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Modelling Groundwater Vulnerability to Contamination using DRASTIC Model through Geospatial Techniques over Northern Kwazulu-Natal, South Africa

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Abstract

This study models groundwater vulnerability to contamination in three northern district municipalities (Amajuba, Zululand and Umkhanyakude) in KwaZulu Natal province in South Africa using GIS-based DRASTIC model. The method considers seven parameters: depth to water table (D), recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). DRASTIC parameter maps are generated in ArcGIS environment and relevant weights assigned. A weighted overlay analysis is then employed to generate the groundwater vulnerability map for the study area. Finally, the groundwater vulnerability map is combined with land use/cover to obtain groundwater pollution risk map. Results indicate that 22, 45, 21 and 12% of the total area are under low, moderate, high, and very high groundwater contamination vulnerable zones, respectively. Low, moderate, high, and very high groundwater pollution risk are found in 23, 40, 27 and 10% of the total area, respectively. These results can be used by environmental managers, spatial planers and other policy makers in formulating integrated and sustainable development plans to ensure optimal groundwater exploitation and conservation in the northern KwaZulu Natal region.

1. Introduction

Groundwater is "the water from rainfall or surface water body such as lakes and streams that infiltrates into the soil and bedrock and deposits into the subsurface in small pores and spaces between rocks and soil particles" (Adnan et al., 2018). Its contamination is mostly caused by various anthropogenic activities such as urban development, mining, agriculture, waste disposal and metallurgical industries, among other activities. For example, groundwater contamination by high nitrate concentrations is caused by urban development and agricultural activities (Ouedrago et al., 2016). The concept of groundwater vulnerability assessment is to "distinguish between areas where the groundwater system is more vulnerable to contamination and areas with lower groundwater vulnerability" (Oke & Fourie, 2017). It distinguishes between specific and intrinsic vulnerability which measures the "likelihood that groundwater systems maybe degraded" (Ouedrago et al., 2016) if "pollutants are to contact the groundwater table after infiltration at the ground surface" (Adnan et al., 2018).

Various studies have been undertaken to assess the vulnerability of groundwater to contamination in different hydrogeological environments at different scales (continental, national, regional, municipal, village and borehole). Some studies have concentrated in assessing groundwater vulnerability to contamination to minimize adverse consequences on groundwater resources, protect aquifers and achieve the safety and conservation of the aquifers (e.g., Adnan et al., 2018; Machdar et al., 2018) while others have estimated the pollution risk of groundwater (Ouedrago et al., 2016; Machdar et al., 2018).

Groundwater vulnerability assessment methods range from simple inexpensive approaches such as GIS based qualitative methods to complex expensive methodologies such as process-based and statistical methods as discussed by various authors (e.g., Barber et al., 1993; Sililo et al., 2001; Adnan et al., 2018; Kumar et al., 2019). GIS based qualitative methods based on assigned rating and weighting of hydrogeological factors, are the most used methods for evaluating groundwater vulnerability to contamination (Sililo et al., 2001; Duarte et al., 2019). The GIS based qualitative methods can be used to assess intrinsic groundwater vulnerability, defined as "the capacity with which a contaminant introduced at the ground surface can reach and diffuse in groundwater " and specific groundwater vulnerability defined as "the vulnerability of groundwater to a particular contaminant or a group of contaminants" (Ouedrago et al., 2016). Intrinsic groundwater vulnerability is based on the properties of hydrogeological settings and systems whereas the specific vulnerability focusses on the properties of a contaminant, load, and its behaviour (Sililo et al., 2001; Ouedrago et al., 2016; Duarte et al., 2019).

The commonly used hydrological parameters are described by DRASTIC model (Aller et al., 1987). The DRASTIC model refers to a combination of seven major factors affecting and controlling groundwater movement: D - depth to the groundwater table, R - net recharge, A - aquifer media, S - soil media, T - topography, I - impact of the vadose zone and C - hydraulic conductivity (Aller et al., 1987). Many authors have used DRATIC model for assessing groundwater vulnerability to contamination in various parts of the world, we only mention a few here, e.g., South Africa (Musekiwa & Majola, 2013), Africa (Ouedrago et al., 2016), Peshawar District, Pakistan (Adnan et al., 2018), India (Mondal et al., 2017; Kumar & Krishna, 2020; Bera et al., 2022), Indonesia (Machdar et al., 2018), Central Portugal (Duarte et al., 2019), Liberia (Koon et al., 2023), United Arab Emirates (Khan et al., 2022), Iran (Khosravi et al., 2021), and Melaka State in Malaysia (Shirazi et al., 2013). DRASTIC variables can be observed using remote sensing techniques and other ground-based measurement systems while geographical information systems (GIS) are mostly used for mapping, analysis, and modelling of observed/deduced/derived DRASTIC variables to estimate groundwater vulnerability to contamination.

Although groundwater vulnerability to contamination has been determined at a national scale in South Africa (Maherry et al., 2010; Musekiwa & Majola, 2013), local interpretation and application of such results are normally difficult due to the small-scaled analysis and representation of details. Therefore, there is a need for a sub-national (local scale) determination and analysis of groundwater vulnerability to contamination to enable large scale representation of details to facilitate meaningful groundwater resource planning and conservation. The aim of this study is to assess groundwater vulnerability to contamination in northern KwaZulu-Natal in South Africa (specifically, Amajuba, Zululand and Umkhanyakude district municipalities), using GIS and remote sensing techniques to map and model DRASTIC parameters. Land use/cover is also included to assess risks associated with groundwater vulnerability to contamination using a modified DRASTIC model.

2. Materials and Methods

2.1. Study Area

Northern KwaZulu Natal (NKZN) is located at the northern region of KwaZulu Natal province in South Africa, it consists of three district municipalities (Amajuba, Zululand and Umkhanyakude) as shown in Figure 1. Amajuba District Municipality (ADM) is located at the north-west corner of KwaZulu Natal (KZN), it borders Free State and Mpumalanga provinces. Zululand District Municipality (ZDM) is located on the northern region of KZN bordered by Swaziland and Mpumalanga province to the North. Umkhanyakude District Municipality (UKDM) is located to the east of KZN. NKZN region has a total surface area of 35,756 km^2.

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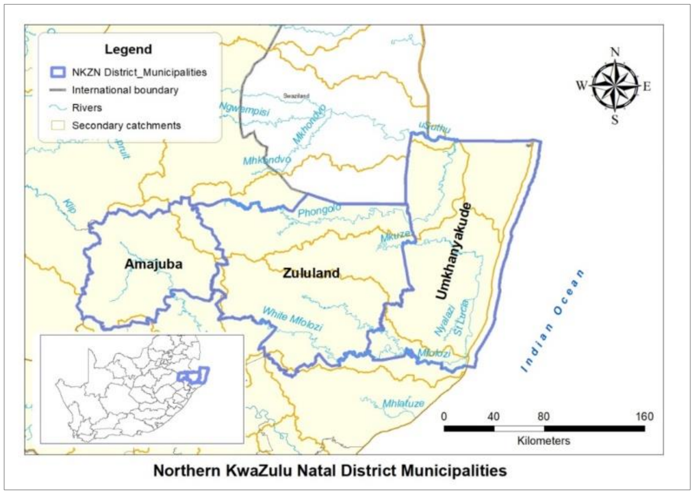
NKZN region is characterised by heavy summer rainfall and little rainfall in winter. Thunderstorms and mist (at higher elevations) are the contributing forms of precipitation in the region. NKZN has a mean annual precipitation ranging from 493 to 1,682 mm, but along the coastal region the range is 1,200 -1,400 mm (UKDM, 2016). The mean annual temperature ranges from 4 to 31°C and decreases to 21°C along the coastal region (ZDM, 2019). Geological formations of the parent material have a clay forming potential with silica content, which are passed on to the shallow soils, hence presence of swelling black clays and sands. Lime is abundant in most of the landscape. A high proportion of the area is under thicket, grassland, and wetland while the rest is used for cultivation and settlement. The grasslands have been disturbed by livestock grazing and soil erosion, but not completely transformed. The NKZN population is 2,112,727 according to the Stats SA (2016) census.



Source: Analysis, 2022

Figure 1. Spatial location of the study area

Groundwater protection from anthropogenic activities in NKZN region has failed due to a lack of proper mechanism for evaluating groundwater, and a lack of information relating to groundwater management (UKDM, 2016). Mining, industry and farming activities, and shallow groundwater levels are some of the causes of groundwater pollution in NKZN (UKDM, 2016; ADM, 2018). Contaminated groundwater has in turn caused outbreak of bacteria related diseases such as cholera, particularly in ADM (Institute of Natural Resources, 2019). Thus, there is a need for groundwater management information to improve groundwater quality in the northern KwaZulu-Natal since it is facing a pollution risk from poor land use planning, growing population, agricultural activities, poor water quality and management and development of new mines (Foster et al., 2002; Adnan et al., 2018).

The stress on valuable groundwater resource is increased by population growth, social and economic development (UKDM, 2016; ADM, 2018; ZDM, 2019). In rural areas of South Africa such as some parts of NKZN, groundwater is an important source of water supply, for agricultural, domestic, and industrial activities (Ersoy & Gültekin, 2013; Machdar et al., 2018). Hence, there is an increasing demand for groundwater to meet the needs of rural communities (UKDM, 2016; ADM, 2018). The need for groundwater quality preservation can therefore not be overemphasised.

2.2. Data Description

This study used secondary data from various organisations in South Africa and United States Geological Survey (Table 1). The DRASTIC model factors/parameters obtained from various organisations included depth to the groundwater table, recharge, aquifer media, soil media, topography, impact of the vadose zone and conductivity. In addition, land use/cover datasets for 2018 are included for pollution risk assessment.

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Table 1. Datasets and Sources

Parameter	Spatial resolution/structure	Source
Depth to groundwater (D)	1×1 km (water level map)	South Africa's Department of water and Sanitation
Net Recharge (R)	Scattered/nonuniform	South Africa's Department of Water and Sanitation
Aquifer media (A)	1: 250000 (geological map)	South Africa's Council for Geoscience and Department of Water and Sanitation
Soil media (S)	Scattered/ nonuniform	South Africa's Department of Water and Sanitation
Topography (T)	30 × 30 m (DEM – SRTM-1)	United States Geological Survey
Impact of vadose zone (I)	1:250000 (Geological map)	South Africa Spatial Data Infrastructure and Council for Geoscience
Hydraulic Conductivity (C)	Scattered/ nonuniform	South Africa's Council for Geoscience
Land use/cover	30 by 30 m (2018 Landsat imagery)	United States Geological Survey

Source: Analysis, 2022

A brief description of each of the hydro-geologic factors is given below following previous studies (Aller et al., 1987; Ouedrago et al., 2016; Adnan et al., 2018; Machdar et al., 2018; Kumar et al., 2019). Depth to water table (D) means the distance from the topographical surface to the water table, it indicates the distance contaminants must pass through before reaching the groundwater. Net Recharge (R) is the amount of water in a unit area that infiltrates the ground surface and transports contaminants to the water table. It is the most important cause for contaminants to reach the water table, thus areas of high net recharge are more vulnerable to contamination. Aquifer media (A) are consolidated and unconsolidated rocks below the earth surface which hold underground water. The type of rock affects the travel of contaminants due to their differences in permeability: low permeable rocks are less vulnerable to contamination because they slow down the travel of contaminants while high permeable rocks are more vulnerable to contamination because they facilitate travel of contaminants to the underground water. Soil media (S) are the topmost layer of the earth rocks and weathered part lying between the earth surface and the uppermost bedrock. These layers (soil media) highly affect the descending movement of contaminants.

Topography (T) is the gradient of the earth terrain which is followed by the rainwater and stream water. Flat lying areas are more vulnerable to groundwater contamination than steep areas because water is stored for longer periods of time increasing the chances of attenuation. Impact of the vadose zone (I) is the upper portion of the subsurface where the soil and rock pores either contain water or air, thus also termed unsaturated zone. The impact of the vadose zone is measured in terms of permeability, porosity, and thickness since its influence on the vulnerability of groundwater to contamination is like that of aquifer and/or soil media. Hydraulic Conductivity (C) is the rate at which water is transmitted by the aquifer material, thus the higher the hydraulic conductivity, the higher the rate assigned, and an aquifer would be highly vulnerable. Land use/cove is an additional parameter integrated with DRASTIC parameters to evaluate and assess the risk to pollution in a study area. Land use/cover parameters such as mines/quarries, and cultivated areas are more vulnerable to groundwater contamination.

2.3. Modelling Groundwater Vulnerability to Contamination

The DRASTIC Model (Aller et al., 1987) has been used in this study for modelling groundwater vulnerability to contamination. The datasets required are discussed in section 2.2, in this section, we discuss the next steps after data collection/acquisition. These include ranges, rates, and weights for DRASTIC and anthropogenic factors (Table 2). This is followed by a weighted overly analysis procedure. The factors/parameters are then related to each other to determine the iinfluence of each factor to groundwater contamination as described by Aller et al. (1987). Five (5) is assigned to most significant factor(s) and one (1) is assigned to least significant factor(s) as shown in Table 2. Each DRASTIC factor is then divided into ranges or significant media type and then, each range for each DRASTIC factor is assigned a rate from 1 (least

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significant) to 10 (most significant). The DRASTIC Index (DI) is then calculated using eq. 1 (Aller et al., 1987),

$$DI = Dr \times Dw + Rr \times Rw + Ar \times Aw + Sr \times Sw + Tr. \times Tw + Ir \times Iw + Cr \times Cw \text{ ....(eq.1)}$$

where *D*, *R*, *A*, *S*, *T*, *I*, *C* are the seven DRASTIC factors while *r*, and *w*, are the rates and weights, respectively. The DRASTIC Index values indicate levels of groundwater vulnerability to contamination.

Table 2. Range, rate, and weight for DRASTIC and anthropogenic parameters

DRASTIC Parameter	Range	Rate	Weight
Depth to groundwater	0 – 5	10	5
	5 – 15	9	
	15 – 30	7	
	>30	5	
Net Recharge	<50	1	4
	50 – 100	3	
	100 – 180	6	
	>180	8	
Aquifer Media	Intergranular and fractured.	8	3
	Fractured	9	
	Intergranular	10	
Soil Media	Sand	9	2
	Sandy-loam	6	
	Sandy clay	5	
	Loam	4	
	Clay loam	3	
	Clay	2	
Topography	0 – 2	10	1
	2 – 6	9	
	6 – 12	5	
	12 – 18	3	
	>18	1	
Impact of the Vadose Zone Media	Igneous/Metamorphic rock	3	5
	Tillite	5	
	Sedimentary rock	6	
	Alluvial, Sand, Waterbody	8	
	Basalt	9	
Hydraulic Conductivity (m/day)	0.00001	8	3
	0.1	9	
	100	10	
Anthropogenic Parameter	**Categorization**	**Rating**	**Weight**
Land use/cover	Forest/barren land	1	5
	Water bodies/wetlands	3	
	Shrub/grassland	4	
	Built-up	8	
	Mines and quarries	9	
	Cultivated land	10	

Source: Analysis, 2022

We also used a modified DRASTIC model in this study, by incorporating anthropogenic influences, sources of contaminants, transportation pathways and traps. A modified approach referred to as Drastic Specific Vulnerability Index (DSVI) has been used by a number of authors (e.g., Musekiwa & Majola, 2013; Sakala et al., 2018; Ouedrago et al., 2016; Adnan et al., 2018; Mondal et al., 2017; Machdar et al., 2018). Therefore, a modified DRASTIC approach was adopted in this study to develop a pollution risk map. The pollution risk map generated shows a modified DRASTIC Index obtained by integrating land use information with DRASTIC parameters (see eq. 2) using a weight of 5 for the land use parameter.

DOI: 10.14710/geoplanning.10.2.111-122

$$MDI = DI + Lr \times Lw \text{........(eq.2)}$$

where, MDI is the resultant index for a Modified DRASTIC Index, DI is the DRASTIC Index and $Lr \times Lw$ is the product of rate and weight for land use/cover, being the land use index.

A geodatabase was created in ArcGIS environment for the depth to groundwater, net recharge, aquifer media, soil media, topography, impact of the vadose zone media, hydraulic conductivity and land use/cover data. These factors were then reclassified, and assigned relative rates and weights. A weighted overlay analysis was used to model both DRASTIC and Modified DRASTIC indices using eq. 1 and 2, respectively.

Finally, land use/cover as an additional parameter was integrated with DRASTIC parameters to evaluate and assess the risk to groundwater pollution in the study area. Land use parameters such as mines and quarries, and cultivated areas are more vulnerable to groundwater contamination, hence they are assigned higher rates. Land use/cover or anthropogenic activities such as agriculture, mining, industrial and commercial, have a great impact on groundwater vulnerability to contamination. Land use/cover was grouped into six classes, namely: mines and quarries, built-up (residential, commercial, industrial, and urban), forest/baren land, shrub/grassland, water bodies/wetlands and cultivated land. This parameter (land use/cover) was rated and assigned a weight of 5 because anthropogenic activities have the most significant influence on groundwater contamination.

3. Results and Discussion

3.1. Derived DRASTIC Parameters and Land Use/Land Cover Over NKZN

Reclassified maps for the seven DRASTIC parameters and land use/cover in the study area are shown in Figure 2. Groundwater levels (depth from the ground surface) ranging from 0 to 39 m is reclassified into four levels: 0 - 5, 5 - 15, 15 - 30 and >30 m according to Aller et. al. (1987) and Adnan et. al. (2018). These levels are then assigned rates of 10, 9, 7 and 5, respectively (Figure 2a). Areas along the northeastern boundary in UKDM and from the western side along the boundary between ADM and ZDM have higher water-table (less than 15 m from ground surface) thus more vulnerable to contamination, hence assigned high rates. Recharge in the study area comes from inflows by various rivers such as Mfolozi, Mkuze, Ngagane and Pongola. The recharge map was reclassified and assigned rates of 8, 6, 3, and 1 as shown in Figure 2b. High recharge areas depict a potential of high pollution risk to contamination and act as a vehicle for transporting contaminants to the groundwater. Shirazi et. al. (2013) mentioned that "recharge is controlled by land cover, slope, permeability of soil, and rainfall". Therefore, high recharge areas in UKDM and along the boundary between ADM and ZDM are associated with shallow intergranular aquifers and lower lying areas with a permeable sedimentary layer, hence a higher rating.

The aquifer national dataset acquired for South Africa had dolomite, fractured, fractured and intergranular and intergranular aquifer types. These were reclassified for the study area into 3 classes: fractured, fractured and intergranular, and intergranular, then, assigned ratings of 9, 8 and 10, respectively as shown in Figure 2c. The intergranular aquifer east of the study area in UKDM was assigned a higher aquifer rate because groundwater flows and fills the spaces between soil particles and fractured rocks. Resulting in a higher permeable aquifer media thus higher groundwater vulnerability to contaminants. Soil media affect groundwater vulnerability of the study area. Clay material restricts the movement of contaminants and results in low groundwater contamination risk at the center to the west of the study area, while groundwater contamination is high in areas with sand that do not contain silts and clays towards the eastern boundary of the study area. The soil media map was reclassified into ranges and then assigned rates from 2 to 9 as shown in Figure 2d.

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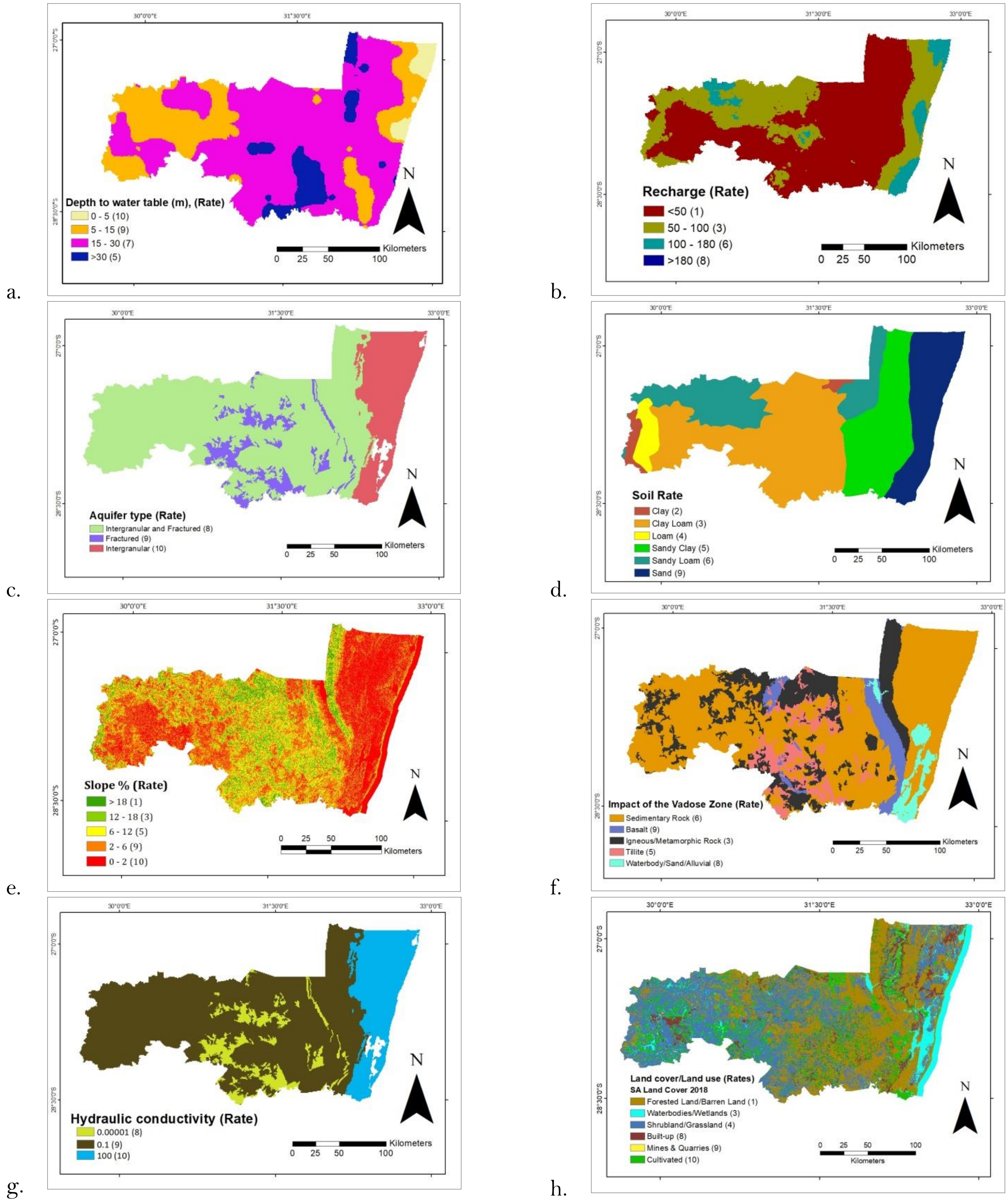

Source: Analysis, 2022

Figure 2. Reclassified DRASTIC Parameters and Land Use/Cover NKZN: **a** – depth to groundwater, **b** – net recharge, **c** – aquifer media, **d** – soil media, **e** – slope, **f** – vadose zone, **g** – hydraulic conductivity and **h** – land use/cover

Topography helps determine the possibility of contaminants running off or remaining on the surface long enough in a specific area to infiltrate into the ground water. The 1 arc-second SRTM – DEM was used to derive the slope percentages of the study area. The slope map was reclassified into five classes according to Aller et. al. (1987) and assigned rates from 1 to 10 as shown in Figure 2e. The study area is mainly associated with shallow slopes, mainly observed towards the western and eastern boundaries. These areas have a high potential for contaminants to infiltrate, thus high groundwater vulnerable zones.

The time available for attenuation of the contaminants below the soil horizon and above the water table is determined by the vadose zone material (Aller et. al., 1987). The vadose zone media map was reclassified and assigned rates from 3 to 9 according to Aller et al. (1987) and Shirazi et al. (2013), as shown in Figure 2f. This unsaturated layer above the water table mainly comprises of porous material in the study area. They include sand and basalts of UKDM and ZDM that contain sufficient openings between grains, fractures, joints, and cracks, hence higher rates.

The hydraulic conductivity values of the aquifer media obtained from Musekiwa & Majola (2013) were used. The number of void spaces due to intergranular porosity, fracturing, and bedding planes within the aquifer determines the hydraulic conductivity (Aller et. al., 1987). Hydraulic conductivity was assigned rates from 8 to 10, as shown in Figure 2g. Higher rates were assigned to high hydraulic conductivity associated with a higher potential for groundwater contamination observed along the eastern boundary of the study area.

Land use/cover has a great impact on the vulnerability of groundwater in the study area. The pollution potential varies throughout the study area because of various land use patterns shown in Figure 2h. There is high area coverage for forested land (with planted forest and natural woodland) at 34% of the entire area of study and grassland at 31.5%. The land use/cover map was reclassified and assigned rates from 1 to 10 according to Shirazi et al. (2013) and Ouedrago et al. (2016). Highly vulnerable land use/cover classes include cultivated lands, mines/quarries, and built-up areas, in order of decreasing vulnerability to pollution.

3.2. Groundwater Vulnerability to Contamination and Pollution Risk Over NKZN

The resulting DRASTIC index values ranged from 102 to 191, and these were reclassified into four classes (Figure 3) using the natural breaks (Jenks) classification method. The groundwater vulnerability to contamination in Northern KwaZulu Natal (NKZN) was classified into low vulnerability for DRATIC indices 102 to 129, moderate (129 – 146), high (146 – 164), and very high (164 – 191). High groundwater vulnerable areas are mainly located along the eastern boundary line of the study area indicating greater pollution potential zone where the slope is gentle. High to very high DRASTIC index values in these areas may be mainly due to low depth of groundwater, soil media and high net recharge. The central part of the study area has low to moderate DRASTIC index values which can be due to steep slopes that restrict contaminants from infiltrating to the groundwater table, thus run off because they cannot remain on the ground surface long enough in a specific area to infiltrate. The clay loam soil texture in the central part of the study area may have contributed to the low DRASTIC index values due to low permeability.

The low groundwater vulnerable areas of NKZN cover 22% of the total area as shown in Table 3, this is due to deep groundwater with less recharge and steep slopes. Very highly groundwater vulnerable areas cover 12% of the total area which is due to the shallow water table with high net recharge and flat lying areas. The moderately vulnerable groundwater area is the largest with 45% of the total area (Table 3), which is threatened by an intergranular and fractured aquifer as well as high recharge.

The rated land use/cove (Figure 2h) with its assigned weight was integrated with the ground water vulnerability to contamination results (Figure 3) as an additional parameter to generate the modified DRASTIC index or pollution risk map (Figure 4). The pollution risk map shows which anthropogenic activities are more responsible for the vulnerability of groundwater to contamination. The modified DRASTIC index values ranged from 107 to 241, and these were reclassified into four classes using the natural breaks (Jenks) classification method. The four classes of pollution risk are low (107 – 145), moderate (145 – 168), high (168 – 192), and very high (192 – 241).

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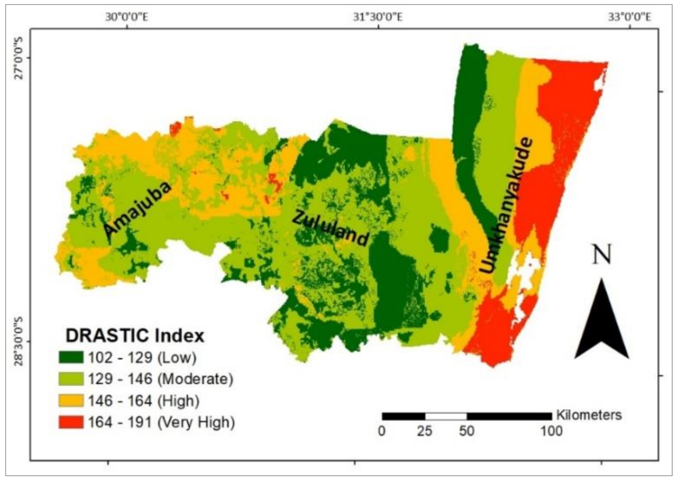
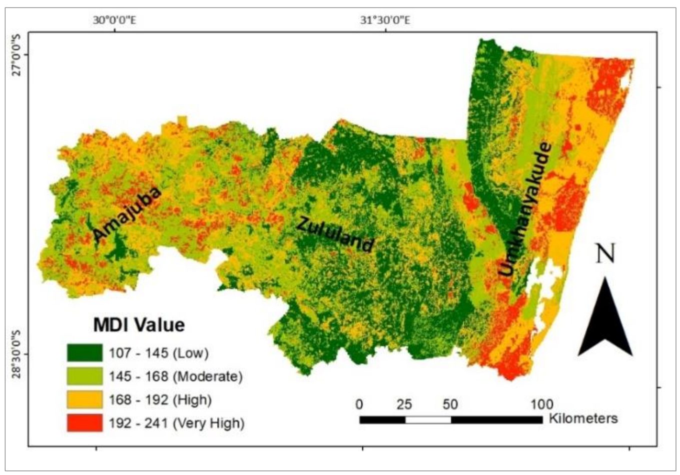


Source: Analysis, 2022

Figure 3. Groundwater Vulnerability to Contamination in NKZN



Source: Analysis, 2022

Figure 4. Groundwater Pollution Risk in NKZN

Most groundwater vulnerable areas are located along the eastern boundary of NKZN, this is due to flat lying areas where industrial, commercial, and agricultural activities are located. These activities fall under built-up, cultivated, grassland, and forested land, covering 9.4, 20.3, 31.5, and 34.1% of the area of study, respectively (see Figures 2h and 4). Water resources such as wetlands are under pressure along cultivated areas which explains high to very high pollution risk in parts of NKZN. Mines and quarries which include extraction and waste dump sites, are the second most vulnerable land use class because they significantly change the properties of hydrogeological parameters thus a high rating, but they cover only 0.1% of the area of study. Therefore, they are slightly insignificant to contribute to the high and very high risk to groundwater pollution in NKZN.

Groundwater pollution risk map (Figure 4) shows that low pollution risk areas account for 23% while very high pollution risk areas account for 10% of the entire area of study (Table 3). Most of the areas fall in high pollution risk areas (27%) and moderate pollution risk areas (40%). The most vulnerable areas are along the eastern boundary of NKZN which are the results of industrial, commercial, and agricultural activities. These highly vulnerable areas are a priority area requiring interventions to reduce groundwater pollution.

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Table 3. DRASTIC Index (DI) and Modified DI over NKZN

	DRASTIC Index range		Percentages	
Vulnerability classification	**DRASTIC Index**	**Modified DI**	**DRASTIC Index**	**Modified DI**
Low	102 – 129	107 – 145	22%	23%
Moderate	129 – 146	145 – 168	45%	40%
High	146 – 164	168 – 192	21%	27%
Very high	164 – 191	192 – 241	12%	10%

Source: Analysis, 2022

A nitrate level data from a study conducted by Maherry et al. (2010) to assess the state of nitrate pollution in groundwater over South Africa shows high nitrate concentration along the eastern boundary of NKZN. This correlates with the groundwater vulnerability to contamination (Figure 3) and pollution risk (Figure 4) over NKZN obtained in this study: where high to very high groundwater vulnerability to contamination and pollution risks are observed along the eastern boundary of NKZN. This only serves as a rough validation of DRASTIC and modified DRASTIC results obtained in this study. More representative groundwater quality data would be required for a rigorous validation of the results obtained in this study.

4. Conclusion

Groundwater vulnerability to contamination and related pollution risks were modelled using DRASTIC and modified DRASTIC models through geospatial techniques in three District Municipalities of Northern KwaZulu Natal (NKZN) in South Africa. Seven hydrogeological parameters of the DRASTIC model were acquired, processed, stored, and managed in a geodatabase created in ArcGIS environment. These parameters were reclassified and assigned ranges, rates, and weights, then modelled to generate a groundwater vulnerability map. The groundwater vulnerability map was combined with the land use/cover of 2018 to determine pollution risk to groundwater. Results obtained show that 33 – 37% of NKZN region is highly to very highly vulnerable to groundwater contamination while moderate groundwater vulnerability to contamination was observed in 40 – 45% of the NKZN region. Borehole level groundwater quality is needed for a rigorous validation of these results, this was a major challenge for this study. However, approximate validation adopted, though not rigorous, shows that our results are valid. This study raises awareness on groundwater contamination and pollution risk in NKZN region, to guide water managers and decision makers in developing integrated groundwater management plans to ensure optimal, sustainable, and safe exploitation of underground water resources in NKZN. Our future studies will consider detailed analysis of groundwater vulnerability to contamination at local scales in other regions of interest in South Africa. We recommend collection of borehole level groundwater quality data to facilitate a rigorous validation of DRASTIC model results.

5. Acknowledgments

We are grateful to the South African's Department of Rural Development and Land Reform (DRDLR) for the financial support granted to the first author through a postgraduate scholarship at the University of Cape Town. The following organizations are appreciated for directly providing or making relevant data freely available on their websites; South African's Department of Water and Sanitation, South African's Council for Geoscience, Division of Geomatics - University of Cape Town, and United States Geological Survey. We appreciate the two anonymous reviewers, for their constructive comments, suggestions and questions that have been used to improve the quality of this manuscript.

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