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Evaluating the Risk of Cement Kiln Dust Landfill on Groundwater Vulnerability to Pollution

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Abstract

Cement manufacturing is an important industry in Jordan and throughout the world. As with most large manufacturing industries, waste materials are generated. These industrial waste materials should be well-managed to protect environmental components. Cement kiln dust (CKD) is a significant waste material of the cement manufacturing process. If CKD is non-compliant with required clinker/cement quality standards, it can be placed in a standalone landfill. This study aims to evaluate the risk of CKD landfilling on groundwater vulnerability to pollution in the Qatrana cement plant area using the DRASTIC model developed by USEPA and select the appropriate CKD landfill design configuration. The measured DRASTIC index value of 81 indicates that the potential for polluting groundwater in the study area is of very low vulnerability. Thus, no risk on the groundwater aquifer systems in the study area may result from CKD landfilling. Based on the results of the DRASTIC index and the nature of the study area, the most appropriate landfill design configuration according to the international guidelines was suggested.

Keywords: Cement kiln, CKD, DRASTIC, Groundwater, Landfill, Risk, Vulnerability, Jordan

INTRODUCTION

Jordan is an area rich with raw materials required for cement manufacturing, and the cement sector forms a main driver in the economic development in Jordan. As with most large manufacturing industries, industrial waste materials are generated from cement manufacturing. These industrial waste materials should be well-managed in order to protect environmental components. One of the significant industrial waste of the cement manufacturing process is Cement kiln dust (CKD).

CKD is generated in the kiln during cement clinker production. The CKD is an alkali particulate mixture of partially calcined and unreacted raw mix. The particulate matter control devices such as cyclones, baghouses, and electrostatic precipitators capture and collect these particulates. Similar to the cement kiln raw mix, the CKD consists essentially of calcium carbonate and silicon dioxide. Still, the amount of alkalies, chloride, and sulfate is usually higher in the dust. Insignificant amounts of trace metals are found in the CKD, and therefore metal concentrations are not often a concern for most applications (Adaska and Taubert, 2008).

CKD varies in the physical-chemical composition between plants. Therefore, the managing of dust is a case of plant-by-plant. The primary quantity of the CKD at many cement plants is recycled back into the kiln to supplement the raw mix (Adaska and Taubert, 2008; USEPA, 2010; Elbaz et al., 2019; Seo et al., 2019). Other cement plants may sell their CKD for beneficial reuse or recycle. Equipment limitations for handling the CKD or chemical constituents in the CKD that would be detrimental to the final clinker product or would make the product non-compliant with required quality standards are the main reasons for not returning CKD to the kiln system. The CKD portion that is not reused or recycled can be placed in landfills (Bhatty et al., 2004).

In 2007 the Qatrana Cement Company was established with a total investment of 500 million USD. In the first quarter of 2011, the plant started operating to meet the demand of Jordanian and foreign markets Iraq, Palestine, and Syria with a daily production capacity of 5000 tons (Qatrana Cement, 2020). CKD is one of the industrial waste materials generated from the Qatrana cement plant. As the generated CKD composition and characteristics are not suitable to be recycled back into the kiln, it is decided to dispose of CKD quantities in a standalone landfill within the cement plant area.

The area selected for this study is the proposed CKD landfill located within the Qatrana cement plant in the Qatrana area within Karak governorate in Jordan (Figure 1). This study aims to evaluate the risk of CKD landfilling on groundwater vulnerability to pollution in the Qatrana cement plant area using the DRASTIC model and select the appropriate CKD landfill design configuration.

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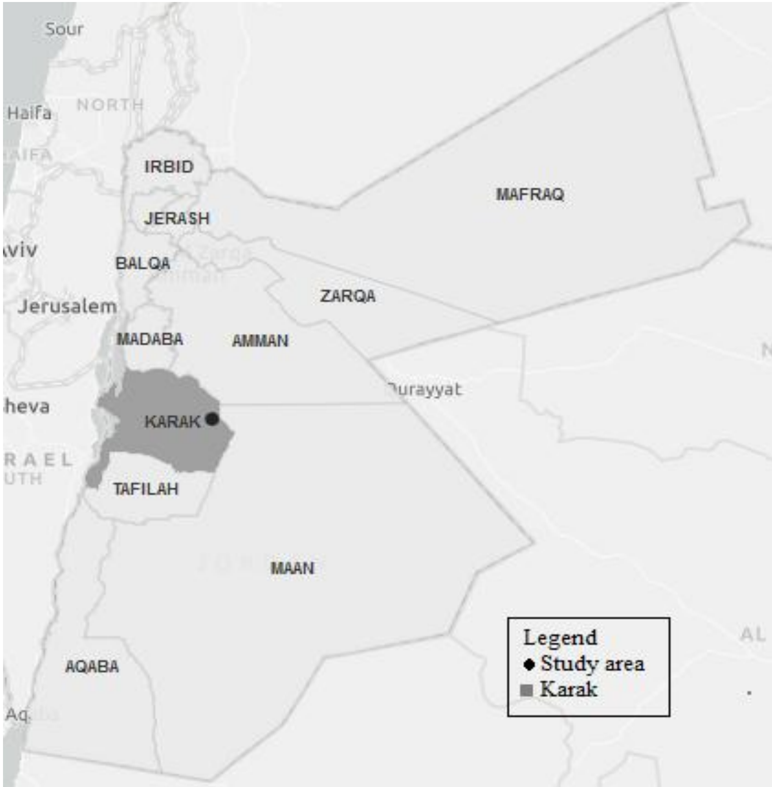

Figure (1): Study Area in Karak Governorate - Jordan

DESCRIPTION OF STUDY AREA

Topography

The study area location is in the southeastern desert region of Jordan and 80 km south of Amman. The altitude is approximately 800 meters above sea level.

Climate

The study area climate is characterized by a relatively short rainfall period during the winter season between November and March, while an extensive drought describes the summer season. Around 3°C is the average minimum temperature of the coldest month, while the average maximum temperature of the hottest month is 35°C. The potential evaporation rate ranges from about 1.9 mm/day in December to about 10.1 mm/day in July. The closest rainfall station to the study area is the Qatrana rainfall station, and the average annual rainfall amount is less than 100 mm. The long-term annual rainfall amount in the study area is shown in Figure 2 (Jordan Meteorological Department, 1989-2019).

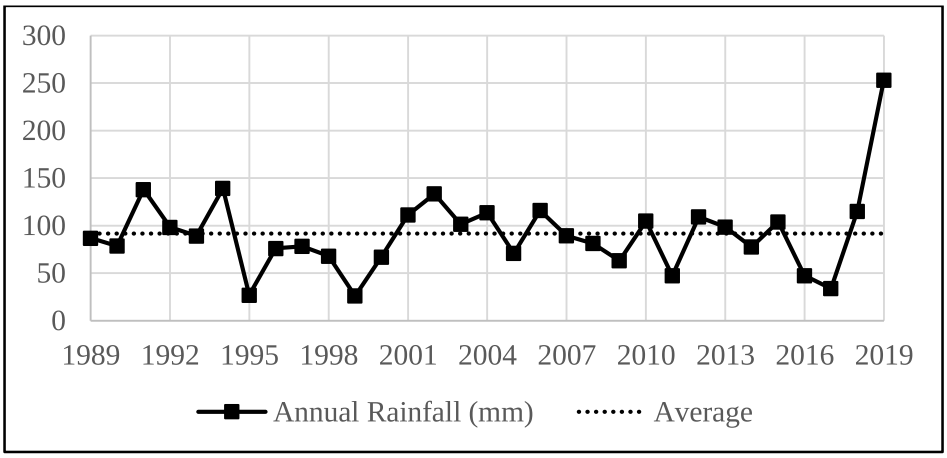

Figure (2): Annual Rainfall (mm) at the Study Area (1989 – 2019)

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Geology

The study area's general geology is dominated by a thick sequence of sedimentary rocks related to Cretaceous age, which is subdivided into two main sequences: Lower and Upper Cretaceous rocks. The Upper Cretaceous rocks are the most abundant rocks exposed in the study area. The Upper Cretaceous rocks consist of two major geological formations: the Balqa group underlain by the older Ajlun group. This series consists of limestone, dolomitic limestone, marly limestone, chalky limestone (Bender, 1974). Ajlun Group sub-divided to Naur limestone formation (A1/2), Fuheis, Hummar, Shuayb formations (A3/6), Wadi Sir limestone formation (A7). Balqa Group subdivides to Wadi Umm Ghudran Formation (B1), Amman Silicified limestone formation (B2), Muwaqqar chalk-marl formation (B3 or MCM) and Umm Rijjam (B4). The study area is located within the outcrops of (A7/B2) formation. The lithological description of the study area is presented in Table 1.

Table 1. Lithological description at the study area

Depth (m)	Formation	Lithology	Geological Description
0.0-5.0	Alluvium	-	Gravel of limestone, chert, silt, and silty clay and marl
5.0-62.0	Umm Rijjam (B4)	limestone and chert	Limestone: grey to fine whitish crystal, medium-hard. Marly limestone: yellowish, soft to medium-hard inter bedding with thin beds of chalky limestone and thin beds of chert: dark grey and very hard and massive.
62.0-188.0	Muwaqqar formation (B3)	limestone and chert	Limestone: fine beige crystal, medium-hard, inter bedding with thin beds of chert: dark grey, very hard and massive, thin beds of marl: greyish, soft, and fine-grained.
188.0-370.0	Amman formation (B2) / Wadi Sir limestone formation (A7)	limestone, chert, marl limestone, dolomitic limestone, and chert	Limestone: phosphorite, whitish, medium-hard, and fine crystal. Marl: greyish, soft, and fine-grained. Chert: dark grey, very hard and massive. Dolomitic Limestone: grey, medium-hard, and medium crystal.

Water resources

The study area lies in the Mujib groundwater basin (Figure 3), which is considered one of the most important basins in Jordan. At Mujib basin, there are three main groundwater aquifer systems: Rum group, Kurnub sandstone group (K), and Amman-Wadi Sir group (A7/B2) (Powell, 1989). The (A7/B2) aquifer related to the Upper Cretaceous limestone aquifer is considered the principal aquifer in the study area. Infiltration of rainfall in the outcrop area is regarded as the primary source of water recharge to Amman-Wadi Sir aquifer. No surface water resources are found in the study area.

Figure (3): Study Area at Mujib Groundwater Basin

BACKGROUND

Several factors affect the chemical and physical properties of CKD. Because plant operations differ considerably from the raw mix, type of operation, dust collection facility, and type of fuel used, the terms typical or average CKD when comparing different plants can be misleading. The dust from each plant can vary significantly in chemical, mineralogical, and physical composition (Klemm, 1993). However, to provide a general reference point, the typical CKD composition has been reported by the Bureau of Mines as given in Table 2 (Haynes and Kramer, 1982).

Table 2. Typical composition of CKD (Haynes and Kramer, 1982)

Constituent	% by weight
$CaCO_3$	55.5
SiO_2	13.6
CaO	8.1
K_2SO_4	5.9
$CaSO_4$	5.2
Al_2O_3	4.5
Fe_2O_3	2.1
KCl	1.4
MgO	1.3
Na_2SO_4	1.3
KF	0.4
Others	0.7

Excess chlorine or alkali in some cement manufacturing raw materials (e.g., clay) may produce cement kiln dust, which must be well managed through reuse, recycle, or safe disposal in CKD standalone landfill. The alkalinity of CKD causes pH to increase, reducing the mobility of most metals. CKD materials themselves also have very low permeability (LDWG, 2015). USEPA Technical Background Document on Groundwater Controls at CKD Landfills (USEPA, 1998) describes factors that contribute to releasing the CKD constituents into the sub-surface environment. These include:

- Presence of a shallow groundwater flow system with conduit flow characteristics (e.g., karst aquifer or fractured bedrock aquifer).
- CKD disposal below the natural water table or groundwater infiltration into the waste unit.
- Surface runoff or erosion transporting CKD constituents to surface water bodies and/or wetlands can be a source of groundwater recharge.
- Shortage of an impermeable cover to control percolation of rainwater and/or surface water into the waste unit.

USEPA evaluation of CKD facilities in the Report to Congress (USEPA, 1993a) stated that the factors that lead to lower the potential of groundwater pollution from CKD landfilling include: deeper water table, more impermeable underlying soils (e.g., clay, shale), and low recharge rates. However, CKD materials themselves have very low permeabilities and can act as impermeable barriers to groundwater flow and infiltration.

The state of California determined that compacted CKD would be an acceptable landfill cover material from detailed geotechnical testing. CKD was also used as a fill material to protect the landfill from erosion from future storm events. The cost of the CKD was also calculated as only 20% of what was estimated for alternative cover and fill materials (Adaska and Taubert, 2008).

Based on the results of USEPA modeling of landfill designs, most engineering controls (i.e., the Subtitle D technical default standard) are required in cold climates with more than 1 meter of precipitation per year. CKD landfill design with fewer engineering controls (i.e., a compacted CKD bottom and top layers, vegetated cover, and no leachate collection) are expected to achieve the performance standard at sites with about 250 mm or less of precipitation per year (USEPA, 1997).

Portland Cement Association proposed two CKD landfill design configurations (Abeln et al., 1993), which are similar to the USEPA designs (USEPA, 1998), namely, "Modified CKD Low" and Modified CKD High" presented in Table 3.

Discarded CKD from cement plants should be analyzed for leachate quality parameters (metals and organics) if they are to be landfilled to protect the environment and prevent groundwater pollution (UNEP, 2011).

Table 3. Summary of CKD landfill design configurations (USEPA, 1998)

Design Variable	Baseline CKD Landfill	Modified CKD Low	Modified CKD High	Subtitle D (composite liner; leachate collection)	Subtitle C (double liner: leachate collection)
Cover Layer	Uncompacted CKD (no cover)	15 cm topsoil 61 cm compacted CKD (k = $2x10^{-5}$ cm/sec)	31 cm topsoil 15 cm sand drainage layer (k =$2x10^{-3}$ cm/sec) Geotextile support fabric 61 cm compacted CKD	15 cm topsoil 46 cm sand 60 mil HDPE geomembrane 61 cm compacted soil cap	61 cm topsoil 31 cm sand 30 mil HDPE geomembrane 61 cm compacted soil cap
Liner Layer	Uncompacted CKD (no liner)	122 cm compacted CKD (k = $2x10^{-5}$ cm/sec)	Geotextile filter fabric 31 cm sand (leachate collection layer) Geotextile support fabric 122 cm compacted CKD	31 cm sand (leachate collection layer) 60 mil HDPE geomembrane 61 cm clay	31 cm sand (leachate collection layer) 30 mil HDPE geomembrane 31 cm sand (leachate detection layer) 30 mil HDPE geomembrane 61 cm clay
Slope of Final Cover	NA	NA	2 percent slope	2 percent slope	3 percent slope
Ground-water Monitoring	Yes	Yes	Yes	Yes	Yes
Leachate Collection	No leachate collection	No leachate collection	Yes	Yes (required)	Yes (required)

NA: Not Applicable, k: Hydraulic Conductivity

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METHODOLOGY

The DRASTIC model was used to evaluate the groundwater pollution vulnerability in the study area that may result from CKD landfilling and then select the appropriate landfill design configuration. USEPA developed the DRASTIC model as "A Standardized System for Evaluating Groundwater Pollution Potential of Hydrogeology Settings". The model provides an inexpensive method for evaluating groundwater resource vulnerability to pollution based on hydrogeologic settings. It simulates the pollutant transfer time from the topsoil to the groundwater system. The numerical value for the DRASTIC index is a combination of rating and weights (USEPA, 1985).

The term DRASTIC is an acronym for key factors within the hydrogeological settings that control groundwater pollution. These factors, which presented in Figure 4, are depth to water table, net recharge, aquifer media, soil media, topography (slope), the impact of the vadose zone material, and hydraulic conductivity (USEPA, 1985; Aller et al., 1987).

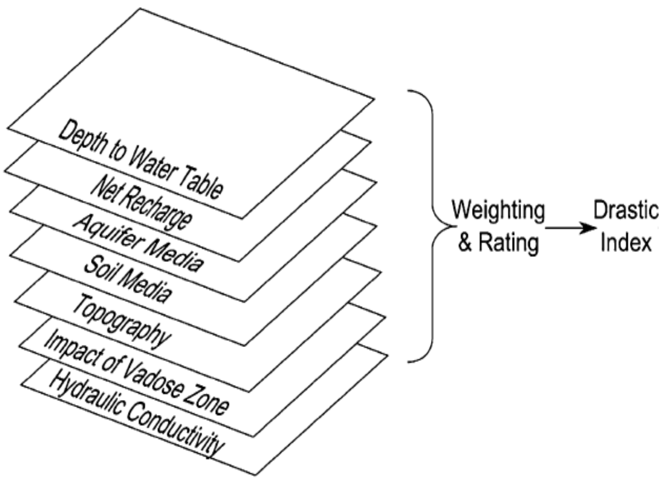

Figure (4): DRASTIC Model Flowchart

The DRASTIC model uses a numerical relative rating and weight system that include (Aller et al., 1987):

- Rating: Each range for each DRASTIC factor has been evaluated concerning others to determine the relative significance of each range with respect to pollution potential. The rating of the DRASTIC factor is from 1 to 10.
- Range: Each DRASTIC factor has been divided into either ranges or significant media types that impact potential pollution.
- Weight: The weight represents an attempt to define the relative importance of each factor in its ability to affect pollution transport to and within the aquifer. It ranges from 1 to 5.

The formula for determining the DRASTIC index is:

$$DRASTIC\ index = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

where D, R, A, S, T, I, and C are the factors of the DRASTIC model, w is the weight of the factor, and r its rating.

RESULTS AND DISCUSSION

The DRASTIC rating and weights for each parameter for the study area are presented in Table 4. Each parameter rating is multiplied by the weight to get the parameter value (Aller et al., 1987). These values are then summarized to arrive at a DRASTIC index, which represents the pollution index.

The DRASTIC index can be divided into five categories: very low, low, moderate, high, and very high. If the site of the study area has a high or very high DRASTIC index value, it means that the area is more vulnerable to pollution and accordingly requires to be managed more carefully.

The Rating Number for each factor has been determined for the study area as follows:

- Groundwater Depth: The depth to groundwater table in the study area is approximately 160 m.
- Groundwater Recharge: Assuming an effective porosity of 2%, groundwater recharge would be around 10 mm/yr (1.0 cm) or 10% from the average annual rainfall.
- Topography%: Generally, the area is flat and the slope of less than 2%.
- Hydraulic Conductivity: Due to karst features, joint, sinkholes, caves, and solution breccias, A7/B2 aquifer has a wide range of hydraulic conductivity values from 0.0846 m/day to 8.64 m/day.
- Aquifer Media and Vadose Zone Material: The formation (Balqa, B1) is intercalated between B2 and A7. This formation (B1) composed of alternating marl, marly limestone, chert, and sandstone. A7/B2 formation is an aquifer with permeability varying due to joints, fractures, and karstification of limestone—the thickness of the A7/B2 aquifer range from 100-300 m.

The DRASTIC index for the study area is computed, as presented in Table 5. The DRASTIC index values range from 65 to 223, which means the great potential to pollute the groundwater. The classes of the DRASTIC vulnerability index are shown in Table 6 (Aller et al., 1987).

Table 4. DRASTIC rating and weight values for the hydrogeological parameter setting

Depth to Water Table (m)		Recharge (cm)		Topography (%)		Conductivity (m/day)	
Range	Rating	Range	Rating	Range	Rating	Range	Rating
0-1.5	10	**0-5**	**1**	**0-2**	**10**	0.041-4.1	1
1.5-4.6	9	5-10.2	3	2-6	9	**4.1-12.3**	**2**
4.6-9.1	7	10.2-17.8	6	6-12	5	12.3-28.6	4
9.1-15.2	5	17.8-25.4	8	12-18	3	28.6-40.8	6
15.2-22.9	3	>25.4	9	>18	1	40.8-81.6	8
22.9-30.5	2					>81.6	10
> 30.5	**1**						
Pollution Weight 5		Pollution Weight 4		Pollution Weight 1		Pollution Weight 3	

Aquifer Media		Vadose Zone Material	
	Rating		Rating
Massive Shale	2	Confining Layer	1
Metamorphic / Igneous	3	Silt / clay	3
Weather Metamorphic Igneous	4	Shale	3
Glacial Till	5	Limestone	3
Bedded Sandstone, Limestone	**6**	Sandstone	6
Massive Sandstone	6	**Bedded Limestone, Sandstone**	**6**
Massive Limestone	8	Sand and Gravel with Signification Silt	6
Sand and Gravel	8	Sand and Gravel	8
Basalt	9	Basalt	9
Karst Limestone	10	Karsts Limestone	10
Pollution Weight 3		Pollution Weight 5	

Soil Media	Rating
Gravel	10
Sand	9
Peat	8
Shrinking Clay	7
Sandy Loam	6
Loam	5
Silty Loam	**4**
Clay Loam	3
Pollution Weight 2	

Bold values represent the study area.

Table 5. DRASTIC index computations

DRASTIC Factor	Range	Rating	Weight	Result
Depth to W.T. (m)	160	1	5	5
Recharge (cm)	1.0	1	4	4
Topographic/Slope (%)	< 2%	10	1	10
Conductivity (m/day)	0.0846-8.64	2	3	6
Aquifer Media	Bedded sandstone, limestone	6	3	18
Vadose Zone Media	Bedded sandstone, limestone	6	5	30
Soil Media	Silty Loam	4	2	8
DRASTIC index				81

Table 6. Criteria of the vulnerability degrees evaluation

Vulnerability degree	DRASTIC index
Very Low	65 - 96
Low	96 – 127
Moderate	127 – 158
High	158 – 189
Very High	189 – 223

The main aquifer is naturally protected from the source of contaminants occurs on the surface as obtained by the results, where the class of very low vulnerability class extends over the study area (DRASTIC index is 81). This result means that in the unlikely event that CKD landfilling is discharged from the landfill to the groundwater resources. Accordingly, there is no risk on the groundwater aquifer systems in the study area.

Based on the results of the DRASTIC model and the nature of the study area, the landfill design configuration according to the international guidelines should include the following:

- A 150 mm vegetative soil layer with a permeability of 1.9×10^{-4} cm/sec.
- A 6 mm lateral drainage layer with a permeability of 7 cm/sec to eliminate infiltrated water into the vegetative layer.
- To avoid clogging the drainage layer by fines, a geofabric placed above the drainage layer.
- A 61 cm soil barrier with a permeability of 2.5×10^{-5} cm/sec under the drainage layer.
- A side slope of 3:1 (3 horizontal to 1 vertical).
- According to the climatic setting, the minimum total lift for The CKD layer has three values of permeability (1×10^{-4} cm/sec, 1×10^{-5} cm/sec, and 1×10^{-6} cm/sec). In uncompacted CKD at some sites or with mild to heavy compaction at other sites, these ranges of permeabilities could be achieved or may occur naturally.
- No engineered bottom liner or leachate collection.
- Groundwater monitoring is required.

CONCLUSIONS

This study has assessed the risk of CKD landfilling on groundwater vulnerability to pollution in the Qatrana cement plant in one of the most important groundwater basins in Jordan, namely, Mujib. CKD is generated in the kiln during cement clinker production. It is a particulate mixture of partially calcined and unreacted raw mix, clinker dust and ash, enriched with alkali sulfates, halides and other volatiles.

Because of the CKD composition, the managing of dust is a case of plant-by-plant. If CKD is non-compliant with required clinker/cement quality standards such as in the case of Qatrana cement plant, it can be placed in a specific purpose landfill. Thus, the factors that lead to lower potential for groundwater pollution from CKD landfilling in the study area include deeper water table, more impermeable underlying soils (e.g., clay, shale), and low recharge rates. However, CKD materials themselves have very low permeabilities and can act as impermeable barriers to groundwater flow and infiltration.

The DRASTIC model, which was developed by USEPA, was applied to assess the groundwater pollution vulnerability in the study area that may result from CKD landfilling. The measured DRASTIC index value of 81 points out that the potential for polluting groundwater in the study area is of very low vulnerability. Thus, no risk on the groundwater aquifer systems in the study area may result from CKD landfilling if the suggested landfill design configuration is implemented. Both the results of the DRASTIC model and the CKD landfill area play a key role in the selection of the appropriate CKD landfill configuration. Nevertheless, the CKD landfill should be necessarily designed according to the international guidelines, and the groundwater system in the landfill area should be regularly monitored.

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