Advances in Environmental Technology 3 (2017) 177-184

Advances in Environmental Technology

journal homepage: http://aet.irost.ir

Simulation of municipal landfill leachate movement in soil by HYDRUS-1D model

Maryam Pazoki*, Reza Ghasemzade, Seyyede Parisa Ziaee

Graduate Faculty of Environment, University of Tehran, Tehran, Iran

ARTICLE INFO

Article history:
Received 27 April 2017
Received in revised form
10 October 2017
Accepted 14 October 2017

Keywords:
Hydrus-1D
Leachate
Low rate
Municipal solid waste

ABSTRACT

Different numerical and analytical models are presently available that provide the tools to predict pollutant and water transfer processes between the soil surface and the groundwater level. Among the existing models, the Hydrus-1D model has been used for years in the prediction of water and pollutants transfer in the unsaturated zone. The main purpose of this paper was to model the movement of the landfill leachate in the soil at the Aradkouh landfill and predict the changes in nitrogen and phosphorus concentration in the leachate at different depths. Two pilots were used in this study, one included the local soil and the other contained local soil with Vetiver grass (*Chrysopogon zizanioides*). After its initial purification, the resultant leachate entered the pilot and was collected after passing through the soil. Finally, the flow of the leachate movement as well as the nitrogen and phosphorus concentration changes in soil were modeled by using Hydrus-1D. The prediction model for the phosphate and nitrogen concentration changes at different depths showed that the best results were obtained in the surface charge of 0.12 m^3/m^2.week and by the pilot with the Vetiver grass. The results showed that the use of Vetiver grass in surface purification increased the efficiency of the purification.

1. Introduction

The most important issue concerning the modeling of leachate release in soil is a proper understanding of the behavior of the unsaturated zone. In past decades, we have witnessed considerable advances in the conceptual understanding and quantification of water flow and contaminant transport processes. The different numerical and analytical models that are currently available have the ability to predict pollutant and water transfer processes [1-4]. Aboutalebi et al. used a multiobjective method for the optimization of the quality of water networks in river-reservoir systems [5]. Richards' equation for unsaturated conditions and the Fickian-based convection-dispersion equation for the transfer of pollutants are the most common models in this regard. A definitive solution to these equations is needed to predict the movement of water and contaminants in unsaturated soil and to analyze the laboratory and field results. Therefore, appropriate models can be helpful in processing the limited information obtained in the laboratory and on site for different soils. The use of models to predict the movement of salts and pollutants could save much time and expense. However, this prediction is useful and practical when the accuracy of the model used for estimation has been studied [6]. Therefore, before employing these models, their performance should be evaluated under controlled conditions. In controlled conditions, the model parameters are first optimized according to the observed data. Hence, conducting research is necessary for evaluating and selecting a suitable model in addition to optimizing the model parameters in precise and controlled experimental conditions before use in actual conditions. In general, high volume activities must be done to prepare the input data; the mesh design and graphical presentation of output results are problematic and have limited the use of different

*Corresponding author. Tel: +989123186604
E-mail address: mpazoki@ut.ac.ir
DOI: 10.22104/AET.2017.2140.1106

numerical models. Among the existing models, the Hydrus-1D model reduces these disadvantages; accordingly, it has been used in the prediction of water and pollutants transfer in the unsaturated zone for many years [7]. The Hydrus-1D software is one of the advanced models associated with the one-dimensional motion of water, salts, and heat in the soil. This model was developed by Simon and colleagues (1998) at the Laboratory of Soil Salinity in the United States and includes Richards' numerical equation to study the water movement in the soil. It also includes a convection-dispersion equation for studying the salts and heat motion in the soil; these equations have been resolved by the finite element method. This model can simulate the movement of salts in the soil under saturated and unsaturated conditions and estimate characteristics of the soil by the inverse method [8]. The main advantages of this model are its simplicity, free access, compatibility with the Windows environment, ability to apply different conditions, and high accuracy [9]. These advantages have encouraged the use of this model in similar studies [10,11]. Many scientists have measured the pattern of water distribution in the soil. Sling (2002), Gardenas et al. (2005), Wang et al. (2006), and Lazaruych et al. (2007researchers) have used Hydrus-1D software in simulations [12-14]. However, in studies and motion simulation of leachate in soil along with the prediction of the concentration of nitrogen and phosphorus in the leachate, the above mentioned software has not been incorporated. Among the natural purification systems, the slow rate irrigation system is the most appropriate system for the surface purification of leachate. This system has a high removal potential and can remove significant amounts of BOD, suspended and soluble solids, and coliforms. The pretreatment methods used in land filtration systems to remove large suspended solids of irrigation facilities [15,16]. The use of use of plants to protect soils and purify sediments as well as polluted water has been accepted as a practical method in the world and is used widely. Phytoremediation is the name used for different ways of using plants for eliminating water and soil pollution. Plants can break down pollutant organic matter. They can also act as a filter or trap to absorb and stabilize heavy metals. One of the plants that can be used for phytoremediation is permanent Vetiver grass with the scientific name of Chrysopogon zizanioides. This plant originated in the Indian subcontinent and based on its extraordinary properties, it was primarily was used by the World Bank for water and soil conservation in India in the mid-1980 [17]. The application of the Vetiver system to check sewage and leachate is a new and innovative plant regeneration technology that shows the extraordinary power of this plant. The Vetiver system is a green, natural, simple, and practical solution with affordable costs [18].

2. Materials and methods

This paper employed the Hydrys-1D model to study the motion simulation of leachate and to predict the changes in the concentration of ammonia nitrogen, nitrate nitrogen and phosphate in the soil at the Aradkouh municipal solid waste landfill.

2.1. Landfills Specifications

The Aradkouh landfill, with a history of nearly forty years, is located twenty-five kilometers from the southernmost part of Tehran and at the beginning of the Tehran-Qom road. This landfill hosts 7000 to 8000 tons of waste daily, and the amount of leachate in the site is on average 637,500 liters per day [19]. Regarding the underground water, the water level is very low in this area and the drilled wells have saltwater and limited water yield, roughly about 5.0 to 3 liters per second.

2.2. Pilot Features

For this study, two pilots were used that were 70 cm in diameter and 120 cm in height and were filled with soil to the height of 90 cm. A punched metal plate was embedded at the end of each pilot for drainage, and a pipe was inserted diagonally per 30 cm into the pilot for leachate sampling. In this study, two different pilot models were used for purification. The local soil was utilized in the first pilot, and the second one used the local soil along with Vetiver Grass.

2.3. Sampling

The sampling was performed twice a week with three rest days (so as not to create anaerobic conditions). The samples were studied during the slow current in three surface charges of 0.12, 0.24, 0.6 m^3/m^2.week on the average for eight weeks and three times at any speed. Finally, effluents were transferred to the laboratory in containers to test the parameters (ammonia nitrogen, nitrates nitrogen and phosphate) for this study.

2.4. HYDRUS 1D model

The Hydrus-1D model numerically solves the Richards' equation for water flow in a saturated, partially saturated and unsaturated state as well as the convection-dispersion equations for the transfer of heat and pollutants. This model also considers the parameter of water uptake by plants in the equation of water flow. This model is also capable of predicting water transport in heterogeneous soils with different levels of porosity and permeability. Also, liquid penetration can be modeled vertically, horizontally and diagonally. In in regard to fluid transfer fluid transfer, we can introduce different conditions for head and inlet pressure at the same time as the boundary condition for the model. Also, the boundary condition affected by weather conditions and free drainage conditions can be introduced as other boundary conditions to the model. In this model, to predict the influence of the leachate in a compacted clay liner, Richards' differential equation is solved by using the finite element Galerkin 3 numerically [20]. Richards' differential equation is as follows:

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x}+\cos\alpha\right)\right]-S \tag{1}$$

In this equation, h = head of the leachate; θ= moisture; t= time; x is the vertical axis coordinate for positive upward movement; S=parameter for water absorption by plants; α=flow angle to the longitudinal axis; and K is the hydraulic conductivity of the soil. The moisture content and soil hydraulic conductivity are a function of soil suction in semi-saturated soils. According to this model, the moisture content of the soil is calculated by the Van Genuchten relationship, and the amount of the hydraulic conductivity of the soil is calculated by using Van Genuchten-Mualem relationship (Equation 2) [11]. These relations are as follows:

$$\Theta(h)=\begin{cases}\Theta_r+\dfrac{\Theta_S-\Theta_r}{(1+|\alpha h|^n)^m} & h\le 0\\ \Theta_S & h\ge 0\end{cases} \tag{2}$$

$$K(h)=K_S S_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \tag{3}$$

where θ_r and θ_s are residual moisture and moisture of saturated soil, respectively; K_s is saturated hydraulic conductivity; α is an experimental constant that has an inverse relationship with air entry point; n is porosity index; L is an experimental parameter of form; and S_e is effective saturation that is defined as follow:

$$S_e=\frac{\Theta-\Theta_r}{\Theta_s-\Theta_r} \tag{4}$$

2.5. Calibration Model

Since it is expected that the soil hydraulic properties would change in the interaction of soil with leachate with a high organic load, the first step after selecting a model is its calibration. At this stage, after establishing the physics of the model, observation points are introduced to the model and the data collected in the laboratory that contains the moisture content of the soil profile and concentrations of pollutants over time are entered into the model. Thus, the model does the inverse modeling by using the presented equations in the previous section, and the soil hydraulic parameters and the absorption coefficient are adjusted in such a way that the observed data with the predicted results are in concordance with the model. In this case, the hydraulic parameters of the calibrated model are determined when in contact with leachate with a high organic load.

2.6. The Monte Carlo uncertainty

The uncertainty of the stability and used parameters in simulation models could affect its reliability. In many cases, these coefficients are obtained by using empirical or semi-empirical relations or during the calibration of the model. In many instances, these coefficients and constants may have differences with the actual values in the environment. However, during modeling for modifying other values in the model, the model output has an apparent compliance with the boundary conditions. The measurement errors and changes in constants and coefficients are not usually considered in real terms during modeling. The Monte Carlo simulation method is used as a tool for integrated and simultaneous analysis of different combinations of uncertainties. In this method, in each performance, a possible value is produced between related low and high uncertainties for each of the uncertainties whose frequency follows the probability distribution function of uncertainty. Thus, in each performance, there is a set of solutions that are in one-to-one correspondence with uncertainties. Each one represents one of the possible states of compliance.

3. Results and discussion

As can be seen in Table 1, the physical properties of soil such as bulk density, moisture content, etc. were determined by the ASTM standard test method. Also, soil salinity parameters were calculated by using the WRAP-125 instruction of the University of California.

Table 1. Results of local soil sample

TDS (g/lit)	EC (ms/cm)	Phosphate	Nitrate	pH	ω %	K (cm/s)	Bulk density (g/cm^3)
5.2	10.01	4.39	2.78	8.2	14.6	1.37×10^{-6}	1.94

* Units of carbonate, bicarbonate, chloride, sulfate, nitrate, and phosphate are in mmol/liter.

Depending on the soil texture triangle that corresponds to the classification of the US Department of Agriculture (4USDA), this soil is placed in the range of loamy texture. In this section, the experimental results in different flow rates and in the height of the two pilots (Sampling was taken in the pilots every 30 cm) are listed below:

Input to the pilot: The output of primary purification unit

Sample B: Local soil pilot (soil control)

Sample C: Local soil pilot with Vetiver Grass

In this section, the Hydrus-1D model output results in pilots B and C in the three-levels of 0.12, 0.24 and 0.6 m^3/m^2.week on the average of eight weeks and changing the concentration at different depths and times are provided. Figures 1 to 3 show the results related to the trend of changes in nitrate output of the pilots of B and C in the three levels of 0.12, 0.24 and 0.6 m^3/m^2.week on the average of eight weeks, the first week until the eighth week (T_0 to T_7) of the model output.

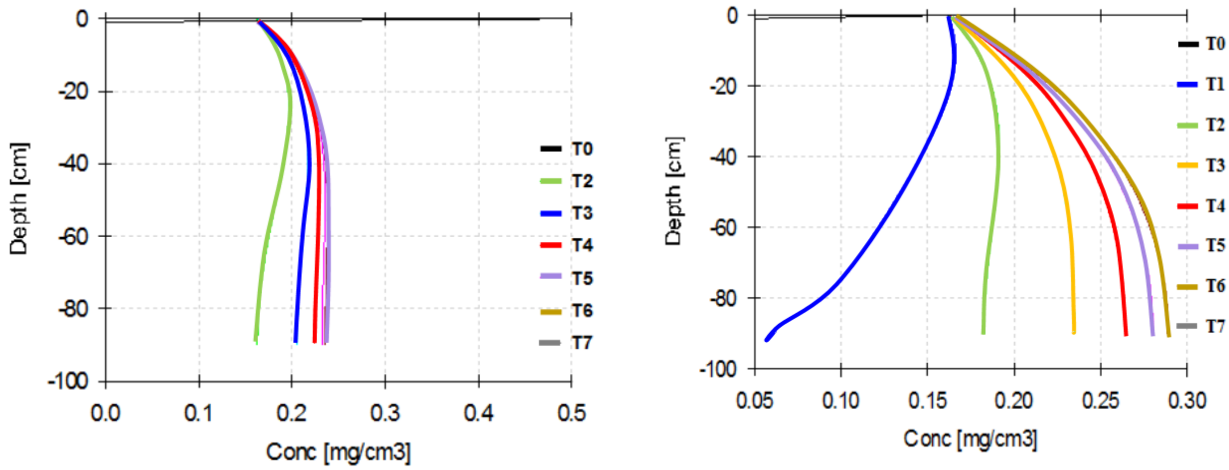

Fig. 1. Nitrate concentration at various depths in the surface charge of 0.12 m^3/m^2.week for the first week until the eighth (T_0 to T_7) in pilots B (right) and C (left)

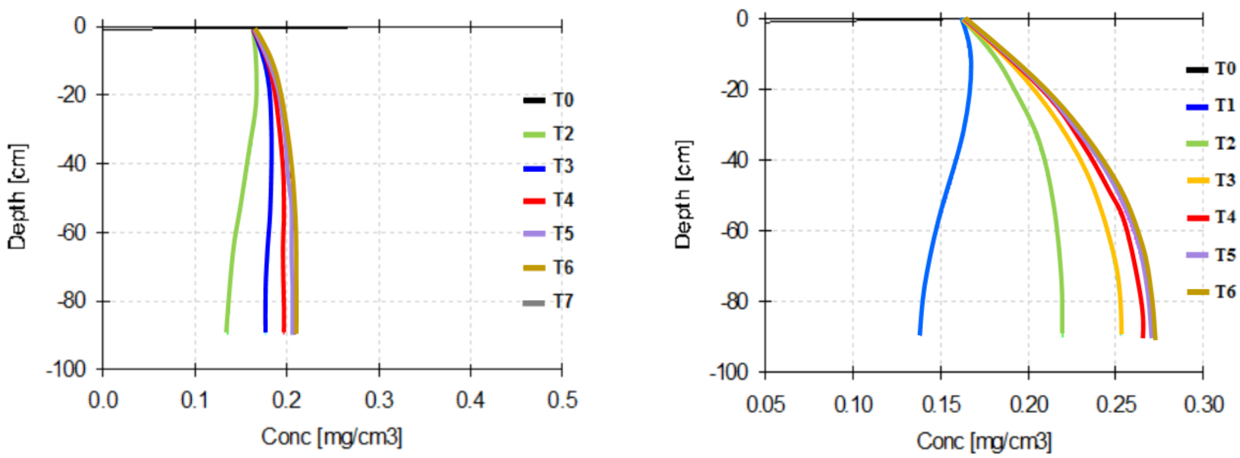

Fig. 2. Nitrate concentration at various depths in the surface charge of 0.24 m^3/m^2.week for the first week until the eighth (T_0 to T_7) in pilots B (right) and C (left)

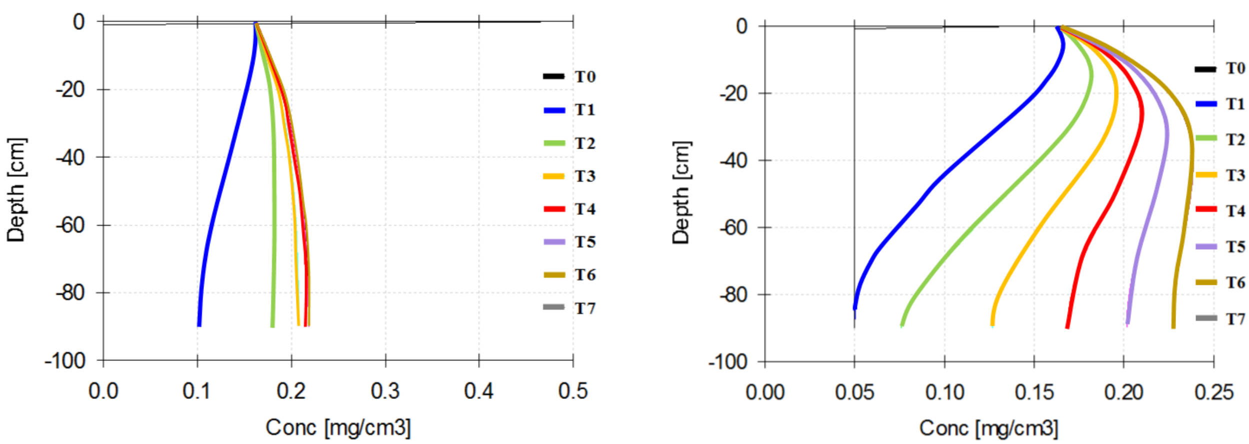

Fig. 3. Nitrate concentration at various depths in the surface charge of 0.6 m^3/m^2.week in the first week to the eighth (T_0 to T_7) in pilots B (right) and C (left)

As can be seen in Figures 1 to 3, in general, the amount of nitrate output increased. We can see that the output of pilot B in the surface charge of 0.12 m^3/m^2.week had the largest increase, and the output of C with the surface charge of 0.6 m^3/m^2.week had the lowest value. Also, the graph shows that in pilot C, in all derbies some of the nitrates have been used by plants, and this amount was less than the other pilot. Most of the input ammonia and converted ammonia in natural systems was temporarily adsorbed on soil particles and organic particles through the ion exchange reaction. The adsorbed ammonia will be made available to plants and microorganisms or it will be converted through biological dandruff, made under anaerobic conditions, to nitrate nitrogen. Having more nitrates in the output as compared to the input showed the high efficacy of the system because organic nitrogen and ammonia were converted to nitrate under the nitrification process that led to an increase in the amount

of nitrate in the effluent. Part of the nitrogen can be adsorbed to surface biomass, and sometimes nitrification can occur and part of the nitrate is inverted to nitrogen gas (N_2). As can be seen, the overall output value of nitrate increased. It is noteworthy that some of the nitrates have been used by the plants in pilot C in all derbies, and this amount was less than the other pilot. (B) The trend of organic nitrogen change at different speeds in the two pilots, B and C. Figures 4 to 6 show the results of the process of change in organic nitrogen discharged from the pilots B and C in three- levels of 0.12, 0.24 and 0.6 m^3/m^2.week in the first week until the eighth week of the model output.

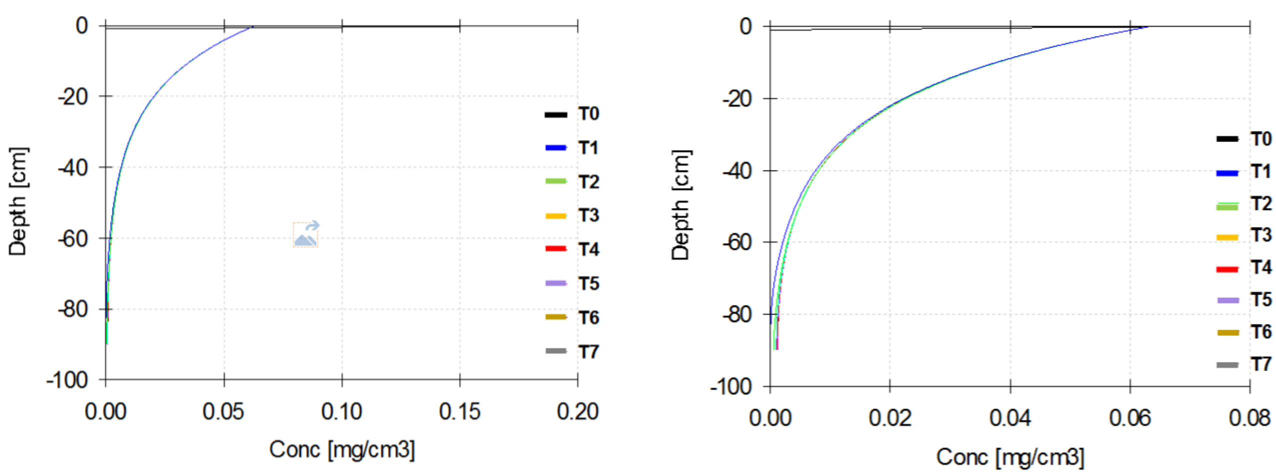

Fig. 4. Concentration of organic nitrogen at various depths in the surface charge of 0.12 m^3/m^2.week for the first week until the eighth (T_0 to T_7) in pilots B (right) and C (left)

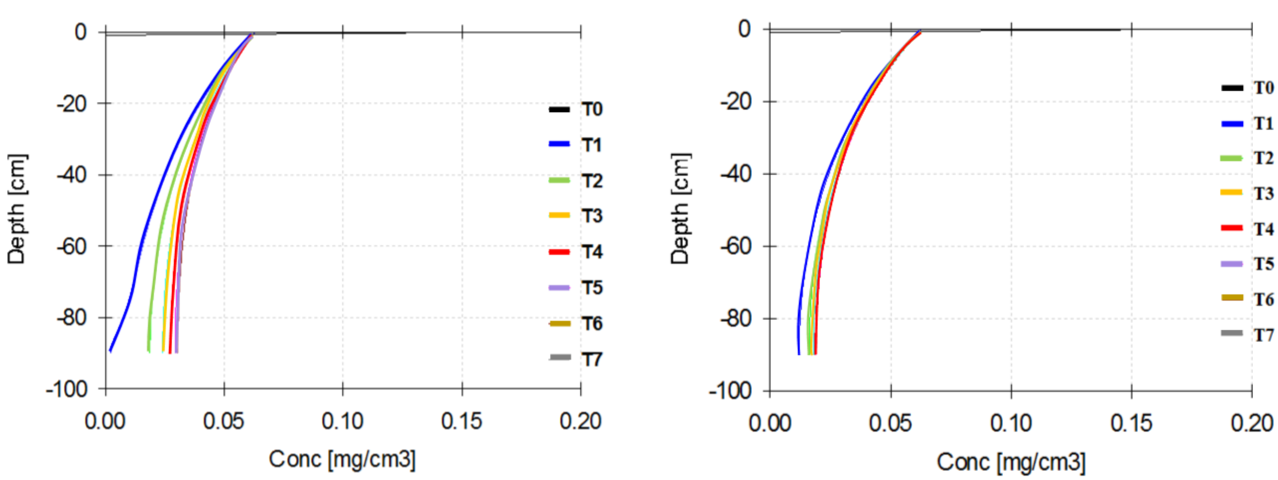

Fig. 5. Concentration of organic nitrogen at various depths in the surface charge of 0.24 m^3/m^2.week for the first week until the eighth (T_0 to T_7) in pilots B (right) and C (left)

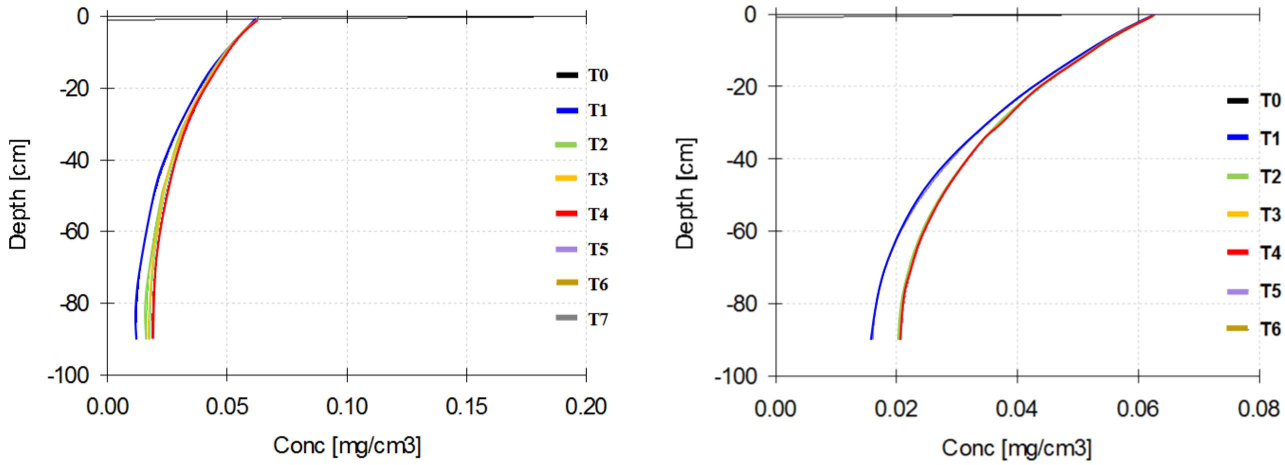

Fig. 6. Concentration of organic nitrogen at various depths in the surface charge of 0.6 m^3/m^2.week in the first week to the eighth (T_0 to T_7) in pilots B (right) and C (left)

As can be seen in Figures 4 to 6, in general, the amount of organic nitrogen output decreased. In this model's results, pilot C output with the surface charge of 0.12 m^3/m^2.week (pilot with Vetiver Grass) had the lowest nitrogen. Also, as can be seen in the graph, the removal rate in pilot C at all speeds in the higher depths, plant roots, and rhizosphere network caused a greater reduction in the organic nitrogen. Also, we can see that after six weeks, the pilot output reached a steady-state, and the output level was almost the same in the following weeks. The biodegradable section of organic nitrogen was converted to ammonia and ammonium ions, and ammonification occurred by microorganisms in the bed. Also, a fraction of the ammonium ions were absorbed by another group of microorganisms and used to build protoplasm and cellular proteins; also, the cellular uptake of nitrogen (assimilation) occurred which ultimately reduced the amount of organic nitrogen and TKN in output. According to the results, the highest removal rate of ammonia nitrogen, TKN, and phosphorus was in the pilot that contained Vetiver grass. This occurred because the biological activity was higher due to the integration and biological accumulation of bacteria in the plant root zone or the rhizosphere; therefore, the removal efficiency of nutrients such as nitrogen and phosphorus was higher. This happened because part of the nitrogen and phosphorus was absorbed by plant roots in this region; we also had cellular uptake by microorganisms of the rhizosphere, and the rest being absorbed to biofilm through the soil bed.

C: Trend of Phosphate change at different speeds in the two pilots, B and C.

Figures 7 to 9 show the results of phosphate output changes in the three-levels of 0.12, 0.24 and 0.6 m^3/m^2. week in the first week until the eighth week of the model output.

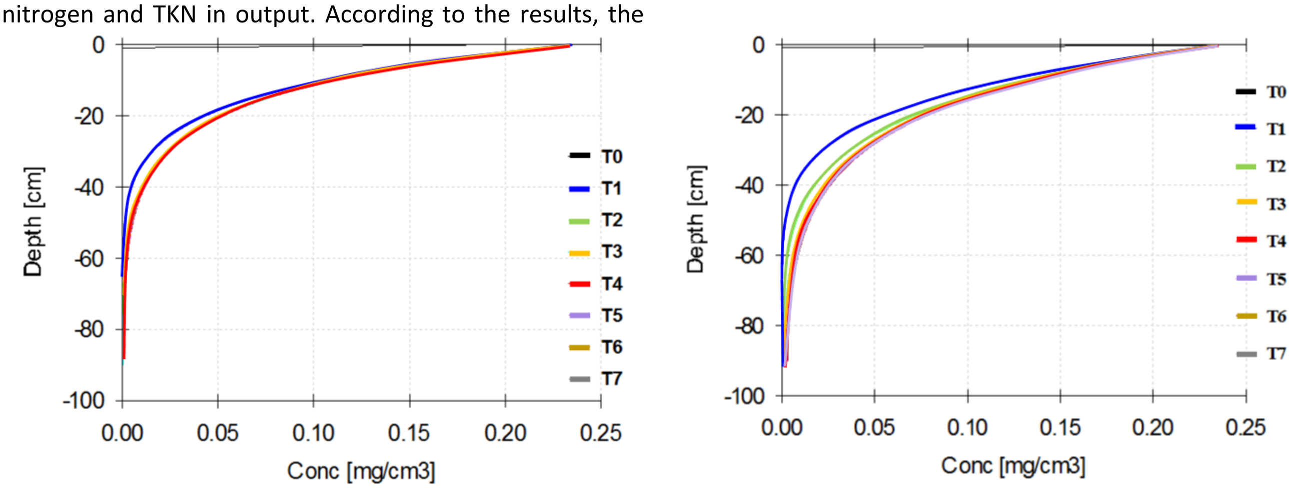

Fig. 7. Concentration of phosphate at various depths in the surface charge of 0.12 m^3/m^2.week for the first week until the eighth (T_0 to T_7) in pilots B (right) and C (left)

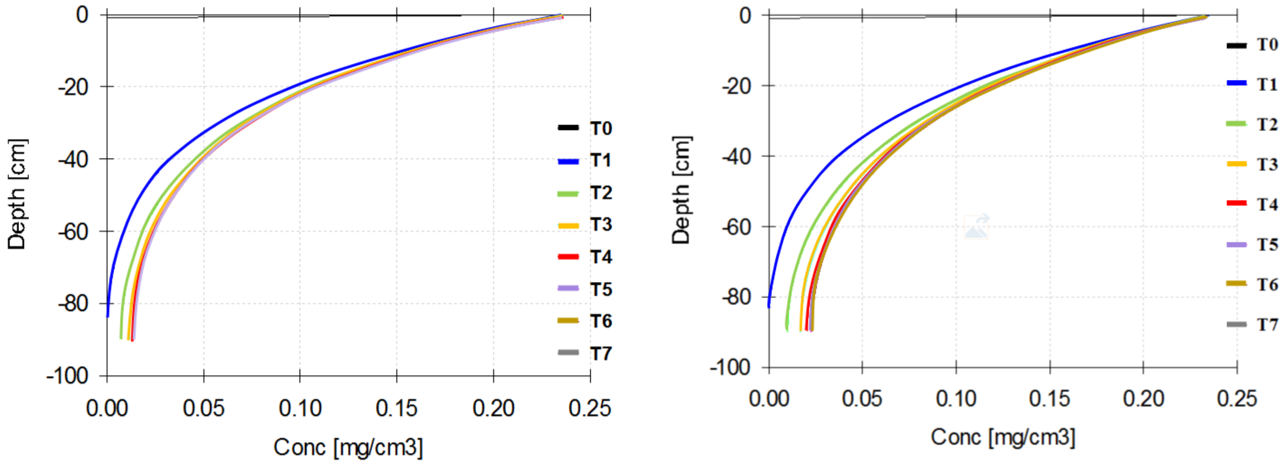

Fig. 8. Concentration of phosphate at various depths in the surface charge of 0.24 m^3/m^2.week for the first week until the eighth (T_0 to T_7) in pilots B (right) and C (left).

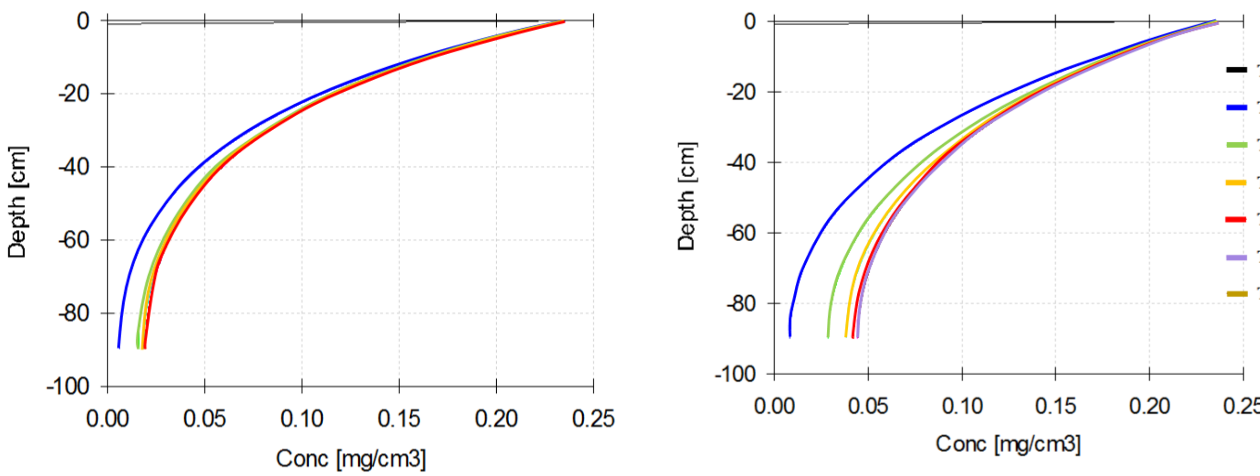

Fig. 9. Concentration of phosphate at various depths in the surface charge of 0.6 m^3/m^2.week in the first week to the eighth (T_0 to T_7) in pilots B (right) and C (left)

As can be seen in Figures 7 to 9, in general, the amount of phosphate output decreased. In the model results, the output of pilot C with the surface charge of 0.12 m^3/m^2. week (pilot with Vetiver grass) was the lowest. At the root of the plant in place of the rhizosphere where the biological activity was higher due to the integration and biological accumulation of bacteria in the plant root zone or the rhizosphere, the removal efficiency of nutrients such as nitrogen and phosphorus was higher. This resulted because part of the nitrogen and phosphorus was absorbed by the plant roots in this region, and there was also cellular uptake by microorganisms of the rhizosphere; the rest will be absorbed to biofilm through the soil bed. Thus, as shown in the diagram above, phosphate reduction was higher in pilot C at all speeds in higher depth. Also, we can see that after six weeks, the pilot output reached a steady-state, and the output level was almost the same in the following weeks.

4. Conclusions

The aim of this study was to simulate the movement of leachate and predict the concentration changes of nitrogen and phosphorus in the soil of the Aradkouh landfill. A comparison of the obtained results of this study is defined in the following points. The motion simulation of leachate in the soil was shown by using Hydrus-1D software. The higher the organic loading rate, the lesser the nitrogen and phosphorus removal efficiency would be. In the less hydraulic load, the nitrogen and phosphorus removal was higher because the hydraulic retention time increased. The results showed that the use of Vetiver grass in ground purification increased the purification efficiency and played a significant role in the removal of nitrogen and phosphorus. Modeling via the Hydrus-1D software correctly estimated this phenomenon. The use of the reverse estimation method to obtain soil hydraulic parameters is an appropriate method, but its use requires the empirical knowledge and calculations to achieve convergence in solution. The use of the reverse technique led to comprehensive answers when the number of data and their diversity was high. If there is insufficient data, it is better to reduce the number of hydraulic parameters in the inverse solution.

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