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Using COP Model to Map the Vulnerability of Groundwater Wells Adjacent to Landfills

Almoayied Assayed [1,*], Samer Talozi [2], Rana Ardah [1], Nanci Alziq [1], Siham Bataineh [2] and Aisha Alhushki [1]

[1] Water, Environment and Climate Change Centre, Royal Scientific Society, Amman 11941, Jordan
[2] Faculty of Engineering, Jordan University for Science and Technology, Irbid 22110, Jordan
* Correspondence: almoayied.assayed@rss.jo; Tel.: +962-791524516

Abstract: Protecting the quality of the groundwater is of the utmost importance, particularly in countries such as Jordan, where the groundwater comprises a significant portion of the total water resources. A groundwater vulnerability assessment is one of the viable preventive measures that is normally used to preserve this strategic water resource. Groundwater vulnerability maps provide information on the groundwater basins that are vulnerable to contamination, particularly those coming from the landfills, and thus, they can be used for sustainable land use planning. The general goal of this study was to map the groundwater vulnerability to contamination and evaluate the impact of landfills on the groundwater quality at five landfill sites in Jordan, i.e., Akaider, Al-Husaineyat, Madaba, Dair Alla, and Azraq by using a COP hydrogeological model. The COP method is an European approach for aquifer vulnerability in the karst regions. This method uses the parameters: C—Concentration of flow; O—Overlying layers; P—Precipitation. Unlike the other methods, the COP model allows for us to assess the impact of the karst systems if they exist. For the study area, daily rain records from three weather stations surrounding each landfill were used. Along with the vulnerability maps, Peizometric maps for Akaider, Azraq, Dair Alla, Madaba and Al-Husaineyat were produced that assisted in our efforts to determine the wells located in the upstream and downstream of each targeted landfill. The water quality was tested two times in the upstream and downstream wells of each targeted landfill to explore the potential impacts of the landfills on the groundwater wells. The developed vulnerability maps show that most of the lands surrounding the landfills' areas, within a diameter of 15 km, are located in low to very low vulnerability areas, except for the Al-Husaineyat landfill in Mafraq where a significant part of it lies in a moderate vulnerability area across a fault section. Additionally, the results of the water analysis from the surrounding wells indicated that there was no clear evidence of the contamination of the groundwater resulting from surrounding landfills, which was in agreement with the produced vulnerability maps.

Keywords: COP model; groundwater vulnerability; peizometric map; landfills; water quality

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1. Introduction

Groundwater constitutes of nearly 55% of the total water resources in Jordan, representing about 601MCM, of which, 448MCM is renewable, whereas the rest is non-renewable [1]. Population growth and climate change have exacerbated the water scarcity in Jordan, lowering the water share per capita to less than 100 m^3/year [2]. This extreme water shortage in Jordan underlines the importance of preserving this scarce resource from contamination.

As a result of modernization and population growth, chemicals and wastes are released into the environment by anthropogenic activities, which may end up in the groundwater. Groundwater resources are not polluted easily, but once this occurs, it is not only expensive, but it is also difficult to restore the water quality [3]. Therefore, putting in place preventive procedures is essential to maintain the groundwater's cleanliness, particularly in water-scarce countries such as Jordan.

Landfills have been the primary disposal approach in Jordan. One of the activities that may have adverse effects on the groundwater is municipal solid waste (MSW) dumping/landfilling for all types of waste, i.e., municipal solid waste, industrial sewage and hazardous waste [4]. Nevertheless, landfilling is the most common practice, with it being used to dispose municipal solid waste, mainly due to its affordability [5]. In general, groundwater near landfills are under threat to become contaminated as a result of the leachate permeate that is drained out of the landfills [6,7]. The rate and characteristics of leachate produced depend primarily on the solid waste composition, particle size, degree of compaction, hydrology of the site, landfill age, moisture and temperature conditions and available oxygen [8]. The research has shown that leachate contains various toxic chemicals with a high concentration of nitrate and phosphate that can pass through and pollute both the ground- and surface water [9]. Through leachate migration, environmental problems may occur over time due to the subsequent contamination of the groundwater resources, jeopardizing their usability for many purposes.

One of the preventive measures to protect the groundwater is to assess its vulnerability to contamination before commencing any aboveground anthrophonic activities, i.e., industrial, domestic and agriculture ones [10]. Groundwater vulnerability maps provide information on the groundwater basins that are vulnerable to contamination, particularly those coming from the landfills, and thus, they can be used for sustainable land use planning [11].

The aquifer vulnerability can be categorized as intrinsic vulnerability and specific vulnerability; the former describes the degree of vulnerability considering the natural protection through hydro-geological formations, while the latter describes contaminant characteristics, along with the aquifer formation attributes [12,13]. Multiple approaches have been developed to evaluate this vulnerability. They include (1) process-based methods, (2) statistical methods and (3) overlay and index methods. The process-based methods utilize simulation models to approximate the contaminant movement, but they are inhibited by data limitations and computational difficulties. The statistical methods employ statistics to verify the associations between the spatial variables and the actual occurrence of contaminants in the groundwater [14]. Their limitations include insufficient water quality observations, data accuracy and careful selection of the spatial variables. The overlay and index methods such as DRASTIC, GOD, AVI and SINTACS combine the factors controlling the movement of the pollutants from the ground surface into the saturated zone, resulting in vulnerability indices at different locations [15]. The main advantage of the overlay and index methods is that some of the factors such as rainfall and the depth to the groundwater can be available over large areas, which makes them suitable for regional-scale assessments [16]. However, their major weakness is the subjectivity in assigning numerical values to the descriptive entities and relative weights for the different attributes [17]. Additionally, the overlay and index methods are able to distinguish the degrees of vulnerability at the regional scales where different lithologies exist [18], but they are much less effective at assessing the vulnerability in the carbonate aquifers as they do not take into account the peculiarities of karst. This particular shortcoming has been behind the development of a new method for groundwater vulnerability called “COP”, which considers the special hydrogeological properties of karst. The method can be applied in different climatic conditions and different types of carbonate aquifers (diffuse and conduit flow systems) using different levels of available data. The COP method is an European approach for conducting aquifer vulnerability studies in karst regions. The method was introduced by the Group of Hydrogeology in the University of Malaga/Spain in the framework of the COST 620 program as a standard method for groundwater vulnerability mapping in the karst aquifers [19].

The COP method is the acronym of three main factors used to assess the vulnerability of an aquifer: concentration, overlaying layers and precipitation. This method assesses on one hand, the capacity of the overlying layers, namely the soil and unsaturated zone to attenuate the contaminant. On the other hand, since the karst aquifers are characterized by a diffused and a concentrated infiltration, the C factor defines the infiltration processes, while the P factor underlines the role of the climatic conditions, namely, precipitation in the definition of vulnerability [19].

Several vulnerability studies have been conducted in Jordan over the last couple of years. However, none of these studies [20–24] used the COP model to look into the potential pollution cycle between the landfills and the nearby groundwater wells. Al-raggad et al. (2012) found that the groundwater is moderately polluted and not drinkable in more than 50% of the samples collected in their study in Jordan Valley. They concluded, through vulnerability mapping, that the agriculture return flow (drainage water) was the primary source for groundwater pollution [21]. Kuisi et al. (2014) studied the vulnerability of the Amman-Zarqa basin, and they found that the contaminants from point sources were the main cause for groundwater contamination in the highly vulnerable karstic limestone aquifer of Amman Wadi Es Sir (Aquifer-B2/A7) [23]. Ibrahim M. et al. (2015) concluded in their groundwater vulnerability mapping in Al Mafraq that urgent pollution prevention measures should be taken within the whole basin after finding that 60% of the basin area was moderately vulnerable using a modified DRASTIC method [24]. Leachate accumulation in landfills was investigated by Al-Tarazi et al. (2008) [25] who found that the contamination of the aquifer of Amman-Zarqa with coliform bacteria is attributed to leachate from the *Rusaifeh* municipal landfill. Another study targeted the groundwater in the north-east of the Jordan Yarmouk Basin, and the authors found that the *Akaider* municipal landfill was behind the elevated levels of heavy metals in all of the water samples [26]. Ministry of Water and Irrigation (MWI) and Federal Institute for Geosciences and Natural Resources (BGR) developed a vulnerability map for the entire Jordan using COP model, yet they did not include landfills or any source of pollution in their study [27].

The aim of this paper is to map the groundwater vulnerability to contamination at five landfill sites in Jordan, i.e., *Akaider*, *Al-Husaineyat*, *Madaba*, *Dair Alla and Azraq* by using a COP model. This is the first paper that addresses the groundwater vulnerability using the COP model in Jordan, and it is the first of its kind to provide a thorough water quality analysis for the groundwater wells that are adjacent to landfills based on peizometric mapping. This paper demonstrates the importance of vulnerability maps for scientific-based decisions.

2. Materials and Methods

2.1. Study Area and Data Collection

The vulnerability assessment was conducted for the groundwater wells that are based close to five major landfills in Jordan: *Akaider*, *Al-Husaineyat*, *Madaba*, *Dair Alla and Azraq*. Table 1 shows several hydrogeological and geographical features of the study area. The coordinates of the targeted landfills are shown in Table 2. All of the updated data that are needed to develop the vulnerability maps were obtained from all of the stakeholders including the Ministry of Municipal Affairs (MoMA), the Ministry of Environment (MoEnv), the Ministry of Health (MoH), the Ministry of Water and Irrigation (MWI) and the Ministry of Energy and Mineral Resources (MEMR), as shown in Table 3.

Table 1. The targeted landfills.

Landfill	Governorate	Establishment Year	Area (Dunm) 1 Dunm = 1000 m^2	Type of Solid Waste Received by the Landfill	Annual Precipitation (mm/yr)	Area Geology	Flash Floods	Environmental Problems
Madaba	Madaba	1992, expanded several times, the last was in 2014.	140	Municipal waste, dead animals (carcasses) and some spoiled food. Diseased carcasses as well as spoiled food are buried in separate halls than those that are used for municipal waste	250–300	Limestone	No flash floods	Fires during summer with no bad smells. No leachate or water pollution problems
Akaider	Irbid	1982	800–1000	Municipal waste, olive mills' waste, and liquid sludge. It is used to receive different types of hazardous and liquid waste till the mid of 2015	Less than 200	Limestone (many layers with different hardness). Upper layers are mix of clay and sand	No flash floods	Bad smells and flies
Al-Husaineyat	Mafraq	1987	380	Municipal waste and dead animals (carcasses)	160–300	Basalt rocks and high-salinity sand.	Occasional flash floods occur	Bad smells, flies and fires due to high temperature.
Dair Alla	Balqa'a	1998	350	Municipal waste	Around 300	Dispersed soil	No flash floods	Bad smells and fires due to high temperature.
Azraq	Zarqa	Officially launched in 2022 but it was used informally.	200	Municipal waste	Less than 200	NA	Flash floods exist	A new landfill and it is being built to be a sanitary landfill.

Table 2. The coordinates of the targeted landfills.

Landfill	Decimal Degrees—Lat/Long	Degrees, Decimal Minutes—Lat/Long	Degrees, Minutes, Seconds—Lat/Long	UTM—Lat/Long	MGRS	Altitude (masl)
Dair Alla	32.120642°, 35.562850°	32°07.238′ N, 35°33.771′ E	32°07′14.31″ N, 35°33′46.26″ E	36S 741,792.68 mE 3,556,684.52 mN	36SYA4179356685	−280
Akaider	32.514244°, 36.109111°	32°30.855′ N, 36°06.547′ E	32°30′51.28″ N, 36°06′32.80″ E	37S 228,426.10 mE 3,601,122.63 mN	37SBS2842601123	670
Al-Husaineyat	32.256217°, 36.349556°	32°15.373′ N, 36°20.973′ E	32°15′22.38″ N, 36°20′58.40″ E	37S 250,311.47 mE 3,571,919.58 mN	37SBR5031171920	660
Madaba	31.688194°, 35.815253°	31°41.292′ N, 35°48.915′ E	31°41′17.50″ N, 35°48′54.91″ E	36R 766,860.10 mE 3,509,320.88 mN	36RYA6686009321	750
Azraq	31.940921°, 36.982643°	31°56.455′ N, 36°58.959′ E	31°56′27.32″ N, 36°58′57.51″ E	37R 309,310.29 mE 3,535,663.74 mN	37RCR0931035664	507

Table 3. The type and source of the collected data to build the vulnerability maps.

Data	Type of Data	Data Source
Weather Stations	Point feature	MWI
Precipitation (mm/day) 2006–2016	Excel Sheets	MWI
Topography/Slope	DEM Raster (30 m × 30 m)	ASTER tiles that are already mosaicked for all Jordan
Land use/Land cover	Satellites image from ArcGIS online	Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Soil Texture	Access database	RSS
Soil Thickness	Polygon feature	RSS
Lithology layer type	Polygon feature	MWI
Lithology layer elevation	Raster	MWI
Karstic feature	Absence	MWI & BGR
Groundwater monitoring wells	Point feature	MWI

2.2. Data Verification

The collected data were verified preliminary through field surveys and site visits to all of the landfills and their surrounding watersheds. These visits and surveys aimed at observing, on the ground, how the landfills are being managed, and we collected field data such as leachate stream, nearest community, close groundwater wells and other sources of pollution. A technical committee representing all of the stakeholders that operate and manage the targeted landfills was formed to review the collected data. Moreover, all of the required updated data were gathered from all of the stakeholders, and several meetings were arranged with the Federal Institute for Geosciences and Natural Resources (BGR) and the French Development Agency (AFD) to coordinate the efforts to find out the synergies between this study and other current initiatives in Jordan that tackle solid waste and groundwater. This implies the importance of being inclusive and involving all of the stakeholders when one is developing vulnerability maps.

2.3. Building the Vulnerability Maps Using COP Model

1. Calculating the C Factor: The C factor allows us to assess the impact of the karst systems if they exist. Karst systems are characterized by a duality of infiltration, where the infiltration can occur diffusively on the entire catchment, and/or it is concentrated in sinkholes or dolines (fast flow pathways). In the COP method, the catchment was divided into two main zones. The first zone (Scenario 1) includes the recharge area of the karst features, namely, dolines or sinkholes. The second zone (Scenario 2) consists of the rest of the area, where no surface karst features were identified. In the area of this study, (Scenario 2) was used due to the absence of karst formations.
2. Calculating the O Factor: The O factor represents the overlying layers, namely, the soil cover (OS) overlying the unsaturated lithology (OL).
    - OS factor: The OS factor represents the texture and thickness of the soil. The thicker the soil cover is, then the higher the likelihood is of contaminant attenuation occurring. Furthermore, fine soil textures (i.e., clay) have a lower degree of hydraulic conductivity, and they are therefore characterized by longer transit times. Additionally, due to their sorption capacity for ionic species, they are more likely to attenuate some types of contaminants (ionic or charged species). The OS factor increases with an increasing thickness and finer soil texture, denoting a low groundwater vulnerability. For the study area, a soil database was utilized to identify the soil texture and depth at various sampling locations. These data were geo-processed using ArcGIS tools such as selection, joining and interpolation in order to produce the OS Factor layer. To obtain more details about the tools used and the process, one should refer to the main report.

- OL factor: The OL factor is representative of the unsaturated zone below the soil layer and above the groundwater table. To calculate it, the following are determined first: (1) type of lithology, (2) the confinement of the aquifer and (3) the thickness of the unsaturated zone. It is calculated according to the following equation (OL $= [ly \times m] \times cn$), where the product of *ly* and m is calculated separately, reclassified and multiplied by the degree of confinement. *ly* is the lithology type, *m* is the thickness of each layer and *cn* is the confining condition. For the study area, the soil database was utilized to determine the lithology and confinement of the aquifer. The thickness of the unsaturated zone was determined using the static water level data collected during the field surveys. The lower the value of the product of *ly* is and *m* the lower the protection value is, the higher the vulnerability is.
- O factor: finally, the O Factor is calculated by summing the OL and the OS factors.

3. Calculating the P Factor: The P Factor represents the climatic conditions in the catchment. It is the sum of two sub-factors (PQ and PI) defining the amount and intensity of precipitation, respectively, for the wet years. For the study area, daily rain records from 3 weather stations surrounding the landfill were used.
4. Calculating the COP Index: The multiplication of the three factors, namely, C, O and P, yields the COP factor/index which represents the degree of groundwater vulnerability to contamination. The final map is the reclassified according to the vulnerability classes, as shown in the table below (Table 4).

Table 4. COP vulnerability index.

[COP] Score	
COP Index = [C] × [O] × [P]	
XVI	
COP Index	**Vulnerability Classes**
(0–0.5]	Very high
(0.5–1]	High
(1–2]	Moderate
(2–4]	Low
(4–15]	Very low

2.4. Maps Verification

2.4.1. Identifying the Direction of Water Flow

The directions of the groundwater flow have been mapped through piezometric surveys to aid in determining where the wells are located at the upstream and downstream adjacent to each targeted landfill within 15 km diameter.

2.4.2. Water Quality Monitoring

In order to study the potential impacts of the landfills on the surrounding water wells, two rounds of water sampling from upstream and downstream of the wells took place during different seasons. Table 5 shows all of the details related to the monitored water wells, which is where water samples were collected.

Table 5. Groundwater wells at the upstream and downstream of each landfill.

Number of Well	Description	GARMIN GPS			Static Water Level (SWL)—Measured Manually by Using the Amescope Apparatus (Meters)	Upstream/Downstream of the Landfill	Distance from the Landfill (km)
		Longitude (E)	Latitude (N)	Altitude (H)			
Madaba							
CC1005	Private Well/ Production well	35.82505	31.68775	774	A grab sample was collected and analyzed on 22 March and 12 October 2017	Upstream	1
CC1024	Private Well/ Production well	35.79661	31.65909	716	220.915, where a grab sample was collected and analyzed on 22 March and 12 October 2017	Downstream	4
Akaider							
AD3025	Production Well	36.04656°	32.55990°	528	A grab sample was collected and analyzed on 10 April and 8 October 2017	Downstream	8
AD1121	Production Well	36.23585	32.45537	605	A grab sample was collected and analyzed on 10 April and 8 October 2017	Upstream	14
Al-Husaineyat							
AL3004	YWC's Well/ Production well	36.43270°	32.27504°	729	A grab sample was collected and analyzed on 12 April and 8 October 2017	Upstream	9
AL3328	Private Well/ Production well	36.22838°	32.25175°	659	A grab sample was collected and analyzed on 12 April and 8 October 2017	Downstream	12
Dair Alla							
AB4771	Production Well	35.59435°	32.12101°	−259	A grab sample was collected and analyzed on 10 May 2017	Downstream	4
AB3435	Production Well	35.62706°	32.17323°	−200	A grab sample was collected and analyzed on 10 May and 22 October 2017	Upstream	9
Azraq							
Azraq	Production well	36.92769°	31.87862°	516	A grab sample was collected and analyzed on 12 July 2017	Downstream	14

3. Results and Discussion

3.1. Developing the Vulnerability Maps Using COP Models

The final vulnerability maps were developed by using the three hydrogeological data maps and overlaying them to produce the final maps. As a result, five vulnerability maps for the targeted landfills (Akaider, Al-Husaineyat, Madaba, Dair Alla and Azraq) were developed using the COP method within a diameter of 15 km. Table 6 shows the source of data used for each landfill to develop the vulnerability map based on the COP factors.

The developed maps showed that most of the lands surrounding the landfills (Akaider, Madaba, Dair Alla and Azraq) areas, within a diameter of 15 km, have low to very low vulnerability to groundwater pollution (Figures 1–5). The vulnerability map for the Al-Husaineyat landfill in Mafraq showed that there is a significant part of it lies in a moderate vulnerability area across the fault section.

3.2. Developing the Peizometric Maps

There were two purposes to this activity, the first one was to understand the flow direction of the surrounding wells adjacent to the targeted landfills, and the second one was to measure the static water level for the monitoring wells surrounding the targeted landfills.

The principle of piezometric mapping lies in determining the direction of the groundwater flow by knowing the movement of the groundwater based on the land's topography as the water moves from the area of higher elevation to the area of lower elevation.

Differential GPS (Leica Viva GNSS-GS16) was used to take the coordinates and the altitude of each observation/monitoring well. The static water levels of the monitoring wells were measured manually by using the Amescope apparatus. However, some wells are equipped with digital telemetries that take up all of the space in the inch pipe, and thus, make the manual measurement of the static water level impossible to acquire. Based on the information collected during the site visits (Table 7), the Peizometric maps for Akaider, Azraq, Dair Alla, Madaba and Al-Husaineyat have been prepared (Figures 6–10). The directions of the groundwater flow assisted the project team to determine the wells located at upstream and downstream of each targeted landfill.

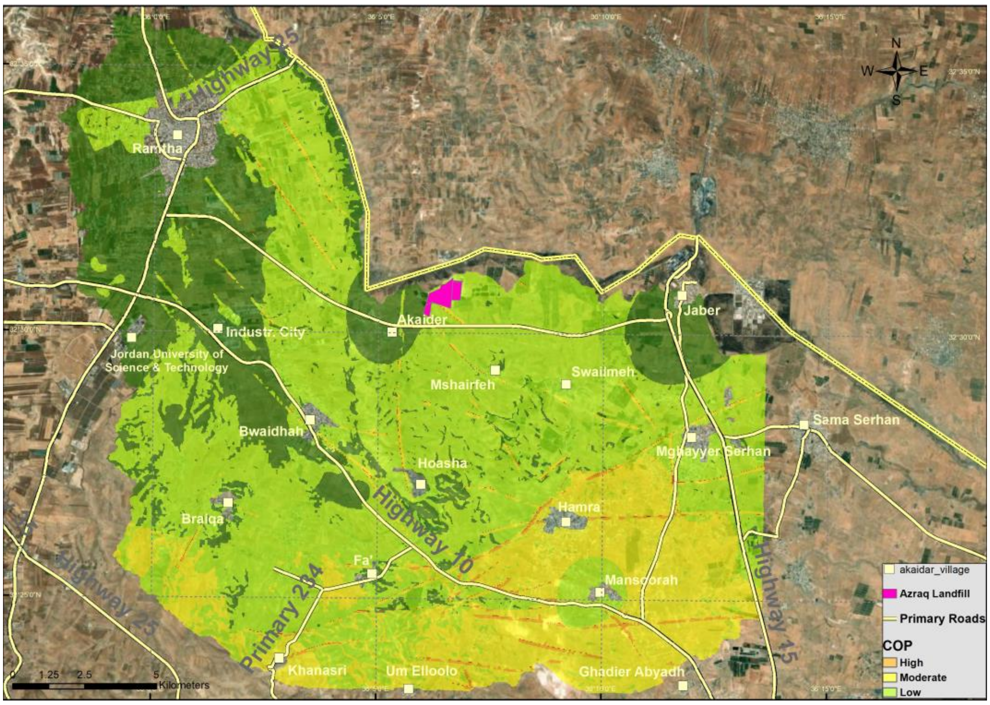

Figure 1. The COP INDEX value for Akaider landfill.

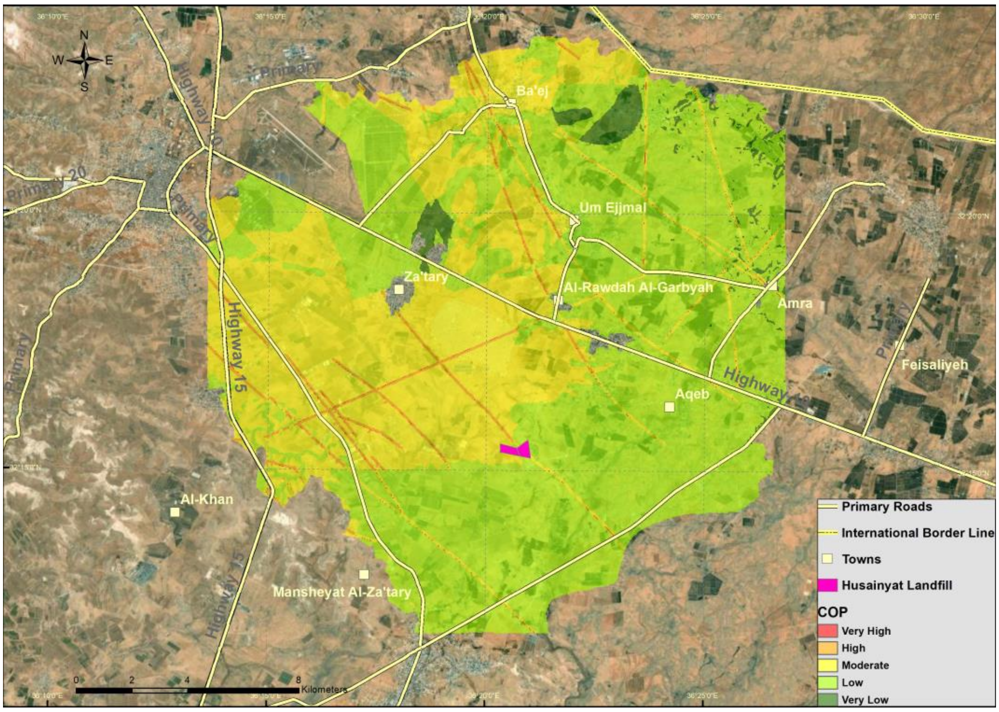

Figure 2. The COP INDEX value for Al-Husaineyat landfill.

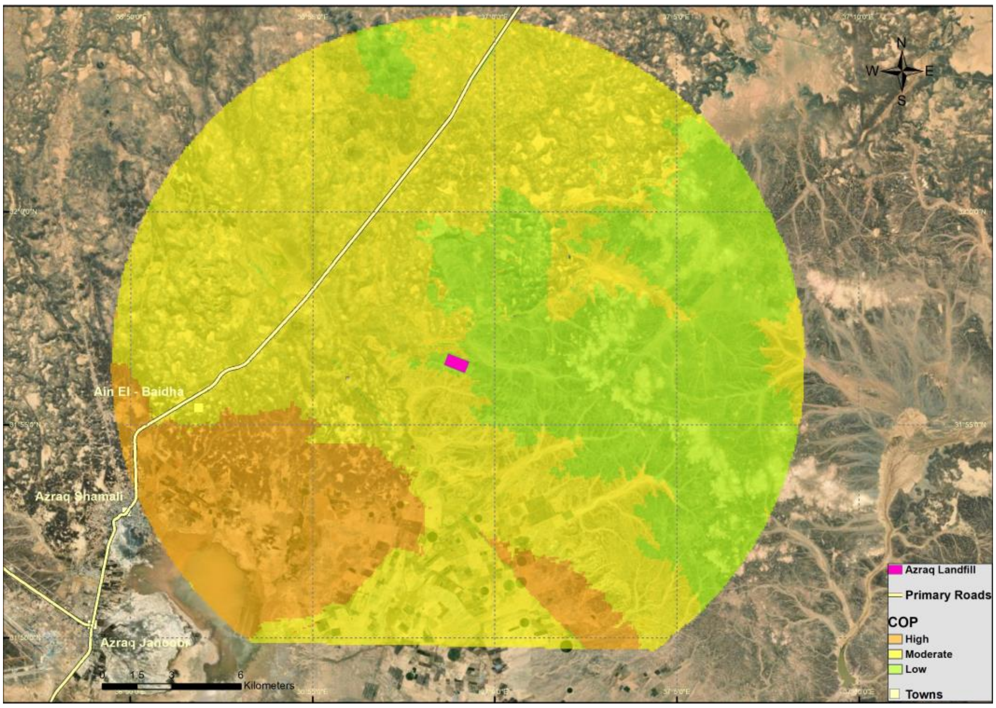

Figure 3. The COP INDEX value for Azraq landfill.

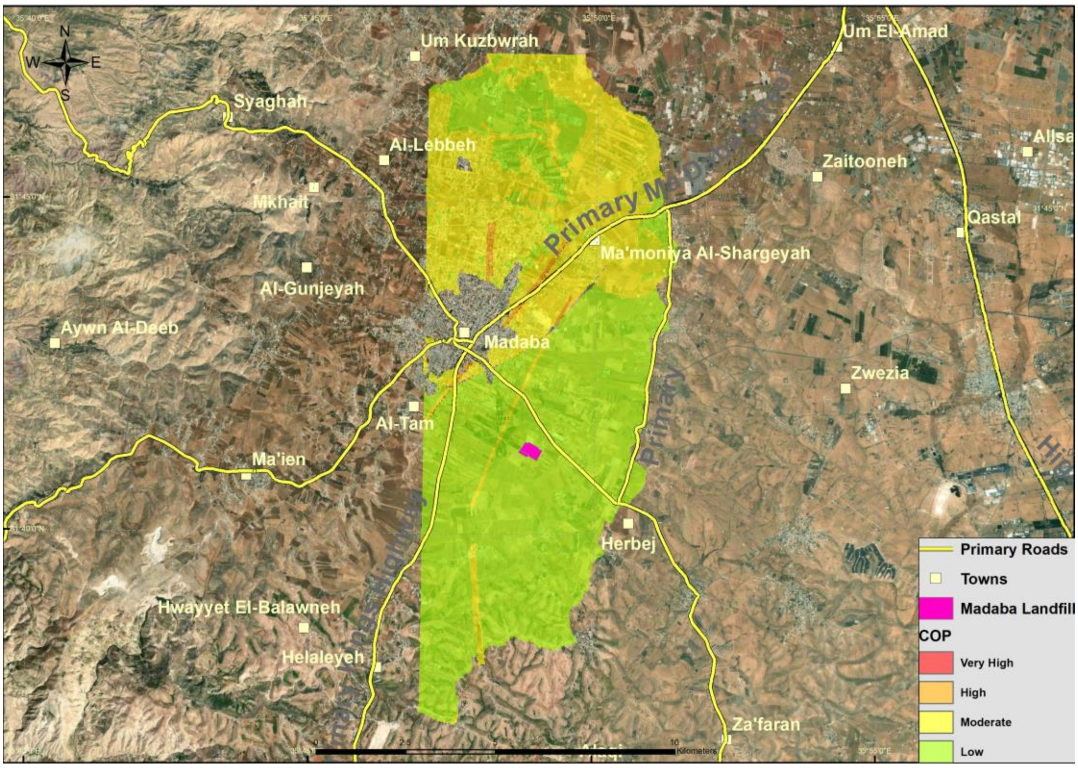

Figure 4. The COP INDEX value for Madaba landfill.

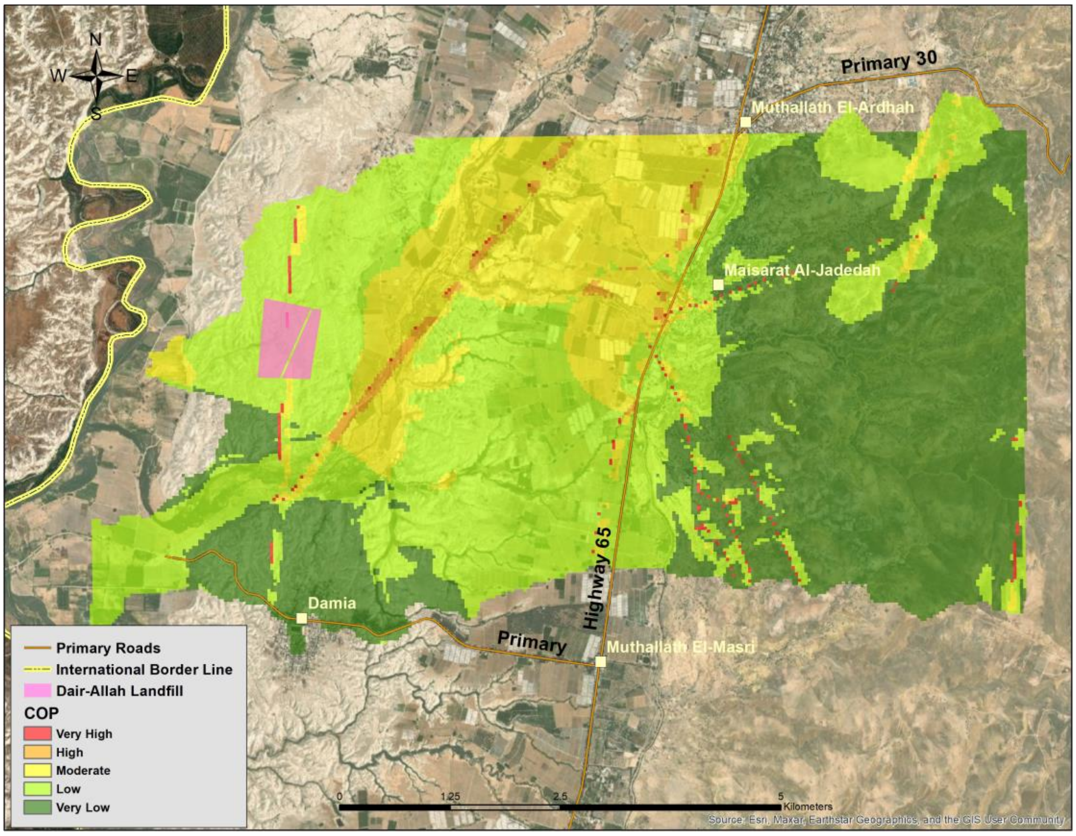

Figure 5. The COP INDEX value for Dair Alla landfill.

Table 6. The source of data used for developed the vulnerability maps using COP method.

Landfill Name	P FACTOR		C FACTOR				O FACTOR						
							OS				OL		
	P Score	Data Source	Scenario 2	Surface Feature	Slope and Vegetation	Data Source	Texture	Data Source	Soil Thickness SS	Data Source	Lithology and Fraction	Data Source	Confining Condition
Akaidar	N.A INTER-POLATION IDW	RSS EXCEL SHEET	SCENARIO 2	Non-karstic terrains/absence	Calculate NDVI index (July/2013) between bands 4 and 5 from LanSat8 and apply the rules in table (XI) in Slope and NDVI Rasters around the Akaidar Landfill	Slope: DEM 30 M Vegetation cover: LanSat 8 Satallites image	N.A INTER-POLATION IDW	RSS	RSS EXCEL SHEET	RSS SHAPE FILE	A7B2, B3, B45, Basalt	RSS RASTER	UNCONFINED
Al-Huseinyat	N.A INTER-POLATION IDW	RSS EXCEL SHEET	SCENARIO 2	Scarcely developed or dissolution features/fissured karst	Calculate NDVI index (July/2013) between bands 4 and 5 from LanSat8 and apply the rules in table (XI) in Slope and NDVI Rasters around the Huseinyat Landfill	Slope: DEM 30 M Vegetation cover: LanSat 8 Satallites image	N.A INTER-POLATION IDW	RSS	RSS EXCEL SHEET	RSS SHAPE FILE	A7B2, Basalt	RSS RASTER	UNCONFINED
Dair Alla	N.A INTER-POLATION IDW	RSS EXCEL SHEET	SCENARIO 2	Non-karstic terrains/absence	Calculate NDVI index (July/2013) between bands 4 and 5 from LanSat8 and apply the rules in table (XI) in Slope and NDVI Rasters around the DairAllah Landfill	Slope: DEM 30 M Vegetation cover: LanSat 8 Satallites image	N.A INTER-POLATION IDW	RSS	<0.5 M	NO DATA	A7B2	NO DATA	UNCONFINED
Madaba	N.A INTER-POLATION IDW	RSS EXCEL SHEET	SCENARIO 2	Scarcely developed or dissolution features/fissured karst	Calculate NDVI index (July/2013) between bands 4 and 5 from LanSat8 and apply the rules in table (XI) in Slope and NDVI Rasters around the Madaba Landfill	Slope: DEM 30 M Vegetation cover: LanSat 8 Satallites image	N.A INTER-POLATION IDW	RSS	RSS EXCEL SHEET	RSS SHAPE FILE	A7B2, B3	RSS RASTER	UNCONFINED
Azraq	P = 1	NO DATA	SCENARIO 2	Non-karstic terrains/absence	Calculate NDVI index (July/2013) between bands 4 and 5 from LanSat8 and apply the rules in table (XI) in Slope and NDVI Rasters around the Azraq Landfill	Slope: DEM 30 M Vegetation cover: LanSat 8 Satallites image	SANDY = 0	NO DATA	<0.5 M	NO DATA	B45, Basalt	RSS RASTER	UNCONFINED

To compare these maps with the other vulnerability maps, the authors of [26] used the DRASTIC index to study the environmental potential impacts of the Akaider landfill. It was found that Akaider is located within a moderate vulnerability zone. This means that the groundwater in the underlying groundwater basins is not completely safe, while in our COP vulnerability map, the Akaider landfill is found to be based in an area with low sensitivity to groundwater pollution. This can be explained by the different set of data used in both models along with the fact that the COP model has a different index compared to that of DRASTIC. Nevertheless, the study in [28] did not produce peizometric maps nor did it collect samples from the nearby wells to verify their results.

3.3. Water Quality Monitoring

The site visits to the area of the targeted landfills were conducted to collect the water samples from the production wells around the landfills in order to monitor the quality of groundwater from upstream and downstream of the aquifers. Physical, chemical, and microbiological analyses, an organic pollutant analysis and a PAACs analysis were performed. Two rounds of water sampling were conducted, covering two different periods, i.e., dry and wet, except for Azarq where only one round of sampling was conducted. The results of water analysis are shown in Tables 8 and 9 for the two rounds respectively.

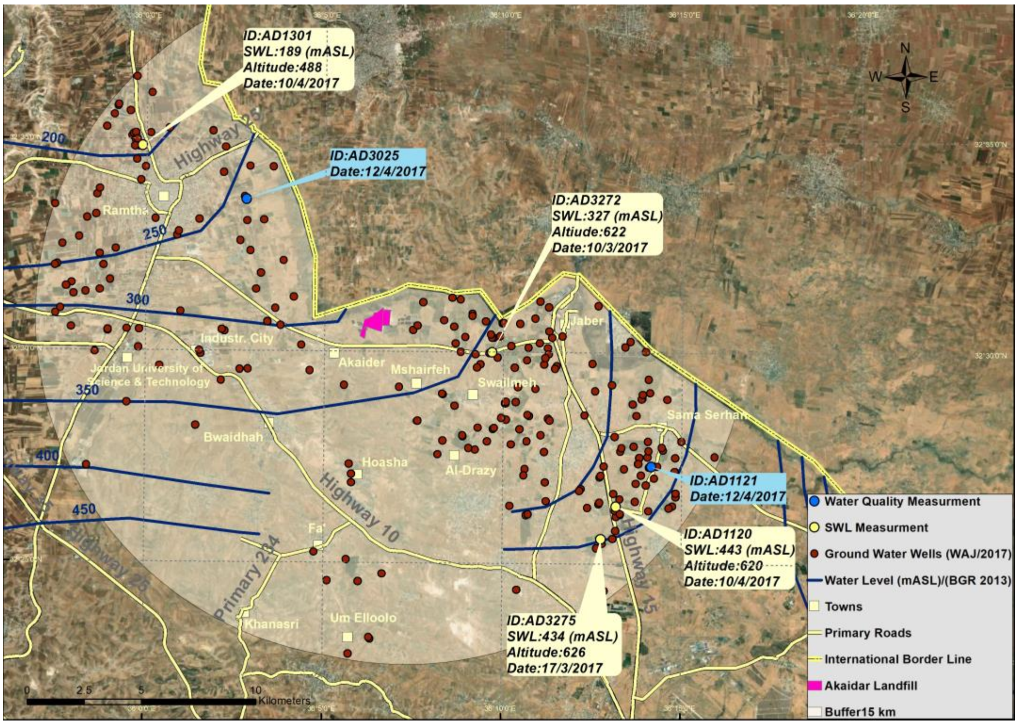

Figure 6. Peizometric map for Akaider landfill.

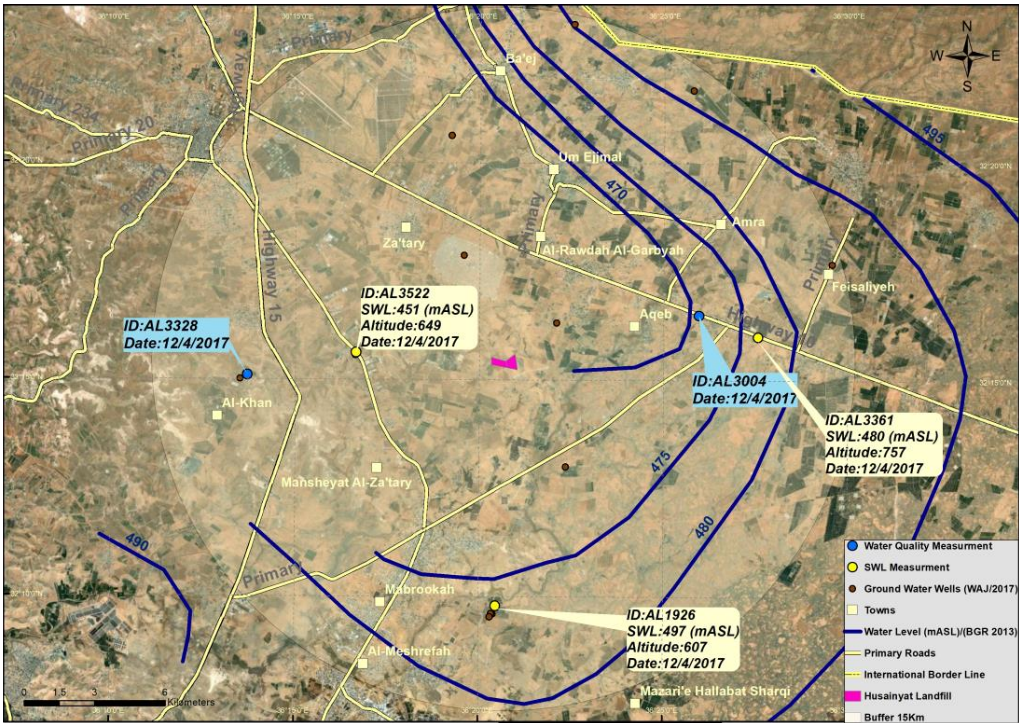

Figure 7. Peizometric map for Al-Husaineyat landfill.

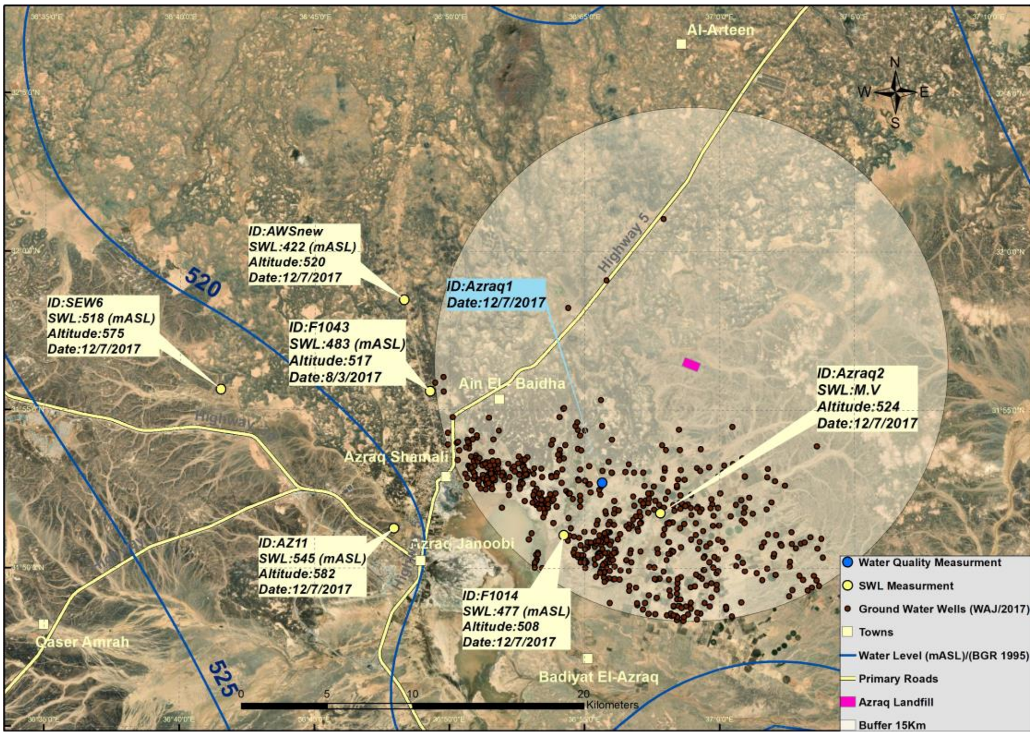

Figure 8. Peizometric map for Azraq Landfill.

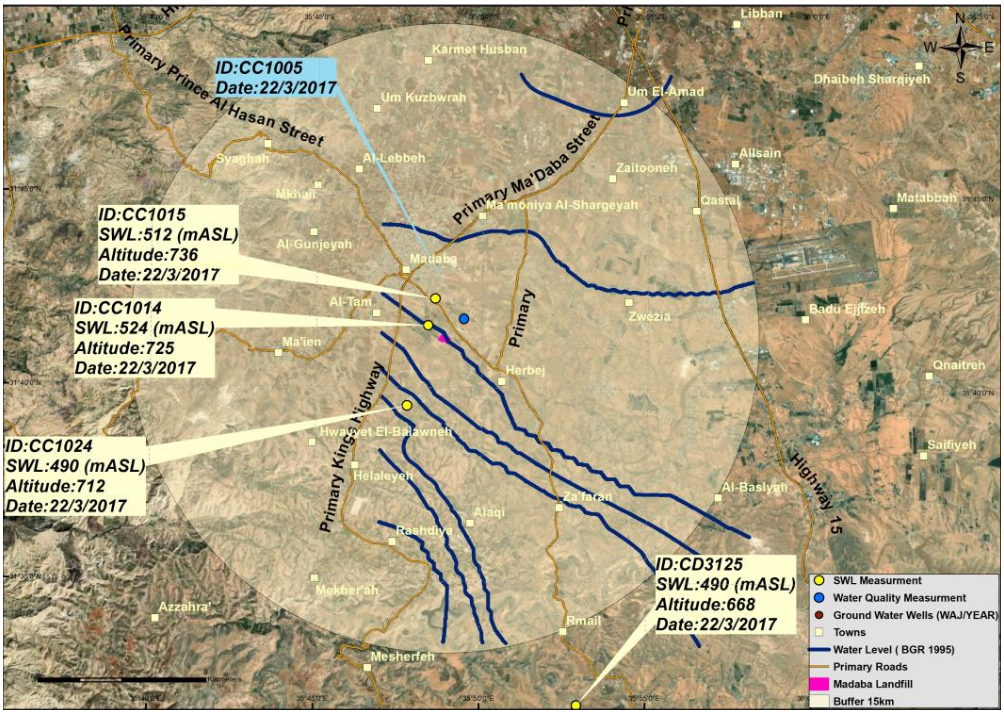

Figure 9. Peizometric map for Madaba landfill.

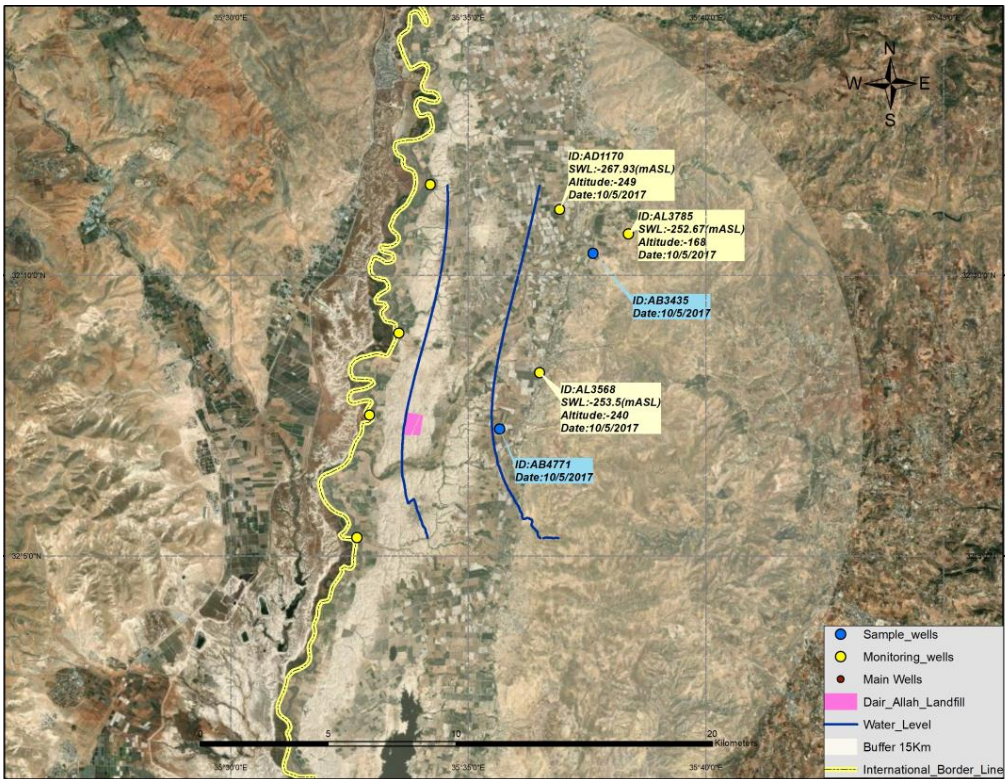

Figure 10. Peizometric map for Dair Alla landfill.

Table 7. The coordinates, static water level and masl of the monitoring wells.

Number of Well	Description	Leica Viva GNSS GPS–Cassini			GARMIN GPS			masl (Altitude-SWL)—Ground Level	Static Water Level (SWL)—Measured Manually by Using the Amescope Apparatus (Meters)	Distance from the Landfill (km)
		Longitude (E)	Latitude (N)	Altitude (H)	Longitude (E)	Latitude (N)	Altitude (H)			
Madaba										
CC1015	Monitoring Well	226,823.17362	1,123,738.1582	736.2081	NA	NA	NA	513.4381	222.77	NA
CC1014	Monitoring Well	226,515.3585	1,122,478.9360	725.5813	35.80632°	31.69333°	723	524.5413	201.04	1
Akaider										
AD3028	Monitoring Well	242,814.0343	1,222,327.8497	490.6215	35.98581°	32.59282°	487	456.1415	34.48	14.5
AD1301	Monitoring Well	243,960.8035	1,220,994.7877	482.3284	35.99796°	32.58074°	488	183.3284	299	12.8
AD3272	Monitoring Well	259,408.5153	1,212,135.826	620.8219	36.16149°	32.50001°	622	325.8219	295	5.2
AD3275	Monitoring Well	264,301.6145	1,204,057.3586	620.5813	36.21253°	32.42657°	626	429.5313	191.05	13.8
AD1120	Monitoring Well	264,924.8818	1,205,519.5843	613.2834	36.21950°	32.43956°	620	436.9934	176.29	13.3
Al-Husaineyat										
AL1926	Monitoring Well	276,628.3473	1,174,874.7456	600.8653	36.34066°	32.16225°	607	491.6953	109.17	10.5
AL3522	Monitoring Well	270,534.9639	1,185,597.3328	647.9349	36.27719°	32.25951°	649	450.5949	197.34	6.8
AL3361	Monitoring Well	287,662.9688	1,186,481.7577	748.9591	36.45907°	32.26580°	757	472.6571	276.302	10.4
Dair Alla										
AL3568	Monitoring Well	207,552.438	1,171,511.626	−257.311	35.60817°	32.13637°	−240	13.5 cmasl	11.96	4.6
AL3785	Monitoring Well	210,473.936	1,176,250.929	−178.825	35.63938°	32.17899°	−168	84.67 cmasl	84.89	9.7
AD1170	Monitoring Well	208,207.756	1,177,043.455	−239.754	35.61536°	32.18625°	−249	18.93 cmasl	17.70	8.8
Azraq										
F1014	Monitoring Well	330,406.7973	1,141,366.7123	528.9169	36.90419°	31.85089°	508	498.3469	30.57	12.4
F1060	Monitoring Well	NA	NA	NA	36.97376°	31.83974°	520	NA	NA	11.3
F1280	Monitoring Well	323,838.4212	1,148,207.1597	511.6086	36.83588°	31.1339°	515	487.4786	24.13	90.5

Table 8. Analyses results of the grab wells water samples (first round).

Parameter	Unit	Jordanian Standard for Drinking Water No. 286/2015-Allowable Limit	Sampling Date/Sample Code/Result									Test Method No. and Date
			AlHoseinyat 12/04/2017 AL3004	**AL3328**	**Madaba 22/03/2017 CC1005**	**CC1024**	**Akaider 10/04/2017 AD1121**	**AD3025**	**Deir Alla 10/05/2017 AB4771**	**AB3435**	**Azraq 12/07/2017 Azraq1**	
Physical and Chemical Analyses												
pH	SU	6.5–8.5	7.84	7.79	7.39	7.32	8.18	7.85	6.90	6.90	7.59	4500—H^+, B, 2011 *
Alkalinity	mg/L	—	115	201	283	241	134	234	462	409	128	2320—B, 2011 *
EC @ 25 °C	µs/cm	—	594	1070	1532	1415	719	786	4740	7840	1895	2510—B, 2011 *
BOD_5	mg/L	—	<2	<2	2.07	2.16	<2	2.0	5.93	7.74	<2	5210—B, 2011 *
COD	mg/L	—	11.3	5.5	6.4	6.9	<5	7.6	12.6	19.8	<5	5220—B, 2011 *
Cl	mg/L	≤500	79.9	173	216	146	103	98.3	902	1856	397	4500—Cl, D, 2011 *
TKN	mg/L	—	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	4500 –Norg, B, 2011 *
NH_4	mg/L	≤0.2	0.234	0.105	<4.5	<4.5	0.097	<0.08	0.164	0.101	<0.08	ASTM D 1426-15
NO_2-N	mg/L	≤0.913	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	0.074	<0.001	<0.001	4500—NO_2, B, 2011 *
NO_3-N	mg/L	≤11.3	1.00	8.26	0.697	<0.226	1.12	<0.226	32.4	16.9	1.07	4110—B, 2011 *
SO_4	mg/L	≤500	42.5	42.3	236	315	53.6	30.9	518	1056	165	4110—B, 2011 *
Phenol	mg/L	—	<0.002	<0.002	0.062	0.026	<0.002	<0.002	<0.002	<0.002	0.005	5530—C, 2011 *
Na	mg/L	≤200 **	68.4	70.5	94	73	88.7	57.8	577	1064	198.8	3111—B, 2011 *
Mn	mg/L	≤0.4	<0.05	<0.05	0.06	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	3120—B, 2011 *
Fe	mg/L	≤1.0	<0.1	<0.1	1.8	1.1	<0.1	<0.1	0.7	<0.1	<0.1	3120—B, 2011 *
As	mg/L	≤0.01	<0.01	<0.01	<0.05	<0.05	<0.01	<0.01	<0.1	<0.1	<0.05	3120—B, 2011 *
Ba	mg/L	≤1.0	<0.2	<0.2	0.22	0.21	<0.2	<0.2	<0.2	<0.2	<0.1	3120—B, 2011 *
Cd	mg/L	≤0.003	<0.005	<0.005	<0.01	<0.01	<0.005	<0.005	<0.005	<0.005	<0.01	3120—B, 2011 *
Cr	mg/L	≤0.05	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	3120—B, 2011 *
Hg	mg/L	≤0.006	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	3112—B, 2011 *
Pb	mg/L	≤0.01	<0.01	<0.01	<0.05	<0.05	<0.01	<0.01	<0.05	<0.05	<0.05	3120—B, 2011 *
Se	mg/L	≤0.04	<0.01	<0.01	<0.1	<0.1	0.015	<0.01	<0.1	<0.1	<0.05	3120—B, 2011 *
Microbiological Analyses												
TCC	MPN/100 mL	<1.1	1.1	<1.1	<1.1	13	<1.1	<1.1	140	<1.1	23	9221—BC, 2006 *
TTCC	MPN/100 mL	<1.1	<1.1	<1.1	<1.1	2	<1.1	<1.1	2	<1.1	<1.8	9221—EC, 2006 *
VOCs Analyses												
Benzene	µg/L	≤10	<10	<10	<10	<10	<10	<10	<10	<10	<10	SOP 17/01/01/01-23 Issue (1)
Tetrachloroethylene (PCE)	µg/L	≤40	<10.53	<10.53	<10.53	<10.53	<10.53	<10.53	<10.53	<10.53	<10.53	SOP 17/01/01/01-23 Issue (1)
Trichloroethylene (TCE)	µg/L	≤20	<12.95	<12.95	<12.95	<12.95	<12.95	<12.95	<12.95	<12.95	<12.95	SOP 17/01/01/01-23 Issue (1)
Ethylbenzene	µg/L	≤300	<8.25	<8.25	<8.25	<8.25	<8.25	<8.25	<8.25	<8.25	<8.25	SOP 17/01/01/01-23 Issue (1)
Total Xylene	µg/L	≤500	<15.32	<15.32	<15.32	<15.32	<15.32	<15.32	<15.32	<15.32	<15.32	SOP 17/01/01/01-23 Issue (1)
Toluene	µg/L	≤700	<8.35	<8.35	<8.35	<8.35	<8.35	<8.35	<8.35	<8.35	<8.35	SOP 17/01/01/01-23 Issue (1)

Table 8. *Cont.*

Parameter	Unit	Jordanian Standard for Drinking Water No. 286/2015-Allowable Limit	Sampling Date/Sample Code/Result									Test Method No. and Date
			AlHoseinyat 12/04/2017 AL3004	AL3328	Madaba 22/03/2017 CC1005	CC1024	Akaider 10/04/2017 AD1121	AD3025	Deir Alla 10/05/2017 AB4771	AB3435	Azraq 12/07/2017 Azraq1	
PAHs Analyses												
Acenaphytlene	µg/L	—	<0.04	<0.04	X	X	<0.04	<0.04	<0.04	<0.04	<0.04	6410-B, 2011 *
Flourene	µg/L	—	<0.07	<0.07	X	X	<0.07	<0.07	<0.07	<0.07	<0.07	6410-B, 2011 *
Phenanthrene	µg/L	—	<0.07	<0.07	X	X	<0.07	<0.07	<0.07	<0.07	<0.07	6410-B, 2011 *
Anthracene	µg/L	—	<0.06	<0.06	X	X	<0.06	<0.06	<0.06	<0.06	<0.06	6410-B, 2011 *
Pyrene	µg/L	—	<0.2	<0.2	X	X	<0.2	<0.2	<0.2	<0.2	<0.2	6410-B, 2011 *
Benzo (a) anthracene	µg/L	—	<0.3	<0.3	X	X	<0.3	<0.3	<0.3	<0.3	<0.3	6410-B, 2011 *
Chrycene	µg/L	—	<0.3	<0.3	X	X	<0.3	<0.3	<0.3	<0.3	<0.3	6410-B, 2011 *
Benzo (b) flurene	µg/L	—	<0.35	<0.35	X	X	<0.35	<0.35	<0.35	<0.35	<0.35	6410-B, 2011 *
Benzo (k) flurene	µg/L	—	<0.35	<0.35	X	X	<0.35	<0.35	<0.35	<0.35	<0.35	6410-B, 2011 *
Benzo (a) pyrene	µg/L	—	<0.6	<0.6	X	X	<0.6	<0.6	<0.6	<0.6	<0.6	6410-B, 2011 *
Indeno (1,2,3cd) pyrene	µg/L	—	<1.1	<1.1	X	X	<1.1	<1.1	<1.1	<1.1	<1.1	6410-B, 2011 *
Dibenzo (a,h) anthracene	µg/L	—	<1.3	<1.3	X	X	<1.3	<1.3	<1.3	<1.3	<1.3	6410-B, 2011 *
Benzo (g,h,I) pyrene	µg/L	—	<1.3	<1.3	X	X	<1.3	<1.3	<1.3	<1.3	<1.3	6410-B, 2011 *

—: No requirement with reference to the mentioned Jordanian standard. *: Standard Methods for the Examination of Water and Wastewater, Online. **: A maximum of 300 mg/L was allowed in case there is no water resource with a better quality, and this had the approval of the Ministry of Health.

Table 9. Analyses results of the grab wells water samples (second round).

Parameter	Unit	Jordanian Standard for Drinking Water No. 286/2015-Allowable Limit	Sampling Date/Sample Code/Result								Test Method No. and Date
			AlHoseinyat 08/10/2017		Madaba 12/10/2017		Akaider 08/10/2017		Deir Alla 22/10/2017		
			AL3004	AL3328	CC1005	CC1024	AD1121	AD3025	Abu Za'atar Farm	AB3435	
Physical and Chemical Analyses											
pH	SU	6.5-8.5	7.93	7.43	7.02	7.31	8.65	7.17	7.14	7.04	4500—H^+, B, 2011 *
Alkalinity	mg/L	—	113	194	286	225	77.2	222	214	802	2320—B, 2011 *
EC @ 25 °C	s/cmμ	—	563	1063	1635	1395	598	804	5430	8020	2510—B, 2011 *
BOD_5	mg/L	—	2.48	2.48	2.40	<2	2.33	2.07	<2	2.59	5210—B, 2011 *
COD	mg/L	—	<5	<5	<5.0	<5.0	<5	<5	59	54	5220—B, 2011 *
Cl	mg/L	≤500	68.9	165	217	143	107	97.5	1409	1818	4500—Cl, D, 2011 *
TKN	mg/L	—	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	4500 –Norg, B, 2011 *
NH_4	mg/L	≤0.2	<0.08	<0.08	<4.5	<4.5	0.489	<0.08	<4.5	<4.5	ASTM D 1426-15 & 4500 NH_3, B & C, 2011 *
NO_2 - N	mg/L	≤0.913	0.004	<0.001	<0.001	0.009	0.002	<0.001	<0.001	<0.001	4500—NO_2, B, 2011 *
NO_3 - N	mg/L	≤11.3	1.07	8.88	<0.226	<0.226	<0.226	<0.226	18.4	17.0	4110—B, 2011 *
SO_4	mg/L	≤500	41.8	46.6	254	299	39.0	33.7	291	1167	4110—B, 2011 *
Phenol	mg/L	—	0.006	0.006	0.003	0.006	0.004	0.002	0.009	0.004	5530—C, 2011 *
Na	mg/L	≤200 **	67.3	74.2	87.9	69.3	95.5	60.9	519	988	3111—B, 2011 *
Mn	mg/L	≤0.4	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	3111—B, 2011 *
Fe	mg/L	≤1.0	0.12	0.25	4.83	0.51	0.45	<0.1	<0.1	<0.1	3111—B, 2011 *
As	mg/L	≤0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	3120—B, 2011 *
Ba	mg/L	≤1.0	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	3120—B, 2011 *
Cd	mg/L	≤0.003	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	3120—B, 2011 *
Cr	mg/L	≤0.05	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	3120—B, 2011 *
Hg	mg/L	≤0.006	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	3112—B, 2011 *
Pb	mg/L	≤0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	3120—B, 2011 *
Se	mg/L	≤0.04	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	3120—B, 2011 *
Microbiological Analyses											
TCC	MPN/100mL	<1.1	<1.1	<1.1	79	4.5	<1.1	<1.1	2.0	<1.8 ***	9221—BC, 2006 *
TTCC	MPN/100mL	<1.1	<1.1	<1.1	<1.8 ***	4.5	<1.1	<1.1	2.0	<1.8 ***	9221—EC, 2006 *
VOCs Analyses											
Benzene	µg/L	≤10	<10	<10	<10	<10	<10	<10	<10	<10	SOP 17/01/01/01-23 Issue (1)
Tetrachloroethylene (PCE)	µg/L	≤40	<10.53	<10.53	<10.53	<10.53	<10.53	<10.53	<10.53	<10.53	SOP 17/01/01/01-23 Issue (1)
Trichloroethylene (TCE)	µg/L	≤20	<12.95	<12.95	<12.95	<12.95	<12.95	<12.95	<12.95	<12.95	SOP 17/01/01/01-23 Issue (1)

Table 9. *Cont.*

Parameter	Unit	Jordanian Standard for Drinking Water No. 286/2015-Allowable Limit	Sampling Date/Sample Code/Result								Test Method No. and Date
			AlHoseinyat 08/10/2017 AL3004	AL3328	Madaba 12/10/2017 CC1005	CC1024	Akaider 08/10/2017 AD1121	AD3025	Deir Alla 22/10/2017 Abu Za'atar Farm	AB3435	
Ethylbenzene	μg/L	≤300	<8.25	<8.25	<8.25	<8.25	<8.25	<8.25	<8.25	<8.25	SOP 17/01/01/01-23 Issue (1)
Total Xylene	μg/L	≤500	<15.32	<15.32	<15.32	<15.32	<15.32	<15.32	<15.32	<15.32	SOP 17/01/01/01-23 Issue (1)
Toluene	μg/L	≤700	<8.35	<8.35	<8.35	<8.35	<8.35	<8.35	<8.35	<8.35	SOP 17/01/01/01-23 Issue (1)
PAHs Analyses											
Acenaphytlene	μg/L	—	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	6410-B, 2011 *
Flourene	μg/L	—	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	6410-B, 2011 *
Phenanthrene	μg/L	—	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	6410-B, 2011 *
Anthracene	μg/L	—	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	6410-B, 2011 *
Pyrene	μg/L	—	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	6410-B, 2011 *
Benzo (a) anthracene	μg/L	—	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	6410-B, 2011 *
Chrycene	μg/L	—	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	6410-B, 2011 *
Benzo (b) flurene	μg/L	—	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	6410-B, 2011 *
Benzo (k) flurene	μg/L	—	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	6410-B, 2011 *
Benzo (a) pyrene	μg/L	—	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	6410-B, 2011 *
Indeno (1,2,3cd) pyrene	μg/L	—	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	6410-B, 2011 *
Dibenzo (a,h) anthracene	μg/L	—	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	6410-B, 2011 *
Benzo (g, h, I) pyrene	μg/L	—	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	6410-B, 2011 *

—: No requirement with reference to the mentioned Jordanian standard. *: Standard Methods for the Examination of Water and Wastewater, Online. **: A maximum of 300 mg/L was allowed in case there is no water resource with a better quality, and this had the approval of the Ministry of Health. ***: Turbid sample.

The results of the physical, chemical and microbiological analyses showed that there was no clear evidence of the contamination of the groundwater due to the adjacent landfills as most of the results were in compliance with the Jordanian standard for drinking purposes (JS286/2015). However, there were some results, particularly from the Dair Alla wells, slightly exceeded the limits, but since those results were found in both the upstream and downstream wells, we cannot attribute them to the presence of the landfills. However, the intensive agricultural activities and high salinity of the irrigation water in Deir Alla would increase the salinity and nitrogen content of soil which would end up in the groundwater. The nitrogen-based organic pollutants' and PAACs' analyses results of the water samples upstream and downstream of the Akaider, Deir Alla, Madaba and Azraq landfills showed that there was no contamination of the groundwater. This was in agreement with the results of the vulnerability maps, which indicated that the area surrounding these landfills has a low to very low sensitivity to groundwater pollution. On the other hand, the results of the microbiological analyses for the samples taken from the wells near the Al-Husainiyat landfill showed an excess of ammonium and TCC concentrations, which supports the findings of the vulnerability map of the Al-Husainiyat landfill as it was moderately vulnerable to contamination. Although the two rounds of water tests from the upstream and downstream wells gave a satisfactory indication of the validity of the COP-vulnerability maps, more water tests are recommended across different seasons to have a clearer picture on the validity of the COP model.

The results of the water quality study at Akaider, as shown in the table above, were not in agreement with those of the authors of [28] who found that there is a very high risk to the groundwater in this landfill area. They attributed this finding to the landfill's leachate permeated into the ground. However, the authors of [28] linked the risk of groundwater pollution at Akaider to the landfill without conducting vulnerability modeling. Our study found that the natural protection of the groundwater at Akadier site is fairly strong enough to protect the groundwater. Therefore, we believe that a specific vulnerability analysis (not intrinsic) is needed in such cases to describe the contaminant characteristics along with the aquifer formation attributes. Yet, the disagreement in the nitrate and EC results between the current study and the findings of [28] can be attributed to the changes in the land use in the Akaider area, where a drop in agricultural land has been witnessed over the last decade along with a significant reduction in the livestock and farm animals in the surrounding villages. However, the results of heavy metals in the current study are in line with the low levels that have been reported in [28].

Furthermore, the authors of [29] conducted a study to assess the potential pollution of the groundwater around the Akaider landfill area by examining the concentrations of heavy metals (Zn, Cu, Mn, Pb, Cd and Fe) in the water well samples around the study area. The concentrations of Zn, Cu, Mn, Pb, Cd and Fe in all of the water samples are within the maximum permissible limits of the Jordanian drinking water standards. Their study explained that the groundwater is not contaminated with heavy metals and the groundwater around the study area within Yarmouk basin is not affected by the Akaider landfill or the leachate infiltration. This study supports our vulnerability maps which indicated a very low sensitivity to pollution in the Akaider area.

4. Conclusions

The general goal of this study was to map the groundwater vulnerability to contamination and evaluate the impact of the landfills on the groundwater quality at five landfill sites in Jordan, i.e., Akaider, Al-Husaineyat, Madaba, Dair Alla and Azraq, by using a COP hydrogeological model. The literature review showed that no thorough studies have been conducted to study the groundwater vulnerability to contamination by the landfills by using a COP model. The developed vulnerability maps showed that most of the lands surrounding the landfills' areas, within a diameter of 15 km, are located in a low to very low vulnerability areas, except for the Al-Husaineyat landfill in Mafraq where significant part of it lies in a moderate vulnerability area across a fault section. The results of the water analysis from the surrounding wells indicate that there was no clear evidence of the contamination of the groundwater resulting from the surrounding landfills. However, taking necessary precautions and preventive measures for all of the landfills especially those located in areas of medium-to-high vulnerability by lining them and turning them into sanitary landfills are quite important. It is also highly recommended to develop a continuous water quality-monitoring program for the groundwater surrounding the landfills, especially those that are located in medium-to-high vulnerability areas. This study showed the importance of collaboration with all of the stakeholders in such studies to validate the data and ensure the adoption of the modeling outputs by the decision makers.

Author Contributions: A.A. (Almoayied Assayed) wrote the first version of the paper and led the research team. S.T. and S.B. conducted the whole GIS and COP modeling analysis. R.A. was the field team leader and coordinated the whole field activities. N.A. collected the data related to water wells and landfills and reviewed the manuscript. A.A. (Aisha AlHushki) contributed to the discussion part, updated all references and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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