

Research Article

The Contribution of Soil Permeability to Pesticide Aquifer Vulnerability Along the Shores of Lake Naivasha, Kenya

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Abstract

Lake Naivasha has a farming system that is well expanded in the riparian zone. Bordering the lake are some of the biggest flower farms in the world, making it the most important area for cut flowers in Kenya. Agricultural products, especially the ones produced for export have to match a high-quality standard. To achieve these quality standards, it is necessary to have a good program of weed control and pest management. The use of pesticides is one of the most used tools to achieve it. Increasing use of pesticides threatens the quality of surface and ground waters by contamination. Various approaches have been used or proposed for assessing groundwater vulnerability occurring in the vadose zone and groundwater regime, to models that weight critical factors affecting vulnerability through either statistical methods or expert judgment. Soil permeability measures 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. Therefore, the soil's permeability should be considered when applying pesticides. This study used the permeability of soils in the study area to calculate the value of aquifer vulnerability from pesticides used along the shores of Lake Naivasha, Kenya. Soil samples were collected from 19 field sites around Lake Naivasha, and their permeabilities determined, using empirical methods based on grain size distribution. The results showed that all the 19 sites where soils were collected for permeability determination had medium permeability (90 to 841 μms^{-1}) and thus only one zone of low vulnerability was identified throughout the aquifer around Lake Naivasha. The results therefore, resulted in an aquifer vulnerability of 6.78% being determined along the shores of Lake Naivasha, considering pesticide transport to groundwater determined from soil permeability alone. It was concluded that this aquifer vulnerability arising from pesticide mobility was low and groundwater in the area therefore, not at risk of pesticide contamination based on soil permeability alone. Further studies to determine a combined aquifer vulnerability index taking into consideration other contributors is recommended in order to make a decision on the safety of groundwater for domestic use in the study area.

Keywords

Pesticide, Soil Permeability, Aquifer Vulnerability, Contamination, Lake Naivasha, Kenya

1. Introduction

Agricultural products, especially the ones produced for export have to match a high quality standard [1, 2]. To achieve

these quality standards, it is necessary to have a good program of weed control and pest management. The use of pesticides is

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one of the most used tools to achieve it [3-5]. But improper pesticide application results in high toxicity levels causing environmental risk [5, 6].

Pesticide and soil properties influence the mobility (leachability) of pesticides into groundwater [7, 8]. Increasing use of pesticides threatens the quality of surface and ground waters by contamination. Once groundwater is contaminated, analyzing the problem and providing alternative water supplies can be quite expensive [9]. In 1987, U.S. Environmental Protection Agency documented 19 pesticides occurring in groundwater from 24 states attributed to agricultural practices [10]. A study in the same area identified 141 types of pesticides in WHO class I-IV were being used around Lake Naivasha [11].

Most groundwater comes from infiltrated precipitation. Groundwater contamination occurs when water comes in contact with naturally occurring contaminants or with contaminants introduced into the environment by anthropogenic activities [12]. Contaminants associated with human activity most commonly include bacteria, petroleum products, natural and synthetic organic compounds, fertilizer, pesticides and metals [13].

Ecological risk assessment evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors. In general terms, risk is defined as a combination of hazard and vulnerability [14, 15]. Vulnerability indicates the degree of intrinsic weakness of the investigated natural system [16]. In the context of groundwater contamination, 'vulnerability' represents the degree of intrinsic weakness of the aquifer analyzed [17].

Various approaches have been used or proposed for assessing groundwater vulnerability [18-20]. They range from sophisticated models of the physical, chemical, and biological processes occurring in the vadose zone and groundwater regime, to models that weight critical factors affecting vulnerability through either statistical methods or expert judgment. The models are used either under field conditions or in large-scale areas in order to evaluate the fate of pollutants at different levels of sophistication, in relation to processes and dimension. Parametric models considering the intrinsic vulnerability of an aquifer take into account hydrogeological and hydrodynamic characteristics of the subsoil [19, 21]. All parametric models are based on the same principle, i.e. different parameters describing a phenomenon (e.g. groundwater depth, water infiltration, type of soil coverage, hydrology of the aquifer, conductivity, slope etc.) are divided into classes and weighted according to their importance [22, 23].

This study endeavored to estimate aquifer vulnerability using pesticide mobility to groundwater determined from soil permeability. 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 permeability of the soil therefore, ought to be considered when applying pesticide. The coefficient of permeability (k) of a cohesionless soil is

approximately proportional to the square of an effective size (d_{10} in mm) of soil (ie. $k=d_{10}^2 \times 10^4 \mu\text{ms}^{-1}$) [24]. 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}), [25].

2. Materials and Methods

Lake Naivasha is located in Naivasha Subcounty, Nakuru County in the Eastern Rift Valley, about 100km Northwest of Nairobi, Kenya's capital. It is bounded by latitude $0^\circ 49' \text{ S}$ and $0^\circ 52' \text{ S}$ and longitude $36^\circ 18' \text{ E}$ and $36^\circ 21' \text{ E}$. The study area is located in the central portion of the Rift floor at a mean altitude of 1885 m above mean sea level.

Nineteen (19) soil samples for soil properties analysis were conveniently sampled from farms along the shore of Lake Naivasha (Figure 1).

The soils were sampled at a depth of 15-30 cm to eliminate plant roots. The sieve tests were done at the School of Environmental Studies, analytical laboratory, Moi University. 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 $k = d_{10}^2 \times 10^4 \mu\text{ms}^{-1}$ [25, 26], where k is the permeability of the soil and d_{10} the effective size of soil in millimeters.

The sieving test was carried out using the American Society for Testing materials method (ASTM D 422-63) [27] 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); brush; mechanical sieve vibrator (shaker); and 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 (for 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. A known weight of soil for each sample 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 pan 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 for the 19 soil samples were then prepared and the effective size (d_{10}) determined.

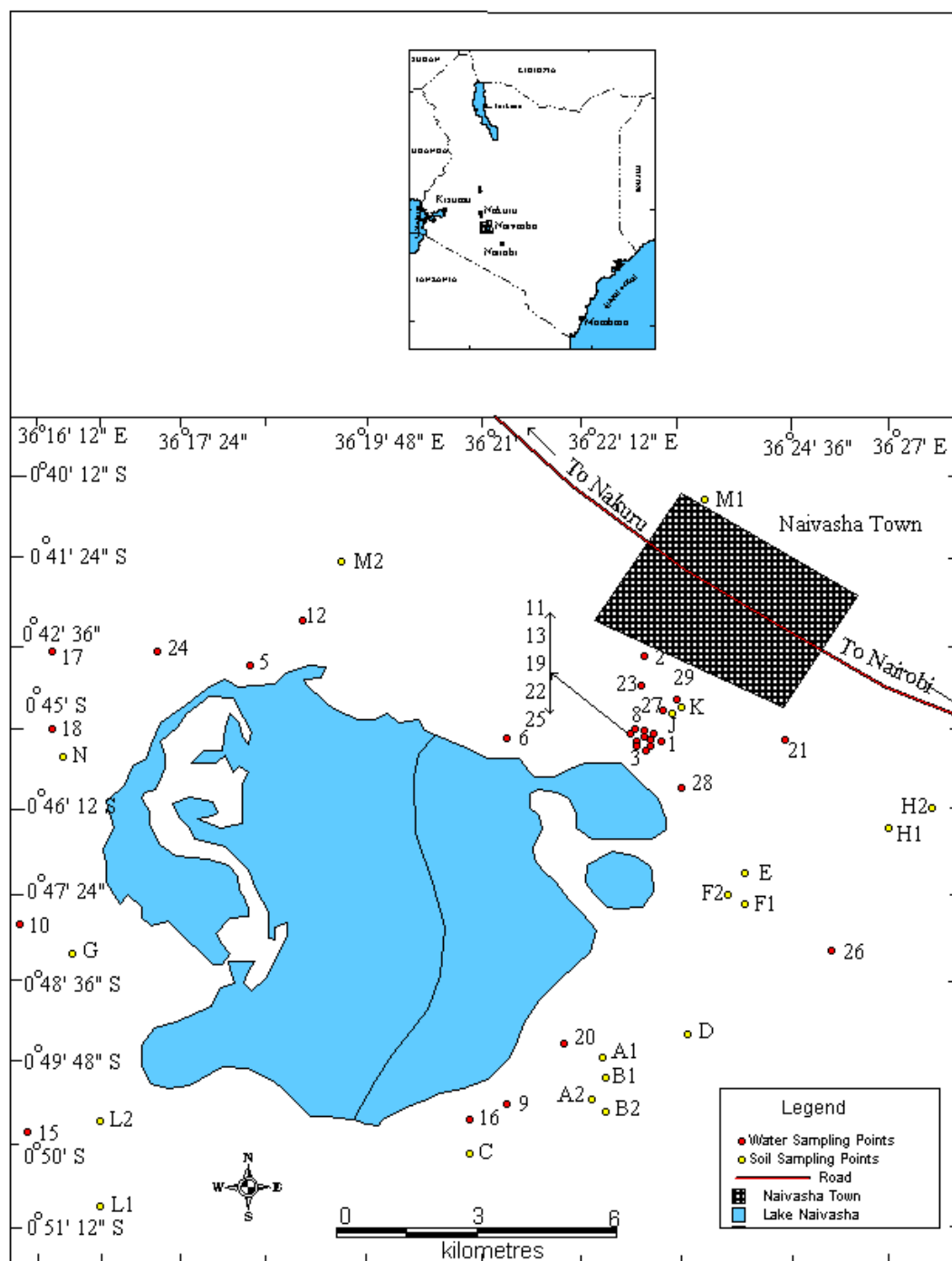


Figure 1. Soil sampling sites.

The vulnerability of the aquifer to pesticide contamination was determined using soil permeability as a measure of pesticides applied on the soil surface to leach into groundwater. The degree of permeability of soils in the study area were weighted according to their importance in contributing to pesticide mobility into groundwater [22]. Table 1 below shows the weights assigned to the coefficients of soil permeability based on the classification of the degrees of permeability [24].

Table 1. Classification of degrees of permeability and their weights.

Degree of Permeability	Permeability (k in μms^{-1})	Weight
High	Over 1000	1.0
Medium	10 - 1000	0.75

Degree of Permeability	Permeability (k in μms^{-1})	Weight
Low	0.1 - 10	0.5
Very low	0.001 – 0.1	0.25
Practically impermeable	Below 0.001	0

3. Results

Figure 2 below shows the soil particle size distribution curve for soil sample F2 determined from one of the 19 sites shown in Figure 1. The figure also demonstrates how the effective size (d_{10}) of sample F2 was determined as 0.15 mm, and used to calculate the soil permeability ($k = 225 \mu\text{ms}^{-1}$).

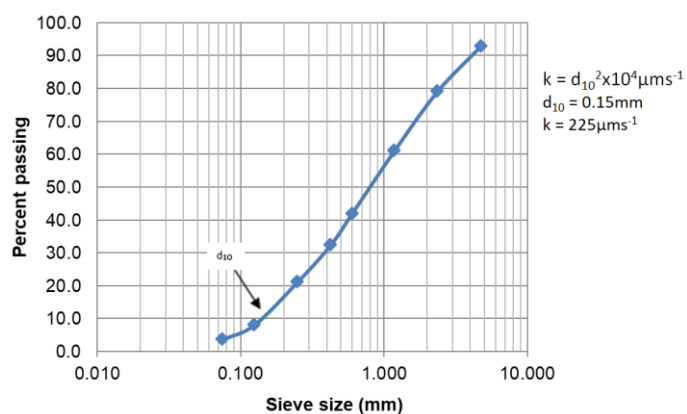


Figure 2. Determination of the effective size (d_{10}) using particle size distribution curve for sample F2.

Table 2 below shows the soil's effective size (d_{10}) and the computed soil permeability for the 19 samples collected at sites shown in Figure 1.

Table 2. The effective size, permeability and permeability weights of soil samples.

S. NO.	Sample	Effective grain size (d_{10} in mm)	Permeability (k) k in μms^{-1}	Permeability Weights (W)
1	A1	0.095	90.25	0.75
2	A2	0.13	169	0.78
3	B1	0.15	225	0.80
4	B2	0.13	169	0.78
5	C	0.1	100	0.75
6	D	0.16	256	0.80
7	E	0.12	144	0.78
8	F1	0.16	256	0.80
9	F2	0.15	225	0.80
10	G	0.25	625	0.88
11	H1	0.16	256	0.80
12	H2	0.13	169	0.78
13	J	0.1	100	0.75
14	K	0.13	169	0.78
15	L1	0.12	144	0.78

S. NO.	Sample	Effective grain size (d_{10} in mm)	Permeability (k) k in μms^{-1}	Permeability Weights (W)
16	L2	0.15	225	0.80
17	M1	0.16	256	0.80
18	M2	0.29	841	0.95
19	N	0.13	169	0.78
Mean Weight, W				0.80

Aquifer vulnerability (V_{aq}) is a function (f) of soil permeability and may be written as:

$$\text{Aquifer vulnerability, } V_{aq} = f(P) \quad (1)$$

Where, P is the soil permeability,

$$\text{Aquifer vulnerability is proportional } (\propto) \text{ soil permeability} \quad (2)$$

From equation (2), aquifer vulnerability is proportional to soil permeability i.e.:

$$V_{aq} \propto P \quad (3)$$

Thus

$$V_{aq} = cP \quad (4)$$

Where, V_{aq} is the aquifer vulnerability considering soil's permeability, and c is a constant associated with soil's degree of permeability.

In order to determine the value of c the logarithm of the weights assigned to the coefficients of permeability was plotted against the logarithm of the coefficients of permeability (Figure 3).

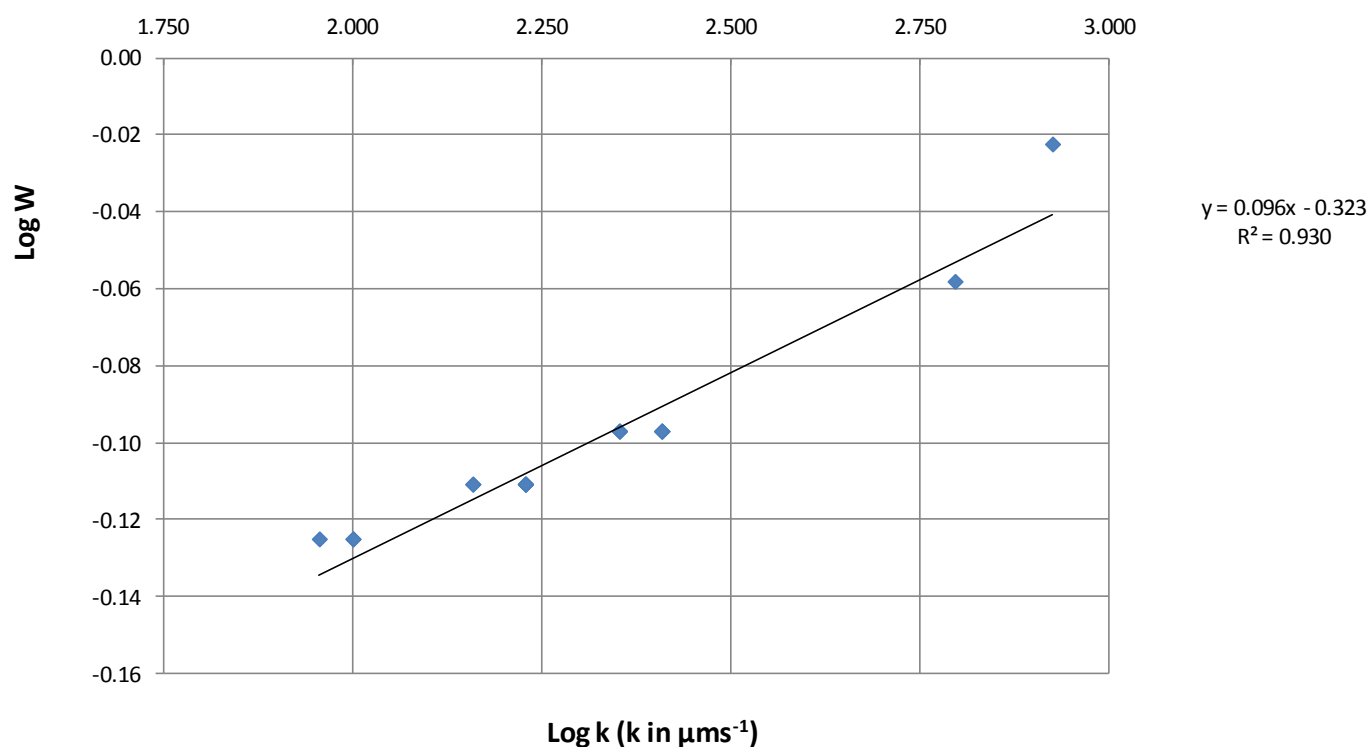


Figure 3. Plot of Log w versus Log k.

Equation (5) below describes the relationship shown by Figure 2,

$$\log W = \log(bP^c) \quad (5)$$

But w stands for the vulnerability (v) of the aquifer assigned to the coefficients of permeability. Equation (5) may therefore be written as

$$\log v = \log(bP^c)$$

or

$$\log v = c * \log P + \log b \quad (6)$$

Where $\log b$ is the intercept and c the slope.

From Figure 3,

$$y = 0.096x - 0.323$$

$$c = 0.096$$

From equation (4), $V_{aqp} = cP$. A mean value of permeability weights was determined from Table 2 as $P = 0.80$.

$$V_{aqp} = 0.096 \times 0.80 \quad (7)$$

$$V_{aqp} = 0.0768 \quad (8)$$

4. Discussion

The aquifer vulnerability around Lake Naivasha from pesticide transport to groundwater determined from soil permeability was calculated to be 0.768 (or 6.78%). This means that the aquifer was 6.78% vulnerable to groundwater contamination by pesticides considering pesticide mobility to groundwater determined from soil permeability alone. Olumuyiwa et al [28], using aquifer vulnerability index model identified three vulnerability zones classified as low, moderate and high. The 19 sites where soils were collected for permeability determination around Lake Naivasha in this study, showed all the sites had medium permeability and therefore only one zone of low vulnerability identified throughout the aquifer around Lake Naivasha. A study by Njoroge [29] in the same area showed aquifer vulnerability from pesticide management practices was high at 45.5% and therefore, exposed groundwater to the risk of contamination by pesticides. A study by Deepesh et al [30] emphasized the need for more studies devoted to vulnerability assessment for source protection. Another study by Giuliano [31] has evaluated other approaches that have been used to assess groundwater vulnerability to pesticides. This study has isolated soil permeability and assessed its contribution to aquifer vulnerability. A lower contribution and therefore, lower risk of groundwater contamination is reported. Determination of a combined aquifer vulnerability index taking into consideration other contributors is recommended in

order to make a decision on the safety of groundwater for domestic use in the study area.

5. Conclusions

The aquifer vulnerability from pesticide mobility to groundwater around Lake Naivasha was determined to be 6.78%. This aquifer vulnerability index from pesticide mobility was low and, groundwater in the area therefore, not at risk of contamination by pesticides based on soil permeability alone. A study to determine a combined aquifer vulnerability index taking into consideration other contributors should be carried out in order to make a decision on the safety of groundwater around Lake Naivasha.

Abbreviations

U.S. EPA	United States Environmental Protection Agency
WHO	World Health Organization
d10	Effective Size of Soil
k	Permeability
μms^{-1}	Units of Permeability in Micrometers per Second
ASTM	American Society for Testing and Materials
Vaq	Aquifer Vulnerability

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Martinez, M. G. and N. Poole, The development of private fresh produce safety standards: implications for developing Mediterranean exporting countries. *Food Policy*, 2004. 29(3): p. 229-255.
- [2] Asfaw, S., D. Mithöfer, and H. Waibel, What impact are EU supermarket standards having on developing countries' export of high-value horticultural products? Evidence from Kenya. *Journal of International Food & Agribusiness Marketing*, 2010. 22(3-4): p. 252-276.
- [3] Chen, C., J. Yang, and C. Findlay, Measuring the effect of food safety standards on China's agricultural exports. *Review of World Economics*, 2008. 144: p. 83-106.
- [4] Wilson, J. S. and T. Otsuki, To spray or not to spray: pesticides, banana exports, and food safety. *Food policy*, 2004. 29(2): p. 131-146.
- [5] Khan, M. J., M. S. Zia, and M. Qasim, Use of pesticides and their role in environmental pollution. *World Acad Sci Eng Technol*, 2010. 72: p. 122-128.

- [6] Ma, J., et al., Sources of water pollution and evolution of water quality in the Wuwei basin of Shiyang river, Northwest China. *Journal of environmental management*, 2009. 90(2): p. 1168-1177. <https://doi.org/10.1016/j.jenvman.2008.05.007>
- [7] Arias-Estévez, M., et al., The mobility and degradation of pesticides in soils and the pollution of groundwater resources. *Agriculture, ecosystems & environment*, 2008. 123(4): p. 247-260.
- [8] Pérez-Lucas, G., et al., Environmental risk of groundwater pollution by pesticide leaching through the soil profile. *Pesticides-use and misuse and their impact in the environment*, 2019. 17: p. 1-28. <https://doi.org/10.5772/intechopen.82418>
- [9] Khadam, I. M. and J. J. Kaluarachchi, Multi-criteria decision analysis with probabilistic risk assessment for the management of contaminated ground water. *Environmental Impact Assessment Review*, 2003. 23(6): p. 683-721. [https://doi.org/10.1016/S0195-9255\(03\)00117-3](https://doi.org/10.1016/S0195-9255(03)00117-3)
- [10] Agency, U. E. P., *Agricultural chemicals in ground water: proposed pesticide strategy*. 1987.
- [11] Mburu, N. S., O. Osano, and M. T. Mutuku, IPM Ameliorates Risks Of Groundwater Pesticide Contamination In Lake Naivasha Basin, Kenya. *International Journal of Science Technology and Management*, Vol.4, Issue.1, August 2015. Pp 253-258. ISSN:2394-1537
- [12] Babiker, I. S., et al., Assessment of groundwater contamination by nitrate leaching from intensive vegetable cultivation using geographical information system. *Environment International*, 2004. 29(8): p. 1009-1017. [https://doi.org/10.1016/S0160-4120\(03\)00095-3](https://doi.org/10.1016/S0160-4120(03)00095-3)
- [13] Aromolaran, O., et al., Assessment of groundwater pollution near Aba-Eku municipal solid waste dumpsite. *Environmental monitoring and assessment*, 2019. 191: p. 1-25.
- [14] Varnes, D. J., *Landslide hazard zonation: a review of principles and practice*. 1984.
- [15] Dewan, A. and A. M. Dewan, *Hazards, risk, and vulnerability*. 2013: Springer.
- [16] Birkmann, J., Risk and vulnerability indicators at different scales: Applicability, usefulness and policy implications. *Environmental hazards*, 2007. 7(1): p. 20-31.
- [17] Civita, M. and M. De Maio, Assessing and mapping groundwater vulnerability to contamination: the Italian combined approach. *Geofísica internacional*, 2004. 43(4): p. 513-532.
- [18] Stempvoort, D. V., L. Ewert, and L. Wassenaar, Aquifer vulnerability index: a GIS-compatible method for groundwater vulnerability mapping. *Canadian Water Resources Journal*, 1993. 18(1): p. 25-37.
- [19] Uricchio, V. F., R. Giordano, and N. Lopez, A fuzzy knowledge-based decision support system for groundwater pollution risk evaluation. *Journal of environmental management*, 2004. 73(3): p. 189-197.
- [20] Ouedraogo, I., Mapping groundwater vulnerability at the pan-African scale. *Université Catholique de Louvain, Ottignies-Louvain-la-Neuve, Belgium*, 2017.
- [21] Kapelj, S., J. Loborec, and J. Kapelj, Assessment of aquifer intrinsic vulnerability by the SINTACS method. *Geologia Croatica*, 2013. 66(2): p. 119-128. <https://doi.org/10.4154/GC.2013.09>
- [22] Zaghi, C. and S. Lucci, Identification of vulnerable areas to pesticides. *Methodological aspects. QUADERNI-ISTITUTO DI RICERCA SULLE ACQUE*, 2000: p. 265-282.
- [23] Ganapathi, H. and P. Vasudevan, Assessment of groundwater vulnerability to pollution in Chennai metropolis using DRASTIC and GIS. *The main sponsor of this issue: NABARD*, 2021. 2(1).
- [24] Jackson, N. and R. K. Dhir, *Coarser-and Finer-grained Soils*, in *Civil Engineering Materials*. 1996, Springer. p. 367-372.
- [25] Mir, B. A., *Manual of geotechnical laboratory soil testing*. 2021: CRC Press.
- [26] Lambe, T. W., *Soil testing for Engineers*. 5 ed, ed. H. S. Poplai. 1993, New Delhi, India: John Wiley Eastern.
- [27] Standard, A., D422-63 (2007) Standard test method for particle-size analysis of soils. *ASTM International*, West Conshohocken. doi, 2007. 10: p. 1520.
- [28] Falowo, O. O., Y. Akindureni, and O. Ojo, Groundwater assessment and its intrinsic vulnerability studies using aquifer vulnerability index and GOD methods. *International Journal of Energy and Environmental Science*, 2017. 2(5): p. 103-116. <https://doi.org/10.11648/j.ijees.20170205.13>
- [29] Njoroge, S. M., The Contribution of Pesticide Management Practices to Aquifer Vulnerability around Lake Naivasha, Kenya. *Journal of Environment*, 2023. 3(1): p. 22-30.
- [30] Machiwal, D., et al., Assessment and mapping of groundwater vulnerability to pollution: Current status and challenges. *Earth-Science Reviews*, 2018. 185: p. 901-927.
- [31] Giuliano, G., Groundwater vulnerability to pesticides: an overview of approaches and methods of evaluation. *Pesticide risk in groundwater*, 2019: p. 101-118.