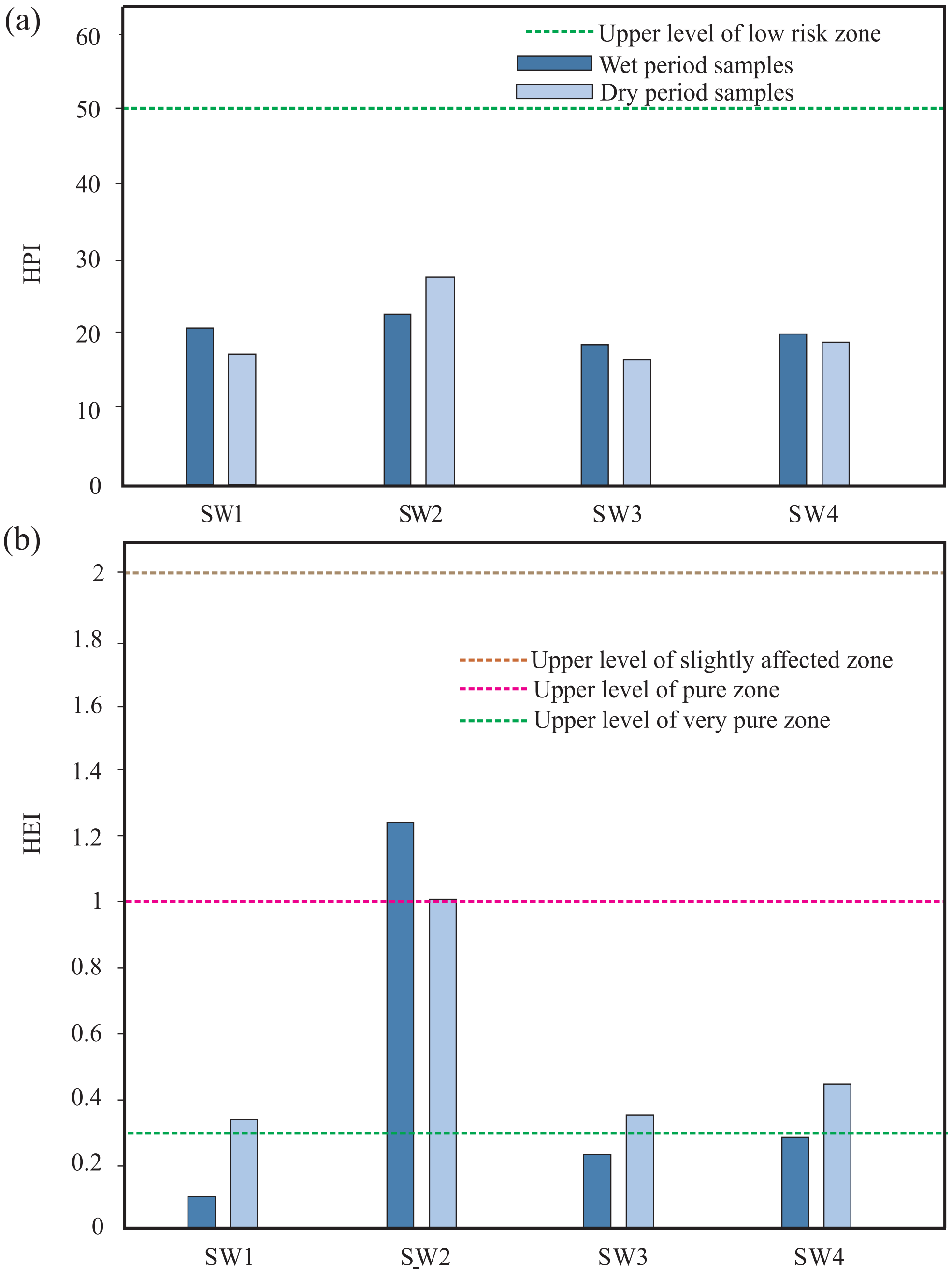

Figure 12. Pollution result histograms of the (a) HPI and (b) HEI.

lithological structure. The presence of water pollution accumulation was indicated by the low resistivity observed from the surface to depth near the waste storage area. However, a decrease in water pollution was observed both at the surface and at depth as one moves horizontally. Slight differences may arise in the lateral distribution of permeability. However, the more acceptable explanation for the small and disconnected highly contaminated water areas in the ERT records is that these contaminated areas may be the remnants of former wild waste landfill area. Because of the unrestrained waste storage in the past, the high level of contamination occurred and today, we can see it in the ERT measurement as small patches of contaminated areas away from the landfill site.

While chemical and hydrogeological analyses only provide information on the water content and movement of water underground, geophysical measurements can

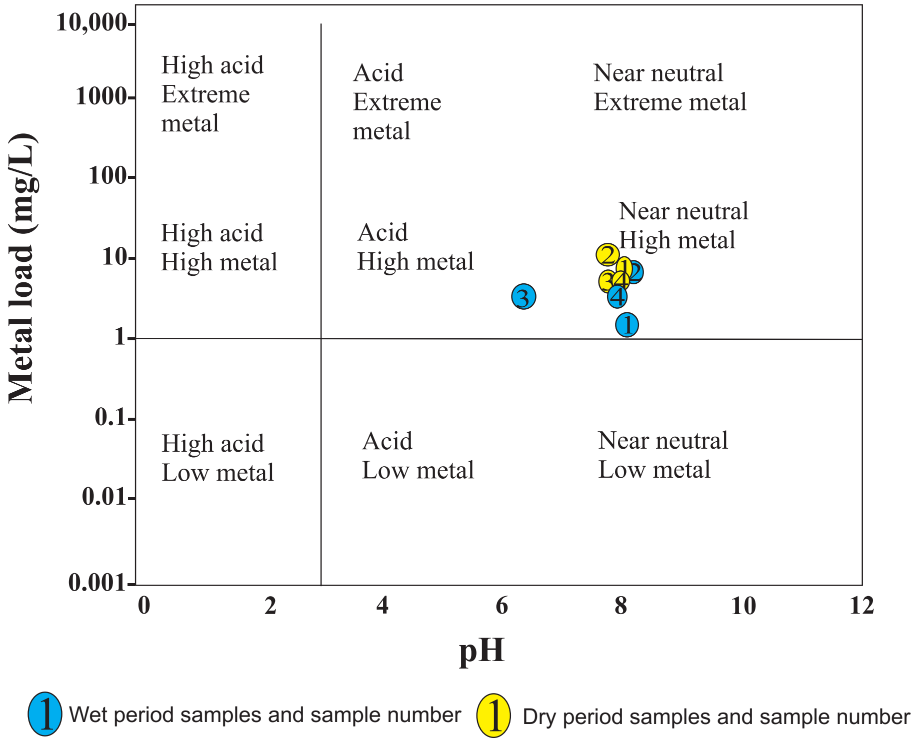

Figure 13. Water sample test results on a diagram of the metal load-pH chart.

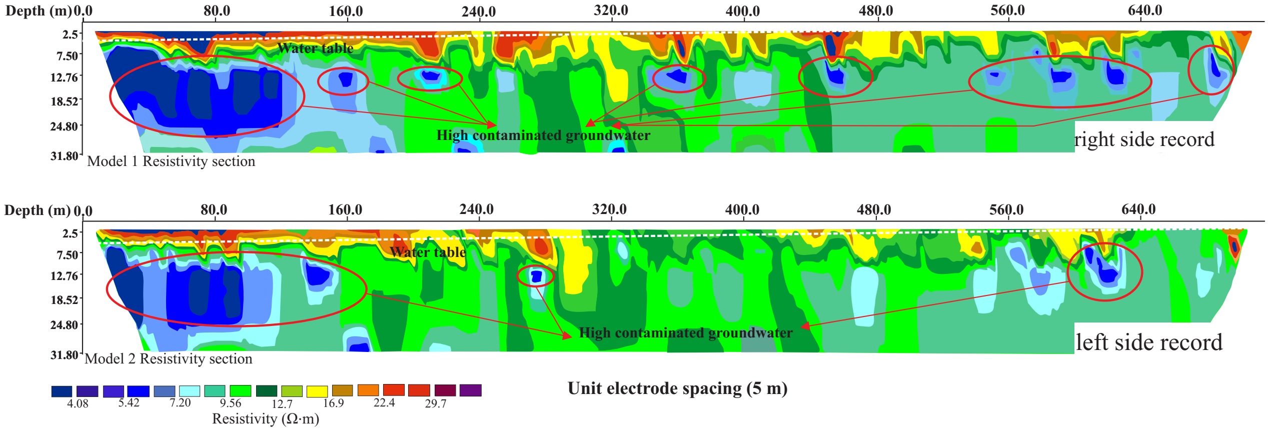

Figure 14. Right- and left-side ERT measurements between BH2 and BH1.

be affected by the rock or ground properties that make up the environment, as well as groundwater. The lower groundwater level, lower hydraulic conductivity, higher clay content in the weathered part in BH2 with respect to BH1 caused a change in the electrical conductivity. In the past, anthropogenic processes, such as burning tires and electric cables, were carried out in the area close to BH2, which may have caused a decrease in electrical conductivity. Additionally, the differences in electrical resistivity may be attributed to the fact that BH1 is farther from the landfill site and is fed by groundwater from side drainage flows that are not contaminated by landfill leachate. As a result, geophysical measurements alone may be insufficient in environmental pollution research. Therefore, studies should be supported by other methods.

It is suggested that the concentration of pollution parameters in the study area should be monitored according to related soil and water pollution regulations at the least, in one-year intervals. These observations may help with surface water and groundwater conservation efforts.

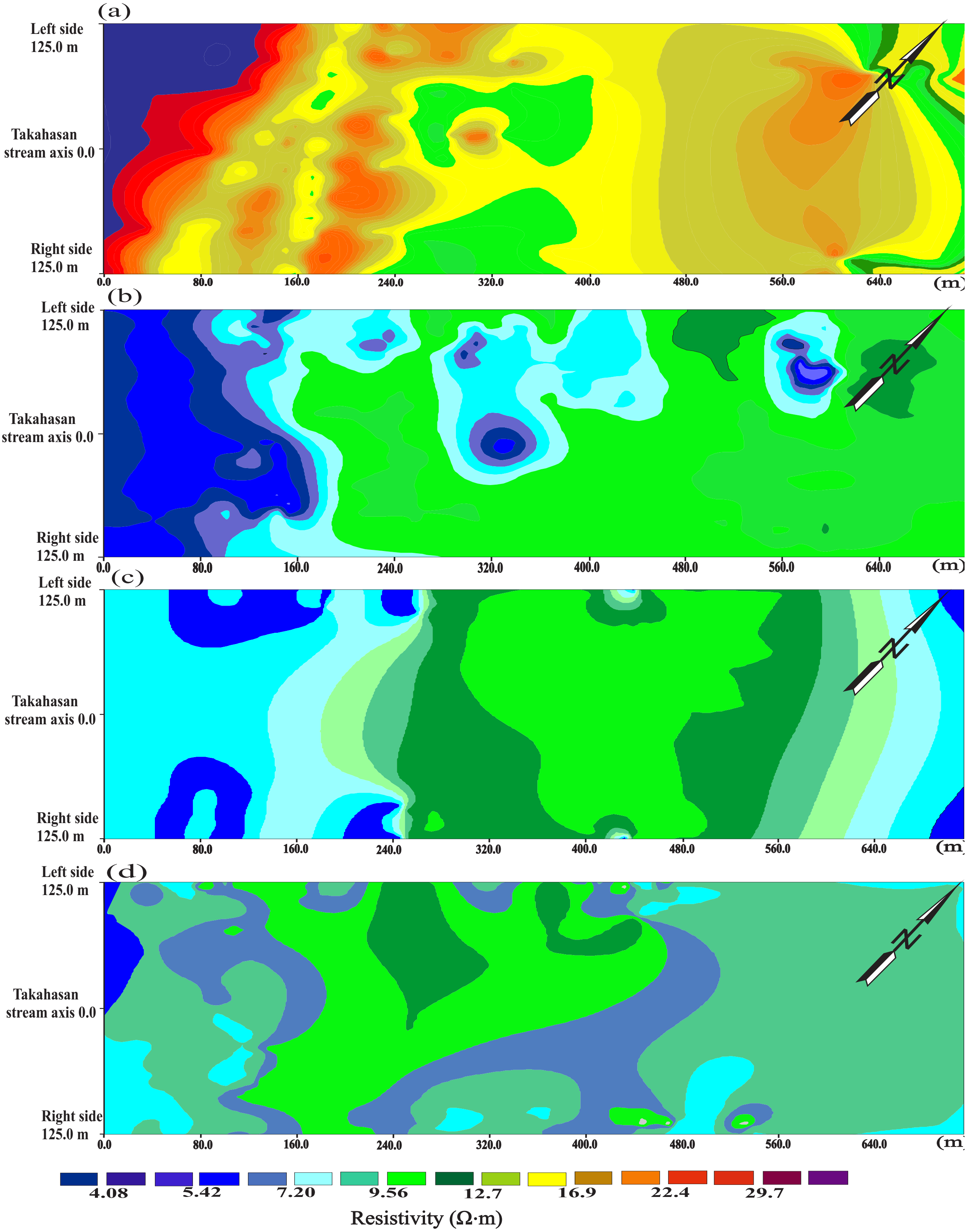

Figure 15. Resistivity maps at depths of (a) 2.5 m, (b) 12.76 m, (c) 24.8 m, and (d) 31.8 m from the ERT resistance measurements on the forehead 125 m to the right and left of Takahasan Stream.

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Contribution of authors

All the authors contributed to the conception and design of the study. Conceptualization, methodological study, and sample preparation were conducted by AK, field work was carried out by AK and OTS, the evaluation of the experimental results was performed by AK, OTS, and CG. The first draft was written by AK, OTS, and CG. All the authors read and approved the final manuscript.

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Data availability

All data generated or analyzed during this study are included in this published article.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix. tResults of the heavy metal analysis on water samples.

HeavyMetal (ppb)	Wet period (May 2021)				Dry period (September 2021)			
	SW1 (Kadirbey)	SW2 (SK2)	SW3 (SK1)	SW4 (Surface water)	SW1 (Kadirbey)	SW2 (SK2)	SW3 (SK1)	SW4 (Surface water)
Ru	0.052	0.079	0.091	0.061	0.168	0.079	0.117	0.092
Rh	0.029	0.038	0.025	0.021	0.017	0.047	0.025	0.021
Ir	0.042	0.062	0.090	0.045	0.070	0.04	0.057	0.049
Be	0.008	0.071	0.015	0.010	0.097	0.032	0.042	0.042
Mn	1.078	224.823	6.202	7.449	20.807	134.676	6.792	8.061
Ga	0.026	1.207	0.071	0.055	0.179	0.115	0.054	0.085
Se	0.001	0.353	0.336	0.200	0.001	3.981	0.043	1.174
Rb	5.316	6.551	2.694	6.542	7.159	4.074	2.767	5.242
Cs	0.744	0.776	0.111	0.103	1.182	0.106	0.098	0.125
Tb	0.008	0.005	0.005	0.006	0.012	0.005	0.005	0.006
Tl	0.016	0.068	0.041	0.029	0.103	0.094	0.059	0.069
Th	0.097	0.572	0.400	0.233	0.506	0.113	0.178	0.2
Ti	150.75	280.13	210.54	215.89	182.93	402.06	235.91	288.42
Mo	0.594	42.285	1.127	1.205	1.732	63.308	1.867	1.84
Sn	0.041	0.578	0.112	0.188	0.162	0.218	0.185	0.154
Sb	0.084	0.554	0.085	0.257	0.345	0.580	0.271	0.438
W	0.246	8.805	0.625	0.702	1.029	18.217	1.946	0.666
B	44.505	590.49	461.49	436.781	55.338	681.975	696.516	725.04
Mg	20.565	49.36	56.125	60.794	27.138	117.842	76.329	92.13
Al	46.350	430.2	198.09	149.982	791.994	435.019	266.330	407.86
V	11.209	13.38	18.931	15.349	15.217	15.215	17.550	28.80
Fe	231.67	728.0	505.02	639.407	666.372	1,118.379	586.690	760.97
Co	0.123	9.64	0.423	0.653	0.764	3.74	1.652	0.93
Ni	1.63	147.36	6.144	20.970	5.656	80.015	11.557	33.89
Cu	0.001	17.53	0.138	3.208	4.169	9.98	6.482	4.94
As	3.667	1.55	0.845	1.354	6.037	2.601	2.331	4.323
Sr	444.43	497.88	468.48	468.64	570.245	1,404.182	611.137	652.85
Ag	0.04	0.21	0.007	0.001	0.475	0.415	0.924	0.284
Cd	0.004	0.08	0.009	0.008	0.465	0.678	1.057	0.266
Ba	233.41	80.80	158.52	187.95	292.515	170.829	209.357	288.16
Pb	0.163	6.189	2.935	0.306	1.063	1.897	0.001	0.77
Bi	0.021	0.077	0.042	0.031	2.446	1.964	3.630	1.29
Zn	0.383	13.64	0.626	2.202	0.001	0.023	0.058	0.001
Cr	2.144	87.55	8.255	3.72	3.385	9.883	6.082	5.48
Hg	0.002	0.25	0.051	0.017	0.046	0.412	0.022	0.026