Preparing input data for a national-scale groundwater vulnerability map of Southern Africa[#]

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Abstract

Groundwater quality is affected by virtually every activity of society, thereby making groundwater protection complicated and of national importance. However, protection of the groundwater will always be cheaper and less protracted than restoring an already polluted aquifer.

In compiling a national-scale groundwater vulnerability map of Southern Africa, it was decided to use the widely known DRASTIC methodology that includes the following components:

- the **D**epth to groundwater
- the **R**echarge due to rainfall
- the **A**quifer media
- the **S**oil media
- the **T**opography
- the **I**mpact of the vadose zone
- the **C**onductivity (hydraulic).

This methodology is well suited to gridded information sets of factors influencing groundwater vulnerability. The fact that the major strength of a grid cell-based model lies in its analytical capabilities, makes the ARC/INFO geographic information system (GIS) the ideal choice for manipulation and displaying the data surrounding the DRASTIC model.

This paper outlines the techniques used in compiling the data sets for those factors that influence the susceptibility of groundwater to contamination over Southern Africa and the techniques involved in manipulating and displaying these data in a GIS. The different techniques employed in the gathering and calculation of the different information sets required by the DRASTIC model to describe the groundwater vulnerability are presented in detail. The final output, which is in the form of a colour paper map, will be useful in presenting the concept of groundwater vulnerability and groundwater protection to the layman.

Introduction

Southern Africa has an average mean annual precipitation of approximately 460 mm distributed over roughly 1 x 10^6 km^2. This average is well below the world average of approximately 860 mm and therefore groundwater has to play an important role in supplying water to many regions in Southern Africa, and in particular the rural areas. Concern is being expressed in terms of the quality of Southern Africa's groundwater resources and consequently attention is being focused on the need for a proactive approach to protect these resources from contamination.

Groundwater protection is complex and, as groundwater is affected by virtually every activity of society, the development and implementation of effective groundwater protection programmes are difficult exercises. In addition, many potentially hazardous contaminants are colourless, odourless and tasteless, and therefore difficult to detect by passive means (Barcelona et al., 1988). In spite of these problems, a comprehensive integrated approach to groundwater protection is essential if groundwater quality standards for highest beneficial use are to be met and maintained.

Not all land-use activities pose the same pollution threat to groundwater resources and different parts of the environment have varying capacities for dealing with pollution (Born et al., 1988). Consequently, it is necessary to review the susceptibility of an aquifer to contamination in two separate but essentially interrelated ways, namely, by considering pollution risk assessment and aquifer pollution vulnerability. Pollution risk assessment considers factors such as the source, loading and characteristics of the pollutant itself. Aquifer vulnerability on the other hand is used to represent the intrinsic characteristics that determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load (Foster, 1987).

The National Research Council (NRC) has defined groundwater vulnerability to contamination as: "The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer" (NRC, 1993).

Contamination releases to groundwater can occur by design, by accident, or by neglect. Most groundwater contamination incidents involve substances released at or slightly below the land surface. Consequently, it is shallow groundwater that is effected initially by contaminant releases. There are at least 4 ways by which groundwater contamination occurs: infiltration, direct migration, inter-aquifer exchange, and recharge from surface water (Barcelona et al., 1988).

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TABLE 1
RATING VALUES FOR USE IN THE DRASTIC CONCEPT

Depth to groundwater (D_R)

Range (m)	Rating
0 - 5	10
5 - 15	7
15 - 30	3
>30	1

Net recharge (R_R)

Range (mm)	Rating
0 - 5	1
5 - 10	3
10 - 50	6
50 - 100	8
>100	9

Aquifer media (A_R)

Range	Rating
Dolomite	10
Intergranular	8
Fractured	6
Fractured and weathered	3

Topography (T_R)

Range (% slope)	Rating
0 - 2	10
2 - 6	9
6 - 12	5
12 - 18	3
>18	1

Soil media (S_R)

Range	Rating
Sand	8 - 10
Shrinking and/or aggregated clay	7 - 8
Loamy sand	6 - 7
Sandy loam	5 - 6
Sandy clay loam and loam	4 - 5
Silty clay loam, sandy clay and silty loam	3 - 4
Clay loam and silty clay	2 - 3

Impact of the vadose zone (I_R)

Range	Rating
Gneiss, Namaqua metamorphic rocks	3
Ventersdorp, Pretoria, Griqualand West, Malmesbury, Van Rhynsdorp, Uitenhage, Bokkeveld, Basalt, Waterberg, Soutpansberg, Karoo (northern), Bushveld, Olifantshoek	4
Karoo (southern)	5
Table Mountain, Witteberg, Granite, Natal, Witwatersrand, Rooiberg, Greenstone, Dominion, Jozini	6
Dolomite	9
Beach sands and Kalahari	10

The compilation of computer-generated thematic maps that can display contamination potentials or the vulnerability of land areas will greatly enhance public education and participation in groundwater protection activities, and will facilitate the planning and management of groundwater protection programmes.

Parameters needed for describing groundwater vulnerability

The DRASTIC (Aller et al., 1987) concept developed for the USA is well suited for a first attempt at producing a groundwater vulnerability map of Southern Africa. DRASTIC was designed to represent areas larger than 0.4 km² in size, thereby limiting the system to be used as a screening tool and not for site-specific assessments. DRASTIC was developed based on 4 major assumptions:

- the contaminant is introduced at the surface of the earth;
- the contaminant is flushed into the groundwater by precipitation;
- the contaminant has the mobility of water; and
- the area evaluated is 0.4 km² or larger.

Although these assumptions have led to criticism, the strength of DRASTIC lies in the fact that it considers most of the major factors controlling groundwater vulnerability.

The DRASTIC concept revolves around the simple equation

$$\text{DRASTIC INDEX} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W$$

that is applied to each geographic unit (hydrogeological setting) or pixel and where R=rating (Table 1) for each of the 7 parameters and corresponding weights (W) listed below:

Depth to groundwater	(D_W=5)
Recharge	(R_W=4)
Aquifer media	(A_W=3)
Soil media	(S_W=2)
Topography (% slope)	(T_W=1)

Impact of the vadose zone ($I_w=5$)
Conductivity (hydraulic) ($C_w=3$).

Once a DRASTIC index value has been calculated, it is possible to identify areas that are likely to be vulnerable to groundwater pollution relative to one another. DRASTIC was designed as a parametric point count system model (Civita et al., 1991) and is therefore well suited to the GRID module of ARC/INFO (1991) which is a cell-based geoprocessing toolbox that provides a powerful environment for manipulating spatial data.

The principles, assumptions and shortcomings upon which the draft national-scale vulnerability map of Southern Africa is based

As discussed above, the national-scale vulnerability map of Southern Africa was compiled using a modified version of the DRASTIC methodology, first developed by the US Environmental Protection Agency (US EPA) (Aller et al., 1987). Although several vulnerability techniques have been developed world-wide, the 7 criteria considered in DRASTIC generally embody the most significant factors controlling vulnerability to contamination.

DRASTIC does have some limitations, however, and these are contained within the vulnerability map of Southern Africa. For example, it does not consider the impact of human activity on groundwater, nor does it allow for natural or man-induced water quality problems (being intrinsically a vulnerability, as opposed to a risk assessment technique). Some physical parameters neglected by the current method and which have a strong influence on groundwater pollution include fracturing and faulting; the significant effects of precipitation duration and intensity; soil reactivity; differences in specific contaminant mobility; and anisotropy and heterogeneity of the soil, the vadose zone, and aquifer hydraulic conductivity. Dilution is not considered, which could be a significant factor in the limited storativity, hard-rock conditions prevalent over much of Southern Africa.

As many of the data sets required in the preparation of a vulnerability map are not, as yet, available for Southern Africa, a number of assumptions had to be made in creating the various layers. Although these assumptions may, with good reason, be challenged, nevertheless the basic approach to vulnerability mapping and the use of GIS technology to achieve this, remains valid. Probably one of the most important assumptions is that the weightings, as agreed upon for the USA, apply to local conditions. However, as the results are presented in a purely comparative sense, again this assumption is defensible.

It must be borne in mind, however, that no attempt to validate the draft vulnerability map of Southern Africa has taken place and that further research will be necessary before a tool useful to planners and decision-makers will be available.

The 7 factors used as input to the drastic rating system

Depth to groundwater

Depth to groundwater is important primarily because it gives an indication of the distance and the time required for the contaminant to move through the unsaturated zone to the aquifer. Although considerable effort is being directed towards regional groundwater characterisation and the preparation of hydrogeological maps, information pertaining to groundwater is not as well documented as information on surface water (Orpen et al., 1992). The National Groundwater Data Base (NGDB) was established in 1986 and contains computerised data on more than 100 000 boreholes (Seymour, 1994) and the historical records are being entered into the data base at approximately 2 000 borehole records per month. The average depth to groundwater (Fig. 1) for more than 50 000 boreholes in Southern Africa was extracted by Seymour (1993). These average groundwater depths were interpolated onto a rectangular one minute by one minute of a degree grid using inverse distance weighting (IDW) (ARC/INFO, 1991) software. Rundquist et al. (1991) state that the mapable input parameters of DRASTIC are generally available for the whole of the USA. The Southern African groundwater community, unfortunately, are still in the process of capturing the data and on further enhancement of the NGDB will be on par with the USA regarding digital groundwater data availability.

Recharge due to rainfall

The primary source of groundwater is precipitation that infiltrates through the surface above the aquifer. The ACRU hydrological simulation model (Schulze, 1990) was used to estimate the amount of precipitation that would finally end up as recharge. Southern Africa is divided into 712 relatively homogeneous response zones (Dent et al., 1990) which form the basis of the hydrological simulations to determine the amount of net recharge. Input parameters of *inter alia* daily rainfall, soil characteristics, temperature estimates and natural vegetation indices based on the 712 zones concept have been determined for Southern Africa to be used in the ACRU model (Schulze et al., 1990). The net recharge amount for each of the 712 zones (Fig. 2) is determined from the portion that drains into the intermediate or groundwater zone. As net recharge is probably the most difficult groundwater parameter to estimate (Van Tonder and Kirchner, 1990) it is therefore imperative that point and areal estimates of recharge be published in the form of recharge maps or tables to allow researchers a better understanding of this process.

Aquifer media

The term aquifer media refers to the consolidated or unconsolidated rocks that serve as water-bearing units (Aller et al., 1987). At present no digital information is available on the composition of the aquifer media (Fig. 3) and the fourfold classification of rocks/rock assemblages according to origin and nature of aquifer interstices as found in the legend for the National Hydrogeological Map (Vegter, 1992) was used as a point of departure in its compilation and will be refined upon completion of the National Hydrogeological Map. The major assumption used was that the aquifer media would have similar characteristics to those of the overlying geology, which may not always be true.

Soil media

Aller et al. (1987) define soil media to be the uppermost portion of the vadose zone. The Institute for Soil, Climate and Water are currently converting their land-type paper maps into digital form and on completion could form an important input to the dynamic DRASTIC equation. The Broad SIRI Soil Mapping Units Map (Schulze et al., 1990) that contains percentages of dominant soil textures for Southern Africa at a regional scale was used in descri-bing the soil media component (Fig. 4) of the DRASTIC equation.

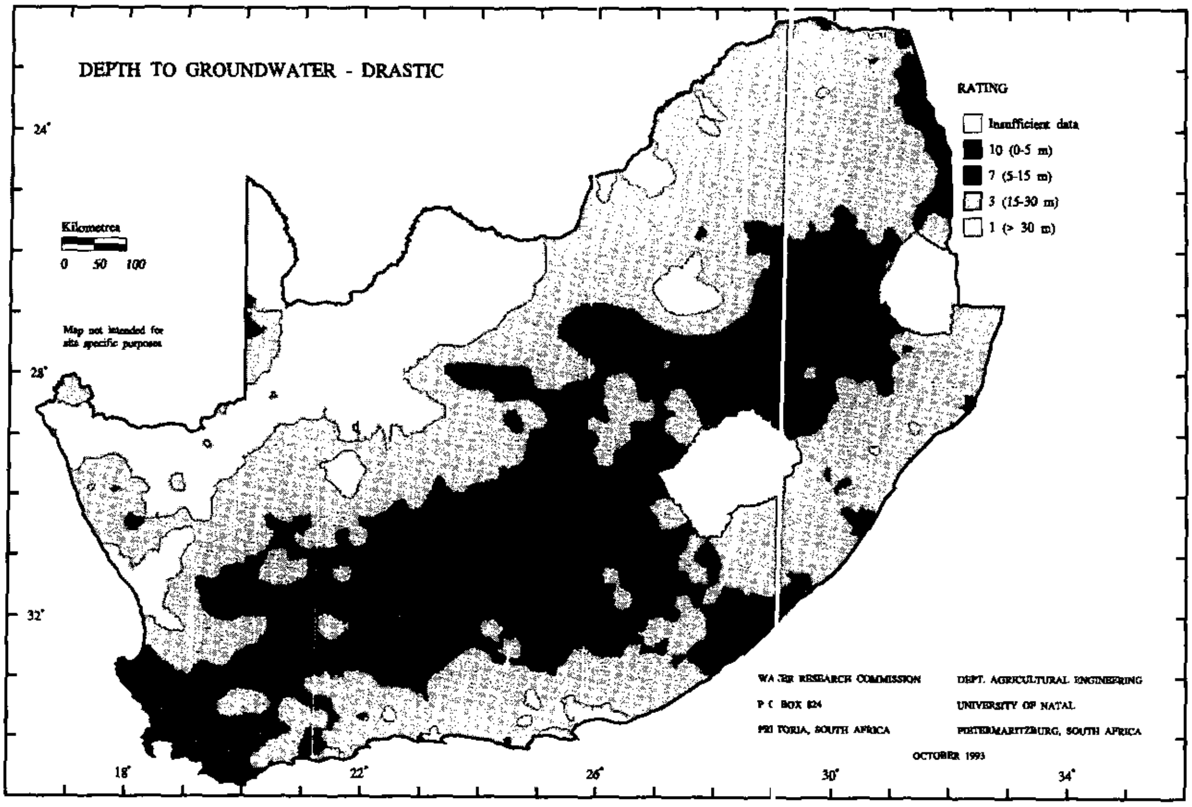

Figure 1
Smoothed average depth to groundwater for Southern Africa

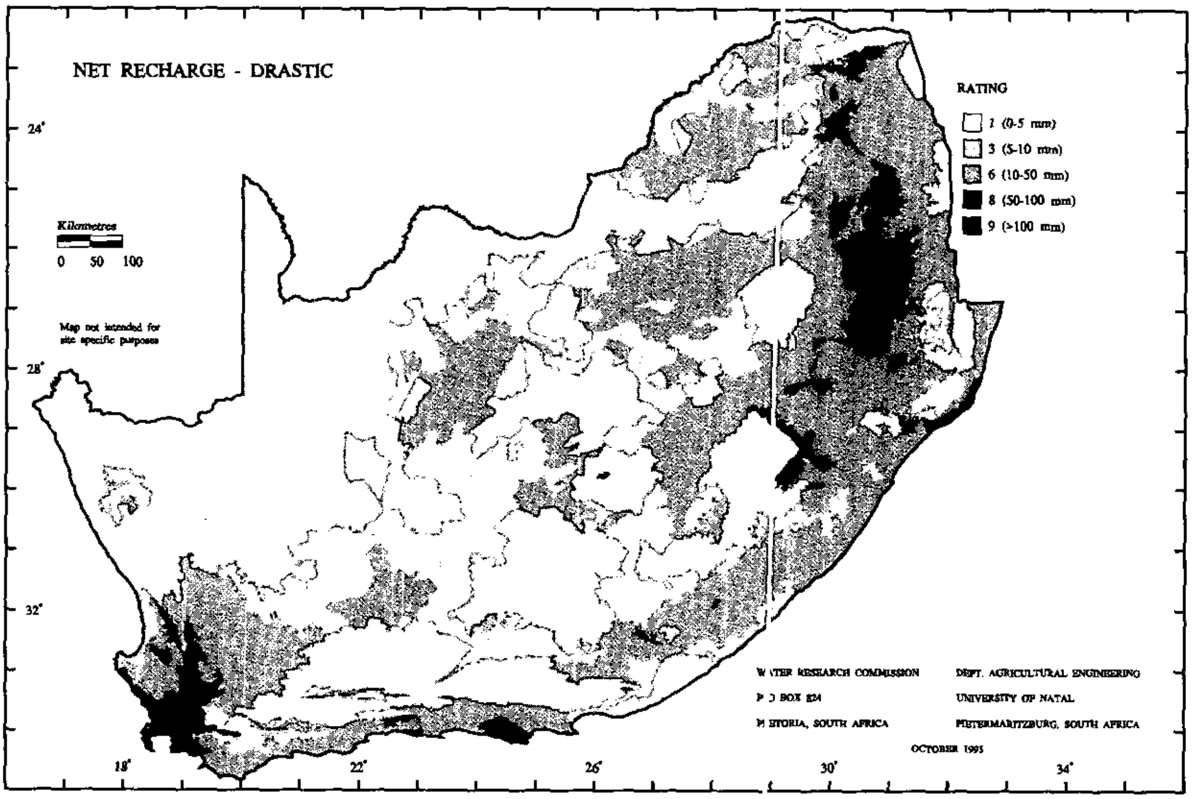

Figure 2
Mean annual recharge due to rainfall for Southern Africa

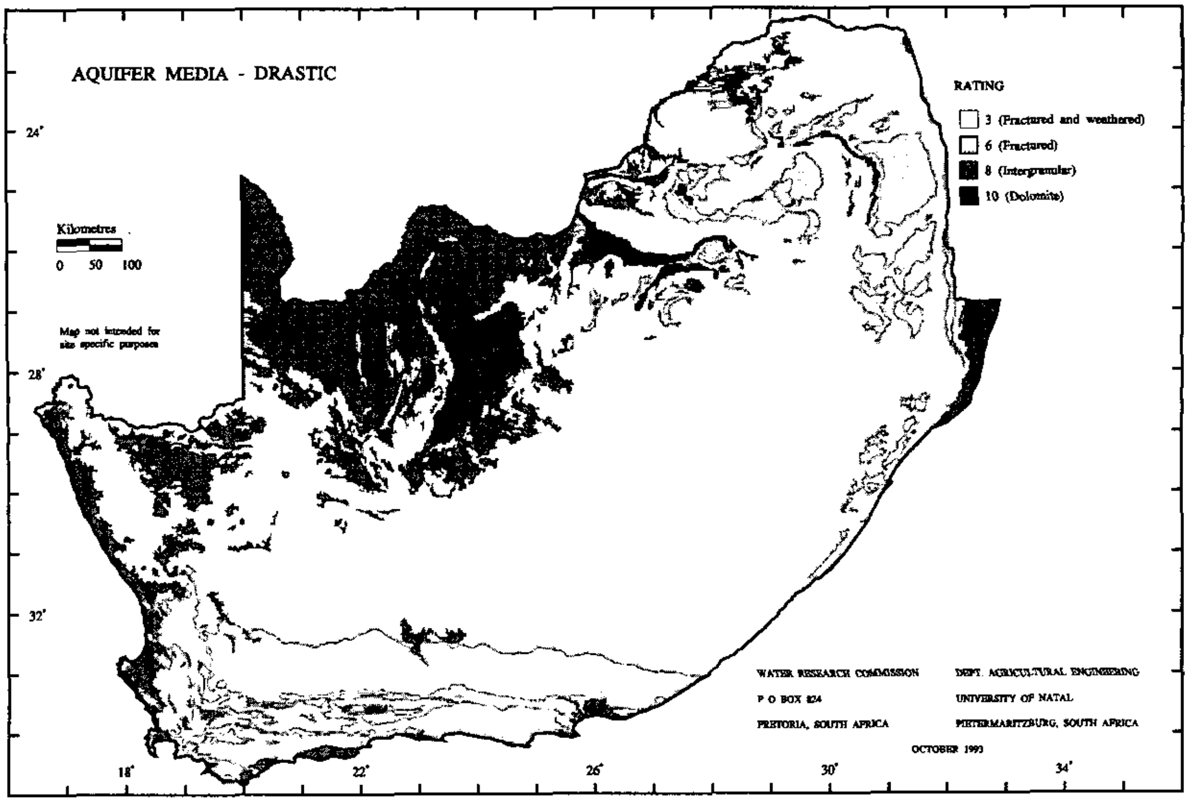

Figure 3
Aquifer media for Southern Africa (after Dept. of Water Affairs and Forestry, 1993)

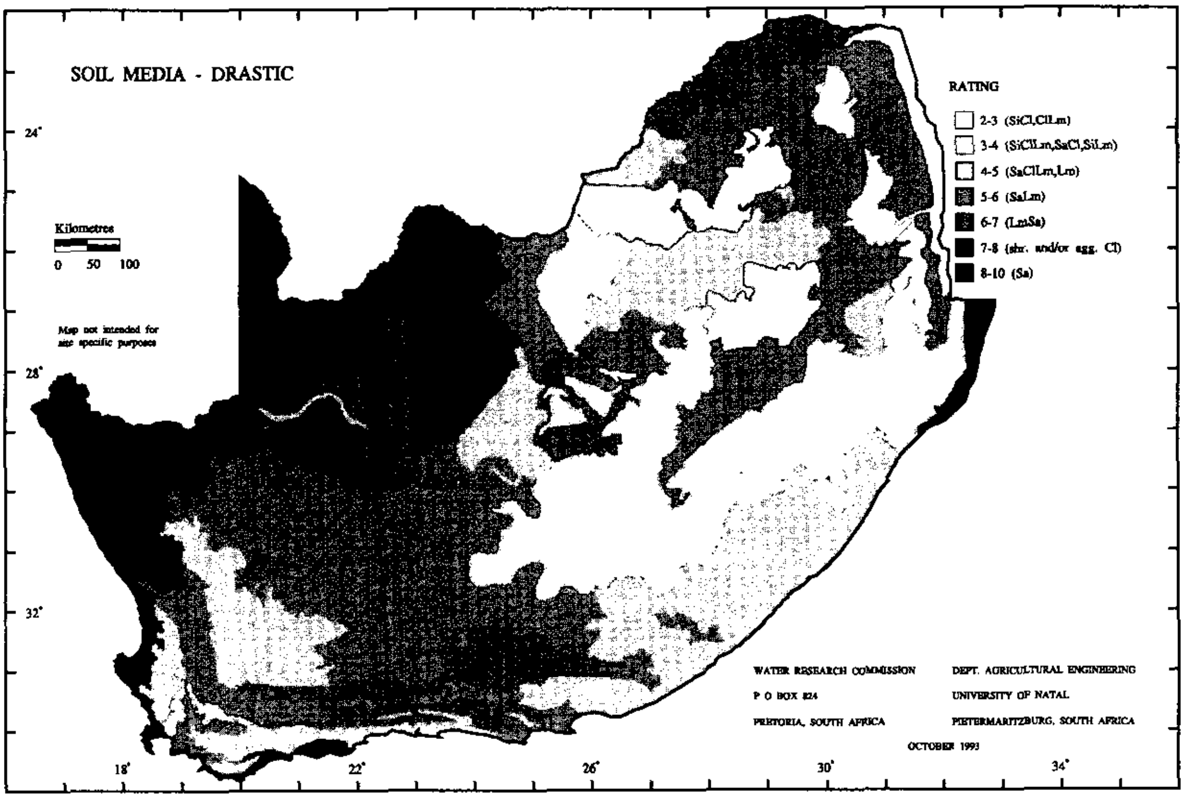

Figure 4
Soil media for Southern Africa (after Institute for Soil, Climate and Water, 1989)

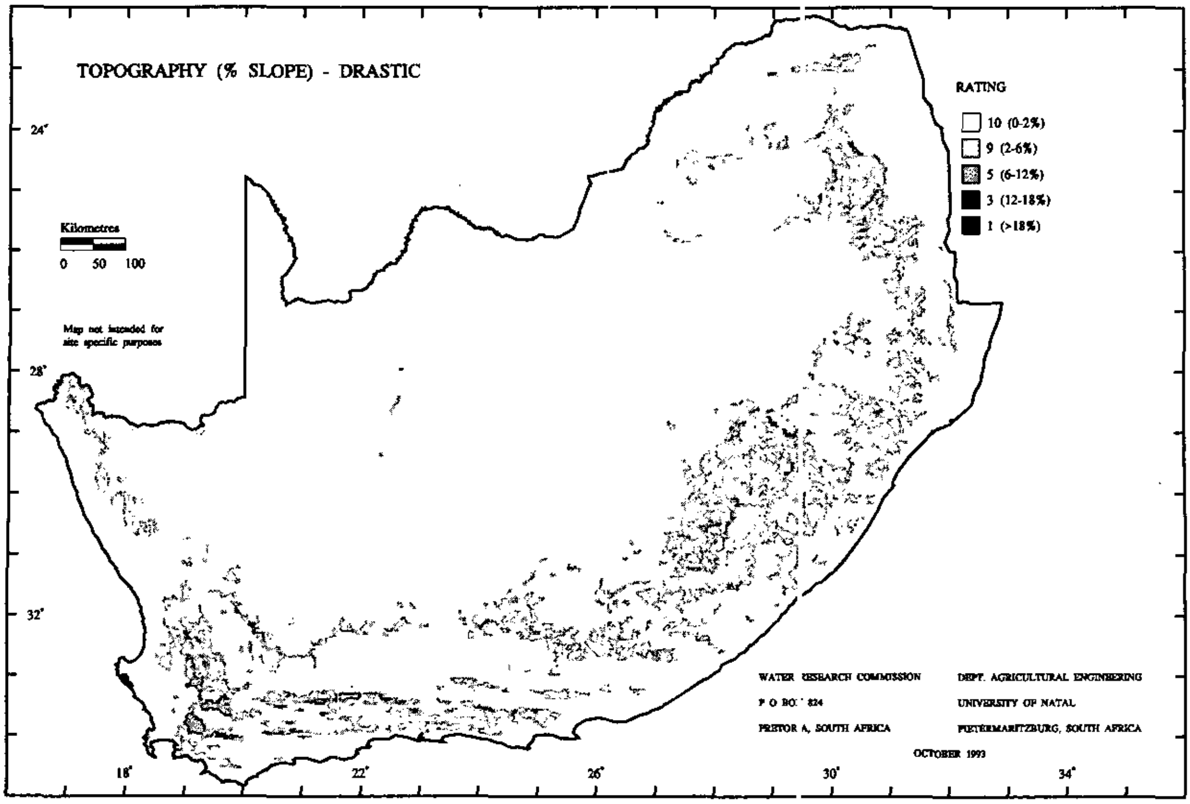

Figure 5
Topography (% slope) for Southern Africa

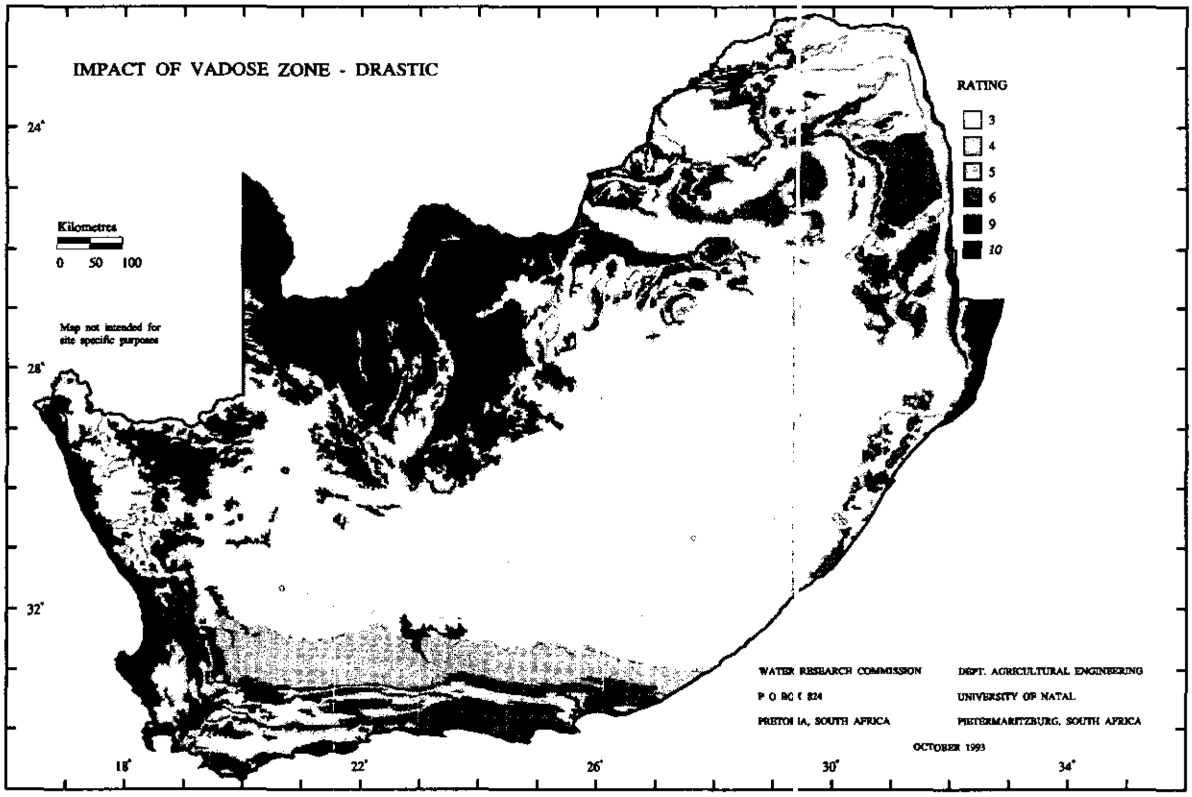

Figure 6
Impact of the vadose zone media for Southern Africa (after Dept. of Water Affairs and Forestry, 1993)

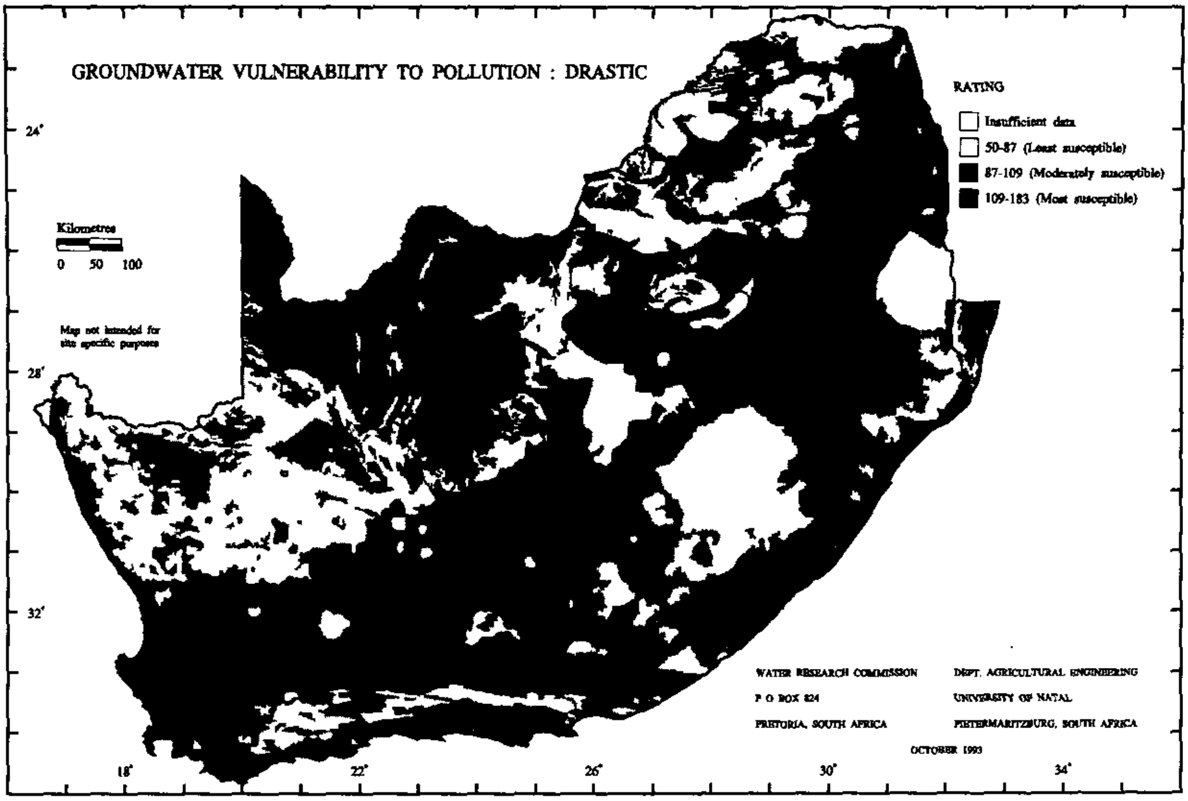

Figure 7
Groundwater vulnerability to pollution for Southern Africa

Topography

Topography will give an indication on whether a pollutant will run off or remain on the surface long enough to infiltrate into the groundwater. The one minute by one minute of a degree altitude grid (Dent et al., 1988) was used to estimate the percentage slope (Fig. 5) over Southern Africa. This was the first and easiest component in determining an index to describe groundwater vulnerability. The authors did take cognisance of the 400 m x 400 m altitude grid of Southern Africa captured by the Directorate of Surveys and Mapping, but decided against using it due to time and financial constraints.

Impact of the vadose zone

The vadose zone is defined as that portion of the geological profile beneath the earth's surface and above the first principal water-bearing aquifer (Cullen et al., 1992). Units on the Geological Map of South Africa at 1:1 000 000 scale (Visser, 1989) were combined in homogeneous response zones on the basis of the probable effect of the vadose zone on the physical retardation of pollutants (Fig. 6).

Hydraulic conductivity

Hydraulic conductivity values for fractured rock aquifers are difficult to estimate and as sufficient information on hydraulic conductivity values for Southern Africa is not available at present, the authors decided to shelve this parameter until the data become available. The considerable variation in terms of hydraulic conductivity over very short distances in hard-rock aquifers throws some doubt on the usefulness of this parameter for Southern African conditions.

Discussion and conclusions

Several techniques have been developed to assess the potential for groundwater contamination on a regional scale. The use of simulation models and various numerical rating techniques have been proposed in the international literature. Essentially, the type of technique employed will depend upon the availability of data and the ultimate use to which the vulnerability assessment will be put. With the arrival of GIS, the inventory, archival, retrieval and display of spatial data and the link to numerical rating systems and simulation models have become a reality. For the purpose of preparing the first national-scale groundwater vulnerability map of Southern Africa, the DRASTIC methodology developed by the US EPA was selected.

The digital images or overlays used to produce the groundwater vulnerability map (Fig. 7) are housed on the Computing Centre for Water Research (CCWR) mainframe computer that is networked to several local and international computer networks. The data conversion models in ARC/INFO make it possible to convert from a number of different formats into the raster format required by GRID and this allows users to manipulate and modify the DRASTIC equation within minutes. For example, a depth to groundwater image (Seed, 1993) was produced and incorporated into the groundwater vulnerability map by importing the image into GRID and recalculating the DRASTIC values. It is, therefore, possible to update the map whenever new data become available which will certainly be the case when the National Hydrogeological Map becomes available in 1994. The groundwater fraternity of Southern Africa must take cognisance that 46 States in the USA have regulations requiring drillers or home-owners to file well completion reports for domestic wells (Ganley, 1989). It is, therefore, of paramount importance that the NGDB be populated at an accelerated rate and that a list be made available of groundwater-related data sets and the organisations that have captured or are in the process of capturing hydrogeological data.

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