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Hydrochemical Characterization of a Tropical, Coastal Aquifer Affected by Landfill Leachate and Seawater Intrusion

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Abstract: The hydrochemistry of landfill leachate and groundwater is affected by not only waste degradation processes, but also by external factors such as the geography of the landfilling site. Knowledge on the fate of landfill leachate in tropical countries will be beneficial for monitoring and regulatory purposes. We studied the Keputih landfill close to the sea at Surabaya, Indonesia: (1) to assess leachate and groundwater hydrochemistry with respect to contamination and seawater intrusion, (2) to investigate the seasonal effects on hydrochemical composition; and (3) to determine redox conditions in order to evaluate the potential for natural attenuation through microbe-mediated electron-accepting processes. We document an influence from sea water intrusion on groundwater hydrochemistry on top of the influences from the landfill itself. Leachate had a high electrical conductivity and high COD, and contained high concentrations of NH_4^+, HCO_3^-, SO_4^{2-}, Fe^{2+} and Cl^-. Concentrations were significantly influenced by season, except for COD and SO_4^{2-}. The groundwater at locations surrounding the landfill was also contaminated by leachate and concentrations of groundwater contaminants were higher than national regulatory standards in Indonesia for drinking water. The abundance of SO_4^{2-} in groundwater indicates a large potential for anaerobic biodegradation of organic compounds. Based on the relative concentrations of Cl^- and SO_4^{2-} an influence of the sea water on groundwater hydrochemistry was obvious. Landfilling in developing countries often occurs in coastal areas, therefore we emphasize the need to study microbial community structure and functioning in relation to degradation of landfill leachate in tropical coastal areas impacted by seawater infiltration.

Key words: Landfill, seawater intrusion, subsurface, natural attenuation.

Introduction

Landfilling of solid waste is considered one of the better disposal options in developing countries because it is generally more economical than alternatives such as incineration and composting (Johannessen and Boyer, 1999). With the increasing generation of solid waste, contamination of the environment has become an

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important urban issue. Excessive rainwater percolating through a landfill can potentially contaminate the underlying subsurface and groundwater.

In general, leachate contains high concentrations of reduced components, especially organic matter, CH_4 and NH_4^+ (Christensen et al., 2001; Kjeldsen et al., 2002). Subsurface microorganisms will oxidize many organic components and simultaneously reduce electron acceptors such as O_2, NO_3^-, Mn(IV), Fe(III), SO_4^{2-} and CO_2, leading to the formation of redox zones in the plume of pollution (Christensen et al., 2001; Kjeldsen et al., 2002). However, natural processes in the subsurface can remove contaminants derived from landfill leachate.

Successful MNA on polluted aquifers, including aquifers polluted by landfill leachate, have been reported for temperate regions like the U.S.A. and European countries (Baun et al., 2003; Cozzarelli et al., 1999; Van Breukelen et al., 2003). Especially in tropical countries, MNA of aquifers contaminated by landfills might be an economical and environment-friendly strategy since local authorities generally have few opportunities to implement and maintain intensive treatment facilities. The high tropical temperatures and humidity may possibly even lead to higher rates of biodegradation of contaminants compared to temperate environments (Chaillan et al., 2004).

We characterized the seasonal variation in the hydrochemistry of the aquifer impacted by the Keputih landfill, one of the landfills serving Surabaya, Indonesia. This coastal city is the second biggest city in Indonesia, having a population of 2.9 million. This study aimed to (i) assess the heterogeneity in leachate and groundwater quality with respect to contamination by landfill leachate and possible seawater intrusion, (ii) investigate the seasonal effects on hydrochemical composition, and (iii) determine the redox conditions in order to evaluate the potential for natural attenuation via terminal electron accepting processes.

Materials and Methods

Field Site Description

Keputih landfill is situated in a region with a tropical climate (latitude 719.20′°18.20′-7° and longitude 11248.60°47.60-112°). Generally, the dry period is from May to November, and the wet period runs from December to April. The temperature in the area varies from 22 to 33.5°C and the difference in temperature between the dry and wet season is fairly small (3-5 °C). Average annual rainfall between 1996 and 2006 ranged from 1860 mm to 2000 mm per year (Schroeder et al., 2004; Surabaya Meteorological and Geophysical Agency, 2007).

The landfill is located in the Eastern part of the greater Surabaya area, occupies about 24 hectares and is surrounded by traditional settlements (Figure 1). The landfilling area was originally part of a natural salt marsh with a typical coastal wetland vegetation (e.g. mangrove and saltmarsh grasses) (Rachmansyah, 2001) and this salt marsh area is extending eastwards to the coast, which is 4 km east of the landfill. The hydrology is strongly influenced by tidal cycles. The sediment of the underlying aquifer is composed mainly of fine sands, silts and clay with high organic matter content as a consequence of alluvial deposits from the river *Brantas*. The depth to the base of the aquifer is about 39 m (Rachmansyah, 2001). Geologically, the area is situated in the *randu glatung* basin and a part of *pamekasan* formation, consisting mainly of alluvial sediments (Van Bemmelen, 1949). The local aquifer is shallow, unconfined, and dates back to the Meocene-Pleistocene age. The area has an elevation of 3-4 m above sea level and the groundwater table is at 0 to 4 m below ground surface, depending on the season. The direction of regional groundwater flow is from West to East (Rachmansyah, 2001).

Landfilling began in the early 1980s and ended in 2001. The landfill received about 4000 m^3 of solid waste daily including municipal waste, demolition waste, and industrial waste that is potentially hazardous (Endah and Pudjiastuti, 1995). At an early stage of the landfilling, refuse was buried in the Western, Northwestern and Northeastern areas (Figure 1). Over time, dumping was extended eastward until the whole area within the borders was completely covered. At the time of closure, in 2001, the refuse at the Eastern part reached a height of 10 m above ground surface.

Installation of Monitoring Wells

To characterize contamination status and redox processes, monitoring wells (PVC pipe, 5 cm Ø, screen length 50 cm or steel, 3 cm Ø) were installed in and surrounding the landfill (Figure 1). Between November 2002 and April 2005, a total of 51 wells were installed to a maximum depth of 6 m, and wells encountered the water table within a few metres below the surface. Wells were grouped into nine clusters (Figure 1) according to their orientation to the landfill. Wells LF1-8 sampled water from the refuse itself, while monitoring wells belonging cluster west (W1-8), northwest (NW1-3), north (N1-12), northeast (NE1-4), east (E1-9), southeast

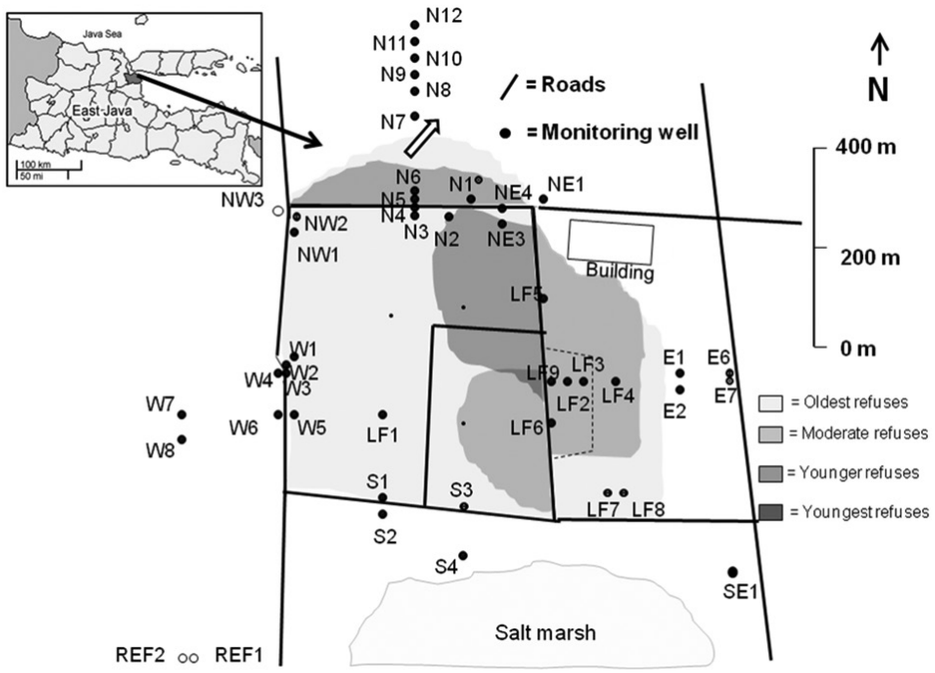

Figure 1: Map of the Keputih landfill site near the coast at Surabaya, Java, Indonesia. Monitoring wells (●) were organized in clusters in (LF) and around the landfill: W, western; NW, northern west; N, northern; E, Eastern; S, southern; SE, southeastern. ○ are reference monitoring wells (REF). Numbers indicate well numbers.

(SE1), south (S1-4) sampled groundwater. Reference (Ref1-2) wells were installed ~600 m southwest of the landfill.

Sampling from Monitoring Wells and Hydrochemical Analysis

The wells were sampled up to six times using a peristaltic pump, in the dry season (November 2002, July 2003 and November 2003) and wet season (January 2004, April 2004 and April 2005). Temperature, electrical conductivity, dissolved oxygen and pH were measured using electrodes (HACH, Loveland, Co; WTW, Hamburg, Germany) placed in flow cells. Groundwater samples for analysis of cations NH_4^+, Fe^{2+} and Mn^{2+}, were filtered on site (0.1 ㎜ Ø, Sartorius) and transfered to 100 ml PE bottles containing preservative (2% [v/v] concentrated HNO_3 for acidification to pH 2). Unfiltered groundwater samples for analysis of chemical oxygen demand (COD) and anions HCO_3^-, PO_4^{3-}, Cl^-, NO_3^- and NO_2^- were kept in 100 ml PE bottles and stored at 4°C until laboratory analysis. Groundwater samples for CH_4 and H_2S analysis were placed in 30 ml amber serum vials without headspace, capped and kept cool (4 to 10°C). Spectrophotometric analysis was conducted for COD, Cl^-, PO_4^{3-}, NO_3^-, NO_2^-, SO_4^{2-} and Mn^{2+}(using commercially HACH kits (Loveland, Co)), NH_4^+ (Nesslerisation, APHA, 1998), Fe^{2+} (Viollier et al., 2000) and H_2S (Cline, 1969), while alkalinity was determined by Gran titration (Stumm and Morgan, 1981). For CH_4 analysis, ten millilitres of groundwater was evacuated using a gas-tight syringe from sampling bottles to a 12 ml crimp-capped serum vial, and from the 2 ml headspace volume of the evacuated vial 100 µL of gas was taken and injected into a gas chromatograph (Hewlett-Packard) equipped with flame ionization detector (GC-FID).

Statistical Analysis

To compare statistical means of hydrochemical parameters within monitoring well clusters, analysis of variance (ANOVA) followed by least-square difference (LSD) post-hoc test were applied to the log-transformed data. All statistical analysis was done using SPSS software version 12.

Calculation of the Seawater Fraction in Groundwater Samples

The fraction of sea water in groundwater samples was calculated as follows, under the assumption of conservative mixing (Appelo and Postma, 2005):

$$f_{sea} = \frac{m_{Cl^-,\,sample} - m_{Cl^-,\,fresh}}{m_{Cl^-,\,sea} - m_{Cl^-,\,fresh}}$$

where $f_{sea,}$ is the fraction of sea water in a sample, $m_{cl^-,sample}$ is the chloride concentration of the sample, $m_{cl^-,sea}$ is the chloride concentration in sea water (566 mM), and $m_{cl^-,fresh}$ is the local background (non-seawater influenced) concentration of chloride, estimated from the groundwater reference well (minimum concentration of 0.4 mM).

Results

Groundwater Hydrochemistry

The hydrochemistry of water samples taken from the landfill was clearly different from those of samples obtained from the reference wells (Table 1). The maximum concentrations of COD and NH_4^+ in the landfill (5016 mg/L and 20.55 mM, respectively) were much higher compared to the references (193 mg/L and 0.35 mM, respectively) (Table 1).

Alkalinity (HCO_3^- concentration) was strongly increased, with maximally 590 mM in the landfill samples, compared to 6.5 mM in the reference wells (Table 1). High concentrations of CH_4 (up to 2.3 mM) were observed in the leachate (Table 1). Concentrations of Fe^{2+} and H_2S were not much different between reference wells and wells in the landfill. PO_4^{3-} is mainly derived from refuse decomposition, and this can be seen by a consistently higher concentration of this nutrient in the leachate; a maximum concentration of 0.38 mM was observed in the landfill.

In order to study the spread of leachate into groundwater, the hydrochemistry of groundwater surrounding the landfill was compared to groundwater in reference wells and in the landfill (Table 1). Groundwater in almost all monitoring wells was coloured (yellow) indicative of groundwater mixed with landfill leachate (brown). Indicators of the presence of landfill leachate (NH_4^+, COD and alkalinity) were also found to be enhanced in wells all around the landfill, except for the southern part. Also some wells in the north, north eastern and eastern parts contained lower concentrations, comparable to the reference wells (Table 1). CH_4 concentrations (< 1 mM) were consistently higher than in reference wells. CH_4 was positively correlated with COD ($r = 0.822$, $p < 0.001$), NH_4^+ ($r = 0.923$, $p < 0.001$), HCO_3- ($r = 0.949$, $p < 0.001$), and H_2S = ($r = 0.797$, $p < 0.001$) but negatively with SO_4^{2-} ($r = –0.307$, $p = 0.23$).

Landfill leachate typically contains high concentrations of salts, which contribute to high electrical conductivity (EC). Very high Cl^- concentrations (84 mM for the dry season and 38.2 for the wet season) were indeed found in landfill leachate, but sometimes also high Cl^- and EC values were found in the reference wells (Table 1). For example, in the dry season on one occasion a very high electrical conductivity (46.7 mS/cm) was found for a reference well (Table 1). This high conductivity is indicative for the intrusion of seawater (EC of local sea water 47 mS/cm) (Indonesian Ministry of Environment, 2004).

High electrical conductivity (EC) and Cl^- were found not only in leachate samples but also in many groundwater samples (Table 1). The highest Cl^- concentrations in groundwater were found in the N, E and N-E clusters (up to 69 mM). Seawater intrusion should also contribute to high Br^- and SO_4^{2-} concentrations (in the absence of significant sulfate reduction). Indeed, Cl^- was positively correlated ($p < 0.001$) with electrical conductivity ($r^2 = 0.56$), SO_4^{2-} ($r^2 = 0.93$) and Br ($r^2 = 0.92$). These results support the occurrence of seawater intrusion. The maximum SO_4^{2-} concentration in groundwater was found in the NE cluster (41 mM; seawater SO_4^{2-} ~29 mM). Low COD and NH_4^+ concentrations (< 50 mg/l and < 3.5 mM respectively) were found for many groundwater samples, such as in the eastern cluster and the reference, suggesting groundwater in these samples was not affected by leachate but seawater.

Under the assumption that the higher Cl^- concentrations in groundwater samples were indeed due to intrusion of sea water, we calculated the fraction of seawater in groundwater using the formula presented in the Methods section. The highest seawater fraction, 15%, was found for the N-E cluster, while the W region cluster wells contained up to 8% seawater.

Seasonal Variation

Hydrochemical parameters for each cluster of observation wells were compared between the dry and wet seasons (Figure 2). Two-way ANOVA showed significant effects of sampling location (well clusters) for COD ($p < 0.01$), NH_4^+ ($p < 0.001$), CH_4 ($p < 0.05$), HCO_3^- ($p < 0.001$) and PO_4^{3-} ($p < 0.001$), but not for other parameters. Seasonal effects were observed for NH_4^+ ($p < 0.05$), CH_4 ($p < 0.05$), HCO_3^- ($p < 0.05$) and Cl^- ($p < 0.001$).

Groundwater from all clusters exhibited higher Cl^- concentrations during the dry season (Figure 2A). SO_4^{2-}, another major component of seawater but not conservative due to the possibility of microbial sulfate

Table 1: Hydrochemistry of groundwater extracted from different monitoring well clusters in and around the landfill during the wet and the dry season

	West		North-West	North		North-East		East		South-East	South	Landfill		Reference	
	Wet	*Dry*	*Wet*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Wet*	*Wet*	*Dry*	*Wet*	*Dry*
Temperature	23-27	30-31	24-27	24-28	22.6-31.6	24-28	23.5-33	25.5-27.5	30-32	27	24.3.28	24.3-29	27-31	24-25	27
pH	6.9-7.5	7.7-6	8-8.3	7-8.3	6.8-8.6	6.5-7..6	6.6-6.7	7-7.6	6.7-7.4	8	7.3-7.5	7.2-8.4	7.4-7.8	7	7.0
EC	2.2-9.8	2.2-6.3	2.5-8.4	1.1-1.4	2.7-4.6	2.3-3.3	1.2-6.1	4.0-4.1	2.6-6.5	6.3	1.5-2.6	6.0-8.1	1.1-2.5	0.2-0.3	0.2-4.7
COD	81-657	241-1280	135-713	13-287	65-1230	64-821	644-1382	11-700	37-1299	0	21-31	1204-5016	1740-3858	11-60	48-192
Ammonium	0.6-3.3	0.6-5.3	9.8-11.4	0.4-22.5	0.2-6.2	0.2-2.3	0-0.2	0.1-2	0.0-3.5	0.02	0.1-0.7	13-88	4.2-21	0.1-0.9	0.1-0.4
Nitrate	0-0.5	0-0.05	0.01-0.09	0-2.2	0-0.2	0-0.22	0-0.07	0-0.4	0-0.11	0.37	0.04-0.3	0-0.66	0-0.1	0-0.2	0.01-0.06
Nitrite	0.0.6	0-1.2	0.05-0.5	0-1.53	0-0.25	0-0.74	0.1-0.62	0-0.1	0-0.17	0.27	0-0.03	0-0.28	0-0.07	0-0.02	0-0.22
Iron (II)	0.1-4.5	0.15-3	0.1-0.4	0.1-1.3	0.01-2	0.03-0.58	0.03-0.94	0.1-2.2	0-1.3	1.3	0.5-1.22	0.013-0.6	0.1-1.7	0.07-1	0.05-0.4
Manganese (II)	0.02-0.35	0.03-0.3	0.3-0.6	0.1-0.68	0.01-0.17	0.01-0.16	0.04-1	0-0.28	0.06-0.9	0.9	0.13-0.7	0-0.44	0.01-0.05	0-0.48	0.2-1.16
Sulfate	0.5-12	0.5-16	0.2-0.5	0.3-13	1.1-8	0.1-12	4-41	0.4-19	1.0-19	0.1	0.7-3.3	0.1-51	0.0-2.4	0.0-0.6	0-1.3
Sulfide	0-1.15	0.03-0.23	0.25-0.65	0.07-1.4	0-0.2	0-0.4	0.01-0.18	0-0.86	0.01-0.44	0.35	0-0.4	0.05-1.44	0.2-1	0-0.5	0.05-1.2
Methane	0-0.1	0.04-0.4	0.00-0.01	0-0.05	0-0.18	0-0.08	0.04-0.6	0-0.1	0-0.04	0	0.0-0.07	0.01-0.5	0-2.3	0-0.12	0
Alkalinity	0.2-20	39-79	7.2-13	0.4-27	12-69	0.1-21	2-21	0.1-26	0.2-26	2.6	0.3-1	13-68	157-590	0.3-6.5	0.4-1.3
Phosphate	0-0.025	0-0.13	0.05-0.18	0-0.07	0-0.24	0-0.02	0.01-0.2	0-0.01	0-0.1	0.04	0-0.03	0.05-0.38	0.16-0.26	0-0.1	0-0.02
Chloride	0.7-11	24-40	12-14	5.1-14	2.9-63	0.5-18	6.0-69	12-18	13-67	9.5	7.6-14	7.3-38	11-184	0.4-3.9	6.3-56

Data are presented as range of concentrations. All values are in mM, except for COD (mg/L), temperature (°C), electrical conductivity (mS/cm) and pH. For North-West, South-East (S-E) and South no data for the dry season were obtained.

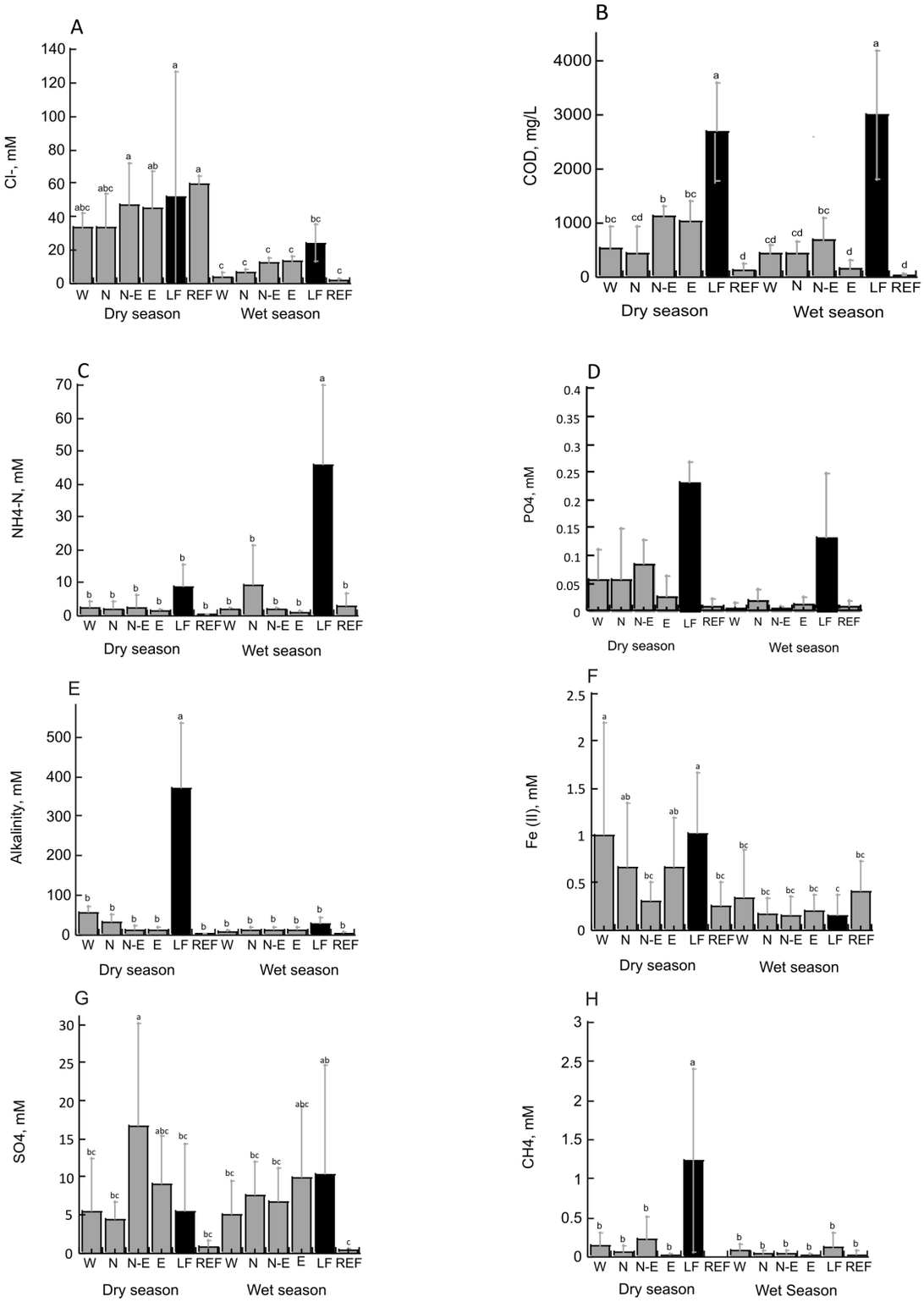

Figure 2: Seasonal and spatial difference in hydrochemical parameters in and surrounding the Keputih landfill, Surabaya. Black bars indicatre landfill leachate samples and grey bars groundwater samples. A. Cl-; B. Chemical Oxygen Demand (COD); C. Ammonia; D. PO43-; E. HCO3-; F. Fe2+; G. SO42-; H. CH4. All data are presented as means, with error bars indicating the standard deviation. Significant differences ($p < 0.05$) between season and clusters of wells are indicated by a different character above the bars. For positions of the wells and well clusters, see Figure 1; W, west; N, north; N-E, northeast; E, east; LF, landfill; REF, Reference.

reduction, did not reveal a clear seasonal trend (Figure 2G). The average concentration of Fe^{2+} in most well clusters showed a seasonal effect (Figure 2F) similar to Cl^-, to a lesser extent it was also observed for Mn^{2+} (data not shown).

The clearest seasonal effects for indicators of landfill leachate were observed for wells in the landfill. NH_4^+ concentration in landfill leachate during the wet season was significantly higher than in the dry season, while NH_4^+ concentration in groundwater wells surrounding the landfill and references were not significantly different between seasons (Figure 2C). The reverse was observed for alkalinity and CH_4, these were during the dry season significantly higher in landfill leachate than the wet season, but was not for groundwater taken outside the landfill area (Figures 2E and H).

Distribution of Redox Species

The groundwater was anaerobic (dissolved oxygen concentrations were always (well) below 0.6 mg/L). Considerable spatial variation in NO_3^- and NO_2^- concentrations were recorded in wells in and surrounding the landfill, but concentrations were generally very low, and often below the detection limit. Fe^{2+} concentrations were high (up to 4.5 mM) in the "contaminated" area during the dry season, especially in west, north, north-east and landfill wells but also in the "cleaner" cluster of eastern wells (max. 1.3 mM), in contrast to the reference wells which exhibited a maximum concentration of 0.4 mM.

We paid special attention to SO_4^{2-} since it was observed that the concentration of this electron acceptor was abundant, especially due to intruding seawater. Seasonality did not significantly affect the SO_4^{2-} concentration, and only a minor influence of sampling location was observed (Figure 2G). H_2S, the product of SO_4^{2-} reduction, was detected in leachate (LF cluster) and groundwater from several sites around the landfill, such as N, E, and reference wells. Distribution of this ion was significantly affected by sampling location ($p < 0.05$) and season ($p < 0.001$). Its concentration in the references wells was slightly higher than that found in landfill samples during the dry season whereas the opposite fact was observed during the wet season. In the wet seasons, groundwater from some wells in the northern area (i.e. N1 and N3) exhibited H_2S concentration (max 1.4 mM) comparable to leachate samples.

CH_4 was observed within the landfill body (LF cluster) at a maximum of 2.3 mM during the dry season but also in "clean" areas like the reference and E wells. In the wet season the highest CH_4 concentration (0.12 mM) was detected in the reference well, compared to other well clusters.

Discussion

Hydrochemical Characteristics and Contamination Status

In this study, landfill leachate and its infiltration into the subsurface around a closed landfill (4-year post closure) in Surabaya, Indonesia, was monitored because it is important to better understand the subsurface fate of leachate in tropical countries.

The composition of Keputih landfill leachate was subject to seasonal variation, containing the highest concentrations of organic matter (COD) and ammonium (ranging from 120 to 5010 mg/L and 247 to 1579 mg/L, respectively) during the wet season. These concentrations exceed the Indonesian national regulatory standard of waste water (for COD: 100 mg/L and ammonium 10 mg/L) (Indonesian Ministry of Environment, 1995).

Compared to other tropical, closed landfills (Buyong et al., 2004; Chu et al., 1994; Mangimbulude et al., 2009), the concentration of COD and ammonium in this leachate were higher: e.g. Chu et al. (1994) reported 147-1500 mg/L for COD and 65-850 mg/L for ammonium while Buyon et al. (2004) 84-1637 mg/L for TOC and 1.5-1020 mg/L for ammonium. Concentrations were also higher than in the Jatibarang landfill in Semarang, Indonesia, which is still in operation (Mangimbulude et al., 2009).

The leachate contaminated the surroundings of the landfill: COD and ammonium concentrations of groundwater in N, NE, E and W areas were higher than in the reference wells. This indicates that four years after the closure of the Keputih landfill, its leachate has still high potential as source of pollution to the environment. Consequently, landfill leachate should be monitored regularly and it should be properly handled to protect the groundwater around the landfill.

The Occurrence and Impact of Seawater Intrusion

Another reason to investigate the Keputih landfill in Surabaya is that this landfill is close to the coast (<4 km distance), in a salt marsh, and seawater intrusion could possibly affect the characteristics of leachate and its decomposition. A study conducted by Rachmansyah (2001) on municipal waste landfills in Surabaya and its surroundings, also suggested that the area around the Keputih landfill is contaminated by seawater.

A major problem in urban areas in most third world countries is finding adequate waste disposal sites. Due to low-income and limitation of available land, coastal areas and salt marshes, which generally have relative little direct economic value, are often converted to waste disposal sites (Hoornweg et al., 1999). This is also the case in Indonesia, for example, besides the Keputih landfill, there are at least three other landfills in Surabaya that are located in areas subjected to seawater intrusion (Rachmansyah, 2001).

The occurrence of landfills in coastal areas implies potential pollution of the marine and coastal environment. Chofqi et al. (2004) reported that since 1999 a coastal aquifer in Marocco has become polluted by an urban landfill.

The groundwater surrounding the Keputih landfill is contaminated by leachate, while also the occurrence of seawater intrusion and seasons affect groundwater quality. Due to fluctuations in seawater intrusion and/or leachate flow over the seasons, the leachate appears to have spread almost all around the landfill. The groundwater at N, NE, E and W regions were more contaminated compared to the groundwater at S and SE regions.

Salinity affects the occurrence and activity of microorganisms, and may therewith influence landfill leachate decomposition and the spread of leachate contaminants through groundwater. Salinity is a major environmental determinant of microbial community composition (Herlemann et al., 2011). Lin et al. (2008) observed that increasing salinity depressed the atrazine degrading activity of the microorganisms.

Potential for the Natural Attenuation of Landfill Leachate

The fate of organic pollutants in contaminant plumes depends on the presence of redox components such as dissolved oxygen, NO_3^-, Fe(III)-oxides and SO_4^{2-} (Baun et al., 2003). Thus, evaluation of natural attenuation can be accomplished by determining the occurrence and loss of electron acceptors (Baun et al., 2003).

Seawater intrusion into fresh groundwater aquifers on the one hand affects coastal groundwater quality. On the other hand, seawater intrusion provides a large source of redox species such as sulfate to support microbial activity, which is relevant if groundwater is polluted with landfill leachate. This study showed that high SO_4^{2-} concentrations were observed in landfill leachate and groundwater, in comparison to other redox elements. Jørgensen (1982) reported that the microbial decomposition of organic matter coupled with the reduction of sulfate is an important mechanism governing carbon and energy in many anaerobic environments. In our study, high concentrations of H_2S and Fe^{2+} were found in landfill leachate and groundwater, indicating that sulfate-reduction and iron-reduction were predominant processes in groundwater. However, this outcome also depends on the mixing proportions of saline groundwater and leachate. If leachate spreads further, it will mix with a larger volume of saline and sulfate containing groundwater, eventually possibly leading to acceptable COD reductions. Moreover, biodegradation of organic matter occurred not only by sulfate reducing bacteria, but could also occur through other anaerobic processes such as methanogenesis.

Overall, there is a need to further study the impact of landfill leachate and salinity on the occurrence and behaviour of subsurface microbial communities in tropical countries.

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