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Predictive Model for Leachate Contamination of Groundwater around a municipal Waste Dump: Case Study of Obosi, Southeastern Nigeria

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Abstract

Landfill wastes undergo several decomposition processes giving rise to various organic and inorganic contaminants that have high toxic implications. These contaminants later dissolve in rain water to form leachate. The leachate in such waste streams could migrate through the porous soil media of the vadose region by several physical processes to contaminate the groundwater of the area. Leachate migration from waste sites to the groundwater is subject to various transport attributes such as hydraulic head, distance of borehole from the waste dump, borehole depth, net recharge of groundwater and leachate concentration. Space and time dependent pollution of groundwaters was predicted by developing a numerical model of polynomial expression which incorporates these transport attributes. The groundwater pollution was conceived to be a function of distance from dumpsite, x_1, porosity and conductivity of vadose region, x_2, depth of borehole, x_3, hydraulic head, x_4 and net recharge of groundwater, x_5. This concept was captured in the expression $y = k + k_1x_1 + k_2x_2 + k_3x_3 + k_4x_4 + k_5x_5$, where y is the composite pollution index. The polynomial was solved by application of matrices algebra embedded in Matlab 7.9. The resulting prediction equation was tested for accuracy by comparison with cation analysis of four boreholes chosen at random within the study area. The one-way ANOVA test revealed that the mean concentrations of all the cations measured differed significantly across the boreholes studied (Sig F values = As 0.005, Pb 0.000, Cu 0.000, Cr 0.000, Co 0.000, Ni 0.000, Mn 0.037, Fe 0.000, Cd 0.000 and Hg 0.000) at $p<0.05$ whereas the pair-wise student's t-test show that except for Hg, the simulated and measured values of the other cations studied were not significantly different at the 95% confidence level (sig. t=0.026). This result indicates that at 95% confidence level, the simulation becomes invalid.

Keywords: prediction, waste dump, Southeastern Nigeria, trace metals, leachate

INTRODUCTION

Open wastes dumping and use of unprotected landfills for solid wastes disposal have been identified as the oldest ways of solid wastes disposal (Pariatamby and Tanaka, 2013). The use of unprotected landfills represents the most viable and commonly used method for solid waste disposal all over the world. This is because it may achieve the reclamation of derelict land (Erses *et al*., 2005). However, this practice is considered one of the major threats to groundwater (Fatta *et al.*, 1999*)* and the scale of this threat depends on the concentration and toxicity of contaminants in the waste's leachate, type and permeability of geological strata, depth of water table and the direction of groundwater flow (Al-Khaldi, 2006). Point sources such as open waste dumps can release high concentrations of contaminants into the groundwater. The leachate generated primarily as a result of precipitation and biodegradation activities on the waste components have the potential to pollute the underlying groundwater aquifers (Jhnamnani and Singh, 2009), and impair its uses (Renou *et al*., 2008). There is a greater possibility of groundwater contamination in areas near open waste dumps and unprotected landfills due to the potential of such facilities to leak leachate originating from them. Such contamination of groundwater resource poses a substantial risk to public health and to the natural environment. Leachate migration from wastes sites or landfills to groundwater is subject to various processes such as weathering, solubility of the waste components, ion exchange and vadose region characteristics. Such characteristics are expressed by porosity and conductivity of

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the vadose region, rock formation and disposition, ion concentration and migration impedance. It equally depend on waste generation rate, wastes type and disposal methods. Many approaches have been adopted for the assessment of the impact of leachate seepage on groundwater. This can be achieved either by the experimental determination of the impurities or through mathematical modeling (Moo-Young *et al.*, 2004, Hudak, 1998 and Stoline *et al.*, 1993). A predictive model for leachate contamination of groundwater aims at predicting the tendency or likelihood for contaminants to reach a specified level or position in the groundwater system after introduction at some location above the uppermost aquifer (Thirumalaivasan, 2001). Obosi in Anambra State has experienced high rates of urbanization and industrialization. This has resulted to environmental challenges consequent on urbanization and industrialization involving population migration. The increase in population is associated with increased volume of generated wastes. The Obosi waste dumpsite is unprotected and has received wastes streams for over 50 years. The leachate in such waste streams could migrate through the porous soil media of the vadose region. Several physical processes leading to contamination of the shallow aquifers of the area occur. In recent times, the impact of leachate on groundwater sources has been extensively studied (Saarela, 2001; Abu and Kofahi, 2001; Christensen *et al.*, 2001; De Rosa *et al.*, 1996 and Flyhammer, 1995). Many researchers have also carried out investigations on the state of groundwater within Anambra state. Most of these studies are limited to spot measurements used for baseline studies (Egboka *et al.* 1983; Ezeabasili *et al.* 2015; Ezeabasili *et al.* 2014; Ogbukagu, 1986; etc). However, none of these studies proposed or used any simulation model capable of modeling leachate contamination pathways and dynamics. They also failed to link groundwater contamination in the area to environmental and hydro-geological attributes such as distance of borehole from the waste dump, porosity and hydraulic conductivity of the vadose region, borehole depth, net recharge of the aquifer and hydraulic head. If leachate contamination of groundwater around waste dumps can be accurately predicted, control and remediation measures can be put in place for adequate waste management. This study therefore presents predictive mathematical model of groundwater pollutant concentrations as a function of contaminant transport attributes. This will serve as a tool to guarantees clean water delivery (Salami *et al.*, 2013).

2. MATERIALS AND METHODS

Field sampling was carried out using standard methods as provided by APHA/AWWA/WEF (1999). All physico-chemical parameters were determined based on National Environmental Standards and Regulations 2009 while heavy metals were determined using FS 240 Varian AAS. The analog map of the study area was digitized and delineated into 8 map groups with each group consisting of a series of concentric cells separated 500m apart with borehole positions geo-referenced therein. Twenty four (24) boreholes located within 4km radius around the Obosi dumpsite constituted the composite sampling locations and the waste dump was the centre of the study cells. Nine (9) trace metals were analysed for in each borehole for two different seasons. Results of analysis from the sampled boreholes were inserted into polynomial equations which were solved simultaneously using Matrix algebra, executed in Matlab 7.2 to arrive at predictive models.

Statistical Analysis: SPSS 17.0 statistical software was used for statistical analysis of data. ANOVA was used to establish the spatial variation in pollutant concentrations between the studied boreholes whereas the student's t-tests analysis was used to conduct a pair wise comparison between the simulated and field measurements.

3. HYPOTHESIS OF THE STUDY

The theory underlying this study consists in the assumption that pollutant concentration in borehole waters which are contiguous depend on such attributes as distance of borehole from the waste dump, hydraulic conductivity of the porous medium, borehole depth, net recharge rate and hydraulic head. This can be represented as

$$y = k + k_1x_1 + k_2x_2 + k_3x_3 + k_4x_4 + k_5x_5 \qquad (1.0)$$

where y is the extent of pollution in a cell contributed by attributes x_1 to x_5 and k's are predictive constants.

If therefore, a concentric circle of eight cells centered at the dump site defined by geographical/spatial coordinates is taken in a group and the cells, defined as 1, 2, 3 … 8, can be identified uniquely, then for a group of bore holes in cells 1, 2, 3… 8, we may write the polynomial equations for contaminant concentrations $y_1, y_2, y_3, \ldots, y_8$ as follows:

$$y_1 = k_1 + k_{11}x_{11} + k_{12}x_{12} + k_{13}x_{13} + k_{14}x_{14} + k_{15}x_{15} \qquad (2.0)$$
$$y_2 = k_1 + k_{11}x_{21} + k_{12}x_{22} + k_{13}x_{23} + k_{14}x_{24} + k_{15}x_{25} \qquad (2.1)$$
$$y_3 = k_1 + k_{11}x_{31} + k_{12}x_{32} + k_{13}x_{33} + k_{14}x_{34} + k_{15}x_{35} \qquad (2.2)$$
$$.y_4 = k_1 + k_{11}x_{41} + k_{12}x_{42} + k_{13}x_{43} + k_{14}x_{44} + k_{15}x_{45} \qquad (2.3)$$
$$y_5 = k_1 + k_{11}x_{51} + k_{12}x_{52} + k_{13}x_{53} + k_{14}x_{54} + k_{15}x_{55} \qquad (2.4)$$
$$y_6 = k_1 + k_{11}x_{61} + k_{12}x_{62} + k_{13}x_{63} + k_{14}x_{64} + k_{15}x_{65} \qquad (2.5)$$
$$y_7 = k_1 + k_{11}x_{71} + k_{12}x_{72} + k_{13}x_{73} + k_{14}x_{74} + k_{15}x_{75} \qquad (2.6)$$
$$.y_8 = k_1 + k_{11}x_{81} + k_{12}x_{82} + k_{13}x_{83} + k_{14}x_{84} + k_{15}x_{85} \qquad (2.7)$$

The equations can be solved by applying matrix algebra as follows:

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \end{pmatrix} = \begin{pmatrix} 1 & x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ 1 & x_{21} & x_{22} & x_{23} & x_{24} & x_{25} \\ 1 & x_{31} & x_{32} & x_{33} & x_{34} & x_{35} \\ 1 & x_{41} & x_{42} & x_{43} & x_{44} & x_{45} \\ 1 & x_{51} & x_{52} & x_{53} & x_{54} & x_{55} \\ 1 & x_{61} & x_{62} & x_{63} & x_{64} & x_{65} \\ 1 & x_{71} & x_{72} & x_{73} & x_{74} & x_{75} \\ 1 & x_{81} & x_{82} & x_{83} & x_{84} & x_{85} \end{pmatrix} \begin{pmatrix} k_1 \\ k_{11} \\ k_{12} \\ k_{13} \\ k_{14} \\ k_{15} \\ k_{16} \\ k_{17} \end{pmatrix} \tag{3.0}$$

The solution to this matrix using MATLAB 7.2 gives the k’s which are expected to be uniquely constant in a given cell and for a given pollutant parameter for any bore hole in the cell.

Figure 1 represents digitized map of the study area delineated into eight concentric study cells and the boreholes contained therein.

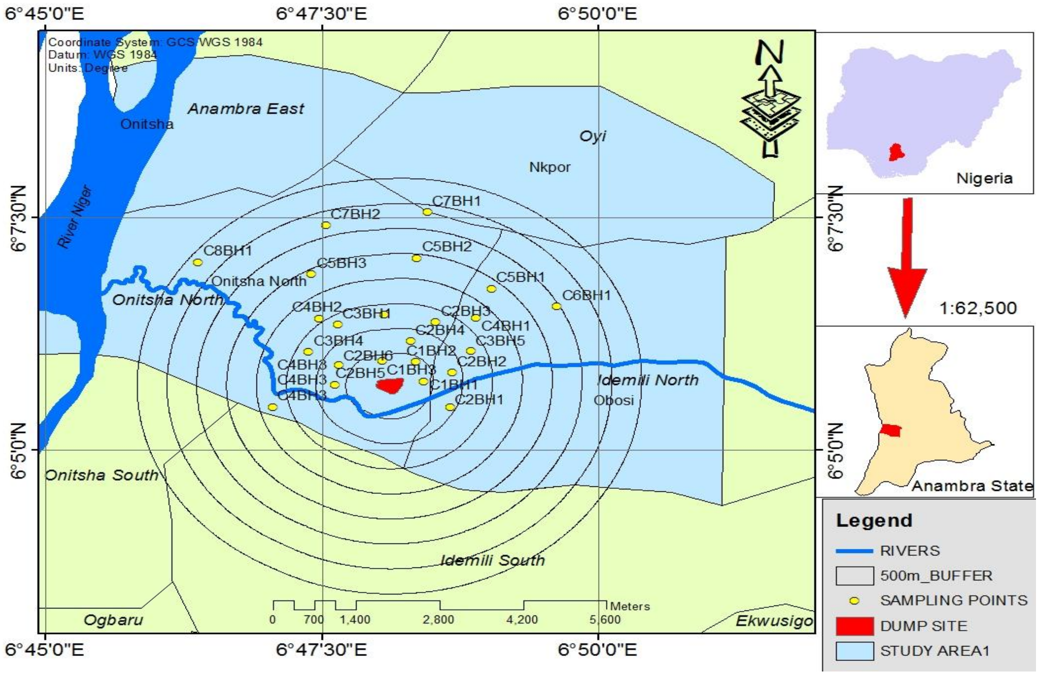

Figure 1: Map of study area showing the study cells and sampling points

4. RESULTS

Tables 1 Show the trace metal levels obtained from the laboratory analysis of water samples in wet and dry seasons.

Table 1: Levels of trace metals in groundwater around the Obosi dumpsite (wet and dry seasons).

SAMPLE	LONG. (E)	LAT (N)	Pb mg/L	Cu mg/L	Cr mg/L	Co mg/L	Ni mg/L	Mn mg/L	Fe mg/L	Cd mg/L	Hg mg/L	Pb mg/L	Cu mg/L	Cr mg/L	Co mg/L	Ni mg/L	Mn mg/L	Fe mg/L	Cd mg/L	Hg mg/L
			WET SEASON									DRY SEASON								
C$_1$BH$_1$	6.8110	6.0970	0.07	0.029	0.000	0.000	0.000	0.000	0.000	0.000	2.200	0.409	0.015	1.042	0.311	0.000	0.294	0.000	0.055	1.106

C_1BH_2	6.8140	6.1010	0.12	0.007	0.000	0.000	0.000	0.000	0.224	0.204	0.000	0.120	0.007	0.000	0.000	0.000	0.200	0.224	0.204	0.236
C_1BH_3	6.8080	6.1020	0.100	0.007	0.000	0.000	0.000	0.072	0.387	0.022	0.700	0.461	0.031	3.106	0.456	0.114	0.694	1.425	0.04	0.288
C_2BH_1	6.8110	6.0910	0.710	0.840	2.029	2.970	0.11.0	0.030	2.000	0.009	1.700	1.513	0.099	4.401	0.000	0.000	1.988	0.000	0.052	0.201
C_2BH_2	6.8180	6.0980	0.400	0.004	0.000	0.000	0.000	0.853	0.072	0.039	0.000	0.373	0.000	2.733	0.164	0.000	0.787	0.139	0.033	0.229
C_2BH_3	6.8150	6.1070	0.530	0.000	0.000	0.003	0.000	0.000	0.023	0.020	0.000	0.251	0.057	1.688	0.000	0.000	0.553	0.000	0.049	0.166
C_2BH_4	6.8060	6.1060	0.160	0.049	0.000	0.015	0.000	3.154	2.275	0.380	0.600	0.519	0.009	0.000	0.000	0.167	0.182	0.000	0.042	0.176
C_2BH_5	6.7990	6.0980	0.160	0.000	0.000	0.005	0.000	0.000	0.085	0.000	1.700	0.345	0.057	0.352	0.140	0.027	0.000	0.000	0.027	0.157
C_2BH_6	6.7990	6.0950	0.170	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.313	0.051	1.981	0.000	0.000	0.223	0.117	0.056	0.159
C_3BH_1	6.8110	6.1120	0.210	0.000	0.000	0.000	0.010	1.712	0.000	0.049	1.700	0.524	0.000	0.000	0.000	0.000	1.244	0.000	0.052	0.099
C_3BH_2	6.8010	6.1080	0.180	0.007	0.000	0.008	0.000	0.374	0.065	0.012	1.400	0.608	0.035	0.000	0.182	0.049	0.138	0.000	0.021	0.139
C_3BH_4	6.7960	6.1030	0.160	0.000	0.000	0.009	0.000	0.000	0.000	0.001	0.000	0.601	0.028	0.000	0.000	0.029	0.212	0.000	0.031	0.153
C_3BH_5	6.8230	6.1010	0.260	0.000	0.000	0.007	0.000	0.000	0.000	0.037	1.300	0.447	0.033	0.000	0.000	0.000	0.428	0.000	0.044	0.079
C_4BH_1	6.8220	6.1080	0.230	0.131	0.000	0.000	0.000	0.000	0.000	0.016	1.600	0.727	0.022	2.171	0.000	0.034	1.314	0.072	0.045	0.092
C_4BH_2	6.7910	6.1070	0.240	0.000	0.000	0.017	0.000	0.000	0.000	0.197	2.800	0.578	0.007	0.000	0.000	0.000	1.022	0.000	0.056	0.133
C_4BH_3	6.7930	6.0900	0.691	0.850	2.011	2.610	0.100	1.010	2.500	0.011	1.400	1.375	0.053	0.000	0.000	0.108	0.093	0.000	0.057	0.228
C_5BH_1	6.8200	6.1160	0.240	0.000	0.000	0.024	0.000	0.605	0.000	0.053	1.800	1.406	0.053	0.374	0.000	0.032	1.370	0.000	0.047	0.145
C_5BH_2	6.8060	6.1180	0.240	0.000	0.000	0.000	0.000	0.254	1.477	0.228	0.000	0.844	0.028	0.000	0.000	0.014	0.526	0.000	0.045	0.172
C_5BH_3	6.7900	6.1150	0.240	0.000	0.000	0.000	0.000	0.000	0.000	0.053	2.000	0.407	0.049	0.000	0.000	0.000	0.726	0.000	0.067	0.123
C_6BH_1	6.8330	6.1110	0.340	0.000	0.000	0.007	0.000	0.772	0.000	0.228	1.300	1.622	0.044	4.137	0.000	0.000	0.812	0.041	0.060	0.176
C7BH1	6.8070	6.1280	0.018	0.690	0.153	1.600	0.065	0.170	1.600	0.015	1.600	0.018	0.690	0.153	1.600	0.065	0.170	1.600	0.015	1.600
C7BH2	6.7910	6.1280	0.710	0.860	0.310	1.000	0.170	0.270	2.610	0.049	1.300	0.710	0.860	0.310	1.000	0.170	0.270	2.610	0.049	1.300
C_8BH_1	6.7730	6.1170	0.580	1.920	1.115	3.150	0.112	0.120	5.810	0.005	0.000	1.195	0.041	0.098	0.046	0.195	0.293	0.000	0.044	0.222

Tables 2 shows the mean concentration of metal cations measured in study cells whereas Table 3 shows the values for the hydrogeochemical attributes (x-values) used for the simulation.

Table 2: mean concentration of metal cations in each study cell

Study cell	arsenic	lead	cupper	chromium	cobalt	nickel	manganese	Iron	cadmium	Mercury
C1	0.000	0.213	0.016	0.691	0.128	0.019	0.210	0.377	0.088	0.755
C2	0.013	0.454	0.097	1.099	0.275	0.025	0.648	0.393	0.059	0.424
C3	0.013	0.374	0.013	0.000	0.026	0.011	0.514	0.008	0.031	0.609
C4	0.018	0.640	0.177	0.697	0.438	0.040	0.573	0.429	0.064	1.042
C5	0.000	0.563	0.022	0.062	0.004	0.008	0.580	0.246	0.082	0.707
C6	0.017	0.981	0.022	2.069	0.004	0.000	0.792	0.021	0.144	0.738
C7	0.000	0.364	0.775	0.232	1.300	0.118	0.220	2.105	0.032	1.450
C8	0.000	0.888	0.981	0.607	1.598	0.154	0.207	2.905	0.025	0.111

Table 3: Values for the hydrogeochemical attributes in the study cells.

Parameters	**Cells**							
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Distance of Boreholes from dumpsite (m) (x_1)	551.50	1051.87	1551.40	2051.60	2551.32	3051.22	3551.06	4051.66
Vadose conductivity (m/day) (x_2)	32.85	32.85	32.85	32.85	32.85	32.85	32.85	32.85
Borehole depth (m) (x_3)	45.75	47.28	61.00	76.25	48.80	67.10	91.50	54.90
Net Recharge (m/day) (x_4)	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45
Hydraulic head (m) (x_5)	6.15	10.68	3.40	13.50	24.54	9.90	18.47	67.24

The k values generated after solving the polynomial equations are shown in table 4.

Table 4: Predictive constants obtained from solving pollutant regression equations

Pollutant	**Predictive constants**					
	k	k_1	k_2	k_3	k_4	k_5
Arsenic	0.000	$9.0x10^{-7}$	$2.368x10^{-4}$	$3.91x10^{-5}$	0.000	$-2.332x10^{-4}$
Lead	0.000	0.0003	0.0188	-0.0092	0.000	-0.0050
Cupper	0.000	-0.0001	-0.0278	0.0173	0.000	0.0218
Chromium	0.000	-0.0278	2.4205	0.2090	0.000	1.8297
Cobalt	0.000	-0.0003	-0.0478	0.0332	0.000	0.0397
Nickel	0.000	0.000	-0.0040	0.0029	0.000	0.0037
Manganese	0.000	0.0002	0.0290	-0.0114	0.000	-0.0150
Iron	0.000	-0.0004	-0.0643	0.0432	0.000	0.0644
Cadmium	0.000	0.000	0.0051	-0.0024	0.000	-0.0028
mercury	0.000	0.000	-0.0086	0.0199	0.000	-0.0066

Substituting these k values into the regression equation for each metal cation gives equations 4.0 to 4.9 below, which are model expressions for prediction of pollution concentration of metallic ionic moieties.

$y_{As} = 9.0x10^{-7}x_1 + 2.368x10^{-4}x_2 + 3.91x10^{-5}x_3 - 2.332x10^{-4}x_5$ (4.0)
$y_{Pb} = 0.0003x_1 + 0.0188x_2 - 0.0092x_3 - 0.0050x_5$ (4.1)
$y_{Cu} = -0.0001x_1 - 0.0278x_2 + 0.0173x_3 + 0.0218x_5$ (4.2)
$y_{Cr} = -0.0278x_1 + 2.4205x_2 + 0.2090x_3 - 1.8297x_5$ (4.3)
$y_{Co} = -0.0003x_1 - 0.0478x_2 + 0.0332x_3 + 0.0397x_5$ (4.4)
$y_{Ni} = -0.004x_2 + 0.0029x_3 + 0.0037x_5$ (4.5)
$y_{Mn} = 0.0002x_1 + 0.0290x_2 - 0.0114x_3 - 0.0150x_5$ (4.6)
$y_{Fe} = -0.0004x_1 - 0.0643x_2 + 0.0432x_3 + 0.0644x_5$ (4.7)
$y_{Cd} = 0.0051x_2 - 0.0024x_3 - 0.0028x_5$ (4.8)
$y_{Hg} = -0.0086x_2 + 0.0199x_3 - 0.0066x_5$ (4.9)

5. DISCUSSION

5.1. Influence of k Values on the Contribution of Metal Ions to Pollution

The negative k_1 values for Cu^{2+}, Cr^{3+}, Co^{2+} and Fe^{2+}in Table 4 show that as the distance increases, the contribution to pollution of these cations decrease (Mor *et al.*, 2006). Ni^{+}, Cd^{2+}, and Hg^{2+} contribution to pollution is not distance dependent. Pb^{2+} and Mn^{2+} which have positive k_1 values show that their contribution to pollution increase with distance. This is an indication of extraneous contamination that is not leachate in origin (Jagloo, 2002). Cu^{2+}, Co^{2+}, Ni^{+}, Fe^{2+} and Hg^{2+} have negative k_2 which indicates that conductivity of the vadose region decreases their contribution to pollution. Pb^{2+}, Mn^{2+} and Cd^{2+} contribution to pollution decrease with depth of borehole (Chove, 2018). The k_4 which represents coefficient of net recharge does not influence the concentration of metal ions. This is expected as the ionic concentrations are diluted or concentrated at equal rates. Furthermore, k_5 which is the coefficient of hydraulic head is negative for Pb^{2+}, Mn^{2+}, Cd^{2+} and Hg^{2+}. Negative k_5 values indicate less contribution of these cations to aquifer pollution, corresponding to increase in the hydraulic head (Mkude, 2015).

5.2. Model Justification

In order to verify the applicability of the simulation equations, four independent boreholes were sampled in the study cells and analyzed as against values from simulation. These values are shown in Table 5.

Table 5: Simulated and observed values for groundwater contaminants in the study area

Parameters	**Simulated Values**				**Measured Values**			
	C2BH1	**C3BH2**	**C4BH3**	**C5BH4**	**C2BH1**	**C3BH2**	**C4BH3**	**C5BH4**
Arsenic	0.009	0.009	0.011	0.008	0.006	0.000	0.038	0.016
Lead	0.325	0.307	0.563	0.284	0.251	0.519	0.345	0.313
Copper	0.034	0.314	0.063	0.945	0.057	0.009	0.057	0.051

Chromium	0.534	0.357	0.893	0.000	1.553	0.215	0.367	0.844
Cobalt	0.160	0.642	0.104	1.726	0.082	0.002	0.008	0.073
Nickel	0.039	0.094	0.062	0.216	0.000	0.167	0.027	0.000
Manganese	0.414	0.288	0.540	0.000	0.772	0.170	0.270	0.120
Iron	0.220	0.882	0.115	0.439	0.224	1.425	0.000	0.139
Cadmium	0.028	0.000	0.009	0.000	0.020	0.022	0.009	0.039
Mercury	0.667	0.946	0.878	1.393	0.176	0.157	0.159	0.099

The pertinent data for leachate migration simulations are presented in Table 6.

Table 6: values for the contaminant migration attributes in Boreholes

Parameters	**Borehoes and Cells**			
	C2BH1	**C3BH2**	**C4BH3**	**C5BH4**
Distance of Boreholes from dumpsite (m) (x_1)	671.20	1121.22	1742.12	2062.33
Vadose conductivity (m/day) (x_2)	32.85	32.85	32.85	32.85
Borehole depth (m) (x_3)	50.00	65.00	60.00	91.50
Net Recharge (m/day) (x_4)	1.45	1.45	1.45	1.45
Hydraulic head (m) (x_5)	6.85	9.85	5.15	22.10

`The one-way ANOVA test revealed that the mean concentrations of all the cations measured differed significantly across the boreholes studied (Sig F values = As 0.005, Pb 0.000, Cu 0.000, Cr 0.000, Co 0.000, Ni 0.000, Mn 0.037, Fe 0.000, Cd 0.000 and Hg 0.000) at $p<0.05$.

Furthermore, the pair-wise student's t-test show that except for Hg, the simulated and measured values of the other cations studied were not significantly different at the 95% confidence level (sig. t=0.026). This result indicates that at 95% confidence level, the simulation becomes invalid.

6. CONCLUSION

A statistical comparison applying ANOVA and student's t-tests show that the model was not more than 95% accurate. The net recharge was shown by the numerical analysis to be insignificant as a pollution factor. Furthermore, the simulations indicate that as radial distance from the landfill increases, concentration of contaminants in groundwater decreases (Anne, 1993). The model can be modified by including an error factor which can be evaluated by comparing two models of similar characteristics with varying factors.

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