Pol. J. Environ. Stud. Vol. 32, No. 2 (2023), 1037-1048
DOI: *10.15244/pjoes/154742*
ONLINE PUBLICATION DATE: 2023-01-23

Original Research

Groundwater Vulnerability Assessment Using Modified DRASTIC Index, the Case of Doornfontein Area (Johannesburg)

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Received: 21 July 2022
Accepted: 17 September 2022

Abstract

Groundwater is an essential resource for the domestic, agricultural, and industrial sectors. Nevertheless, groundwater quality has declined due to the increased use of pesticides and industrial effluent being discharged into water systems. This study aims to assess groundwater vulnerability by using the modified DRASTIC model around Doornfontein, Central Business District (CBD) of Johannesburg. Land use types are considered as a model parameter to produce a modified DRASTIC model, where the result varies between 103 and 219 (low to very high, vulnerable zones). Approximately 5.6% of the study area is covered by very high vulnerable zones and distributed in southern region. High, moderate and low vulnerability zone covers the area of 55.3%, 28.8% and 10.3%, respectively. The study uses a nitrate concentration level to validate the accuracy of the model. The correlation analysis between nitrate level and DRASTIC model shows $R^2 = 0.548$ and significant correlation with the modified DRASTIC model $R^2 = 0.56$. The single parameter sensitivity analysis reveal that land use, aquifer media, soil media, and topography have a prominent role in assessing vulnerability. The study output shows the area is highly vulnerable to contamination, necessitating the relevant authorities' careful attention and protection of the area's groundwater resources.

Keywords: Doornfontein, groundwater vulnerability, DRASTIC, sensitivity analysis

Introduction

Human existence depends profoundly on groundwater resources, primarily in locations where alternative drinking water sources are scarce [1]. Groundwater has been the primary water supply in arid and semi-arid regions due to limited surface water resources [2]. Despite this, groundwater is vulnerable to pollution as a result of various human activities. It is challenging to restore groundwater once it is contaminated because of its complex nature [3]. Therefore, the vulnerability of groundwater to contamination should be continuously monitored to safeguard it from contaminants. Groundwater pollution can be lessened if the regions proper management is implemented. More effective groundwater preservation methods can be adopted by identifying vulnerable areas in the groundwater management system [4].

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Groundwater vulnerability assessment is a valuable approach for generating data which can be used to manage and assess groundwater resources [5]. Such assessment can be used for planning purposes because it enables the creation of models necessary to forecast pollutant accumulation [6]. Several methods have been established to assess groundwater vulnerability, including process-based, statistical, and index based methods [7]. Each method depends on the availability of appropriate data and their spatial distribution [8]. The overlay/index methods are widely used which include (DRASTIC[1], SINTACS[2], and GOD[3]). DRASTIC which is less complex and requires minimal data is the most common approach producing good results in various hydrogeological scenarios [4, 9-11].

Few studies have been conducted at the nationwide and municipal levels in South Africa to assess and predict groundwater risk [12-15]. The studies mentioned above were implemented on a larger scale which is limited in providing detailed and precise information at the catchment level. It is noted that land-use patterns and nitrate concentration affect the DRASTIC technique in evaluating groundwater vulnerability in built-up environments. Numerous studies were conducted to modify the original DRASTIC model based on geological and hydrological conditions, such as DRASTICA, DRASTIC-LU, and pesticides DRASTIC [16-18]. However, studies conducted in South Africa lacked the addition of essential parameters, such as land use [15, 19]. Expanding on these studies, our current study utilised land use parameter to modify the original DRASTIC model using a GIS technique to assess the vulnerability of groundwater to pollution in the Doornfontein, CBD Johannesburg, South Africa. The study's primary objectives are to evaluate the performance of a modified DRASTIC groundwater vulnerability model in Doornfontein district, which is dominated by built-up areas and industrial activities.

Materials and Methods

Study Site Description

The study location where the research was conducted lies within 26°11'24" to 26°11'49.92"S and 28°02'51.36" to 28°03'43.2"E of Doornfontein, Johannesburg. Hydrologically, the area falls in A21C Quaternary catchment within upper Crocodile River catchment Fig. 1. Johannesburg records an annual average runoff of 9% with approximately 54 mm of rainfall washing off Johannesburg's surfaces [20]. The study area receives approximately 705 mm annual rainfall (recorded from the nearest weather station). The dry rainy season coincides with a low mean temperature, with June and July being noted as the coldest months. The summer months are quite wet, with the maximum temperature reached around February. The study area covered approximately 760.55 km^2 and was characterised mainly by built-up areas with a total area coverage of 67.20%, grassland (14.33%), cultivated land (6.87%), forested land (6.6%), barren land, mines and quarries 5% [21]. The Doornfontein region is dominated by built up areas. Therefore, there is a need for groundwater supplies which has been increased due to a continuous expansion of population growth, industrialisation, and urbanisation. However, groundwater quality has been deteriorated due to the withdrawal of wastes from the University of Johannesburg and nearby industries which rises the groundwater nitrate level. In order to ensure the sustainability of groundwater resources, research on the vulnerability of groundwater to nitrate is conducted by gathering data from water samples.

DRASTIC Model for Aquifer Vulnerability Mapping

The US Environmental Protection Agency designed the DRASTIC technique to investigate the groundwater vulnerability to contaminations on a broad scale [9]. The DRASTIC model follows a ranking order that allows systematic contaminants analysis [16]. The model works on the assumption that (i) contamination is emitted at the surface of the earth, (ii) precipitation drives the pollutant into the groundwater, (iii) The pollutant travels simultaneously as the velocity of the water, and (iv) the proposed area has to be at least 0.4 km^2 in size [13]. Seven parameters are overlaid to produce the final DRASTIC index (Table 1). The vulnerability index of each rating scale has five classes: low (1 and 2), moderately low (3 and 4), moderate (5 and 6), moderately high (7 and 8) and high vulnerability (9 and 10). The impact of weighting values varies from 1 to 5, with one being the least significant and five being the most significant.

Input Parameter

Different input data was utilised for the vulnerability assessment and their sources are presented in Table 2. The water depth was obtained in tabular form from the National Groundwater Archive of Department of Water and Sanitation. Net recharge and soil media data were derived from a study made by South Africa's water resources [22]. Data for the aquifer media were collected from the South Africa Council for geoscience website's data repository. The Digital Elevation Model (DEM) for topography data was acquired at 30 m spatial

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[1] Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic Conductivity.

[2] Aquifer depth, seepage water input, unsaturated zone features, soil type, aquifer hydrogeological features, aquifer hydraulic conductivity, the roughness of land surface.

[3] Groundwater assurance, Overall lithology of aquifer and Depth to groundwater table.

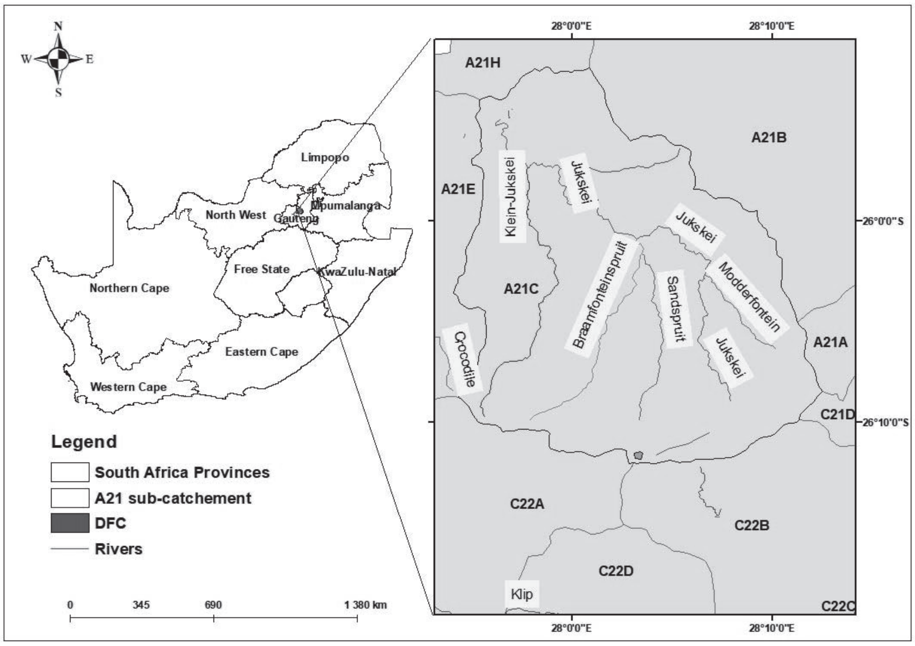

Fig. 1. Illustration of the study area, A21C catchment map within Gauteng Province.

resolution from the USGS earth explorer, Shuttle Radar Topography Mission (STRM). The impact of vadose zone data set was extracted from hydrological map (1:500,000) retrieved from the department of water and sanitation [21]. Data for hydraulic conductivity were found in the literature of Domenico and Schwartz [23]. The land cover data was obtained from the website of South African National Land Cover.

This study utilised ArcGIS, 10.6.1 to process the datasets, including data conversions from one format to another. The final result was calculated using a raster calculator in ArcGIS Map Algebra to get a raster output. All parameter maps were created using a grid map with 20 m by 20 m cells size. The input data was saved in the same workspace and all the data sets were projected to WGS 1984 UTM 35S coordinates. Depending on the hydrogeological features of the regions, the overall index assists in the determination of areas that are more vulnerable to groundwater pollutants.

Modification of DRASTIC Model

The modified DRASTIC model was calculated in this study to show the effects of land use in the final index map. Agricultural, commercial, industrial, and urban land-use patterns impact the groundwater quality.

Table 1. Description of DRASTIC parameters [9].

DRASTIC parameters	Description
Depth-to-groundwater (D)	This describes the vertical space between the ground surface and water table. Greater depths in the water table indicate a lower risk of contamination.
Net recharge (R)	This represents the volume of water that reaches the water table in one area of land, as a result of percolation from the surface. This is the main way for penetrating and transferring contaminants to the saturated zone.
Aquifer media (A)	It describes a geological formation which stores water. The attenuation capacity of aquifer media depends on kind of soil grains occupying it. Small grain size contributes to larger contaminant attenuation capacity of aquifer media.
Soil Media (S)	It is the major determinant of how contaminants and water move from the ground surface to the aquifers.
Topography (T)	This describes how the gradient of the ground surface vary generally. Contaminants are less prone to runoff and more likely to penetrate on low slopes.
Impact of vadose zone (I)	It is the ground area that carries pores that are unsaturated. It exists between the aquifer and the soil surface.
Hydraulic conductivity (C)	This describes the ability of the aquifer to hold water. This metric is linked to a higher vulnerability level.

Table 2. Modified DRASTIC parameters data sources.

DRASTIC parameters	Symbol	Format	Description
Borehole data (m)	(D)	Table	Department of Water and Sanitation, National Groundwater Archive (https://www.dwa.gov.za/niwis2/GroundWaterStatus)
Net recharge (mm/yr)	(R)	Raster	[22] (http://waterresourceswr2012.co.za).
Aquifer media	(A)	Shapefile	South Africa Council for Geoscience (https://www.geoscience.org.za)
Soil Media	(S)	Shapefile	[22] (http://waterresourceswr2012.co.za).
Topography	(T)	Raster	30 m Shuttle Radar Topography Mission, (https://earthexplorer.usgs.gov)
Impact of vadose zone	(I)	Shapefile	DWS 1:500,000 hydrogeological map [21]
Hydraulic conductivity (cm/d)	(C)	pdf	Literature [23]
Land use	(Lu)	Raster	SANLC https://egis.environment.gov.za/gis_data_downloads

In most places, various land-use types and sustainable development practices critically affect groundwater resources. The study area was covered by nine land use classes, including wetland, water bodies, shrubland, grassland, cultivated land, built-up, forest, grassland, and barren land. The rating of each class varied from 5 to 10 depending on their effects on the groundwater system. The final modified DRASTIC index was produced after applying the rated and weighted land use parameter to the original DRASTIC formula [10]. As shown in Table 3, each parameter in the modified DRASTIC model was multiplied with its corresponding weights and rates according to the values assigned by [9, 12]. Among the modified DRASTIC parameters, depth to groundwater, impact of the vadose zone, and land use are the essential parameters, with a weight of 5 followed by net recharge, aquifer media and hydraulic conductivity with a weighting value of 4, 3, and 3, respectively.

$$Modified\ DRASTIC = DRASTIC + LU_r\ LU_w\ index \quad (1)$$

Where LU_r land use rate and LU_w land use weight

Sensitivity Analysis

Single parameter sensitivity analysis (SPSA) was employed to examine how reliable the parameters of the DRASTIC model are [24]. SPSA is utilised to evaluate and assess the analytical data's consistency. The approach determines which parameters are more important for the study and require further accurate and precise information.

Validation of Vulnerability Maps

The standard validation method was developed by comparing various contaminants in groundwater to vulnerability index [25]. This research used nitrate content as the principal contaminant measure because of its naturally low presence in groundwater and strong mobility at great depths [18]. Additionally, nitrate has high solubility in the groundwater system; thus, it indicates the pollution level. Various studies use a nitrate level as an effective validation parameter for vulnerability assessment models such as Li et al. [2]; Ahirwar and Shukla [4]; Maqsoom et al. [18] and Moges and Dinka [19]. The study area groundwater samples were collected and measured from 14 wells which is located in different aquifer types. The nitrate concentration levels are presented in Table 4, the first ten samples were obtained from national groundwater archive and the last four samples were measured from direct boreholes at regular intervals during winter and rainy seasons. All of the samples were collected in the study area to acquire the spatial distribution of the entire study region as presented in Fig. 2. The nitrate value maps were superimposed on the final groundwater vulnerability map using the extracted value to points, Arc GIS tool. The study extracted and plotted the values of nitrate and the index of vulnerability map to show the correlation between them. The correlation of nitrate level with the DRASTIC and Modified DRASTIC model was assessed using a simple linear regression model.

Results and Discussion

Modified DRASTIC Parameters and Their Properties

This section provides the values and properties of the modified DRASTIC parameters for the study area. Each of the DRASTIC parameters are presented in detail.

DEPTH TO GROUNDWATER (D)

The minimum distance to the ground water was recorded at 0.01 m, which is highly vulnerable to pollution and highly rated (10). In contrast, the deep

Table 3. Modified DRASTIC parameter rating and weighting values in the study area [9, 12] .

Parameters	Range	(R)	Vulnerability Index	W	Area (%)
Depth to the water table (m)	0-5	10	Highly vulnerable	5	2.67
	5-15	7	M. high vulnerable		56.90
	15-30	3	M. low vulnerable		39.21
	>30	1	Low vulnerable		1.22
Net Recharge of aquifer (mm/yr)	35-50	6	M. vulnerable	4	99.64
	>50	8	M. high vulnerable		0.36
Aquifer media	Dolomite>5	10	Highly vulnerable	3	0.12
	Intergranular and fractured (2-5 l/s)	9	Highly vulnerable		2.57
	Intergranular and fractured (0.5-2.0 l/s)	8	M. high vulnerable		88.09
	Fractured	6	M. vulnerable		6.33
	Intergranular and fractured (0.1-0.5 l/s)	4	M. low vulnerable		2.89
Soil Media	Sandy loam	6	M. vulnerable	2	99.00
	Sandy Clay loam	5	M. vulnerable		1.00
Topography (%)	0-2	10	Highly vulnerable	1	7.00
	2−6	9	Highly vulnerable		35.00
	6−12	5	M. vulnerable		40.00
	12−18	3	M. low vulnerable		13.00
	>18	1	Low vulnerable		5.00
Impact of Vadose zone	Transvaal	9	Highly vulnerable	5	0.29
	Witwatersrand	6	M. vulnerable		7.15
	Ventersdorp	4	M. low vulnerable		4.21
	Genesis	3	M. low vulnerable		88.35
Hydraulic conductivity (cm/d)	10^{-6}-10^{-5}	1	Low vulnerable	3	3.97
	10^{-5}-10^{-4}	2	Low vulnerable		4.02
	10^{-5}-10^{-3}	3	M. low vulnerable		80.36
	10^{-5}-10^{-2}	4	M. low vulnerable		7.41
	10^{-4}-10^{-2}	5	M. vulnerable		2.72
	10^{-4}-10^{-1}	6	M. vulnerable		1.49
	10^{3}-10^{2}	9	Highly vulnerable		0.03
Land Use	Barren Land	5	M. vulnerable	5	1.44
	Forested	5	M. vulnerable		6.60
	Grassland	5	M. vulnerable		14.32
	Shrub land	5	M. vulnerable		0.38
	Water bodies	7	M. high vulnerable		0.31
	Wetlands	7	M. high vulnerable		1.98
	Cultivated land	8	M. high vulnerable		6.88
	Built-up	10	Highly vulnerable		67.20
	Mine and quarries	10	Highly vulnerable		0.89

Explanation: R (rating), W (weighting), M (Moderately)

Table 4. Location of nitrate samples.

Latitude	Longitude	Nitrate levels (mg/l)
-25.9925	28.1175	4.80
-26.1667	28.00	2.49
-25.9333	28.04722	1.70
-25.9306	28.00	3.65
-25.9194	28.00278	2.44
-26.1383	28.01972	0.16
-26.1917	28.05	9.86
-26.025	28.05	8.11
-26.05	28.02778	3.99
-25.8965	27.99644	0.38
-26.196259	28.055996	4.80
-26.195937	28.05611	3.40
-26.195895	28.055855	14.70
-26.195502	28.055714	6.70

borehole depth was 51 m, which has a minor impact on the aquifer and is low rated (1). Groundwater depth was classified into four categories (Fig. 3a), varying from low to high vulnerable areas. Most of the catchment (56.90%) was covered by moderately high vulnerable, and 39.21% was categorised as moderately low vulnerable. Highly vulnerable areas covered approximately 2.67% of the southern region, and low vulnerability areas in the northern region only covered 1.22%.

NET RECHARGE (R)

Net recharge is the main parameter for percolating and spreading contaminants that reaches the aquifer from the surface. Net recharge was classified into two ranges: moderate vulnerable areas covered around 99.64% of the region with a rating scale of 6. Moderately high vulnerability covered 0.36% of the southern region study areas, with a rating scale of 8 (Fig. 3b).

AQUIFER MEDIA (A)

The Aquifer media output showed that 88.09% of the study area in the north and central zones was covered by intergranular and fractured rocks with 0.5-2.0 l/s yield. Fractured rocks covered 5.33% of the study area on the southern region. Rating scale of 8 and 6 was given for the above aquifer types, respectively. The intergranular and weathered rock with a 0.1-0.5 l/s yield capacity covered 2.89% of the area located in the southeast region, whereas a bearing capacity of 2.0-5.0 l/s covers an area of 2.57% (Fig. 3c). These rocks have 4 and 9 rating scales, respectively. The dolomite aquifer type covered 0.12% of the northern end catchment with a 10 rating scale.

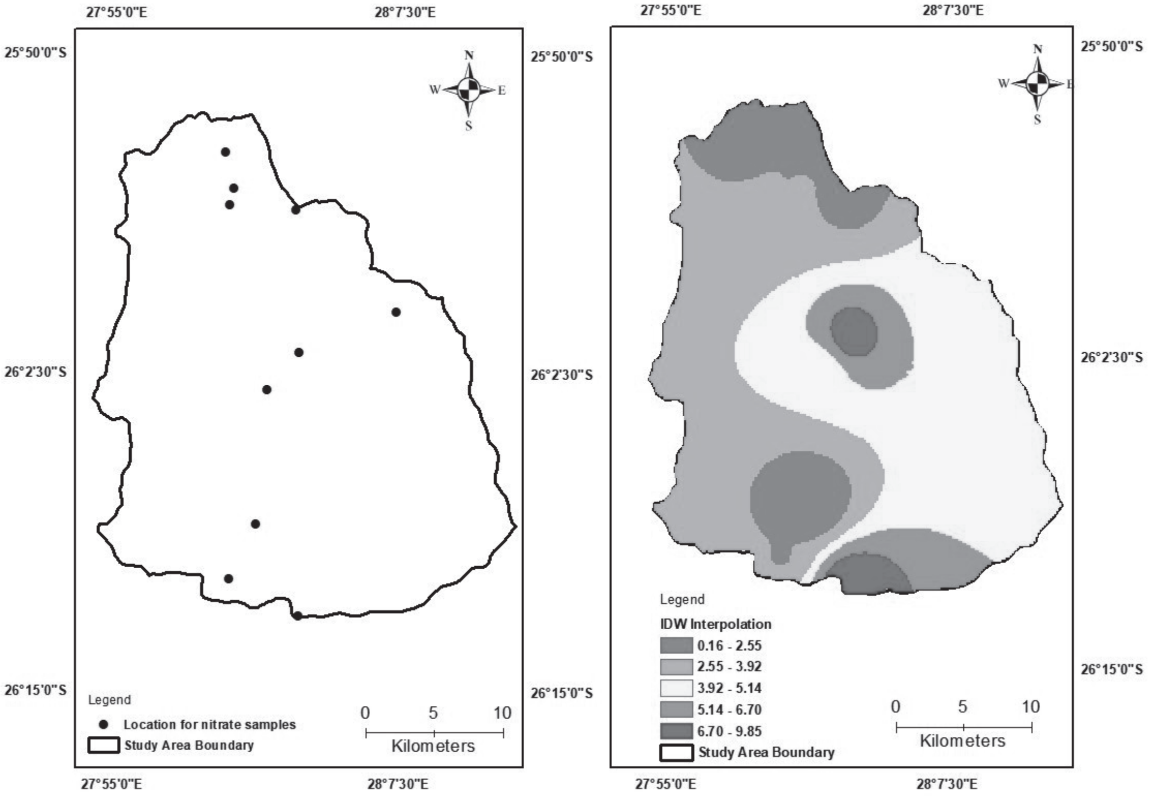

Fig. 2. Point location of the water sample for nitrate concentration.

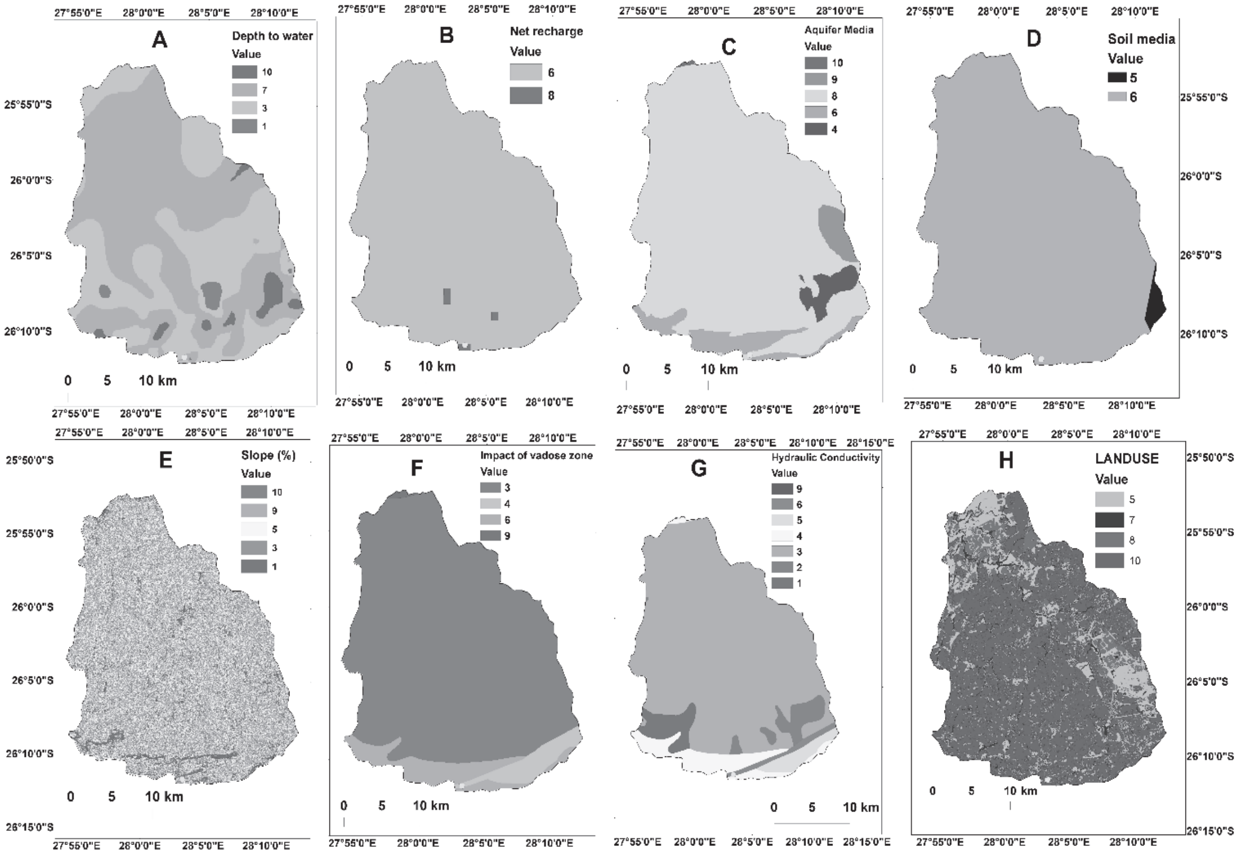

Fig. 3. The rates (R) of modified DRASTIC parameters: a) depth to groundwater, b) net recharge, c) Aquifer media, d) Soil media, e) Topography, f) Impact of vadose zone, g) Hydraulic conductivity, and h) Landuse.
(Refer Table 3) for the rating classification of each DRASTIC parameters

SOIL MEDIA (S)

The study area has two soil classifications: sandy loam and sandy clay loam soils. Sandy loam soil covers (99%) of the central, north, and south-west part with 1% of sandy clay soil in the southeast region of the study area. The soil media classes were given a 5 and 6 rating scale, respectively, as shown in (Fig. 3d). The soil media, which correlates to the unsaturated zone's highest weathered layer regulates the level of recharge which can penetrate downstream [26].

TOPOGRAPHY (T)

The study used a digital elevation model to extract slope and utilised different classes including 0-2% (very gentle gradient), 2-6% (gentle gradient), 6-12% (moderate gradient), 12-18% steep, and >18% very steep gradient. Rating of 10, 9, 5, 3 and 1 was assigned, respectively (Fig. 3e). The slope classification was divided from low vulnerability to high vulnerability areas. Gentle slopes covered 42% of the highly vulnerable area, followed by 40% on a moderate vulnerability zone. Moderately low vulnerable areas and low vulnerable areas cover 13% and 5% of the study area.

IMPACT OF VADOSE ZONE (I)

This is a significant parameter to the DRASTIC model which acts as a buffer between the aquifer and the groundwater during pollutant infiltration [27]. The vadose zone was categorised into four types i.e., Transvaal formation, Genesis formation, Witwatersrand and Ventersdorp basins. Upon pre-processing the data set, vulnerability index of the study area was categorised into three classes: moderately low vulnerability (92.56%) for rating 3 and 4, moderately vulnerable (7.15%) for rating 6, and highly vulnerable (0.29%) areas for rating 9 (Fig. 3f).

HYDRAULIC CONDUCTIVITY (C)

When there is a high hydraulic conductivity in the groundwater, contamination is more likely to increase [28]. An aquifer with a higher flow conductivity can easily impact contaminants by exposing them to high contamination risk [6]. This study utilised the properties and rating scale of all rock classes to determine hydraulic conductivity due to the unavailability of data [23] (Fig. 3g). Gneiss covered 80.36% of the study area, followed by quartzite 7.41%, gabbro 4.02%, and dunite 3.97%. Lava covered 2.72%, with basalt (1.49%)

and dolomite (0.03%), recording the least coverage. The areas of study were categorised into four vulnerability index classes, low (8%), moderately low (87%), moderate (4%) and high (1%) vulnerability areas.

LAND USE (LU)

The LU class rating varies from moderately high vulnerability to high vulnerability areas with a rating scale from 5 to 10, as presented in Fig. 3h). The built-up and mining areas are under high vulnerability and occupied 68.09% of the study area at a rating scale of '10'. The cultivated land and water bodies covered about 9.17% of the area and recorded moderately high vulnerable classification with rating value of '7' and '8', respectively. Moderate vulnerability covers 22.74% of the study area by shrubland, grassland, barren land and forested land with a rating scale of '5' because it contains low nitrogen concentration relative to other classes. A map algebra raster calculator was used to create the LULC rating map as a raster grid.

Final DRASTIC Index

The final DRASTIC index was calculated from seven DRASTIC parameters. The raster calculator was utilised to extract the vulnerability index in the ArcGIS software, and natural break (Jenks) was used to classify the final values. The DRASTIC index showed the highest value (169), which shows that the areas are highly susceptible to contamination. In contrast, the lowest value (78) shows the area has better protection from pollution (Fig. 4a). The standard deviation of the DRASTIC index was recorded at 24.3, and the mean value of 122.1. The produced vulnerability index was separated into four classes and it showed that 53.79% (409.39 km^2) of the area is highly vulnerable to pollution. Approximately, 6.45% (49.79 km^2) of the southern catchment is under very high vulnerable areas. A medium and low vulnerability covered only a small section in the north and central region with area coverage of 18.75% (141.69 km^2) and 21.01% (159.68 km^2), respectively.

Modified DRASTIC Index

The overall modified DRASTIC index was divided into four classes (low to very high) after overlaying the eight parameters (Fig. 4b). The modified DRASTIC index shows a significant change of high vulnerable zones with index values ranging from 103 to 219. The standard deviation of the model was recorded at 31.46, with a mean value of 159.25. Notably, 5.6% of the area (43.41 km^2) is very highly vulnerable with index values ranging from 181 to 219. A high vulnerability zone ranging from 155 to 181 covered 55.26% of the area studied (419.47 km^2). The remaining 10.31% (79.88 km^2) of the study area was covered by the low vulnerability class, and 28.83% (217.79 km^2) by the moderate vulnerability class. The standard DRASTIC model was modified by the addition of the land-use parameter. In the central and southern parts of the catchment, high vulnerability zones were increased from 53.79 to 55.27%. While the moderately vulnerable zone and the low vulnerable zone were reduced by 10.08 and 10.7%, respectively. The majority of the area's groundwater vulnerability is influenced by the type of land use pattern and various anthropogenic activities.

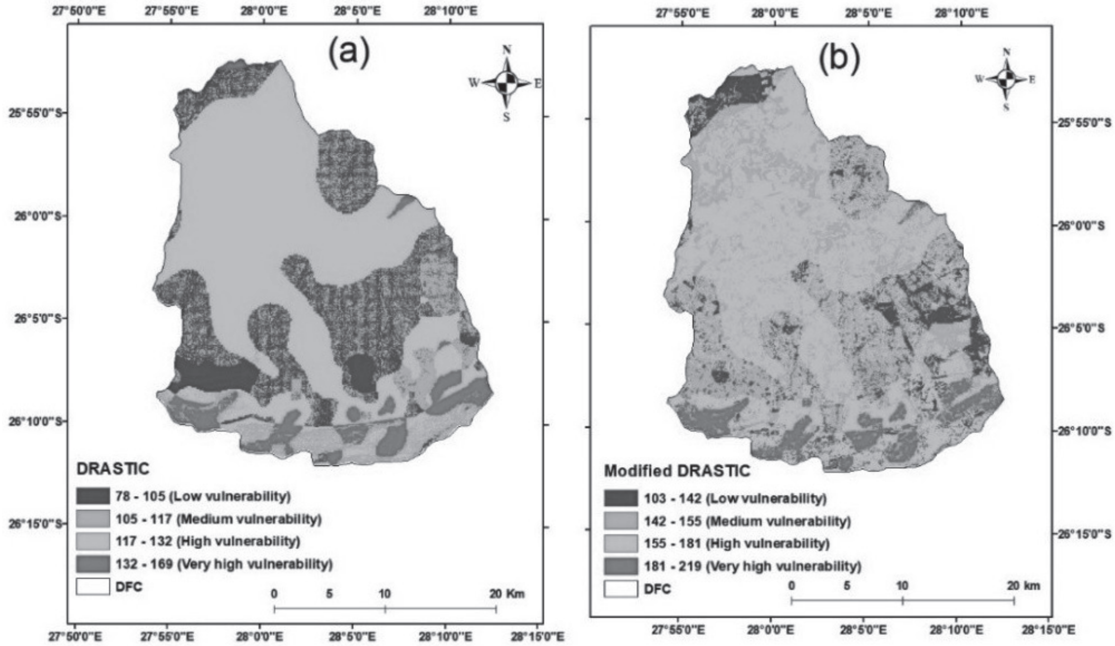

Fig. 4. Vulnerability index maps: a) DRASTIC, b) modified DRASTIC.

Table 5. Statistical summary of the DRASTIC parameters.

Parameters	D	R	A	S	T	I	C	Lu
Minimum	1	6	4	5	1	3	1	5
Maximum	10	8	10	6	10	9	9	10
Mean	5.25	7.00	7.40	5.50	5.60	5.50	4.28	7.50
Standard deviation	3.49	1.00	2.15	0.5	3.44	2.29	2.49	1.80
CV (%)	66.47	14.28	29.05	9.09	61.42	41.63	58.17	24.00

Table 6. Single parameter sensitivity analysis statistical summary

Parameters		D	R	A	S	T	I	C	Lu
Theoretical weight		5	4	3	2	1	5	3	5
Theoretical weight (%)		17.87	14.28	10.71	7.14	3.57	17.85	10.71	17.87
Effective weight (%)	Mean	17.14	15.52	15.10	7.75	4.01	10.54	5.89	24.05
	Min	3.47	11.65	6.94	4.95	0.52	7.73	1.74	3.12
	Max	39.37	24.74	25.00	112.37	9.25	29.03	15.92	35.43
	SD	6.11	1.91	2.50	0.96	1.56	2.73	1.44	7.39

Weight Modification Using Single Parameter Sensitivity Analysis

The modified DRASTIC index statistic summary in Table 5 indicates that the aquifer media and land use recorded high mean values of 7.40 and 7.50, respectively, with a relatively low coefficient of variation (CV) of 29.05 and 24.00. In contrast, the depth of groundwater and topography have a high CV of 66.47 and 61.42 with a mean value of 5.25 and 5.60, respectively. According to the CV result, groundwater depth substantially influences groundwater vulnerability variation, whereas soil media has the least effect on ground water vulnerability. DRASTIC parameters with a high coefficient of variation contribute more to groundwater vulnerability variance, whereas those with a low coefficient of variation contribute less to

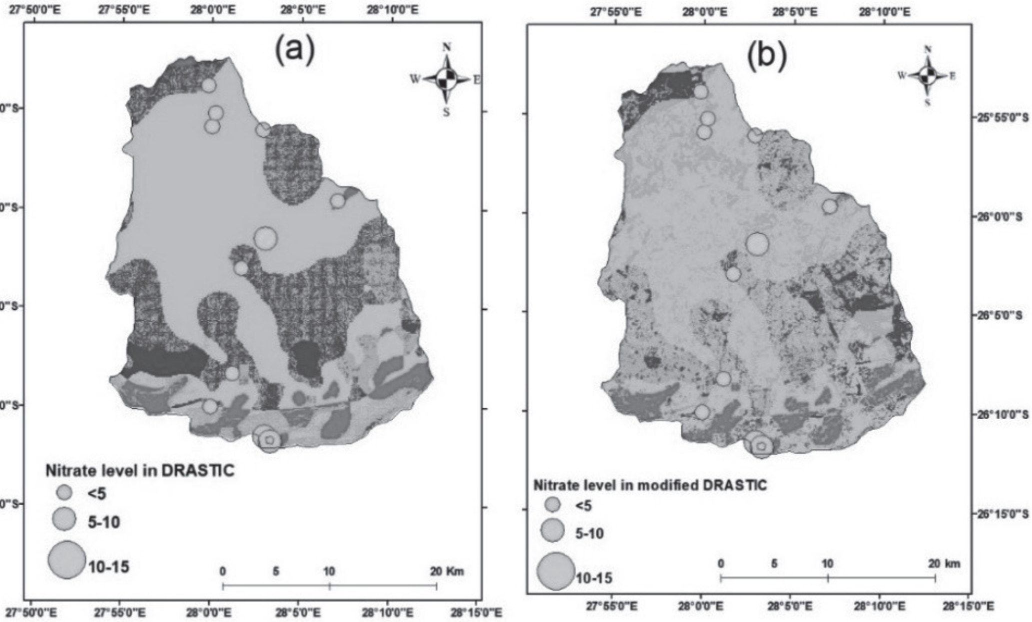

Fig. 5. Nitrate value distribution in: a) DRASTIC, b) modified DRASTIC vulnerability maps.

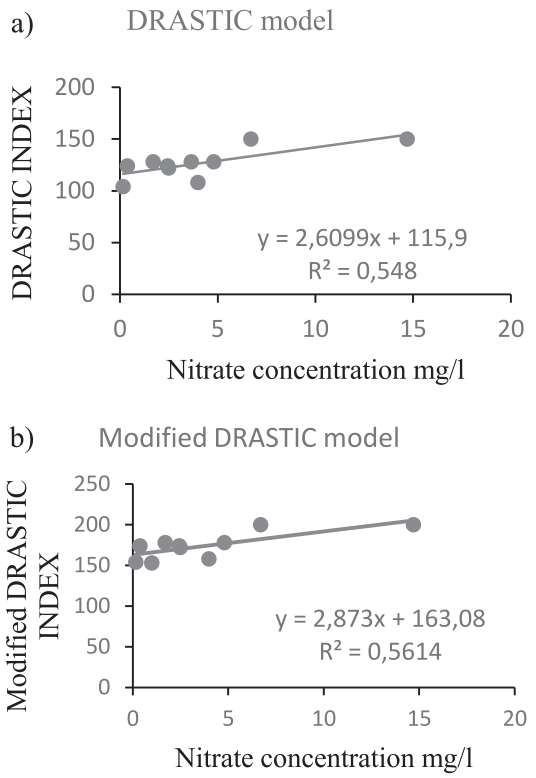

Fig. 6. Regression results of the DRASTIC and modified DRASTIC models.

groundwater vulnerability fluctuation [29].

The effective weight is a function of the single parameter's value in relation to the other parameters and the DRASTIC model's weight [30]. The SPSA result show that some parameters have high effective weight, while others parameters have low weights and deviate from their theoretical weights. Table 6 shows the theoretical weight assigned by modified DRASTIC. Land use, aquifer type, and topography are essential factors as their effective weight (24.05, 15.10 and 4.01%, respectively), exceeding their theoretical weights (17.87, 10.71, and 3.57%, respectively). The theoretical weight of soil media (7.75%) also surpasses its effective weight (7.14%). However, hydraulic conductivity, vadose zone, and groundwater depth recorded high theoretical weight (10.71, 17.85, and 17.87%, respectively) compared to effective weight (5.89, 10.54, and 17.14%, respectively).

Validation of Groundwater Vulnerability Models Using Nitrate

Validation is a crucial component of modelling for the empirical models to yield reliable findings. In the groundwater system, nitrate has no natural source. As a result, its presence in the groundwater system suggests pollution from agricultural, industrial, and anthropogenic sources [19]. Nitrate has been utilised in numerous research, such as [19, 29, 31], as a successful validation parameter for vulnerability assessment models. In this study, the nitrate values are superimposed with the DRASTIC and modified DRASTIC vulnerability maps, as shown in Fig. 5. The result indicates, the northern section of the research region has low vulnerable zones with a low nitrate levels, while the southern part is located in a high vulnerable zones with a high nitrate concentration levels. As a result, rising nitrate levels in the southern section are likely due to industrial activities and waste disposals from human activities. The scatter plot of nitrate concentration level and the vulnerability models are presented in (Fig. 6a and b). The correlation of nitrate and DRASTIC models showed $R^2 = 0.548$ and slight improvement on the modified DRASTIC model $R^2 = 0.56$.

Ghazavi and Ebrahimi [32] stated that more than ten mg/l nitrate concentrations indicate anthropogenic contamination, while the research area's southern catchment had above 14 mg/l in February 2020. As a result, it could be linked to increased human activity in metropolitan areas, which raises nitrate level. The obtained groundwater vulnerability potential map can be used as a more efficient groundwater resource pre-planning, management, and protection tool.

Conclusions

The study's aim was to evaluate the modified DRASTIC models based on their statistical analysis to detect groundwater vulnerability in the Doornfontein area, near Johannesburg CBD. All approaches were used in the GIS platform to incorporate many parameters. The result reveals that about 55.26% (419.47 km^2) of the research area, located in the north eastern, western and central regions, is high at risk of contamination. 5.6% (43.41 km^2) in southern side of the study region was found with a very high vulnerability zone. About 28.83% (217.79 km^2) has a moderate pollution potential, and 10.3% (79.88 km^2) has a low pollution potential. According to the result, the analysis of various areas using the modified DRASTIC map and the nitrate level reveals that the model can give reliable findings for forecasting vulnerability to contamination.

The impact of each parameter on the final index was investigated using an SPSA model. Overall findings reveal that aquifer media, land use, soil media, and topography shows a primary role in assessing vulnerability. Hence, collecting reliable, accurate, and representative data on these factors is required to produce an accurate result. The modified DRASTIC model is more accurate when adequate and exact data is provided. In general, all datasets should be valid and sufficient to allow practical analysis. In the most critical locations for groundwater resource conservation, the modified DRASTIC model produced realistic results. The groundwater vulnerability map is a low-cost method for detecting zones of possible groundwater contamination. In this study, modified DRASTIC model is a valuable tool for creating groundwater susceptibility maps, mainly when used in conjunction with a GIS and a good database. Comparing the vulnerability map and the land-use map makes it possible to pinpoint places with a significant risk of groundwater pollution.

Acknowledgments

The South African Council for Geoscience and the Department of Water and Sanitation are acknowledged for providing data.

Conflict of Interest

The authors declare no conflict of interest.

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