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ABSTRACT
Groundwater contamination by pesticides is an environmental health concern throughout the world. Many pesticides do not leach because they are adsorbed on the soil particles or organic matter even though they may have a relatively high solubility. The objective of this study was to determine the relationship between soil permeability and organic carbon in the transport of pesticides into groundwater along the shore of Lake Naivasha, using regression analysis of soil permeability and organic carbon data collected along the shore. The results showed that the soil organic carbon ($f_{o}$) positively affected the soil permeability ($k$) and were related by the equation $k = 80.724(1.726)^{f_{o}}$. It was concluded that organic carbon increased soil permeability by 30%, thereby recharging the aquifer while at the same time reducing pesticide transport into groundwater. Based on these findings the study recommended that the use of compost (organic amendments) should be increased in place of inorganic fertilizers.

Keywords- Pesticides, pesticide transport, Groundwater contamination, permeability, organic carbon, Lake Naivasha

1. INTRODUCTION
Lake Naivasha is located in Nakuru County in the Eastern Rift Valley, about 100 km Northwest of Nairobi, Kenya’s capital. The farming system is well expanded in the riparian zone of Lake Naivasha; the only fresh water lake in the Rift Valley. Bordering the lake are some of the biggest flower farms in the world with Kenya’s horticultural production of 80 %, making it the most important area for cut flowers in Kenya [1].

Pesticides have different fates after application. Once a pesticide is introduced into the environment, whether through an application, a disposal or a spill, it is influenced by many processes. These processes determine a pesticide’s persistence and movement, if any, and its ultimate fate. The retention and mobility of a pesticide in soil is determined by the extent and strength of sorption reactions, which are governed by the chemical and physical properties of the soils and pesticides involved [2]. In the leaching process, soil properties (total organic carbon content, pH, texture, mineralogy and structure), land use and management (pesticide application rate and timing, tillage), climate, subsoil and vadose zone characteristics, groundwater, and pesticide properties play a decisive role [3, 4]. It is commonly reported that compost (organic amendments) enrich soils of low organic matter content and consequently promote adsorption of pesticides and reduce pesticide mobility [5]. Furthermore, the incorporation of decomposable carbon may stimulate the biodegradation of pesticides by increasing the soil microbial activity [6]. Organic matter with its many adhesion sites delays pesticide leaching below the root zone, allowing microbes more time for degradation. When pesticide molecules adhere to soil particles, they are removed from soil water. This lowers the ability of pesticides to move decreasing pollution danger. Schnitzer et al.[7] underlined the important role played by soil organic carbon from the addition of crop residues in decreasing the mobility and bioaccessibility of benazolin and its metabolites. The permeability of the soil ought to be considered when applying pesticide. Soil permeability is a measure of how fast water can move downward through a particular soil. Water moves quickly through soils with high permeability, losing dissolved chemicals with the percolating water. The coefficient of permeability ($k$) of a cohesionless soil is approximately proportional to the square of an effective size (diameter, $d_{50}$ in mm) of soil (ie. $k= d_{50}^{2} \times 10^{4} \mu m^{-1}$) [8]. The effective size is determined from particle size distribution curves; the diameter read from a curve at the “10% finer” point is used as the effective diameter ($d_{10}$). [9]. Investigation on the relationship between soil permeability and organic carbon in the transport of pesticides into groundwater is presented in this study. This was accomplished using regression analysis of soil permeability and organic carbon data collected along the shore of Lake Naivasha.

2. EXPERIMENTAL PROTOCOLS
2.1 Soil Properties
Nineteen (19) soil samples for soil properties analysis were conveniently sampled from farms along the shore of Lake Naivasha (Fig. 1). The soils were sampled at a depth of 15-30 cm to eliminate plant roots which could have given higher than correct values of organic matter and organic carbon. The properties of the soil (particle size.
distribution and the soil organic carbon) were determined at the School of Environmental Studies, analytical laboratory, Moi University. The particle size distribution was used to determine the permeability of the soil on the shore of Lake Naivasha [9]. A relationship between soil coefficient of permeability (k) and soil organic carbon (f_C) was determined by regression analysis in order to develop an equation describing the two soil properties, and how they influenced pesticide mobility in the soil.

![Figure 1: Soil sampling sites](image)

**2.1. Particle Size Distribution**

The purpose of this test was to determine the quantitative distribution of particle sizes in soils collected from the study area. The information obtained from sieving test was used to calculate the permeability of the soil around Lake Naivasha using the relationship \( k = d_{10}^2 \times 10^9 \mu \text{m}^2\text{s}^{-1} \) [9], where \( k \) is the permeability of the soil and \( d_{10} \) the effective size of soil in millimetres.

The sieving test was carried out in accordance to the American Society for Testing materials method (ASTM D 422-63) [10] using the following apparatus: Stack of Sieve Aperture sizes 4.75 mm to 0.075 mm (including the cover and pan); Electronic Balance (decimal reading to 0.1 g); Rubber pestle, mortar (for crushing the soil if lumped) and; brush; Mechanical sieve vibrator (shaker); Oven Dry (thermostatically controlled temperature).

The following procedure was used for the sieving test: The dried soil samples was taken from the oven and first crushed (in lumped soils) using the rubber pestle and mortar. The mass of samples was accurately determined and labelled; all the sieves and the pan were also separately weighed. A stack of sieve aperture sizes with larger opening sizes of sieve at the top and down to the last one with smaller opening sizes was then prepared. The sieve pan was then placed underneath. The soil was slowly poured into the stack of sieves from the top and the cover placed. The stack was placed onto the sieve shaker (vibrator), and shaken for 10 minutes. The stack was taken out of the vibrator and the mass of each sieve aperture plus retained soil inside weighed, from the top sieve until the last one by one. The weights of the soil retained were recorded in the result sheet and the percentage of particles passing each sieve aperture determined. The soils' particle size distribution curves (Figure 2) for the soil samples were then prepared and the effective size (\( d_{10} \)) determined.

![Figure 2: Determination of the effective size (\( d_{10} \)) using particle size distribution curves](image)

**2.1.2 Organic Carbon Determination**

The soil samples were collected in different days of the week and stored at 4°C to minimise organic compounds loss. The organic matter in the samples was determined at Moi University School of Environmental Studies Analytical Laboratory using the loss-on-ignition (LOI) method.

The loss-on-ignition method was used to destroy the organic matter in the sample by heat destruction. The samples were first oven dried at 105°C to remove water and then weighed to determine their initial weights. A known weight of sample was placed in a ceramic crucible which was then heated to 400 ±5°C overnight [11-14]. The sample was then cooled in desiccators and weighed.

The organic matter (OM) was determined gravimetrically and calculated as the difference between the initial (\( w_i \)) and final (\( w_f \)) sample weights divided by the initial sample weight (\( w_i \)) times 100% [11]: i.e.

\[
\%OM = \frac{(w_i - w_f)}{w_i} \times 100
\]

A conversion factor of 1.724 was used to convert organic matter (OM) to organic carbon (\( f_C \)) (based on the assumption that organic matter contains 58% organic carbon (i.e., \( f_C = OM/1.724 \)) [12].

The values of soil permeability were plotted against those of organic carbon (Figure 3) in order to assess how organic carbon affected soil permeability and in extension the role of organic matter in pesticide mobility in soil.

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3. RESULTS

Table 1 shows the physical and chemical properties of soil influencing the flow of water and the mobility of pesticides in soils around Lake Naivasha. Figure 3 shows a plot of log of soil permeability (log k) versus organic carbon (foc). From Figure 3 the relationship between permeability and organic carbon of the soil in the study area is shown to be, y = 0.237x + 1.907 (R² = 0.298).

Table 1: Physical and chemical Properties of soils around Lake Naivasha

<table>
<thead>
<tr>
<th>Sample NO.</th>
<th>Sample</th>
<th>% organic matter (OM)</th>
<th>% organic carbon (foc)</th>
<th>Effective grain size (d10 in mm)</th>
<th>Permeability k in µms⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A1</td>
<td>1.823</td>
<td>1.057</td>
<td>0.095</td>
<td>90.25</td>
</tr>
<tr>
<td>2</td>
<td>A2</td>
<td>2.036</td>
<td>1.181</td>
<td>0.12</td>
<td>169</td>
</tr>
<tr>
<td>3</td>
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<td>1.948</td>
<td>1.130</td>
<td>0.15</td>
<td>225</td>
</tr>
<tr>
<td>4</td>
<td>B2</td>
<td>2.477</td>
<td>1.437</td>
<td>0.13</td>
<td>169</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>1.990</td>
<td>1.154</td>
<td>0.1</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td>7</td>
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<tr>
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<tr>
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<tr>
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<td>625</td>
</tr>
<tr>
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<td>2.472</td>
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</tr>
<tr>
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<td>2.598</td>
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</tr>
<tr>
<td>14</td>
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<td>169</td>
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<tr>
<td>15</td>
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<td>16</td>
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<tr>
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</tr>
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<td>0.29</td>
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</tr>
<tr>
<td>19</td>
<td>N</td>
<td>5.356</td>
<td>3.107</td>
<td>0.13</td>
<td>169</td>
</tr>
</tbody>
</table>

Mean foc = 1.770

From Fig. 3 k and foc are related by the equation:

\[ y = 0.237x + 1.907 \]  \hspace{1cm}  \text{Eqn. 1}

From Figure 3, \( y = (\log k) \) and \( x = \text{foc} \) \hspace{1cm}  \text{Eqn. 2}

Figure 3 is an exponential curve converted to a linear one using the logarithm as follows:

The exponential function is, \( k = A r^{\text{foc}} \) \hspace{1cm}  \text{Eqn. 3}

The solution for eqn. 3 is found as,

\[ \log(k) = \log(A) + \log(r^{\text{foc}}) \] \hspace{1cm}  \text{Eqn. 4}

The properties of logarithm give:

\[ \log(k) = \log(A) + \log(r) \] \hspace{1cm}  \text{Eqn. 5}

\[ \log(k) = \log(A) + \log(r^{\text{foc}}) \] \hspace{1cm}  \text{Eqn. 6}

From the regression line \( y = mx + b \), eqn. 5 expresses log (k) as a linear function of foc, with

\[ \text{Slope} = m = \log(r) \] \hspace{1cm}  \text{Eqn. 7}

\[ \text{Intercept} = b = \log(A). \] \hspace{1cm}  \text{Eqn. 8}

So r and A are obtained by

\[ r = 10^m \] \hspace{1cm}  \text{Eqn. 9}

and, \( A = 10^b \) \hspace{1cm}  \text{Eqn. 10}

From equation 1,

\[ m = 0.237 \text{ and } A = 1.907 \] \hspace{1cm}  \text{Eqn. 11}

\[ r = 10^{0.237} = 1.726 \text{ and } A = 10^{1.907} = 80.724. \hspace{1cm} \text{Eqn. 12} \]

This gives the coefficient of permeability model from eqn. 3 as,

\[ k = 80.724(1.726)^{\text{foc}} \] \hspace{1cm}  \text{Eqn. 13}

Where \( k \) is the coefficient of permeability of the soil (in \( \mu m s^{-1} \)) and foc the fraction of organic carbon in soil.

4. DISCUSSION

The effective size of soils around Lake Naivasha ranged between 0.095 to 0.29 mm. The coefficient of permeability of the soil calculated from the effective size ranged between 90.25 and 841 \( \mu ms^{-1} \) (Table 1). This range of permeability shows the soils in the study area had medium permeability [8]. This degree of permeability allows some amount of pesticide transport in to the aquifer therefore contaminating groundwater.

The organic matter (OM) of the soils around Lake Naivasha was determined to be between 1.823 and 4.875 percent at 15-30 cm soil depth (Table 1). The higher values of organic matter were found in small scale farms in the Northern show of the Lake where, farmers used compost (organic amendments). Addition of organic matter increases the adsorption of pesticides and decreases their subsequent mobility in the soil profile [15-17]. In a study by [18], the use of compost (organic amendment) drastically reduced the mobility of pesticides in soils with low organic matter content. Deubert [19] reported that as low as 1.0–1.5% of organic matter in soil reduced pesticide leaching. The use of organic fertilizers should therefore be encouraged. The organic carbon (foc) of the soils ranged between 1.06 and 2.83 percent. The lower value of 1.83% organic matter and 1.06% organic carbon is comparable to the value of 2% OM and 1.16% foc used by US EPA in determining the organic carbon based partition coefficient of a pesticide in soil [20].

The coefficient of permeability model was determined as,

\[ k = 80.724(1.726)^{\text{foc}} \] \hspace{1cm}  \text{Eqn. 13}

Where \( k \) is the coefficient of permeability of the soil (in \( \mu m s^{-1} \)) and foc the fraction of organic carbon in soil (Figure 3).

This relationship shows that an increase in organic carbon (≥ 58% organic matter [12] increased the permeability of the soil. Organic matter percentage influences water-
holding capacity. As the percentage increases, the water-holding capacity increases because of the affinity organic matter has for water [21]. The use of organic manure therefore, increases the organic carbon of the soil, which improve the flow of water in the soil because of its affinity for water. A study by Vaeezi [22] showed that coarse sand, organic matter and lime contrary to silt positively affected soil permeability and consequently reduced run off. It has also been shown that permeability is favorably affected by organic matter [23]. Organic matter causes the synthesis of complex organic compounds that bind soil particles into structural units called aggregates. These aggregates help to maintain a loose, open, granular condition that allows water to enter and percolate downward through the soil.

Improved flow of water in soil is important in agriculture as it reduces soil’s water logging which ensures healthy crop plants. Even though the increase in soil water flow could mean transport of pesticides into groundwater, the organic matter introduced into the soil, adsorb the pesticide and therefore, reduce the amount of the chemical leaching into groundwater. Equation 13 which had a coefficient of regression of $R^2 = 0.298$ showed that the use of organic matter increased water infiltration into soil by about 30%, thereby recharging the aquifer while at the same time reducing pesticide transport into groundwater.

5. CONCLUSIONS

Soil tests for the coefficient of permeability showed the soils along the show of Lake Naivasha had medium permeability. The regression analysis on the coefficient of permeability ($k$) and organic carbon ($f_{oc}$) showed organic carbon positively affected soil permeability and had the relationship: $k = 80.724(1.726)^{f_{oc}}$ ($R^2 = 0.298$).

This relationship shows that organic carbon improved the flow of water in the soil. High organic carbon content in the soil increase the concentration of the pesticide in the soil particles ensuring less pesticide is available to leach into groundwater. It was therefore concluded in this study that the use of organic carbon increased soil permeability by 30%, thereby recharging the aquifer while at the same time reducing pesticide transport into groundwater. The use of compost (organic amendments) should therefore be increased in place of inorganic fertilizers.

REFERENCES


