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Groundwater pollution and subsurface sediment contamination in closed MSW landfill, Henchir El Yahoudia

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Abstract
Drilling survey of subsurface geology and groundwater sampling were made at a lakeside of the municipal solid waste (MSW) landfill, Henchir El Yahoudia that is closed in 1999. According to the result of perimeter drilling survey, three aquifers could be recognized below the landfill; 2.0-3.2m, 4.0-6.0m, and 8.5-12.0m in depth. These aquifers were isolated each other using open standpipe piezometer sealed by bentonite for systematic groundwater monitoring. Trace element composition of groundwater respectively showed that Cu, Zn, Pb, and Se are above the quality standard. Potentially toxic element (PTEs) composition of subsurface sediments collected by the drilling survey was also examined. The concentration of non-metal (B, As, Se) and metal (Ti, V, Cr, Co, Ni, Cu, Zn, Mo, Ag, Cd, Sb, Ba, La, Hg, Tl, and Pb) pollutants is extremely high in the uppermost landfill cover layers and the Aquifer-1 sediments, which is probably derived from the landfill.
Keywords
Groundwater pollution, Sediment contamination, Aquifer, Landfill leachate, PTEs

I. Introduction

Groundwater monitoring programme is indispensable after a closure of solid waste landfill to determine the degree to which the landfill capping and closure system is functioning in accord with the design objectives. Main concern is with the excursion/migration of contaminants off the landfill site as leachate or as landfill gas or both. It is essential that the monitoring programme identify the extent to which any excursions/migrations are occurring. The monitoring activities normally include a groundwater monitoring well for detection of off-site migration of contaminants; perimeter monitoring well system, lysimeters under the liner structure, perimeter storm-water ditching system, etc. (McBean et al., 1995).

In this paper we report a preliminary result of monitoring data obtained from perimeter groundwater monitoring wells installed at the Sebkhat Sejoumi lakeside of Henchir El Yahoudia landfill, and discuss about the contamination and pollution of groundwater of the area.

II. Borehole HY1 and Monitoring Wells

The local geology of the area is composed of two geologic systems, Neogene-Paleogene sedimentary rocks and Quaternary lake sediments. The former is a hydrogeologic basement and the later is basin-filling terrestrial deposits consisting of relatively permeable media within the Sejoumi-Manouba hydrogeologic basin. The Sebkhat Sejoumi, an isolated salt lake, is located in the center of the Sejoumi-Manouba hydrogeologic basin, which is accumulating a pile of lake sediments. The sediments consist of unconsolidated to semiconsolidated gravels, sand, silt, clay, marl, and evaporite which are potentially aquifers. The lake water is available in winter (rainy) season but almost completely evaporated in summer (dry) season.

The Henchir El Yahoudia landfill was constructed along the lakeside of Sebkhat Sejoumi for disposing various kind of solid wastes, mostly municipal solid wastes (MSW), generated from the greater Tunis region, which was operated from 1960s to 1999. The landfilling activitiy was terminated in 1999 and landfill capping and closure operations have been made since 1999. Four drilling holes were penetrated around the landfill by ANPE in 2000, and we installed three observation wells, HY1-P1, P2, and P3, for monitoring groundwater from three aquifers in 2002 (Figure 1 and Plate 1).

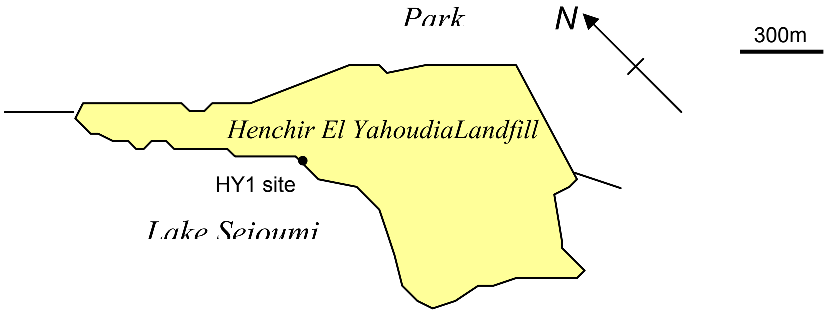

Figure 1: Locality map of the site HY1.

Plate 1: Field photograph of the observation wells HY1-P1, P2, P3, and HY1 test hole (left) and an operation of graoundwater sampling by hand pumping tool (right).

The subsurface geology of the site HY1 is shown as a geologic columnar section of HY1 test hole in Figure 2. The sampling horizons also illustrated in the figure.

According to the lithostratigraphic observation of the HY1 test hole cores, we could recognized three aquifers, Aquifer-1, -2, and –3 from top downward, in the unconsolidated/semiconsolidated Quaternary sediments:

Aquifer-1: -2.00m to –3.20m in depth
Aquifer-2: -4.00m to –6.00m in depth
Aquifer-3: -8.50m to –12.00m in depth

The deposits from surface to –1.50m in depth is recent artificial covers after the closure of the landfill. The basal part of this covering deposits, we could find leachate spill and its contamination zone. Below the deposits, lake sediments of natural geologic unit is exposed (Figure 2). The Aquifer-1 yields strong smell of H_2S.

Each aquifer is isolated by a screen interval of siliceous granule sand layer limited by top and bottom bentonite seals. The well hole is cased by a PVC pipe.

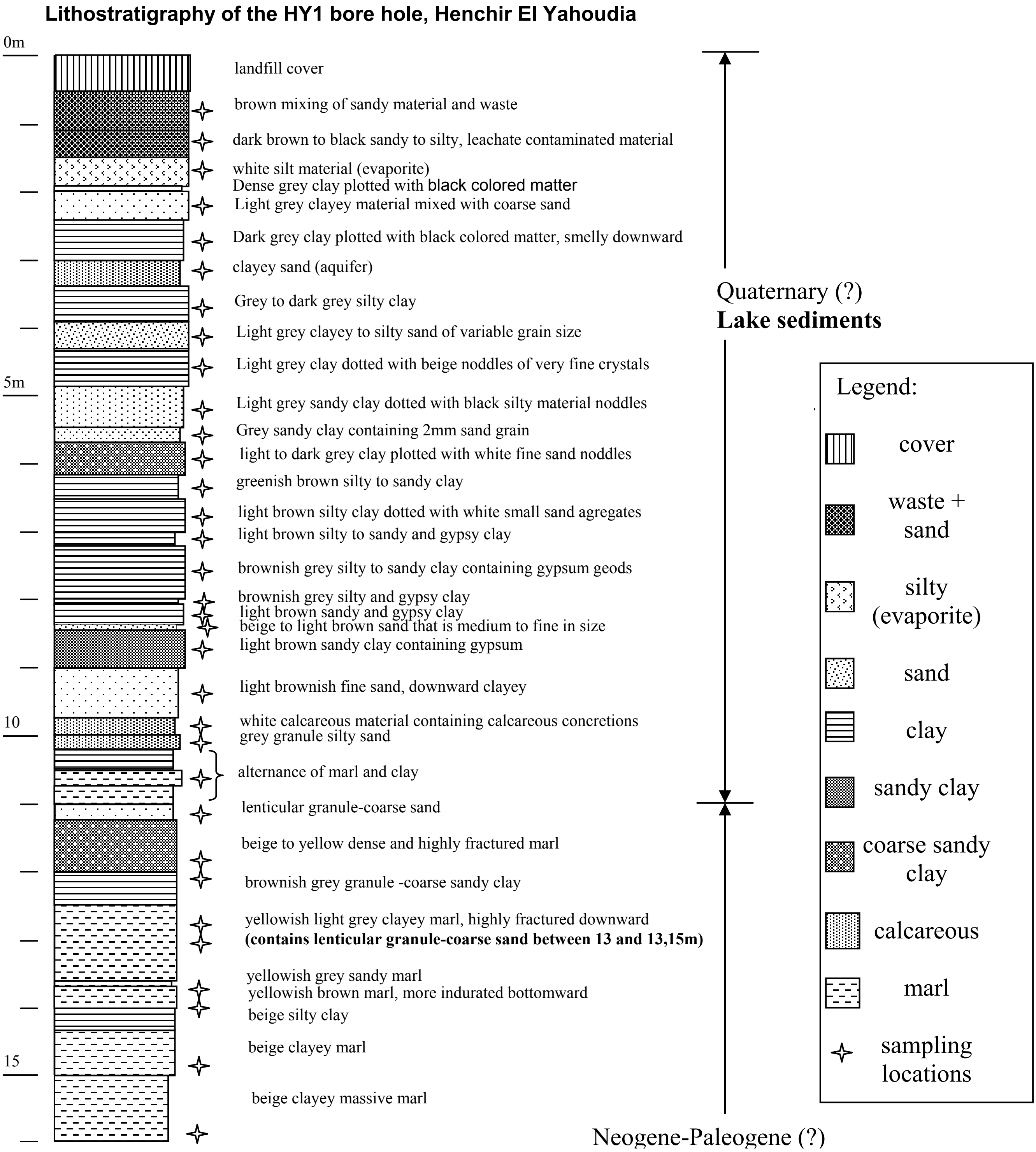

Figure 2: Geologic columnar section of the HY1 test hole in Henchir El Yahoudia (described by Ibrahim and Yoshida in Ibrahim(2002)).

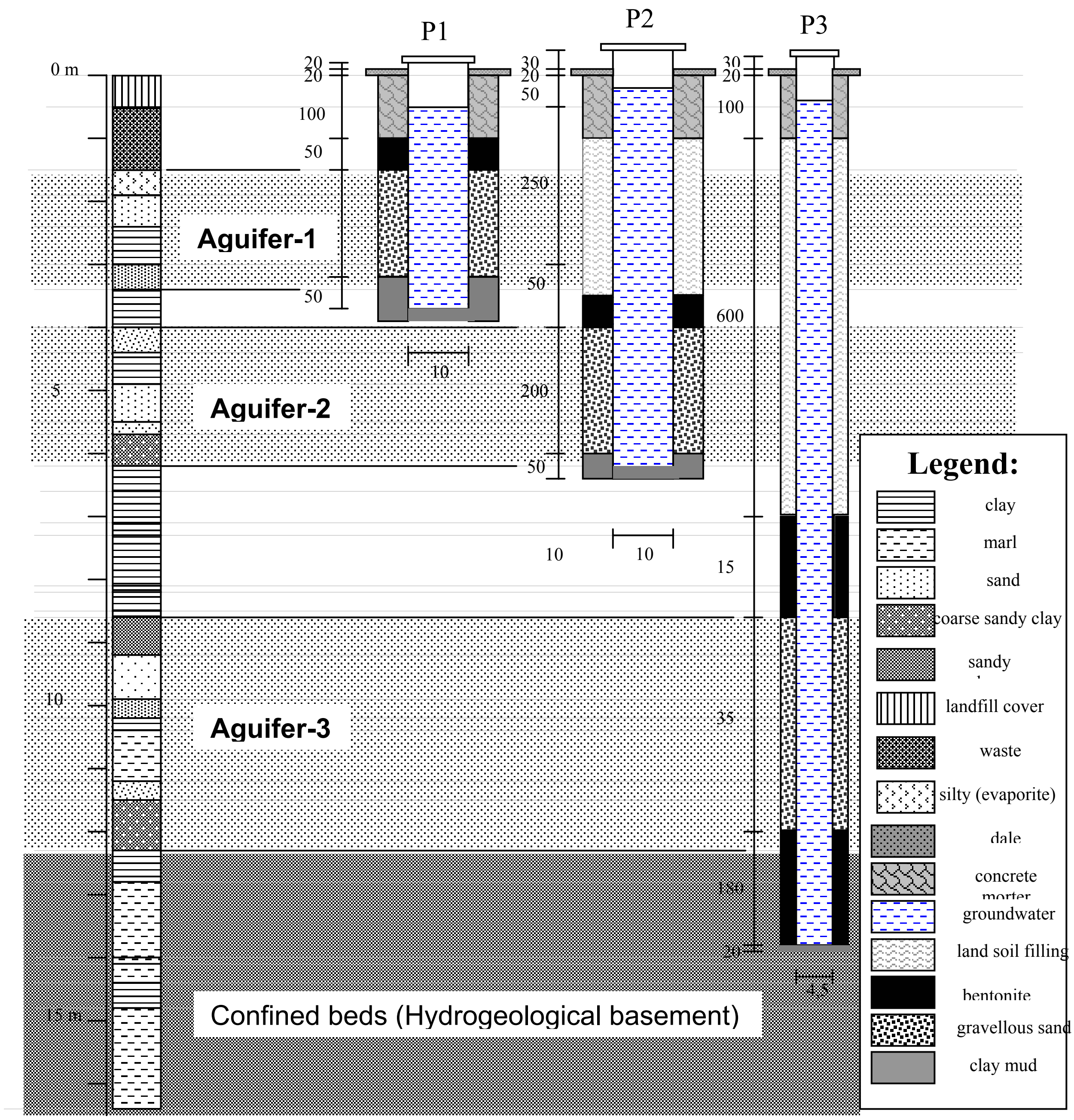

Figure 3: Structure of the groundwater monitoring wells, HY1-P1, P2, and P3 (designed by Yoshida and Ibrahim in Ibrahim(2002)).

III. Samples

The groundwater samples analyzed were collected from three wells, HY1-P1, P2, and P3, at 10th May 2002, two days after the rain fall. Groundwater samples are collected using hand pumping method directly from the well (Plate 1). In order to obtain fresh groundwater sample representing each aquifer, the sampling was made after the complete discharge of groundwater filled in each hole. A total of 33 sediment samples were also collected from the borehole cores of HY1 for examining sediment contamination. Recent lake sediments surrounding the HY1 site, which is contaminated by landfill leachate, also collected from ground surface. The list of samples collected is shown in Table 1.

Table 1: List of samples for analysis

Sample ID	Type	Description
HY1-P1	water	Groundwater samples collected from HY1-P1 well (Aquifer-1)
HY1-P2	water	Groundwater samples collected from HY1-P2 well (Aquifer-2)
HY1-P3	water	Groundwater samples collected from HY1-P3 well (Aquifer-3)
HY1 cores	sediment	Borehole core samples: HY1-0.85, HY1-1.20, HY1-1.68, HY1-2.15 HY1-2.80, HY1-3.15, HY1-3.72, HY1-4.20, HY1-4.62, HY1-4.90 HY1-5.45, HY1-5.70, HY1-6.15, HY1-6.60, HY1-7.00, HY1-7.60 HY1-8.00, HY1-8.10, HY1-8.40, HY1-8.70, HY1-9.40, HY1-9.90 HY1-10.00, HY1-10.53, HY1-11.00, HY1-11.75, HY1-12.25, HY1-12.80, HY1-13.00, HY1-13.73, HY1-14.00, HY1-14.90, HY1-15.90 (Each number is the depth (m)); Total 33 samples

IV. Analytical Methods

IV-1. Water Analysis

The groundwater samples were at first treated by H_2O_2 30% solution to consume all organic matters contained. Then the treated samples was prepared for pH<2.0 using HNO_3. Analysis was made by an Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Total 74 elements were measured: Li, Be, B, Na, Mg, Al, Si, P, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Th, and U.

IV-2. Sediment Analysis

A 15.0 gm sample split was digested in 90 mL aqua regia (HCl-HNO_3-H_2O) at 95°C for one hour. The solution is diluted to 300 mL with distilled water. Analysis was made by an Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) and Mass Spectrometry (ICP-MS). Total 37 elements were measured: B, Na, Mg, Al, P, S, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Sr, Mo, Ag, Cd, Sb, Te, Ba, La, W, Au, Hg, Tl, Pb, Bi, Th, and U. The upper detection limit for Ag, Au, Hg, W, Se, Te, Tl, and Ga is 100 ppm, that for Mo, Co, Cd, Sb, Bi, Th, U, and B is 2 %, and that for Cu, Pb, Zn, Ni, Mn, As, V, La, and Cr is 10 %. The aqua regia digestion of sediment extracts only a fraction of the major elements (pseudo-total analysis) because silicates are not completely dissolved with this method. Owing to this limitation, results are total to near total for trace and base metals and possibly partial for rock-forming elements such as Na, Mg, Al, K, Ca, Mn, and Fe. However, environmentally concerned components like heavy metals or potentially toxic elements (PTEs; Alloways, 1995) not bound to silicates are efficiently dissolved (Ure, 1995), which is indicative for the assessment of toxicity.

V. Results and Discussion

V-1. Groundwater Contamination

The result of groundwater samples collected from three aquifers is shown in Table 2. It indicates that the Aquifer-1 and Aquifer-3 show similar chemical compositions with abundant Na, Mg, K, Ca, Mn, and Cl, while the composition of the Aquifer-2 is relatively poor in most elements except Cd, Ba and Lanthanids. The groundwater collected from the Auifer-1 and Aquifer-3 contains approximately 3% of salt (NaCl) showing a linkage with salt lake water. Potentially toxic elements (PTEs) such as V, Cr, Co, Cu, Zn, As, and Pb are relatively enriched. The concentration of bromine (Br) in Aquifer-1 and 3 is also abnormally high.

Table 2: Results of groundwater analysis

Atomic #	3	4	5	11	12	13	14	15	16	17	19	20	21	22	23	24	25	26
ELEMENT	Li	Be	B	Na	Mg	Al	Si	P	S	Cl	K	Ca	Sc	Ti	V	Cr	Mn	Fe
unit	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppm	ppm	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
YH1-P1	776	< .05	2204	27238880	1683652	302	44318	<20	2284	38322	265488	1474426	83.48	26	42	57	1301.3	26
YH1-P2	304	< .05	728	2575584	213490	556	5278	58	632	3418	33284	700526	3.52	< 10	6	8	156.9	44
YH1-P3	1218	< .05	14234	36768900	2089424	224	14332	<20	3992	50044	190616	2037568	6.4	< 10	68	20	1164.1	76
Detection Limit	1	0.05	20	50	50	1	1	20	1	1	50	50	0.05	10	1	0.5	0.05	10

Atomic #	27	28	29	30	31	32	33	34	35	37	38	39	40	41	42	44	45	46
ELEMENT	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Rb	Sr	Y	Zr	Nb	Mo	Ru	Rh	Pd
unit	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
YH1-P1	17.3	< .2	263.2	302.8	< .05	< .05	104	209.8	98522	91.98	22922.3	< .01	< .5	0.24	75.8	< .05	0.16	< .2
YH1-P2	1.76	< .2	42.4	48.4	< .05	< .05	12	< .5	8328	9.64	12925.9	0.5	< .5	0.06	10.4	< .05	< .01	< .2
YH1-P3	12.22	< .2	331.4	232.4	< .05	< .05	140	< .5	127822	20.6	25604.4	< .01	< .5	0.16	29.8	< .05	< .01	< .2
Detection Limit	0.02	0.2	0.1	0.5	0.05	0.05	1	0.5	5	0.01	0.01	0.01	0.5	0.01	0.1	0.05	0.01	0.2

Atomic #	47	48	49	50	51	52	53	55	56	57	58	59	60	62	63	64	65	66
ELEMENT	Ag	Cd	In	Sn	Sb	Te	I	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy
unit	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
YH1-P1	2.18	< .05	0.04	< .05	1.6	1.84	3690	2.8	335.1	< .01	< .01	< .01	< .01	< .05	< .01	< .01	< .01	< .01
YH1-P2	0.3	1.3	< .01	< .05	0.94	0.18	344	0.12	329.92	0.52	1.5	0.06	1.08	0.12	< .01	0.06	< .01	< .01
YH1-P3	1.72	< .05	0.02	< .05	< .05	1.1	3856	0.28	295.5	< .01	< .01	< .01	< .01	< .05	< .01	< .01	< .01	< .01
Detection Limit	0.05	0.05	0.01	0.05	0.05	0.05	1	0.01	0.05	0.01	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.01

Atomic #	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	90	92
ELEMENT	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Th	U
unit	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
YH1-P1	< .01	< .01	< .01	< .01	< .01	0.06	< .05	17.6	0.24	< .05	< .05	< .01	3.68	< .1	< .01	230.4	< .05	0.2	5.02
YH1-P2	< .01	< .01	< .01	< .01	< .01	< .02	< .05	4.2	0.08	< .05	< .05	< .01	< .05	< .1	0.08	251	< .05	0.26	4.94
YH1-P3	< .01	< .01	< .01	< .01	< .01	< .02	< .05	0.8	0.14	< .05	0.12	< .01	< .05	< .1	< .01	511.4	< .05	< .05	10.36
Detection Limit	0.01	0.01	0.01	0.01	0.01	0.02	0.05	0.1	0.01	0.05	0.05	0.01	0.05	0.1	0.01	0.1	0.05	0.05	0.05

Table 3: Water quality criteria for dissolved PTEs (US EPA, 1999) and wastewater regulation values in Tunisia (N.T.106.002(1989)). Unit micro gram per liter (ug/l)

	Freshwater		Saltwater		HHFC**		N.T106.002 Tunisia
	CMC* (ug/l)	CCC* (ug/l)	CMC (ug/l)	CCC (ug/l)	Water + Organism (ug/l)	Organism only (ug/l)	Wastewater regulation*** (ug/l)
Sb					14	4300	100
As	340	150	69	36	0.018	0.14	50
Be							10
Cd	4.3	2.2	42	9.3			5
Cr(III)	570	74					500
Cr(VI)	16	11	1100	50			10
Cu	13	9.0	4.8	3.1	1300		500
Pb	65	2.5	210	8.1			100
Hg	1.4	0.77	1.8	0.94	0.050	0.051	1
Ni	470	52	74	8.2	610	4600	200
Se		5.0	290	71	170	11000	50
Ag	3.4		1.9				50
Tl					1.7	6.3	
Zn	120	120	90	81	9100	69000	5000
Al	750	87					5000
Ba					1000		500

* Criteria Maximum Concentration (CMC) is an estimate of the highest concentration of a material in surface water to which an aquatic community can be exposed briefly without resulting in an unacceptable effect. Criterion Continuous Concentration (CCC) is an estimate of the highest concentration of a material in surface water to which an aquatic community can be exposed indefinitely without resulting in an unacceptable effect. The CMC and CCC are just two of the six parts of a aquatic life criterion; the other four parts are the acute averaging period, chronic averaging period, acute frequency of allowed exceedence, and chronic frequency of allowed exceedence (US EPA, 1999)

** Human Health For Consumption (HHFC) of Water+Organism or of Organism Only

*** Norme Tunisienne N.T106.002 (1989) 2. Specifications relatives aux rejets dans le domain public maritime, le domaine public hydraulique et les canalisations publiques, Domaine public hydraulique

The groundwater quality is examined using the water quality criteria (US EPA, 1999) and wastewater regulation standards in Tunisia (N.T106.002) as summarized in Table 3. In general CCC (Criterion Continuous Concentration) is more severe than CMC (Criteria Maximum Concentration), and the wastewater regulation values are larger than these CCC and CMC. The concentration of each PTE is comparatively illustrated in Figure 4.

The concentration of Al, Cu, Zn, Se, and Pb in the groundwater samples is above the CCC, and that of Cu, Zn, Se, and Pb is above the CMC. The concentration of Se and Pb is much higher than CCC and CMC, which is above the wastewater regulation (Figure 4). The high concentrations of Cu, Zn, Se, and Pb are possibly due to a pollution caused by the MSW landfill. According to the results of leachate analysis (Yoshida et al., 2002 in this volume), the metalloid Se is the common pollutant between landfill leachate and groundwater, while other elements, Cu, Zn, and Pb (heavy metals), do not exhibit a clear correlation.

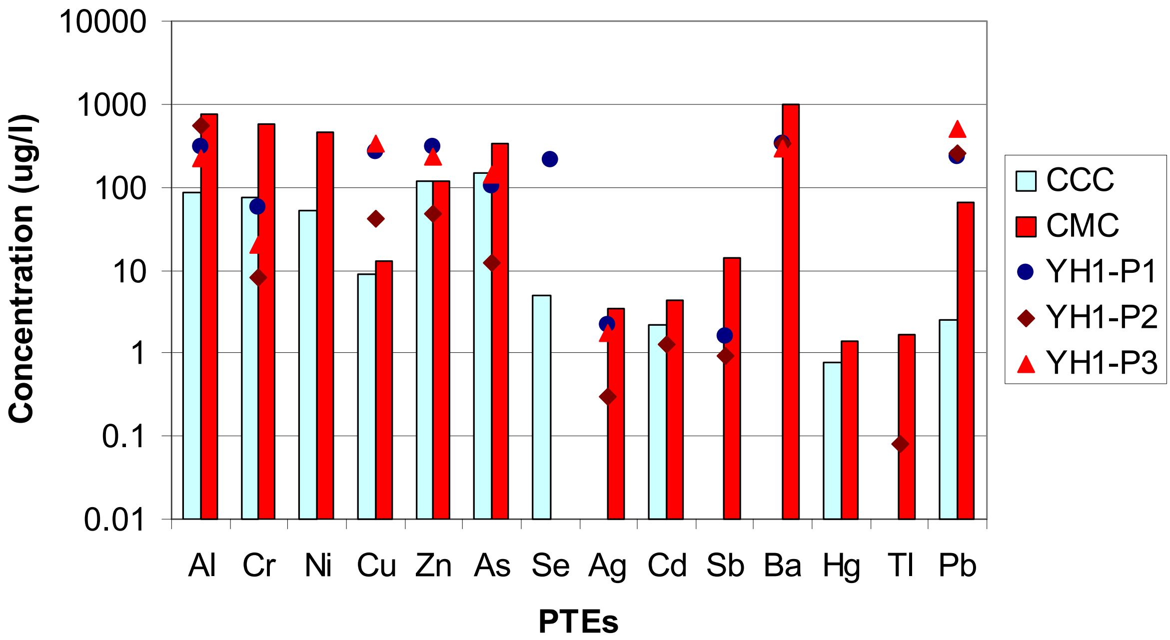

Figure 4: Comparison between observed data and groundwater quality standards (see Table 4). The concentrations of Cu, Zn, Se, and Pb are above the standards.

V-2. Subsurface Sediment Contamination

The results of aqua regia extraction (pseudo-total composition) of subsurface sediments sampled from the HY1 hole are summarized in Table 4. The variation of concentrations of non-metal pollutants, B, As, and Se is illustrated in Figure 5, that of other metal pollutants in Figure 6 (Ti, V, Cr, Co, Ni, Cu, and Zn), Figure 7 (Mo, Ag, Cd, and Sb), and Figure 8 (Ba, La, Hg, Tl, and Pb). In general, recent landfill cover materials (HY1-0.85 and -1.20) exhibit extremely high concentration of these non-metal and metal pollutants, which is probably caused by a direct mixing of solid waste during the operation of landfill capping and reclamation. However the surface lake sediment (sand) immediately below the recent cover materials, that is observed as a densely contaminated black-colored zone by landfill leachate spill, shows relatively moderate to low concentrations of the non-metal and metal pollutants.

Table 4: Results of aqua regia extracted pseudo-total composition of elements in the sediment samples collected from the HY1 borehole cores

ELEMENT	B	Na	Mg	Al	P	S	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
unit	ppm	%	%	%	%	%	%	%	ppm	%	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm
Detection Limit	1	0.001	0.01	0.01	0.001	0.01	0.01	0.01	0.1	0.001	2	0.5	1	0.01	0.1	0.1	0.01	0.1
HY1-0.85	37	0.345	0.40	2.74	0.567	0.28	0.80	9.97	2.0	0.018	35	193.5	413	7.18	12.5	77.0	913.55	2282.0
HY1-1.20	36	0.484	0.42	1.34	0.326	0.30	0.66	9.05	1.4	0.015	29	175.6	504	7.32	162.3	188.9	1067.99	1312.0
HY1-1.68	26	1.539	0.10	0.43	0.016	0.90	0.18	23.55	1.3	0.011	8	8.3	46	0.16	1.1	2.5	13.23	37.0
HY1-2.15	30	0.341	0.55	1.31	0.317	0.42	0.54	12.61	1.8	0.007	25	155.0	391	5.28	37.3	68.2	825.86	932.5
HY1-2.80	26	1.468	1.10	2.14	0.070	0.37	0.53	10.42	4.1	< .001	50	48.6	278	2.56	10.4	25.6	25.73	90.3
HY1-3.15	38	0.335	0.71	1.35	0.306	0.78	0.48	11.98	1.9	0.01	28	143.3	470	6.10	25.2	60.8	693.66	942.1
HY1-3.72	34	1.127	1.22	1.02	0.035	0.21	0.34	7.96	1.8	0.001	25	20.4	192	1.11	5.0	10.8	7.62	31.6
HY1-4.20	18	0.664	0.58	0.78	0.057	0.30	0.24	10.84	1.5	0.005	23	29.2	190	1.59	4.8	11.3	55.97	92.6
HY1-4.62	23	1.938	0.51	0.92	0.026	1.18	0.33	9.57	1.9	0.003	27	20.4	154	1.05	11.4	15.3	8.52	39.6
HY1-4.90	15	0.881	0.42	0.56	0.031	0.20	0.22	7.15	1.6	0.002	15	13.7	156	0.83	2.8	6.4	3.17	26.4
HY1-5.45	15	0.931	0.50	0.67	0.028	0.24	0.20	7.67	1.6	0.001	19	14.1	198	1.06	3.1	7.3	2.75	28.1
HY1-5.70	17	1.007	0.52	0.64	0.020	1.69	0.21	8.45	1.5	< .001	16	13.3	185	0.80	2.6	6.3	6.45	23.3
HY1-6.15	15	0.544	0.49	0.47	0.015	5.79	0.16	12.33	1.0	< .001	12	8.9	133	0.53	1.9	3.4	13.24	13.5
HY1-6.60	32	1.459	0.59	1.30	0.029	3.43	0.48	10.74	2.5	< .001	30	24.2	139	1.69	5.2	13.3	7.77	38.0
HY1-7.00	24	0.896	1.03	0.98	0.024	3.36	0.32	9.70	1.9	< .001	23	18.4	184	1.22	4.4	9.7	11.23	70.8
HY1-7.60	22	0.852	1.31	0.94	0.015	5.69	0.28	9.61	1.8	< .001	22	16.9	182	1.08	5.2	9.0	5.06	27.3
HY1-8.00	20	0.577	0.73	0.91	0.037	2.27	0.28	11.24	2.0	< .001	26	22.5	201	1.33	6.6	15.9	17.11	50.0
HY1-8.10	32	1.227	1.80	1.34	0.023	2.85	0.42	7.34	2.7	0.008	30	26.5	276	1.65	7.7	15.0	7.34	44.1
HY1-8.40	8	0.231	0.26	0.19	0.010	0.14	0.07	7.47	0.7	< .001	17	8.2	98	0.64	2.6	4.0	2.87	16.0
HY1-8.70	43	1.947	2.07	1.46	0.025	1.99	0.59	8.38	3.2	< .001	39	35.9	621	1.90	16.0	20.2	9.11	51.0
HY1-9.40	12	0.627	0.30	0.32	0.020	2.06	0.13	9.04	1.0	0.004	15	12.8	106	0.67	3.5	5.5	21.07	30.0
HY1-9.90	8	1.142	0.31	0.35	0.010	0.41	0.09	26.12	1.1	0.005	17	11.4	90	0.59	3.2	9.7	5.42	12.9
HY1-10.00	11	0.988	0.36	0.63	0.020	0.68	0.14	19.44	2.1	0.003	42	18.3	217	1.72	7.3	22.0	11.00	29.0
HY1-10.53	11	1.889	0.31	0.92	0.014	0.14	0.14	8.97	4.3	0.002	51	27.2	115	1.82	10.7	27.8	14.80	45.5
HY1-11.00	8	1.069	0.27	0.48	0.022	0.17	0.09	23.88	1.9	0.004	29	17.0	184	1.06	5.0	13.8	8.76	22.9
HY1-11.75	7	1.239	0.25	0.64	0.033	0.08	0.09	21.48	3.1	0.001	47	27.2	278	1.45	7.7	22.7	16.38	39.6
HY1-12.25	17	0.879	0.58	0.86	0.023	0.67	0.24	13.51	2.4	0.005	39	23.3	268	1.66	8.7	15.3	10.51	38.9
HY1-12.80	9	1.521	0.25	0.80	0.024	0.09	0.13	12.63	4.9	< .001	74	32.4	302	1.76	15.4	22.7	13.50	41.0
HY1-13.00	9	1.095	0.25	0.65	0.021	0.37	0.11	17.24	3.9	0.003	56	23.9	299	1.79	15.4	22.0	14.13	43.9
HY1-13.73	6	1.044	0.25	0.70	0.025	0.48	0.10	18.63	3.3	0.004	69	26.9	351	1.86	12.6	17.5	19.26	41.4
HY1-14.00	31	1.219	0.69	1.14	0.039	3.29	0.42	11.72	2.5	0.004	32	26.1	180	1.70	6.1	14.2	25.38	51.3
HY1-14.90	6	1.233	0.24	0.64	0.034	0.15	0.10	17.35	3.9	0.003	51	28.0	228	1.25	4.8	19.7	12.35	42.4
HY1-15.90	5	1.460	0.29	0.64	0.053	0.34	0.10	19.54	3.7	< .001	75	29.6	682	3.69	19.2	26.3	19.99	62.9

(meters in depth)

ELEMENT	Ga	As	Se	Sr	Mo	Ag	Cd	Sb	Te	Ba	La	W	Au	Hg	Tl	Pb	Bi	Th	U
unit	ppm	ppm	ppm	ppm	ppm	ppb	ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppb	ppm	ppm	ppm	ppm	ppm
Detection Limit	0.1	0.1	0.1	0.5	0.01	2	0.01	0.02	0.02	0.5	0.5	0.2	0.2	5	0.02	0.01	0.02	0.1	0.1
HY1-0.85	7.3	27.3	1.6	427.6	5.70	3928	6.94	8.99	0.10	1012.9	10.9	0.7	276.1	43	0.20	1125.25	0.66	2.5	0.8
HY1-1.20	4.0	19.9	2.6	387.1	7.12	1736	5.54	10.39	0.08	462.7	6.9	2.7	32.3	72	0.07	628.10	7.11	1.8	0.6
HY1-1.68	0.5	2.5	0.6	136.4	0.54	95	0.07	0.24	0.12	69.1	5.8	< .1	6.7	21	< .02	15.75	2.25	1.1	0.7
HY1-2.15	4.0	12.8	1.2	449.6	3.90	1592	3.81	6.19	0.10	347.1	7.2	0.8	54.4	60	0.08	641.35	12.75	2.0	0.7
HY1-2.80	6.6	5.7	0.5	362.7	1.43	34	0.29	0.29	0.07	162.1	10.5	< .1	2.8	43	0.12	19.67	0.61	4.2	1.0
HY1-3.15	4.5	14.0	1.1	555.3	5.07	1033	4.50	6.43	0.06	329.8	7.1	0.9	54.1	113	0.09	650.66	9.00	2.1	0.8
HY1-3.72	3.2	4.5	0.3	2372.5	0.35	27	0.08	0.17	0.17	169.3	6.0	< .1	1.2	10	0.06	7.63	0.09	2.1	0.8
HY1-4.20	2.3	5.1	0.5	558.4	0.96	127	0.38	0.51	0.07	107.5	4.9	< .1	3.9	15	0.05	48.17	0.57	1.6	0.6
HY1-4.62	2.8	17.5	1.8	668.8	1.85	132	2.42	0.42	0.10	88.3	5.5	< .1	0.6	12	0.73	19.84	0.08	2.1	1.5
HY1-4.90	1.8	3.6	0.3	1838.5	0.48	20	0.12	0.26	0.15	148.4	5.0	< .1	0.6	8	0.05	8.37	0.06	1.7	0.6
HY1-5.45	1.8	3.4	0.3	591.3	0.64	24	0.11	0.18	0.08	65.5	4.6	< .1	0.3	9	0.05	5.68	0.05	1.6	0.5
HY1-5.70	1.8	2.0	0.4	666.3	0.44	46	0.22	0.15	0.09	68.2	4.1	< .1	0.8	< 5	0.05	6.27	0.07	1.4	0.5
HY1-6.15	1.3	0.8	0.9	739.7	0.20	32	0.06	0.09	0.08	46.4	2.7	< .1	1.0	7	0.04	6.51	0.06	1.1	0.5
HY1-6.60	4.0	5.2	0.6	2181.2	1.13	14	0.11	0.20	0.19	94.7	7.5	< .1	0.6	9	0.09	5.45	0.10	3.4	0.4
HY1-7.00	2.9	3.8	0.3	738.1	0.79	57	0.12	0.22	0.06	66.5	5.4	< .1	0.9	5	0.06	12.12	0.13	2.3	0.4
HY1-7.60	2.8	3.1	0.4	820.3	0.68	18	0.04	0.17	0.09	60.3	5.2	< .1	0.2	5	0.06	5.01	0.07	2.4	0.3
HY1-8.00	2.9	5.7	0.7	678.8	0.90	173	0.21	0.28	0.09	85.0	6.1	< .1	2.0	12	0.07	22.82	1.13	2.3	0.5
HY1-8.10	4.1	6.0	0.3	389.3	1.04	37	0.08	0.30	0.06	62.4	8.4	< .1	1.0	16	0.08	9.72	0.11	3.7	0.5
HY1-8.40	0.7	4.5	0.5	154.1	0.45	21	0.30	0.15	0.07	40.6	4.1	< .1	1.6	19	0.02	4.03	0.03	0.8	0.2
HY1-8.70	5.5	4.8	0.5	208.7	1.13	26	0.11	0.23	0.06	115.1	11.0	< .1	1.4	66	0.11	10.28	0.12	4.8	0.7
HY1-9.40	1.3	3.8	0.4	556.4	0.58	39	0.11	0.19	0.08	46.3	3.1	< .1	1.1	39	0.05	8.90	0.06	1.0	0.4
HY1-9.90	1.4	3.8	0.3	328.5	0.50	14	0.07	0.14	0.13	46.5	3.5	< .1	1.7	52	0.03	3.79	0.03	1.4	0.3
HY1-10.00	2.2	11.6	0.3	440.1	1.10	29	0.11	0.26	0.10	53.8	7.6	< .1	1.1	80	0.04	7.08	0.07	2.7	0.3
HY1-10.53	3.4	13.8	0.2	198.7	0.68	5	0.06	0.24	0.06	18.4	5.6	< .1	0.6	20	0.03	7.01	0.15	6.8	0.2
HY1-11.00	1.8	6.5	0.2	390.4	0.38	5	0.08	0.13	0.15	69.3	8.0	< .1	0.6	91	0.02	3.93	0.05	2.6	0.3
HY1-11.75	2.5	9.4	0.2	531.6	0.39	3	0.10	0.16	0.11	45.7	8.7	< .1	0.5	12	0.02	4.39	0.08	4.0	0.3
HY1-12.25	2.9	7.8	0.3	366.3	0.77	27	0.09	0.21	0.06	64.8	7.5	< .1	1.1	130	0.05	11.25	0.09	3.0	0.4
HY1-12.80	3.4	6.3	0.2	398.0	0.46	4	0.08	0.17	0.09	34.6	8.8	< .1	0.7	11	0.03	8.51	0.14	6.7	0.3
HY1-13.00	2.6	8.5	0.5	418.0	0.58	24	0.11	0.18	0.10	46.6	7.2	< .1	0.6	90	0.03	9.52	0.13	5.0	0.3
HY1-13.73	2.6	6.2	0.3	434.3	0.41	10	0.09	0.15	0.10	45.2	7.7	< .1	5.9	53	0.03	6.12	0.09	4.5	0.3
HY1-14.00	4.0	4.5	0.5	2924.8	0.94	68	0.15	0.79	0.28	112.1	7.1	< .1	1.5	38	0.08	29.97	0.12	3.5	0.5
HY1-14.90	2.5	3.7	0.2	540.4	0.20	5	0.09	0.16	0.09	137.3	9.1	< .1	0.9	25	0.02	5.02	0.13	5.9	0.3
HY1-15.90	2.8	9.2	0.8	537.3	1.06	36	0.17	0.32	0.11	129.1	11.0	< .1	1.3	74	0.04	12.51	0.11	4.6	0.8

(meters in depth)

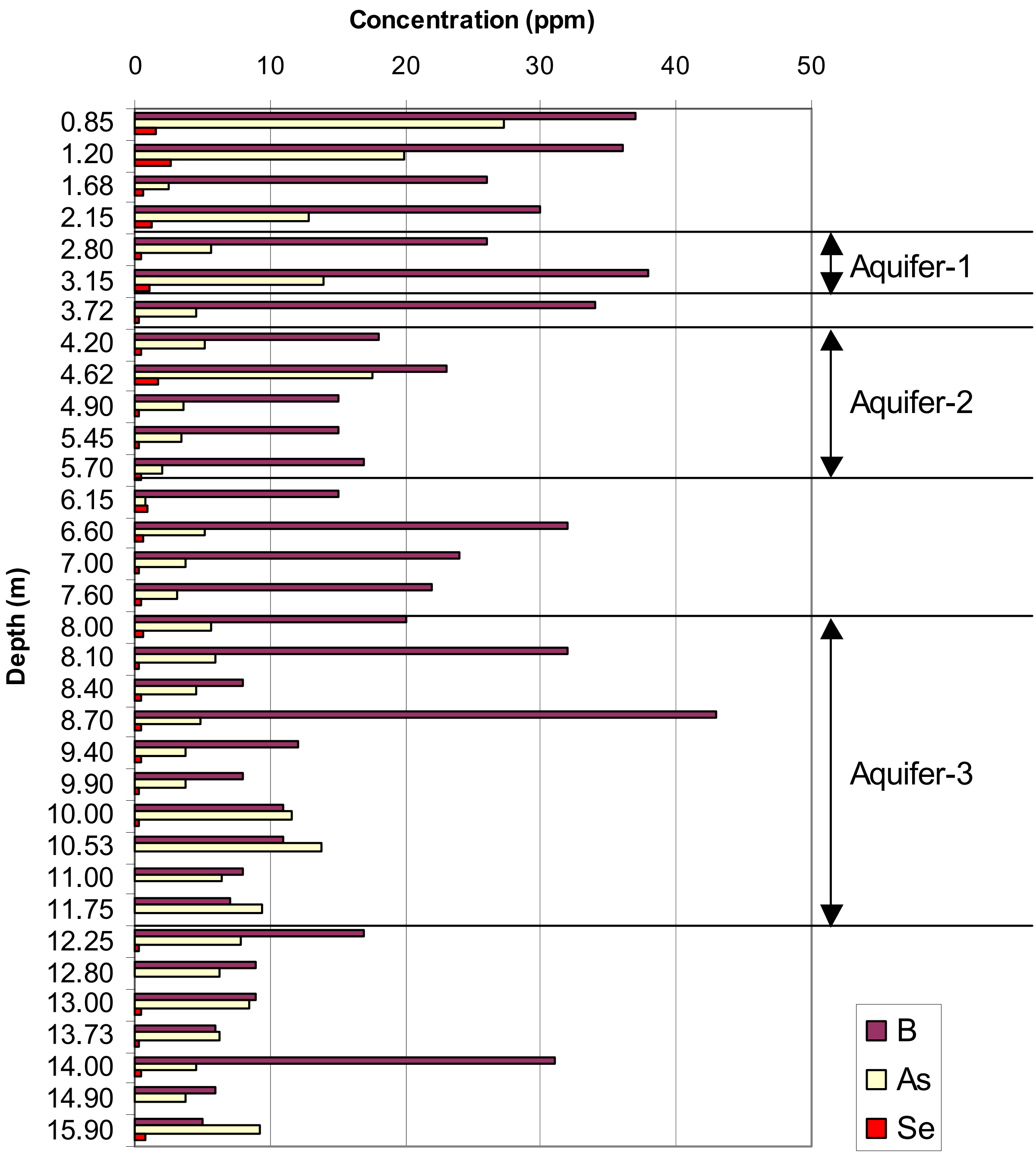

Figure 5: Variation of the concentration of aqua regia extracted non-metal pollutants, B, As, and Se. The uppermost two samples from the recent landfill cover indicate high concentration of these non-metal pollutants. B and Se are relatively abundant in upper half horizons (from the upper part of the Aquifer-3). As is enriched in the recent landfill cover, Aquifer-1, and Aquifer-3.

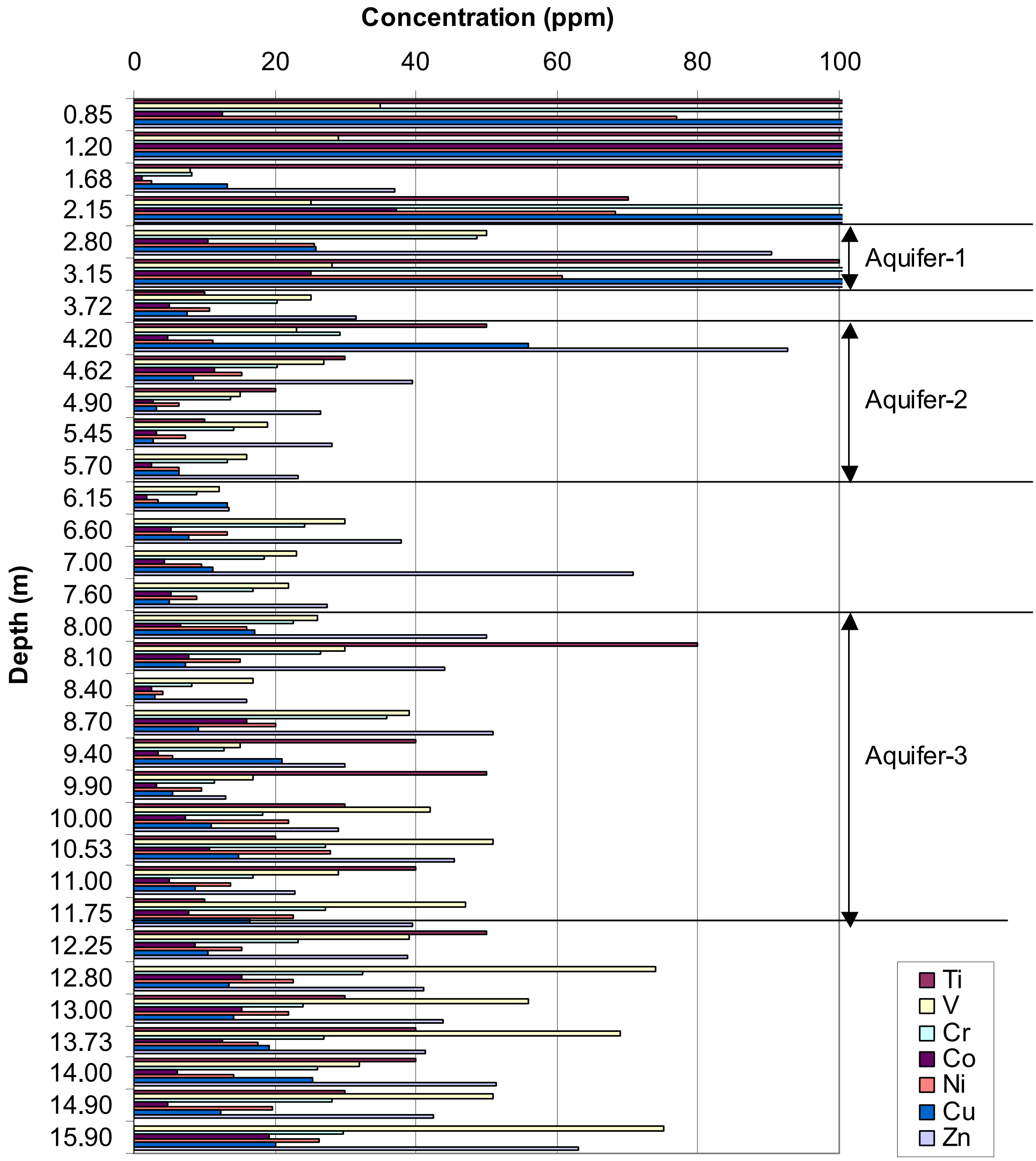

Figure 6: Variation of the concentrations of aqua regia extracted metal pollutants, Ti, V, Cr, Co, Ni, Cu, and Zn. The recent landfill cover materials and Aquifer-1 sediments show extremely high concentrations (out of scale in this diagram) for given metal pollutants. The metal concentrations of Aquifer-2 and Aquifer-3 sediments are showing around background levels.

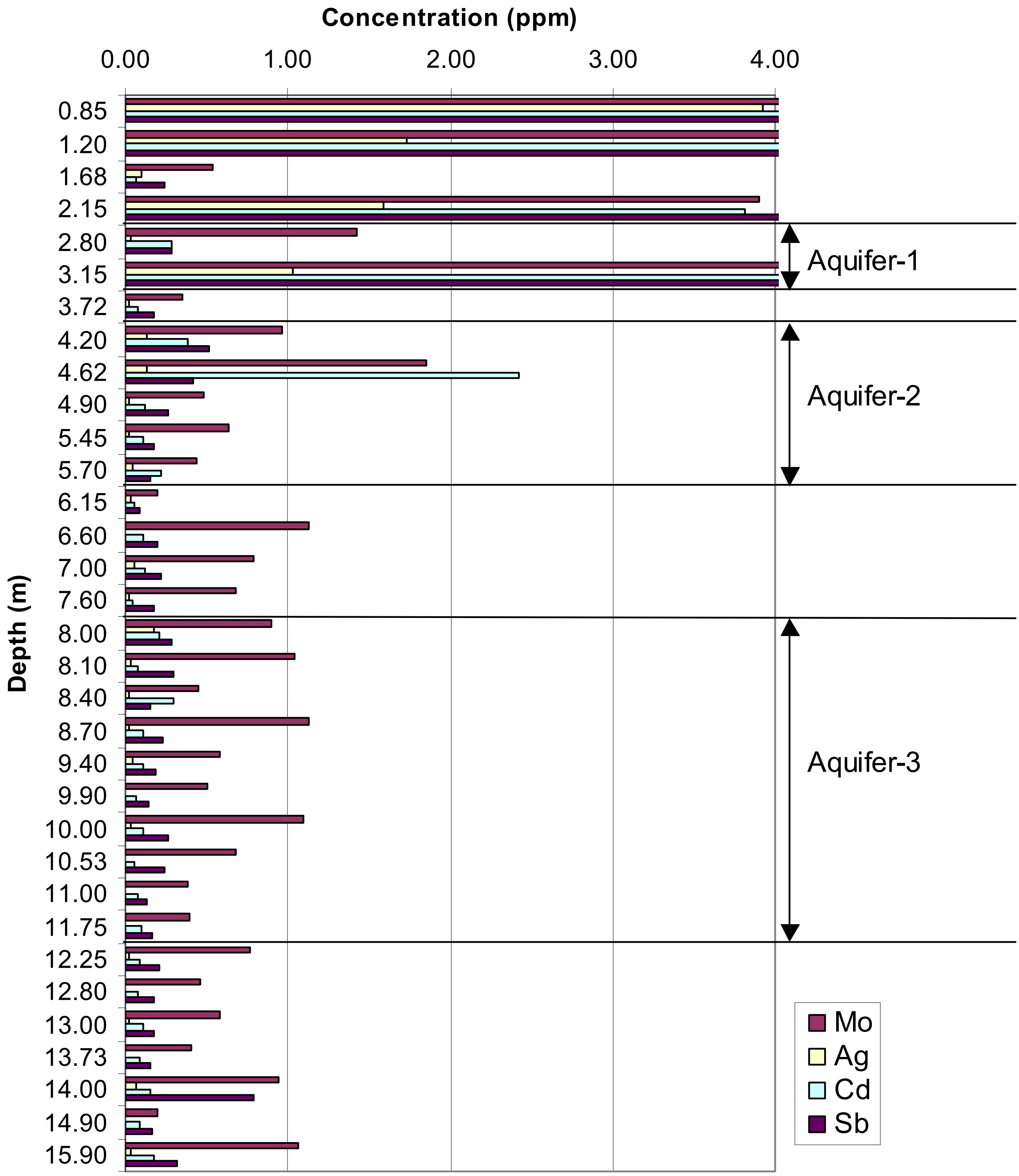

Figure 7: Variation of the concentrations of aqua regia extracted metal pollutants, Mo, Ag, Cd, and Sb. The recent landfill cover materials and Aquifer-1 sediments show extremely high concentrations (out of scale in this diagram) for given metal pollutants. The Aquifer-2 indicate relatively high concentration of Cd. The Aquifer-3 sediments are showing the metal concentrations around background levels.

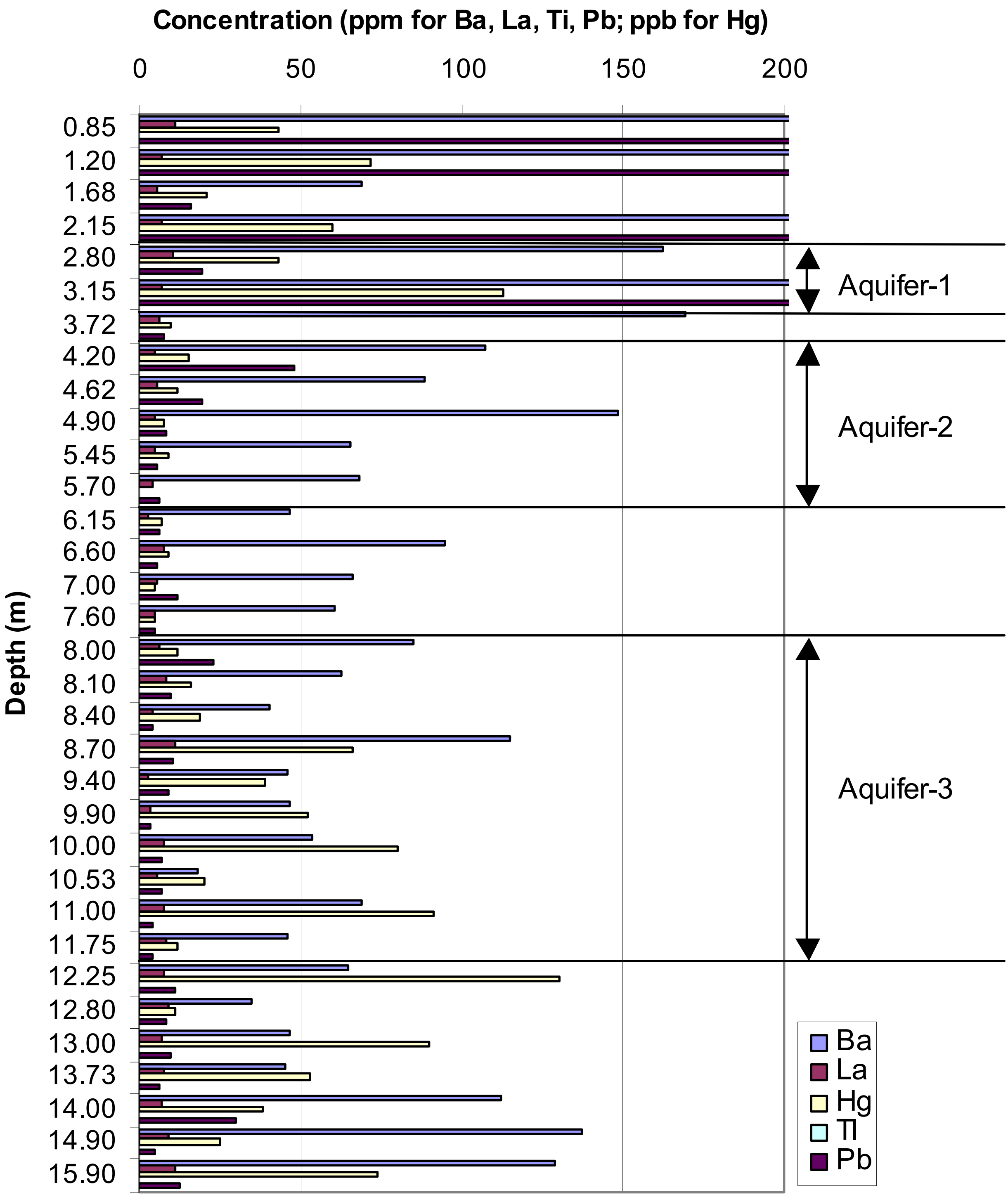

Figure 8: Variation of the concentrations of aqua regia extracted metal pollutants, Ba, La, Hg, Tl, and Pb. The recent landfill cover materials and Aquifer-1 sediments show extremely high concentrations (out of scale in this diagram) for given metal pollutants. Except in the recent landfill cover and the Aquifer-1, the concentrations of Hg is moderate to high in the lower part of the Aquifer-3 and underlying confined beds, which suggest that Hg contamination in the Aquifer-3 is natural origin.

In the case of non-metal pollutants, B, As, and Se, the uppermost two samples collected from the recent landfill cover indicate high concentration of these non-metal pollutants. B and Se are relatively abundant in upper half horizons, above the upper part of the Aquifer-3. Except in the recent landfill cover layers and the Aquifer-1, As is relatively enrich in the lower part of Aquifer-3 and confined beds below the aquifer-3, which suggest that the As contamination has been derived from basement sedimentaries.

The metal pollutants, Ti, V, Cr, Co, Ni, Cu, and Zn, exhibit extremely high concentrations in the recent landfill cover layers and the Aquifer-1 sediments. The metal concentrations of Aquifer-2 and Aquifer-3 sediments are showing around background levels represented by the concentrations in the lowermost confined beds.

In the case of metal pollutants, Mo, Ag, Cd, and Sb, the recent landfill cover layers and the Aquifer-1 sediments also show extremely high concentrations. The Aquifer-2 sediments indicate relatively high concentration of Cd. The Aquifer-3 sediments are showing the metal concentrations around background levels.

The other metal pollutants, Ba, La, Hg, Tl, and Pb, also show extremely high concentrations in the horizons of recent landfill cover layers and Aquifer-1. Except in the recent landfill cover layer and the Aquifer-1, the concentrations of Hg is moderate to high in the lower part of the Aquifer-3 and underlying confined beds, which suggest that Hg contamination in the Aquifer-3 is a natural geologic origin.

Consequently, the subsurface sediment contamination is considerable at the horizons of recent landfill cover layers and the Aquifer-1 sediments, of which depth is above -3.20 meter at the site HY1. In particular, metal pollutants are extremely contaminated in these two horizons.

VI. Conclusion

(1) Groundwater pollution and subsurface sediment contamination are examined using perimeter drilling survey of the Henchir El Yahoudia landfill.
(2) According to the drilling survey, three aquifers are recognized in the area, named Aquifer-1, Aquifer-2, and Aquifer-3 in descending order.
(3) The concentration of Al, Cu, Zn, Se, and Pb in the groundwater samples is above the regulation CCC, and that of Cu, Zn, Se, and Pb is above the regulation CMC. The concentration of Se and Pb is much higher than CCC and CMC, which is above the wastewater regulation. The high concentrations of Cu, Zn, Se, and Pb are possibly due to a pollution caused by the MSW landfill.
(4) The subsurface sediment contamination is considerable at the horizons of recent landfill cover layers and the Aquifer-1 sediments, of which depth is above -3.20 meter at the site HY1. In particular, metal pollutants are extremely contaminated in these two horizons.

Acknowledgements

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