Groundwater Vulnerability Assessment as a Strategy for Preventing Groundwater Pollution: A Case Study of mid River Njoro Catchment, Kenya

Halake G. Rendilicha[1*], Patrick G. Home[1] and James M. Raude[1]

Abstract- Groundwater pollution is becoming a major concern worldwide. The impact of polluted groundwater resources is three-fold: artificial water scarcity, human health problems and an impediment to economic development. Groundwater vulnerability assessment helps prevent and protect groundwater resources. Mid River Njoro catchment has experienced increased human settlements, industrial and intensive agricultural activities over the years, threatening the quality of water from wells and boreholes. This study assessed the vulnerability of groundwater resources of the Mid River Njoro catchment, Kenya, to contaminations, using a modified DRASTIC model in a GIS environment. The groundwater vulnerability map prepared using parameters such as groundwater depth, net recharge, aquifer media, topography, impact of vadose zones, hydraulic conductivity and land use types. The nitrate measurements used to validate the vulnerability map. From the results, three different vulnerability zones determined include very low (6.1%), low (87.4%) and moderate (6.5%). The validation results obtained from Pearson's correlation (0.49) and chi-square (5.01), revealed a positive relationship between the vulnerability index and nitrate concentrations. To protect groundwater system from future deterioration, a protective measure must be put in place before implementing any human activities that have the potential to cause groundwater contaminations.

Keywords: Groundwater pollution, Groundwater Vulnerability, DRASTIC, GIS, Land-use

I INTRODUCTION

A Backgound

Groundwater is an important, valuable and renewable natural resource which constitute about 95% of the freshwater supply available for mankind, making it essential to human life and economic development [1]. Over the past 50 years, the use of groundwater has significantly increased and expected to rise higher soon due to population growth and frequent droughts [1].

According to [2] about 300 million people in Africa do not have access to safe and clean drinking water, many of whom are amongst the poorest and most vulnerable in the world [3]. In Kenya, about 17 million people living in the arid and semi-arid lands (ASALs) meet their water demands from the groundwater sources [4].

Despite its importance, groundwater has not received enough attention when it comes to its protection against surface pollution, especially in Kenya [4]. The groundwater system is

vulnerable to pollution from environmental degradation and wastewater caused by anthropogenic activities. Intense agricultural activities, fertilizer applications and release of industrial and municipal wastes have resulted in groundwater contamination [5].

The biggest challenge with polluted groundwater systems is the remedial process, which is very expensive, time-consuming and requires advanced technologies which may not be available in a developing country like Kenya [6]. Moreover, contaminated groundwater can result in health risks and high cost of treatment. As such, it is salient to prevent and protect groundwater resources from surface pollution to secure a clean and continuous supply of groundwater for future generations. And groundwater vulnerability assessment to surface pollution constitutes a significant step towards attaining sustainable groundwater resources development.

The concept of groundwater vulnerability assessment arose from the needs to prevent groundwater pollution [7] and sustainably promote groundwater management, to assure a predictable supply of clean groundwater for future generations. The fundamental principle of a groundwater vulnerability assessment is to explain why some land areas easily polluted than others. The purpose of a groundwater vulnerability assessment is basically to subdivide an area according to the vulnerability index [8]. The vulnerability map provides the necessary information from which land use and related human activities could be planned and controlled as an integral part of an overall policy of groundwater protection at national, regional and catchment level [9].

Many approaches developed to assess the groundwater vulnerability to pollution, such as process-based methods [10] statistical methods [11] and overlay and index methods [6]. Overlay and index methods have been the most widely used in building the groundwater vulnerability map because of the availability of data as compared to the other two approaches [12]. The most common is the GOD system [13] the DRASTIC system [6], the AVI rating system [14], the SINTACS method [15] and EPIK method [16]. The statistical and process-based

Halake G. Rendilicha, Department of Soil, Water and Environmental Engineering, JKUAT (+254710953283; e-mail: hguyo@jkuat.ac.ke); Patrick G. Home, Department of Soil, Water and Environment Engineering; James M. Raude . Department of Soil, Water and Environment Engineering

methods are unpopular because they are constrained data, computational difficulty and expertise required to implement. This study assesses the vulnerability of the groundwater in the Mid River Njoro catchment, Kenya to human activities using a modified DRASTIC overlay and index method. The delineation of groundwater vulnerability zones is a very necessary strategy to protect and efficiently manage groundwater system within the study area. This study further reveals the importance and feasibility of vulnerability assessment in protecting and controlling groundwater pollution.

B Drastic Vulnerability Assessment Model

Drastic model [6] is one of the most widely used overlay and indexing techniques for assessing intrinsic groundwater vulnerability of an area. It was developed in the USA through a collaboration between the US Environmental Protection Agency (EPA) and the National Water Well Association (NWWA) to help environmental managers, planners and administrators. The model consists of two major components: the hydrogeological component and the ranking system called the DRASTIC index.

The hydrogeological component is based on the seven parameters such as depth to groundwater table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), the impact of the vadose zone (I), and hydraulic conductivity (C). These parameters are assigned some ratings and weights established by the committee of experts using the Delphi technique [6]. The hydrogeological parameters are those believed to influence groundwater recharge and movement in the subsurface. The recharge is the vehicle that moves contaminants from the surface, through the unsaturated zone into the groundwater aquifers [6].

The relative ranking scheme uses a combination of weights and ratings to produce a numerical value called DRASTIC INDEX, which describes the vulnerability of the groundwater systems. The rates, weights and ranges of the original DRASTIC model are explained in [6]. The final DRASTIC index (DI) is a summation of the seven-weighted-rated parameters as shown in Eq (1).

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

Where D, R, A, S, T, I, and C are the seven parameters, r is the rating value and w is the weight associated to each parameter. The vulnerability index calculated from Eq (1) is dimensionless. It measures the susceptibility of groundwater system to pollution. The regions with higher DRASTIC index value are more vulnerable to contamination than those with the low index value.

Despite its popularity, the DRASTIC model has some shortcomings, which prompted some researchers to modify it, to achieve more accurate results and improve its applicability. The major drawback of the DRASTIC model is the subjectivity in the assigning of weights and ratings plus the doubt regarding the selection of some parameters and exclusion of others [17] and disregard to the influence of human activities on the groundwater system. Owing to these limitations many researchers have attempted to modify the model [18], [16], [19], [20]. This study modified the original DRASTIC method by substituting the soil medium parameter with the land-use type to capture the influence of human activities on the groundwater system. Besides, the study area has been under intensive agriculture that affected the natural protection provided by microbial activities in the undisturbed topsoil layer.

C The Study Area

The study area covered Mid River Njoro catchment, located at the southwestern part of the Rift valley, Kenya and covers a land area of approximately 55.10 km^2. The area stretches between latitudes 0º 30’ S and 0º 18’ S and longitudes 35º 46’ E and 35º 55’ E. Figure 1 shows the location and boundary of Mid River Njoro catchment in Nakuru County. The area experiences a trimodal precipitation pattern with long rains occurring from April to May, short rains occurring from November to December, and an additional small peak occurring in August. The rainfall ranges from 800 mm to 1700 mm while the potential evaporation is in the ranges of 1200 mm to 1500 mm. Average annual minimum and maximum temperatures are 9ºC and 24ºC respectively [21] The study area dominated by various agricultural activities with an extensive application of fertilizers in the farms. The rest of the land covered by settlements, patches of forests and rivers. Based on topographical maps, the highest ground elevation is 2377 m while the lowest is 2133 m above the sea level, resulting in a difference of height of 244m. The primary supply of drinking water in the area comes from boreholes with that have water depth ranging from 23 m to 138 m.

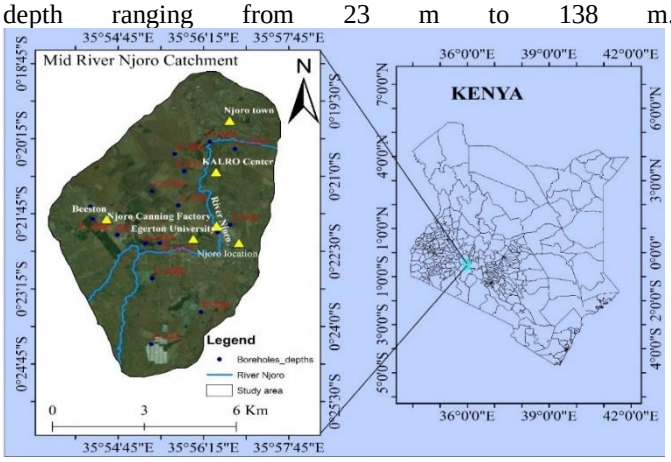


Figure 1: Study area location

D Land-use

Over the years the area has experienced drastic land-use changes from forest cover to intensive agricultural fields. Some of the important centres found in the mid-zone of the catchment are Kenya Agricultural and Livestock Organization (KALRO), formerly Kenya Agricultural Research Institute (KARI), Njoro Canning Industry and Egerton University. The main economic activities in the study area are agricultural-based industries including vegetable and milk processing, large-scale wheat and barley farming. Light manufacturing industries such as timber milling and quarrying are also a mainstay of the local economy [22].

E Geology

The geology comprises a succession of Miocene–Pleistocene volcanic, primarily phonolites, trachytes and basalts, with pyroclastics and intervening lacustrine beds being more widespread in occurrence during the Pleistocene [23], [24]. Much of the rift floor area is draped by Holocene

pyroclastic, basalt flows, and volcanic soils [23]; grid faults that occur in this section of the rift [24], [25], [26] are masked by the superficial materials. As assessment of borehole geo-logs in the study areas indicate that the top brown soils and sediments are on the order of 10 m thick or more. Below them are lava flows of rhyolites, basalts, trachytes or phonolitic trachytes, with varying thicknesses, from thin (10 m or less) to thick (sometimes 30–40 m), that alternate with consolidated pyroclastic materials such as tuffs, agglomerates, ashes and their derivatives comprising loose tuffaceous sands or pumiceous gravels. These also comprise thin layers (5 m or less) to thick (>50 m). This series occurs up to depths exceeding 200 m [27]. The mid River Njoro catchment is within the bigger rift valley aquifer with the static water levels being shallower than the depth at which water was initially struck suggesting the presence of confined shallow aquifers [28]. The depth at which groundwater samples were collected ranged from 22 m to 126 m. Aquifer lithological studies identified three types of aquifer media; sediments (including volcaniclastics), trachyte and tuffs. Sediment units intercalated in the volcanic formation forming the main sources of groundwater.

II MATERIALS AND METHODS

A Development of modified DRASTIC index

The sources of data for this study are field surveying, laboratory analysis and secondary sources. Due to the presence of industrial and agricultural activities in the study area, the original DRASTIC method is modified and used for groundwater vulnerability assessment. The modified DRASTIC index (m-DI) describes the level of susceptibility as a function of six hydrogeological factors and land use type. These form seven thematic layers of modified DRASTIC model that reclassified using rating values adapted were from [6] and [29] and [16]. The weight factor, based on [6] and [29] and [16] was also assigned to each thematic layer and the final modified DRASTIC index calculated using (2).

$$mDI = D_r D_w + R_r R_w + A_r A_w + T_r T_w + I_r I_w + C_r C_w + Lu_r Lu_w \quad (2)$$

Where D, R, A, T, I, and C are the six parameters in original DRASTIC method and Lu is the land-use type of the study area. Since the [6] did not propose any classification criteria for the DRASTIC index results, many studies used the [30] and [31] classification systems shown in Table 1.

Table 1: Criteria of evaluating the degrees of vulnerability [30], [31].

Index value		Vulnerability class	
Groundwater depth (m)	4.5 - 9	7	5
	9 - 15	5	
	15 - 22	3	
	22 - 30	2	
	>30	1	
Net recharge (mm/yr.)	<50	1	4
Aquifer media	Sand	8	3
	Sandstones	6	
	Igneous	3	
Topography (%)	0 - 2	10	1
	2 – 6	9	
	6 – 12	5	
	< 80	Very low	
	80 – 120	Low	
	120 – 160	Moderate	
	160 - 200	High	
	>200	Very high	

C Chi-square value

The spatial relationship between the modified DRASTIC vulnerability map and nitrate concentration map was calculated as an area cross-tabulation, one map being in rows and the other in columns. An area cross-tabulation table summarizes the overlap of all possible combination of the two input maps. The chi-square test is a quantitative measure of the degree of association between two maps and the calculations are based on

The different parameters used to build the modified DRASTIC model are arranged in a geospatial database using the spatial analyst tool of ArcGIS software as shown in Figure 2.

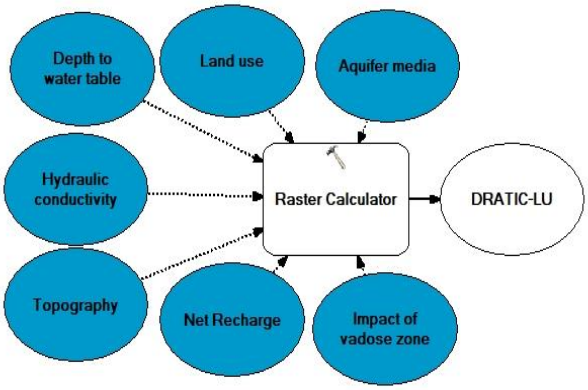


Figure 2: Modified DRASTIC model flowchart

Table 2 shows the rating and weighting values of the modified DRASTIC model for the study area.

B Pearson's Correlation Coefficient

The linear dependence between the modified DRASTIC index and the observed nitrate concentration analyzed by calculating Pearson's correlation coefficient (r) of the two variables. For this purpose, the groundwater vulnerability index at each borehole was extracted using GIS technique. Nitrate measurements were recorded at each borehole. The graph of vulnerability index values and observed nitrate at each borehole was plotted and Pearson's correlation coefficient (r) determined.

Table 2: Rating and weighting values of the modified drastic model

m-DI parameters	Range	Rating	Weight
	12 – 18	3	
	>18	1	
Impact of Vadose zone	Sandstone	6	5
	Igneous	7	
	Sand	8	
Hydraulic conductivity (m/d)	5.24 - 12	2	3
Impact of land use	Forest	1	5
	Agroforestry	3	
	Agricultural land	4	
	Built up area	8	

the number from the area cross-tabulation. The area table between the two maps (say A and B) becomes the matrix T, with elements $T_{i,}$ j, where, i is the number of classes in map B (rows of the table) and j is the number of classes in A (columns of the table). The marginal total of T is the sum of i-th (T_i) rows and j-th (T_j) columns (Graeme et al., 2014). The expected area (T_{ij}*) is given by the product of sum of the rows (T_i) and columns (T_j), divided by marginal total (T), as shown (3).

$$T_{ij}^{*} = \frac{T_i - T_j}{T} \quad (3)$$

Then, the chi-square statistic is given by (4).

$$X^2 = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{(T_{ij} - T_{ij}^{*})}{T_{ij}^{*}} \quad (4)$$

Equation (4) is a classical chi-square equation (observed-expected)^2/expected expression, which has a lower limit of 0, in case the observed areas equals the expected areas [32] The chi-square value increases as the difference between the observed areas and expected areas increases in magnitude up to an upper limit variable. The overall value of chi-square represents the overall association between the modified DRASTIC model index and the observed nitrate concentration, hence validating its performance.

For this purpose, the observed nitrate values at the borehole locations were interpolated using the ordinary Kriging interpolation of ArcGIS10.1 and classified into seven classes. The nitrate concentration map reclassified using the Spatial Analysts Tools of ArcGIS 10.1. The obtained modified DRASTIC vulnerability map also classified according to criteria proposed by [30] and [31]. The area cross-tabulation table of the reclassified nitrate concentration and the final vulnerability map obtained using available ArcGIS tools. Then, the chi-square table calculated using (4).

III RESULTS AND DISCUSSION

A Depth to groundwater table (D)

Groundwater table depth in this study taken as the distance between the ground surface to the level at which water is first encountered or sensed (strike water level) by the Dipper-T water level meter and other depths obtained from geological report no. 86 of the Molo area. It determines the thickness of the vadose zone and hence, the distance the contaminants must travel before reaching the aquifers. The depth at which water encountered ranges between a few meters to 126 m below the surface. The depth to the groundwater was reclassified into five classes using reclassify tool in spatial analyst with regard to the original DRASTIC system as shown in Figure 3.

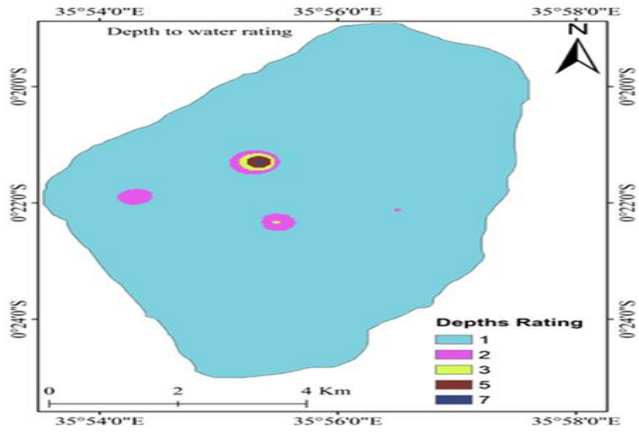


Figure 3: Groundwater depth rating

D Net recharge (R)

Net recharge is the amount of water per unit area of land which enters the ground surface, infiltrate through the soil and vadose zone and finally reaches the water table. From the hydrogeological reports of the boreholes and the borehole completion reports the study area has the net recharge less than 50mm and an absolute value of one is assigned to the rating value of this parameter (Figure 4).

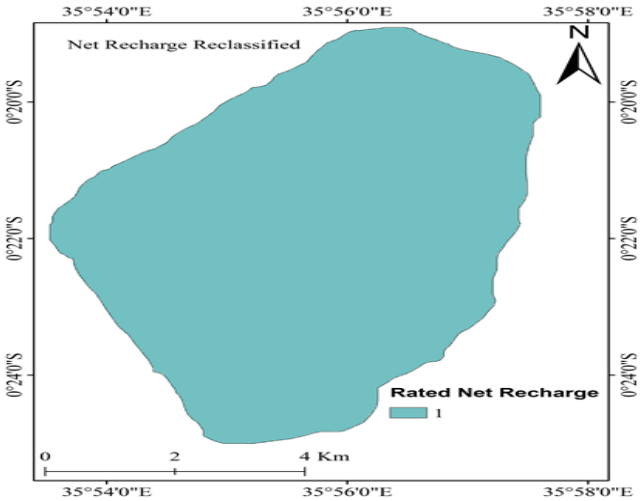


Figure 4: Net recharge rating

C Aquifer media (A)

Aquifer material plays a critical role in groundwater contamination because of its characteristics related to hydraulic conductivity and porosity of the water-bearing formations. Depending on these aquifer properties the contaminants might spread both horizontally and vertically within the aquifer or restricted to just point of introduction. The main lithological constituents of the study area are sand, sandstones and igneous rock and a rating value 8, 6 and 4 assigned respectively as shown in Figure 5.

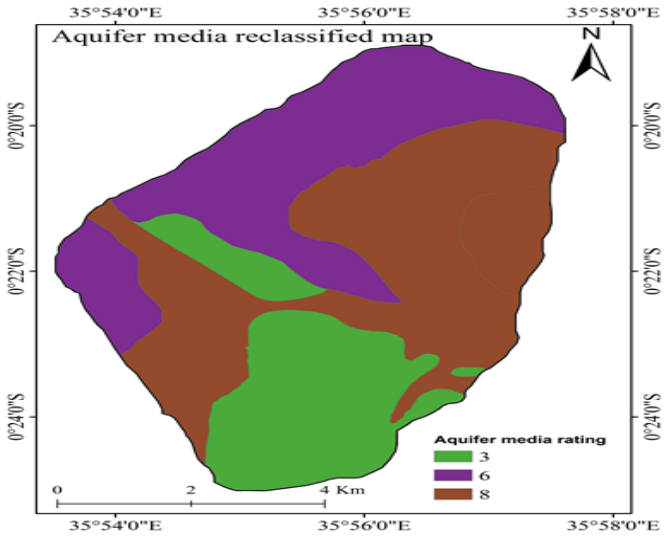


Figure 5: Aquifer media rating

D Topography (T)

The slope (topographic) map was derived from the Shuttle Radar Topography Mission (SRTM) 30 metres image of Kenya and slope percentage calculated using the Spatial Analysts Tools of ArcGIS 10.3. The slope percentages are rated based on the standard DRASTIC model with 10 being the lowest slope (Figure 6). Generally, the slope of the study area is for most part, a flat plain and gently undulating category covering which increases groundwater vulnerability.

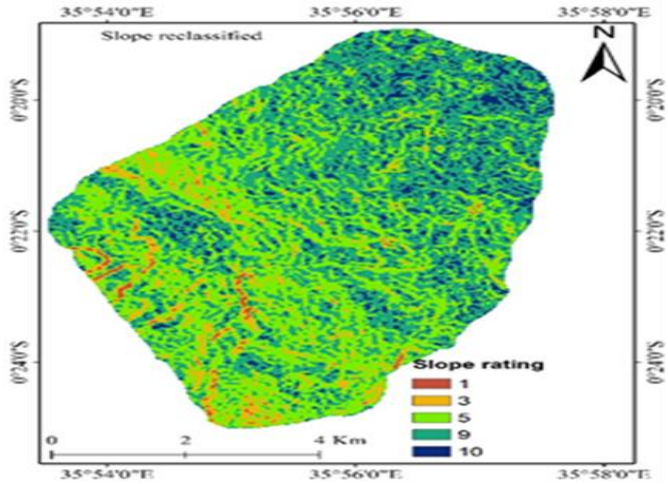


Figure 6: Slope rating

E Impact of vadose zone (I)

The vadose zone plays an important role in controlling groundwater pollution because it controls infiltration rate and the environment for attenuation of the various type of contaminants. Within the vadose zone, pollutants may be biodegraded, mechanically filtered, chemically reacted, volatilized and dispersed and this decrease with increase depth to the water table. The vadose zone of the study area comprises of black ashes, eutaxitic welded tuffs, pumice and pyroclastic and sediments rocks. The rating value assigned to each geological class is shown in Figure 7.

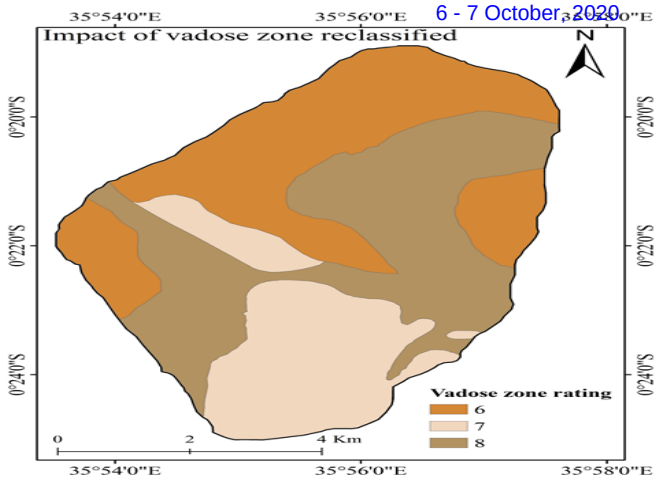


Figure 7: Impact of vadose zone rating

F Hydraulic conductivity (C).

Hydraulic conductivity controls the rate of groundwater movement in the aquifer (saturated zone), thereby controlling the degree and fate of contaminants. Hydraulic conductivity values obtained from the pumping test results in the borehole completion reports and hydrogeological survey reports. The point hydraulic conductivity values were reclassified according to original DRASTIC model rating values, using ArcGIS spatial analyst tools and one class was obtained for the study areas (Figure 8).

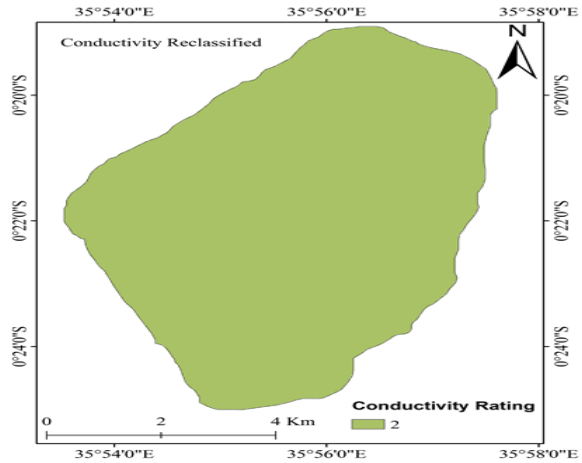


Figure 8: Hydraulic conductivity rating

G Impact of land use type (LU).

Google Earth satellite imagery of 2015 used to generate a land-use map of the study area. This layer substitutes the soil media parameter of the original DRASTIC model, necessitated by the fact the topsoil of the study area has been removed over the years due to human settlements and agricultural activities thereby losing its biological properties to control groundwater pollution. The major land-use types identified are agricultural land, built-up areas, forest and agroforestry. The land-use types were reclassified according to the rating and the weight values adapted from [29] and [16] as

shown in Figure 9.

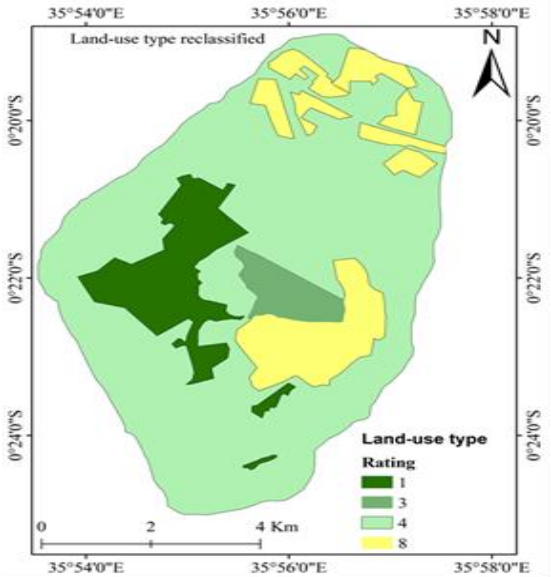


Figure 9: Land use type rating

A The groundwater vulnerability map

The groundwater vulnerability map prepared using the six hydrogeological data layers and one land use layer in the GIS software environment. The modified DRASTIC index scores ranged from 69 to 129. These indices classified according to Table 1 and the study area categorized into three vulnerability zones: very low (6.1%), low (87.4) and moderate (6.5%) as shown in Figure 10. The computed modified DRASTIC indices identify areas which are more vulnerable to groundwater pollution. A high index value reflects high groundwater potential while a low index value indicates a low groundwater potential area. The resulting groundwater vulnerability map of the study area indicates the low potential of contamination. The areas with moderate vulnerability overlapped built-up area and those with very low vulnerability had patches of the forest cover and must have undergone deforestation in the recent past. A larger percentage of the study area (87.4%) has a low class of groundwater vulnerability to contamination which may be attributed mainly to land use types and somewhat impact of vadose zone and aquifer media.

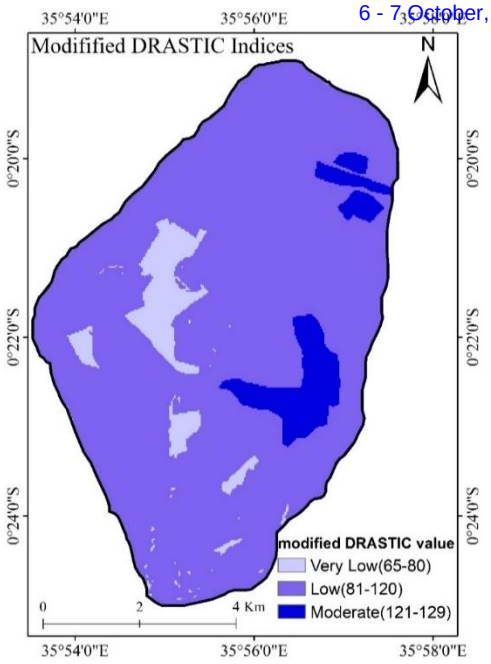


Figure 10: Modified DRASTIC indices of the study area

IV MODEL VALIDATION

Validation is an essential process to ensure the model performs accurately and reliably so that scientific inference is from it. Figure 11, display the Pearson's correlation coefficient 'r" between the nitrate concentrations and the modified DRASTIC values.

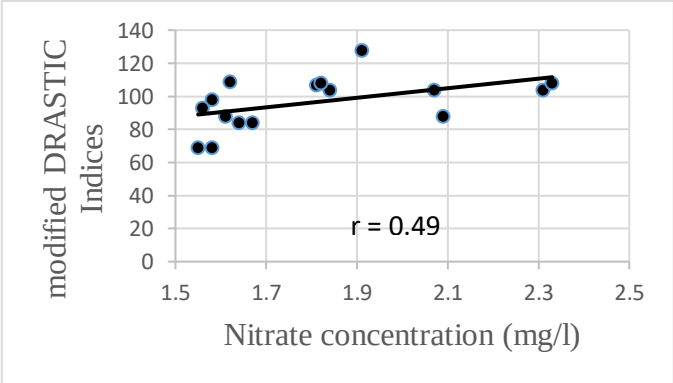


Figure 11: Modified DRASTIC indices and nitrate concentrations

The Pearson's correlation coefficient, 'r' was found to be 0.49, which indicate a moderate positive correlation between the nitrate concentration and the obtained groundwater vulnerability index values, thereby confirming the validity of the obtained results.

Chi-square test also carried out to test the association between the modified DRASTIC index map and the nitrate concentration map. The area cross-tabulation analysis between the reclassified nitrate concentration map and the modified DRASTIC Indices carried out using spatial analyst tools of ArcGIS 10.3 and the result presented in Table 3.

The Chi-square value increases as the difference between the observed areas and expected areas increases in magnitude up to an upper limit variable. Therefore, the small value (5.01) of chi-square value in this correlation means that the two maps are related though the relationship is very minimal. The chi-

square result may be affected by the observed extreme values of nitrate concentration at KALRO dairy borehole.

Table 3: Chi-square values for the Modified DRASTIC Index

m-DI Classes	Nitrate class1	Nitrate class2	Nitrate class3	Nitrate class4	Nitrate class5	Nitrate class6	Nitrate class7	Nitrate class8	Nitrate class9	Total
Class VL	0.69	0.00	0.15	0.23	0.14	0.21	0.32	0.35	0.13	2.21
Class L	0.00	0.01	0.03	0.11	0.02	0.06	0.09	0.00	0.01	0.34
Class M	0.48	0.12	0.07	0.58	0.04	0.22	0.33	0.23	0.39	2.47
Total	**1.17**	**0.13**	**0.25**	**0.91**	**0.20**	**0.50**	**0.74**	**0.58**	**0.52**	**5.01**

The statistical spatial relationship between the modified DRASTIC maps and nitrate map tested using Pearson's correlation coefficient and chi-square. Pearson's correlation coefficient and chi-square value were calculated as a relative measure to define the spatial dependency between two maps. The validation results (Pearson's correlation coefficients and chi-square) obtained, demonstrated that the modified DRASTIC vulnerability map represent contamination situation in the Mid River Njoro catchment.

V CONCLUSIONS AND RECOMMENDATIONS

In the present study, modified DRASTIC model is used to investigate the groundwater vulnerability of the Mid River Njoro catchment, Kenya. The obtained groundwater vulnerability map can be used as the first step in protecting the groundwater system from surface pollution. The results show that the study area has a low potential of contaminations because of the natural protection offered by the hydrogeological settings of the study area. The land-use types seem to be a major threat to the future of groundwater use since moderate vulnerability zones are found in built-up areas. To protect groundwater system from future deterioration, a protective measure must be put in place before implementing any human activities that have the potential to cause contaminations such as major agricultural projects and industries. A better option to septic tanks such as sewer systems should be preferred

ACKNOWLEDGEMENTS

This work was supported by the Jomo Kenyatta University of Agriculture and Technology. The authors are grateful the chairperson JKUAT Programme and Training Committee for the financial support.

REFERENCES

[1] Foster, S., Chilton, J., Nijsten, G.-J., & Richts, A. (2013). Groundwater - a global focus on the "local resource." Current Opinion in Environmental Sustainability, 5(6), 685–695.

[2] Adelana, S., & MacDonald, A. (2008). Applied Groundwater Studies in Africa: IAH Selected Papers on Hydrogeology, volume 13.

[3] MacDonald, A. M., Bonsor, H. C., Dochartaigh, B.´E.´O., & Taylor, R. G. (2012). Quantitative maps of groundwaterresources in Africa. 7, 7. Environ. Res. Lett. 7 021003.

[4] Mumma, A., Lane, M., Kairu, E., Tuinhof, A. & Hirji, R. (2011). Kenya Groundwater Governance Case Study. Water papers; World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/17227 License: CC BY 3.0 IGO.".

[5] Mishra, N., Khare, D., Gupta, K. K., & Shukla, R. (2014). Impact of land use change on groundwater—a review. Adv Water Resour Protect, 2, 28-41.

[6] Aller, L., Lehr, J. H., Petty, R., & Bennett, T. (1987). A Standardized System to Evaluate Ground Water Pollution Potential Using Hydrogeologic Settings. National Water Well Association, p. 20. Retrieved; http://rdn.bc.ca/cms/wpattachments/wpID3175atID5999.pdf

[7] Yin, L., Zhang, E., Wang, X., Wenninger, J., Dong, J., Guo, L., & Huang, J. (2013). A GIS-based DRASTIC model for assessing groundwater vulnerability in the Ordos Plateau, China. Environmental earth sciences, 69(1), 171-185.

[8] Vrba, J. and Zaporozec, A. (1994). Guidebook on mapping groundwater vulnerability. Retrieved from agris.fao.org.

[9] National Research Council. (1993). Ground Water Vulnerability Assessment: Contamination Potential under Conditions of Uncertainty. National Academy Press, Washington DC.

[10] Leone, A., Ripa, M. N., Uricchio, V., Dea´k, J., & Vargay, Z. (2009). Vulnerability and risk evaluation of agricultural nitrogen pollution for hungary's main aquifer using drastic and gleams models. Journal of Environmental Management, 90(10):2969–2978.

[11] Burkart, M. R., Kolpin, D. W., & James, D. E. (1999). Assessing groundwater vulnerability to agrichemical contamination in the Midwest US. Water Science and Technology, 39(3), 103-112.

[12] Massimo, V. (2010). The combined approach when assessing and mapping groundwater vulnerability to contamination. Journal of Water Resource and Protection, 2(01), 14.

[13] Foster S.S.D. (1987). Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In Vulnerability of soil and groundwater to pollutants,38, (pp. 69–86).

[14] Van Stempvoort, D., Evert, L. W. L. (1993). Aquifer vulnerability index: a GIS compatible method for groundwater vulnerability mapping. Can Wat Res J, 18, 25–37.

[15] Civita, M. (1994). The Cards of groundwater vulnerability to pollution: Theory & Practice. Pitagora, Bologna.

[16] Doerfliger, N. and Zwahlen, F. (1998). Practical guide: groundwater vulnerability mapping in karstic regions (EPIK). Swiss Agency for the Environment, Forests and Landscape (SAEFL), Bern, 56.

[17] Panagopoulos, G. P., Antonakos, A. K., & Lambrakis, N. J. (2006). Optimization of the DRASTIC method for groundwater vulnerability assessment via the use of simple statistical methods and GIS. Hydrogeology Journal, 14(6), 894–911. https://doi.org/10.1007/s10040-005-0008-x.

[18] Babiker, I. S., Mohamed, M. A., Hiyama, T., & Kato, K. (2005). A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. Science of the Total Environment, 345(1), 127–140.

[19] Denny, S. C., Allen, D. M., & Journeay, J. M. (2007) DRASTIC-Fm: a modified vulnerability mapping method forstructurally controlled aquifers in the southern Gulf Islands, British Columbia,

Canada. Hydrogeol J.15(3):483.
[20] Khan, A., Khan, H.H. & Umar, R. (2017). Impact of land-use on groundwater quality: GIS-based study from an alluvial aquifer in the western Ganges basin. Appl Water Sci 7, 4593–4603 doi:10.1007/s13201-017-0612-7
[21] Sombroeck, W. G. (1982). Exploratory soil map and Agro - climatic zone map of Kenya. Exploratory soil survey, EI, Kenya Soil survey, Nairobi.
[22] Olang LO, Kundu, P, Bauer T (2011) Analysis of spatio-temporal land cover changes for hydrological impact assessment within the Nyando River Basin of Kenya. Environ Monit Assess (2011) 179: 389. https://doi.org/10.1007/s10661-010-1743-6
[23] McCall GJH (1967) Geology of the Nakuru: Thompson's Falls–Lake Hannington area. Geological Survey of Kenya, Nairobi, 122 pp.
[24] Baker, BH (1986) Tectonics and volcanism of the southern Kenyan Rift Valley and its influence on sedimentation. In: Frostick LE, Renaut RW, Reid I, Tiercelin J-J (eds) Sedimentation in the African Rifts.Geol Soc Lond Spec Pub 25:267–284.
[25] Schlüter T (1997) Geology of East Africa. Borntraeger, Berlin, 484 pp.
[26] Woldegabriel G, Olago D, Dindi E, Owor M (2016) Genesis of the east African rift system. In: Schagerl M (ed.) Soda Lakes of East Africa. Springer, Cham, Switzerland.
[27] Mogaka DN (2010) Geophysical characterization of the lithology and structure of the Olobanita Well Field, Lower Lake Baringo Basin, Kenya Rift: implication on groundwater occurrence. MSc Thesis, University of Nairobi, Nairobi, Kenya
[28] Isaac K and Janet S (2013) Hydrogeochemistry of shallow and deep water aquifers of Menengai geothermal area, Kenya rift valley. GRC Transactions, vol.37.
[29] Secunda, S., Collin, M. L., & Melloul, A. J. (1998). Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Israel's Sharon region. Journal of environmental management, 54(1), 39-57.
[30] Civita M, De Regibus C (1995) Sperimentazione di alcune metodologie per la valutazione della vulnerabilità degli acquiferi. Atti 2° Conv. Naz.
[31] Corniello A, Ducci D, Napolitano P (1997) Comparison between parametric methods to evaluate aquifer pollution vulnerability using GIS: an example in the "Piana Campana", southern Italy. Engineering geology and the environment. Balkema, Rotterdam, pp 1721–1726
[32] Graeme, F & Bonham-Carter (2014). Geographic information systems for geoscientists: modelling with GIS, volume 13. Elsevier.