Numerical Simulation of the Mass Flow of Leachate in a Municipal Solid Waste Fill (Part 2) - Vertical Flow Systems

Olayiwola Ademola Gbolahan Oni PhD

University of Ado-Ekiti, Ado Ekiti, Nigeria, West Africa
Current Address: Proworks Ltd., 13 Newman Street, Southampton, UK
onilayi@gmail.com

Abstract: A numerical simulation of the mass of leachate solute in a vertical flow system in a waste fill has been undertaken. The simulation technique involves dividing the waste body into refuse layers of equal and constant volumes and iterating with different time-steps. The principle of mass conservation in steady flow continuity has been applied to replicate the characteristics of the measured solute in saturated and oversaturation conditions of vertical flow in a waste fill. Comparison of modeled and the actual measurements shows a reasonable fit, indicating that the simulation model and underlying principles are suitable for simulating the solute mass flux. [Journal of American Science 2010:6(7):358-366]. (ISSN: 1545-1003).

Keywords: municipal waste, leachate solute, simulation, vertical flow, waste layers

1. Introduction

The negative consequence of the practice of waste landfill has been the driving force for continuous effort to minimise the volume of biodegradable and recyclable components of the stream of municipal waste sent to landfill sites in the developing nations of the world. In the UK, despite the bottom position of "landfilling" in the waste management hierarchy, and the utmost priority given to composting and waste recycling, landfill sites still remain the final destination of 85% of municipal solid waste (Price, 2001). A lot of well documented investigations have shown that leachate emissions, especially from old landfills (Kjeldsen, 1993; Kjeldsen et al., 1998; Looser *et al*., 1999; Baun *et al.*, 2000), which have existed prior to the promulgation of stringent laws that require engineering of landfills, can pollute groundwater resources. In an era of worldwide fiscal austerity and lean resources for avoidable calamities, there has been a lot of governmental funding into the understanding of the formation and containment of leachate, which is the potential pollution by-product of the landfill of waste. For instance, in the UK, the tax credit scheme enables landfill site operators to contribute money to enrolled Environmental Bodies (EBs) to undertake works and waste researches which, are included in the approved environmental projects contained in the Landfill Tax Regulations (ENTRUST, 2010). Although leachate is often referred to the leached wastewater exiting landfill sites; in reality, leachate is the leached water within the landfill, starting from the topmost layers to the basal layers.

Whereas the early investigations on waste were undertaken on the bulk waste quantity and chemical composition of the contaminant solute inherent in the leached water (Farquhar, 1973; Thompson and Zandi, 1976; Berger *et al*., 1996, Reinhart and Al-Yousfi, 1996), recent investigations have focused more on the leachate quantity in the waste lifts (Bleiker, 1995; Oni, 2000; Oni and Richard, 2004; Oni and Okunade, 2009) and the characteristics of the mass flux of the solute in the bulk waste (Rosqvist and Bendz, 1999; Rosqvist and Destouni 2000; Beaven and Hudson, 2003; Beaven et al., 2005; Rosqvist *et al.*, 2005). Ever since the foremost classic investigations on waste by Farquhar and Rovers (1973) and Sowers (1973, it has been acknowledged that waste is complex in occurrence, formation, nature, emplacement. The heterogeneity of waste varies within site, and from site to site. Therefore, there has not been any formulated model that has been able to universally or exactly model the physical and chemical properties of waste fills (El Fadel *et al.*, 1997). Bearing this in mind, any large-scale experiment or model that can reasonably replicate the in situ properties of waste is an accomplishment.

Numerical modelling is common for simulating the characteristic of porous material, especially soils (Narasimhan and Witherspoon, 1978; Indraratna and Redana, 2000; Hatami and Bathurst, 2006); however there has not been any known significant work undertaken on the solute mass flow in various layers of the waste fills. In most cases, the simulation on the solute of the leached water in waste fills has been stochastically undertaken to estimate the volumetric content of the inherent water participating in the bulk volume of the waste fill.

In this paper, the modelling of the mass flow of leachate in various layers of a waste fill has been undertaken using a formulated simulation model. In the first part of the series of this topic, the fundamentals of simulation technique as applied to steady flow in a recycling flow pattern in waste fills was explicitly described. In this paper fundamentals, as applied to vertical flow systems is described and used for the 2-dimesional visualisation of various simulation's assumed conditions. As the majority of reported investigations on landfill leachate has been on vertical flow systems, this study will be of interest to stakeholders in the Waste industry. Efforts have been made not to literarily repeat many aspects that have been well described in Part 1.

2. Methodology

2.1 Experimental data

A mass flow model has been formulated and used to simulate the mass flow (concentration flux) in the vertical flow in a waste fill located in large-scale test cell reported by Oni (2009). A diagrammatic description of the tests is depicted in Figure 1. The test procedure has been well described in a previous paper (Oni, 2009). Tracers were used to trace the movement of the leachate solute thus enabling the mass flux to be monitored via the concentration measurements. In the oversaturated condition, tracers, Lithium (30mg/l), Bromide (345mg/l), Coomassie Brilliant Blue (0.1g/) and Sodium Chloride (5g/l) were introduced into the surface pond overlying a waste fill in a steady flow condition. The tracers were inputted in "top hat" pulses at 1l/h and sprinkling on the waste in pulses continued for 48 hours following which the sprinkling reverted to water to washout the inherent tracer in the waste. The tests ended when there was evidence that the majority of the tracers have been flushed out through the continuous measurement of the concentration of the outflow from the base of the waste fill, via the gravel bed. The same procedure was undertaken for the saturated flow tests except for not having a surface pond. The tracer and water input in this condition was directly on the surface of the bare waste. In this study, however only the test data for the non-reactive tracer -Sodium Chloride was used for validating the simulation model. It is worth to note that the word "oversaturated" has been used to distinguish the vertical flow with or without surface pond. The enormous side wall flow observed in the vertical flow with surface pond in a previous study (Oni, 2009) perhaps justifies this term.

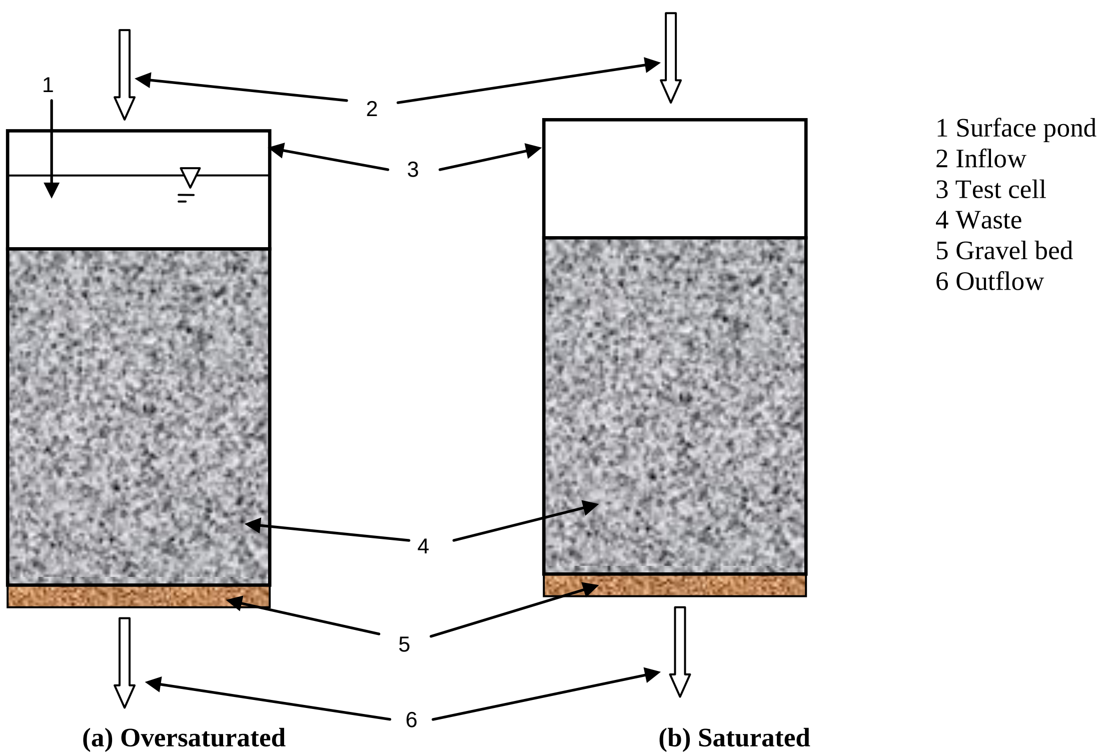

Figure 1: The vertical flow test.

2.2 Simulation process

The waste fill is divided into layers of equal and constant volume. The waste thickness of each layer is not the same due to the heterogeneity of waste. Owing to the variability of waste properties within an emplaced fill, it is assumed that this approach will minimise errors that would have occurred if the waste fill is divided into small grids, commonly used for soils, which are predominantly homogenous. Moreover, there is no acceptable model that can reasonably describe the horizontal and vertical components of flow within a waste grid. The simulation model is conceptualised on conservation of mass for an elemental volume in water flow continuity. It is derived such that there is a mass balance in the flow system of waste layers and adjoining gravel bed and surface pond and is made dimensionless by division by the original concentration of the tracer as follows. The relative concentration is an effective numerical measure of the leachate mass in waste flows and is thus given as:

$$\frac{C_i}{C_o} = \left(\frac{1}{C_o V}\right) \times \left((M_{i-1} + \Delta M) - \left(\left(\frac{M_{i-1} + \Delta M}{V + \Delta V} \right) \times \Delta V \right) \right)$$

[1]

where:

C_i = concentration of the tracer (solute) in an elemental volume at time i

C_o= initial (maximum) concentration of the tracer (solute) at source

V =constant volume of an elemental volume

M_{i-1} = the mass of the tracer (solute) in an elemental volume at time i-1

ΔM = incremental mass of the tracer (solute) added to an elemental volume from time i-1 to time i

ΔV = incremental volume of the tracer (solute) added to an elemental volume from time i-1 to time i.

The flow diagram for the solution technique is similar to the one which has been well depicted in Part 1 of this topic. It consists of the division of the waste fill into layers and applying the simulation model (Equation 1) to the waste pond, waste layers and the basal gravel layer in the iteration pattern described as in Figure 2.

The symbols in the diagram above are defined in the form below:

$\Delta M1_{in}$ = mass of the tracer (solute) input to the layer 1 from time i-1 to time i

$\Delta M1_{out}$ = mass of the tracer (solute) output from layer 1 from time i-1 to time i

n = the number of layers; gb= gravel layer; sp= surface pond

It is worth to note that for any time-step - time i-1 to time i, that:

$\Delta Msp_{out} = \Delta M1_{in}$; $\Delta M1_{out} = \Delta M2_{in}$; $\Delta M2out = \Delta M3_{in}$; $\Delta Mn_{out} = \Delta Mgl_{in}$; ΔMgb_{out} is the measured mass of solute out of the gravel bed.

Whereas the iterations are undertaken for various time-steps and number of waste layers, the volume of each waste layer is limited to a maximum that is equivalent to the pore volume of the basal gravel, which has been measured to be approximately 31. Consequently, the time-step is also limited to a maximum, which is equivalent to time that will enable the maximum volume to pass through an elemental volume under a steady flow condition.

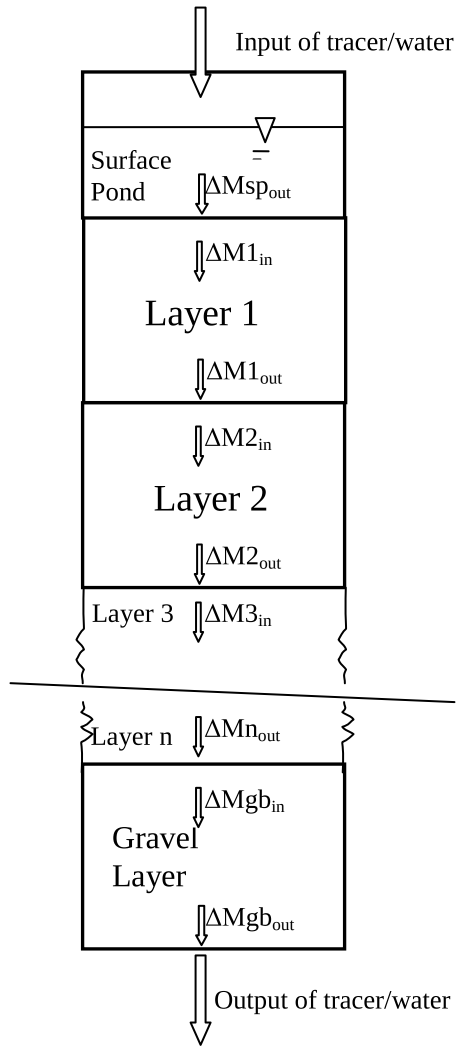

Figure 2: Schematics of the pattern of the simulation's iteration.

3. Results

The simulation in this study has been undertaken for both the saturation and oversaturation conditions of the vertical flow in the waste fill whose hydro-physical properties were determined and shown in Table 1. The saturated discharge has been previously determined prior to the solute tests to give a full saturation (100%) flow through the waste fill. The oversaturated discharge was made higher to enable steady gravitational flow through the waste using the water head (potential) of the surface pond.

Table 1: Hydro-physical properties of the waste fill

Waste properties	Dry density of waste (kg/m^3)	Volume of surface pond (l)	Pore volume of waste (l)	Pore volume of gravel (l)	Effective porosity- (%)	Discharge rate - saturated (l/h)	Discharge rate -oversaturated (l/h)	Saturated hydraulic conductivity (m/s)
Measured values)	722	11.76	35.17	3.0	7.5	0.547	1.0	1.65×10^{-6}

The simulation has been undertaken for different time-steps and waste layer volumes. The depiction of the breakthrough curve (BTC) for each waste layer and the gravel bed in the saturated conditions of the waste fill using various conditions are shown in Figures 3-6. In general, the trend of the BTC appears relatively similar, consisting of a rise to a peak concentration from an initial zero and then reducing gradually to insignificant values with a long tail end, in all waste layers and gravel bed in varied conditions.

In order to further investigate the influence on the chosen time-step and elemental volume of waste on simulation result, modelling with the maximum allowable pore volume of waste layer with varying time-steps were undertaken and are depicted in Figures 4-6. It is observed that the maximum obtained concentration in each waste layer and gravel bed decreases as the time spread is increased and consequently the BTC becomes more spread out. Comparison of the various modelled BTCs obtained from various assumed conditions with the real BTC from actual measurement (Figure 7) shows that the BTC obtained for the maximum allowable time-step and elemental volume (Layer = 3l; Time-step = 5.5h) is the best replicate, and thus chosen for the simulation.

The simulated and real BTC of Sodium Chloride in the saturated condition is shown in Figure 7. Although the shape of the simulated and real BTC is a bit different, the general characteristics trend of the temporal leachate solute flux is reasonably similar, with both having a maximum BTC of approximately 0.6. Similarly, the simulated BTCs for the layers of oversaturated waste fill in various modelled conditions are shown in Figures 8-10. As in the saturated condition, the characteristic behaviour of the waste appears the same for various simulation conditions and the division of the waste into too many layers (Figure 8) appears to minimise the characteristic differences in the mass flow in different waste layers, thereby nullifying such condition for realistic simulation results. Furthermore, increasing the time-step and elemental volume appears to minimise the error incurred in simulation, as the quantity of temporal mass averaged in each layer during a time-step is increased. The BTC of the leachate solute obtained through simulation and measurements in the surface pond and outflow from the waste fill in the oversaturated condition is shown in Figure 11.

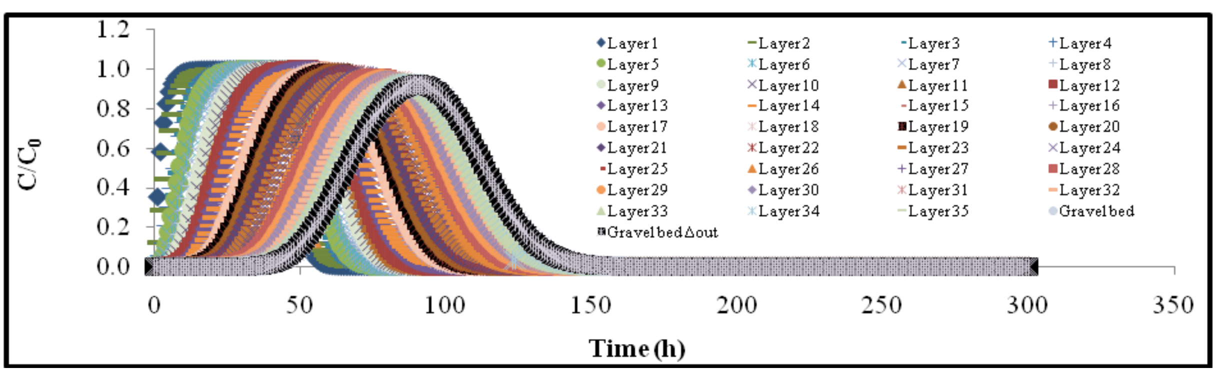

Figure 3: Simulated BTC of Solute Tracer -Sodium Chloride in a Saturated Vertical Flow (Layer = 1l; Time-step = 1h).

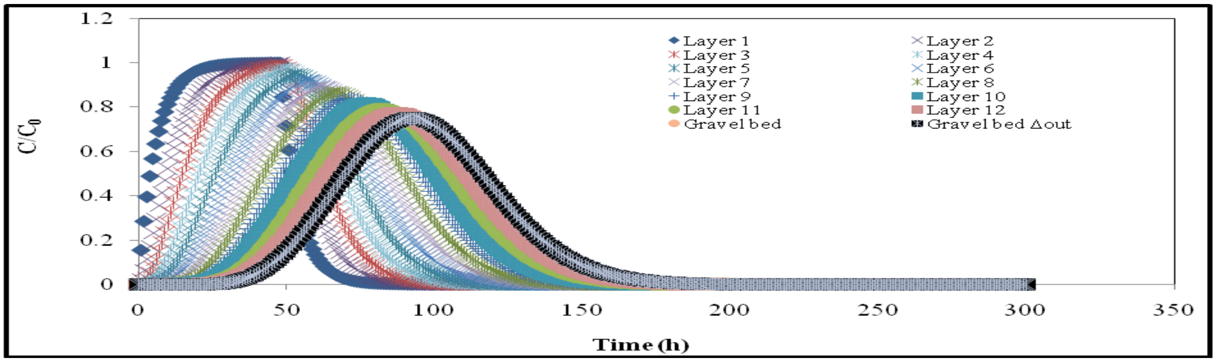

Figure 4: Simulated BTC of Solute Tracer -Sodium Chloride in a Saturated Vertical Flow (Layer = 3l; Time-step = 1h)

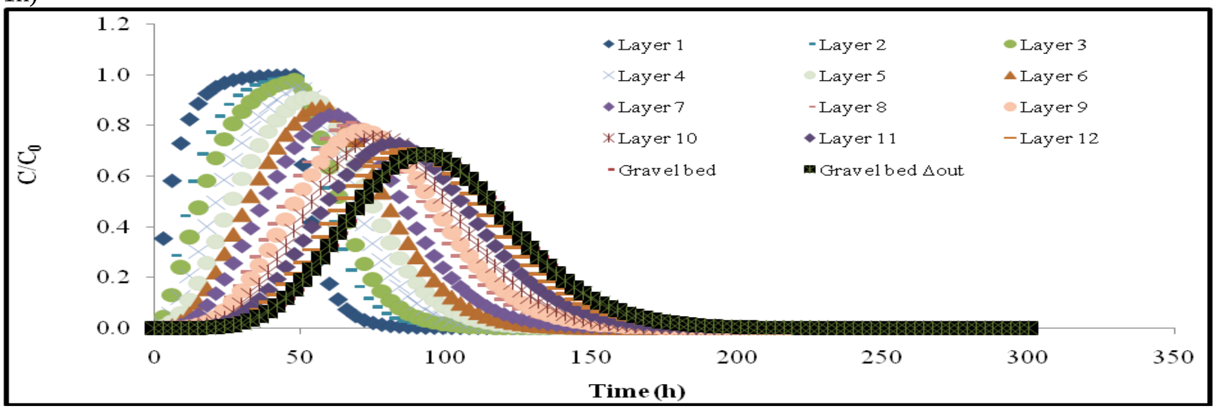

Figure 5: Simulated BTC of Solute Tracer -Sodium Chloride in a Saturated Vertical Flow (Layer = 3l; Time-step = 3h)

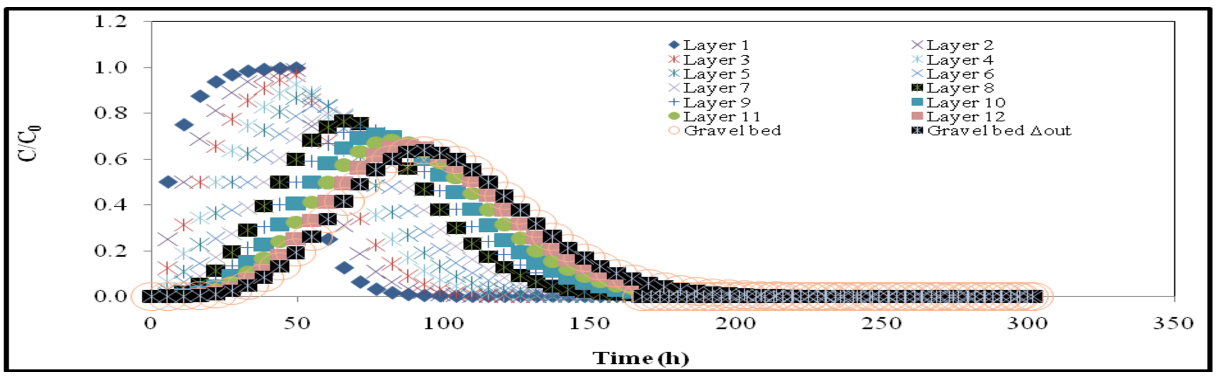

Figure 6: Simulated BTC of Solute Tracer -Sodium Chloride in a Saturated Vertical Flow (Layer = 3l; Time-step = 5.5h)

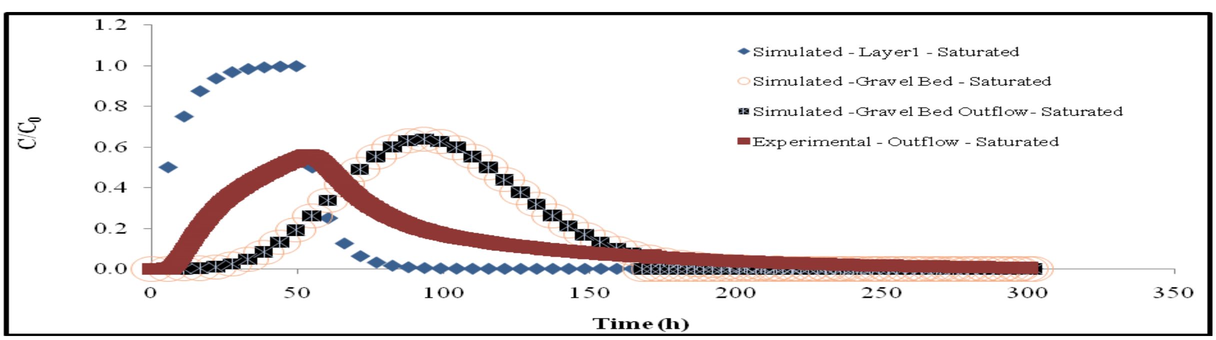

Figure 7: Comparison of Simulated and Real BTC of Solute Tracer -Sodium Chloride in a Saturated Vertical Flow

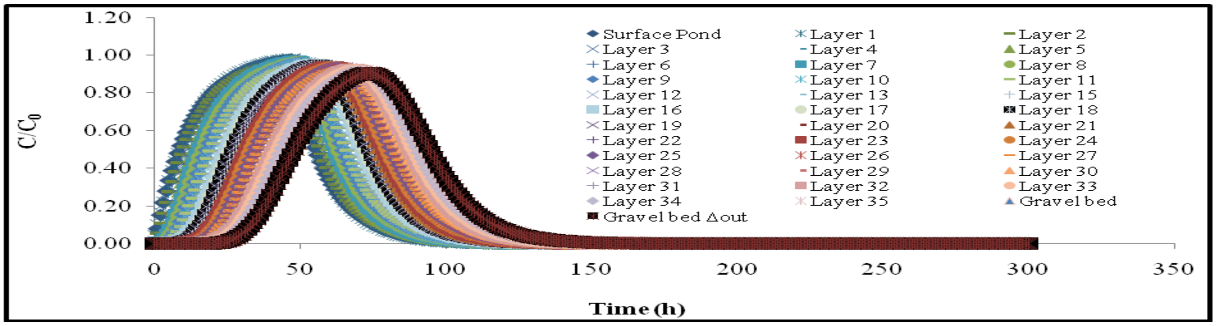

Figure 8: Simulated BTC of Solute Tracer -Sodium Chloride in an Oversaturated Vertical Flow (Layer = 1l; Time step = 1h)

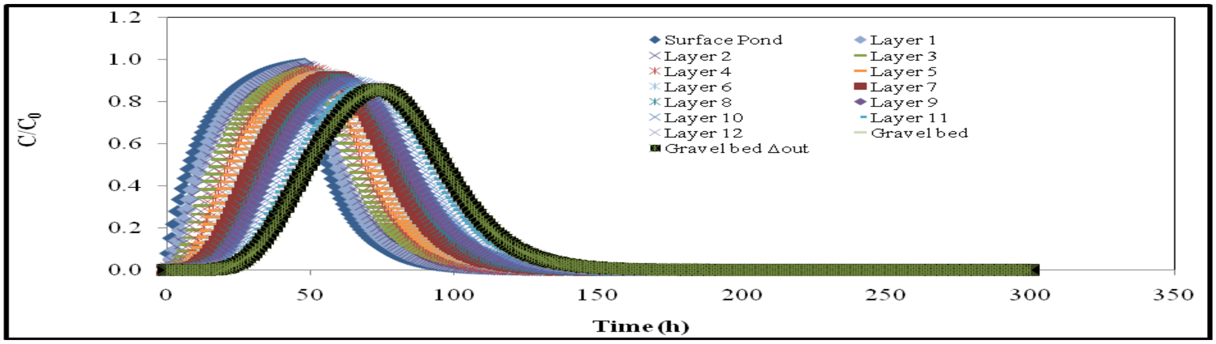

Figure 9: Simulated BTC of Solute Tracer -Sodium Chloride in an Oversaturated Vertical Flow (Layer = 3l; Time-step = 1h)

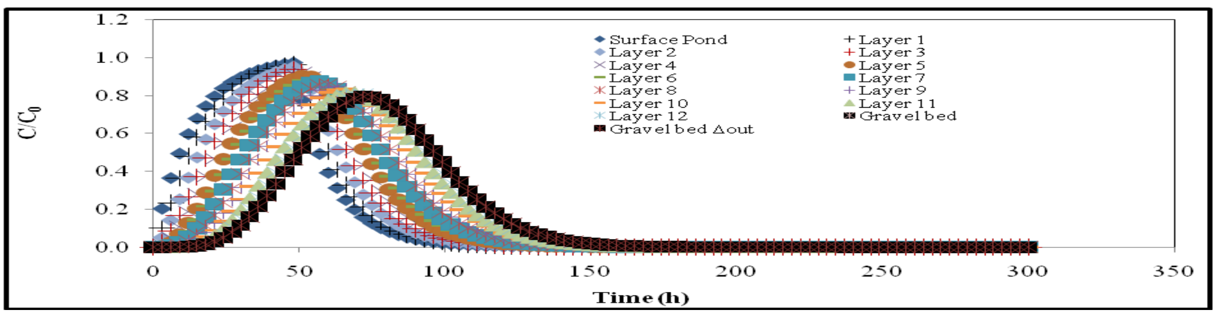

Figure 10: Simulated BTC of Solute Tracer -Sodium Chloride in an Oversaturated Vertical Flow (Layer = 3l; Time-step = 3h)

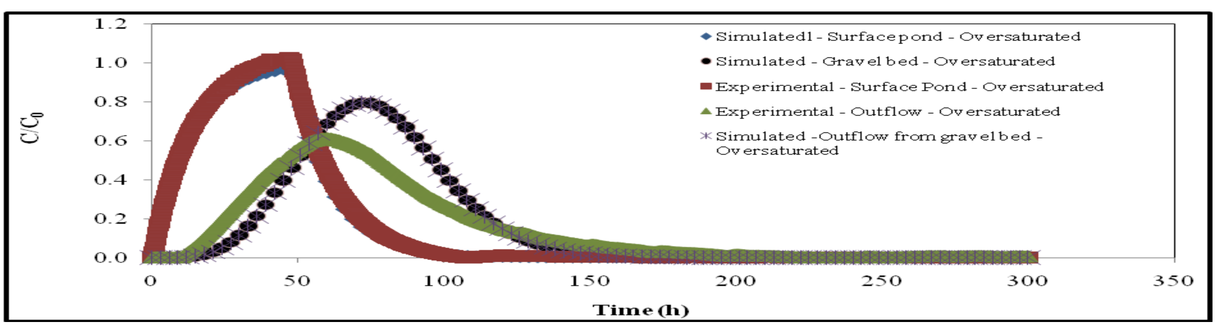

Figure 11: Comparison of Simulated and Real BTC of Solute Tracer -Sodium Chloride in an Oversaturated Vertical Flow

4. Discussion

In general, the shape of the BTC varies gradually from the topmost waste layer to the gravel bed; with the maximum concentration in the waste layers closest to the topmost layer. This could be probably explained in terms of dilution of solute in the waste layers as the solute is being transported away from source input/contact, which is the surface of the topmost waste layer. An increase in the number of the waste layers appeared to smooth the difference in the characteristics of each owing to the averaging method of estimation used in the simulation, as seen in Figure 3. However, the rate of change in the waste layers becomes more defined as the time-step and volume of the waste layers chosen are increased. Similarly, the BTC curve becomes more dispersed as the distance of the waste layer from the topmost layer increases. In fact the maximum concentration attained in the gravel bed appears to decrease as the time-step and layer volume is increased. This is owing to minimisation of errors due to the increased mass of solute being used to average the concentration in each waste layer in the simulation process.

The concentration of the temporal volume of leachate out of each waste layer has been computed, although not depicted herein, and are similar to the concentration existing in each layer, as can be seen for the basal gravel bed. This is expected and shows that the simulation technique is correct as it is based on average values of the fast and slow components the mass flow of the inherent leachate flux in each waste layer, gravel bed and the surface pond.

The quick attainment of the maximum concentration in the real BTC compared to the simulated values in Figure 7 is owing to the fast advective solute, and the relatively long tail is due to the relatively slow portion of the solute during tracer inflow and the water washout periods. As earlier stated, dilution becomes more significant as the position of the waste layers from the source of solute input decreases. The basis of the simulation technique is based on full dilution in each waste layer, and the similarity of the real BTC with that of the first layer showed that dilution of the inputted solute with the inherent water in each waste layer and the gravel bed is not 100% owing the relative fast velocity of the solute in preferential flow paths. It thus appears that the real shape of the BTC in the waste layers will be similar to that of the first layer and not smoothen out, as simulated using the average values. However, the simulation has well represented the average characteristic trend of the mass flux in the waste layers of the saturated fill.

In the oversaturated condition, there has been a very good match between the BTC for the surface pond using the measured data and by simulation (Figure 11), and there has been a good match between the simulated and real BTC for the outflow from the waste fill via the grave bed, in comparison to the saturated conditions in Figure 7. In particular, the shape and dispersion of the simulated and real BTC of the outflow appears reasonably similar, compared to saturated conditions. The reason appears obvious. In the oversaturated flow condition, the inputted tracer is thoroughly mixed with the inherent water and thus the solute mass that infiltrates into the waste fill at the topmost layer is well diluted and thus significantly reduces the effect of the fast advective component of the leachate solute in a mass flow through subsequent layers and the basal gravel layer. In saturated layer, the tracer is inputted into the bare waste surface in sprinkles and thus the infiltrating undiluted solute may be transported through a preferential path and thus not fully mixed within each waste layer.

Although the simulation technique appears more suited to the mass flow in the waste fill with overlying pond, the average characteristic trend of temporal leachate mass in the waste fill in varying saturated conditions has been reasonably replicated with the numerical simulation used in this study. Moreover, the individual solute mass within each waste lift has been depicted quantitatively therefore enabling a good visualisation and understanding of leachate flux within a waste fill subjected to a steady state vertical flow. This type of numerical simulation will be quite effective when assessing alternate designs or operation of a landfill system as these require basically the prediction of average flux characteristics under varying flow patterns in the waste fill. In general, this study has shown that numerical simulation is a very effective way of understanding the hydro-physical processes in a vertical flow in a waste fill.

5. Conclusion

Numerical simulation has been successfully used in this study for estimating and visualising the temporal mass of leachate solute in individual layers of a waste fill and the gravel bed under a steady flow state. This has been undertaken by depicting the BTC of saturated and oversaturated flows in a refuse fill

The simulation technique may be useful in assessing and predicting solute flux in varying flow conditions in municipal solid waste fills.

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Corresponding Author:
Olayiwola Ademola Gbolahan Oni PhD
University of Ado-Ekiti, Ado Ekiti, Nigeria
Current Address: Proworks Ltd., 13 Newman Street, Southampton, SO16 4FL, UK
E-mail: onilayi@gmail.com

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