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Impact of Humra landfill on groundwater quality: Case study of Jordan

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ABSTRACT

Solid waste disposal in landfills or open dumps may cause significant impacts on groundwater, which is the main source of water in Jordan. This paper aimed to investigate the impact of Humra landfill on groundwater quality. Forty-eight samples of groundwater and four samples of leachate were collected and analyzed for pH, TDS, EC, TN, NH_4, NO_3, Cl, PO_4, BOD, COD, and heavy metals during different seasons. The results revealed that the leachate has high concentrations of pollutants with average values of 27230, 1340, 1891, 940, 1428, and 3477 mg/l for TDS, Cl, NH_4, NO_3, BOD, and COD; respectively. High correlations between BOD with COD, pH with TDS, and TDS with NH_4 were found. Analyses of groundwater quality showed that about 52%, 50%, 50%, 50%, 14.5%, and 23% of samples exceeded drinking water standards of Cl, TDS, NH_4, Fe, Cu, and Mn, respectively. It was found that 75%, 75%, 60%, 50%, 37%, and 21% of the samples exceeded NO_3, Ni, Cd, Cr, and Pb standard limits, respectively. The concentration of TN, BOD, and COD in groundwater decreased as the distance from the landfill site increased, while the other parameters showed insignificant trends. The calculated Leachate pollution index (LPI) was 22.48 indicating a potential impact of landfill on groundwater and could cause a health risk that needs urgent action. On the basis of on the obtained results, it can be concluded that the landfill site has an impact on groundwater quality, which needs an immediate plan to avoid uncontrolled impacts. It is recommended to install landfill lining with a leachate collection system. Surface hydrology should be directed to reduce the impact of surface runoff on leachate transport.

Keywords: Humra landfill, groundwater quality, Jordan, leachate, upstream, downstream.

INTRODUCION

Many countries around the world suffer from water stress, but Jordan is perhaps the most affected one. This challenge is driven by many parameters including limited water resources, high population growth rate, urbanization, successive refugee fluxes from the regional countries, water pollution, and climate change. It was reported that the available water resources in Jordan were 3300 m^3/c.yr in 1948, whereas now it is less than 200 m^3/c.yr, which is far below the limit of water scarcity amounting to 500 m^3/c.yr (Alqatarneh and Alzboon, 2022). During the last few decades, water has been exposed to different sources of pollution due to industrialization, urbanization, and environmental issues. Water pollution can be caused by illegal discharge of industries, wastewater without adequate treatment, septic tanks, agricultural activities and leachate of solid waste, in addition to surface runoff.

Solid waste may cause significant impacts of water pollution due to the illegal dumping of waste which may reach water resources and cause contamination by different solid and liquid materials. The direct disposal of solid waste into the environment results in soil and water pollution. It is estimated that the daily amount of solid waste generated in Jordan in 2015 was more than 3700 tons with an average generation rate of 0.87 kg/c. d and 0.99 kg/c. d for rural and urban areas, respectively. The annual amount of solid waste increased from 1.5 million tons in the year 2000 to more than 2 million in 2015 and it is estimated to reach 6 million in 2039. While only 10% of waste is recycled, most of the solid waste is transported to engineering landfills (50%), or to controlled dumps (35%), while 5% is disposed of in open dumps (Aldayyat et al., 2018). Landfilling is the most common method for solid waste management in Jordan. There are 21 landfills in Jordan, of which 2 are in the northern region, 6 are in the central region, 4 are in the eastern region, and 9 are in the southern region. More than 60% of waste is disposed of in the two largest landfills (Al-Ghabawi in the central region and Al-Akaider in the northern region) (Abushgair et al., 2016).

Pollutants in leachate can be categorized in four groups: dissolved organic compounds, inorganic compounds, heavy metals, and synthetic organic compounds (xenobiotics). The leachate from landfill pollutants contains high concentrations of chlorides (up to 16,200 mg/l), conductivity (up to 42,800 µS/mg/l), COD (up to 68,500 mg/l), BOD (55,880 mg/l), NO_3-N (up to 10.4 mg/l), NO_2 (14.6 mg/l), NH_3 (up to 2,000 mg/l), TSS (up to 14,460 mg/l), TDS (up to 100,000 mg/l), SO_4 (up to 720 mg/l), and heavy metals, mainly Fe, Zn, Mg, Cr, Cd, Cu, Ni and Pb (Abd El-Salam and Abu-Zuid, 2015). The concentrations of pollutants in the leachate depend on many parameters, such as the composition of waste, age of waste, decay rate, degree of maturation, temperature, climate conditions, site hydrology, soil interaction, and operational conditions.

The impacts of landfills on groundwater have been reported in many international studies. Abd El-Salam and Abu-Zuid (2015) found high concentrations of pollutants in groundwater wells near the landfill site for all detected parameters, and the levels of chloride and sulfate exceeded WHO standard limits. Concerning the heavy metals, Mn concentration ranged from 0.257 to 0.357 mg/l and Fe concentration ranged from 0.456 to 1.23 mg/l which exceeded EPA allowable limits of 0.05 and 0.3 mg respectively, while the heavy metals concentrations were within the EPA allowable limits. Similarly, Parvin and Tareq (2021) found high concentrations of Fe up to 3.26 mg/l, and up to 1.7 mg/l, and the concentrations of pollutants varied as a result of the rainy season. Akinbile et al. (2015) investigated the impact of landfills on groundwater quality in three monitoring wells at 50, 80, and 100m away from the landfill site. They found that the concentrations of TDS, TH, Ca, NO_3^-, NO_2^-, and Cl decreased as the distance increased and the wells that were close to the landfill site had higher concentrations of contaminants. Even though the ion concentrations are within the allowable limits, water needs treatment before being used. Also, high levels of biological indicators were detected (Total coliform bacteria and Escherichia coli) and they exceeded the allowable WHO limits, which required urgent action to save human health. Detectable limits of heavy metals were measured, mainly iron, zinc, chromium, and lead, but within the allowable standard limits. A survey of the impacts of landfills on surface and groundwater quality in Bangladesh showed that the surface water has been contaminated with heavy metals (Zn, Mn, Pb, Cd, Cu, Fe, Ni, and Cr), while the concentrations of COD, and TDS exceeded the standard limits. The contamination of surface water was attributed to the surface runoff during the rainy season and the hydraulic connection with groundwater. Most water quality indicators within a distance of one kilometer away from the landfill site are below the safe level of the applicable standards. A similar study has been conducted in Greece and found that the groundwater in the wells near the landfill site was unsuitable for drinking or irrigation, and most of the physicochemical parameters considered – such as color, hardness, TDS, Cl, NH_3–N, COD, Na, K, Ca, and heavy metals (Ni, Fe, and Pb) exceeded the allowable standards limits given of EPA (Benaddi et al., 2022). Faecal coliform bacteria have been found in groundwater at a distance of 0.3 km from the Rowfabad landfill up to 71/100 ml (Parvin and Tareq, 2021).

Landfills do not affect water only, but extend to soil, ecosystem and the environment. Also, landfill leachate works as an inhibitor for plant seeds, and growth, whereas the inhabitation rate increased during low rainfall (Vaverková et al., 2018).

Humra Landfill is located in the west-central part of Jordan and has been utilized for waste disposal since 1989. The site receives an average of 240,000 tons/y covering an area of 318,000 m^2 and serves approximately 400,000 people. Humra landfill is an important site, because it is the only official one in the region, and there are several surface and groundwater resources nearby. Groundwater and springs around the landfill site support the socioeconomic sectors and greatly increase families' income. Since it began operations, there has been no monitoring program or environmental impact assessment of the various environmental aspects of the site, primarily water resources. All conducted studies revealed this highly necessitates that hazards and risks of landfills should be assessed and managed to save the environment and its species from landfill hazards. For all these reasons, it is necessary to determine the environmental impacts of the site on water resources. To the best of the authors' knowledge, this is the first investigation of the impact of the site on water resources. The study findings provided clear evidence of the potential contamination of groundwater caused by the operation of the site. The results will also give decision-makers the necessary information about the site and its impact, allowing them to implement the proper mitigation measures.

The present work aimed to assess the environmental risk of groundwater quality in the area surrounding the Humra landfill site through water sampling from the wells and springs that have been selected for this purpose. In order to delineate how far groundwater quality has been affected by the downward transport of leachate from the Humra open landfill site, various physical and chemical analyses in addition to groundwater level measurements were considered.

METHODOLOGY

Study area

The Humra landfill site is located in Balqa governorate, 5 km to the west of Al-Salt City and about 11 km to the east of Jordan Valley. The landfill center is located at 32°3'36.40" longitude and 35°39'27.43" latitude, with an elevation of 340 m above sea level (asl). The site is surrounded by numerous hills and valleys. The site is only accessible via a single paved road from Al-Salt City. Al-Salt City is the largest community in the area with a population of 105,000 people, whereas Dhahret Er-ramel, is the closest community with a population of 2,300 inhabitants and is located 4.5 km to the west of the site. The area has very low vegetation cover, there are farms to the east of the site, while the vegetation cover in the west and north is sparse, with just scattered shrubs, small trees, and grasses along the valley plains. Since the most plants in the area are rainfed trees, fertilizers are not applied.

Site description

The total area of the landfill is about 318,000 m^2. Fifty-four laborers are working on the site, of which 20 are for daily landfilling, whereas 34 are for maintenance and planting. Regarding the equipment, there are 5 trucks, 3 bulldozers, 3 loaders, 2 water tanks, 3 tractors, one fuel tank, and one light truck. Received waste is segregated at the site by a private company and the recyclable materials are transported to industry. The garbage waste is dumped in natural depressions (Wadis) and covered with soil within two hours of dumping. Since there is no lining system, the leachate is not collected, and seeps to the downstream areas by gravity.

Topography and soil

Generally, the surrounding area has a steep slope ranging from more than 1000 m a.s.l. in Al-Salt city to less than -360 m in Jordan River. Similarly, the landfill site has a sharp slope from the east to the west and the highest elevation point is 365 m a.s.l., while the lowest point elevation is less than 260 m a.s.l. It is worth mentioning that due to the hilly nature of topography and the presence of folds, the slope is not constant and changes from one point to another. The high slope of the landfill site resulted in transporting the leachate to the west part of the site which can be realized clearly (Figure 1). Also, the high slope will cause transport of stormwater and flood from the upstream area (east) which could affect the leachate transport.

Climate

The climate of the site is similar to the Mediterranean Sea, rainy cold during winter and dry hot during summer. Average maximum temperature during August reaches about 29.6 °C at Al-Salt City while the minimum temperature during January falls to 4 °C. The prevailing winds blow from the west and southwest. The average annual rainfall is about 521 mm, and most of the precipitation occurs during November to March while it is rare during June and July (Matarneh, 2017). It is worth mentioning that the landfill site has a higher temperature than Al-Salt City and less precipitation because of its lower elevation in comparison to Al-Salt City. High precipitation will increase landfill leachate, while temperature may affect waste decomposition and odor generation.

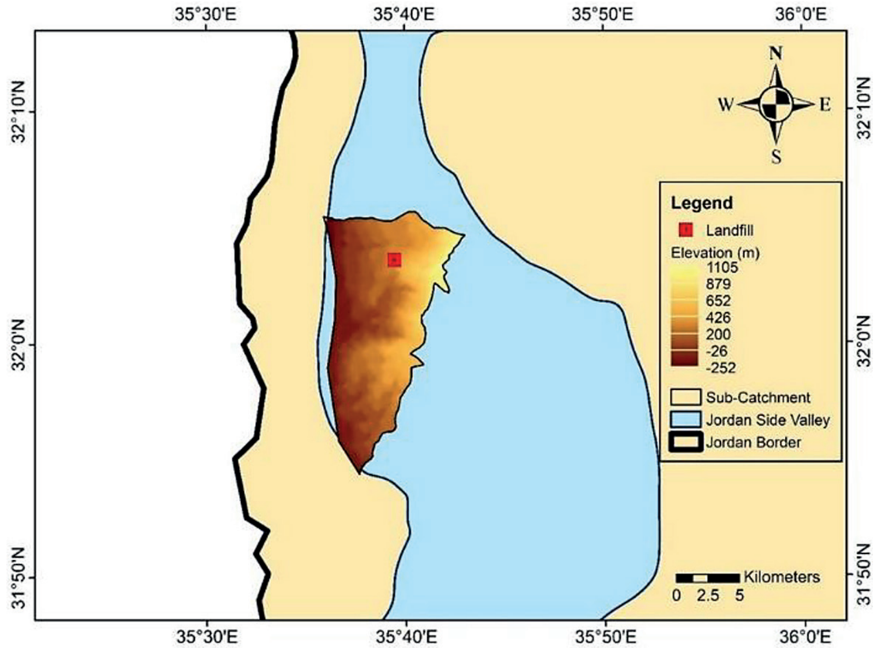

Figure 1. Topography of the study area

Geology and groundwater

The geology of the study area consists of arenaceous deposits of lower cretaceous sandstone sequence which is known locally as Kurnub and the upper cretaceous limestone layer. These deposits are divided into three groups: Kurnub group (K) and Balqa/Ajlun groups (B/A). The groundwater level in the study area ranged from -225 to -300 m below the sea level (Figure 2). Groundwater recharge is about 11% at the study area while evaporation is about 76% (Ministry of Water and Irrigation of Jordan, 2022).

Sampling protocol and water quality analysis

Samples of water quality were taken from 6 wells and 6 springs in the area, additionally, samples were taken from the landfill leachate.

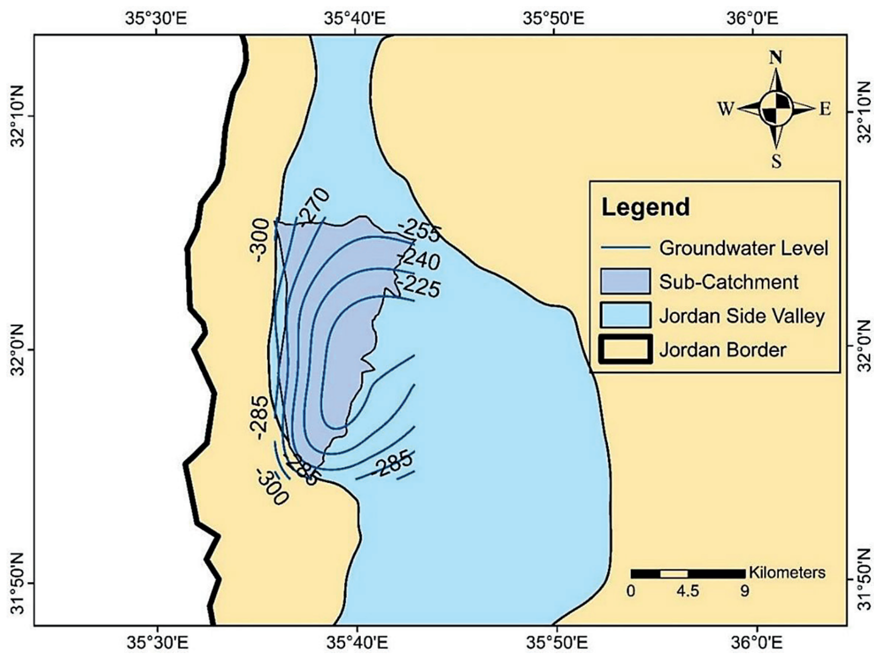

Figure 2. Groundwater level in the study area

The sampling procedure has been conducted on seasonally basis (four rounds) starting on 29/5/2022 and ending on 11/4/2023. The sampling period covers the potential seasonal variation in groundwater during rainy and dry periods. Water conductivity, TDS, and pH were measured in the field, while Cl^-, NH_4, NO_3, alkalinity, COD, BOD, PO_4, and heavy metals were analyzed in the labs. Each round of samples was taken from each site and placed in special sterile containers for water testing, which were placed in an ice box. The procedure for sample collection, labeling, preservation, shipping to the lab, and analysis was conducted according to standard methods (American Public Health Association [APHA] et al., 2023).

The sample volume was three times the needed for analyses. The samples from the well were taken after 10 minutes of pumping to ensure representative samples. Any cross-contamination from any source has been avoided. The water sample was labeled as NRS, where N refers to the first three letters of the source name, R refers to the round number (1, 2, 3, and 4), and S refers to the sample number. Additionally, the sampling date was recorded, and any other notice or comment related to the sampling conditions. Table 1 below illustrates the water sources and its locations (Coordinates).

The parameters pH, EC, TDS, NO_3, and Cl were analyzed in field using a portable multiparameter meter. Additionally, the tests of COD, PO_4, NH_4 and total nitrogen were determined using Spectrometer 7000 XD while TOC was analyzed using visible spectrum spectrophotometery. Moreover, BOD was determined using OxiTop. Furthermore, total alkalinity was measured using Hanna kit. Heavy metal (Cd, Pb, Fe, Zn, Ni, Mn, Cu and Cr) concentrations were analyzed using ICP-MS.

RESULTS AND DISCUSSION

Characteristics of landfill leachate

Field tests

The pH values range from 7.34 to 8.34 with an average value of 8.07. A higher value was detected during the first and second rounds (R1, R2) while it decreased in R3 and R4 during the winter season. Usually, young landfill leachate has a lower pH (about 6.5), whereas old one has a higher pH, and the stabilized landfills have a pH range of 7.5–9 (Lindamulla et al. 2022). Since the landfill is exposed to environmental conditions, it is expected that high temperatures during summer season will enhance the volatility of fatty acids, subsequently increasing pH, which appeared noticeably in R1 and R2 results. Also, rainfall during the rainy season provides a dilution of the alkaline waste and decreases pH. Also, the generation of NH_4 from the decomposition of organic nitrogen increases acidity. However, the elevated pH of leachate may have resulted from anaerobic digestion of waste and consumption of volatile fatty acid by methane process bacteria (Morris et al., 2019).

Table 1. Locations and types of groundwater sources

Source name	Source type	Coordinates		Sampling date
		Long.	Lat.	
Wadi Al-Hamam spring	Spring	32.0421	35.655	Round 1: 29/5/2022 (Spring season) Round 2: 28/9/2022 (Summer season) Round 3: 19/12/2022 (Autumn season) Round 4: 11/4/2023 (Winter season)
FID 2	Well	32.090	35.586	
Al-Dalafeh spring	Spring	32.041	35.655	
Al-Dafaly spring	Spring	32.050	35.660	
Ayesh spring	Spring	32.064	35.680	
FID 6	Well	32.064	35.587	
Kuferhuda spring	Spring	32.068	35.696	
Yazidiyeh well	Well	32.065	35.750	
AL-Sakna well	Well	31.919	35.622	
Aira well	Well	31.991	35.605	
Ayyash well	Well	31.993	35.585	
Bastet Al-Faras spring	Spring	32.009	35.611	
Humra landfill	-	232.060	35.657	

The concentrations of TDS showed high variation during the different rounds and ranged from 43200 in R1 to 11757 mg/l in R4. Lindamulla et al. (2022) found that TDS values ranged from 7400–3015 mg/l for the old landfills and 14390–17850 mg/l for the young ones. High TDS in the Humra landfill indicated that the landfill is considered young and has high dissolving of ions.

Chemical parameters

The concentration of biochemical oxygen demand (BOD) ranged from 963 mg/l in R2 (September 2022) to 2680 mg/l in R4 (April 2023). The concentration of BOD is an indicator of the amount of biodegradable waste in the leachate. Solid waste in Jordan contains a high percentage of waste and food (up to 60%) which explains the high concentration of BOD in the leachate samples. Similar to BOD, the concentration of chemical oxygen demand (COD) increased from 2410 mg/l in R2 to 6100 mg/l in R1. The ratio of BOD:COD ranged from 0.37 to 0.43, indicating a high content of inorganic matter or nonbiodegradable materials. The narrow range of BOD/COD ratio (the low ratio) during September 2022 could be attributed to the effect of evaporation of volatile solids during the summer season, while the low concentration during April 2023 is due to the effect of dilution by rainfall. A high BOD/COD ratio indicates a young landfill and that the biodegradable materials have not decomposed completely. Figure 3 shows the high correlation between BOD and COD concentration indicating the constancy of the waste type and source.

During aerobic and anaerobic decomposition, microorganisms consume organic matter as a source of food and energy, which results in decreasing the organic content in the landfill over time. This explains the high concentration of BOD and COD in young landfills in comparison with old ones. Also, the site will continue to receive waste for many decades, which will maintain a high BOD:COD ratio. Lindamulla et al. (2022) found that the concentrations of BOD and COD were: 159 and 1813 mg/l for old landfills and 531 and 2712 mg/l for new ones, and the ratio of BOD/COD was between 0.5 to 1 for young landfills whereas it was <0.1 for old ones.

Solid waste, usually contains significant amounts of nitrogen from food, agricultural waste, and some chemical compounds. In the landfill, ammonia nitrogen is generated due to the breakdown of amino acids through a biological decomposition process. Ammonia represents most of the total nitrogen and its generation in landfills continues for a long time (Lindamulla et al., 2022). Total Kjeldahl nitrogen represents the sum of organic and ammonia nitrogen. Nitrate may be found in landfill leachate as a result of aerobic decomposition of ammonia. In open dump landfills, atmospheric oxygen is available for aerobic decomposition, which enhances the nitrification process and produces nitrate. It was found that the leachate contains a higher concentration of ammonium (1310–2432 mg/l) than nitrate (474–1640 mg/l) for all samples indicating a young landfill and fresh leachate, with majority of nitrogen components not yet converted to nitrate

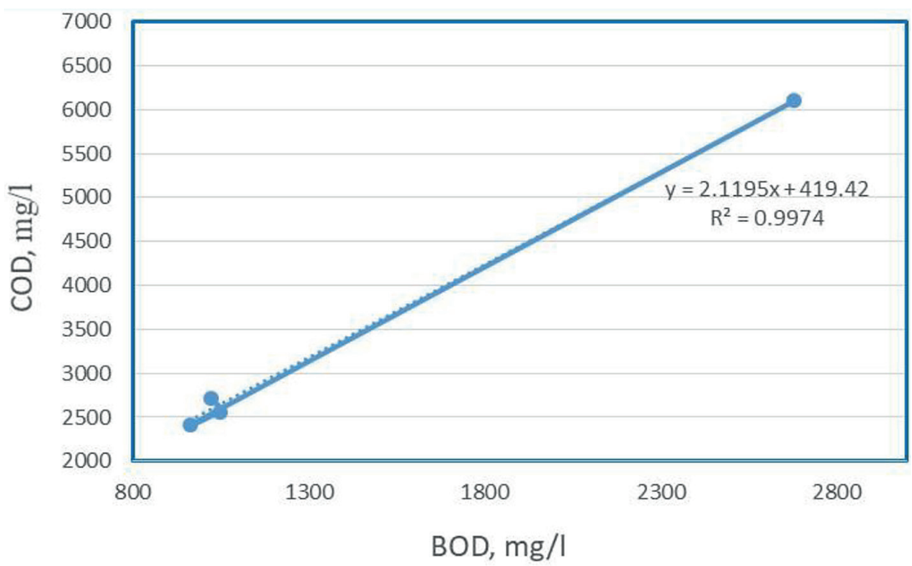

Figure 3. Correlation between BOD and COD

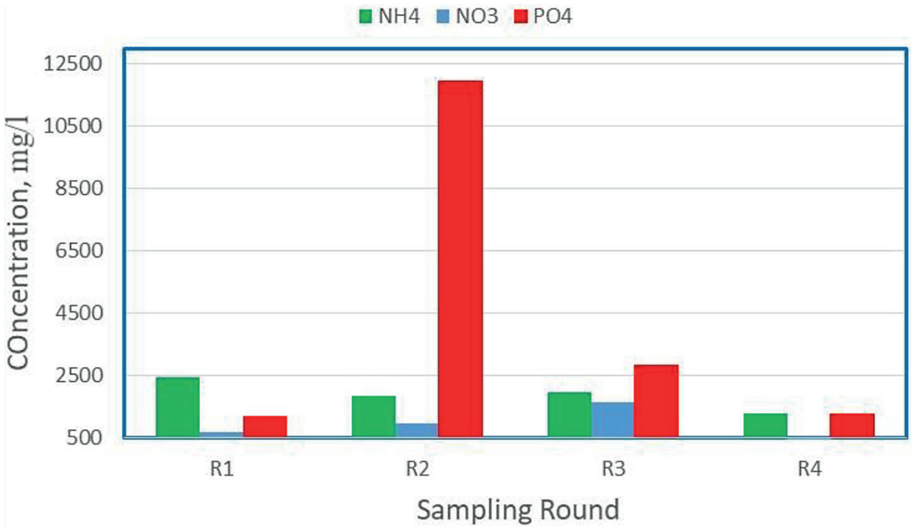

Figure 4. Average concentration of NH_4, NO_3 and PO_4 in leachate

(Figure 4). The ratio of nitrate to ammonium ranged from 1:1.2 to 1:3.57 and a higher ratio was found for September samples. Similarly, Lindamulla et al. (2022), reported a high concentration of NH_4-N in leachate samples from 145 disposal sites reaching more than 1000 mg/l. Özkaraova and Oral (2022) reported a high concentration of NH_4 (1669 mg/l) in the leachate of the Samsun landfill with a low concentration of NO_3 (7.9 mg/l). In contrast, Morris et al. (2019), found that the concentration of NO_3 (354 mg/l) was more than that of NH_4 (161.3 mg/l).

Phosphate concentrations ranged between 1180 to 11950 mg/l with food waste and fertilizers are expected to be the primary sources. This is much higher than what was reported previously by Morris et al. (2019), (TP = 16 mg/l), as well as Özkaraova and Oral (2022), (TP = 14.2 mg/l). The high PO_4 may be attributed to the agricultural and yard waste from the local communities, where fertilizers are applied for plant growth.

Chloride ions are non-biodegradable and have high mobility in water, making them an excellent tracer for detecting contaminant transport and flow direction. Food waste, fertilizers, and soluble salts from home kitchens, restaurants, and hotels are the main sources of chloride in solid waste. The concentration of Cl^- ranged from 7793 mg/l to 18990 mg/l, with the greatest value observed in September 2022 and the lowest in May 2022. Similar to the other parameters, the concentration of Cl^- is affected by the type of waste and environmental conditions, mainly rainfall, and evaporation. A high concentration of Cl^- was also found in the leachate samples from Samsun landfill up to 10,773 mg/l (Özkaraova and Oral 2022), while lower concentrations were reported by Lindamulla et al. (2022), ranging from 4338 mg/l to 14,343 mg/l.

Heavy metals

The presence of heavy metals in the landfill leachate depends mainly on the composition of waste and the environmental conditions, such as runoff. In addition to food, batteries in waste are the primary source of Ni in leachate. Other natural sources of nickel include flora and animals, dust, dirt, and rocks. It has been reported that young leachate has higher concentrations of metals (Ni, Hg, Pb) than mature ones (Amano et al., 2021), which explains the elevated concentration of Ni in leachate samples. The source of zinc in leachate samples could be cosmetics, soap, colors, or fungicides in waste. Chromium waste is generated from natural sources such as leaching from rocks and soil or anthropogenic sources from many industries such as textiles, leather tanning, and electroplating. Lead-based paints, medicines, cosmetics, soil, and dust are the main sources of lead in solid waste.

The concentration of Fe varied from 1.2 to 84.0 mg/l with an average value of 36.8 mg/l. The landfill sites receive all types of municipal waste including iron and tin-based materials resulting in a high concentration of Fe in the leachate samples. Many researchers reported significant concentrations of Fe in the leachate samples, up to more than 100 mg/l (Lindamulla et al., 2022), and 2.6–25 mg/l (Parvin and Tareq, 2021).

Low concentration of Cr (0.1–17.42 mg/l), Cu (0.035–4.63 mg/l), Mn (0.012–2.2 mg/l), Ni (0.05–11.22 mg/l), Zn (0.05–2.62 mg/l) were detected. Very low concentrations of Pb (0.003–0.15 mg/l) and Cd (0.005–0.095 mg/l) were measured.

Agbemafle et al. (2020) determined the concentrations of heavy metals in leachate samples from four landfills in Ghana. They reported the Cr concentration that ranges between 0.38 to 0.55 mg/l, Cu 0.17 to 0.9 mg/l, Zn 0.03 to 0.1 mg/l, and Pb 4.97 to 5.35 mg/l.

Correlation between pollutants

Table 2 shows the correlation matrix between the considered parameters. pH has a high correlation with EC, TDS, COD, and BOD. Ion concentrations in the waste are strongly affected by the pH value. A high correlation between BOD and COD was found (0.99) which is related to the organic nature of waste. A high correlation (0.99) between NH_4 and EC indicating the high content of nitrogen ions in the leachate solution. Negative correlations between pH and Pb (-0.6), Fe (-0.52), Zn (-0.90), Ni (-0.44), Mn (-0.62), and Cu (-0.55) were found. This result indicating a strong relationship between pH and the content of heavy metals. The high pH decreases the solubility of metals in the solution which explains the negative correlation between pH with heavy metals concentration. Also, adsorption of heavy metals in the soil layers increased along with pH, lowering the concentration of these metals in the leachate. It was reported that the trend of metals release with pH will be positive (increase release with pH increase) for the anions and negative (increase release with pH decrease) for the cations (Król et al., (2020). Similarly, Lindamulla et al., (2022) found significant a correlation between BOD and COD (0.81), between nitrogen and BOD (0.76), as well as between nitrogen and COD (0.72), whereas negative correlations between pH with BOD (-0.43) and COD (-0.32) were reported. Also, they reported negative correlation between pH with heavy metals in landfill leachate. Król et al., (2020) showed that the heavy metals decreased with pH increase, and the maximum reduction was found at pH of 8, 8, and 9 for Ni, Cr and Cu, respectively. This reduction was attributed to the sorption and/or precipitation process.

Leachate pollution index (LPI)

The leachate pollution index (LPI) was calculated using Equation 1 (Salami et al., 2015).

$$LPI = \sum_{i=1}^{n} WiPi \quad (1)$$

where: Wi – the weight for the i leachate pollutant, Pi – the sub-index of the i leachate pollutant.

Sub-index curves were used to determine the sub-index values based on the concentration of each pollutant as reported by Salami et al. (2015). In case the concentration of some pollutants is unavailable, LPI can be calculated relative to the total weight (Wi) of pollutants as shown in Equation 2:

$$LPI = \sum_{i=1}^{n} WiPi \,/\, \sum_{i=1}^{n} Wi \quad (2)$$

The overall rating of pollutants was calculated using Equation 1, and Equation 2 was used to determine the final LPI based on the considered parameters (Table 3). The weight of the considered parameters represents only 71% of the total weight of all parameters (100%). For this reason, the final LPI was determined by dividing the overall rating of all parameters by 0.71 as shown in Equation 2. The calculated LPI

Table 2. Correlation between leachate pollutants

Parameters	pH	EC	TDS	Cl-	NH_4	NO_3	PO_4	Alkalinity	COD	BOD
pH	1	0.87	0.87	-0.09	0.82	-0.22	0.23	0.14	0.75	0.77
EC		1	0.99	-0.02	0.99	0.18	-0.02	-0.18	0.78	0.81
TDS			1	-0.04	0.99	0.16	-0.04	-0.16	0.79	0.82
Cl-				1	0.02	0.75	0.78	-0.87	-0.64	-0.60
NH4					1	0.26	-0.05	-0.25	0.75	0.78
NO3						1	0.18	-0.98	-0.37	-0.33
PO4							1	-0.38	-0.47	-0.44
Alkalinity								1	0.43	0.38
COD									1	0.99
BOD										1

Table 3. The calculated leachate pollution index (LPI) of considered parameters

Parameter	Concentration	Weight	Sub index value	Overall pollutant rating
pH	8.07	0.055	3	0.165
TDS	27230 (mg/l)	0.05	64	3.2
Chloride	1340 (mg/l)	0.049	10	0.49
BOD	1428 (mg/l)	0.061	32	1.952
COD	3447 (mg/l)	0.062	57	3.534
TKN	256 (mg/l)	0.053	8	0.424
Pb	0.055 (mg/l)	0.063	5	0.315
Fe	36.804 (mg/l)	0.045	5	0.225
Zn	1.206 (mg/l)	0.056	5	0.28
Ni	3.280 (mg/l)	0.052	10	0.52
Cu	1.518 (mg/l)	0.05	8	0.4
Cr	9.310 (mg/l)	0.064	70	4.48
Sum		0.71		15.98
LPI				22.48

was 22.48 which is considered extremely high and could pose a health risk and environmental pollution needs urgent action to control. TDS, BOD, and COD are the main contributors to the calculated LPI, which reflects the high concentration of organic substances and surfactants in the solid waste. Also, Cr has a high impact on the calculated LPI due to its high concentration in the R3 and R4 leachate samples. It was reported that any landfill with LPI of more than 7.378 is not accepted and has the potential to pollute the groundwater in the vicinity of the site. Similarly, Ofomola et al. (2017) found LPI in four landfills in Nigeria exceeded the acceptable limit of 7.37. Salami et al. (2015) reported high LPI for the Lagos landfill ranged from 16.67 to 23.54.

Characteristics of the groundwater

Field tests

The pH values ranged from 7.71 to 8.71, 5.82 to 8.01, 5.93 to 7.84 and 6.03 to 7.71 with average values of 8.12, 6.97, 7.08, and 7.04 for R1, R2, R3 and R4, respectively. Groundwater has lower pH values than leachate, but both have higher levels during R1.

The impact of rainfall recharge is responsible for the low levels during R3 (December 2022). The Ayesh well sample had the highest pH values for all rounds, whereas the FID2 samples for R2, R3, and R4 had the lowest pH values. Likewise, the maximum average value was found in the Ayesh well, whereas the minimum was found for FID2. FID2 well is located to the northwest of the landfill site, while the Ayyash well is located to the northwest of the landfill site, which corresponds with the direction of groundwater flow and might be responsible for the elevated pH in the well.

Figure 5 shows TDS and EC levels for the different sampling rounds. The average TDS values were 1483, 2012, 2068, and 2156 mg/l with standard deviations of 1246, 2386, 2440 and 2444 for R1, R2, R3 and R4, respectively. A high standard deviation indicates that there is a high variation in TDS values among the different wells and springs. This could be attributed to the depth of groundwater, the nature of the soil, and the impact of the landfill as explained later. The average concentration of TDS for all rounds ranges from 418 mg/l in the Yazidiyeh well to 7619 mg/l in FID 2. The Yazidiyeh well is located to the east of the landfill site and upstream of flow direction and was selected to be used as a reference source. The low pH value in FID 2 can be explained by the high concentration of TDS. The average values of EC were: 2948, 4024, 4120, and 4314 µs/cm with high correlation with TDS (R^2= 1). Negi et al. (2020) reported high concentration of TDS in groundwater in the vicinity of landfill (161–679 mg/l) and exceeded the standard limits for 50% of samples.

Chemical parameters

Table 4 illustrates the average, maximum, minimum and standard deviation for the considered parameters. Out of 48 samples, 42, 15, 2, 2, 2 samples are free of PO_4, NH_4, BOD, COD,

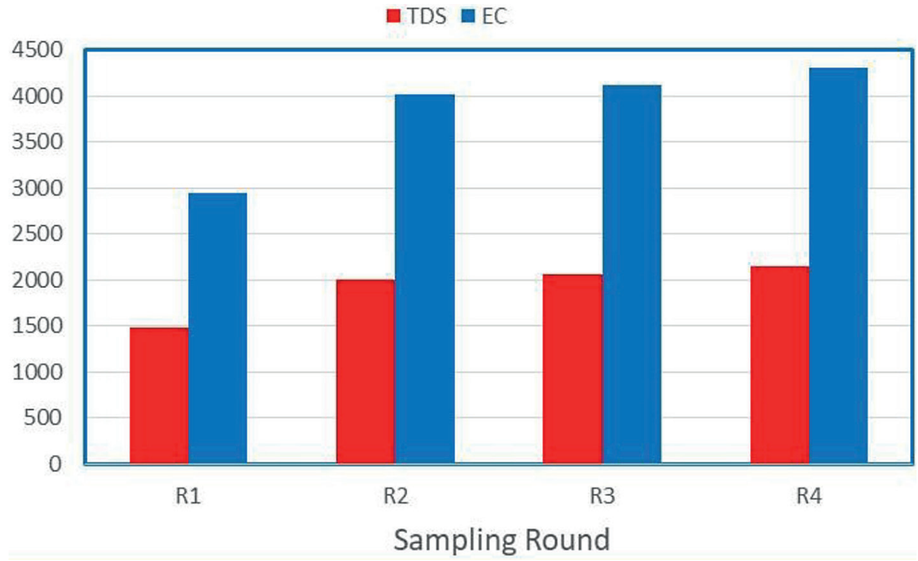

Figure 5. TDS and EC in groundwater samples

and TN, respectively, representing 87%, 31%, 4%, 4%, and 4% of the total samples. For all rounds, there is a significant concentration of BOD and COD with average values reached 131 and 354 mg/l in round 4, indicating an organic source. The higher concentration of both parameters was found during the fourth round (April 2023) followed by the second round (September 2022), while the lowest concentration was found for the first round. The correlation coefficient between BOD and COD was 0.84, 1, 0.96, and 0.92 for R1, R2, R3 and R4, respectively. The BOD: COD ratio ranged from 0.27 to 0.65, 0.26 to 0.46, 0.26 to 0.58, and 0.24 to 0.44 for R1, R2, R3 and R4, respectively. The main source of nitrogen compounds in groundwater is related to the contamination with agricultural waste, animal waste, wastewater, and solid waste through the nitrification process. In the nitrification process, NH_4 is converted to NO_3 which explains the high concentration of NO_3 in comparison to NH_4. The presence of NH_4 in water samples may indicate a recent or continuous contamination source. Only six samples had very low concentrations of PO_4 (<5 mg/l) primarily from spring samples indicating a surface source of PO_4. All samples showed an elevated level of Cl^- ranging from 177 to 5634 mg/l with average values of 6482, 1218, 1264, and 1319 mg/l for R1, R2, R3, and R4; respectively. There are many potential sources of Cl^- including landfill leachate, fertilizers, pesticides, wastewater of septic effluent, and animal waste. Negi et al. (2020) found that the landfill has a high impact on COD concentration in groundwater, and the maximum level (up to 128 mg/l) was measured in the wells that are close to the landfill site. Similarly, they found a high impact of landfill on ammoniacal nitrogen (up to 9.8 mg/l), Na (up to 98 mg/l), K (up to 42 mg/l), SO_4 (up to 57 mg/l), and Cl^- (up to 115 mg/l). The impacts of landfills on groundwater quality in Morocco indicated high concentration of contaminants in the wells that are located adjacent to the landfill sites, with a significant concentration of COD (30–138.8 mg/l), BOD (2.2 to 41.7 mg/l), NH_4 (0.1–7 mg/l), TN (2.4–43.2 mg/l), and PO_4 (0.06–0.71 mg/l) (Benaddi et al., 2022).

Heavy metal concentrations

Figures 6 and 7 shows the concentrations of the heavy metals in the different rounds. The average concentrations of all parameters in R1 and R2 were less than 0.1, while the concentration increased significantly during R3 and R4 for most of the heavy metals. In R1, all samples showed a detectable limit of Cd, Ni and Mn while undetectable limits were found for Pb, Fe, Zn, Cu and Cr. For R2, out of 12 sources, detectable limits were found in 12, 1, 2, 7, 4, and 8 sources for Cd, Fe, Zn, Mn, Cu, and Cr; respectively. The concentration of the heavy metals increased during R3, and 8 sources have detectable levels of Pb, Fe, Zn, Ni, Cu, and Cr, while Mn was detected in 9 samples and Cd was not detected in any sample. Similar to R3, R4 showed increases in the concentration of most

Table 4. Average concentrations of chemicals in groundwater samples

Parameter	Statistical analysis	Chloride	TN	NH4	NO3	PO4	Alkalinity	COD	BOD
R1	Max	24367.0	9.00	105.20	210.88	0	240.00	87.00	29.90
	Min	0	1.00	0.11	0	0	95.00	10.00	5.80
	Av.	6482.30	3.42	11.93	69.94	0	173.00	37.58	15.09
	SD	9061.37	3.03	29.67	61.51	0	38.91	20.55	6.37
R2	Max	5667.94	16.46	9.00	216.56	4.90	1350.00	3256.0	1273.80
	Min	177.123	2.30	0.00	10.18	0	150.00	0	0
	Av.	1218.64	8.61	0.92	72.04	0.98	398.75	310.00	121.59
	SD	1552.19	4.95	2.55	58.77	1.82	351.79	929.00	363.57
R3	Max	5634.73	14.33	1.36	754.21	4.00	2000.00	312.00	92.80
	Min	177.123	0	0.00	24.35	0.00	13.10	6.90	2.10
	Av.	1264.31	5.79	0.23	200.95	0.83	801.66	66.27	23.55
	SD	1591.49	5.32	0.43	197.29	1.52	854.97	83.56	25.72
R4	Max	5645.81	13.91	7.80	486.27	0	273.00	922.00	224.10
	Min	177.12	0.27	0.00	50.49	0	123.00	179.00	78.50
	Av.	1319.66	6.11	0.77	249.44	0	200.92	354.00	131.31
	SD	1595.013	4.75	2.24	157.02	0	41.83	187.02	34.61

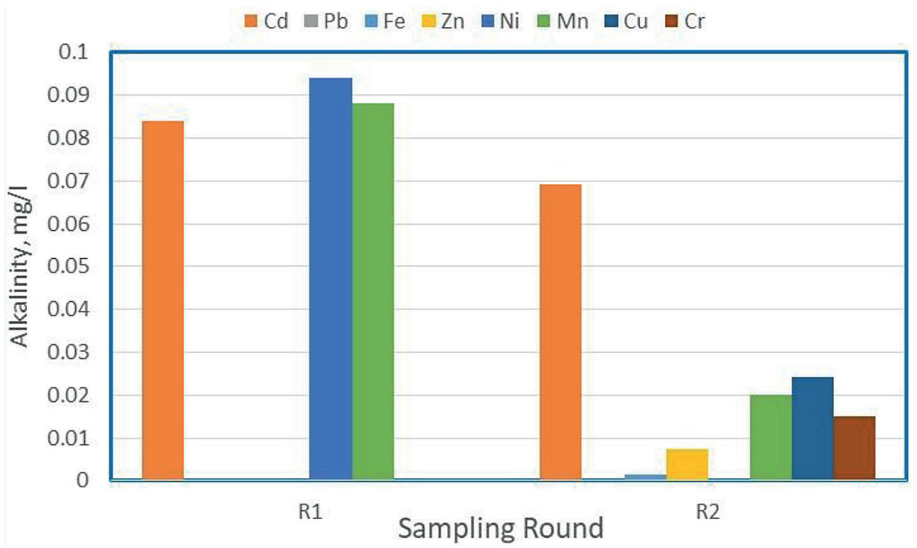

Figure 6. Heavy metal concentrations in the R1 and R2 samples

of the considered parameters, while Pb, Fe, Zn, Ni, Cu, and Cr, were detected in 66.6%, 91.6%, 50%, 91.6%, 75%, 91.6%, and 75%, respectively. However, Cd was not detected in any source. The high concentration during R3 and R4 could be attributed to the impact of the seasonal rainfall, runoff and infiltration during winter. It is important to mention that the concentration of heavy metals is affected strongly by the concentration of these metals in soil, soil adsorption capability, chemical reactions, and the direction of groundwater flow (Ammari et al., 2021; Al-Kharabsheh, 2022). On the other hand, a study carried out by Negi et al. (2020) investigated the impact of landfill on groundwater and it reported very low concentrations of Pb (0–0.007 mg/l), Zn (0–4.04 mg/l), and Cu (0–0.27 mg/l).

Suitability of groundwater for drinking purposes

The concentrations of the measured parameters were compared with Jordanian standards for drinking water (JS 286/2015). Regarding the substances with palatability impacts on drinking water quality, it was found that 13 samples did

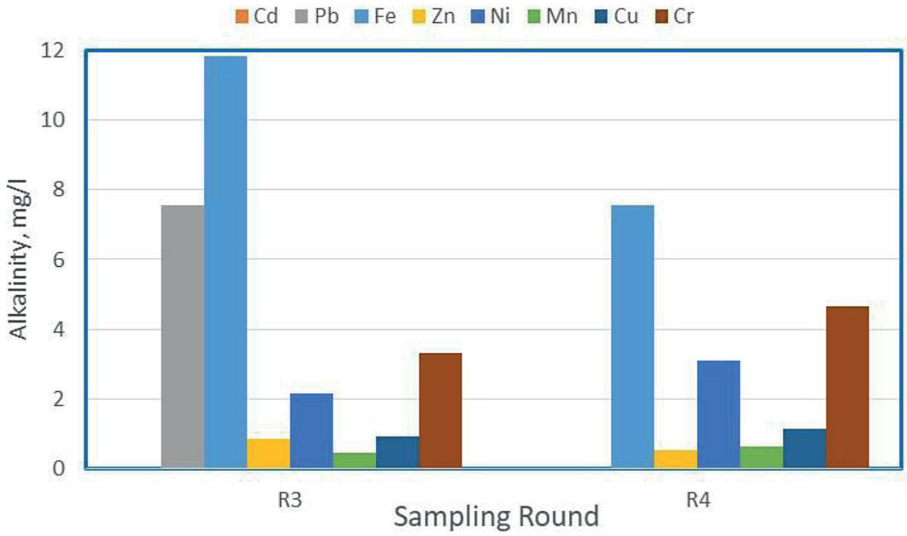

Figure 7. Heavy metal concentrations in the R3 and R4 samples

not meet the pH standard (6.5–8.5). Out of these, 12 samples were below 6.5, and one above 8.5 with all exceedances related to the well samples. About 50%, 50%, %52%, 50%, 14.5% and 23% of samples exceeded TDS, NH_4, Cl, Fe, Cu, and Mn standard limit, respectively. All samples have the Zn concentration below the standard of potable water. Most of the exceedances occurred during R3 and R4, which could be attributed to the impact of recharge during the rainy season. Comparison of the inorganic elements with Jordanian standards showed that 21%, 37%, 60%, 50%, and 75% of the samples exceeded Pb, Cr, Ni, Cd, and NO_3 standards. About 26.4%, 18%, 24%, and 31.6% of the exceedances occurred during R1, R2, R3, and R4, respectively. On the basis of the obtained results, it can be concluded that the groundwater in the area is not suitable for drinking purposes due to the high exceedance of the most considered parameters. All groundwater sources violated the applicable standards in one or more parameters during the study period. In comparison with Wthe HO guidelines for drinking water, 2%, 80%, 21%, 17%, 41%, and 17% of the samples exceeded pH, NO_3, Pb, Cr, Mn, and Cu limits.

Upstream and downstream concentrations

Figures 8a through 8j show the concentrations of pollutants in upstream and downstream sources. In comparison with the upstream sources, the downstream sources have higher concentrations of the considered indicators. For example, the concentration of TN was 2.4, 7.9, 3.4, and 4.1 mg/l in the downstream wells in rounds R1, R2, R3, and R4, respectively, compared with 5, 2.9, 1.7, and 2.4 mg/l in the upstream wells. This result shows the impact of the landfill on groundwater quality. There are three springs within a radius of 2.5 km from the landfill (Wadi Hamam, Dafaly, and Dalafah springs), one spring located at a distance of 7 km (Bastest Al-Faras spring), and all wells are located at a distance of more than 6.6 km. Regarding the impact of the source site on the concentration of the pollutants, it was found that the concentration of TN, BOD, and COD decreased with distance increase to the Humra landfill, whereas the other parameters showed insignificant trends. In general, lower correlation may indicate the impacts of other sources. The correlation coefficient (R^2) between the concentration of pollutants and the distance ranged from 0.21–0.53, 0.23–0.89, 0.22–0.96 for TN, COD, and BOD of springs and 0.07–0.24, 0.09–0.37, 0.13–0.38 for wells, which indicates a better correlation for the spring source than the well source (Figure 9a through Figure 9f). The high correlation of the spring source may indicate the impact of direct surface pollution from the leachate due to the runoff, convection, and diffusion. Low correlation for well sources could be attributed to the depth of groundwater (up to 650 m) and the effectiveness of the soil in removing pollutants through different mechanisms such as Adsorption, chemical and biological reactions, dispersion and diffusion.

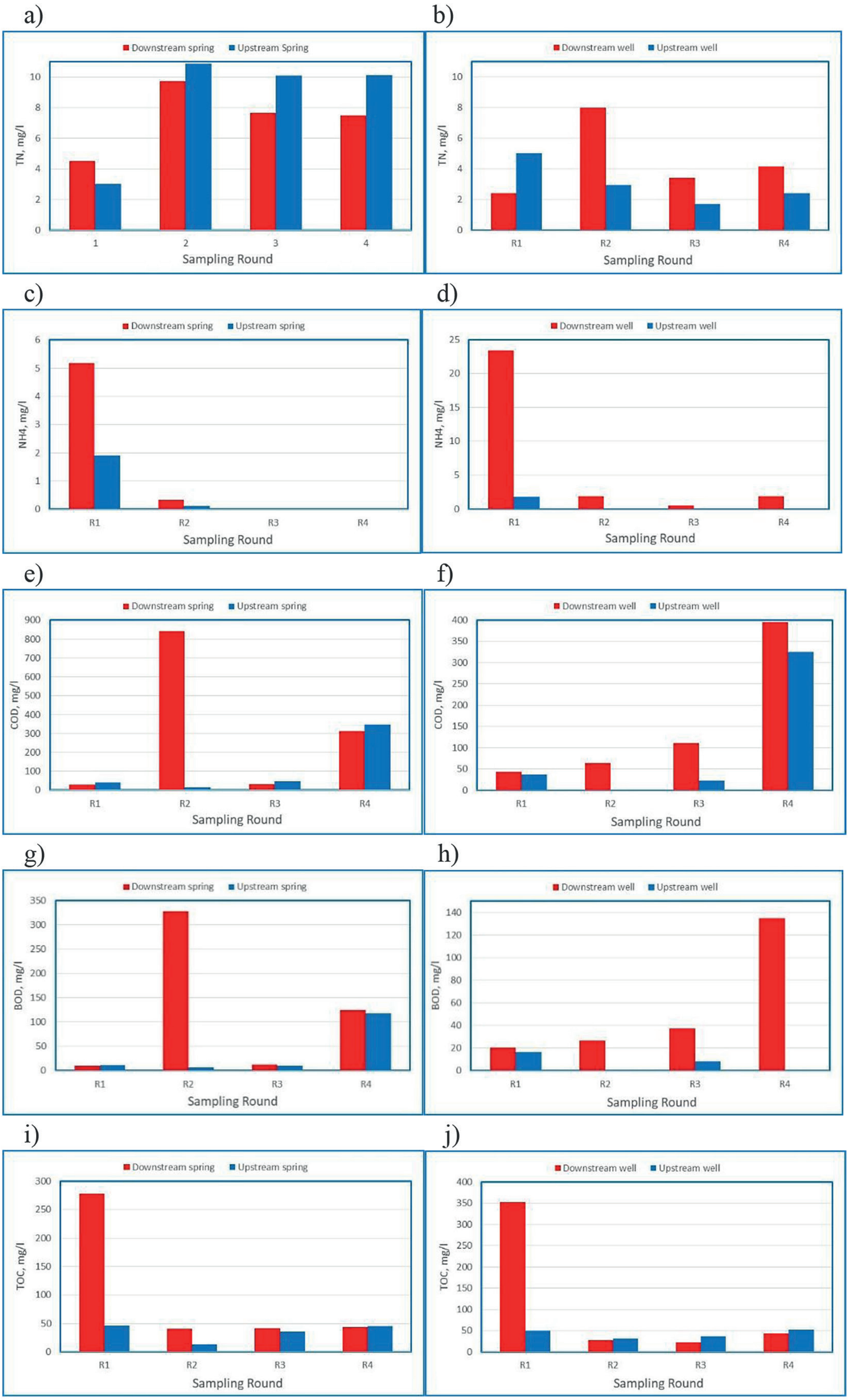

Figure 8. Comparison of concentrations of the pollutants in the upstream and downstream sources. Springs are in the left-hand charts: a, c, e, g, i, whereas wells are in right-hand charts: b, d, f, h, j

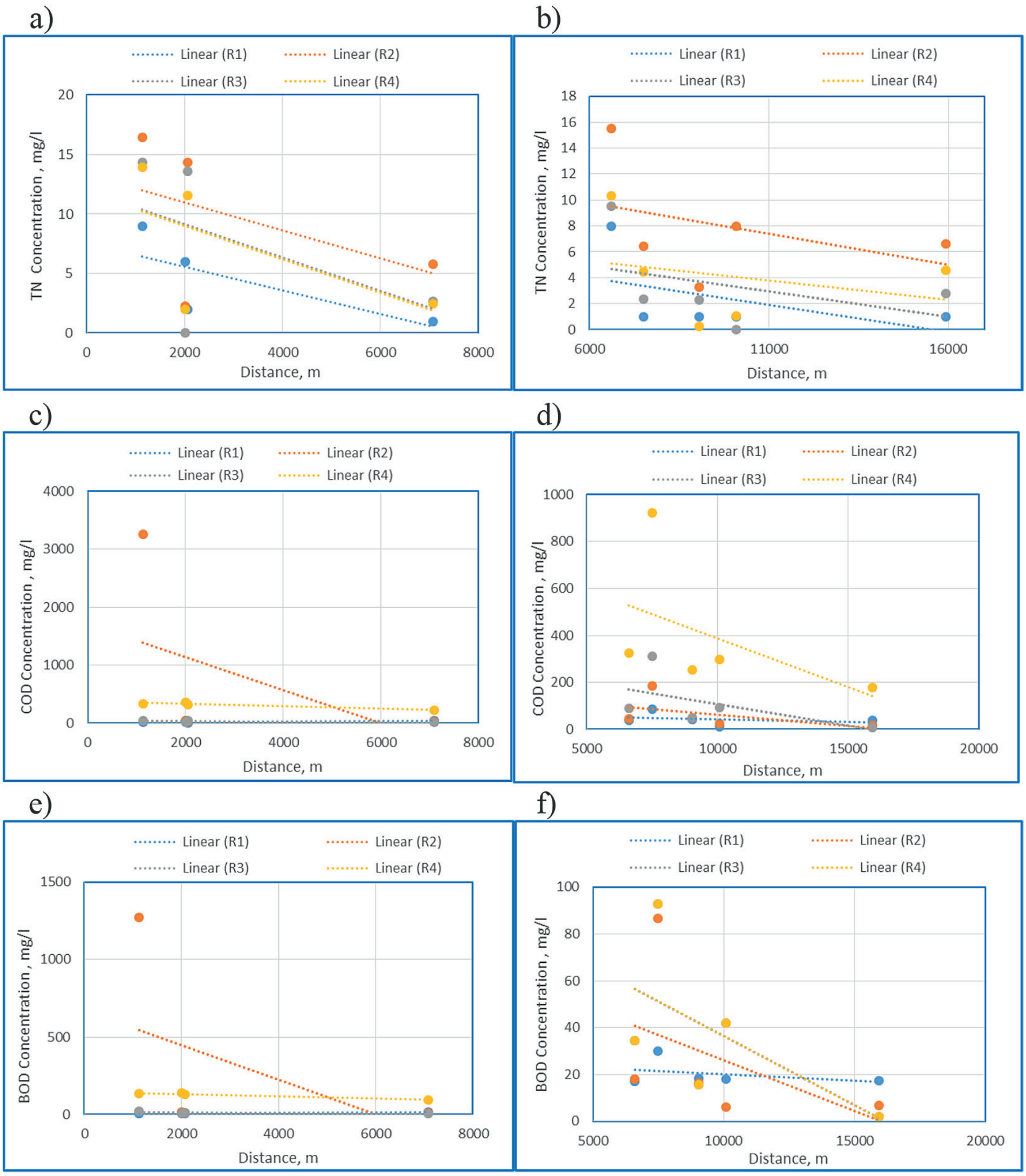

Figure 9. The relationship between the distance to the landfill and the concentration of pollutants in springs (Left-hand charts: a, c, and e) and wells (Right-hand charts: b, d, f)

CONCLUSIONS

The present study has led to the conclusion that Humra landfill leachate has high concentrations of groundwater quality in terms of TDS (27230 mg/l), nitrogen (2831 mg/l), and organics (BOD = 1428 mg/l, COD = 3477 mg/l). Subsequently, the LPI is extremely high (22.48). Specifically, between 14.5% and 75% of samples taken from groundwater sources surrounding the landfill showed higher concentrations than Jordanian drinking water quality standards in one or more parameters. The evidence from this study indicates that concentrations of pollutants in the downstream sources are higher than those in the upstream sources. Moreover, the landfill impact is higher on the sources close to the landfill site than on the sources farther away. The study findings will assist decision-makers and waste management professionals in understanding the impacts of landfills and how to mitigate it. To reduce the impact of landfill on groundwater, it is recommended to control pollution at sources by promoting segregation and recycling process, controlling illegal dump, capacity building of the solid waste management sector and developing spill emergency plan. For operating, it is recommended to apply liner layer to control leachate, control surface drainage, apply daily and final cover, as well as closure and post closure system. A periodical groundwater monitoring system is necessary including routine sampling and emergency plan.

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