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A Modflow Assisted Simulation of Leachate Plume Pathway from the Idemili North Municipal Dumpsite, Anambra State Nigeria.

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Abstract
This study was conducted to simulate leachate plume migration from the Idemili North waste dumpsite for a period of 20 years' prediction using MODFLOW. Point sources such as landfills and open waste dumps can release high concentration of contaminants into groundwater due to leachate migration. The leachate generated as a result of precipitation, dissolution and biodegradation on an active landfill surface, results to the transport of organic and inorganic contaminants from the landfill waste and their subsequent discharge through infiltration, into groundwater in underlying aquifers. Leachate has the potential to contaminate and impair groundwater use in the affected area. The Idemili North waste dumpsite is unprotected and has received wastes streams for over 50 years. Finite difference was used to simulate the groundwater and leachate flow pathways. Model results were displayed in three dimensional images showing leachate plume concentration profiles. The profiles showed that leachate along with contaminants migrated towards the North-Southern and South-Eastern direction. It also revealed that the migration would not exceed 281.25m radius from the waste dump center in the next 20 years.
Keywords: *Leachate, Simulation, Groundwater, Landfill, Modflow*

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I. Introduction

Groundwater sources have their origin in the water cycle and are held in aquifers beneath the ground surface. These aquifers can be penetrated by wells for the provision of potable water. Groundwater is an important source of drinking water in many areas, including Nigeria. The potability is based on the levels of contaminants contained in it resulting from its source rock compositions or anthropogenic activities. The protection of groundwater from contamination is a global issue and much resource has been invested in the process of its conservation. Anthropogenic impaction of groundwater quality is exhibited in leachate constituents of groundwater and waste disposal practices are recognized as of paramount importance in groundwater quality (Tamer *et al*., 2011). Waste management has become increasingly complex due to the increase in human population, industrial and technological revolutions (Christopher, 2011). Open dumps are the oldest ways of disposing of solid wastes (Kurian *et al*., 2008), most of which have been closed in developed countries but in our growing metropolis, some are still being used (Adamu *et al.,* 2014). Currently, sanitary landfill represents a viable and the most commonly used method for solid waste disposal all over the world because it may achieve the reclamation of derelict land (Erses *et al*., 2005). Landfills are considered one of the major threats to groundwater (Fatta *et al., 1999)*, but the scale of this threat depends largely on the concentration and toxicity of contaminants in leachate, type and permeability of geological strata, depth of water table and the direction of groundwater flow (Al-Khaldi, 2006). The notorious Idemili North waste dump has received wastes streams for over 50 years and Bagchi, (2004), observed that certain pollutants, including toxic substances could be contained in such waste streams. Since Idemili is located in the rainforest eco-zone of Nigeria where precipitation could reach as high as 2000mm per annum (NIMET, 2014), toxic pollutants are leached in the waste streams and could migrate through seepage and other physical processes to contaminate groundwater aquifers of the area.

Leachate Production

Most wastes deposited in landfills are not inert. Degradation of many components of waste including food, paper and textiles consumes oxygen thereby changing the redox potential of the liquid present and potentially influencing mobility of other constituents. Plastics, glass and metal compounds tend to be less reactive and degrade more slowly, however, under certain conditions, metals may, become rapidly mobilized. Percolating rain water provides a medium in which waste, particularly organics, can undergo degradation into simpler substances through a range of biochemical reactions involving dissolution, hydrolysis, oxidation and reduction, processes controlled to a large extent within landfills and dumps by microorganisms, primarily bacteria. Mechanisms regulating mass transfer from wastes to leaching water, from which leachate originates can be divided into three groups of processes; Hydrolysis of solid waste and biological degradation, Solubilisation of soluble salts contained in the waste and Suspension of particulate matter. The first two groups of processes, which have the greatest influence on the composition of leachate produced, are associated with the stabilisation of waste. Initially, organic matter, in the form of proteins, carbohydrates and fats, is decomposed under aerobic conditions (i.e. oxidised), through a series of hydrolysis reactions, to form carbon dioxide and water together with nitrates and sulphates via a number of intermediate products such as amino acids, fatty acids and glycerol. Such oxidation reactions are exothermic, so temperatures in the landfill become elevated. Carbon dioxide is released as a gas or is dissolved in water to form carbonic acid (H_2CO_3) which subsequently dissociates to yield the bicarbonate anion (HCO_3^-) at near neutral pH.

Aerobic decomposition of organic matter depletes the waste deposit of oxygen (O_2) as buried waste in the landfill or refuse dump becomes compacted and circulation of air is inhibited. As oxygen becomes depleted, it is replaced as the oxidizing agent by in succession, nitrate (NO_3), manganese (as MnO_2), iron (as Fe $(OH)^3$) and sulphate (SO_4^{2-}). In general, the aerobic stage is short, no substantial volumes of leachate are produced, and aerobic conditions are rapidly replaced by anaerobic conditions. The main stages of anaerobic digestion are (i) acidogenic (acid) fermentation, (ii) intermediate anaerobiosis, and (iii) methanogenic fermentation, all three of which can be operating simultaneously in different parts of the landfill.

Acidogenic fermentation brings about a decrease in leachate pH, high concentrations of volatile acids and considerable concentrations of inorganic ions (e.g. Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+). As the redox potential drops, sulphate is slowly reduced, generating sulphides, which may precipitate iron, manganese and heavy metals that are dissolved by the acid fermentation. Decrease in pH is due to production of volatile fatty acids (VFAs) and to high partial pressures of carbondioxide (CO_2), whilst the increased concentrations of anions and cations results from leaching (lixiviation) of easily soluble organic material present in the waste mass.

Breakdown of organic material reduces the redox potential to <330mV, which allows the next stage of the process to become initiated. Leachate from this phase is characterized by high values of biochemical oxygen demand (BOD, commonly > 10,000 mg/L), high BOD5/COD (chemical oxygen demand) ratios (commonly>0.7), acidic pH values (typically5-6) and ammonia (NH_3) due to hydrolysis, and fermentation in particular of proteins. Intermediate anaerobiosis commences with a gradual increase in the methane (CH_4) concentration in the gas, coupled with a decrease in H_2, CO_2 and volatile fatty acids. Conversion of the volatile fatty acids leads to an increase in pH values and to alkalinity, with a consequent decrease in the solubility of calcium, iron, manganese and the heavy metals, which are probably precipitated as sulphides. Ammonia is released but is not converted to nitrate in such an anaerobic environment. Methanogenic fermentation, the final stage in the degradation of organic wastes, operates within the extremely limited pH range of 6-8. At this stage in the degradation process, the composition of leachate is characterized by almost neutral pH, and low concentrations of volatile acids and total dissolved solids (TDS), indicating that solubilisation of the majority of organic components is almost complete, although waste stabilization will continue for several decades. The biogas being produced has a methane content of generally>50percent, whilst ammonia continues to be released by the acidogenic process. Leachate produced at this stage is characterized by relatively low BOD values, and low ratios of BOD/COD. Degradation processes convert nitrogen into a reduced form (ammonium), and bring about mobilization of manganese and iron and also liberation of hydrogen sulphide gas. Production of methane indicates strongly reducing conditions with a redox potential in the order–400 mV. Unlike carbon dioxide, methane is poorly soluble in water. Due to the decomposition of organic matter, leachate derived from landfills or dumps comprises primarily dissolved organic carbon, largely in the form of fulvic acids (Christensen *et al.*, 1998). The solubility of metals in leachate is enhanced through complexation by dissolved organic matter. The solubility of organic contaminants (e.g. solvents) in waste may also be slightly enhanced through the presence of high levels of organic carbon in leachate. Hydrophobic compounds may be mobilized through leachate, as they adsorb to organic carbon in solution. For example, benzene- and naphthalene- sulphonates comprise between 1 and 30 per cent of the dissolved organic carbon in landfill- leachates recently analyzed in Switzerland (Riediker *et al.*, 2000).

Leachate Migration

In unsealed landfills above an aquifer, waters percolating through landfills and refuse dumps often accumulates 'mound' within or below the landfill as shown in Figure1. This is due to production of leachate by degradation processes operating within the waste, in addition to the rainwater percolating down through the waste. The increased hydraulic head developed promotes downward and outward flow of leachate from the landfill or dump. Downward flow from the landfill threaten sunder lying groundwater resources whereas outward flow can result in leachate springs yielding water of a poor, often dangerous quality at the periphery of the waste deposit. Observation of leachate springs or poor water quality in adjacent wells/boreholes are indicators that leachate is being produced and is moving. Leachate springs represent a significant risk to public health. One method used to reduce the generation of leachate and, hence, hydraulic heads generating flow from a closed landfill is to place a capping of low permeability material (e.g. clay or high density polyethylene - HDPE) over the waste deposit in order to reduce infiltration of rainwater. Groundwater pollution potential from older capped landfills may therefore be higher than from younger, open landfills.

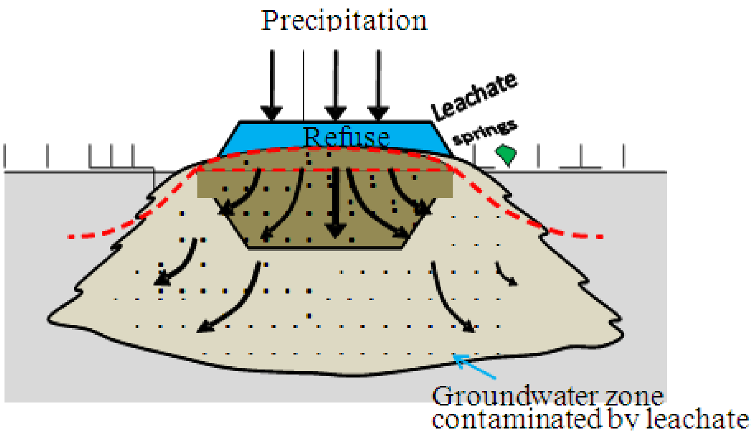

Figure 1: Conceptual diagram of leachate migration from a landfill

Leachate migration is also affected by the manner in which waste is deposited. Compaction of waste prior to deposition reduces its permeability, whereas regular application of a topsoil cover between the loading of waste to landfills induces layering. These characteristics inevitably give rise to preferential flow paths through landfills.

Leachates Effects

Leachates contain a host of toxic and carcinogenic chemicals, which may cause harm to both humans and the environment. Leachate-contaminated groundwater can adversely affect industrial and agricultural activities that depend on well water. For certain industries, contaminated water may affect product quality, decrease equipment lifetime, or require pretreatment of the water supply, all of which cause additional financial expenditures. The use of contaminated water for irrigation can decrease soil productivity, contaminate crops, and move possibly toxic pollutants up the food chain as animals and humans consume crops grown in an area irrigated with contaminated water (Mpofu, 2014).

II. Methodology

Groundwater and leachate flow simulation

Groundwater modelling is the approximate visual representation of a field situation. It is used to predict the behavior of groundwater systems. Due to variations in hydrogeology and geology of the earth, there is great dynamism in its hydraulic conductivity, storage, effective porosity etc. One of the best tools employed in predicting and optimizing the behavior of groundwater, its contamination rate and concentration is groundwater modelling. Groundwater models are divided into two categories: groundwater flow models and solute transport models. Groundwater flow models accounts for the distribution of head, while solute transport models accounts for concentration of solute as affected by advection, dispersion and chemical reactions, which slow down or transform solutes.

Conceptual model

From the hydrogeology of the equipotential map of the study area, it was concluded that the flow was North-south to South-east. It was observed that the southern part of the modelled area has a higher conductivity value while towards the north-western parts have lower conductivity. It was also assumed that the topography was a gentle slope from north to south, which gives rise to a laminar flow regime. Also inferred was that the northern boundaries have a constant head boundary while the south have a river boundary condition. The thickness of the aquifer to that of the river was at 20m. The aquifer was treated as an unconfined system. Based on geology, it was assumed that the southern part with higher conductivity were coarse sands and fine sand while the north-western parts with lower conductivity were more of fine sand with clay intercalations. The aquifer base was at 90m with an assumed elevation of 100m. The aquifer was assumed to be homogenous. For the steady state flow model, a recharge rate of 2000 mm/year was assumed and evapotranspiration of 1000 mm/year. The recharge rate for both steady and transport flow was distributed equally all over the system while the only way out was towards the southern part of the study area into the Idemili river (effluent conditions). Apart from the above description, it was assumed that there are no sources or sinks in the study area.

Numerical model

The modelling of the study area was set up using MODFLOW. Therefore, finite difference was used to simulate the flow. Most of the modelling applications that have to do with unconfined aquifers use the Dupuit assumptions, which ensures horizontal flow by requiring that there is no change in head with depth (Anderson and Woessner, 2002). This assumption was also applied to the study area since it is an unconfined aquifer and the assumption turns a three- dimensional problem into a two –dimensional one. The modelled domain was discretized into 1600 equally sized blocks (40 x 40). The height was 11200m and width was 11400m. The boundaries of the study area were set as the first and the second type of boundary conditions. To the northern part, the Dirichlet boundary condition holds, and describes a constant head. The head value varies from top to down, 90m at the top and 45m at the down. The other boundary conditions are of the second type-boundary conditions, which is the Neumann boundary condition. It is with a constant gradient of zero and therefore no flow occurred.

The modelled groundwater flow was calculated from a partial differential equation, which is based on the law of mass conservation and Darcy's law. This is given below as follows:

$Ss \times dh/dt = \mathrm{div}\,(K \times \mathrm{grad}\,(h))$

Where;

Ss = Specific yield,

h = Hydraulic head,

t = Time and

K = Hydraulic conductivity.

The borders of the modelled region where set as boundaries of the first and second order. That is, the Dirichlet and the Neumann types respectively.

III. Result Presentation And Discussion

The groundwater flow direction in the study area and leachate plume spread patterns from the Obosi waste dumpsite are represented below.

Groundwater Flow in the Study Area

Figure 2 shows the groundwater flow pattern in the study area. From the hydrogeology of the equipotential map of the study area, it was observed that the flow was North-Southern to South-Eastern direction. It was also observed that the southern part of the modeled area has a higher conductivity value while towards the north-western parts have lower conductivity. The topography was a gentle slope from north to south, which gives rise to a laminar flow regime. Furthermore, the northern boundaries have a constant head boundary while the southern boundaries have a river boundary condition. The recharge rate for both steady and transport flow was distributed equally all over the system, while the only way out was towards the southern part of the study area into the Obosi river (effluent conditions).

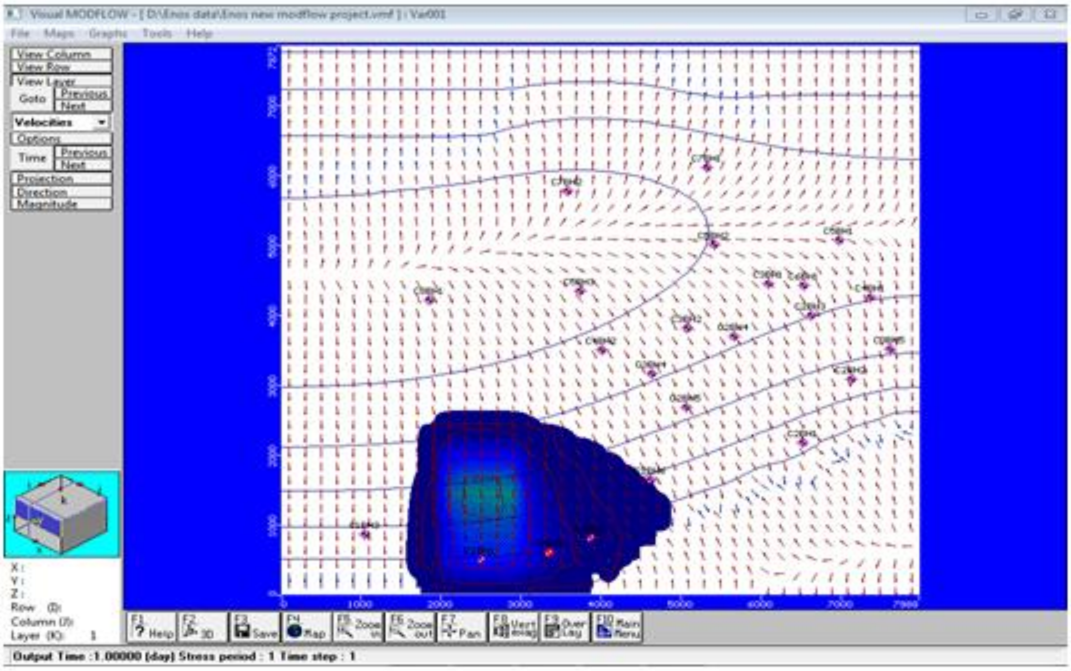

Figure 2: Groundwater flow direction in the study area

Leachate Plume Spread

The leachate plume spread from the waste dumpsite was simulated for a period of 730, 1460, 2190, 2920, 3650, 5475 and 7300 days. This is presented in figures 3 – 9. There was an increase in the plume diameter for a period of 6 years, after which the plume ceased to expand. The migration would not exceed 281.25m radius from the waste dump center in the next 20 years.

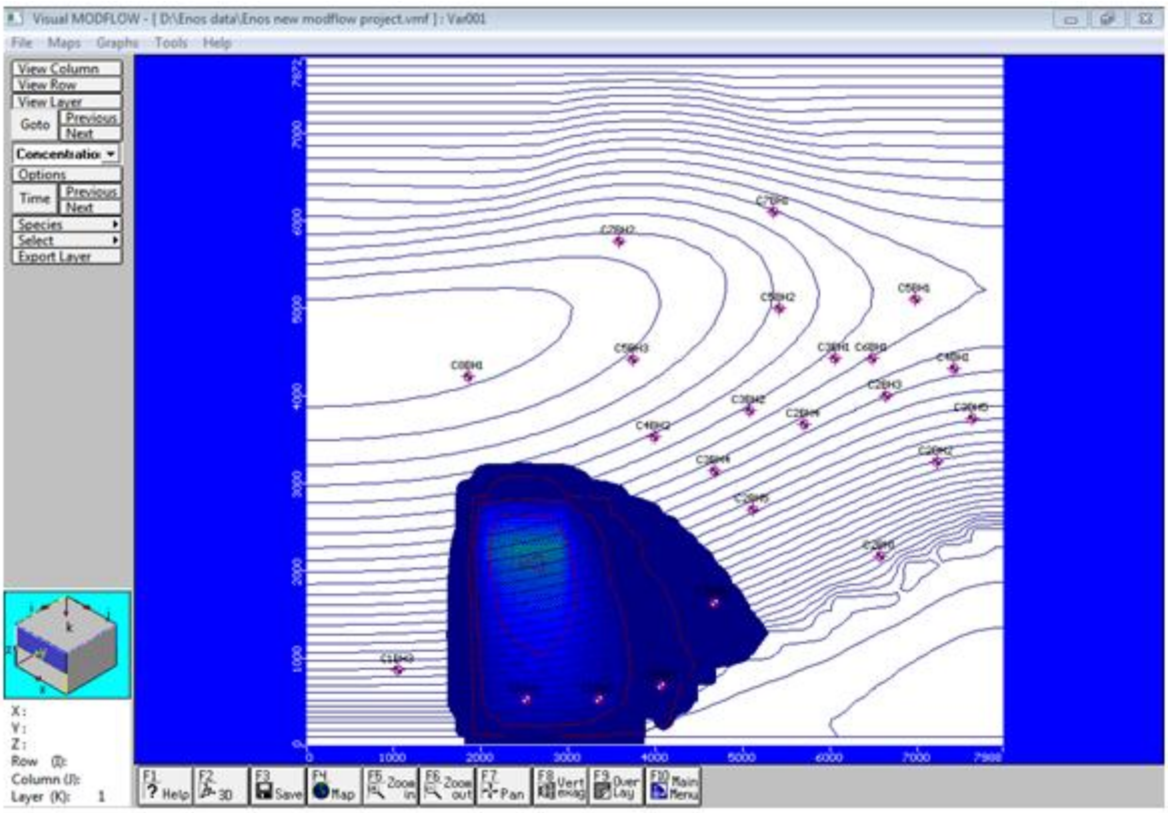

Figure 3: Leachate plume spread after 730 days (2 years) interval

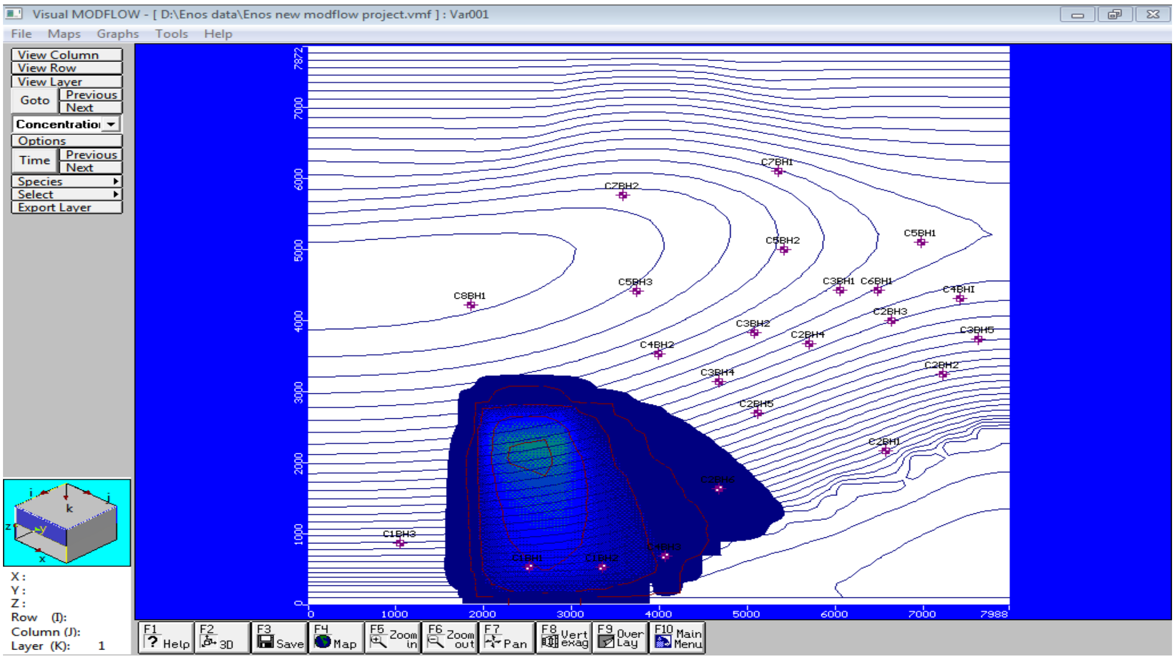

Figure 4: Leachate plume spread after 1460 days (4 years) interval

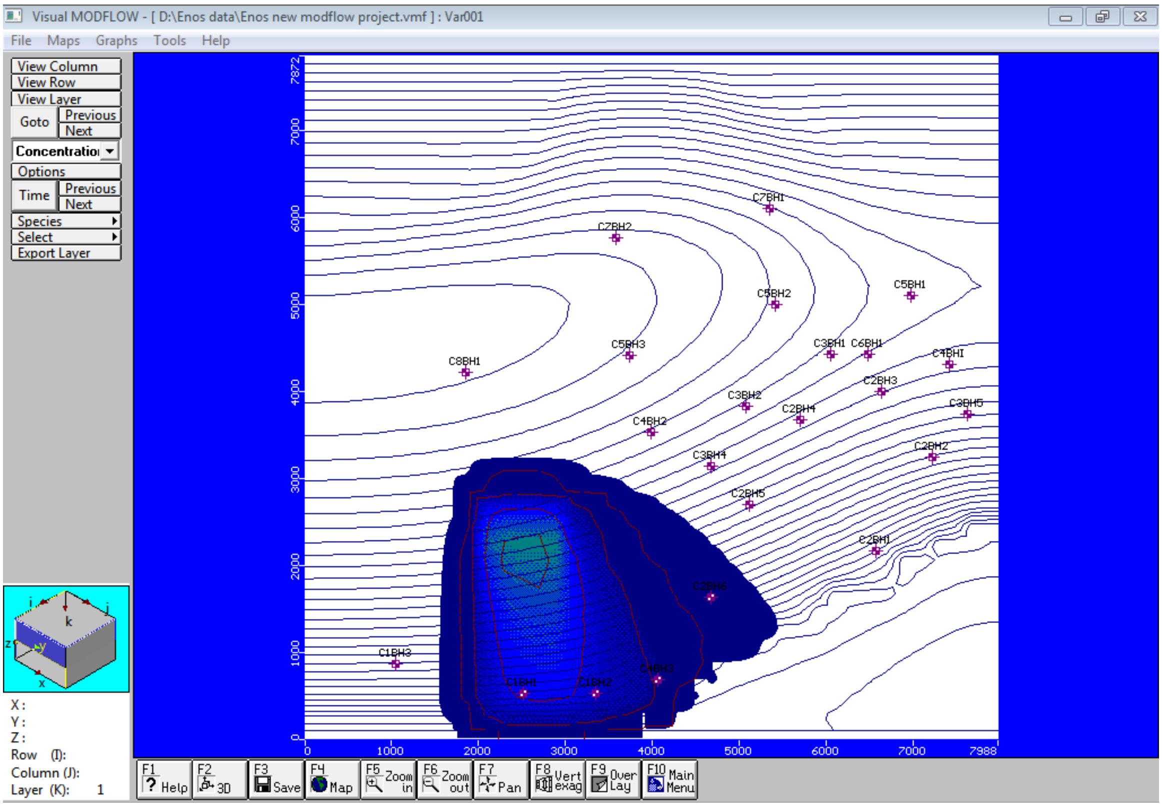

Figure 5: Leachate plume spread after 2190 days (6 years) interval

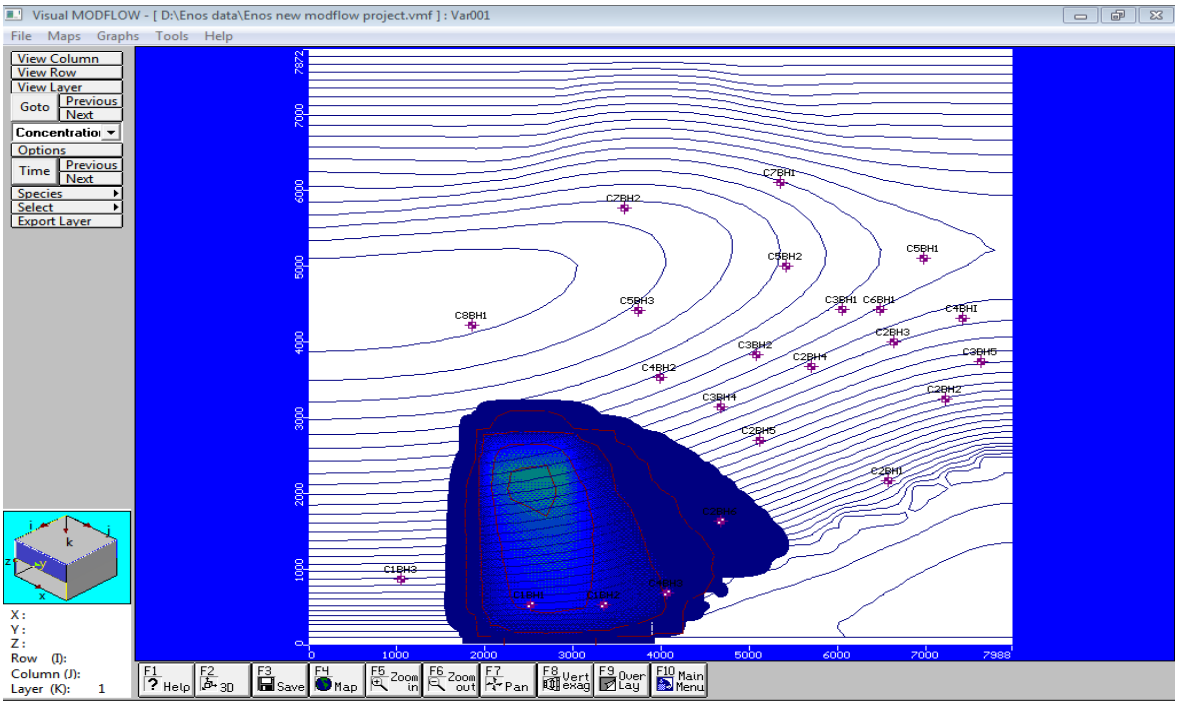

Figure 6: Leachate plume spread after 2920 days (8 years) interval

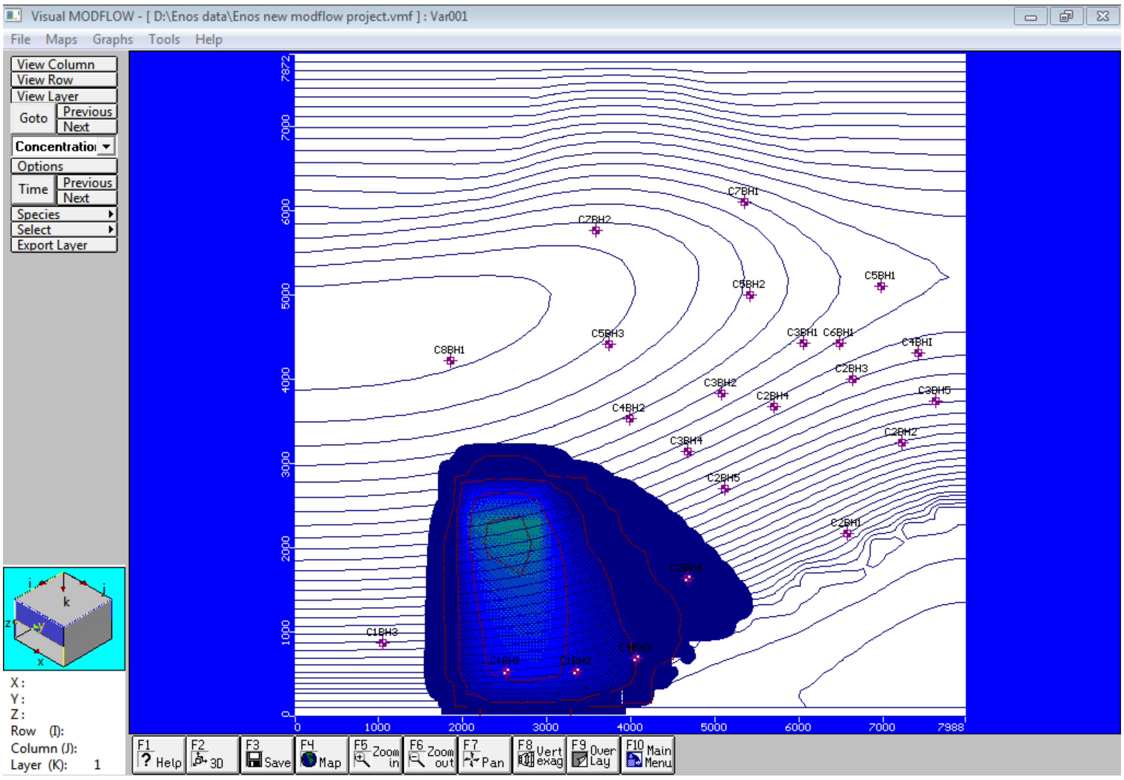

Figure 7: Leachate plume spread after 36500 days (10 years) interval

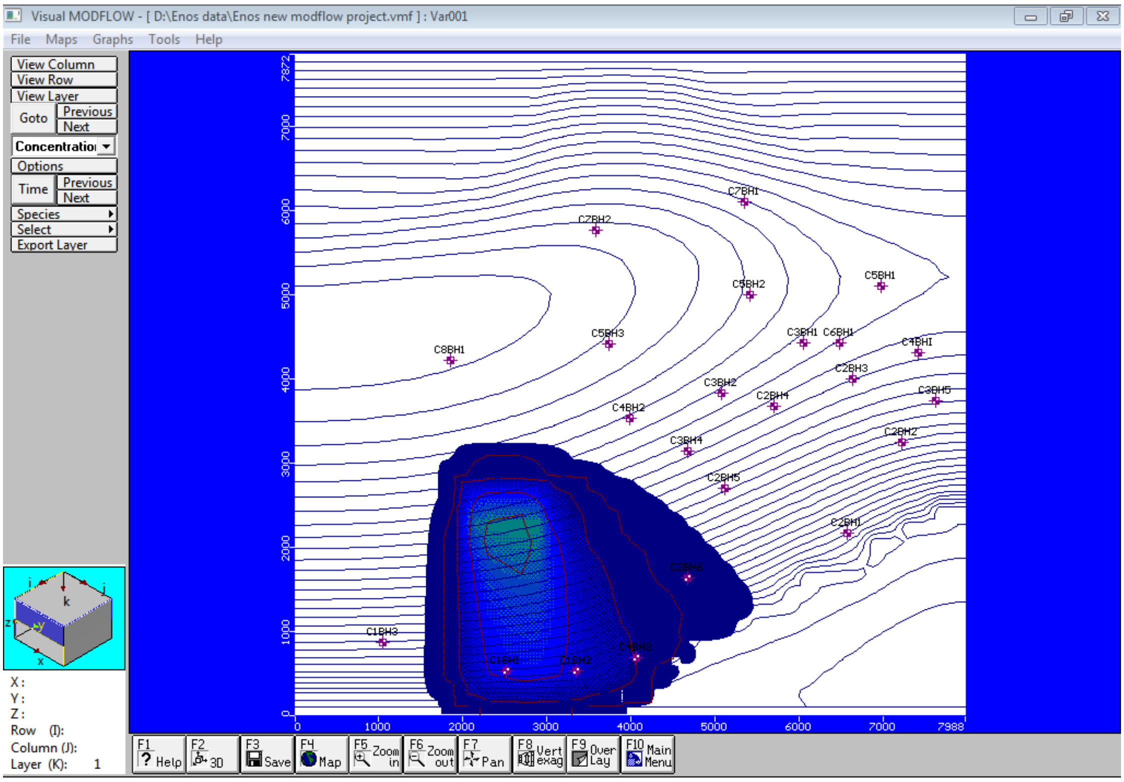

Figure 8: Leachate plume spread after 5475 days (15 years) interval

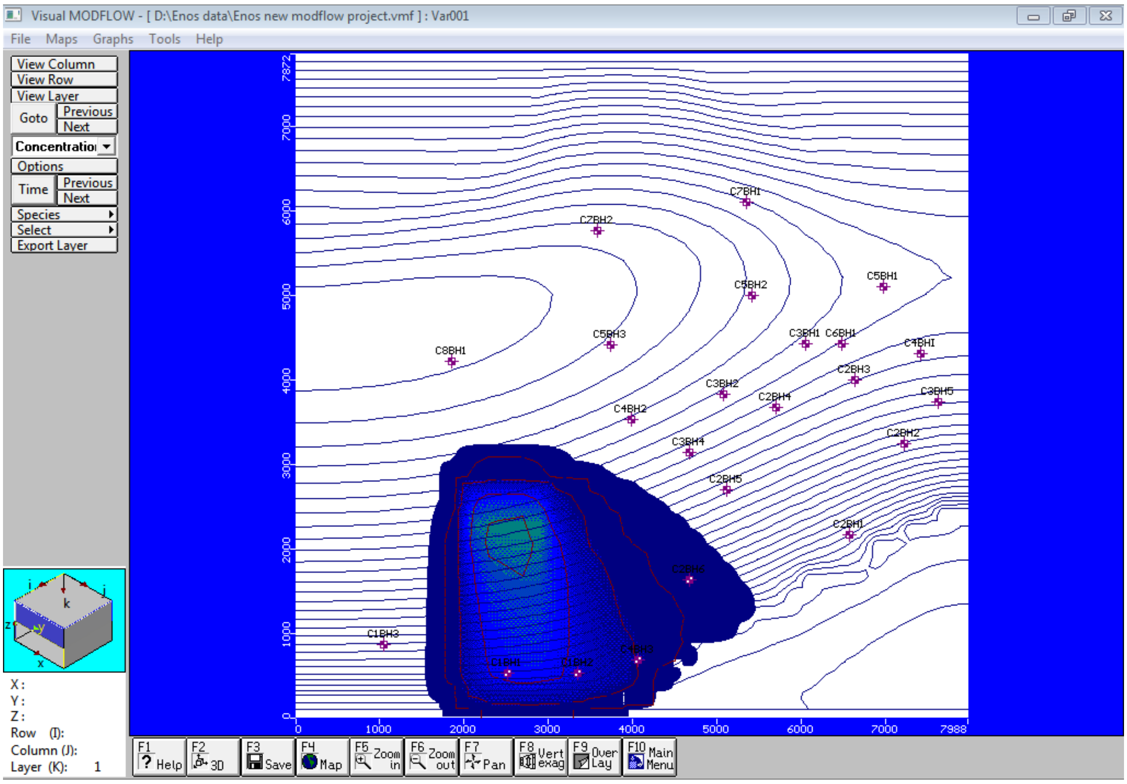

Figure 9: Leachate plume spread after 7300 days (20 years) interval

Table 1 summarizes the plume spread in diameters for the simulated period.

Table 1: Leachate plume spread in days from the Idemili North waste dump site

Time (Days)	Plume Diameter (m)
730	125.00
1460	437.50
2190	562.50
3650	562.50
5475	562.50
7300	562.50

There was an increase in the plume diameter for a period of 6 years, after which the plume ceased to expand. The migration would not exceed 281.25m radius from the waste dump center in the next 20 years.

IV. Conclusion And Recommendation

The groundwater flow direction in the study area was found to be predominantly in North-southern to South-eastern direction, towards the Obosi River. The leachate plume spread was also found to follow the same path. Furthermore, the simulation suggests that leachate generated from the waste dumpsite could have contaminant risks on boreholes located South-eastern part of the dumpsite.

It is therefore recommended that a contaminant migration mitigation measure should be performed to reduce the risk of groundwater contamination in the study area and prior attention should be given to the problem of open waste dumping, with regard to public health and groundwater risks. Monitoring wells should be sited at strategic locations for continuous monitoring of groundwater contamination in the aquifer and consumption of groundwater within a 281.25m radius of the waste dump must be avoided. Furthermore, the operation of the Obosi dumping site and any other similar dumping sites in the country must be stopped as soon as possible so as to avoid groundwater and public health problems while a temporary disposal options should be considered which should be free of environmental pollution and public health risks. Finally, engineered landfills should be constructed with adequate provisions for proper collection and treatment of leachate.

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