Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol.14, No.4, 2024

Assessment of Groundwater Vulnerability to Pollution Using a Modified DRASTIC Model in the Stony Athi Sub-catchment, Kajiado County, Kenya

Morris Wahome Mathenge[1*], Gladys Muthochi Gathuru [2] and Esther Chepkoech Kitur [3]
Department of Environmental Sciences and Education, Kenyatta University, P.O. Box 43844 - 00100, Nairobi, Kenya
* E-mail of corresponding author: mathenge.morris@ku.ac.ke

Abstract

Groundwater is increasingly becoming vulnerable to pollution in response to an increase in anthropogenic activities and changes in climatic trends. Anthropogenic activities cause land use and land cover changes, which may result to considerable threats to groundwater quality. Climate change has the potential to affect groundwater quality through reduced recharge, increased evapotranspiration and abstraction rates. Assessment of groundwater vulnerability to pollution is therefore necessary so as to delineate zones that are more susceptible to degradation for appropriate planning and management. The objective of this study was to assess the groundwater vulnerability to pollution in the semi-arid Stony Athi sub-catchment of Kajiado County, Kenya. DRASTIC, an overlay and index model, was used to prepare a vulnerability index map on a Geographic Information System platform. The DRASTIC model determines the vulnerability index by taking into account seven parameters that influence water transfer from the surface to the groundwater zone, namely, depth to water, net recharge, aquifer media, soil media, aquifer transmissivity, impact of vadose zone and hydraulic conductivity. The model was modified to incorporate a land use and land cover parameter. The Modified DRASTIC Vulnerability Index was calculated as the sum of the product of ratings and weights assigned to each parameter on a scale of 1 to 10 and 1 to 5, respectively. Groundwater vulnerability to pollution was categorized based on the United States Environment Protection Agency classification of low, moderate, high and very high vulnerability. Results indicated that 4% of the study area can be classified as having a high vulnerability, 9% moderate vulnerability while 87% has a low vulnerability. Groundwater nitrate concentration measured in selected boreholes within the study area indicated a positive correlation with the calculated vulnerability index.

Keywords: Groundwater pollution vulnerability; DRASTIC; Geographic Information System; Stony Athi sub-catchment

DOI: 10.7176/JEES/14-4-05

Publication date: June 30th 2024

1. Introduction

Globally, groundwater is increasingly becoming vulnerable to pollution in response to an increase in anthropogenic activities and changes in climatic trends. Anthropogenic activities cause land use and land cover changes, which may result to considerable threats to groundwater quality. Climate change has the potential to have an impact on groundwater quality through reduced recharge, increased evapotranspiration and abstraction rates. Assessment of groundwater vulnerability to pollution is therefore necessary so as to delineate zones that are more susceptible to degradation for appropriate planning and management.

In Kenya, knowledge of groundwater vulnerability to pollution is still highly fragmented. There is a gap in information on the scale, temporal and spatial distribution of groundwater pollution vulnerability across much of the country. To reduce this gap, the present study was conducted in the semi-arid Stony Athi sub-catchment of Kajiado County, Kenya, with the objective of assessing the spatial distribution of groundwater vulnerability to pollution in an attempt to delineate pollution-prone zones using the DRASTIC model. This model has been shown to help better characterize groundwater vulnerability and is applicable in a variety of geographical areas with different environments.

The Stony Athi sub-catchment has experienced a demographic shift from rural pastoral communities to urban populations mainly due to changes in sedentary lifestyles of the local inhabitants (Said et al., 2016). Urbanization has also been occasioned by migration from other parts of the country due to availability of relatively cheap land for settlement and employment opportunities (Morara *et al*., 2014, Said *et al*., 2016). Demographic pressure and urbanization has therefore transformed the predominantly rangeland landscape into agricultural land, urban settlements, commercial enterprises and industries in the last three decades (Mathenge *et al*., 2019). Economic activities of pastoralism and livestock herding are rapidly changing to agriculture, real estate and industry. Such changes have the potential of affecting groundwater quantity and quality and therefore groundwater protection is a crucial challenge to ensuring access to sustainable potable water.

2. Literature Review

Groundwater is an important source of water for human use due to its capacity to buffer short-term climatic variability; comparatively good quality; and affordability of infrastructure for its abstraction, compared to surface water (Wang *et al*., 2010). Groundwater is the major water source in the semi-arid and arid areas and is often considered a reliable and seemingly unlimited resource (Salahat *et al*., 2014). However, it is under threat due to inappropriate use resulting to groundwater overdraft and degradation through pollution (Salahat *et al*., 2014). Groundwater replenishment is mostly facilitated by rainfall through the process of recharge, through which pollutants may be introduced into the sub-surface. Pollution problems therefore arise due to the hydraulic continuity between surface water and groundwater systems.

Groundwater pollution vulnerability is the tendency or likelihood of pollutants to reach the groundwater system after introduction at the surface (Machiwal *et al*., 2018) and is an important element for land use planning and groundwater resource management (Ewusi *et al*., 2016; Ghazavi & Ebrahimi, 2015; Oroji, 2018). Different techniques and methodologies to estimate groundwater pollution vulnerability have been developed (Gupta, 2014; Maria, 2018: Rendilicha *et al*., 2018). These methods include process-based models that are based on analytical or numerical solutions representing coupled processes that govern pollutant transport (Padilla *et al*., 2017; Asada *et al*., 2017); statistical or empirical methods based on the probability theory (Zhang *et al*., 2020); and overlay and index methods that are GIS-based qualitative methods based on subjective rating of parameters that govern groundwater replenishment. Overlay and index methods such as DRASTIC, GOD, SINTACS, AVI and SI constitute the most popular methods used for groundwater vulnerability assessment (Olumuyiwa *et al*., 2017).

Elsewhere, comparative studies have applied different overlay and index methodologies to evaluate groundwater vulnerability. Olumuyiwa *et al*., (2017) applied AVI and GOD approaches to assess vulnerability of a water bearing formation in Southwestern Nigeria. Oroji (2019) applied various methods, namely, DRASTIC, SINTACS, SI and GOD in the Hamadan – Bahar Plain, Iran, and the results indicated that the DRASTIC model is better than other models. Ghazavi and Ebrahimi (2015) used the DRASTIC and GOD models in Iran, and the results also indicated that the DRASTIC is better than GOD. Shrestha *et al*., (2017) evaluated three index-overlay methods, namely, DRASTIC, GOD, and SI to assess shallow groundwater vulnerability and risk to pollution in Kathmandu Valley of Nepal. Shrestha *et al*., (2017) concluded that while DRASTIC and GOD methods are comparable, the SI method was better-suited to assess the vulnerability and risk to groundwater pollution in their study area. Maria (2018) made an attempt to compare several vulnerability methods and concluded that DRASTIC has good accuracy compared to the others. The DRASTIC model was subsequently applied in this study.

The DRASTIC model was developed by the United States Environmental Protection Agency that provides a standardized evaluation for the intrinsic groundwater vulnerability (Aller *et al*., 1987; Patel *et al*., 2022). It is the most commonly used modelling technique among the overlay and index methods (Al-Abadi *et al*., 2017, Abdulrafiu *et al*., 2016, Duarte *et al*., 2019). DRASTIC is an acronym for seven hydrological and geological parameters that influence water flow from the surface to the groundwater zone namely, depth to water (D), recharge (R), aquifer type (A), soil properties (S), topography (T), impact of the vadose zone (I), and the hydraulic conductivity (C).

Each of the seven parameters is assigned a typical range and a rating (r) relative value on a scale of 1 to 10. On this scale, the higher values represent more sensitive areas for pollution. Moreover, each criterion is also assigned a weight factor (w) that ranges from 1 to 5 indicating the relative importance of each parameter. In the end, the linear equation of the total impact criterion score is the DRASTIC vulnerability index. The DRASTIC method assumes that the pollutant is sourced at the earth's surface; the pollutant is carried to the aquifer by rain water; the pollutant has the mobility of water and the size of the area under evaluation is larger than 0.4 sq. km.

3. Study Area

Stony Athi sub-catchment is bounded by latitudes 1°28' and 1°50' S and longitudes 36°40' and 37°15' E covering an area of about 1,745 km^2 (Figure 1). It spreads across three counties, namely, Kajiado County (77%), Machakos County (21%) and Makueni County (2%). The sub-catchment lies in the semi-arid Athi-Kapiti plains, which slopes gently from west to east with relief ranging from 2,082m to 1493 m above sea level with a mean of 1787 m. The sub-catchment is part of the head-waters of the Athi River, which is the second largest river in Kenya. Rainfall is bimodal with mean annual rainfall ranging between 300 to 800 mm (Morara *et al*., 2014, Amwata *et al*., 2015). The area can be divided into three geological groups namely; the Precambrian Mozambican system group, also referred to as the Basement System composed of gneisses and schists; the Tertiary volcanic rocks, mostly composed of phonolites and tuffs and the Tertiary sediments composed of agglomerates and soft tuffs (Matheson, 1966, Guth & Wood, 2013).

Figure 1: Map of Stony Athi Sub-catchment

4. Methodology

The DRASTIC model was used to evaluate the groundwater vulnerability to pollution based on various variables comprisisng of hydrogeological, physical and land use and land cover LULC) parameters. Spatial data of seven DRASTIC parameters and an additional parameter of land use and land cover (LULC) were obtained from various sources as presented in Table 1. The data sets were compiled into spread sheets using Microsoft Excel, where the ratings and weights were assigned according to the ranges described by Aller *et al*. (1987) (Table 2). The parameters were then used to derive a DRASTIC index, a dimensionless metric that represents the vulnerability of groundwater. The index was presented in form of a vulnerability map of the study area. The flow chart of the analytical process of its determination is presented in Figure 2.

Figure 2: DRASTIC Analytical Flow Chart

Table 1: Sources of DRASTIC Model Data

Parameter	**Source**
Depth to water	Water Resources Authority (WRA) records Field borehole levelling
Net recharge	Calculated using WetSpass recharge model (Mathenge *et al*., 2020)
Aquifer media	Geological map of study area (Matheson, 1966)
Soil media	Soil and agro-climatic map of Kenya (Sombroek *et al*., 1982) Harmonized world soil data (HWSD) (Karim & Saeid, 2019) Field soil sampling and laboratory tests
Topography	Shuttle Radar Topography Mission *(SRTM)*
Impact of vadose zone	Geological map of the study area (Matheson, 1966)
Hydraulic conductivity	Geological map of the study area (Matheson 1966) Physical Geology (Earle, 2019)
Land use and land cover	USGS website, Landsat-8 OLI/TIRS, path 168/61 (Mathenge *et al*., 2020)

The numerical values were imported into ArcMap 10.8 software as point attributes, then converted into shapefiles and finally as vector map layers using the inverse distance weighting interpolation tool and then classified. The layers were reclassified and used for overlay analysis in which each parameter was classified on a scale of one to ten, where one denotes the least vulnerable and ten the most vulnerable. The ratings were further scaled into weights according to their relative potential to pollution on a scale of 1 to 5; 1 being the least significant and 5 the most significant. The product of ratings and weights for all the parameters were subsequently added to obtain the DRASTIC vulnerability index (DVI) as shown in Equation (1).

$$\mathrm{DVI} = \sum_{i=1}^{i=7} (\mathrm{Wi} \times \mathrm{Ri}) \qquad (1)$$

Where, DVI = DRASTIC Vulnerability Index

Wi = weighted coefficient and

Ri = rating coefficient.

Table 2: DRASTIC Ranges, Ratings and Weights used in this Study (After Aller *et al*., 1987)

Parameter	**Range**	**Rating**	**Weight**
Depth to water (m)	0.5-1.5	10	**5**
	1.5-4.6	9	
	4.6-9.1	7	
	9.1-15.2	5	
	15.2-22.8	3	
	22.8-30.4	2	
	>30.4	1	
Recharge (net) (mm)	0-50.8	1	**4**
	50.8-101.6	3	
	101.6-177.8	6	
	177.8-254	8	
	>254	9	
Aquifer media	Weathered volcanics	4	**3**

Parameter	Range	Rating	Weight
	Weathered Metamorphic	4	
	Sediments	8	
Soil media	Sandy Loam	6	**2**
	Loam	5	
	Clay Loam	3	
	Clay	1	
Topography (% slope)	0-2	10	**1**
	2-6	9	
	6-12	5	
	12-18	3	
	>18	1	
Impact of vadose zone	Confining Layer	1	**5**
	Silt/Clay	3	
	Sand and Gravel with Silt	6	
Hydraulic Conductivity (m/day)	0.04-4.1	1	**3**
	4.1-12.3	2	
	12.3-28.7	4	

The land use land cover parameter (LULC) was added to the DRASTIC equation to incorporate the effects of land use and land cover for which the ratings and weights were assigned according to the description given by Maqsoom *et al*., (2020) as presented in Table 3. Thus, the US EPA DRASTIC formula was modified to obtain the Modified DRASTIC vulnerability index (MDVI) shown in Equation (2).

$$\mathrm{MDVI} = \sum_{i=1}^{7}(\mathrm{Wi} \times \mathrm{Ri}) + LrLw \quad \ldots\ldots(2)$$

Where, MDVI = Modified DRASTIC Vulnerability Index

Lr = rating of the LULC parameter

Lw = weight of the LULC parameter

Table 3: Ranges, Ratings and Weights for Land Use and Land Cover (After Maqsoom *et al*., 2020)

Parameter	Land use and land cover	Rating	Weight
Land use and land cover (LULC)	Built up area	7	**5**
	Agricultural land	5	
	Bare land	3	
	Grass land	2	
	Shrub land	2	
	Forested area	2	

The eight parameter index layers were overlaid using the ESRI GIS software, ArcMap 10.8. The Geoprocessing tool, weighted sum overlay in the Spatial Analyst extension in the Arc toolbox was used to obtain the overall vulnerability index map. The resulting vulnerability indices were then correlated with nitrate concentration of samples from selected boreholes within the sub-catchment to test its validity. The vulnerability classes were then categorized according to the US EPA DRASTIC Index and vulnerability categories namely, low, moderate, high and very high vulnerability (Jaseela *et al.*, 2016) as presented in Table 4.

Table 4: Groundwater Vulnerability Index and Vulnerability Class

DRASTIC Index	**Vulnerability category**
1 – 100	Low
101 – 140	Moderate
141 – 200	High
>200	Very high

5. Results and Discussion

The purpose of this study was to assess the groundwater vulnerability to pollution in the semi-arid Stony Athi sub-catchment of Kajiado County using an overlay and index model, namely DRASTIC, on a GIS (Geographic Information System) platform. The DRASTIC model incorporates seven parameters that govern water transfer from the surface to the groundwater zone, namely, depth to water, net recharge, aquifer media, soil media, aquifer transmissivity, impact of vadose zone and hydraulic conductivity. The model was modified to incorporate land use and land cover parameter as an eighth parameter. The parameters were used to generate a groundwater vulnerability index map.

5.1 Depth to Water Level (D)

Depth to water refers to the depth of groundwater rest level. It indicates the distance that a pollutant travels from the surface to the aquifer. A contaminant will take a longer time if the water level is deep, thus shallow water levels imply more vulnerability to pollution. Depth to the water level in the study area was grouped into five classes with a range of between 4.6 m to more than 30.4 m below the surface. The ratings ranged between 1 and 7 (Table 5). The depth to water rating map is shown in Figure 3.

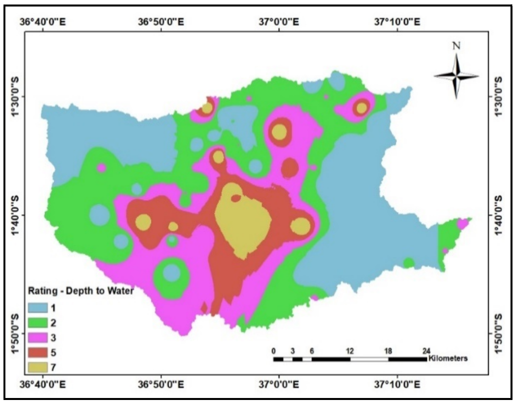

Figure 3: Depth to Water Rating Map

Table 5: Depth to Water (Weight (Dw) = 5)

Range (m)	**Rating (Dr)**	**Total Weight (Dw x Dr)**
4.6 – 9.1	7	35
9.1 – 15.2	5	25
15.2 – 22.8	3	15
22.8 – 30.4	2	10
>30.4	1	5

5.2 Net Recharge (R)

Net recharge is the quantity of water that is added to the aquifer from the surface. Recharge is the means of transport for the pollutant. Higher recharge leads to greater chances for pollutants to reach the aquifer. Groundwater recharge in the study area was assessed using the WetSpass Model (Mathenge *et al*., 2020). WetSpass is an acronym for 'Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State'. It is a GIS physically based, spatially distributed watershed model for estimation of long-term average recharge (Batelaan & De Smedt, 1997). The model characterizes the water balance in a region and is applicable in a variety of geographical areas with different environments. The Net recharge in the study area was grouped into four classes with rating values ranging between 1 and 8 (Table 6). The rating map is presented in Figure 4.

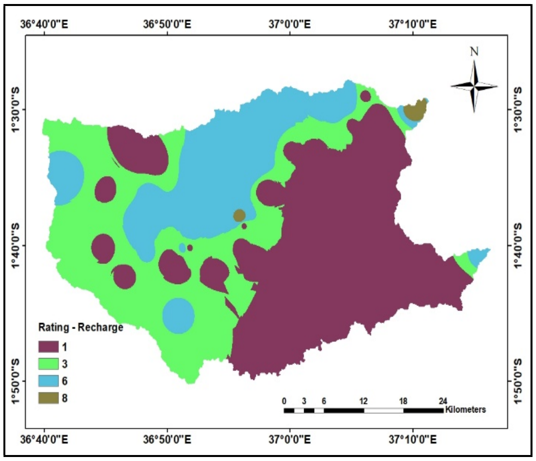

Figure 4: Net Recharge Rating Map

Table 6: Net Recharge (Weight (Rw) = 4)

Range (mm)	Rating (Rr)	Total Weight (Rw x Rr)
0 – 50.8	1	4
50.8 – 101.6	3	12
101.6 – 177.8	6	24
177.8 – 254.0	8	32

5.3 Aquifer Media (A)

Aquifer media represents the properties of the saturated zone. Coarse-textured unconsolidated and fractured consolidated aquifers have higher permeabilities and are more vulnerable. Generally, aquifers are closely linked with the three major rock systems, namely, volcanic, metamorphic and sedimentary rocks. Quartzo-feldspathic and granitoid gneisses, have the least permeability while volcanic aquifers, comprising of phonolites and tuffs show moderate permeability. The contact zones between the two rock formations, comprising of sediments have a relatively higher permeability. The rates and weights of the aquifer media were classified into the three groups (Table 7). The interpolated rating map of the aquifer media is shown in Figure 5.

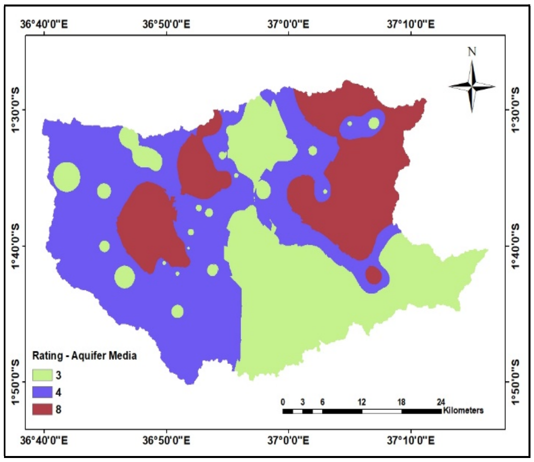

Figure 5: Aquifer Media Rating Map

Table 7: Aquifer Media (Weight (Aw) = 3)

Range	Rating (Ar)	Total Weight (Aw x Ar)
Sediments	8	24
Volcanics	4	12
Basement	3	9

5.4 Soil Media (S)

Soil controls the rate at which a pollutant can infiltrate to reach the aquifer. Coarse-textured soils have higher infiltration rates, and thus the more the vulnerability of the aquifer. Soils in the study area comprises of sandy loam, sandy clay loam, clay loam, sandy clay and clay (Table 8). The ratings were assigned as per the original DRASTIC values ranging between 1 and 6 for the different soil types. The soils were classified into four groups as shown in the rating map (Figure 6).

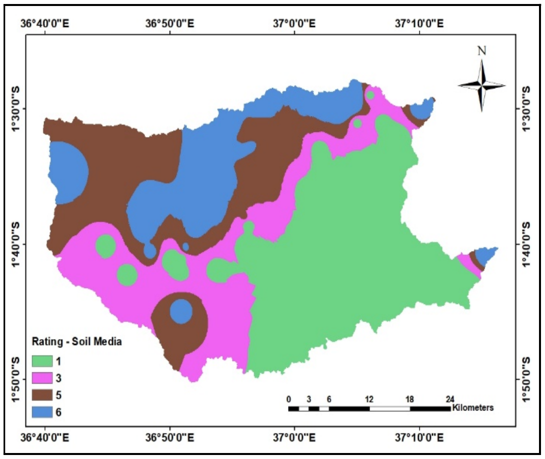

Figure 6: Soil Media Rating Map

Table 8: Soil Media (Weight (Sw) = 2)

Range	Rating (Sr)	Total Weight (Sw x Sr)
Clay	1	2
Clay loam	3	6
Loam	5	10
Sandy loam	6	12

5.5 Topography (T)

Topography reflects the slope of the surface. Slope determines the likelihood of a pollutant remaining long enough on the surface for infiltration to occur. Gentle slopes have little surface runoff and the potential for groundwater pollution is higher. Conversely, steep slopes have high runoff and the vulnerability for pollution is lower. Topography was split into four classes in the range of 0 – 2%, 2 – 6% and 6 – 12% and 12 – 18% and assigned ratings as per the original DRASTIC model ranging between 3 and 10 (Table 9). The rating map is presented in Figure 7.

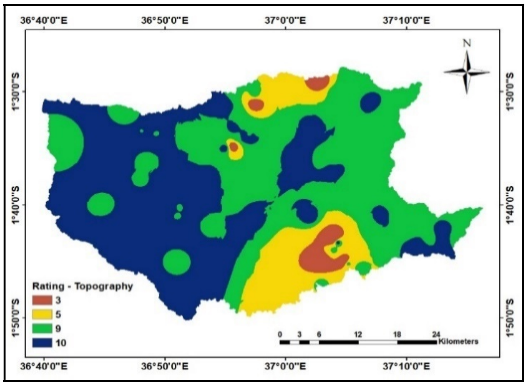

Figure 7: Topography (slope) Rating Map

Table 9: Topography (Weight (Tw) = 1)

Range (%)	Rating (Tr)	Total Weight (Tw x Tr)
0-2	10	10
2-6	9	9
6-12	5	5
12-18	3	3

5.6 Impact of Vadose Zone (I)

The vadose zone is the zone immediately above the water table that is not saturated and determines the time of travel of a pollutant to the aquifer. In this study, this zone was designated as clay in areas covered by volcanic tuff since clay is the main product of weathering of tuff. Areas covered by phonolite were designated as a confining layer, since the phonolites are not intensely weathered. Areas covered by the basement rocks were designated as sand and gravel with silt. The parameter values assigned are presented in Table 10 and Figure 8, with ratings ranging between 1 and 6.

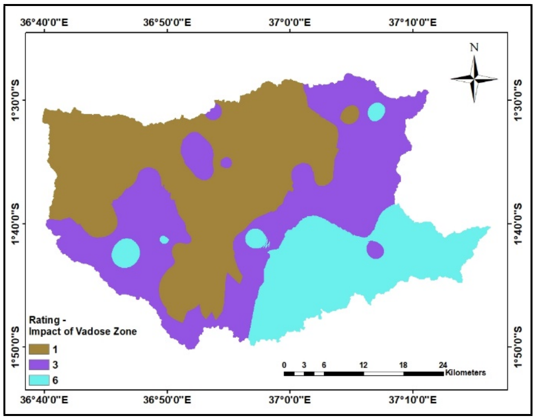

Figure 8: Impact of Vadose Zone Rating Map

Table 10: Impact of Vadose Zone (Weight (Iw) = 5)

Range	Rating (Ir)	Total Weight (Iw x Ir)
Confining layer	1	5
Clay	3	15
Sand and gravels with silt	6	30

5.7 Hydraulic Conductivity (C)

Hydraulic conductivity is the flow rate through an aquifer. The more the hydraulic conductivity, the higher the rate at which pollutants are spread, thereby increasing pollution vulnerability. Aquifer types in the study area were grouped into 3 classes, namely fractured basement, fractured volcanic rocks and sediments with values of hydraulic conductivity ranging between 0.04 and 28.7 m/day (Table 11). The spatial distribution of the hydraulic conductivity ratings is presented in Figure 9.

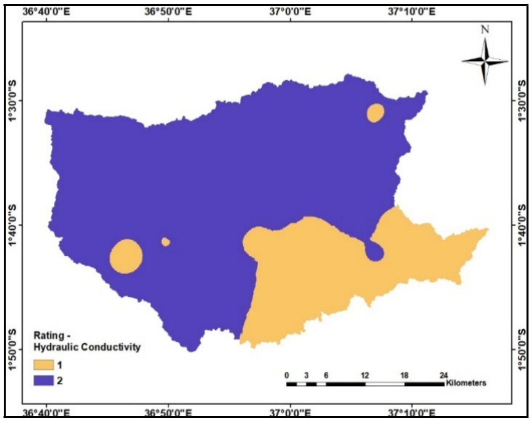

Figure 9: Hydraulic Conductivity Rating Map

Table 11: Hydraulic Conductivity (Weight (Cw) = 3)

Aquifer type	**Range (m/day)**	**Rating (Cr)**	**Total Weight (Cw x Cr)**
Fractured basement	0.04-4.1	1	3
Fractured volcanic rocks	4.1-12.3	2	6
Sediments	12.3-28.7	4	12

5.8 Land Use and Land Cover (L)

Land use is the human utility of the surface of the earth such as agricultural, residential, industrial, etc. while land cover is the assemblage of the physical features on the earth's surface such as vegetation, water, bare ground, etc. Groundwater vulnerability to pollution is influenced by different land uses and land cover. In this study, six land use and land cover (LULC) classes were established namely; built-up area, agricultural land, grassland, shrub land, forested area and bare land. The built-up category comprised of 3.4% of the total area; rangelands, comprising of grassland and shrub land dominate the landscape at 92.7% while forested area was 1.4%. Agricultural land comprised of 0.7% while bare land was 2.0% of the total area. The LULC was assigned a value of 5 and incorporated into the DRASTIC model as an additional parameter. The ratings ranged between 2 and 7 as shown in Table 12 while the spatial distribution is presented in Figure 10.

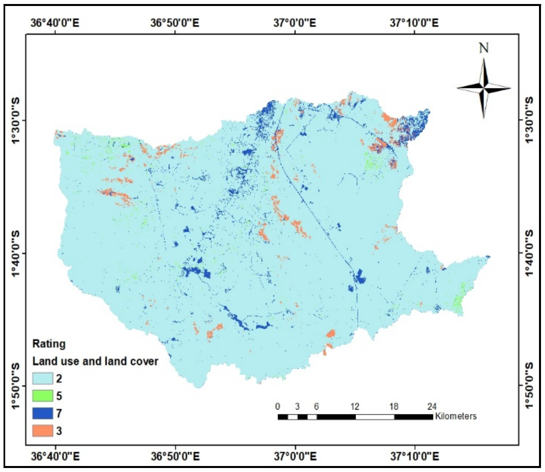

Figure 10: Land use and land cover rating map

Table 12: Land Use and Land Cover (Weight (Lw) = 5)

Range	**Rating (Lr)**	**Total Weight (Lw x Lr)**
Built up area	7	35
Agricultural land	5	25
Bare land	3	15
Grass land	2	10
Shrub land	2	10
Forested area	2	10

5.9 Modified DRASTIC Vulnerability Index

Finally, the study area was divided into three vulnerability classes ranging between a minimum value of 33 and a maximum value of 150. The vulnerability classes were categorized according to the US EPA DRASTIC Index and vulnerability categories as given in Table 13. The classes fall within low, moderate and high vulnerability as shown in the vulnerability zone map in Figure 11. The area coverage with low vulnerability was 1,433 km^2 (87%); moderate vulnerability category was 148 km^2 (9%) while areas with high vulnerability cover an area of 72 km^2 (4%).

The spatial MDVI vulnerability map shows that moderate to high vulnerability areas occur along a stretch extending from the north-east to south-west and tend to be aligned along the major roads and towns. These are the areas that have been characterized by accelerated urban development and agricultural activities. The vulnerability classes in this stretch had MDVI that ranged from 101 to 150. Low vulnerability areas having an MDVI of less than 100 occur in the north-western and much of the south-eastern regions, which are largely rangelands that have not been highly affected by human activities. The centrally located areas also have relatively lower slope terrains that are mostly covered with loam and sandy loam, which allow enhanced recharge and hence increased vulnerability to pollution.

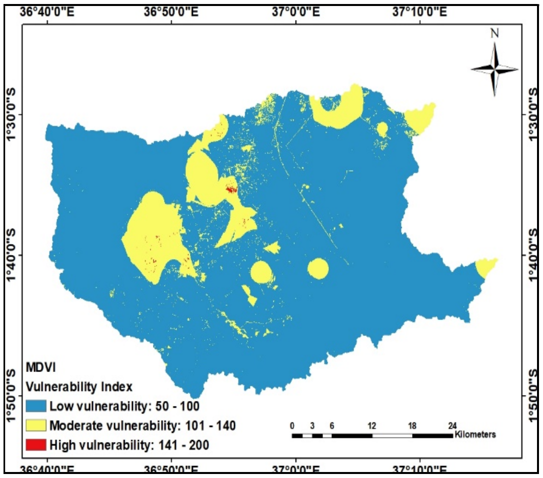

Figure 11: Modified DRASTIC Vulnerability Index Map

Table 13: Modified DRASTIC Classes

Vulnerability class	**Range**	**Area (km^2)**	**%**
Low	<100	1,433	87
Moderate	101-140	148	9
High	141-200	72	4

Results of the groundwater pollution vulnerability were verified with nitrate concentration of water samples from selected boreholes within the study area. Nitrate is a typical groundwater contaminant associated with intensive human activities. Naturally, nitrate concentration is low in groundwater and is commonly used as a vulnerability validation parameter (Moges & Dinka, 2021). Nitrate is highly soluble and mobile and as such occurs in groundwater when carried from the surface by rain water (Khosravi *et al*., 2018). Therefore, presence of nitrate in groundwater most likely indicates pollution sources from anthropological activities. Nitrate concentration was correlated with index values extracted from the modified DRASTIC Index map to verify its validity. A scatter plot of nitrate concentration against the modified vulnerability indices indicated a positive correlation at $R^2 = 0.4489$ (Figure 12).

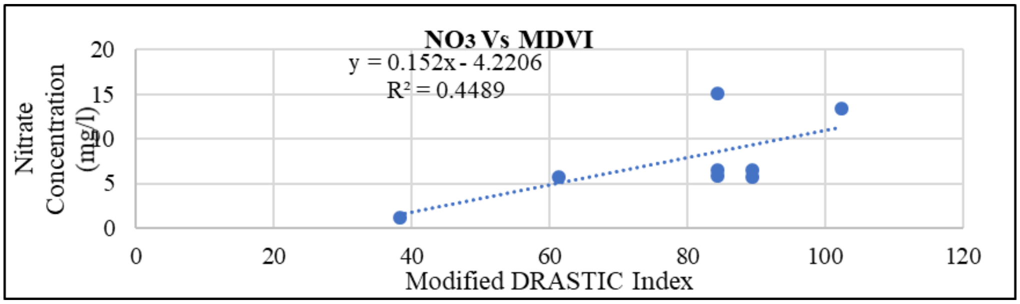

Figure 12: Correlation between nitrate concentration and MDVI

6. Conclusion

This study aimed at generating a groundwater vulnerability map of the Stony Athi sub-catchment using a GIS-based DRASTIC model. Assessment of groundwater vulnerability to pollution was found to be essential as the area falls under the arid and semi-arid lands (ASAL). This implies that the area receives low rainfall, experiences frequent drought and rivers are seasonal such that availability of clean water is acute. This forces communities to rely on water from dry river beds, water pans and unprotected shallow wells which are usually contaminated. Groundwater is the only reliable source of clean water but is under threat from pollution due to land use and land cover changes that have transformed the natural rangelands to agricultural land, urban areas and industries, which may introduce pollutants to the groundwater.

Seven parameters were used to represent the natural setting of the sub-catchment while land use and land cover was incorporated as an eighth parameter. A groundwater pollution vulnerability map was generated and classified into low, moderate and high vulnerability categories ranging between a minimum value of 33 and a maximum value of 150. Results indicated that 4% (72 km^2) of the study area can be classified as having a high vulnerability, 9% (148 km^2) has moderate vulnerability while 87% (1,433 km^2) has a low vulnerability. The vulnerability index results indicated a positive correlation with nitrate concentration in selected boreholes within the sub-catchment.

Low vulnerability areas occur in the north-western and much of the south-eastern regions of the study area, which are largely rangelands that have not been highly affected by human activities while moderate to high vulnerability areas occur along a centrally located northeast-southwest stretch. This stretch is along the major road network, human habitation as well as having relatively lower slope terrains that are mostly covered with loam and sandy loam which allows enhanced recharge.

This study concludes that DRASTIC is a useful tool for the initial step of evaluating groundwater pollution to assist in planning, managing and protecting groundwater resources. Groundwater zones that are vulnerable to anthropogenic pollution can be better classified using the model before they are committed for socio-economic activities. The responsible authorities can then use groundwater pollution vulnerability maps as an early warning sign, so that practical strategies and actions can be designed to avoid or mitigate detrimental impacts on groundwater quality for sustainable development.

Acknowledgement

The Department of Environmental Sciences and Education at Kenyatta University is greatly acknowledged for providing professional support. The corresponding author would also like to thank the National Research Fund (NRF) for providing funds to accomplish the publication of this article being part of a post-graduate research project.

References

Abdulrafiu, O. M., Adebola, A., & Oladele, O. (2016). Vulnerability assessment of groundwater pollution in the vicinity of an active dumpsite (Olusosun), Lagos, Nigeria. *Chemistry International*, *2*(4), 232-241

Al-Abadi, A.M., Al-Shamma'a, A.M., & Aljabbar, M.H. (2017). A GIS-based DRASTIC model for assessing intrinsic groundwater vulnerability in north-eastern Missan governorate, Southern Iraq. *Applied Water Science*, *7*(1), 89-101

Aller, L., Bennet, T., Lehr, J. H., Petty, R. J., & Hachet, G. (1987). DRASTIC: A standardized system for evaluating groundwater pollution potential using hydro-geological settings. EPA/600/2-87/035. U.S. Environmental Protection Agency, Ada, OK, USA

Amwata, D. A., Nyariki, D. R., & Musimba, N. R. (2015). Factors influencing pastoral and agropastoral household vulnerability to food insecurity in the Dry lands of Kenya: A case study of Kajiado and Makueni Counties. *Journal of International Development*, *28*(5), 771-787. https://doi.org/10.1002/jid.3123

Asada, K., Eguchi, S., Ikeba, M., Kato, T., Yada, S., Nakajima, Y., & Itahashi, S. (2017). Modelling nitrogen leaching from Andosols amended with different composted manures using LEACHM. *Nutrient Cycling in Agro-ecosystems*, *110*(2), 307-326. https://doi.org/10.1007/s10705-017-9899-x

Batelaan, O., & De Smedt, F. (1997). WetSpass: A flexible, GIS based distributed recharge methodology for regional groundwater modelling. In: Gehrels, H., Peters, J., Hoehn, E., Jensen, K., Leibundgut, C., Griffioen, J., Webb, B., & Zaadnoordijk, W-J (eds). Impact of human activity on groundwater dynamics, Publ. no. 269. IAHS, Wallingford, 11–17

Duarte, L., Espinha M., J., & Teodoro, A. (2019). An open source GIS-based application for the assessment of groundwater vulnerability to pollution. *Environments*, *6*(7), 86. doi.org/10.3390/environments 6070086

Earle, S. (2019). *Physical Geology – 2nd Edition*. Victoria, B.C.: BC campus. https://opentextbc.ca/physicalgeology2ed/

Ewusi, A., Asante-Annor, A., Seidu, J., & Fosu-Gyeabour, L. O. (2016). Groundwater vulnerability assessment using Drastic Index and GIS in Kumasi Metropolitan Assembly, Ghana. *Ghana Mining Journal*, *16*(1), 21 – 30

Ghazavi, R., & Ebrahimi, Z. (2015). Assessing groundwater vulnerability to contamination in an arid environment using DRASTIC and GOD models. *International Journal of Environmental Science Technology*, *12*, 2909–2918

Guth, A., & Wood, J (2013). Geology of the Kajiado Region, Kenya. *Maps of the Southern Kenya Rift*. https://doi:10.1130/2014.dmch016.s4

Gupta, N. (2014). Groundwater vulnerability assessment using DRASTIC method in Jabalpur District of Madhya Pradesh. *International Journal of Recent Technology and Engineering*, *3*(3). ISSN: 2277-3878

Jaseela, C., Prabhakar, K., & Harikumar, P. S. P. (2016). Application of GIS and DRASTIC Modeling for Evaluation of Groundwater Vulnerability near a Solid Waste Disposal Site. *International Journal of Geosciences*, *07*(04), 558–571. https://doi.org/10.4236/ijg.2016.74043

Karim, A., & Saeid, A. V. (2019). Harmonized world soil database in SWAT https://doi.org/10.1594/PANGAEA.901309

Khosravi, K., Sartaj, M., Tsai, F. T.-C., Singh, V. P., Kazakis, N., Melesse, A. M., Prakash, I., Tien Bui, D., & Pham, B. T. (2018). A comparison study of DRASTIC methods with various objective methods for groundwater vulnerability assessment. *Science of the Total Environment*, *642*, 1032–1049. https://doi.org/10.1016/j.scitotenv.2018.06.130

Machiwal, D., Jha, M. K., Singh, V. P., & Mohan, C. (2018). Assessment and mapping of groundwater vulnerability to pollution: Current status and challenges. *Earth-Science Reviews*, *185*, 901–927. https://doi.org/10.1016/j.earscirev. 2018.08.009

Maqsoom, A., Aslam, B., Khalil, U., Ghorbanzadeh, O., Ashraf, H., Faisal Tufail, R., Farooq, D., & Blaschke, T. (2020). A GIS-based DRASTIC Model and an Adjusted DRASTIC Model (DRASTICA) for Groundwater Susceptibility Assessment along the China–Pakistan Economic Corridor (CPEC) Route. *ISPRS International Journal of Geo-Information*, *9*(5), 332. https://doi.org/10.3390/ijgi9050332

Maria, R. (2018). Comparative studies of groundwater vulnerability assessment. *IOP Conference Series: Earth and Environmental Science*, *118*, 012018. https://doi.org/10.1088/1755-1315/118/1/012018

Mathenge, M. W., Gathuru, G. M., & Kitur, E. L. (2019). Spatial-temporal land use and land cover changes in the Stony Athi sub-catchment, Kenya. *IOSR Journal of Applied Geology and Geophysics, 7*(5), 43-49. https:// doi: 10.9790/0990-0705024349

Mathenge, M. W., Gathuru, G. M., & Kitur, E. L. (2020). Spatial-temporal variation of groundwater recharge from precipitation in the Stony Athi sub-catchment, Kenya. *International Journal of Environmental Sciences, 3*(1), 21-41. ISSN 2519-5549

Matheson, F.J. (1966). *Geology of the Kajiado Area; Report No. 70*. Ministry of Natural Resources and Wildlife; Geological Survey of Kenya. https://library.wur.nl/isric/fulltext/isricu_i2753_001.pdf

Moges, S.S., & Dinka M.O. (2021). Assessment of groundwater vulnerability using the DRASTIC model: A case study of Quaternary catchment A21C, Limpopo River Basin, South Africa. *Journal of Water and Land Development*, *49*(IV– VI) 35–46. doi 10.24425/jwld.2021.137094

Morara, M. K., MacOpiyo, L., & Kogi-Makau, W. (2014). Land-use, land cover change in urban pastoral interface: A case study of Kajiado County, Kenya; *Journal of Geography and Regional Planning*, *7*(9), 192-202. https://doi.org/10.5897/jgrp2014.0448

Olumuyiwa, O. F., Yemisi, A., & Olajumoke, O. (2017). Groundwater assessment and its intrinsic vulnerability studies using aquifer vulnerability index and GOD Methods. *International Journal of Energy and Environmental Science*, *2*(5), 103-116. https://doi: 10.11648/j.ijees.20170205.13

Oroji, B. (2019). Assessing groundwater vulnerability by pollution mapping in Iran: Case study Hamadan – Bahar Plain. *Geofísica Internacional, 57*(3), 161-174

Padilla, L., Winchell, M., Peranginangin, N., & Grant, S. (2017). Development of groundwater pesticide exposure modeling scenarios for vulnerable spring and winter wheat-growing areas. *Integrated Environmental Assessment and Management*, *13*(6), 992–1006. https://doi.org/10.1002/ieam.1925

Patel, P., Mehta, D. and Sharma, N. (2022) 'A review on the application of the drastic method in the assessment of groundwater vulnerability', *Water Supply*, 22(5), pp. 5190–5205. https://doi:10.2166/ws.2022.126

Rendilicha, H. G., Home, P.G., & Raude, J.M. (2018). A review of groundwater vulnerability assessment in Kenya. *Acque Sotterranee - Italian Journal of Groundwater*, *7*(2). https://doi.org/10.7343/as-2018-328

Said, M. Y., Ogutu, J. O., Kifugo, S. C., Makui, O., Robin S., Reid, R. S., & de Leeuw, J. (2016). Effects of extreme land fragmentation on wildlife and livestock population abundance and distribution. *Journal for Nature Conservation*, *34*, 151–164

Salahat, M., Al-Qinna, M., Mashal, K., & Hammouri, N. (2014). Identifying major factors controlling groundwater quality in semi-arid area using advanced statistical techniques. *Water Resources Management*, *28*(11), 3829-3841. https://doi.org/10.1007/s11269-014-0712-1

Shrestha, S., Kafle, R. and Pandey, V.P. (2017). 'Evaluation of index-overlay methods for groundwater vulnerability and risk assessment in Kathmandu Valley, Nepal', *Science of The Total Environment*, 575, pp. 779–790. https://doi.org/10.1016/j.scitotenv.2016.09.141

Sombroek, W. G., Braun, H. M. H., & Van der Pouw, B. J. A. (1982). *Exploratory soil map and agro-climatic zone map of Kenya*, 1980. Kenya Soil Survey

U.S. EPA, (1993). A review of methods for assessing aquifer sensitivity and ground water vulnerability to pesticide contamination. U.S. Environmental Protection Agency, EPA/813/R-93/002, 147 p.

Wang, L., Dochartaigh, B. O., & Macdonald, D. (2010). A literature review of recharge estimation and groundwater resource assessment in Africa. *British Geological Survey Internal Report*, IR/10/051, 31pp

Zhang, Q., Wang, L., Wang, H., Zhu, X., & Wang, L. (2020). Spatio-Temporal Variation of Groundwater Quality and Source Apportionment Using Multivariate Statistical Techniques for the Hutuo River Alluvial-Pluvial Fan, China. *International Journal of Environmental Research and Public Health*, *17*(3), 1055. https://doi.org/10.3390/ijerph17031055