Groundwater Vulnerability Map for South Africa

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Abstract

Vulnerability of groundwater is a relative, non-measurable and dimensionless property which is based on the concept that some land areas are more vulnerable to groundwater contamination than others. Maps showing groundwater vulnerability assist with the identification of areas more susceptible to contamination than others. They are useful in planning, policy formulation and decision-making for groundwater management and protection. Overlaying these maps with maps showing the location of contamination sources and land use enables the creation of risk maps.

There are various methods for assessing groundwater vulnerability and from these the DRASTIC approach has been highlight in various studies as the most appropriate. This is mainly due to the fact that it is suitable for regional applications and the required input data are readily available. The DRASTIC index can be modified to incorporate anthropogenic influences on groundwater contamination and the modified form is called the DRASTIC Specific Vulnerability Index (DSVI). This paper discusses the creation of a groundwater vulnerability map for South Africa using the DSVI approach. The data used include the depth to groundwater, recharge, aquifer types, soil types, topography, the vadose zone, hydraulic conductivity and land use. These parameters were rated, weighted and combined to create the final map. The result was compared to groundwater quality data and similarities were found between the maps.

1. Introduction

DRASTIC is a model for evaluating pollution potential of large areas and its name is an acronym derived from the following seven parameters required for its use (Piscopo, 2001):
(1) Depth to water table; (2) **R**echarge (net); (3) **A**quifer media; (4) **S**oil media; (5) **T**opography; (6) **I**mpact of the vadose zone; and (7) **C**onductivity (Hydraulic).

The equation used for the DRASTIC Index is:

$$\text{DRASTIC Index (DI)} = D_rD_w + R_rR_W + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w$$

Where, r is the rating of the parameter and
w is the importance weight of the parameter (normally from 1 to 5) (Table 1).

Table 1: Description of parameter weights used when assessing groundwater vulnerability

Weight	Significance	Description
1	Least	Negligible contribution to factors that have an impact on an aquifer
2	Less	Little effect in enhancement or reduction of vulnerability due to the feature properties.
3	Moderate	Medium effect.
4	More	Consideration in the assessment process is crucial due to its properties in relation to aquifer vulnerability.
5	Most	Has the most important properties that could affect aquifer vulnerability.

The following are the assumptions for the DRASTIC model:

i) any contaminant is introduced at the land surface and into groundwater by precipitation;

ii) the contaminant has the mobility of water; and

iii) the area evaluated is 0.4 km^2 or more (Kim and Hamm, 1999).

Leal and Castillo (2003) propose a modified DRASTIC index that incorporates anthropogenic influences on groundwater contamination. An example of an anthropogenic impact is provided by Stigter et al. (2006) who consider the impact of agricultural diffuse pollution on contamination. Also, areas with a high degree of human activity may also have a higher risk of soil and groundwater contamination (Meinardi et al., 1994). In this paper, land use is considered to be an important parameter when assessing groundwater vulnerability since human activities may control the presence or absence of contaminants.

To incorporate the potential anthropogenic sources of contamination, an Anthropogenic Impact (AI) parameter can be added to the DRASTIC index to obtain the DRASTIC Specific Vulnerability Index (DSVI) proposed by Leal and Castillo (2003). The DSVI is defined as

$$DSVI = DRASTIC\ Index + AI_r AI_w$$

Where AI_r is the AI rating, and AI_w is the AI parameter weighting.

Robins et al., 2007 critique the use of the DRASTIC approach for groundwater vulnerability assessment in South Africa by arguing that the weight of the recharge parameter should be reduced in order to ensure that poorly productive but socially important aquifers are assessed. This recommendation was adopted in this study as indicated by the weights shown in Section 2.2.

The groundwater vulnerability map currently in use in South Africa was created by GEOSS (Geohydrological and Spatial Solutions International) for the Groundwater Resources Assessment II (GRA2) study conducted by the Department of Water Affairs 2004 and this was also based on the DRASTIC method. The vulnerability map created in this paper differs from the GRA2 map as the one in this paper is based on the DSVI and it incorporates land use, which caters for the impact of different land use types on pollution (Lynch et al., 1994). It also uses a different rating method, based on the Analytical Hierarchy Process (AHP) and assigns a smaller weight to recharge.

2. Methodology

The DRASTIC approach involves three steps, first is the selection of the datasets followed by the rating and finally the weighting of parameters. The datasets used are discussed in Section 4 and these were converted to raster format before being analysed in ArcGIS. This section 3 discusses the rating and weighing of the parameters.

2.1 Rating of Parameters

The different classes of the parameters are rated according to the purpose of the study and the properties of different units of the study area. The Analytical Hierarchy Process (AHP) for multicriteria decision analysis was used. AHP involves the following steps (Saaty, 1980):

i) Defining the problem; that is the ranking the parameters that affect groundwater vulnerability.
ii) Creating a structural hierarchy from the goal at the top, then the objectives and lastly the criteria/parameter classes'.
iii) The various parameters classes' are evaluated by comparing them to one another (in pairs), one at a time, assessing which of the two is more important relative to vulnerability. In making the comparisons; data about the parameters or expert judgments about the parameters' relative meaning and importance can be used.
iv) Pairwise comparison matrices are constructed from the results and these are used to rate the collective classes against each other till the final rating values are obtained for all parameters. The rating value is between 0 and 1. Parameter classes with a value of 1 represent more vulnerable areas and 0 the least vulnerable. For example, a parameter class assigned a value of 0.2, has twice the impact of one with a weight of 0.1.

2.2 Weighting of Parameters

The next step is the assigning of weights for the different parameters; the values go from 1 to 5 with 5 being the most significant to aquifer vulnerability and 1 the least significant. The corresponding weights are shown in Table 2 below.

Table 2: Weighting of parameters.

Parameter	Weight	Parameter	Weight
Depth to groundwater (D_w)	5	Topography (T_w)	1
Recharge (R_w)	3	Impact of vadose zone (I_w)	5
Aquifer media (A_w)	4	Hydraulic Conductivity (C_w)	3
Soil Media (S_w)	2	Land use (AI)	1

3. Datasets

3.1 Depth to Water Table

The depth to water table is the distance contaminants have to travel before reaching the aquifer and it indicates contact time with the surrounding media. In a confined aquifer, due to the low permeability of the confining media, the travel of contaminants is slowed down and the contaminants cannot easily reach the aquifer. These types of aquifers are therefore less vulnerable to pollution when compared to unconfined aquifers (Hasiniaina et al., 2010). This depth to groundwater map (Figure 1) was derived from the National Groundwater Database (NGDB) and using inverse distance weighting (IDW) was interpolated to cover South Africa. Figure 1 shows the classes and their ratings.

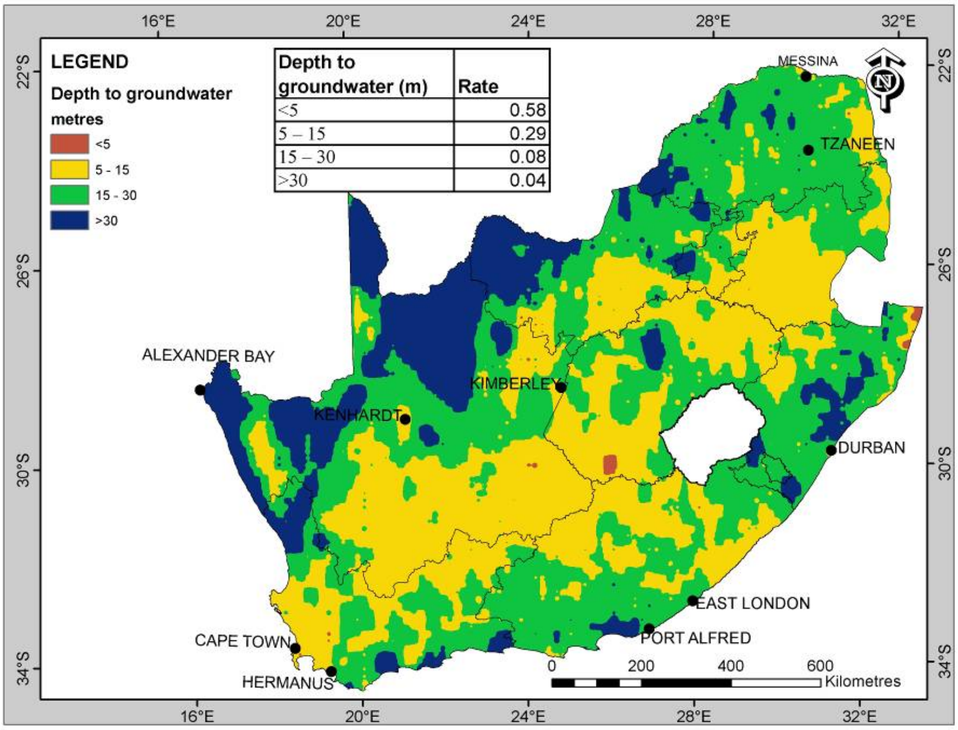

Figure 1: Depth to groundwater map with classes and rates

3.2 Net Recharge

Recharge is the principal vehicle for leaching and transporting solid or liquid contaminants to the water table (Aller et al., 1987). High recharge areas are more vulnerable than low recharge areas. The recharge map compiled by DWA as part of the Groundwater Resources Assessment study of 2004 was used. The map is shown in Figure 2 with the classes and rates.

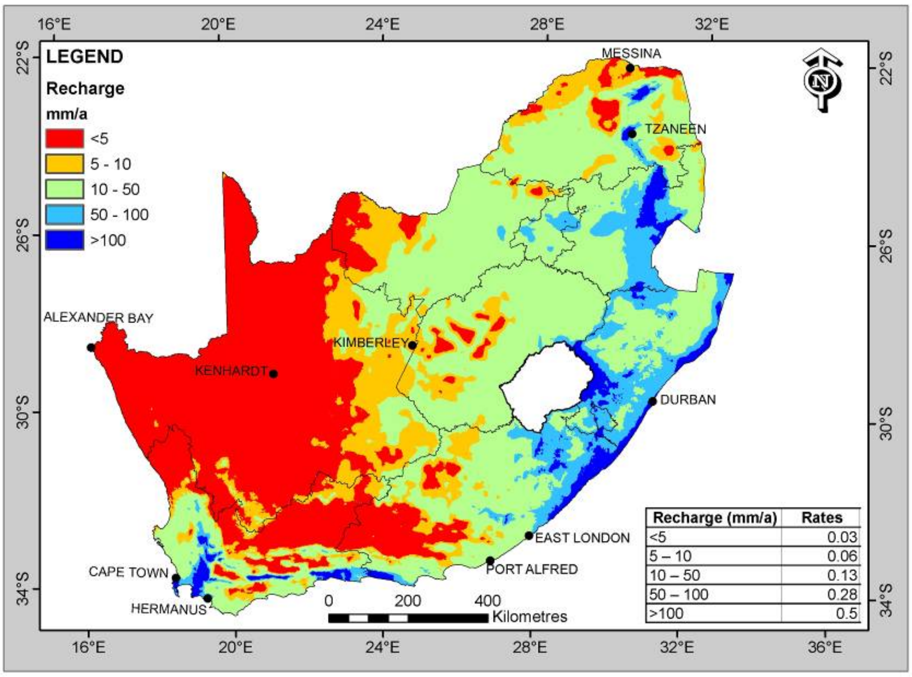

Figure 2: Recharge map and the rates for the different classes

3.3 Aquifer Media

The type of aquifer affects groundwater vulnerability; the more fractured and the higher the permeability of the rock, the higher the vulnerability. The 1:1 000 000 scale geological map of South Africa from the Council for Geoscience (Keyser, 1997) was used and grouped into different aquifer types (see Figure 3). The 1:500 000 hydrogeological map from DWA could have been used but it does not provides as much detail as the 1:1 000 000 data. The ratings assigned to each aquifer class are shown in Figure 3.

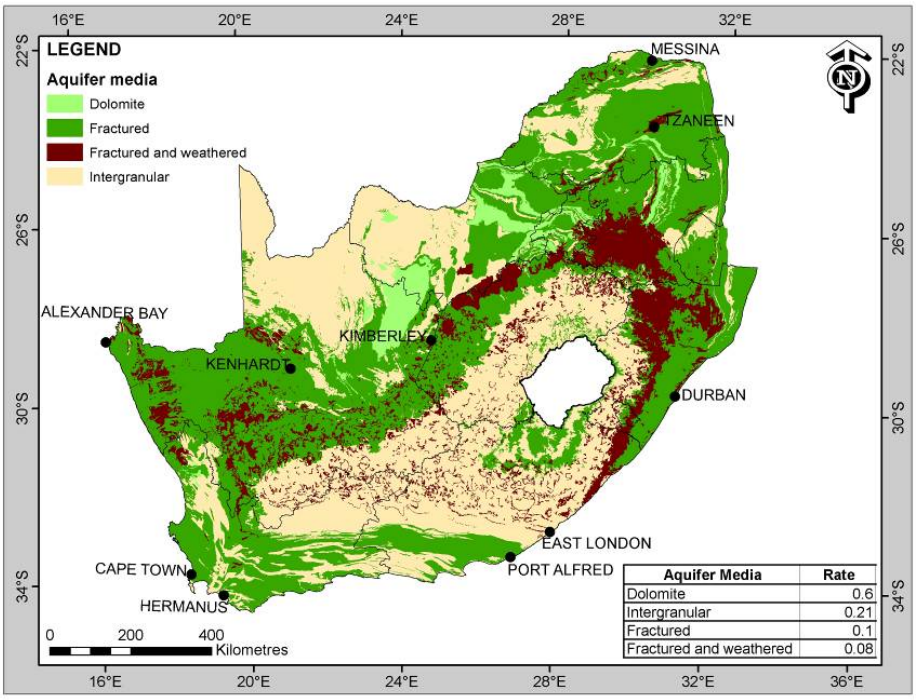

Figure 3: Aquifer media map and rates for the different media

3.4 Soil Media

Soils with a high organic matter or high clay content lessen the potential for contamination when compared to soils with a low clay and organic matter content. Consequently, sandy soils are assigned a higher rating than clay soils. The soil data used was from the Water Resources Assessment Study done in 1990 (Midgley et al., 1994) based on data from the Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW). Figure 4 shows the broad soil texture classes and the rates.

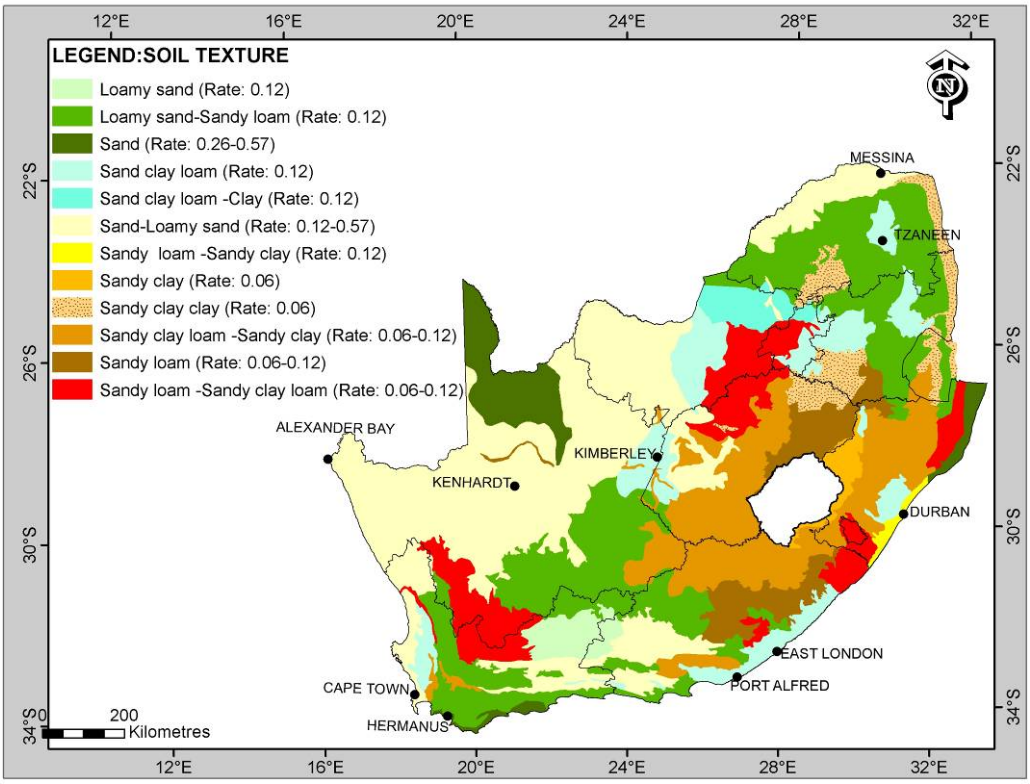

Figure 4 : Soil texture map and rates for the different soil types

3.5 Topography (slope)

In areas of low slope there is a greater chance of the pollution infiltrating the aquifer as opposed to areas of high slope (where the pollutant is more likely to run off).The 90 metre shuttle radar topography mission (STRM) data was used. This data was converted to slope values using ArcGIS 3D Analyst. The slope map is shown in Figure 5 with the ratings for the different slope classes.

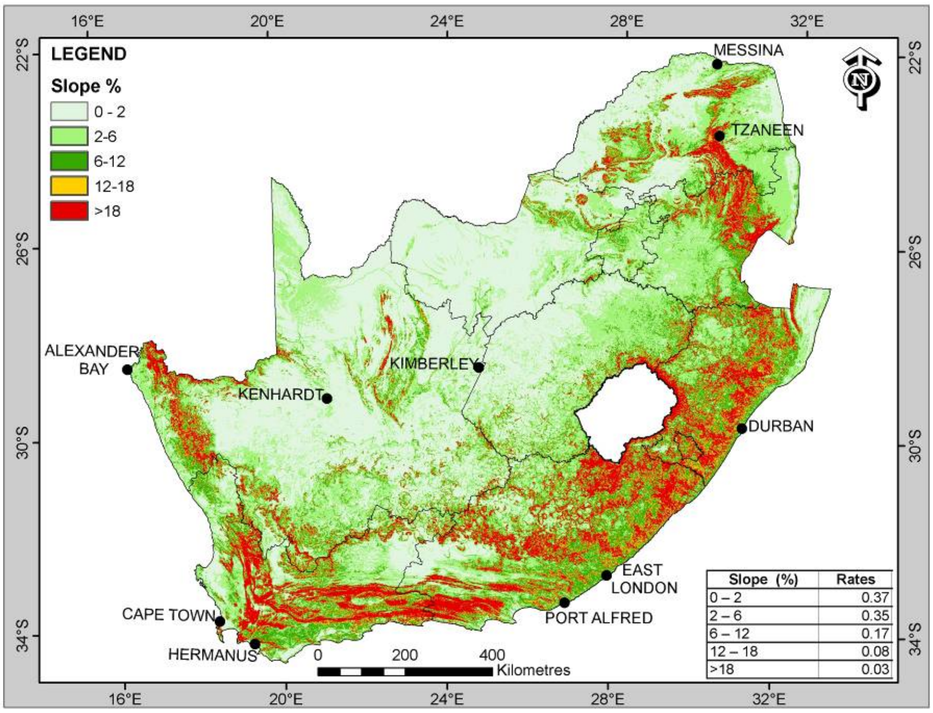

Figure 5: Slope classes used for the study area

3.6 Impact of the Vadose Zone

The vadose zone, also termed the unsaturated zone is the portion of the subsurface in which soil pores contain either air or water. This zone contains natural organisms with the ability to break down contaminants into secondary products.

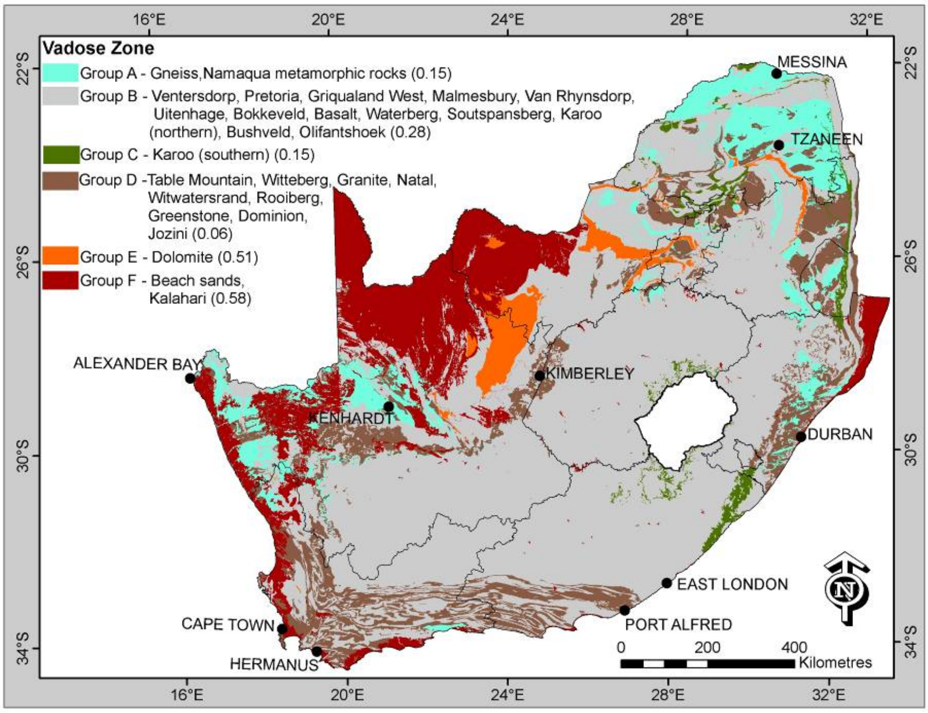

Figure 6: The classes for the impact of the vadose zone parameter (the rates are in brackets)

The characteristics of the vadose zone, aquifer including the soil porosity, the permeability and the depth to water levels therefore determine the contact time with these organisms since the path length and route will be influenced by vadose zone characteristics (Hasiniaina et al., 2010). Values were assigned to each aquifer media derived from the 1:1 000 000 geology map. The values and ratings are shown in Figure 6.

3.7 Hydraulic Conductivity

Hydraulic conductivity values were assigned to the different aquifer types (see Figure 3). These approximate values were taken from geology literature which lists typical values for different geology types. There were no field measurements conducted to verify these values. The ratings are listed in Table 3. The higher the conductivity, the greater the rate assigned.

Table 3: The ratings for the hydraulic conductivity of different aquifer types

Aquifer type	**Hydraulic Conductivity**	**Rate**
Dolomite	$1x10^4 – 1x10^2$	0.6
Integranular	$1x10^2 – 1x10^1$	0.21
Fractured	$1x10^1 – 1x10^{-5}$	0.1
Fractured and weathered	$1x10^1 – 1x10^{-1}$	0.08

3.8 Land Use

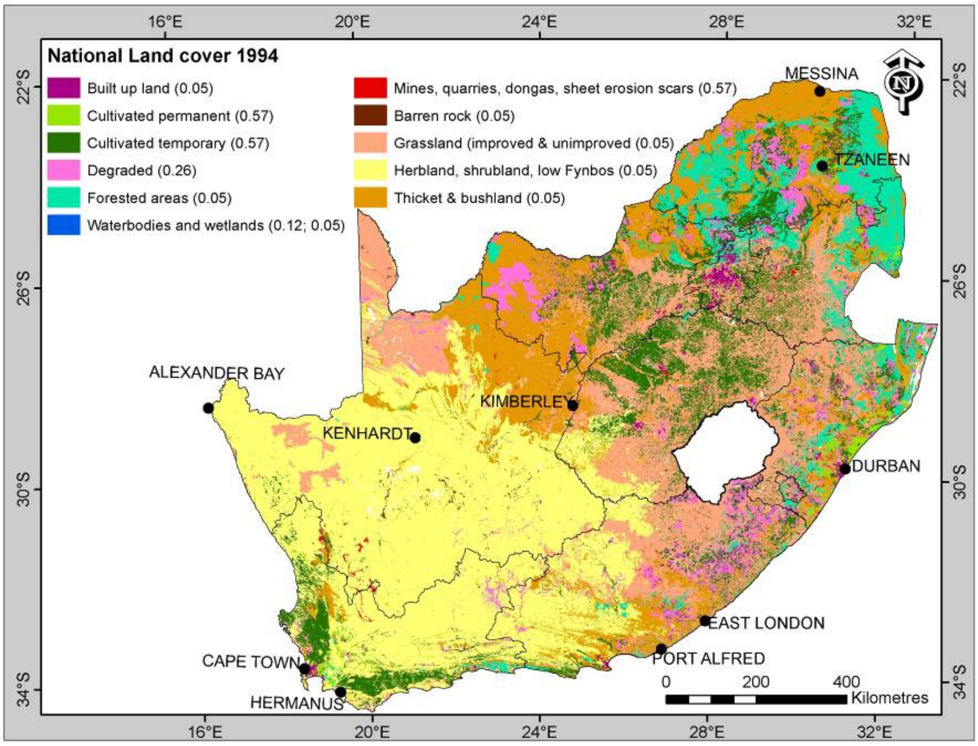

Figure 7: The different classes for the land use parameter and the rates are in brackets

In terms of land use, irrigation water or agricultural chemicals lead to the occurrence of non-point source pollution hence cultivated areas are assigned higher ratings than other land use classes. According to Merchant (1994) cited in Secunda et al., 1998, extensive agriculture land use over prolonged periods of time at the same area can result in the altering of the soil colloidal nature and the degree of percolation through the soil matrix. Areas with high levels of human activity, i.e. built up urban areas have a high risk of soil and groundwater contamination (Meinardi et al., 1994). Mine and quarries, dongas and sheet erosion also significantly contribute to groundwater pollution. The National land cover map created from 1994 Landsat satellite imagery was used in this study. Figure 7 shows the generalized classes and ratings. If the study were conducted at smaller scale, then more detailed land use data, for example data from aerial photography or high resolution satellite imagery could be used.

4. Results

The groundwater vulnerability map was created by multiplying the different parameters with their weights and adding them together. The resulting map is shown in Figure 8 and the raster has a spatial resolution of 150 x 150 metres.

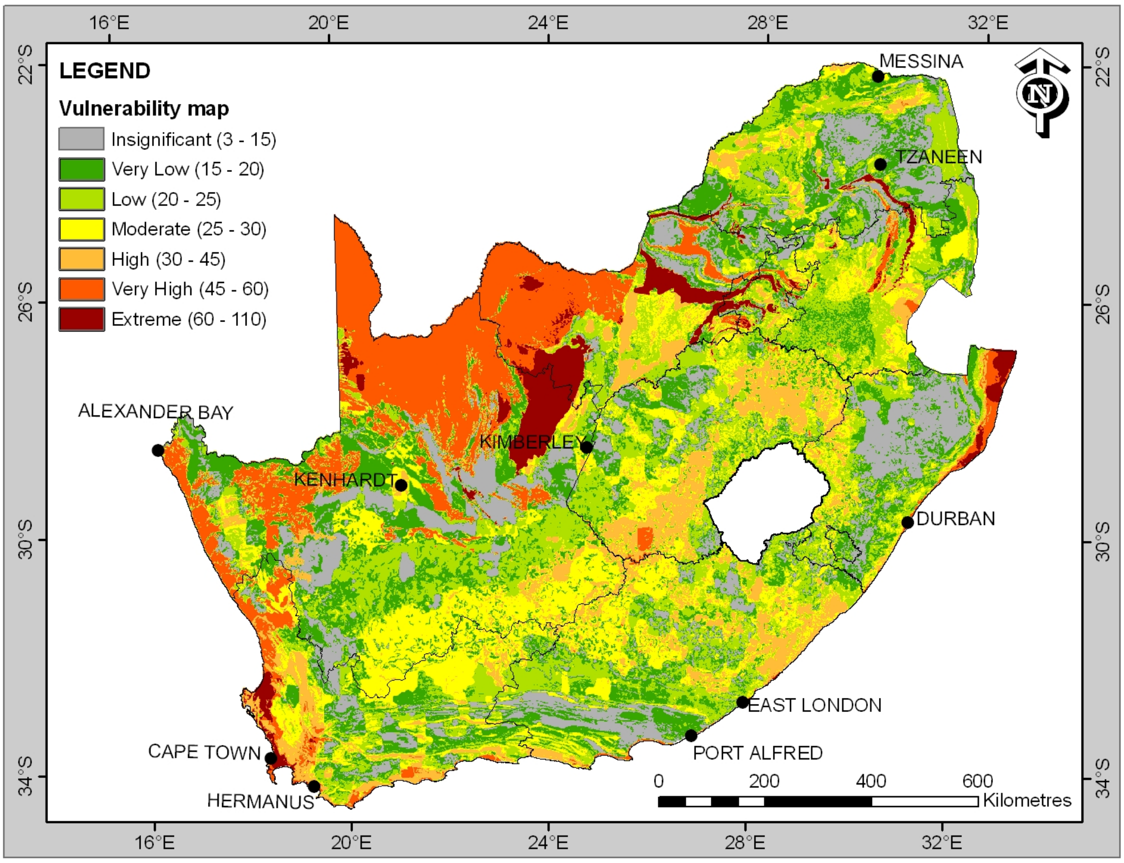

Figure 8: The resulting vulnerability map of South Africa

5. Conclusions and Recommendations

Pathak and Hiratsuka (2011) used nitrate concentration values to verify their groundwater vulnerability map. Another approach is to correlate between groundwater vulnerability and poor water quality. Similar approaches were followed in this study with the use of groundwater nitrate and electrical conductivity (EC) maps to verify the accuracy of the groundwater vulnerability result. Overlaying borehole electrical conductivity (EC) data from the NGDB with the vulnerability map shows some relation, especially the "insignificant" and the "high" vulnerability classes, though the pattern is not so clear with the other classes. It might be that the classification system used for the groundwater vulnerability classes is inadequate (Figure 9).

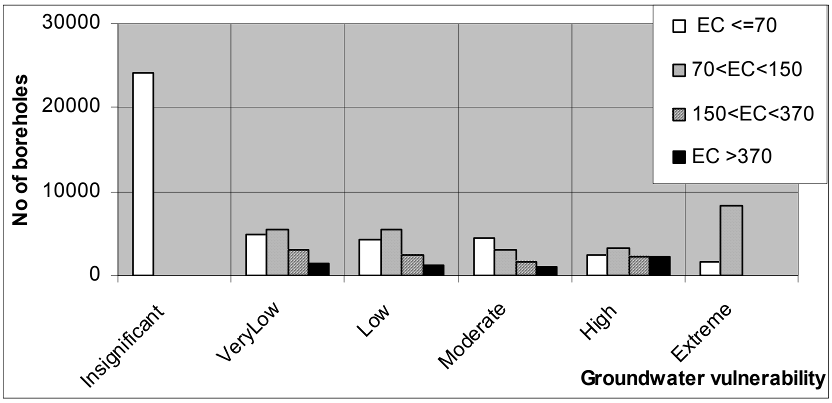

Figure 9: Comparison of the groundwater vulnerability map with borehole EC values

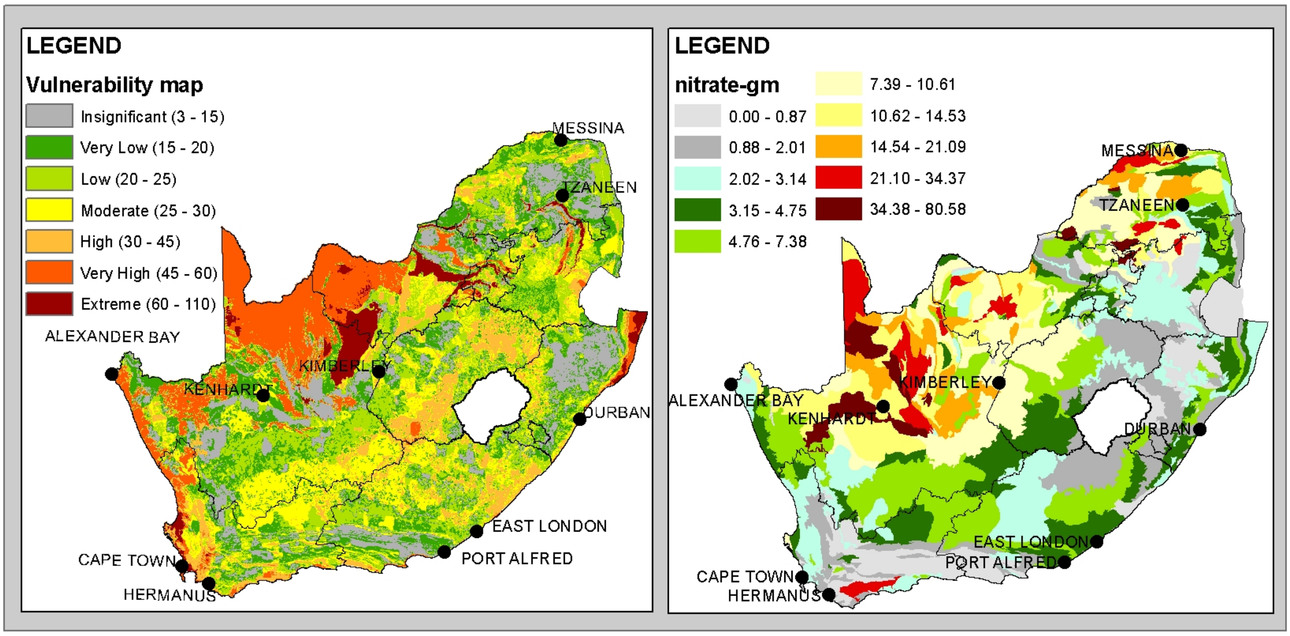

Figure 10: Comparison of the groundwater vulnerability map with the nitrate map (from the NORAD 1:500 000 database).

There are similarities between the groundwater vulnerability map and the NORAD nitrate map of South Africa (Figure10). The problem with the use water quality values for verification in South Africa is that there is a scarcity of data in some parts of the country (Maherry et al., 2010). Also, the locations of some of the boreholes in the NDGB are inaccurate.

The overall utility of a vulnerability map is dependent on the scale at which the map has been compiled, the scale at which data were gathered, and the spatial resolution of mapping. Thus, lack of representative data and their relation to the scale of the map are major limitations. Attempts to extract site-specific information from a map generated for regional planning is a major potential misuse of this vulnerability map. Each map type should only be used for the purpose for which it was produced (Vrba and Zaporozec, 1994). Periodical updating of the map, adding the disclaimer on map and educating individuals in it can reduce possible misuse.

6. References

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