



ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

Water Conservation and Management (WCM)

DOI: <http://doi.org/10.26480/wcm.01.2026.139.147>



RESEARCH ARTICLE

GROUNDWATER QUALITY STABILITY AND CHROMIUM RISK IN A SEMI-ARID AQUIFER: IMPLICATIONS FOR WATER CONSERVATION AND SUSTAINABLE MANAGEMENT NEAR LANDFILL AND WASTEWATER DISPOSAL SITES

Amjad Al-Tarawneh^{a*}, Sadam Al-Ramadain^a, Tayel El-Hasan^b, Eid Al-Tarazi^c, Jafar Abu Rajab^c, Fayza AlShamaen^d

^aPrince Faisal Center for Dead Sea, Environmental and Energy Research, Mutah University, Karak 61710, Jordan.

^bDepartment of Chemistry, Mutah University, Mutah, Karak 61710, Jordan.

^cDepartment of Earth Sciences and Environment, Prince El-Hassan bin Talal Faculty for Natural Resources and Environment, The Hashemite University, Jordan.

^dAqaba Water Company, Geographic Information System Unit, Ministry of Water and Irrigation.

*Corresponding Author Email: amjtar@mutah.edu.jo

This is an open access journal distributed under the Creative Commons Attribution License CC BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited

ABSTRACT

Article History:

Received 27 February 2026
Revised 20 March 2026
Accepted 25 March 2026
Available online 09 April 2026

Groundwater is the main freshwater source in semi-arid areas, thus, needs protection from human pollution. The municipal solid waste landfill and an untreated wastewater disposal facility are located in Al-Lajjoun region of central Jordan which situated within the recharge zone of the Amman-Wadi Sir (A7/B2) carbonate aquifer, this study investigates the sustainability and the groundwater quality. for that reason, untreated wastewater and soil samples impacted by leachate, and eight production wells were observed in the summer and winter. Major ions, trace metals, and physicochemical properties were examined and compared with Jordanian drinking water standards. The results show that the groundwater hydrochemistry is mainly consistent during the year, where the majority of parameters falling within permitted limits. Nevertheless, chromium concentration in all wells continuously exceed drinking water regulation, indicating a recurring pollution problem. Meanwhile, the landfill leachate saturated soils demonstrated high concentrations of Fe, Cr, Cd, Pb, Ni, Zn, and Mn compared with baseline values. Untreated wastewater had high organic and nutrient concentrations. The high metal concentrations in leachate affected soils lead to a possible permanent risk to the aquifer sustainability even in the absence of direct hydraulic mixing between wastewater and groundwater, particularly, in structurally fractured carbonate systems. The findings demonstrate the aquifer's resilience under current conditions, Also, shows the necessity for long-term hydrochemical monitoring, engineered barrier structures, and preventive management to ensure groundwater conservation in arid zones.

KEYWORDS

Groundwater conservation, semi-arid aquifer, Landfill leachate, Wastewater disposal, Heavy metals, Chromium contamination, Hydrochemistry, Water quality management, Aquifer sustainability.

1. INTRODUCTION

Groundwater consider as the main source of freshwater in the arid and semi-arid areas which characterised with scarce and highly inconsistent surface water supply (Salamah et al., 2023). Jordan is one of the most water-scarce countries, with per capita below the water poverty threshold (Al-Mubaidin et al., 2022; Al-Hamaideh et al., 2023; Al-Harahsheh et al., 2023; Salamah et al., 2023; MoWI, 2024). sustainable water security is an important issue for Jordan's prosperity, health, and food security "National Water Strategy 2023-3040" (MoWI, 2023).

The quality of groundwater is endangered by landfills and wastewater disposal sites, especially if located in areas with karstified or fractured carbonate aquifers that could provide optimal paths for the movement of contaminants (Powell, 1988; Xu et al., 2018). Elevation of dissolved salts, organic matter, nutrients, and hazardous metals including Cr, Cd, Pb, and Ni are usually found in leachate produced by the breakdown of solid waste,

which cause serious problem to ecosystems and human health (Bibi et al., 2016; Botsou et al., 2019).

The leachate causes a long-term risk to groundwater quality as mentioned by many studies. This research showed a clear link between landfills and groundwater hydrochemistry, highlighting higher amounts of salt, potassium, and chlorides that increases with the age, amount of waste, and location of the dump (Huang et al., 2024b). Pollutant rised during time of high precipitation and even the closed sites considered to be sources of chemical and microplastic pollution physicochemical and microbiological degradation and heavy metals could be entering the water table through soft soil, this was tracked using resistivity mapping (Alao, 2023; Przydatek et al., 2025; Grzegorz, 2025).

In semi-arid climates, due to low recharge rates and excessive evaporation, which extend the persistence of contaminants (Laluraj and Gopinath, 2006; Tumolo et al., 2020). Amman-Wadi Sir (A7/B2) aquifer's

Quick Response Code



Access this article online

Website:
www.watconman.org

DOI:
10.26480/wcm.01.2026.139.147

recharge zone is one of the most important groundwater systems in Jordan. It contains an untreated wastewater dumping site and municipal solid waste landfill in the Al-Lajjoun region of central Jordan (Obeidat et al., 2013; Al-Ajarmeh, 2020). These landfills could promote the pollutant transport along fractures and faults, structural characteristics connected to the Al-Karak-Al-Fiha graben further increase aquifer susceptibility (Powell, 1988; Jiries et al., 2025).

The objectives of this study are to: (1) investigate the groundwater hydrochemistry, (2) analyze pollution suspected by untreated wastewater and landfill leachate, and (3) evaluate results for groundwater conservation, in a semi-arid aquifer system.

2. STUDY AREA AND HYDROGEOLOGICAL SETTING

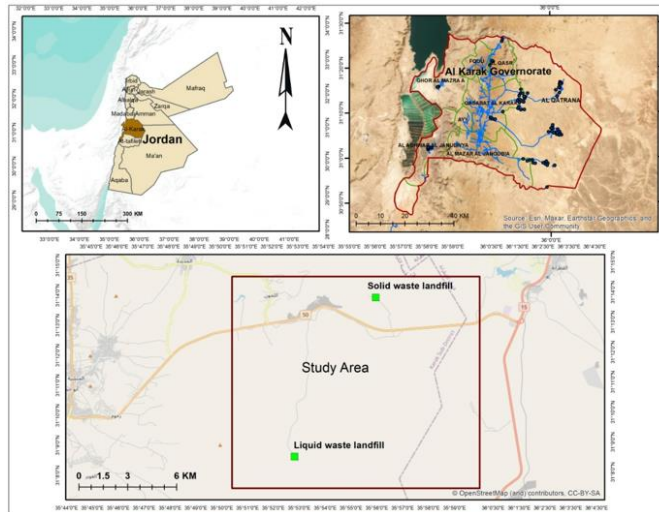


Figure 1: Map displays the location of the studied area.

2.2 Hydrogeological Setting

The study area is located in the Al-Mujib Dam catchment basin, which is regarded as one of Jordan's most significant basins. Figure 2 shows the three primary groundwater aquifer systems in the Al-Mujib basin: Rum, Kurnub sandstone (K), and Amman-Wadi Sir group (A7/B2) (Al-Ajarmeh,

2.1 Location and Physiography

The research area is situated in central Jordan, around 12 km west of Al-Qatrana and 23 km east of Al-Karak City (Fig. 1). Wadi Dabhah's elevation is roughly 640 meters above sea level, whereas the Al-Ghwayer region's elevation is close to 1150 meters. Low to moderate relief defines the terrain, with sometimes severe grades over deeply incised wadis in the northeastern sector (Al-Ramadain et al., in press).

With the exception of a small flow from Al-Lajjoun springs, surface drainage is primarily ephemeral and active during the winter rainy season. The Al-Karak-Al-Fiha graben, which trends NW-SE and has a significant impact on topography, drainage, and groundwater flow patterns, structurally controls the region (Powell, 1988).

2020). The primary aquifer in the research region is thought to be the (A7/B2) aquifer associated with the Upper Cretaceous limestone aquifer. The main source of water recharge to the Amman-Wadi Sir Aquifer is thought to be rainfall infiltration in the outcrop area. The A1/6 sequence, which is primarily composed of marls, marly limestone, and limestone, is beneath the A7/B2 aquifer.

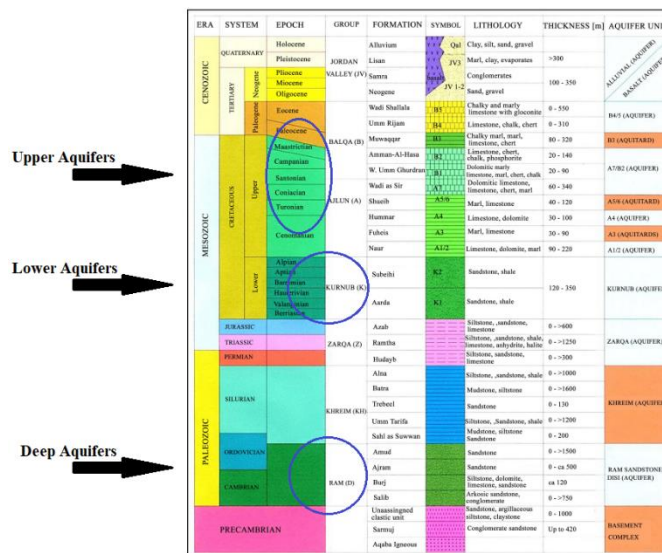


Figure 2: Jordan geological lithological column and the upper, lower and deep aquifers, (modified after, Margana et al., 2009).

The research area's aquifer system, named as A7/B2, has a thickness of around 320 meters and exhibits a range of thicknesses in Central Jordan, from 100 to 320 meters at various locations (Powel, 1988). The A7/B2 is an unconfined, phreatic upper aquifer made mainly of fractured carbonate deposit with karstic characteristics. In the research region, A7/B2 groundwater flows in a north-northeast direction.

2.3 Climate

The research area has a semi-arid climate with a long, hot, dry summer and a brief rainy season from November to March. The average daily temperature varies from roughly 3 °C in the winter to 35 °C in the summer. The average daily evaporation at Al-Qatrana station is about 8.2 mm (Jiries

et al., 2009; Jordan Meteorological Department, 2019). Evaporation rates are considerable, ranging from around 0.9 mm/day in December to more than 10 mm/day in July. Rainfall ranges from 50 to 300 mm each year, with the majority falling between January and March. The average annual rainfall over a lengthy period of time is often less than 100 mm. Over the past ten years, extended drought conditions have increased the strain on groundwater resources and decreased the natural diffusion of pollutants.

2.4 Wastewater and Solid Waste Disposal Sites

About 30 kilometers east of Al-Karak City is the Al-Lajjoun untreated wastewater disposal site, which was created in 2004 (Figure 3). With a

design capacity of roughly 600 m³/day in summer and up to 750 m³/day in winter, it receives untreated wastewater from homes, hospitals, and auto maintenance (MWI and BGR, 2005). In order to minimize seepage, the facility consists of six stabilization ponds (anaerobic, facultative, and maturation ponds) enclosed with high-density polyethylene (HDPE) over a layer of sandstone (Al-Malahmeh, 2006). Usually, wastewater travels in the direction of Al-Mujib Dam along Wadi Al-Lajoun.

The largest trash disposal facility in the Al-Karak Governorate is the Al-Lajoun solid waste landfill, which was established in 1996. It covers around 488 acres and receives 200–250 tons of municipal solid waste every day (Al-Sarayreh and Alsarayreh, 2021). Concerns about leachate formation and infiltration continue despite management efforts, emphasizing the necessity of ongoing hydrochemical monitoring to preserve groundwater quality (Al-Omari et al., 2021; Baba, 2023).

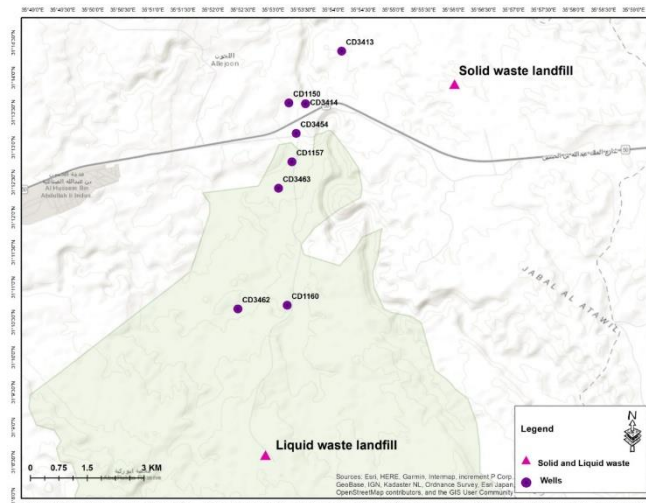


Figure 3: Map showing the locations of landfills for both liquid and solid waste as well as water wells.

3. MATERIALS AND METHODS

3.1 Sampling Strategy

Groundwater samples were collected from eight productive wells during summer and winter seasons. Additional samples included untreated wastewater and leachate-saturated soil from landfill sites.

3.2 Analytical Procedures

Physicochemical parameters, major ions, and trace/heavy metals were determined following internationally recognized standard analytical methods. Comprehensive quality assurance and quality control (QA/QC) protocols, including instrument calibration, use of blanks, duplicates, and standard reference materials, were implemented to ensure data accuracy and reliability. Statistical analyses were conducted using SPSS software.

To evaluate the potential leaching impacts of landfill leachate and untreated wastewater on groundwater quality, groundwater sampling was carried out at eight productive wells. From each well, three water samples were collected during two hydrological periods representing the summer and winter seasons. All samples were collected in pre-cleaned 1 L polyethylene bottles. In addition, a leachate-saturated soil sample was collected from the solid waste dump site at a depth of 1.5 m, and a representative sample of untreated wastewater was obtained from the wastewater disposal site for comparative assessment.

3.2.1 Physicochemical parameters

The samples were analyzed for the physicochemical parameters of the total dissolved solids (TDS), total suspended solids (TSS), total alkalinity (TA), pH, dissolved oxygen (DO), electrical conductivity (EC), turbidity, and total hardness (TH) according to the standard methods 2540C, 2540D, and 2320 B, 4500-H + B, 4500-O G, and 2510 B, 2130 A, 2340C, respectively (Rice and Bridgewater, 2012; Al-Harahsheh et al., 2023).

3.2.2 Heavy metals

Following acidification, the water samples were filtered using a cellulose acetate syringe filter with a pore size of 0.45 µm. After the leachate-saturated soil sample was dried and then sieved to a size of less than 2 mm, it was grinded using a mortar and pestle, oven-dried for an entire night at 105 °C, and digested by 8 mL of aqua regia (2 mL HNO₃ and 6 mL HCl) with 200 mg of soil sample. According to Standard Method 3111 B (Prell-Swaid and Schwedt, 1994, Rice and Bridgewater, 2012; Al-Harahsheh et al., 2023; El-Hasan & Al-Tarawneh, 2020), samples of soil and water were analyzed for heavy metals (Cr, Cu, Pb, Fe, Mn, Zn, and Ni) using Atomic Absorption Spectroscopy (AA-7000, Shimadzu Scientific Instruments, Japan).

2.2.3 Major cations and anions

An ion chromatography analyzer (Eco IC, Metrohm, Switzerland) was used to analyse the water samples for anions (Cl, SO₄, Br, NO₃, PO₄, and F) and

cations (Li, Na, NH₄, K, Ca, and Mg) after they had been filtered using a cellulose acetate syringe filter (Rice & Bridgewater, 2012; Al-Harahsheh et al., 2023; Jiries et al., 2004).

3.2.4 Quality assurance (QA) and quality control (QC)

In order to guarantee the accuracy of the results, we conducted three primary activities: 10% of all samples were analyzed in duplicate and distributed at random; duplicate determinations had to agree with 5% of their average relative percentage duplicate (RPD); and the recovery of the QC sample had to fall between 80-120% in order to be accepted.

3.2.5 Statistical analysis

Every sample was examined three times. SPSS software was used to interpret the data. Mean ± SD was used to express the results. When assessing the statistical significance of group differences, only p values less than 0.05 are deemed significant.

4. RESULTS

Tables 1, 2, and 3 provide an overview of the physicochemical properties, heavy metal concentrations, and main ion composition of the water samples that were collected during the summer and winter. Groundwater suitability for drinking purposes was assessed by comparing the measured values with the Jordanian Drinking Water Standards (JDWS). In both sampling seasons, the majority of examined parameters generally met JDWS limits. However, all groundwater samples had chromium (Cr) contents that were consistently higher than the allowable limit.

Interactions between groundwater and pipe-scale deposits in the water distribution system, which have been shown to function as secondary sources of chromium release into drinking water, may be the cause of the ongoing elevation of Cr (Ni et al., 2024). Temporal stability of groundwater quality during the study period was indicated by seasonal statistical analysis, which showed no significant variations between summer and winter concentrations for the examined parameters (p > 0.05). Table 4 illustrates the analytical findings of the leachate-saturated soil that was collected from the solid waste landfill.

4.1 Physicochemical Characteristics of Groundwater

In both seasons, groundwater samples showed moderate electrical conductivity, near-neutral to slightly alkaline pH values, and slightly elevated dissolved oxygen contents. There are no statistically significant seasonal fluctuations in these parameters, which indicate steady hydrochemical conditions and typically good groundwater quality.

4.2 Heavy Metals in Groundwater and Wastewater

Chromium was one of the heavy elements that were found to have continuously high amounts in groundwater samples, above the JDWS threshold in both summer and winter. Other trace metals, however, stayed

within permissible bounds. However, untreated wastewater samples showed high levels of a number of heavy metals, indicating the impact of human inputs and inadequate treatment before disposal.

4.3 Major Ion Chemistry

Groundwater's primary ion composition stayed within drinking water standards' allowable bounds, suggesting little geochemical disturbance and little effect from pollution sources. On the other hand, nitrate, phosphate, and ammonium concentrations in untreated wastewater samples were noticeably high, indicating significant organic and nutrient

loading related to wastewater disposal methods.

4.4 Contamination of Leachate-Saturated Soils

In comparison to background soil levels, landfill leachate-affected soils showed significant enrichment with Fe, Cr, Cd, Pb, Ni, Zn, and Mn. The mobilization and accumulation of metals from the breakdown of solid waste and leachate percolation are reflected in this enrichment, which suggests a significant human influence. If leachate mobility is not controlled, the elevated metal concentrations point to a possible long-term risk to underlying groundwater resources.

Table 1: Physical parameters of the studied wells during summer and winter seasons (means ± SD, n = 3).

Parameter	Season	Sample name									JDWS standard
		CD1150	CD1157	CD3413	CD3454	CD3462	CD3414	CD3463	CD1160	Untreated wastewater	
COD [mg/L]	Summer	27±1.4	29±1.5	22±1.1	27±1.3	19±0.9	33±1.6	27±1.3	26±1.3	155±8	FW*: - TW**: 300
	Winter	30±2.3	33±3.1	28±2.3	26±2.2	23±2.3	30±2.6	27±1.5	28±2.4	250±13	
BOD ₅ [mg/L]	Summer	4±0.2	4±0.2	5±0.3	1±0.1	4±0.2	7±0.4	4±0.2	3±0.2	70±4	FW: - TW: 60
	Winter	5±0.3	5±0.3	4±0.2	3±0.1	6±0.3	9±0.5	8±0.4	5±0.3	130±6	
pH [pH unit]	Summer	7.1±0.4	7.4±0.4	7.5±0.4	7.5±0.4	7.6±0.4	7.6±0.4	7.6±0.4	7.6±0.4	7.3±0.4	FW: 6.5-8.5 TW: 6-9
	Winter	7.1±0.4	7.1±0.4	7.1±0.4	7.1±0.4	7.3±0.4	7.1±0.4	7.1±0.4	7.1±0.4	7.2±0.4	
EC [µs/cm]	Summer	1219±61	1326±66	1120±56	1246±62	729±37	766±38	1206±60	1621±81	4410±221	FW: 750-2300 TW: -
	Winter	1233±62	1371±69	1257±63	1256±63	1275±64	1032±52	1211±61	1622±81	2900±145	
DO [%]	Summer	96.2±4.8	96.2±4.8	95.6±4.8	94.5±4.7	95.5±4.8	94.2±4.7	94.9±4.8	94.6±4.7	35.2±1.8	FW: - TW: -
	Winter	93.0±4.7	93.0±4.7	94.7±4.7	94.7±4.7	94.4±4.7	92.1±4.6	96.0±4.8	94.0±4.7	15.5±0.8	
DO [mg/l]	Summer	6.7±0.3	6.7±0.3	6.8±0.3	6.6±0.3	6.7±0.3	6.6±0.3	6.6±0.3	6.6±0.3	2.2±0.1	FW: - TW: 2<
	Winter	8.2±0.4	8.4±0.4	8.4±0.4	8.2±0.4	8.5±0.4	7.9±0.4	8.1±0.4	8.1±0.4	1.4±0.07	
O ₂ [%]	Summer	20±1	20±1	20±1	20±1	20±1	20±1	20±1	20±1	6.9±0.4	FW: - TW: -
	Winter	20.2±1.0	20.0±1.0	19.6±1.0	19.6±1.0	20.0±1.0	19.3±1.0	20.2±1.0	19.5±1.0	3±0.15	
TSS [mg/L]	Summer	4±0.2	1±0.05	2±0.1	3±0.2	3±0.2	1±0.05	2±0.1	3±0.2	13±0.7	FW: - TW: 50
	Winter	4.0±0.2	2.0±0.1	3.0±0.2	1.0±0.1	4.0±0.2	6.0±0.3	6.0±0.3	5.0±0.3	7±0.35	
TDS [mg/L]	Summer	668±33	701±35	580±29	669±33	422±21	422±21	674±34	1052±53	2437±122	FW: 1000 TW: 1500
	Winter	717±36	769±38	711±36	709±35	695±35	525±26	637±32	975±49	1466±73.3	

Table 2: Metal concentration in the water of the studied wells during summer and winter season (means ± SD, n = 3).

Parameter	Season	Sample name									JDWS standard
		CD1150	CD1157	CD3413	CD3454	CD3462	CD3414	CD3463	CD1160	Untreated wastewater	
Cd [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	FW: 0.003 TW:
	Winter	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	0.02±0.0008	
Cr [mg/L]	Summer	0.1±0.004	0.1±0.005	0.1±0.007	0.2±0.008	0.2±0.009	0.2±0.009	0.2±0.010	0.2±0.012	0.1±0.006	FW: 0.05 T
	Winter	0.1±0.007	0.2±0.008	0.2±0.01	0.2±0.01	0.3±0.01	0.2±0.01	0.3±0.01	0.3±0.01	0.2±0.01	

Table 2(Cont.): Metal concentration in the water of the studied wells during summer and winter season (means ± SD, n = 3).

Co [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	FW: - TW: 0.05
	Winter	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	0.020±0.001	
Cu [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	FW: 1 TW: 2
	Winter	0.01±0.0004	0.01±0.0007	0.02±0.001	0.02±0.001	0.03±0.001	0.03±0.002	0.03±0.002	0.04±0.002	0.02±0.009	
Fe [mg/L]	Summer	B.D	0.14±0.007	0.87±0.043	0.24±0.012	1.01±0.059	1.08±0.09	0.13±0.006	0.14±0.007	0.16±0.008	FW: 1 TW: 2
	Winter	0.02±0.0010	0.02±0.0009	0.03±0.001	0.03±0.002	0.03±0.002	0.05±0.002	0.04±0.002	0.07±0.004	0.04±0.002	
Mn [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	FW: 0.1 TW: 0.4
	Winter	B.D	B.D	0.006±0.0003	B.D	B.D	0.008±0.0004	0.007±0.0003	0.008±0.0004	0.015±0.007	
Ni [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	FW: 0.07 TW: 0.2
	Winter	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	
Pb [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	0.01±0.0006	FW: 0.01 TW: 0.2
	Winter	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	0.04±0.002	
Zn	Summer	B.D	B.D	B.D	B.D	B.D	B.D	0.12±0.006	B.D	B.D	FW: 4 TW: 5
	Winter	B.D	B.D	B.D	B.D	0.05±0.003	0.09±0.004	0.09±0.005	B.D	B.D	

*FW: Fresh water, **TW: Treated wastewater

B.D: Below detection limit, which was 0.002 mg/L for Cd, 0.005 mg/L for Cr, 0.01 mg/L for Co, 0.006 mg/L for Cu, 0.01 mg/L for Fe, 0.006 mg/L for Mn, 0.02 mg/L for Ni, 0.03 mg/L for Pb, and 0.002 mg/L for Zn.

*FW: Fresh water, **TW: Treated wastewater

Table 3: Anions and cations concentration in the water of the studied wells during summer and winter seasons (means ± SD, n = 3).

Parameter	Season	Sample name									JDWS standard
		CD1150	CD1157	CD3413	CD3454	CD3462	CD3414	CD3463	CD1160	Untreated wastewater	
F [mg/L]	Summer	0.01±0.001	0.26±0.01	0.22±0.01	0.18±0.01	B.D	B.D	0.52±0.03	0.64±0.03	B.D	FW: 2 TW: 2
	Winter	B.D	0.2±0.01	0.3±0.01	0.2±0.01	0.2±0.01	B.D	0.5±0.02	0.6±0.03	B.D	
CL [mg/L]	Summer	134±7	195±10	127±6	151±8	76±4	96±5	189±9	188±9	97±49	FW: 500 TW: 500
	Winter	124±6	183±9	148±7	140±7	195±10	94±5	177±9	200±10	393±20	
Br [mg/L]	Summer	3±0.1	3±0.1	3±0.1	3±0.1	2±0.1	2±0.1	3±0.1	3±0.1	B.D	FW: - TW: -
	Winter	1.1±0.06	1.2±0.06	1.2±0.06	0.9±0.04	0.9±0.04	0.8±0.04	1.2±0.06	0.9±0.05	7±0.4	
NO₃ [mg/L]	Summer	B.D	B.D	0.2±0.01	B.D	B.D	0.1±0.01	B.D	0.5±0.02	52±3	FW: 50 TW: 20
	Winter	B.D	B.D	0.2±0.01	B.D	0.2±0.01	B.D	0.1±0.01	0.6±0.03	179±9	
SO₄ [mg/L]	Summer	119±56	88±4	117±6	103±5	41±2	58±3	79±4	256±13	299±15	FW: 500 TW: 500
	Winter	108±5	80±4	126±6	99±5	65±3	65±3	75±4	309±16	120±6	
PO₄ [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	FW: - TW: 5
	Winter	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	32±2	
Li [mg/L]	Summer	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	FW: - TW: 2.5
	Winter	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	B.D	

Table 3(Cont.): Anions and cations concentration in the water of the studied wells during summer and winter seasons (means ± SD, n = 3).

Na [mg/L]	Summer	81±4	104±5	89±5	85±4	73±4	75±4	97±5	123±6	599±30	FW: 200 TW: -
	Winter	84±4	107±5	101±5	88±4	105±5	69±3	104±5	131±7	355±18	
NH₄ [mg/L]	Summer	0.08±0.04	0.04±0.02	0.07±0.04	B.D	0.15±0.07	0.09±0.04	0.08±0.04	0.06±0.03	14±0.7	FW: 0.2 TW: 4
	Winter	B.D	B.D	0.1±0.05	B.D	B.D	B.D	B.D	B.D	B.D	
K [mg/L]	Summer	2±0.1	2±0.1	3±0.1	2±0.1	6±0.3	5±0.3	3±0.2	6±0.3	64±3	FW: 10 TW: -
	Winter	2±0.1	2±0.1	3±0.2	2±0.1	2±0.1	2±0.1	B.D	B.D	57±3	
Ca [mg/L]	Summer	112±6	92±5	87±4	104±5	47±2	49±2	80±4	113±6	67±3	FW: 200 TW: -
	Winter	99±5	56±3	91±5	90±5	68±4	70±4	81±4	104±5	92±5	
Mg [mg/L]	Summer	45±2	50±3	42±2	47±2	17±1	19±1	44±2	67±3	32±2	FW: 150 TW: -
	Winter	49±3	53±3	52±3	50±3	46±2	43±2	48±2	75±4	64±3	

*FW: Fresh water, **TW: Treated wastewater

B.D: Below detection limit, which was 0.001 mg/L for the PO₄, 0.002 mg/L for NH₄, 0.002 mg/L for Li, 0.005 mg/L for Br, 0.001 mg/L for F, and 0.002 mg/L for NO₃.

Table 4: Metal concentration and physical parameters of leachate-saturated soil (means ± SD, n = 3).

Parameter	Sample ID	
	Soil Leachate	Blank soil from Al-Lajjoun (Jiries et al., 2009)
pH [unit]	7.7±0.4	-
EC [µs/cm]	2080±104	-
Cd [mg/L]	9±0.4	0.576
Cr [mg/L]	54±3	0.26
Co [mg/L]	12±1	-

Table 4(Cont.): Metal concentration and physical parameters of leachate-saturated soil (means ± SD, n = 3).

Cu [mg/L]	24±1	0.185
Fe [mg/L]	28595±1429	9900
Mn [mg/L]	357±18	6.31
Ni [mg/L]	35±2	0.59
Pb [mg/L]	27±1	0.855
Zn [mg/L]	21±1	0.405

Another method is to use the Sodium Adsorption Ratio (SAR) Vs to investigate how liquid wastewater landfills affect groundwater aquifers. The electrical conductivity diagram for untreated wastewater and well water (Fig. 4) demonstrates the stark differences between the two. It demonstrated that there was no potential mixing between groundwater and untreated wastewater. It is consistent with other hydrochemical indicators that show the research area's groundwater is unaffected by untreated wastewater landfills.

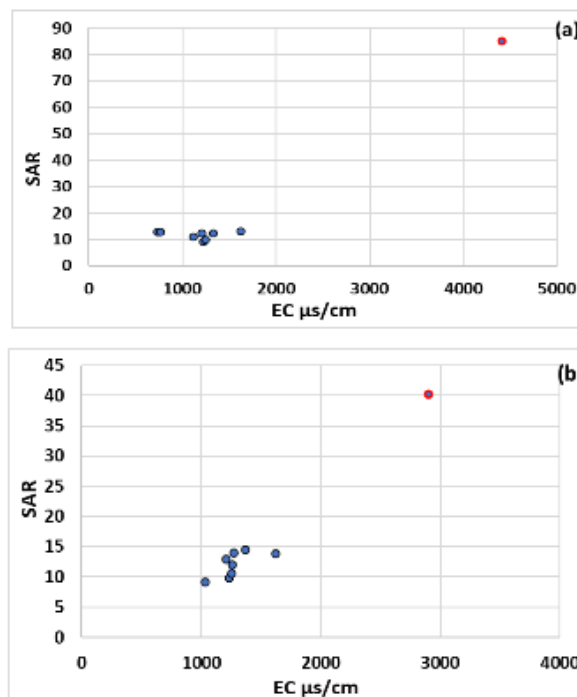


Figure 4: SAR Vs. Electrical conductivity diagram for well water and untreated wastewater in (a) summer and (b) winter.

5. DISCUSSION

Essential data regarding the water quality in the study area can be obtained by analyzing the physicochemical and biological properties of the untreated wastewater, landfill leachate, and groundwater wells under examination. With the exception of chromium (Cr), which consistently exceeded permissible limits, the groundwater quality was largely in compliance with the Jordanian Drinking Water Standard (JDWS) 286/2008 (Table 4). According to Tables (1, 2, and 3), the untreated wastewater and landfill leachate are significantly higher than the Jordanian Reclaimed Wastewater Standards (No. 893/2021), suggesting potential risks to the environment and human health.

5.1 Groundwater hydrochemistry and seasonal stability

In both summer and winter, the groundwater samples examined in this study showed moderate electrical conductivity, near-neutral to slightly alkaline pH values, and comparatively high dissolved oxygen contents. These features are in line with groundwater moving through carbonate aquifers in mostly oxic environments, where pH and ionic composition are controlled by bicarbonate buffering and calcite dissolution (Powell, 1988; Masri, 1996; Laluraj and Gopinath, 2006). Similar hydrochemical stability has been demonstrated for carbonate aquifers in semi-arid environments, where short-term climatic effects are mitigated by lengthy residence lengths and little recharge (Tumolo et al., 2020).

The lack of statistically significant seasonal changes ($p > 0.05$) for the majority of physicochemical parameters indicates that the studied area's groundwater quality is only slightly impacted by short-term climatic variability and comparatively low rainfall. According to reports for the Amman-Wadi Sir (A7/B2) aquifer system, this stability is probably due to the thick carbonate aquifer's buffering ability and the comparatively lengthy groundwater residence periods (Margane et al., 2002; Al-Ajarmeh, 2020). Major ion concentrations and total dissolved solids maintained within JDWS limits for drinking water, suggesting that anthropogenic inputs and mineral dissolution processes have not yet caused widespread salinization or geochemical degradation of groundwater quality, as is frequently seen in more extensively exploited semi-arid aquifers (Bibi et al., 2016; Salamah et al., 2023).

5.2 Heavy metal contamination and chromium exceedance

The only element among the examined trace metals that continuously surpassed drinking water limits in every groundwater sample was chromium. Instead of episodic or seasonal pollution, the persistence of high chromium contents across seasons and wells indicates toward a continuous lithogenic source. Groundwater systems affected by industrial products, landfill-related inputs, and infrastructure corrosion have all shown similar patterns of persistent chromium enrichment (Botsou et al., 2019; Ni et al., 2024). Leaching from industrial products, corrosion and release from pipe-scale deposits in the water distribution system, or localized geogenic contributions increased by water-rock interactions in carbonate formations are some possible sources (Kim et al., 2021; Huang et al., 2024a).

Because of its toxicity, mobility in oxic environments, and established dangers to human health, chromium contamination is a serious concern regardless of the source (El-Hasan et al. 2011; Xu et al., 2018; Ni et al., 2024). Groundwater levels of other heavy metals, such as Cd, Ni, Cu, Pb, and Zn, were typically below detection limits or below allowable limits, suggesting little metal mobilization under the current hydrochemical conditions. However, as documented in comparable semi-arid urban environments, infrequent detections of Fe, Mn, and Pb, especially in wastewater samples, may be connected to corrosion processes, redox-driven mobilization, and anthropogenic inputs (Botsou et al., 2019; Abdoli et al., 2024).

5.3 Untreated wastewater and nutrient loading

Untreated wastewater samples showed higher levels of nitrate, phosphate, ammonium, chemical oxygen demand (COD), and biochemical oxygen demand (BOD₅) than groundwater, indicating significant organic and nutrient stresses and inadequate treatment effectiveness. Remaining biodegradable organic matter and possible oxygen depletion problems during environmental discharge are indicated by elevated BOD₅ and COD levels (Al-Sulaiman and Khudair, 2018; Kim et al., 2021). Wintertime elevated nitrate concentrations also suggest low denitrification efficiency and possible contributions from residential sewage inputs and agricultural runoff (Bibi et al., 2016; Abdoli et al., 2024).

Such wastewater poses a serious risk of metal and nutrient migration into surface and subsurface water bodies if it is not sufficiently restricted, particularly along structurally regulated pathways typical of fractured carbonate terrains (Powell, 1988; Xu et al., 2018). It has been

demonstrated that long-term discharge of nutrient-rich wastewater increases nitrate persistence in groundwater, especially in semi-arid aquifers with low natural attenuation capacity (Tumolo et al., 2020).

5.4 Environmental effect of landfill leachate-affected soils

Extreme heavy metal enrichment in contrast to background soil concentrations was found in the leachate-saturated soil samples collected from the solid waste landfill. Significant anthropogenic impact resulting from landfill leachate infiltration is indicated by particularly high levels of Fe, Cr, Cd, Pb, Ni, Zn, and Mn; this is consistent with findings from landfill-impacted soils in semi-arid regions globally (Jiries et al., 2009; Xu et al., 2018). Metal mobility and solubility are improved by neutral pH and high electrical conductivity, which raises the possibility of movement downward toward the water table (Botsou et al., 2019; Huang et al., 2024b).

The level of metal enrichment, particularly for cadmium and chromium, makes the landfill a long-term source of contamination that could endanger groundwater quality if leachate formation and migration are not controlled. The area's karstification, fractured bedrock, and structural properties may make it more convenient for pollutants to move from the vadose zone into the aquifer system (Powell, 1988; Jiries et al., 2025).

5.5 Implications for groundwater sustainability

The high metal concentrations detected in soils affected by solid waste landfill leachate and the ongoing chromium poisoning present serious long-term risks to aquifer integrity, even if the current groundwater quality generally exceeds national drinking water regulations. Similar research has shown that groundwater degradation is often irreversible in similar hydrogeological situations when intervention is delayed (Tumolo et al., 2020; Huang et al., 2024a). Continued leachate migration and untreated wastewater discharge could gradually decline groundwater quality in the absence of effective management actions, requiring higher remediation costs.

The study these results highlight the need for integrated groundwater protection strategies, such as enhanced wastewater treatment efficiency, engineered landfill liners and leachate collection systems, regular hydrochemical monitoring, and the integration of hydrogeological and geophysical investigations to discover preferred contaminant pathways (Xu et al., 2018; Abdoli et al., 2024).

5.6 Implications for Groundwater Management and Conservation

Groundwater resources are important national resources because renewable surface water is scarce in semi-arid regions like central Jordan. Future sustainability and regional water security are essential to the conservation of the Amman-Wadi Sir (A7/B2) aquifer since it is an important source of domestic and agricultural resources.

Given that existing hydrochemical data show little seasonal variability and general groundwater stability, the consistent excess of chromium in all examined wells is a significant warning signal. Even slight but persistent trace metal concentration can accumulate over time, especially in aquifers with prolonged residence times and insufficient recharge rates. As a result, preventive management techniques are extremely important when compared to reactive ones.

From a sustainability perspective, the following activities are recommended:

- Installation of an observation well as part of a specialized groundwater monitoring network surrounding landfills and wastewater disposal sites.
- Regular hydrochemical monitoring to identify emerging patterns with intervals of no more than six months.
- To reduce vertical permeability, engineered landfill liners and leachate collection systems could be installed or reinforced.
- Use of advanced treatment or leachate recirculation before discharge.
- Identify preferred contamination routes in fractured carbonate formations, hydrogeophysical investigations (such as electrical resistivity) should be integrated every two to three years.
- Using risk-based management frameworks that connect regulatory response levels to hydrochemical indicators.

Preventing permanent groundwater degradation is more cost-effective than future remediation due to Jordan's high water scarcity index. Thus, to ensure aquifer resilience in the face of increasing anthropological and

environmental challenges, active conservation planning is required.

6. CONCLUSIONS

In accordance with other parallel studies, the results of this study confirm that the regional groundwater aquifers are typically situated at sufficient depths to remain isolated from both solid and liquid landfill systems due to the semi-arid climate and low rainfall (Al-Ramadain et al., in press). The hydrochemical properties of groundwater, which indicate no signs of contamination, confirmed this finding. Significant differences in the physical, chemical, and biological characteristics of groundwater, untreated wastewater, and landfill leachate further suggest that there is currently very little hydraulic mixing or contact.

The findings clearly show that the soil quality at solid waste disposal sites has been significantly and persistently degraded by landfill leachate. In order to reduce persistent ecological and public health risks, this emphasizes the critical necessity for focused remedial actions, efficient leachate containment, and stringent environmental monitoring. It is highly advised to merge regular hydrochemical investigations with geoelectrical surveys at intervals of two to three years as an efficient monitoring strategy because the landfill sites lack monitoring wells.

Inadequate treatment performance is indicated by significant exceedances of COD, BOD₂, nitrate, phosphate, ammonium, and lead in the untreated wastewater landfill. This raises major questions about the wastewater's possible reuse for aquifer recharging or agriculture. Additionally, heavy metal concentrations in landfill leachate-saturated soils are several times greater than background levels, with abnormally high levels of iron, chromium, cobalt, nickel, and lead. Soils from the solid waste dump showed similar enrichment patterns, especially for Cr, Cd, Pb, and Ni, indicating that these soils could be secondary sources of groundwater pollution. High electrical conductivity, near-neutral pH, and active redox conditions increase metal mobility and make it easier for trace metals to be released, which over time poses a latent risk to groundwater quality.

AUTHORS CONTRIBUTION

Amjad, Tayel, and Sadam conceptualized the study and supervised the research. Sadam, Eid, and Jafar carried out field sampling, including groundwater, soil, and treated wastewater collection. Hydrochemical analyses were performed by Amjad and Tayel. Fayza conducted geospatial analyses, including coordinate processing and the preparation of maps for groundwater wells and landfill sites. All authors contributed to data interpretation and participated in the writing, critical revision, and final approval of the manuscript.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflicts of interest associated with this study.

FUNDING STATEMENT

This study was funded by the Deanship of Scientific Research at Mutah University (Grant No. 812/2023). The funders had no role in the study design, data collection and analysis, interpretation of results, decision to publish, or preparation of the manuscript.

REFERENCES

Abdoli, S., Asgari Lajayer, B., Dehghanian, Z., Bagheri, N., Vafaei, A. H., Chamani, M., and Price, G. W., 2024. A review of the efficiency of phosphorus removal and recovery from wastewater by physicochemical and biological processes: Challenges and opportunities. *Water*, 16(17), Pp. 2507.

Al-Ajarmeh, R., 2020. Evaluating the risk of cement kiln dust landfill on groundwater vulnerability to pollution. *International Journal of Engineering Research and Technology*, 13(10), Pp. 2686–2693. <https://doi.org/10.37624/IJERT/13.10.2020.2686-2693>.

Alao, J. O., 2023. Impacts of open dumpsite leachates on soil and groundwater quality. *Groundw Sustain Dev* 20: 100877.

Al-Athamin, E. A. A., Hemidat, S., Al-Hamaiedeh, H., Aljbour, S. H., El-Hasan, T., and Nassour, A., 2021. Sustainability assessment of municipal solid waste management in Jordan: A case study of Al-Karak governorate. *Sustainability*, 13(23), Pp. 13043. <https://doi.org/10.3390/su132313043>

Al-Hamaideh, H., Al-rfo'u, F., Al-Hamaideh, K., El-Hasan, T., Alakayleh, Z., 2023. Springs water quality assessment for drinking purposes: a case study of Busaira Jordan. *Iraqi Geological Journal*. 56(2), Pp. 48–56. DOI:10.46717/igj.56.2A.4ms-2023-7-13

Al-Harahsheh, A., Al-Tarawneh, A., Al-Ma'abreh, A., Ramadeen, S., El-Hasan, T., and Al-Alawi, M. M., 2023. Assessing of drinking water quality in Al-karak province in central Jordan; based on water saturation indices. *Heliyon*.9(1): e18862. DOI: 10.1016/j.heliyon.2023.e18862

Al-Malahmeh, M., 2006. Quality of treated wastewater produced from Al-Lajjoun wastewater treatment plant, Jordan, M.Sc. Thesis, Mutah University.

Al-Mubaidin, M., Al-Hamaiedeh, H., and El-Hasan, T., 2022. Impact of the Effluent Characteristics of Industrial and Domestic Wastewater Treatment Plants on the Irrigated Soil and Plants. *Jordan Journal of Earth & Environmental Sciences*, 13(3) : Pp. 223-231.

Al-Ramadain, S., Al-Tarawneh, A., Al-Tarazi, E., El-Hasan, T., Abu Rajab, J., AlShamaen, F. (In press). Electromagnetic Geophysical Investigation of Solid and Liquid Landfills and Their Potential Impact on Groundwater at Al-Lajjoun, Central Jordan.

Al-Sarayreh, H. K., and Alsarayreh, D. W., 2021. Assessment and suitability study of landfills in Jordan, Al-Karak using Geographic Information Systems (GIS). *International Journal of Geoinformatics*, 17(3), Pp. 61–80. <https://doi.org/10.52939/ijg.v17i3.1899>

Al-Sulaiman, A. M., and Khudair, B. H., 2018. Correlation between BOD5 and COD for Al-Diwaniyah wastewater treatment plants to obtain the biodegradability indices. *Pakistan Journal of Biotechnology*, 15(2), Pp. 423-427.

Baba, A.H., 2023. Effect of leachate on groundwater. *International Research Journal of Engineering and Technology (IRJET)*. 10(12):Pp. 611-615.

Bibi, S., Saifullah, Naeem, A., and Dahlawi, S., 2016. Environmental impacts of nitrogen use in agriculture, nitrate leaching and mitigation strategies. In *Soil science: Agricultural and environmental perspectives* Pp. 131-157. Cham: Springer International Publishing.

Botsou, F., Karageorgis, A. P., Paraskevopoulou, V., Dassenakis, M., and Scoullou, M., 2019. Critical processes of trace metals mobility in transitional waters: implications from the remote, Antinioti Lagoon, Corfu Island, Greece. *Journal of Marine Science and Engineering*, 7(9), Pp. 307.

El-Hasan, T., and Al-Tarawneh, A., 2020. Heavy-Metal Contamination and Distribution within the Urban Soil Cover in Mutah and Al-Mazar Municipal Area. *Jordan Journal for Earth and Environmental Sciences*, 11(3), Pp. 202-210.

El-Hasan, T., Szczerba, W., Buzanich, G., Radtke, M., Riesemeier, H., and Kersten, M., 2011. Cr (VI)/Cr (III) and As (V)/As (III) ratio assessments in Jordanian spent oil shale produced by aerobic combustion and anaerobic pyrolysis. *Environmental science & technology*, 45(22), Pp. 9799-9805.

Grzegorz, P., 2025. Assessment of the impact of a non-operational municipal landfill site on groundwater quality: a case study from southwestern Poland. *Environmental Monitoring and Assessment*, 197(8), 872. <https://doi.org/10.3390/app15158223>

Huang, Z., Liu, G., Yuan, Y., Xi, B., and Li, R., 2024b. Assessment of the impact of landfills on groundwater quality in Eastern China: a comprehensive analysis of inorganic solutes. *Environ Earth Sci* 83, 497 (2024). <https://doi.org/10.1007/s12665-024-11805-w>.

Huang, Z., Liu, G., Zhang, Y., Yuan, Y., Xi, B., and Tan, W., 2024a. Assessing the impacts and contamination potentials of landfill leachate on adjacent groundwater systems. *Science of The Total Environment*, 930, 172664.

Jiries, A., El-Hasan, T., Al-Hiwati, M., and Seiler, K. P., 2004. Evaluation of the Effluent Water Quality Produced from Phosphate Mines in Central Jordan. *Mine Water and the Environment*. 23 (3): 133-137. DOI:10.1007/s10230-004-0053-z

Jiries, A., El-Hasan, T., El-Naqa, A., Al-Nasir, F., Taani, R., Samara, M., and Al-Wahsha, S., 2009. Wastewater Resources Management in Rural Areas in Jordan. Unpublished Report, UNESCO, Amman. P43.

Jiries, A.G., Oroud, I.M. and El-Hasan, T.M., 2025. Estimating groundwater recharge in a semiarid Mediterranean climate using a daily water balance model, GIS tools and chloride mass balance model: The Karak Plateau, Jordan. *Hydrogeology Journal*. <https://doi.org/10.1007/s10040-025-02942-y>

- Jordan Meteorological Department. 2019. Annual report (Unpublished report).
- Kim, T., Hite, M., Rogacki, L., Sealock, A. W., Sprouse, G., Novak, P. J., and LaPara, T. M. 2021. Dissolved oxygen concentrations affect the function but not the relative abundance of nitrifying bacterial populations in full-scale municipal wastewater treatment bioreactors during cold weather. *Science of the Total Environment*, 781, Pp. 146719.
- Laluraj, C. M., and Gopinath, G., 2006. Assessment on seasonal variation of groundwater quality of phreatic aquifers—a river basin system. *Environmental Monitoring and Assessment*, 117(1), Pp. 45-57.
- Margana, A., Borgstedt, A., Subah, A., and Hajali, Z., 2009. Groundwater Resources Management. Delineation of Surface Water Protection Zones for the Wala Dam. Technical Report No. 12.
- Margane, A., Hobler, M., Almomani M., Subah A., 2002. Contributions to the groundwater resources of Northern and Central Jordan 583 Jordan, *Geol. Jb.*, C.68, p52, Hannover
- Masri, A., 1996. Geological map of Dhiban (Wadi Al-Mujib), sheet N. 3152-1. NRA, Unpublished report, Amman.
- Ministry of Water and Irrigation (MoWI). 2023. National Water Strategy (2023-3040); Amman, Jordan: Ministry of Water and Irrigation.
- Ministry of Water and Irrigation (MWI), 2005. and the German Federal Institute for Geosciences and Natural Resources (BGR) . regional reports.
- Ministry of Water and Irrigation, Jordan. 2024. National Water Conservation Plan [PDF]. Ministry of Water and Irrigation.
- Ni, R., Chu, X., Liu, R., Shan, J., Tian, Y., and Zhao, W., 2024. Chromium immobilization and release by pipe scales in drinking water distribution systems: The impact of anions. *Science of The Total Environment*, 906, 167600.
- Obeidat, M. M., Awawdeh, M., and Abu Al-Rub, F., 2013. Multivariate statistical analysis and environmental isotopes of Amman/Wadi Sir (B2/A7) groundwater, Yarmouk river Basin, Jordan. *Hydrological processes*, 27(17), Pp.2449-2461.
- Powell, J.H., 1988. The geology of Al-Karak. Map sheet No. 3152 III. Hashmite Kingdom of Jordan, N.R.A. Bulletin 8.
- Prell-Swaid, A., and Schwedt, G., 1994. A Screening Procedure for Heavy Metals in Soil Extracts by Alcohol Dehydrogenase and Urease Inhibition Eine Screening-Methode für Schwermetalle in Extrakten aus Bodenproben, basierend auf der Inhibierung der Enzyme Alkoholdehydrogenase und Urease. *Acta hydrochimica et hydrobiologica*, 22(2), Pp. 70-75.
- Przydatek, G., Ciuła, J., Barsan, N., Mirila, D., and Mosnegutu, E., 2025. Groundwater Quality Analysis: Assessing the Impact of a Closed Landfill, A Case Study on Physico-Chemical and Microplastic Contaminants. *Applied Sciences*, 15(15), 8223.
- Rice, E. W., and Bridgewater, L., 2012. Association. APH Standard Methods for the Examination of Water and Wastewater, 10.
- Salamah, E., El-Hasan, T. and Abu-Jamah, M., 2023. Dam Safety in Jordan: Factors Affecting Dam Safety, Responsibilities and Required Actions. *Engineering*. 15, Pp. 514-532. <https://doi.org/10.4236/eng.2023.159038>
- Tumolo, M., Ancona, V., De Paola, D., Losacco, D., Campanale, C., Massarelli, C., and Uricchio, V. F., 2020. Chromium pollution in European water, sources, health risk, and remediation strategies: An overview. *International journal of environmental research and public health*, 17(15), Pp.5438.
- Xu, Y., Xue, X., Dong, L., Nai, C., Liu, Y., and Huang, Q., 2018. Long-term dynamics of leachate production, leakage from hazardous waste landfill sites and the impact on groundwater quality and human health. *Waste Management*, 82, Pp. 156-166.

