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Understanding soil contamination by leachate from landfills

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ABSTRACT

One of the major environmental problems nowadays is the contamination of soils and groundwater. Although landfilling has appeared as the simplest and most economical method to eliminate municipal solid waste, but in many developing countries like Lebanon and with the absence of solid waste management plans, open dumps, uncontrolled landfills and open burning are sadly predominant. Wastewater leachate collected from these dumps is very toxic; it shows for example high concentration of Pb (0.024 ppm), Cd (11.5 ppm), As (1.648 ppm) and Hg (0.1076 ppm). The main purpose of this paper is to study the fate and transport of leachate contaminant through different soil matrix and to demonstrate the effect of soil properties in contaminant movement, its spatial distribution and concentration. The behavior of contaminant is tested for different hydraulic conductivities of soil and in the absence or presence of a bottom clay liner. Analysis of the contaminant transport from a dumpsite located near a riverbed in Lebanon is carried out using SEEP/W and CTRAN/W. The results confirm that the contaminant transport is largely affected by the hydraulic conductivity of soil; in the case of lower hydraulic conductivity, time taken by contaminants to reach the riverbed will increase about seven times. Also, the results prove the importance of installation of a clay liner at the bottom of landfills as it retards the migration of contaminants.

Keywords: landfill, leachate, contaminant transport, advection-dispersion analysis, clay liners.

1 INTRODUCTION

Rapid growth of population, urbanization, industrial and economic development all around the world in the past decade have resulted in a massive increase in waste generation. Waste generation continues to grow and the World Bank estimates that waste generation will increase from 2.01 billion tons in 2016 to 3.40 billion tons in 2050.

Lebanon is a developing country where the municipal solid waste (MSW) generation rate has increased by 26% between 1994 and 2011 (Sweep-Net, 2014). In addition to the high rate of waste generation, the increasing number of Syrian refugees and the absence of any waste management plan have led to hundreds of open dumps and non-engineered landfills and open burning of waste all over the country (Shellito, 2016; Cherri et al., 2016). This inappropriate solid waste disposal causes serious Geo-environmental problems and lead to contamination in soils, groundwater and rivers. A study achieved by LARI (Lebanese agricultural research institute) in 2017 found that no water source in Lebanon was free of contamination. The river waters in Lebanon are nothing but wastewater.

The infiltration of water into landfills and its percolation through waste as well as the squeezing of the waste due to self-weight causes leachate generation. Heavy metals in solid wastes lead to serious problems because they cannot be biodegraded (Hong et al., 2002). Dumpsites in Lebanon not only receive municipal solid waste but also medical, industrial and chemical waste. Wastewater leachate collected from these dumpsites is very toxic (Borjac et al, 2019; Khalil et al, 2018); it shows for example high concentration of heavy metals, Pb (0.024 ppm), Cd (11.5 ppm), As (1.648 ppm) and Hg (0.1076 ppm). Leachate generated from landfills in Lebanon seeps into groundwater aquifers and contaminants are spread into adjacent river system by groundwater flow and pollute the ecosystem.

Bar Elias is a Lebanese town in the Zahlé District, Bekaa Governorate. The Ghzayel river which passes by Bar Elias, is the most important tributary of the Litani River and its largest pollutant. Like in other

Lebanese towns, open dumpsites and uncontrolled landfills are scattered in Bar Elias along the riverbed. The dumpsite, subject of this study, is located in Bar Elias few meters away from the Ghzayel river. Few studies have assessed the contaminant migration from landfills in Lebanon. The main purpose of this paper is to study the fate and transport of leachate contaminant through different soil matrix and to demonstrate the effect of soil properties in contaminant movement, its spatial distribution and concentration.

2 THEORETICAL BACKGROUND

2.1 Landfills and leachate generation

Landfills are well engineered facilities that are used for disposal of solid waste and are located, designed, monitored, operated and financed to ensure compliance with federal regulations. One of the main objectives in the design of a landfill site should be the proper management of polluted water and leachate migration, therefore mitigating the risk of health and environmental damage. Leachate is a highly polluted wastewater that contains a wide range of contaminants including organic, inorganic matters, and heavy metals (Bhalla et al, 2013; Christensen, 1994; Kanmani et al, 2013; Kostova, 2006). Modern landfills are highly engineered and controlled systems that utilize liners to minimize the impact of waste materials, particularly solid waste. The liners are typically made of compacted clay, geosynthetic clay, geomembrane, geotextiles or combinations of all these. The characteristics and rate of leachate produced from a landfill are dependent upon the age of the landfill, temperature and moisture content. Then, the quality and quantity of leachate is highly variable, depending on the fluctuations of rainfall amount, composition and characteristics of the waste, age, precipitation rate, site hydrology, compaction, cover design, interaction of leachate with the environment and landfill operational patterns (Jhamnani and Singh, 2009). In order to protect the environment from this toxic liquid, a low hydraulic conductivity liner must be placed at the bottom of the landfill. Open dumping sites existing all over Lebanon produce toxic leachate that reaches directly groundwater flow in the absence of any bottom liner or barrier.

2.2 Contaminant fate and transport

Soil is a natural body consisting of several layers of mineral constituents of variable thicknesses (Birkeland, 1999). There are three main types of soil: sand, silt and clay. Particle size and distribution will affect a soil's capacity for holding water and therefore the movement of pollutants. The soil texture triangle uses the particle size distribution of soil to determine the soil classification (figure 1). Studies have shown that physical properties of soil layers have a serious impact on the fate and transport of contaminant (AL-Daood, 2011; Kumar et al, 2006; Siracusa et al, 2007). The significant soil properties controlling leachate displacement and mass transport include effective porosity, degree of saturation, particle size distribution, soil fabric, pore structure and specific surface (Francisca et al, 2012). Most natural soils are highly variable in their properties, and are rarely homogeneous. The contaminant transport in soil is largely controlled by the soil heterogeneities. These heterogeneities are mainly manifested through the hydraulic conductivity. Hydraulic conductivity, exhibits spatial variability and has a significant impact on the contaminant transport within the soil media (Rubin, 2003; Warrick et al,1980; Wilding,1985). Throughout the past decades, numerous studies have been conducted regarding the effects of soil heterogeneity on the spatial distribution of solutes and stochastic modeling of contaminant transport (Bhattacharjee et al., 2002; Foussereau et al., 2000; Freeze and Cherry, 1979; Harter and Yeh, 1996; Hu et al., 2009; Leblanc et al., 1991; Wheater et al., 2000; Zhan and Wheatcraft, 1999). Saturated hydraulic conductivity (K_{sat}) is the most important soil hydraulic property; it gives an indication of the soil’s ability to transmit water (Klute and Dirksen, 1986). The movement of contaminants in coarse soils (gravel and sand) is greater than its movement in fine soils (clay and silt) (Eltarabily et al, 2015).

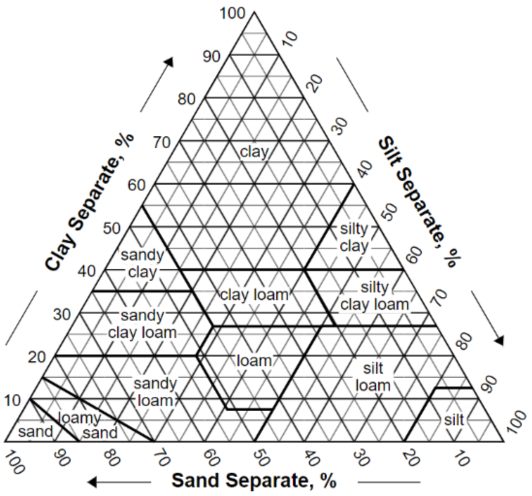

__Figure 1.__ Soil texture triangle, showing the 12 major textural classes, and particle size scales as defined by the United States Department of Agriculture (Soil Survey Division Staff,1993).

Several transport mechanisms may aid in the spreading of contamination. These mechanisms are diffusion, advection and dispersion (Fityus et al, 1999). Diffusion is a process in which solutes in a solution flow in response to a gradient concentration. The solution itself don't need a flow for diffusive transport to occur. Release of contaminant from landfill will occur by molecular diffusion if the advective velocity is low. (Shackelford, 1989; Shackelford et al., 1991; Shackelford, 1993).

Advection is the movement of dissolved solute with the flowing groundwater. The dispersion is the process whereby solutes are mechanically mixed by velocity variations at the microscopic level during advective transport (Barbour et al, 1983). The movement of contaminants through soil regimes is analyzed by two techniques: particle tracking analysis and advection-dispersion analysis. Particle tracking analysis only gives us an idea about the distance and time of travel of contaminant. A complete advection dispersion analysis is mandatory to determine the contaminant concentration within the study area.

2.3 GeoStudio Software

The movement of contaminant within the soil matrix is very complex. Therefore, numerical modeling is used to simulate contaminant transport from a landfill through porous media. Nowadays, many computer softwares have been created to solve contaminant transport through porous media. GeoStudio, is a finite element software for geo-engineers used to model the water seepage, contaminant transport and particle tracking in response to the movement of water, diffusion, advection, dispersion and adsorption through soil. SEEP/W and CTRAN/W are two modules of GeoStudio. First, leachate seepage through saturated and unsaturated soils is determined by SEEP/W. It depends on the fundamentals that the water seepage through saturated and unsaturated soil supports Darcy's law.

Results of previous stage are used to assess contaminant transport by advection-dispersion mechanisms at the bottom of the landfill using CTRAN/W. This module studies the transport of contamination through porous media. It utilizes the SEEP/W flow velocities to compute the movement of dissolved constituents in the pore-water.

3 METHODOLOGY OF WORK

To model the fate and transport of leachate contaminants through soil, a 2D analysis was performed using SEEP/W and CTRAN/W. As shown in figure 2, the model consists of the landfill at the left side, and a potential seepage face and riverbed along the right side. Landfill dimensions are assigned as 100 m bottom width, 30 m depth and a slope of 2:1 is assigned.

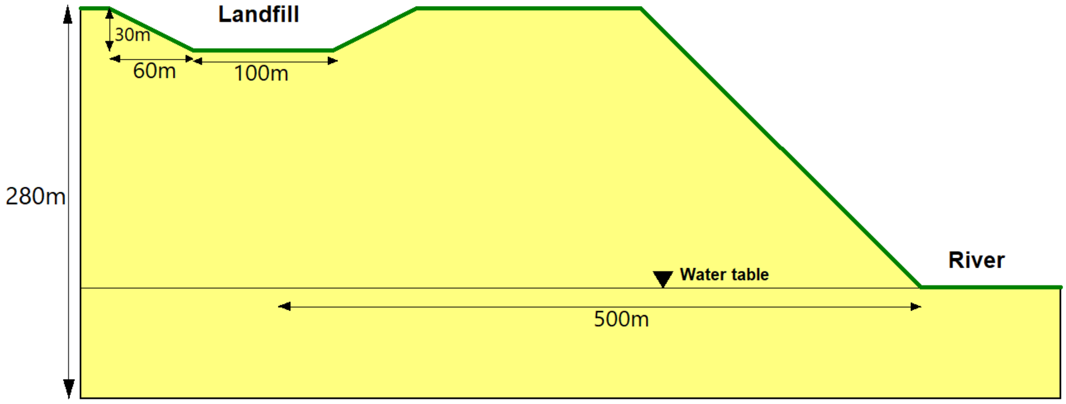

Figure 2. *Cross section view of the landfill*

Concerning identifying the boundary conditions, for the seepage analysis, the total head (H=15m) which equals the elevation head is located in the middle of the landfill site, with a potential seepage face boundary along the entire right side, as it is not known in advance where the water will exit the system. The saturated and unsaturated cases for the transit case are considered.

For the particle tracking analysis, several particles are added at the base of the landfill. These particles will move with the water in the system and will be shown at different times and locations.

For the advection-dispersion analysis, a source concentration is added at the base of the landfill and free exit boundary condition is applied to the slope and the riverbed. One type of contaminant concentration Cadmium (11.5ppm) was chosen to be studied in this research. This concentration is one among other typical concentrations of solid waste contaminants in landfill sites in Lebanon. The coefficient of diffusion of cadmium through soil is assumed $D^* = 3.10^{-10}$ m^2/s (Shackelford, 1991). In our case, due to the geometry of the model and the absence of bottom liner, the movement of contaminant will be controlled by advection-dispersion.

According to geological site investigation, the site soil strata was described to be mainly composed of alternating layers of Sandy lean Clay / Sandy fat Clay. Laboratory and field methods for determining soil hydraulic properties across large land areas are time-consuming and expensive. In this study, the values of hydraulic conductivity parameters for sandy clay soil estimated by Carsel and Parrish (1988) and Clapp and Hornberger (1978) were used: these values are respectively $K_{sat} = 2.16\times10^{-6}$ m/s and $K_{sat} = 3.24\times10^{-7}$ m/s.

A clay liner is assumed to be present only in one model at the bottom of the landfill. The parameters used in the numerical model and the properties of the liner are summarized in table 1.

Table 1. *Considered parameters in the numerical model*

Parameters	**Value**
Model dimensions	2D
Saturated water content (θ_s)	0.38 (m^3/m^3)
Residual water content (θ_r)	0.08 (m^3/m^3)
Saturated hydraulic conductivity for soil (K_s)	$K_1 = 2.16*10^{-6}$, $K_2 = 3.24*10^{-7}$ (m/s)
Dry density (ρ_d)	1500 (Kg/m^3)
Diffusion parameter D^*	$3*10^{-10}$ (m^2/s)
Saturated hydraulic conductivity for clay liner (K_s)	$1*10^{-9}$ (m/s)

In order to illustrate the impact of hydraulic conductivity on soil and the presence or absence of liner in the bottom of the landfill, the cases shown in table 2 are studied.

Table 2. *Studied cases*

Cases	Description
Case 1	$K_1 = 2.16*10^{-6}$ m/s without bottom clay liner
Case 2	$K_1 = 2.16*10^{-6}$ m/s with bottom clay liner
Case 3	$K_2 = 3.24*10^{-7}$ m/s without bottom clay liner
Case 4	$K_2 = 3.24*10^{-7}$ m/s with bottom clay liner

4 RESULTS AND DISCUSSIONS

4.1 Advection – dispersion analysis

The results of the two models SEEP/W and CTRAN/W show the distributions of the total head, and the contamination distributions for any time. After assigning all the properties to the model, SEEP/W analysis was initially run to display the velocity vectors in flow direction, then followed by CTRAN/W for contaminant transport analysis.

Time taken by leachate to reach the riverbed with concentration of 1g/m^3 respectively for case 1 and case 3 is 110 days and 750 days. In case 2, the hydraulic conductivity is K_1 and a bottom clay liner is installed, concentration at the riverbed will take 10760 days to reach 1g/m^3. In case 4, concentration at the riverbed will take 10810 days to reach 1 g/m^3. Figure 3 to figure 6 are the graphical representations of advection-dispersion analysis of leachate through soil. The contours represent the different concentration of leachate through the research period; from which the red color (concentration 10 - 12 g/m^3) indicates the maximum concentration while the blue color (concentration 0 - 2 g/m^3) indicates the minimum concentration.

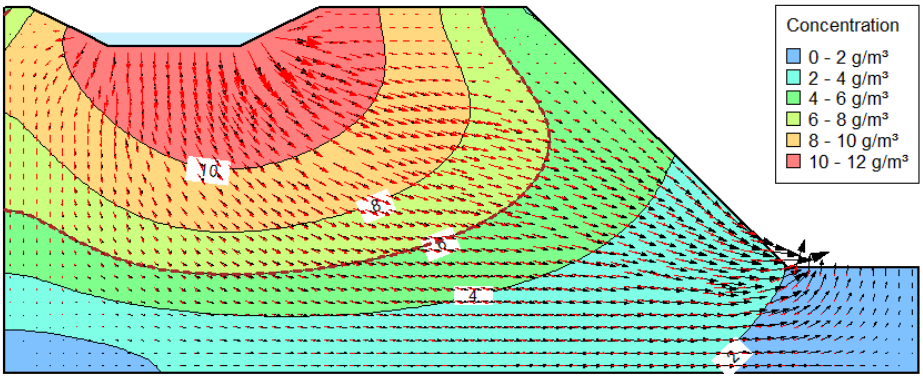

Figure 3. *Advection-dispersion analysis for case 1 after 110 days*

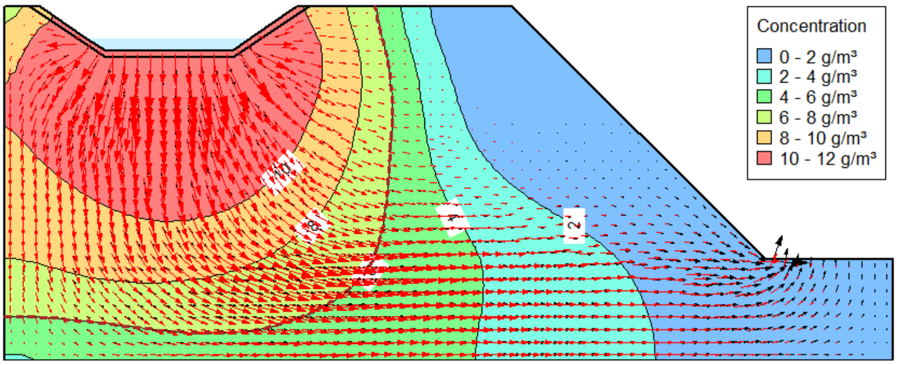

Figure 4. *Advection-dispersion analysis for case 2 after 30 years*

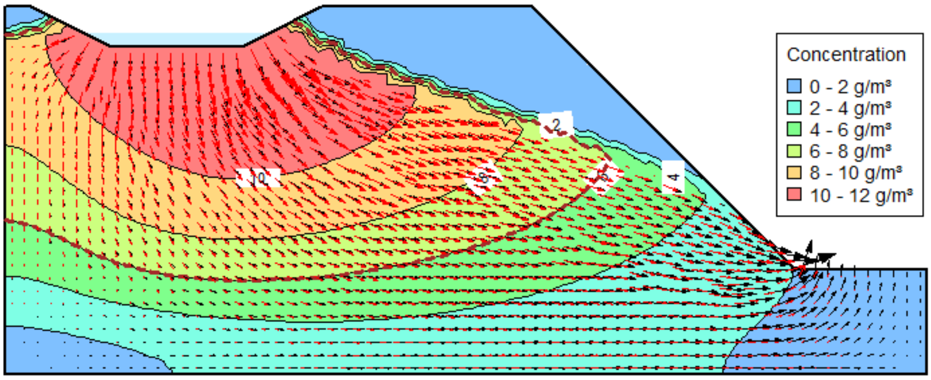

Figure 5. *Advection-dispersion analysis for case 3 after 750 days*

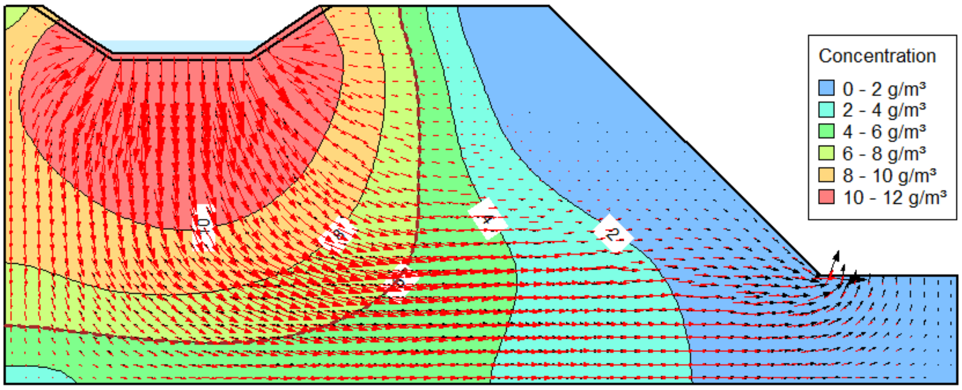

Figure 6. *Advection-dispersion analysis for case 4 after 30 years*

Results of the model showed that in soil with lower hydraulic conductivity (case3), the leachate will take more time to reach riverbed than the case of soil with high conductivity (case1) which confirms that when the permeability decreases, the concentration of the contaminant movement through soil decreases. What is important to observe is the shape of the contour lines showing the concentration of contaminants. While cases 1 and 3 (figures 3 and 5) are similar with the fact that the contamination reaches the slope and the river bed (although in different times), Cases 2 and 4 (figures 4 and 6 respectively) show a totally different shape where the contaminant concentration do not reach either the slope or the river bed. In figure 5 (case 3), the slope of the landfill is not saved from contaminants and will be totally contaminated if we are beyond 3000 days. Figure 7 represents the correlation between concentration of the leachate with the arrival time of contaminant at the riverbed for different values of hydraulic conductivity of soil.

As shown in figure 7, the time taken by leachate to reach the riverbed is highly affected by the hydraulic conductivity of the soil. After 750 days, the concentration of the leachate at the riverbed is still 1 g/m^3 for case 3 (soil with low hydraulic conductivity), while the concentration at the riverbed is 10.5 g/m^3 in the case 1 where the soil has a higher hydraulic conductivity.

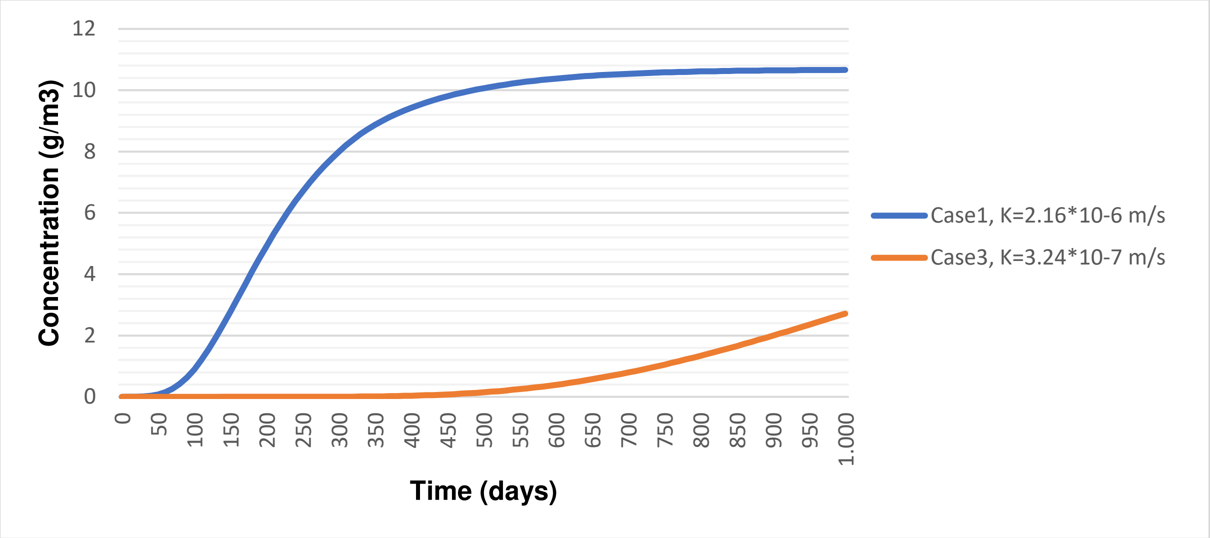

Figure 7. *Concentration of leachate at the riverbed for different value of K*

When comparing case 1 with case 2, or case 3 with case 4, we can understand the importance of the presence of a clay liner at the bottom of the landfill. The correlations between concentration of the leachate with the arrival time of contaminant at the riverbed for the same model with and without bottom clay liner are presented in figures 8 and 9.

Furthermore, figure 8 shows that after 500 days, the concentration of leachate at the riverbed reaches 10.5 g/m^3 for case 1 while it is still 0 g/m^3 for case 2. After 7200 days, the concentration in case 1 is 10.68 g/m^3 while in case 2 it is still 0.1 g/m^3; the concentration in case 1 is around 10 times the concentration in case 2.

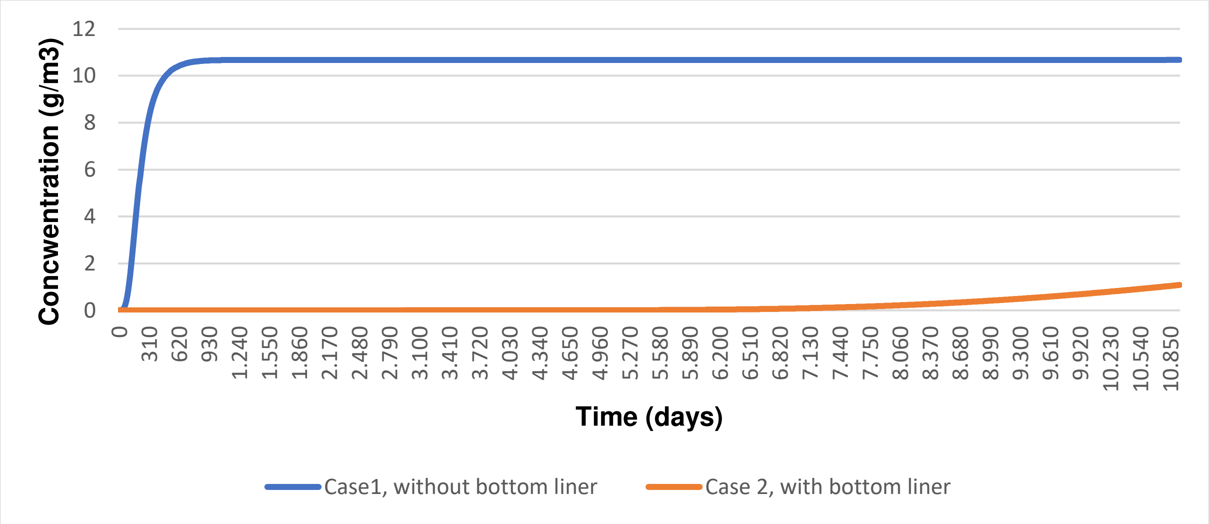

Figure 8. *Concentration of leachate at the riverbed for cases 1 and 2, with and without bottom liner*

Moreover, as shown in figure 9, leachate concentration in case 4 took 10810 days to reach 1 g/m^3, while in case 3 at the same time, this concentration is 10.6 g/m^3; then the concentration at the same time in case 3 is 10 times the concentration in case 4.

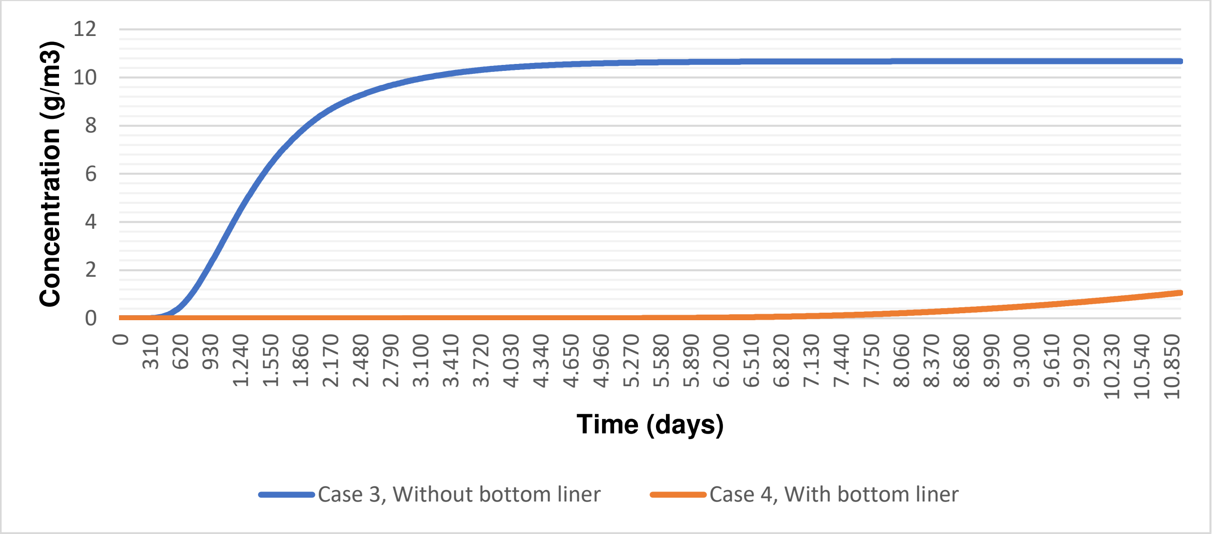

Figure 9. *Concentration of leachate at the riverbed for cases 3 and 4, with and without liner*

4.2 Particle tracking analysis

In particle tracking analysis, the dissolved contaminants are represented by particles. The flow path of particles provides a graphical representation of the contaminant plume movement caused by advection only, while neglecting the effects of dispersion, adsorption and density. Figure 10 represents an example for particle tracking analysis for case 3 and case 4 after 1000 days. After 1000 days, in case 3 with the absence of clay liner, particles almost reach the riverbed, but in case 4 with the presence of clay liner, particles are still near the landfill base.

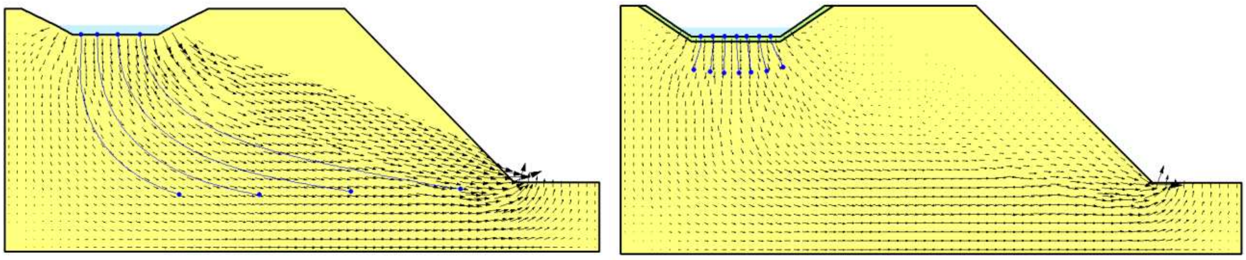

Figure 10. *Particle tracking analysis for case 3 after 1000 days(left). Particle tracking analysis for case 4 after 1000 days(right).*

5 CONCLUSIONS

From the contaminant transport analysis presented in this paper, the following conclusions are drawn:

- The time of contaminant penetration into the soil and reaching the riverbed increase with the decreasing value of hydraulic conductivity. For the same type of soil, in the case of lower hydraulic conductivity, time taken by contaminants to reach the riverbed will increase about seven times.
- Transport of contaminants through the soil matrix occur by diffusion and advection-dispersion. Diffusion is of significant importance only if the flow velocity is low. In our case, due to the high flow velocity controlled by the shape of the model, the transport is mainly conducted by the advection-dispersion process.
- The installation of a liner at the bottom of the landfill is mandatory to reduce leachate contaminant migration into soil. Results proved that contaminants will take thousands of years to reach ground water with the presence of liners, in comparison to several days in its absence. The concentration of leachate at the riverbed in the absence of the bottom liner is 10 times the concentration in its presence.

- Indiscriminate dumping of waste without proper solid waste management practices should be urgently stopped or some remedial measures are required to be adopted to prevent further contamination.

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