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Statistical inference of propagation of a leachate plume

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ABSTRACT

This paper presents a probabilistic assessment of the maximum distance travelled by the contamination plume produced by a Municipal Landfill in South America at the time the ionic concentrations of several contaminants found in the groundwater have been measured. Field and laboratory results of ionic concentrations of contaminants in the groundwater are presented and interpreted. In this beach town, the 22,000 m² landfill is located 2 km from the closest urban district. The landfill has been in operation for 15 years and gathers 18,000 tons/year from the local population, and 4,000 tons/year produced seasonally by the tourists in summer, totalling 22,000 tons/year of solid waste. Several farms located adjacent to the landfill rely on the ground water for the domestic consumption and farming activities. The solid waste has been dumped without any prior engineering design, causing severe environmental problems to the local farmers, who seek compensation from the municipality. The objective of this paper is to assess the potential risk to the surrounding properties by estimating the maximum distance travelled by the leachate plume by proper statistical interpretation of the measured ionic concentrations of several contaminants.

1 INTRODUCTION

The landfill is located in the beach town of São Pedro da Aldeia, 150 km to the North of the City of Rio de Janeiro, in Brazil. Tourism and land farming are the most important local economic activities. The criteria for selecting the site of the landfill did not meet the most basic environmental requirements, while the solid waste has been dumped without any previous engineering design. A thorough interpretation of the chemical tests performed in samples collected from the ground water affected by the landfill is presented by Lima (2003). The statistical assessment takes into account the fluctuations of the contaminant concentrations measured in the monitoring points impacted by the leachate, as well as the seasonal fluctuations of the uncontaminated concentrations measured in a background well distant 419m from the contamination source. The ionic concentrations have been measured in nine monitoring points at 8 different times: February 2000, April 2000, June 2000, September 2000, February 2001, April 2001, August 2001 and September 2001. The assessment also takes into account that the landfill is still in operation and the production of solid waste is limited to 22,000 tons/year, including a peak production of 4,000 tons in 3 summer months. Therefore, the predictions do not account for any increase in the solid waste production beyond the limits above.

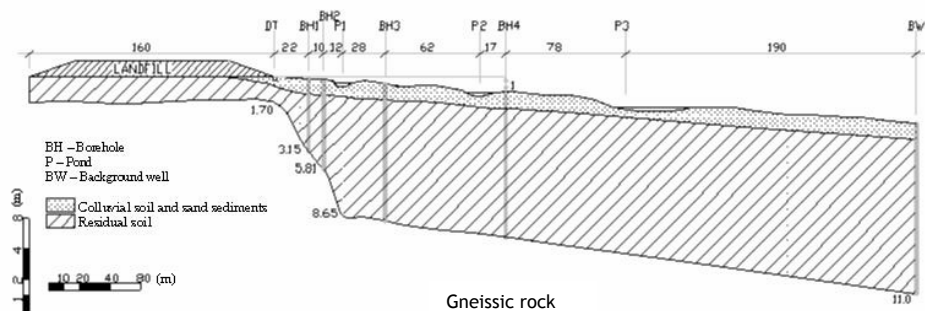


Figure 1: Local soil profile

2 SITE FEATURES

The local soil profile consists of a layer of young residual sandy silt soil of gneissic rock topped by a thin layer of colluvial and sedimentary sediments, about 1-2 m thick (Figure 1). Ionic concentrations of Cl^- , K^+ , Na^+ , Ca^{+2} , Ba^{+2} , HCO_3^- , Fe (total), Mg^{+2} , and NH_4^+ have been measured by Lima (2003) in monitoring points located at increasing distances from the landfill (Table 1). The leachate is collected partially by a trench and drains into a natural ditch (Figure 2). The water table is nearly coincident with the ground level in natural ditch, forming three small natural ponds designated as P1, P2 and P3 in Figure 1. The position of the water table is confirmed by 5 boreholes (BH1 to BH4 and BW) located in the ditch. The boreholes at small distances away from the ditch were dry, similarly to a buried canal. The measured concentrations are interpreted as mean readings (mean concentration within the borehole) (ABNT, 1997; CETESB, 1999), for a given well at a particular time.

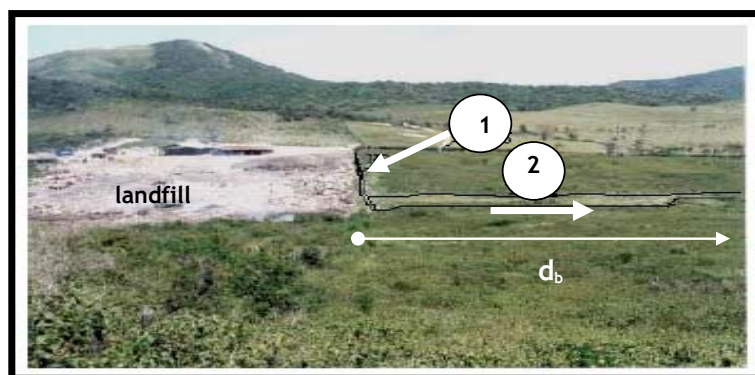


Figure 2: General view of the landfill (Lima, 2003): (1) drainage trench; (2) natural ditch

The three ponds formed along the natural ditch have long been used for animal consumption. The contamination in the first pond (P1) is easily detected by the naked eye. Tests on water samples from the second pond (P2) also indicate that the contamination level there is higher than the legal limits for drinking water established by the Federal Brazilian Environmental Council (CONAMA 357/2005). For example, the ionic concentration of chloride in the second pond averaged 655 mg/l , which is higher than the maximum legal limit of 250 mg/l . The average concentration of chloride in the third pond (P3) was 248 mg/l , with a peak value of 390 mg/l (Feb. 2000) and lower value of 172 mg/l (Jun. 2001).

3 STATISTICAL ASSESSMENTS

The ion Cl^- is probably the most suited to be used as a tracer of the contamination plume advance through the ground water. It is one of the fastest ions in diffusion through the water phase and can be considered as a non-reactive species in nearly all soil conditions (Mitchell, 1993; Fetter, 1993). Cl^- ions travel faster and reach longer distances when compared to other ions. Therefore Cl^- is an excellent tracer in the investigation of contamination plumes generated by MSW landfills.

Table 1. Location of the monitoring points (Lima, 2003)

Distance of monitoring points from the landfill (m)										
Monitoring point	DT	BH1	BH2	P1	BH3	BH4	P2	BH5	P3	BW
Distance to landfill (m)	0.0	22	32	44	72	74	134	151	229	419

DT=drainage trench; BH=borehole; P=pond; BW=background well

Figure 3 shows the oscillations (with time and distance) of the concentration for the ion Cl^- . For wells located more than 100 m from the landfill. The measured concentrations are reasonably constant, with no significant trend to increase with time, at least within the 1 ½ year period of investigation.

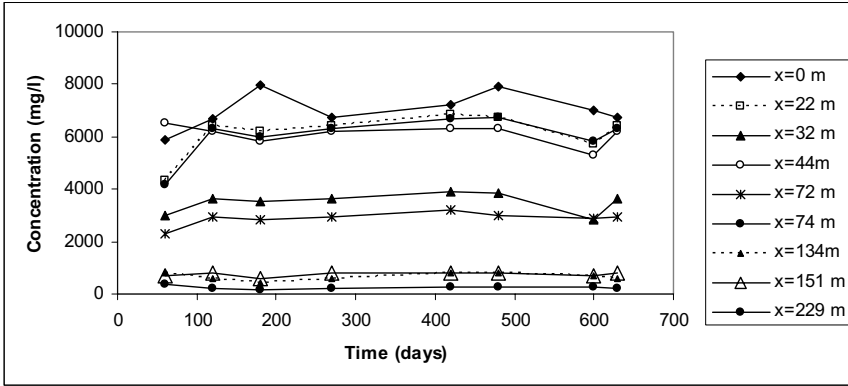


Figure 3: Fluctuation of ionic concentrations of Cl^- with time and distance

Nearly stationary readings with time at large distances from the source may indicate generally that the contamination plume is not propagating further or is moving very slowly downstream while the landfill is still in operation. To account for the scatter in the readings, the statistical procedure presented herein takes into account simultaneously the fluctuations produced by the landfill contamination and the oscillations measured at the background well.

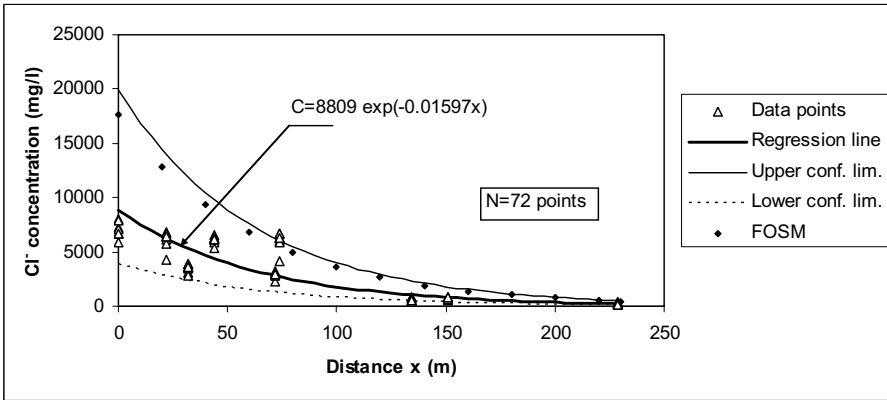


Figure 4: Cl^- decay with distance (95% confidence limits).

For a nearly stationary plume, Figure 4 shows in one plot eight time readings of concentrations of Cl^- for each of the nine monitoring points ($N=72$ data points), where the decaying concentration C_x at a distance x is represented by an exponential trend line as:

$$C_x = C_o \exp(-bx) \tag{1}$$

The regression constants C_o and b in Figure 4 are mean values representing the population of ionic concentrations Cl^- . C_o is the initial mean concentration, and b the exponential mean concentration decay per unit length. The exponentially decaying confidence limits in Figure 4 are obtained by exponential regression. The exponentially decaying variance $V[C_x]$ is estimated from Equation 1, using FOSM (First Order Second Moment) approximation, assuming statistical independence between C_o and b (Pacheco & Vasconcellos, 2006):

$$V[C_x] \cong \exp(-2bx) \left(V[C_o] + x^2 C_o V[b] \right) \quad (2)$$

Statistical independence between C_o and b is explained by the fact that the initial concentration C_o depends primarily on the composition of the landfill, whereas the rate of concentration decay b depends on the advective-dispersive flow and the soil sorption/microbiological characteristics. The exponential functions given by Equations 1 and 2 reflect the advective-dispersive transport with loss of contaminant mass and account for the statistical dispersion of the concentration readings. The variances $V[C_o]$ and $V[b]$ in Equation 2 are determined by mapping the concentrations C_x into the variable y defined as:

$$y = \ln C_x \quad (3)$$

The individual points (x, C_x) mapped into the (x, y) space fit a straight line whose regression parameters are a (intercept, representing the natural logarithm of C_o) and b (slope, representing the concentration decay in Equation 1). The variance of the initial concentration is determined as (Pacheco & Vasconcellos, 2006):

$$V[C_o] = \left[e^{a+\sigma[a]} - e^a \right]^2 = \left[e^a (e^{\sigma[a]} - 1) \right]^2 \quad (4)$$

The confidence limits in the (x, C_x) space (Figure 4) are asymmetrical. The upper confidence limit in Figure 4 can also be estimated by FOSM approximation, where $C_{x,\alpha}$ (concentration at a distance x , for a margin of error α) is obtained from Equations 1 and 2 as:

$$C_{x,\alpha} = C_x + t[(1-\alpha), \nu] \sqrt{V[C_x]} \quad (5)$$

The value $t[(1-\alpha), \nu]$ represents the number of standard deviations above the mean concentration C_x , where t refers to the Student t distribution with ν degrees of freedom. The background distance d_b shown in Figure 1 represents the mean distance travelled by an ion in the leachate. The distance d_b is limited by the point where the mean regression curve decays to a value equal to the background concentration C_b (Table 2) in the background well ($x=419$ m). Thus, from Equation 1:

$$d_b = \left(\frac{1}{b} \right) \ln \left(\frac{C_o}{C_b} \right) \quad (6)$$

The variance of the background distance is estimated from Equation 6, using FOSM approximation, assuming statistical independence between (C_o, b) , (C_b, b) , and (C_o, C_b) , as (Pacheco & Vasconcellos, 2006):

$$V[d_b] \cong \left(\frac{1}{bC_o} \right)^2 V[C_o] + \left(\frac{1}{bC_b} \right)^2 V[C_b] + \left[\frac{1}{b^4} \ln \left(\frac{C_o}{C_b} \right) \right]^2 V[b] \quad (7)$$

The variances $V[a]$ and $V[b]$ of the regression parameters a and b in the transformed linear space (x, y) are determined as (Neter et al., 1982):

$$V[a] = MSE \left[1 + \frac{1}{N} + \frac{\bar{x}^2}{\sum(x_i - \bar{x})^2} \right]; \quad V[b] = \frac{MSE}{\sum(x_i - \bar{x})^2} \quad (8)$$

$$MSE = \frac{\sum(y_i - \hat{y})^2}{N - 2} \quad (9)$$

The value N in Equations 8 refers to the sample size, whereas MSE is the mean square error of the transformed points (x, C_x) with respect to the mean linear regression curve. In the following, $d_{b,\alpha}$ is the background distance corresponding to a given margin of error α . The distance $d_{b,\alpha}$ is estimated by the point where the upper confidence limit decays to a value equal to the background concentration C_b . To account for the variability of the background readings with time, the distance $d_{b,\alpha}$ is estimated by FOSM approximation, assuming statistical independence between (C_o, b) , (C_b, b) , and (C_o, C_b) . Statistical independency between (C_o, b) has already been demonstrated. Statistical independence between (C_b, b) and (C_b, C_o) is ensured as long as the background concentrations C_b are not affected by the leachate contamination. For a given margin of error α , the background distance $d_{b,\alpha}$ obtained from Equations 6 and 7 is:

$$d_{b,\alpha} = d_b + t[(1-\alpha), \nu] \sqrt{V[d_b]} \quad (10)$$

Table 2. Values of mean and C.O.V.

Ion	\bar{d}_b (m)	\bar{C}_0 (mg/l)	\bar{b} (m^{-1})	\bar{C}_b (mg/l)	C.O.V.(%) (d_b)	C.O.V.(%) (C_0)	C.O.V.(%) (b)	C.O.V.(%) (C_b)
Cl^-	310	8810	0.0159	71	11	50	42	12
Na^+	297	6582	0.014	116	18	69	6	11
$Fe(total)$	247	4.17	0.0187	0.6	47	197	9,7	33
HCO_3^-	240	210	0.0105	17.82	38	84	1	32
Ca^{+2}	221	796	0.0189	18.19	23	79	5	34
NH_4^+	200	39.21	0.0172	1.36	27	88	6	8
K^+	151	2570	0.0301	33.81	63	272	7	19
Mg^{+2}	150	4.65	0.01	1.41	14	50	7	14
Ba^+	129	0.82	0.016	0.24	180	190	11	24

The value $t[(1-\alpha), \nu]$ represents the number of standard deviations above the mean value. The expected values d_b , C_o , b and C_b for all ions are listed in Table 2. C_o and b are determined by exponential regression. The coefficient of variation of the background concentration C_b is based on the uncorrelated variance of 8 readings taken at the background well, for each ion. It is seen in Table 2 that: *i*- the maximum mean background distance d_b is reached by the ion Cl^- . The corresponding coefficient of variation is the smallest of all ionic concentrations in Table 2.; *ii*- the coefficient of variation of the initial concentration C_o is the smallest for the ions Cl^- and Mg^{+2} .; *iii*- The regression parameter b shows very small scatter for all ions. Therefore, the regression parameter b is not affected by the high scatter of the regression parameter C_o , regardless of the ion considered, confirming statistical independence between (C_o, b) , (C_b, b) .

The overall statistical assessment is shown in Figure 5. The dashed lines represent the legal Brazilian limit for Cl^- (250mg/l). The solid lines represent the mean background concentration (71 mg/l). The assessment indicates that the contamination produced by the landfill travels on the average 220 m to reach the Cl^- legal limit of 250 mg/l and 300 m to reach the Cl^- background concentration of 71mg/l. These results indicate that the limiting distance of 400 m is considered a safe threshold for water consumption. The probability that the contamination exceeds the Cl^- background concentration at 400 m from the source is less than one to one thousand. The probability that the contamination exceeds the legal limit there is negligible (less than one to one million).

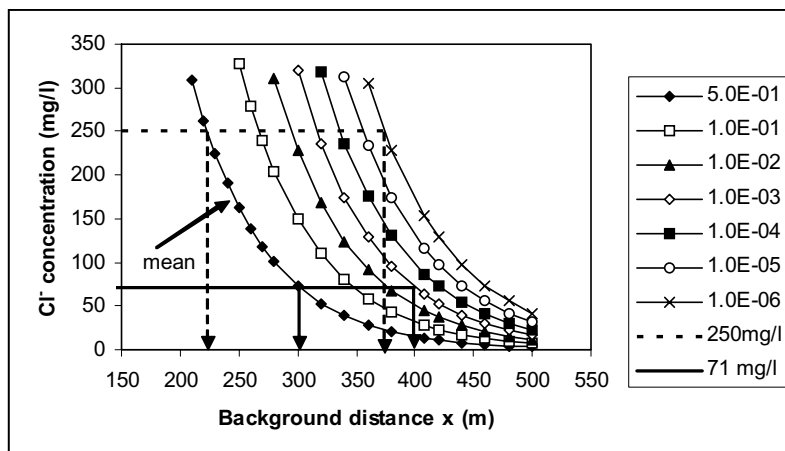


Figure 5: Background distances for different margins of error: the legends (lines with symbols) are margins of error.

4 CONCLUSIONS

The ionic concentration measurements as well as the statistical assessment of the distances travelled by different ions in the groundwater confirm that chloride is a good tracer of MSW leachate contamination. In addition to propagating faster and reaching longer distances compared to other ions in the leachate, Cl^- concentrations also show considerably less scatter with time and distance than other ions found in MSW landfill leachates. The statistical assessment indicates that the distance of 400 m from the contamination source is a safe threshold for water consumption. This assessment considers a limited period of observation of 1 ½ years and does not take into account any future increase in waste production. Therefore, continuous monitoring is essential for full assurance of the groundwater quality.

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