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Geochemical Assessment of Vulnerability of Groundwater to Contaminant at Phuoc Hiep Landfill Site, Ho Chi Minh City, Vietnam

by

Kim Phuong NGUYEN[†], Ryuichi ITOI*, Yoshihito KOMANIWA** and Phong Hoai DINH[††]

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Abstract

A geochemical assessment on vulnerability of groundwater quality and shallow aquifer in the vicinity of the Phuoc Hiep landfill site was carried out with a hydro-chemical approach for identifying various geochemical processes and understanding the impacts of landfill leachate on groundwater quality. Results indicate that hardness, nitrate, fluoride, iron in groundwater and heavy metal in surface water are above the standard for drinking water. Leachate seepage from the landfill is a main contaminant source of groundwater of Na-Cl water type with electrical conductivity (EC) values of 4,275 to 4,575 μS/cm. The pH values of the leachate are between 5.8 and 6.6. Concentrations of Al, Fe and Mn and heavy metals (Pb, Zn and Cu) in the leachate are above the drinking water standards. As a result, the waste leachate has a high content of contaminant that affects groundwater quality in highly productive zones. Two main zones of the aquifer were determined to be most vulnerable using GOD vulnerability model. Thus, these vulnerable zones are not suitable for waste disposal and the aquifer should be protected from leachate.

Keywords: Hydro-geochemistry, Aquifer vulnerability, Groundwater quality, Landfill, Vietnam.

[†] Department of Geo-environment, Faculty of Geology and Petroleum Engineering, HoChiMinh city University of Technology, Vietnam

* Professor, Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University

** Technician, Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University

[††] Student, Department of Geo-environment, Faculty of Geology and Petroleum Engineering, HoChiMinh city University of Technology, Vietnam

1. Introduction

Alluvial aquifers, which constitute the most important hydro-geological reservoirs and are unprotected from surface contaminants, are easily contaminated if no precautionary measures are taken. Solid and liquid wastes play the main role in the contamination of the world's water resources [1]. Many researches have been conducted on alluvial aquifers, namely the interaction of river water and groundwater, and the determination of groundwater contaminants and hydrochemistry of groundwater contamination [2-3].

The vulnerability technique includes hydro-geological parameters that are used to define the conditions of the underlying aquifer and extract the associated susceptibility to pollution. The vulnerability of groundwater to contamination from surface pollution sources has been an important topic for the hydro-geologist. In particular, advances in Geographic Information System (GIS) have created a new area called vulnerability mapping that is based on the analysis of the sensitivity of groundwater to contamination with regards to a group of hydro-geological parameters. For examples, DRASTIC model developed for the US Environmental Protection Agency is considered to be the initiation of the subject. Following DRASTIC, other models such as GOD [4-6] and CALOD [7] have also been developed to provide tools for analyzing aquifer vulnerability to pollution. An aquifer vulnerability map is used to determine a potential groundwater contamination zone and landfill site selection based on hydro-geological and environmental conditions.

Solid waste disposal is an important problem for Vietnam and its environs as well as for Ho Chi Minh City. Most of the uncontrolled solid wastes are dumped on alluvium aquifers and most of them cause environmental problems. Phuoc Hiep landfill is located in the north west of Ho Chi Minh City and is situated on an alluvial aquifer with high groundwater potential (**Fig. 1**). The industrial, residential and agricultural water needs of the region are met entirely from Quaternary alluvial aquifers.

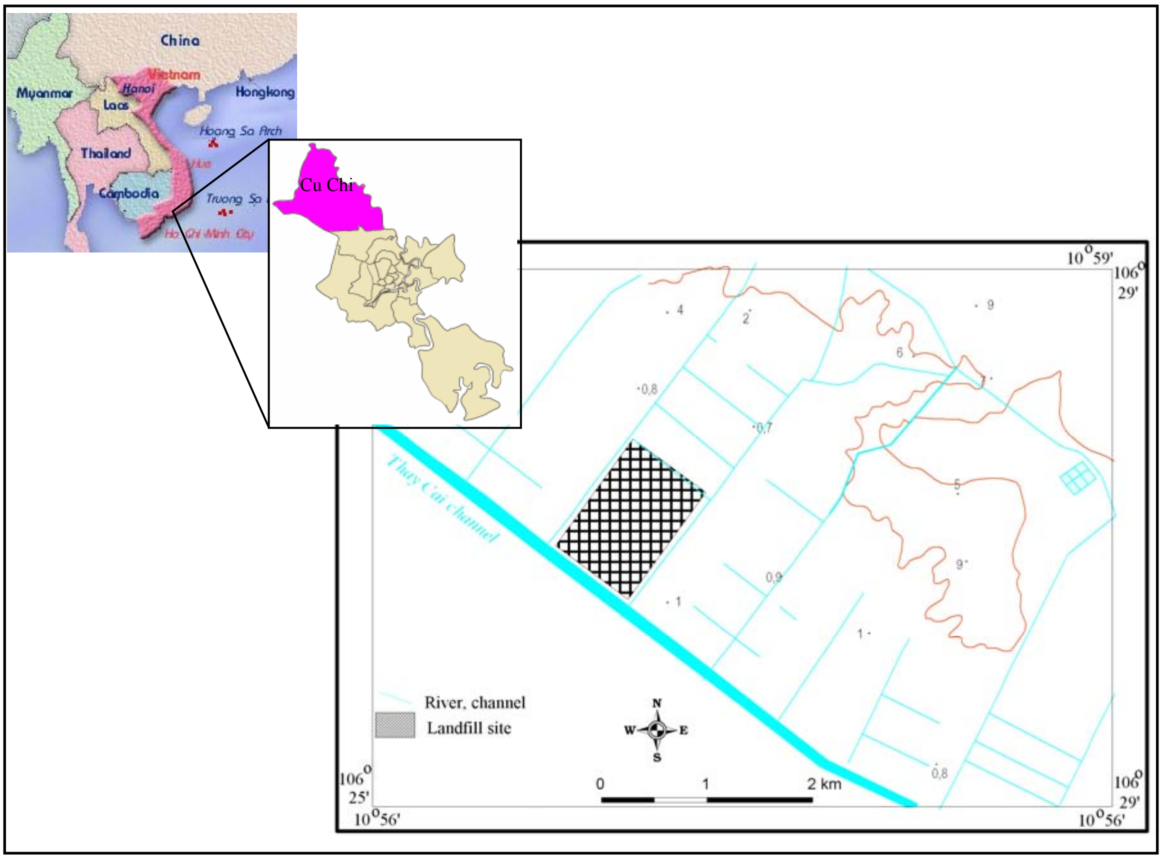

Fig. 1 Location map of the study area.

In this study, the main objectives are to investigate the vulnerability characteristics of the main aquifer and to evaluate the groundwater quality and contamination characteristics derived from the hazardous landfill sites.

2. General Characteristics of the Study Area

Ho Chi Minh city has an area 2,095.24 km^2 with a total population of about 7.5 million in the year of 2010. With incessant development and urbanization, Ho Chi Minh City faces an increase of solid waste. According to Department of Environmental Resource, there are about 6,000 tons solid municipal waste (from 1 million residences in the city); 1,200 tons building material waste, 200,000 tons industrial waste (from 15 industrial zone, 3 export processing zone, more than 800 factories and 23,000 small business or family-enterprise) and about 7 – 9 tons medical waste (from 59 hospitals, 400 medical centers and more than 5,000 clinics). This city demonstrates the typical characteristics of tropical monsoon climate (humid, hot and rainy). The highest monthly precipitation of (250 and 320 mm) occurs from June to September and the lowest levels of (3 – 10 mm) are observed from December to March.

Landfill is the most common method to treat solid waste, however, 90% of landfills in Ho Chi Minh city are of low quality. Amount of 8,000 tons solid waste in Ho Chi Minh City have been disposed at four landfills as Phuoc Hiep, Da Phuoc, Dong Thanh and Go Cat. Among them, Dong Thanh landfill was closed at the end of the year 2001 and thus solid waste in the city has been treated at Go Cat and Phuoc Hiep landfills. However, in fact that Go Cat landfill had treated approximately 3,000 tons/day although its capacity is only 2,000 tons/day. This operation resulted in closure of Go Cat landfill in July 2007. For Da Phuoc landfill, it was expected that it can receive solid waste in August 2007 but this landfill can not be operated in time because of technical reason.

2.1 Geological and hydro-geological settings

The Neogene sedimentary rocks of Nha Be Formation were observed at 200 m depth borehole's 801, 804 and 807 in Cu Chi district. It consists of pebble, gravel and coarse sand in their lower section and fine sand for their upper section. Finally, Quaternary alluvial layers overlie the basement and the Neogene sedimentary rocks. They consist of: (1) early Pleistocene of Trang Bom formation *(*Q_1^1*tb)*; (2) middle Pleistocene of Thu Duc formation (Q_1^{2-3}*tđ*); (3) late Pleistocene of Cu Chi formation *(*Q_1^3*cc*); (4) middle-early Holocene of Binh Chanh formation(Q_2^{1-2}*bc)*; (5) middle-late Holocene of Can Gio formation (Q_2^{2-3}*cg)* and (6) late Holocene. In the study area, sedimentary rock of Cu Chi and Binh Chanh formation formed from sand, silt and clay with gravel is widely observed in the north east while Can Gio formation formed from fine sand, clay, peat with plant were identified in the west (**Fig. 2**).

The geological characterization revealed that the most important water bearing units in the study area are the alluvial aquifers. The Quaternary aquifers such as Holocene aquifer and Pleistocene aquifer are composed of alluvial deposits (**Fig. 3**).

Holocene aquifer (Q_2): with silty sand and clayey materials are located along the Thay Cai channel and in the center of the study area. This is unconfined aquifer which thickness ranges from 2 to 5 m from north to south.

Pleistocene aquifer (Q_1^{1-2}): this aquifer consists of granular material such as sand and gravel are mainly located from the center to the east. The sandy aquifer is used to supply drinking waters, as well as for irrigation and industrial uses because of high-yield aquifer. This is unconfined aquifer and is recharged from the surface and from water seeping by river. Groundwater flow direction is northwest-southeast with hydraulic gradient being from 2×10^{-4} to 1×10^{-3} 9). Groundwater from areas near the waste sites is being exploited from this Pleistocene aquifer.

Groundwater levels in the alluvial aquifer are 25 – 65 m above sea level. The groundwater flow direction in the study area was determined to be from north to south. It should be noted that more than 90% of the pumped groundwater is obtained from the alluvial aquifer, where the solid waste is located. However, from the 1990s to the present, rapid industrialization and consequent population growth over the last 10 years have led to increased groundwater demand, resulting in excessive overdraft.

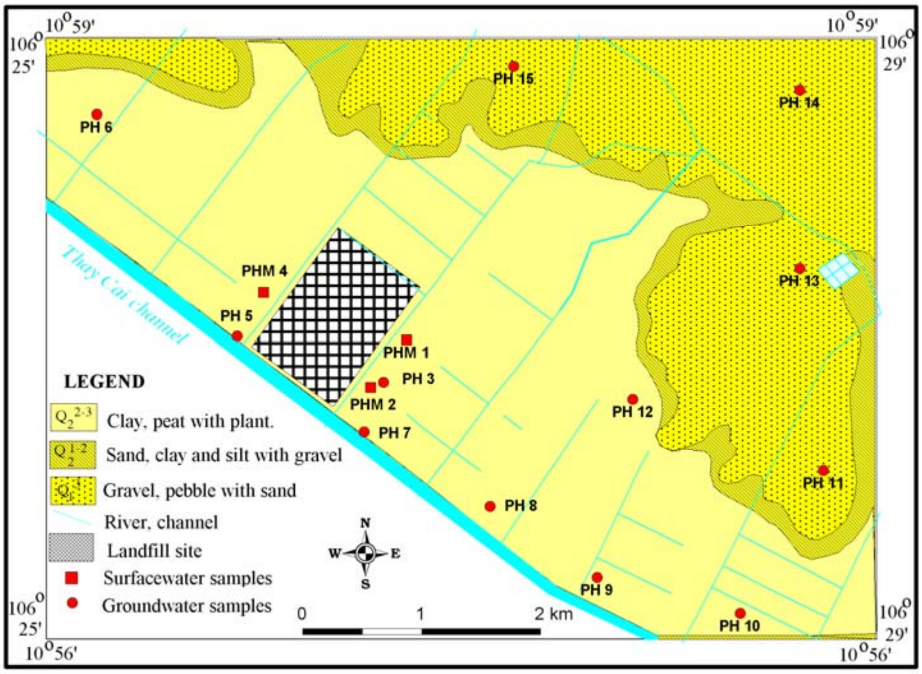

Fig. 2 Geological and sampling location map of the study area.

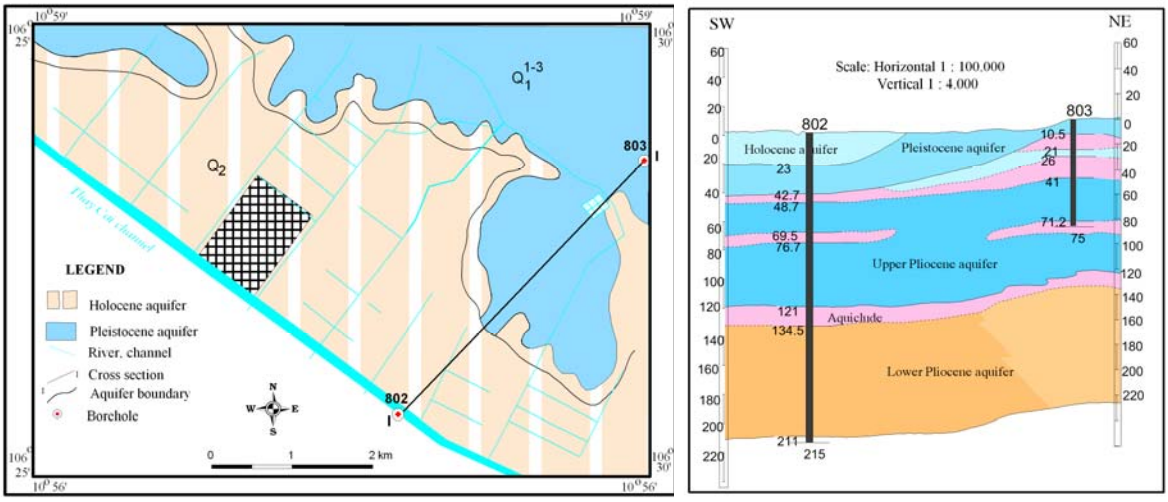

Fig. 3 Hydro-geological map of the study area.

3. Sampling Procedure and Database

A total of 24 groundwater sampling points were selected to represent the condition of groundwater and 6 samples from surface water were taken from September 2009 to January 2010.

One sample was taken from the landfill leachate (L1). During the sampling, the waters were pumped for 15 – 20 min, then the first sample was taken. All samples were filtered through 0.45μm filter paper. Two sets of samples were taken at each sampling point: a 250 ml sample for major ions (cations and anions) and a 100 ml sample for Fe, Mn, Al and heavy metals. All water samples were stored in polyethylene bottles. Hydrochloride acid was then added to make pH of the sample less than 2. The pH values were measured using field equipment. Cations and anions (Cl^-, NO_3^-, SO_4^{2-}, NH_4^+, Na^+, K^+, Ca^{2+} and Mg^{2+} ions) were determined by ion chromatography (Dionex ICS-90). Total alkalinity as HCO_3^- was measured by titration using methyl orange and bromcresol green indicators in the laboratory. Trace elements and heavy metals were analyzed with ICP-AES (Inductively Coupled Plasma Atomic Emission Spectrometry) (Vista-MPX) in Kyushu University laboratory. The Aquachem 4.0 computer program was used to assess the water chemistry of the samples.

The database for vulnerability analysis is presented in **Table 1**. The GIS integration of the database was performed on an Arc View platform developed by the Environmental Systems Research Institute (ESRI) Inc [8)]. The general project area was revised and reduced based on the locations of the boreholes given in **Table 1**. Moreover, the domain of interest could be considered an area in which the interpolation of the 15 borehole values is more accurate and the interpolation errors are minimized. The GOD model was used in this study to understand the surficial aquifer vulnerability condition. The vulnerability assessment is based on three parameters: i) G: mode of groundwater occurrence, ii) O: overlying lithology, and iii) D: depth to water table [4-5)]. The flow chart presented in **Fig. 4** illustrates the evaluation procedure of the GOD model. According to the GOD procedure, the aquifer vulnerability can be classified into four group such as neglect, low, moderate and very high vulnerability to contamination.

Table 1 Database for aquifer vulnerability assessment.

Well No.	X	Y	Groundwater occurrence	Overall lithology of aquifer	Depth to groundwater	G	O	D	GOD index
PH 3	657806	1211343	Unconfined	Silty sand and clay	20	1.0	0.5	0.7	0.35
PH 5	656577	1211733	Unconfined	Sand, silt with gravel	22	1.0	0.7	0.6	0.42
PH 6	655400	1213600	Unconfined	Sand	25	1.0	0.6	0.6	0.36
PH 7	657643	1210924	Unconfined	Silty sand and clay	18	1.0	0.6	0.7	0.42
PH 8	658700	1210300	Unconfined	Sandy gravel	27	1.0	0.7	0.6	0.42
PH 9	659600	1209700	Unconfined	Sand, clay with gravel	24	1.0	0.8	0.6	0.48
PH 10	660800	1209400	Unconfined	Coarse sand and gravel	28	1.0	0.8	0.6	0.48
PH 11	661500	1210600	Semi-confined	Sand and clayey gravel	30	0.5	0.8	0.6	0.24
PH 12	659900	1211200	Unconfined	Silty sand and gravel	29	1.0	0.7	0.6	0.42
PH 13	661300	1212300	Semi-confined	Sandy gravel	32	0.5	0.8	0.6	0.24
PH 14	661300	1213800	Semi-confined	Coarse sand and gravel	35	0.5	0.8	0.6	0.24
PH 15	658900	1214000	Semi-confined	Coarse sand and gravel	38	0.5	0.8	0.6	0.24

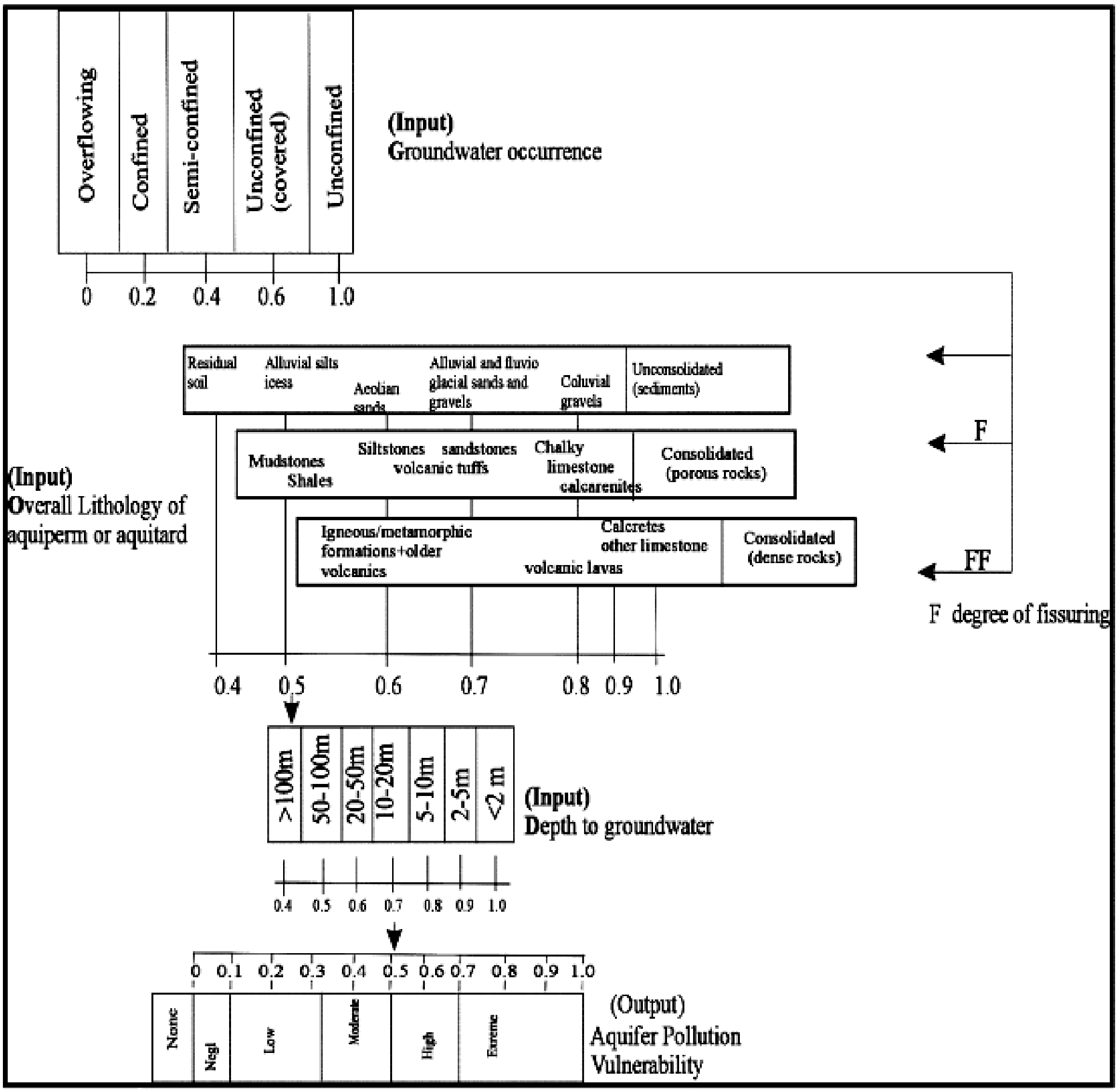

Fig. 4 GOD model for evaluation of aquifer vulnerability index $^{4-5)}$.

4. Results and Discussions

4.1 Landfill leachate and surface water composition

Several important geo-environmental properties of the Phuoc Hiep landfill site are summarized according to EIA report $^{9)}$ in **Table 2**. The landfill site is located near the Thay Cai channel and is situated within the boundaries of the Cu Chi district (**Fig. 2**). The drinking waters of these areas are mostly provided from the shallow aquifer that is formed as a result of the alluvial deposits. The southern and eastern portions of the site, on the other hand, are highly populated residential areas. There are several groundwater production wells, which have been used for agricultural activities near the landfill site. According to geo-environmental conditions, the sandy aquifer site is unsuitable for waste disposal facilities.

Table 2 Characteristics of the Phuoc Hiep landfill site.

Parameters	Geo-environmental criteria [10)]	Phuoc Hiep landfill
Area		50 ha
Numbers of dumping box		4
Area of dumping box		150 x 298 = 4.47 ha
Maximum height of dumping box		25 m
Total capacity		2.7 million tons
Storing capacity		3,000 tons/day
Characteristics of dumping pit		
Geotextile layer		
Clay: K = 0.8		Clay: K = 0.8
Sand: K = 0.95		Sand: K = 0.95
HDPE layer		
Sand: K = 0.95		Sand: K = 0.95
Macadam: K = 0.8		Macadam: K = 0.8
Thickness of barrier bedrock	>3 m	No
Depth to groundwater	>3 m	20 m
Distance to river bed	> 90 m	15 m
Distance to motorway	>300 m	2000 - 3000 m
Distance to urban	>1000 m	5000 – 6000 m

Results of the chemical analyses of the leachate derived from the Phuoc Hiep waste disposal area and surface water are presented in **Table 3**. The Phuoc Hiep landfill is mainly composed of municipal waste: 15 – 20% food waste, 15 – 20% paper, 3 – 5% metals, 5 – 10% plastics, and the rest industrial waste [9)]. The composition of the leachate seepage is directly related to the composition of the landfill. Water from the landfill is dark brown and Na-Cl type with high dissolved solids (**Table 3** and **Fig. 5**). The concentrations of major ions are higher in arid season than in wet season. Electrical conductivity values are between 4,275 and 4,575 µS/cm. High EC values, which are assumed as a contamination indicator for ground and surface waters, are due to the high concentrations of dissolved solids in the leachate.

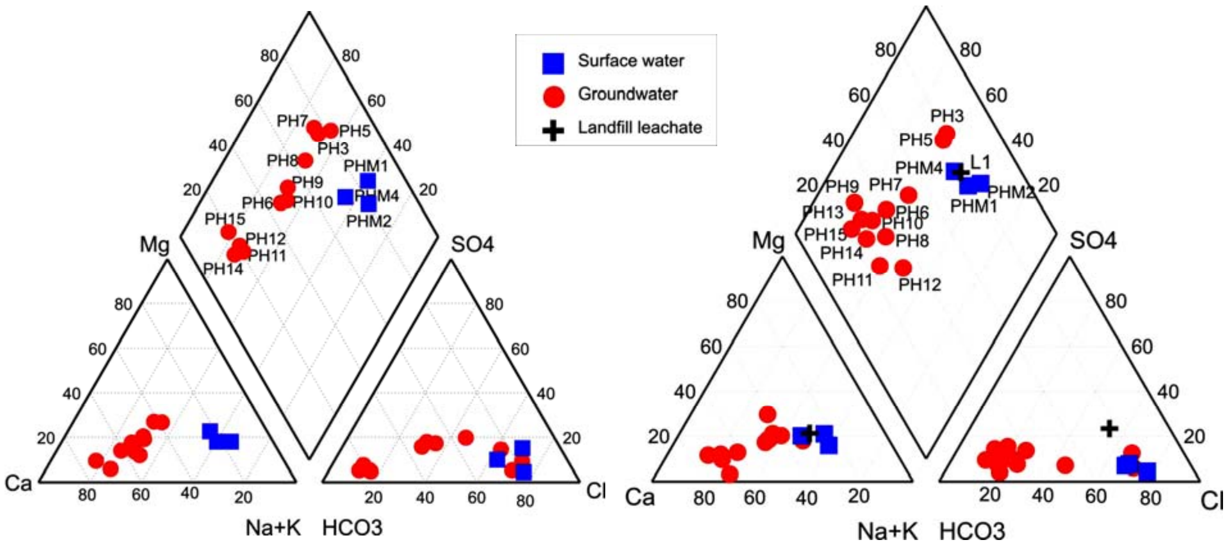

Fig. 5 Piper diagram of water sampled in Sep, 2009 (left) and Jan, 2010 (right).

Hardness values for wastewater vary between 525 and 795 with an average of 660. Increase of concentrations of the major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) causes an increase in hardness. The pH values of the leachate are between 5.8 and 6.6. Concentrations of Al, Fe, Mn, and trace elements (Cu, Pb, Zn, Cr, Cd and As) in the leachate are above the drinking water standards (**Table 3**) for both arid and wet seasons. As a result, the chemical composition of the waste leachate is highly hazardous to the environment and the water sources.

Surface waters were taken from small channels along the landfill. The landfill is considered as the point source for all the contaminants for surface water because leachate from landfill is illegally discharged to these channels. Waters from these channels are brown with yellow scum or black, highly condensed and stink (**Fig. 6**). Relatively similar chemical characteristics (high EC, NH_4^+, NO_3^-, Cl^-, other anions, major cation, trace elements and heavy metal) present between water from these channels and landfill leachate (**Table 3**). It can be said that surface waters have been organically polluted from the landfill leachate as high values of COD, BOD_5 and presence of E.coli and coliforms. Moreover, **Fig. 5** shows that these samples are of Na-Cl type and locates near the landfill leachate (L1).


Discharge pipe near the leachate

Surface water near PHM 2 and PHM 4 sample

Fig. 6 Surface water near landfill site.

4.2 Aquifer vulnerability

The groundwater in the study area is fed with rainfall locally infiltrating the land surface, and some activities at the land surface control the groundwater quality. The GOD model [4-5] was used to evaluate the regional groundwater pollution potential in this study. The vulnerability map of the surficial aquifer is presented in **Fig. 7**. According to vulnerability mapping, two main zones (moderate and low vulnerable) within the alluvial aquifer were determined by the data obtained from the 15 drilled wells. The area around the Thay Cai channel and the landfill site has a GOD Index value in the ranges from 0.3 to 0.5 and is considered to be a moderately vulnerable. The other zones have a low vulnerability according to the GOD Index value of less than 0.3. The alluvial aquifer was divided into two zones on the basis of GOD vulnerability index model.

4.2.1 Moderate vulnerability zone

Areas of moderate vulnerability generally have high scores from the most important parameters including the depth to groundwater and the upper layer lithology. Such sites are generally considered not to be suitable for solid waste disposal or other industrial activities. Under extreme conditions, these sites could be used by taking all the necessary precautions to avoid any groundwater contamination. In the study area, candidte areas for waste disposal are generally located over the western parts of the Holocene aquifer (**Fig. 3** and **Fig. 7**). The lithology of these areas is mostly alluvial gravels and sands that are potential aquifers for groundwater production. The recharge from the surface is very high due to the well-drained and permeable material. The area, however, has a medium permeable material such as silty sand and includes some impermeable soil (clay) at various depths. Therefore, the leakage from surface contaminant sources is transported slowly compared to the sandy aquifer (GOD index around 0.35). In the study area, the hazardous landfill disposal site is situated on the sandy aquifer.

4.2.2 Low vulnerability zone

Areas of low vulnerability are generally located in the central and eastern part of the Pleistocene aquifer (**Fig. 3** and **Fig. 7**). These areas are mostly covered by granular material but it is considered to be of low vulnerability because depth to groundwater is deep compared to the Holocene aquifer. Therefore, the leakage of surface contaminant sources may take more time. Moreover, these areas are mostly covered by residential areas.

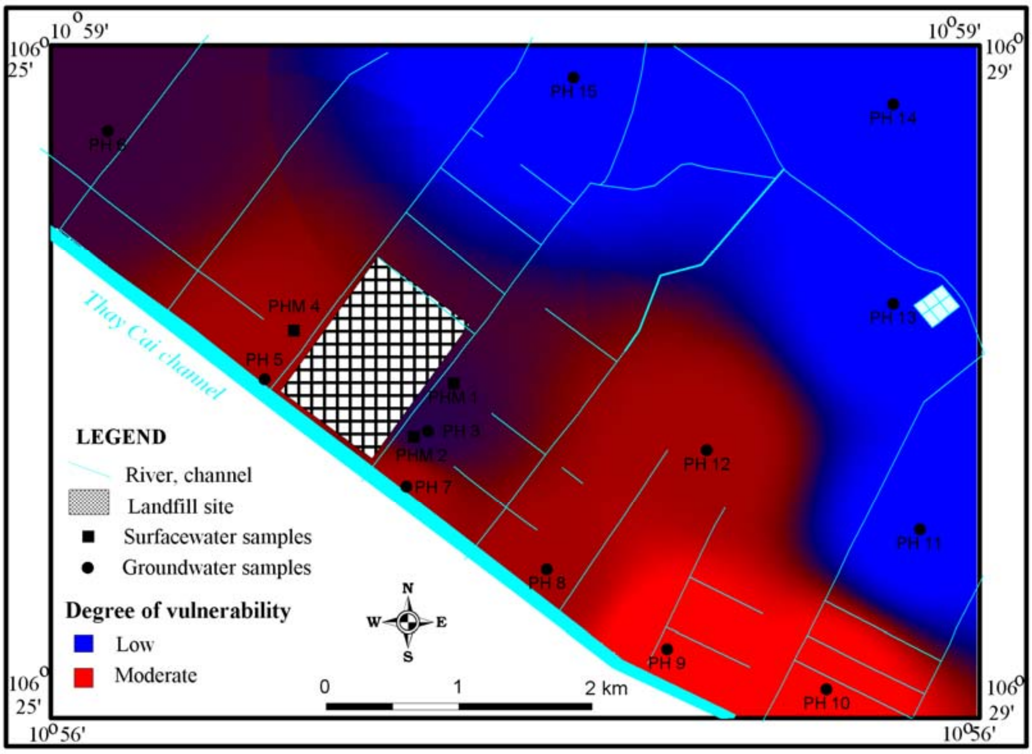

Fig. 7 The vulnerability map of the shallow alluvial aquifer.

4.3 Groundwater quality

The pH of the groundwater is near neutral (6.4 – 8.4) for both the moderate and low vulnerability aquifers (**Table 4**). The pH values for samples PH 3, PH 5, and PH 7, which are near the landfill site, are 6.7 – 8.4. EC values vary between 175 and 590 µS/cm in the wet season (September 2009) and 238 and 583 µS/cm in the dry season (January 2010). An average EC value for the vulnerable zone in the dry season is higher than those in the wet season. Wells near the landfill site also have relatively high ion concentrations and EC values show that leachate seepage affects groundwater quality, especially during the dry season. The hardness values of the groundwater in the vulnerable areas are remarkably high (>145 mg/L $CaCO_3$) for Wells PH 3, PH 5, and PH 7. Hardness values also differ according to the groundwater recharge conditions from the surface. Average hardness values in groundwater samples for the dry season and wet season range from 70 to 394 (mg/L $CaCO_3$) and from 50 to 180 (mg/L $CaCO_3$), respectively. It is important to note that the recharge from the surface into the vulnerable aquifers is assumed to decrease hardness of groundwater during the wet season. The mean hardness value for the leachate is about 660 (mg/L$CaCO_3$) and percolation of the leachate to the aquifer causes the hardness in groundwater to increase. Average value of Ca^{2+} and Mg^{2+} concentrations are around 185.1 mg/L (61.2 mg/L – 309 mg/L) and 41.9 mg/L (20.7 mg/L – 63.1 mg/L) in the vulnerable aquifer (PH 3, PH 5 – 10 and PH 12), and 92.9

mg/L (57.8 mg/L – 128 mg/L) and 11.1 mg/L (3.9 mg/L – 18.3 mg/L) in the low vulnerability aquifer (PH 11 and PH 13 – 15) during the dry season. Relatively high concentrations of Ca^{2+} and Mg^{2+} are obtained in moderately vulnerable zone (**Table 4** and **Fig. 7**). This is explained by dilution of the leachate composition when the leachate is mixed with the groundwater.

Based on their chemical composition and Piper diagram (**Fig. 5**), water types of the groundwater are of dominantly Ca-Na-(Mg)-HCO_3 during the arid and wet season, except PH 9 and PH 12 are Ca-Na-(Mg)-HCO_3-Cl type. However, water from PH 3, PH 5 and PH 7, which are located close to the waste disposal area are of Ca-Na-(Mg)-Cl type (**Fig. 5**). Na^+ concentrations for groundwater samples reach up to 190 mg/L in the vulnerable aquifer and 62.1 mg/L in the low vulnerability aquifer in the arid season. High Na^+ concentrations are probably derived from mixing with the leachate (in which Na^+ concentrations reach up to 1,500 mg/L). Cl^- with concentrations of 21 – 409 mg/L is an important ion for groundwater in the study area. High Cl^- concentrations are resulted in the contributions of the leachate seepage and contaminants derived from other industrial activities to the groundwater. The nitrate concentrations in waters are between 1.62 and 19.65 mg/L in the arid season (**Table 4**) with an average of 10.6 mg/L. Nitrate concentrations decrease in the wet season due to the dilution and vary from 1.66 to 17.57 mg/L with a mean value of 9.62 mg/L. For the leachate, nitrate concentrations are 3.8 and 37.2 mg/L for the wet and arid seasons, respectively. Although the nitrate concentrations are high in the wells located near the waste disposal area, higher nitrate concentrations were obtained from sample PH 10 and PH 12, which is located quite far from the waste disposal area (**Table 4** and **Fig. 7**). Since nitrogenous materials are rare in the geological record, nitrate in the groundwater is due to anthropogenic activity. Therefore, infiltration of some fertilizers and seepage from urbanization raised nitrate concentrations above the drinking water standards (10 mg/L in WHO, 2002) for some wells (**Table 4**).

There is a relationship between total metal concentration and pH for the groundwater samples from the study area. Sample L-1, which is the leachate seepage, is of weak acidic with high metal content. The other groundwater samples show near neutral characteristics; they therefore have low metal content when compared with the leachate water. The groundwater samples have low Cu, Ni, Mn, Pb, and Zn concentrations, generally below detection limits. However, some wells near the waste disposal site shows some trace element concentration with detectable level. In particular, it is shown that the Fe concentration in the groundwater is mainly caused by the industrial contaminant from the landfill leachate. Similarly, the same ion contents are observed to be highest at or near the landfill site (**Table 4**). Fe concentration values vary between 0.51 and 10.95 mg/L exceeding the Vietnam drinking water standards (**Table 4**). These wells are located in the vulnerable zone and are affected by the landfill leachate in which Fe concentrations reached up to 60.1 mg/L in the arid season. Some industrial waste leachate is responsible for the high Fe concentration [6)]. Many of the wells located near waste site are not suitable for drinking water purposes.

4.4 Protection of groundwater from the landfill site

In the study area, an examination of the wells in the vulnerable area indicates that it is underlain by coarse sand and gravel. The hydraulic conductivity of the sand layer in the landfill site is 6.65×10^{-2} cm/s [9)]. The depth of the groundwater level is below 20 m. Due to an increase in the groundwater level of about 3 – 5 m resulting from both precipitation and a decrease in irrigation activity, the interaction between groundwater and the leachate is accelerated. The migration of contaminant from the landfill in the moderate vulnerable zone is faster than at the low vulnerability aquifer. When the contaminant reaches the groundwater aquifer, contaminant movement can be accelerated by groundwater pumping and groundwater flow direction in the aquifer.

Leachate seepage changes the geochemical properties of the groundwater. The effects of the waste disposal area located on the highly vulnerable aquifers are discussed above. The groundwater quality and the degree of pollution in the vulnerable sandy aquifer differ from other low vulnerability aquifers. Therefore, the hydro-geological conditions and aquifer lithology are related to groundwater contamination in the alluvial aquifer, which is not suitable for landfill construction. Disposal of the urban waste and other industrial contaminant must be avoided on the vulnerable aquifer. Contaminated groundwater supply wells (PH 3, PH 5 and PH 7) near the waste site were recently abandoned. Therefore, the groundwater management program and protection strategy of the aquifer should be prepared. To protect the groundwater, the vulnerable aquifer under the waste disposal area should be isolated by cement grouting. The grouting wells should be performed at the landfill basement and separated by 2 – 5 m depending on the soil permeability. In addition, monitoring wells and leachate control wells should be drilled in the landfill. The waste surface should also be covered by impermeable barrier clays to avoid rainfall infiltration to the waste landfill.

5. Conclusions

Based on the hydro-geological and geochemical investigations performed in the study area, contamination due to hazardous landfill activities has been determined. According to GOD vulnerability mapping, the shallow aquifer was determined to have two main vulnerability zones. The hazardous landfill site is located on a vulnerable zone that supplies water demand local residences. With respect to chemical composition, water from the landfill was dark brown and of Ca-Na-Cl type with high dissolved solids, and included some toxic elements such as As, Al, Fe, Mn, Ni, and Cd. Leachate seepage was near neutral with high metal content. Groundwater samples near the waste disposal area showed the same water facies (Ca-Na-(Mg)-Cl) with leachate seepage. High Na^+ and Cl^- concentrations are the results of the mixing of leachate seepage with groundwater.

Chemical analyses showed that the groundwater was more or less enriched in a number of elements. Major ions in particular increased around the waste disposal area. Na^+, Cl^-, and SO_4^{2-} were enriched, depending on the mixing of the leachate with the groundwater. Some ions were therefore above the drinking water standards for the water near the waste disposal area. The hydro-geological features of the study area indicated that contaminants derived from the waste disposal area infiltrate through the vulnerable sandy aquifer and move to the south with groundwater flow. Hydro-geological features of the vulnerable aquifer are not suitable for a waste disposal site and cause the contaminants to infiltrate through to the groundwater in the region. Therefore, the landfill site should be rehabilitated and protected for future groundwater quality. In addition, it is important that the landfill sites should be carefully planned and that their environmental impacts be properly mitigated.

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Table 3 Chemical composition of landfill leachate and surface water. Unit is Mg/L, except as noted.

	Landfill leachate			**Surface water**						**Standards**	
	Dry	Wet	Vietnamese standard 11)	Dry 9)			Wet			Vietnamese standard 12)	WHO 13)
				PHM 1	PHM 2	PHM 4	PHM 1	PHM 2	PHM 4		
pH	5.8	6.6	5 - 9	6.7	5.3	7.2	6.2	5.7	7.9	6.5 – 8.5	6.5 – 8.0
EC (μS/cm)	4575	4275		643	980	1094	570	823	947		
SS	240	1520	100								
TDS	2400	7500	1000								600
COD	9000	5670	80	3540	5700	7500	1853	3126	5690	15	
BOD_5	8100	2300	50	3620	4035	5430	1072	2680	3520	6	
TOC	3500	-	-								
NH_4^+	950	1370	10	5.4	28	8.78	2.16	33.3	6.1	0.5	35
NO_3^-	37.2	3.8	50	8.24	23.1	16.8	6.24	16.1	13.6	10	10
Hardness (mg/l $CaCO_3$)	795	525		170	203	400	85	108	147		200
Cl^-	1550	1449	600	378	570	857	323	481	561	250	250
HCO_3^-	2880	1050		216	223	368	133	235	283		
SO_4^{2-}	1500	863		95	47	253	75	12	168		250
Na^+	2600	1517		220	330	196	120	224	91.4		200
K^+	1400	263		5.4	6.3	7.9	2.9	3.7	5.8		
Ca^{2+}	1825	824		79.6	114	118	41.5	55.3	73.9		100-300

	Landfill leachate			**Surface water**						**Standards**	
	Dry	Wet	Vietnamese standard [11)	Dry [9)			Wet			Vietnamese standard [12)	WHO [13)
				PHM 1	PHM 2	PHM 4	PHM 1	PHM 2	PHM 4		
Mg^{2+}	567	378		45	47.2	45.6	15.7	27	36.1		< 100
Mn	13.3	5.7	1	1.15	2.08	0.1	1.12	-	-	0.5	0.1
Fe	60.1	35.1	5	16.1	36.5	5.9	2.65	30.2	3.9	1	0.2
Al	12	3.7		0.15	0.2	0.38	0.1	0.05	0.22	0.5	0.1
Zn	0.62	0.32	2	0.29	0.63	0.47	0.18	0.18	0.34	1	5
Cd	0.003	0.01	0.01	0.008	0.004	0.005	0.02	0.014	0.01	0.005	0.03
Cu	1.31	1.96	1	0.6	1.84	1.24	1.1	2.01	1.5	0.2	2
Ni	0.69	1.52	0.5								0.002
Pb	0.07	0.05	0.5	0.01	0.007	0.07	0.018	0.03	0.05	0.01	0.01
Cr	0.43	0.125	0.1								
As	0.31	0.215	0.1							0.02	0.01
E. Coli							600	-	$1.1x10^6$	50	
Coliforms			5000				4300	93	$4.6x10^6$	5000	

Table 4 Chemical composition of the groundwater in the study area. Unit is Mg/L, except as noted.

Parameters	Date	PH3	PH5	PH6	PH7	PH8	PH9	PH10	PH11	PH12	PH13	PH14	PH15
pH	09/2009	6.7	8.1	7.2	7.1	6.9	7.5	7.1	7.1	7.1	7.5	6.4	7.2
	01/2010	6.9	8.4	7.7	6.7	7.3	7.9	7.3	6.9	7.4	7.2	6.8	7.6
EC (μS/cm)	09/2009	443	380	494	341	590	493	388	328	377	226	175	224
	01/2010	543	429	451	412	527	498	583	384	412	364	238	288
Hardness	09/2009	180	150	64	167	60	72	86	50	58	89	109	111
	01/2010	394	205	110	185	194	161	252	96	103	136	124	106
HCO_3^-	09/2009	182	123	268	166	115	242	262	220	345	267	291	314
	01/2010	201	221	344	486	358	465	452	269	326	304	316	362
NH_4^+	09/2009	1.4	2.8	3.78	3.54	4.36	4.43	5.99	0.91	2.99	1.12	0.81	1.07
	01/2010	2.1	3.4	8.8	12.4	13.1	13.4	14.1	3.99	9.19	1.9	2.06	3.07
NO_3^-	09/2009	3.24	3.14	1.66	3.81	4.73	6.45	15.4	3.49	17.57	1.13	1.51	1.87
	01/2010	6.24	7.14	5.66	8.81	9.73	8.85	9.42	1.31	19.65	1.62	2.28	2.93
SO_4^{2-}	09/2009	51.6	47.7	61.5	28.2	50.5	68.4	71.7	10.5	18.3	17.6	14.9	23.2
	01/2010	91.5	49.7	63.2	58.6	67.3	51.9	59	12.5	30.8	49.2	27.5	35.8
Cl^-	09/2009	286	270	75.2	262	84.4	99.8	90.5	24.8	37.1	29.4	21.7	25.4
	01/2010	360	409	88.8	262	58.9	76.4	83.9	44.4	74.8	35.2	45.6	36
Na^+	09/2009	120	110	95.8	105	129	123	121	60.8	80.4	50.7	38.6	20.8
	01/2010	190	159	115	167	146	70.3	128	62.1	96.6	33.2	56.7	30.3
K^+	09/2009	5.9	5.7	4.8	6.1	7.9	8.5	8.7	5.29	3.71	5.13	6.55	7.97
	01/2010	8.5	6.9	5.1	8.6	12.7	13.6	12.5	6.4	14.3	4.2	8.1	9.2
Mg^{2+}	09/2009	45	47.5	45.6	37.7	44	30.9	24.5	19.7	25	10.2	5.5	7.5
	01/2010	54	51.5	63.1	45.6	43.1	31	35.3	18.3	20.7	8.4	3.9	11.2
Ca^{2+}	09/2009	180	115	118	195	190	209	186	115	180	85.7	105	95.4
	01/2010	216	169	140	204	173	309	267	57.8	61.2	94.6	128	101

Parameters	**Date**	**PH3**	**PH5**	**PH6**	**PH7**	**PH8**	**PH9**	**PH10**	**PH11**	**PH12**	**PH13**	**PH14**	**PH15**
Fe	09/2009	4.65	3.17	5.9	6.19	7.95	5.75	9.6	1.9	8.6	2.1	0.6	0.51
	01/2010	8.15	1.67	6.13	7.39	10.95	7.33	10.6	3.23	4.8	2.38	5.97	3.56
Mn	09/2009	0.18	-	0.15	0.17	0.1	-	0.21	0.05	0.12	0.01	-	0.02
	01/2010	0.12	-	0.05	0.17	-	-	0.15	0.01	0.11	0.08	-	0.04
Cu	09/2009	0.05	0.03	0.2	0.47	0.1	0.27	0.04	-	0.06	-	0.03	0.03
	01/2010	0.1	0.09	0.6	0.5	0.05	0.34	0.09	-	0.08	0.02	0.07	0.07
Zn	09/2009	0.1	0.23	0.15	0.11	0.12	0.14	0.01	0.08	0.03	-	0.05	-
	01/2010	0.3	0.31	0.17	0.33	-	0.24	0.08	-	0.01	0.01	0.03	-