A REVIEW OF THE USE OF DRASTIC IN ASSESING THE VULNERABILITY OF AQUIFERS TO CONTAMINATION, AND A CASE STUDY OF THE USE OF DRASTIC ON A LOCALISED SCALE IN SOUTH AFRICA

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Degree of Masters of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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ABSTRACT

The use of DRASTIC – an aquifer vulnerability to contamination assessment tool, is analysed and reviewed for its applicability in helping develop a national aquifer management systems from the vulnerability maps produced by DRASTIC. Furthermore, the use of DRASTIC in assessing the vulnerability of an aquifer on a localised scale has been performed. The study showed that DRASTIC yields accurate results on localised scales where sufficient information is available. The use of DRASTIC on a national scale is subject to the scale of the input data and will only produce an aquifer vulnerability map that may be used as a general national development tool that cannot be applied to site specific developments.

Dedicated to:

My late father,
Dimitrios Vagis, the man who believed in me and taught me that the only limits we have are those we self impose.
Truly the greatest man I have ever met.

My mother,
Maria Vagis, who’s shear persistence made this research project a reality.

My sister
Amalia Vagis who never gave up on me

&
My husband
Panagiotis Wills, for his patience and support.

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1. INTRODUCTION

Pollution can be defined as the addition to water of any substance which can potentially alter the water's quality so as to decrease its usage value. To assess the level of such pollution, the vulnerability of groundwater to pollution may be expressed as the sensitivity of its quality to human activities (Bachmat and Collin).

Bachmat and Collin further stipulated that vulnerability assessment of water resources should aim at providing preliminary decision making in such areas as designation of land use control; delineation of monitoring networks and management of water resources in the context of regional planning as related to protection of groundwater quality.

In 2000 The Department of Water Affairs and Forestry of South Africa (DWAF) published the First Edition of the "Policy and Strategy for Groundwater Management in South Africa".

As stated in the document, groundwater constitutes about 65% of South Africa's total water supply, and geographically almost two thirds of South Africa's population depends on groundwater for their domestic needs.

The document acknowledged that ground water is vulnerable and states the following, "*It is common for groundwater to be poorly managed. This is because of its invisible nature - it takes a long time to notice when it has become polluted and, unlike surface water, it has limited ability to purify itself. It is difficult, and often impossible, to restore polluted groundwater, and certainly very expensive*.

The major reason for poor management of groundwater resources, however, is ignorance. Water managers lack knowledge and information about where it occurs, the importance of its protection, and how to protect it."

DWAF in the document states that for effective water management to occur, management plans must be part of broader, regional development plans that include agricultural, mining, manufacturing, rural and urban development and ecological needs. Protecting surface and groundwater in an integrated manner is central to successfully managing the country's limited water resources.

The protection of groundwater resources is complex as it is affected by virtually every activity of society and influenced by most forces of nature. Furthermore many potential contaminants are colorless, tasteless and odorless and thus cannot be easily detected.

In order to protect these resources an integrated national groundwater management plan must be in place. The first step in developing such a plan is to know and understand the aquifers susceptibility to contamination. This has to be assessed in two separate but inter-related ways, the first being pollution risk assessment and the second aquifer pollution vulnerability.

As different land uses and different pollutants have different effects on an aquifer, the pollution risk assessment would consider factors such as source, loading and characteristics of the pollutant, while aquifer pollution vulnerability would consider the characteristic of the aquifer itself that render the aquifer vulnerable to the imposed contaminant.

It is this aquifer vulnerability that will be discussed and quantified in this report.

The vulnerability of an aquifer has been defined in many ways, with the most comprehensive being the definition given by *Duijvenbooden and Waegeningh*.

> *The sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer*.

In 1987 the Environmental Protection Agency (EPA) of America developed an aquifer vulnerability assessment model called DRASTIC. The purpose of DRASTIC was to create a tool that would take into account the intrinsic characteristics of an aquifer in assessing the aquifers vulnerability to contamination.

DRASTIC has been widely used internationally in assisting countries to develop groundwater management plans by creating aquifer vulnerability maps that would assist in regional development. DRASTIC has also been used South Africa to create a draft aquifer vulnerability map of the country.

The purpose of this report is to explore the DRASTIC tool and investigate the variety of cases for which it has been applied to, in an attempt to assess it's suitability for assisting in creating aquifer management plans on national levels.

The study has been extended to assess the use of DRASTIC in assisting with the creation of management plans on localised scales. A case study using DRASTIC on a mining project was conducted. The purpose of this study was to establish if conducting a DRASTIC analysis on the underlying aquifer prior to mining activities commencing, would have provided the mine with an accurate understanding of the aquifers vulnerability to contamination and allowed the mine to create an aquifer management plan that would have minimise the impact the mining activities would have had on the aquifer.

2. DRASTIC

2.1. Background Information to DRASTIC

A number of approaches have been taken world wide for assessing the effect on groundwater quality of pollution infiltration and resultant aquifer contamination. These include mapping of groundwater resource vulnerability, as well as the development of comprehensive index reference systems to describe the resultant levels of pollution potential and water resource vulnerability – one of these indexing programs being DRASTIC.

DRASTIC was developed by the American Environmental Protection Agency (EPA) in 1987. The purpose of DRASTIC was to create a system that would provide a way of assessing the groundwater pollution potential of any hydrogeological system in the United States.

The system incorporates the key hydrogeologic factors that influence the vulnerability of a region to groundwater pollution. Having been developed for a country with an extensive range of geological regions, DRASTIC is inherently applicable to a large variety of hydrogeological systems, thus making it potentially suitable to be used as a global tool.

The system was developed to be capable of generalising the pollution potential for any area of 100 acres or larger. It was developed with the assumption that the pollutant has the mobility of water, is introduced at the surface and carried to the aquifer as the aquifer is recharge by precipitation.

In assessing the aquifers vulnerability to contamination using DRASTIC, the process needs to be divided into two steps. The first step is the classification of the region under question into hydrogeological settings. These settings are the major geologic factors that affect and control groundwater movement into, through and out of the area. The second step is applying a scheme of relatively ranked hydrogeological parameters, DRASTIC, in order to evaluate the relative groundwater pollution potential of any hydrogeologic setting.

The main physical characteristics of hydrogeological setting that affect the *in-situ* groundwater pollution potential are identified as being:

D - Depth to groundwater
R - Recharge (Net)
A - Aquifer Media
S - Soil Type
T - Topography (Slope)
I - Impact of the Vadose Zone Media
C - Conductivity (Hydraulic) of the Aquifer

The first letter of each of these factors were arranged to form the acronym DRASTIC. Each factor was evaluated with respect to the others in order to determine its relative importance and was assigned a relative weighting ranging from 1 to 5 as listed in **Error! Reference source not found.**. The factors with the greatest impact on groundwater vulnerability were assigned a weighting of 5 and those with the least impact a weighting of 1. The assigned weights are constants and may not be changes. A second weighting system was developed for dealing with agriculture pesticides as the pollutant as listed in Table 2-2.

FACTOR	WEIGHT
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact on Vadose Zone Media	5
Hydraulic Conductivity of the Aquifer	3

Table 2-1:Assigned Weightings for DRASTIC factors

FACTOR	WEIGHT
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	5
Topography	3
Impact on Vadose Zone Media	4
Hydraulic Conductivity of the Aquifer	2

Table 2-2: Assigned Weightings for Pesticide DRASTIC factors

Each DRASTIC factor was divided into ranges or significant media types which have an impact on the pollution potential. The range of each factor was assessed with respect to the others to determine the relative significance of each range to pollution potential. A rating was assigned to each range for each factor. These ratings are also applicable to the Pesticide DRASTIC.

The ranges for each factor have been discussed below, with the ratings applicable to each of these ratings also being given.

2.2. DRASTIC Factors

2.2.1. Depth to Water

By evaluating the depth to water, one is able to determine the depth of material that the contaminant must travel through before it reaches the groundwater. The deeper the aquifer the greater the time of travel of the pollutant is, and the longer the time of contact it has with the soil media. Thus the depth of the aquifer affects the degree of attenuation or dilution of the contaminant, and subsequently the degree of resultant contamination of the aquifer.

The depth to water in an unconfined aquifer is calculated as the depth from the ground surface to the water table. The water table is assumed to be where all the pore spaces in the surface are filled with water. It does not include saturated zones that have insufficient permeability to yield significant quantities of water to be considered an aquifer.

When evaluating the depth to groundwater in a confined aquifer one must determine the depth to the top of the aquifer. This depth also corresponds to the base of the confining layer.

When considering a semi-confined or “leaking” aquifer the depth to water can be evaluated by assuming the aquifer is either confined or un-confined.

Table 2-3 summarises the ranges and associated ratings of the DRASTIC, Depth to Water factor.

RANGE (feet)	RANGE (m)	RATING
0 -5	0 – 1.5	10
5 -15	1.5 – 4.6	9
15 -30	4.6 – 9.1	7
30 - 50	9.1 – 15.2	5
50 -75	15.2 – 22.9	3
75 -100	22.9 – 30.5	2
100+	30.5+	1

Table 2-3: Ranges and Rating for Depth to Water

2.2.2. Net Recharge

Precipitation is considered to be the main source of groundwater. Net recharge of an aquifer is defined as the total amount of water per unit area introduced at the surface that infiltrates the ground and reaches the aquifer.

It is this recharge water that transports the contaminant vertically through the soil media to the aquifer and then transports it within the aquifer. The greater the quantity of recharge water, the greater the possibility of the contaminant being leached and transported to the water table.

It must also be noted that if the quantity of recharge water is excessive, it may dilute the pollutant and in turn decrease the pollution potential. This is however not considered in the DRASTIC ranges and ratings for this factor.

Precipitation is not the only source of recharge water for an aquifer. Other sources such as irrigation, artificial recharge and waste water from industries/mines must also be assessed when determining an aquifer's net recharge.

Net recharge here is expressed in inches per year or mm per year and the ranges and ratings for this factor are listed in Table 2-4.

RANGE (inches/year)	RANGE (mm/year)	RATING
0 to 2	0 to 5	1
2 to 4	5 to 10	3
4 to 7	10 to 18	6
7 to 10	18 to 25	8
10+	25+	9

Table 2-4: Ranges and Rating for Net Recharge

2.2.3. Aquifer Media

The consolidated or unconsolidated rocks which acts as the aquifer is referred to as the aquifer media. The path the contaminant must follow, the surface area of rock the contaminant is in contact with prior to reaching the aquifer, and the time the contaminant takes to reach the aquifer is governed by the aquifer media and its flow system.

These factors play a roll in the degree of sorption, reactivity or dispersion of the contaminant in the aquifer. In general, the larger the grain size and the more fractures or openings in an aquifer, the higher the permeability and the lower the attenuation capacity of the aquifer media.

The DRASTIC model has defined 10 possible aquifer media and has attributed ranges and ratings for each of these. Below is a description of each media as selected and defined, by *Aller et al* [2]. They have been listed below in order of increasing pollution potential.

1. Massive Shale: Thick bedded shale, claystone or clays which typically yield only small quantities of water from fractures and which have a low pollution potential. The pollution potential of this type of aquifer is influenced by the degree of fracturing.

2. Metamorphic / Igneous Rock: Consolidated bedrock of metamorphic or igneous origin which contain little or no primary porosity and which yields water only from fractures within the rock. Typically well yields are low and the relative pollution is a function of the degree of fracturing.

3. Weathered Metamorphic / Igneous Rock: Unconsolidated material, commonly termed regolith or saprolite, which is derived by weathering of the underlying consolidated bedrock, and which contains primary porosity. The pollution potential is largely influenced by the amount of clay material present; the higher the clay content, the lower the pollution potential.

4. Glacial Till: Unconsolidated to semi-consolidated mixtures of gravel, sand, silt and clay-size particles which are poorly sorted and stratified. The low permeability of the till produces low yields to wells. Although glacial tills exhibit low permeabilities, wells completed in tills are typically shallow and may be more susceptible to contamination. Fracturing of the tills may also influence pollution potential.

5. Bedded Sandstone, Limestone and Shale: Typically thin-bedded sequence of sedimentary rocks which contain primary porosity. The controlling factor in the determination of pollution potential is the degree of fracturing.

6. Massive Sandstone: Consolidated sandstone bedrock which contains both primary and secondary porosity and is typified by thicker than the Bedded Sandstone, Limestone and Shale sequence. Pollution potential is largely controlled by both the degree of fracturing and the primary porosity of the sandstone.

7. Massive Limestone: Consolidated limestone or dolomite bedrock which is characterised by thicker deposits than Bedded Sandstone, Limestone and Shale sequence. Pollution potential is largely affected by the degree of fracturing and the amounts of solution cavities in the limestone.

8. Sand and Gravel: Unconsolidated mixtures of sand and gravel-sized particles which contain varying amounts of fine materials. Sand and/or gravels which have only small amounts of fine material, are termed “clean”. In general, the cleaner and more coarse-grained the aquifer, the greater the pollution potential.

9. Basalt: Consolidated extrusive igneous bedrock which contains bedding planes, fractures and vesicular porosity. The term is used herein in a genetic sense, even though it is actually a rock type. Pollution potential is influenced by the amount of interconnected openings which are present in the lava flow material.

10. Karst Limestone: Consolidated limestone bedrock which has been dissolved to the point where large, open, interconnected cavities and fractures are present. This is a special case of Massive Limestone.

In instances where more than one aquifer media is present the predominant one is to be used in the analysis. The size and water yielding capacity of the aquifer can be used in determining which media is the predominant aquifer of the system.

For each type of media a range and ratings have been attributed in order to allow the user to adjust the rating according to the specific information about the aquifer. However a typical rating per media has also been provided that can be used when limited information is available. These rating can be found in Table 2-5.

RANGE (Type)	RATING	TYPICAL RATING
Massive Shale	1 to 3	2
Metamorphic/ Igneous Rock:	2 to 5	3
Weathered Metamorphic/ Igneous Rock	3 to 5	4
Glacial Till	4 to 6	5
Bedded Sandstone, Limestone and Shale	5 to 9	6
Massive Sandstone	4 to 9	6
Massive Limestone	4 to 9	6
Sand and Gravel	4 to 9	8
Basalt	2 to 10	9
Karst Limestone	9 to 10	10

Table 2-5: Ranges and Rating for Aquifer Media

2.2.4. Soil Media

Soil for the purpose of use in DRASTIC has been defined as the upper most portion of weathered material on the earths surface, that averages a depth of 1.8m or less.

The type of soil present at the surface has a large affect on the amount of water that can penetrate through it and recharge the aquifer. It is during this recharge that the contaminants are transported from the surface to the aquifer, with the soil media playing an important role in the prevention/facilitation of the contaminant through to the aquifer. The higher the clay content and the thicker the soil layer, the lower the pollution potential, as soil permeability is lower with the possibility of attenuation higher. Conversely the amount of organic matter present in the soil may be a significant factor for lowering the pollution potential.

The soil media is best described by using the basic soil type it is composed of. The basic soil types as classified by the Soil Conservation Service of the United States Department of Agriculture have been adopted for the use in DRASTIC and have been listed below in order of increasing pollution potential as they appear in *Aller et al* .

1. Nonshrinking and non-aggregate clay: Illitic or Kaolinitic clays which do not expand and contract with the addition of water and therefore do not form vertical secondary permeability which increases the pollution potential.

2. Clay Loam: A soil textural classification which is characterised by 15%-55% silt, 27% - 40% clay and restrictive permeabilities, it has a low pollution potential.

3. Muck: A soil consisting of fine, dark-coloured, well decomposed organic material that typically contains a higher mineral or ash content than peat. Muck contains the largest amount of plant fibre of the organic soils, thus limiting permeability.

4. Silty Loam: A soil texture classification characterised by 50% - 80% silt, 12% - 27% clay and 0% - 50% sand. The pollution potential is still low, but higher than a Clay Loam because of the typically lower percent of clay.

5. Loam: A soil textural classification characterised by 20% - 25% silt, 7% -27% clay, and 0% - 50% sand. The pollution potential is still low, but higher than a silty loam because of a lower percent of clay and silt.

6. Sandy Loam: A soil texture classification characterised by 0% - 50% silt, 0%- 20% clay and 15% - 50% sand. The pollution potential is greater than a loam due to the higher percent of sand.

7. Shrinking and/or Aggregate Clay: Characterised by montmorillonitic clays or smectites which have an expanding lattice that swell and contract with alternating wetting and drying. Desiccation cracks may form as the soil dries. These cracks may later be shut as the clay swells when hydrated. Pollutants, however, may move rapidly through the desiccation cracks upon initial wetting of the soil. Although usually of low permeability, this medium can have a seemingly high pollution

potential based on the secondary vertical permeability created by the cracking of the media upon drying.

8. Peat: A soil consisting of un-decomposed to partially decomposed plant material that is fresh enough to be identified. Although peats contain organic matter which may be significant for contaminant attenuation, they are relatively permeable, thus pollution potential is high.

9. Sand: A size-based delineation of angular or rounded particles ranging in size from 1/16mm to 2mm. Sand is typically free of silts and clays and therefore has a high pollution potential.

10. Gravel: A particle-based size classification typified by particles larger than 2mm in size. Gravel soils commonly include a mixture of sand, silt, clay and gravel particles, with a preponderance of large sized particle. Permeability is rapid and pollution potential is high.

11. Thin or Absent: If a soil layer is not present of if the layer is so thin as to be considered ineffective for contamination attenuation, the pollution potential is very high. Thin or absent should generally be chosen when the soil profile is 25mm or less in thickness.

Table 2-6 below lists the ratings associated with each soil media.

RANGE (Type)	RATING
Nonshrinking and non-aggregate clay	1
Clay Loam	2
Muck	3
Silty Loam	4
Loam	5
Sandy Loam	6
Shrinking and/or Aggregate Clay	7
Peat	8
Sand	9
Gravel	10
Thin or Absent	10

Table 2-6: Ranges and Rating for Soil Media

2.2.5. Topography

The slope or variation in slopes of the land surface is termed the topography of the area. Percent slope is calculated as the change in vertical height “rise” over the change in horizontal distance or “run”. The topography of an area describes whether the pollutant will run off or remain on the surface long enough to infiltrate it.

In general the shallower the slope the higher the pollution potential as the water and contaminants will not run off but infiltrate the surface. Table 2-7 below lists the various ranges of topography (as percentage slope) and their associated ratings.

RANGE (%)	RATING
0 to 2	10
2 to 6	9
6 to 12	5
12 to 18	3
18+	1

Table 2-7: Ranges and Ratings for Topography

2.2.6. Impact of the Vadose Zone Media

The Vadose zone is the section of soil below the soil horizon and just above the water table. This zone can either be un-saturated or discontinuously saturate. The type of vadose zone affects the attenuation of the pollutant as biodegradation, neutralisation, mechanical filtration, chemical reaction, volatilisation and dispersion are all process that can occur in this zone. Biodegradation and volatilisation decrease with depth.

The type of vadose zone controls the path the contaminant must travel through and the travel time impacting on the degree of attenuation of the pollutant. The quantity of material the pollutant comes in contact with as well as the degree of fracturing in this zone, affects the pollution potential. The Vadose zone media and their pollution potential are described below with respect to use in DRASTIC as detailed by *Aller et al*.

1. Confining Layer: This media is chosen when evaluating a confined aquifer. A confining layer represents an impermeable layer which restricts the movement of water into the aquifer.

2. Silt/Clay: A deposit of silt and clay-sized particles which serve as a barrier to retard movement of liquids. The high clay content provides a low pollution potential. Shrinking clays and higher silt concentrations increase the pollution potential.

3. Metamorphic/Igneous Rock: Consolidated rock of metamorphic or igneous origin which contain no significant primary porosity and which permit movement of liquids through fracturing. The relative pollution potential is a function of the degree of fracturing.

4. Shale: A consolidated thick-bedded clay rock that may be fractured. Pollution potential is low but increases with the degree of fracturing.

5. Limestone: Consolidated massive limestone or dolomite which typically contains fewer bedding planes than Bedded Limestone, Sandstone and Shale sequences (see No.7 below). Pollution potential is influenced by the degree of fracturing, with a high density of fracturing increasing the chance of pollutant migration.

6. Sandstone: A consolidated sand rock which contains both primary and secondary porosity and is typified by thicker bedding, as opposed to Bedded Limestone, Sandstone, Shale sequence. Pollution potential is largely controlled by the degree of fracturing and the primary porosity of the Sandstone.

7. Bedded Limestone, Sandstone, Shale: Typically thin-bedded sequences of sedimentary rock that contain primary porosity, but where the controlling factor in determining pollution potential is the degree of fracturing.

8. Sand and Gravel with Significant Silt and Clay: Unconsolidated mixture of sand and gravel which contains an appreciable amount of fine material. These deposits have a high concentration of clay, thereby reducing the permeability of the deposits. These deposits are commonly referred to as “dirty” and have a lower pollution potential than “clean” sands and gravels. In general, finer-grained and “dirtier” sands have a lower pollution potential than coarser-grained “dirtier” gravels.

9. Sand and Gravel: Unconsolidated mixture of sand to gravel-sized particles which contain small amounts of fine materials. The range in rating reflects principally a grain size distribution where unsorted smaller grained deposits have a lower pollution potential and larger grained, well-sorted deposits have a higher pollution potential.

10. Basalt: Consolidated extrusive igneous bedrock which contains bedding planes, fractures and vesicular porosity. This is a special case of Metamorphic/Igneous. The term is used in DRASTIC in a generic sense, even though it is actually a rock type. Pollution potential is influenced by the number and amount of interconnected openings present in the lava flowing materials. Pollution potential is typically high because there is little chance for the attenuation once the pollutant enters the fracture system.

11. Karst Limestone: Consolidated limestone bedrock which has been dissolved to the point where large open interconnected cavities and fractures are present. This is a special case of Limestone where pollution potential is high based on the amount of open area in the rock.

For an unconfined or semi-confined aquifer the pollution potential is evaluated by using the most significant media in the vadose zone. This meaning that in a multi layer system, the relative thickness and the pollution potential of each media must be considered before choosing the most influential media on the pollution potential in the Vadose zone.

When assessing a confined aquifer, the “Confined Layer” media must be used, irrespective of the other media present in the vadose zone.

Table 2-8 provides a list of the type of vadose zone media and a range of ratings per type. This allows the user to more accurately choose a rating, if aspect such as the grain size, sorting, homogeneity etc of the media is known. A typical rating per media has also been provided that can be used with confidence.

RANGE (Type)	RATING	TYPICAL RATING
Confining Layer	1	1
Silt/Clay	2 to 6	3
Metamorphic/Igneous Rock	2 to 8	4
Shale	2 to 5	3
Limestone	2 to 7	6
Sandstone	4 to 8	6
Bedded Limestone, Sandstone, Shale	4 to 8	6
Sand and Gravel	6 to 9	8
Sand and Gravel with significant Silt and Clay	4 to 8	6
Basalt	2 to 10	9
Karst Limestone	8 to 10	10

Table 2-8: Ranges and Rating for Vadose Zone Media

2.2.7. Hydraulic Conductivity of the Aquifer

The ability of water to flow through a given system will also influence the ability of a pollutant to be carried away from its point of introduction in a system. Hydraulic conductivity is the ability of the aquifer material to transmit/transport water and in so doing, transmit/transport the pollutant.

Hydraulic conductivity is governed by the amount of inter connections of the void spaces in the aquifer, and are calculated from aquifer pumping tests. Table 2-9 below shows the ranges of Hydraulic conductivity measured in gallons/day/foot^2 (GPD/ft^2) and their associated ratings.

RANGE (GPD/ft^2)	RATING
1 to 100	1
100 to 300	2
300 to 700	4
700 to 1000	6
1000 to 2000	8
2000+	10

Table 2-9: Ranges and Rating for Hydraulic Conductivity

2.3. The DRASTIC Index Value and its significance

It is important to note that all the DRASTIC parameters are interconnected and in essence dependant on one another. For example the rate of recharge depends on the soil media, topography and the effect of the vadose zone.

The DRASTIC Index Value is the result of an algorithm that combines all the DRASTIC factors together to form a single value depicting the aquifer's vulnerability to pollution.

The DRASTIC Index Value is the sum of the weighting of each DRASTIC factor multiplied by its respective rating. Mathematically it can be written as follows:

DRASTIC Index= $D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W$

Where R refers to the rating of each factor and W to the weighting.

The minimum value for the DRASTIC index that one can calculate (assuming all seven factors where used in the calculation) is 24 with the maximum value being 226. The higher the DRASTIC Index the greater the vulnerability and possibility of the aquifer being polluted if a pollutant is introduced at the surface or just below it.

3. SOURCES OF GROUNDWATER CONTAMINATION

The pollution of groundwater can occur due to a variety of human activities. In evaluating the vulnerability of an aquifer to contamination, it is also very important to assess the type of contaminant being introduced as well as the source of contaminants. Here the source of contaminants will be considered and as discussed in *Lehr et al,* these can in general be divided into three groups:

1. Contaminants that are introduced at the land surface, in streams or in surface impounds that are water soluble;
2. Contaminants that are disposed in the ground above the water table;
3. The disposal, storage or extraction of material below the water table.

In applying DRASTIC to case specific aquifer studies the source of the contaminant plays an important role in assessing which of the DRASTIC parameters are of most importance. By doing this one can also reassess the allocated weightings.

Possible sources of contaminants under the three groups listed above will be discussed in this chapter. These sources have been limited to the scenarios likely to occur in South Africa. The DRASTIC parameter having the greatest effect on the pollution potential for each given scenario, will also be highlighted.

3.1. Contaminants introduced at the surface

3.1.1. Important DRASTIC Parameters

Contaminants can either be dry or wet. A dry contaminant introduced at the surface will be dissolved by rainfall and result in groundwater contamination, where as a wet contaminant can penetrate the land surface without the aid of rainfall.

The most important DRASTIC parameters when analysing the effect of a dry contaminant are:

- Depth to Water
- Net Recharge
- Soil media
- Impact of the Vadose zone

The depth to water governs the time of contact the pollutant has with the unsaturated zone, with the soil media and Vadose zone, affecting the attenuation of the pollutant in this unsaturated zone. The net recharge determines the amount of leachate generated.

For a wet contaminant introduced at the soil surface, the DRASTIC parameters that are considered to have the greatest effect on pollution potential of the aquifer are:

- Depth to Water

- Soil Media
- Impact of the Vadose zone

Net recharge is of less importance in this case as the contaminant is already in a liquid form.

3.1.2. Contaminants introduced at the land surface due to Mining activities

South Africa is renowned for its wealthy mineral resources, and is ranked as one of the largest mining countries in the world. With the extent of mining occurring in South Africa it is important to consider the impact that these activities have on groundwater resources as well as to identify the possible sources of contaminants.

The possible sources of dry contaminants are ore stockpiles, waste rock dumps and spillages from the process plants.

Both stockpiles and waste rock dumps are generally left exposed to the natural elements and placed piled on unlined surfaces. Contamination of groundwater from these sources generally occurs from precipitation infiltrating into them, leaching out minerals and heavy metals and seeping into the subsurface. Rain runoff from the stockpiles or dumps now contaminated can also seep into the subsurface or enter the catchment's river and infiltrate into the groundwater.

Wet contaminants in the mining process usually originate from tailings. Tailings are the fine mining wastes generated from the on-site processing operations of cleaning and concentrating the ore.

These tailings are in a liquid form and usually placed in a containment area on unlined surfaces and kept uncovered to form tailings dams. Water stored in these dams contain contaminants and can penetrate the subsurface and pollute the groundwater. Once the tailings dams are allowed to dry out (which only occurs once mining activities have ceased) precipitation can penetrate into the dams and form leachate that seeps into the ground at the base of the dams leading to groundwater contamination. Runoff from the sides of the dam walls can also be a source of groundwater contamination.

Groundwater contaminants associated with tailings dams are acids, metals, dissolved solids and in many cases radioactive materials.

In general, the extend and type of groundwater contamination due to mine stockpiles, rock dumps or tailings dams are mainly dependant on the mineralogy of the material being mined, the size and configuration of the structure, the climate of the area, the hydrology of the mine site and also on the control measures implemented by the mine to prevent groundwater contamination. Measures that can be implemented is as the lining of the area the waste facilities are placed on, with clay materials or geosynthetic liners that decrease the permeability of the soil and hence decrease the amount of seepage from these facilities, and hence the amount of contaminant entering the aquifer.

3.1.3. Contaminants introduced at the land surface due to agricultural activities

Contaminants from agricultural activities can be divided into two broader groups, these being animal feedlots and plant cultivation.

Animal feedlots can be considered as point source contamination sights. The major pollutants from such feedlots are from animal wastes that contain large quantities of organic nitrogen and ammonium, and to a lesser extent phosphates, bacteria and chlorides. (*Miller D.W*)

Cattle feedlots are ranked as the greatest producers of waste followed by sheep, poultry and hog feedlots. The management of the feedlots is the most significant factor in minimising contamination of the underlying aquifers, with the type of soil and slope of the area being the key DRASTIC parameters. The steeper the topography and the coarser the soil, the waste is introduced onto, the greater the risk of nitrate contamination of the aquifer.

Agricultural activities involving plant cultivation use large amounts of pesticides and fertilizers. In general, as described by *Houzin et al*, organic fertilisers such as animal manure stimulate the growth of microbes that assist with the uptake of nutrients by plants, are combined with inorganic fertilisers that contain nutrients such as nitrogen, potash, phosphates, fluorine, cadmium, calcium, magnesium cobalt and molybdenum. The two are mixed in order to provide optimum growth conditions by increasing soil water capacity, absorption capabilities and resistance to acidification.

Most nitrogen fertilisers are not easily absorbed into the soil, leaving up to 65% of the available nitrogen available for leaching into the groundwater. The increase in nitrogen in aquifers underlying agricultural land has directly been linked to the use of nitrogen fertilizers at the surface.

Contamination due to the use of pesticides is not easily traceable as there are over 50 000 different pesticide products available using over 1 200 different chemicals (*US EPA 19979b*). Contamination due to pesticides can thus not be attributed to one element as is the case with fertilisers. Yet groundwater contamination due to the use of chemical pesticides has been identified in shallow aquifers and in regions with permeable soils.

Pesticides are either absorbed by the soils or exposed to degradation and leaching to the groundwater. The degree of contamination is dependant mainly on the soil media, depth to the aquifer and the composition of the pesticide and its ability to be absorbed by the soil. Extensive tilling of the soil and irrigation also increase the ability for the pesticide to leach into the groundwater (*Aller et al*).

3.1.4. Contaminants introduced at the land surface due to accidental spillages

Whilst transporting, handling or storing materials, accidental spills of the hazardous and even non-hazardous material may occur.

The effect of an accidental spill on an aquifer is primarily governed by the surrounding hydrogeological settings, the capacity for attenuation or degradation of the spilled substance, the characteristics (hazardous / non-hazardous) of the substance and most importantly the remediation activities carried out at the site directly after the spillage has occurs. (*Aller et al*)

3.1.5. Contaminants introduced at the land surface from airborne sources

Contamination of aquifers from airborne sources constitutes a relatively small proportion but one that is steadily increasing. The major source of pollution is automobile exhaust fumes and various other industrial emissions. Increased levels of lead, cadmium and mercury in ground water in highly urbanised and industrial areas can be attributed to airborne sources. (*Owe et al*)

Hubert et al discuss how Acid rain is of great concern in heavily urbanised and industrialised areas. High concentrations of sulphur, sulphur dioxide products, nitrogen, nitrogen dioxide products and hydrogen ions found in acid rain results in the decrease in the pH of aquifer waters as well as potentially toxic concentrations of these elements in the water.

3.2. Contaminants introduced in the ground above the water table

3.2.1. Important DRASTIC Parameters

When considering dry contaminants that need to de dissolved before they can be transported to the aquifer the key DRASTIC parameters that need to be considered are discussed by *Lehr et al* as being:

- Net Recharge
- Hydraulic conductivity
- Aquifer media

The net recharge governs the amount of leachate generated, while the hydraulic conductivity affects the migration rate and the aquifer media the degree of attenuation that can occur.

A liquid contaminant's effect on an aquifer is governed directly by its possible attenuation and migration rate. These are governed by the following DRASTIC parameters (*Lehr et al*):

- Depth to Water
- Impact of the Vadose zone
- Hydraulic conductivity
- Aquifer media

Net recharge is of less importance in this case as the contaminant is already in a liquid form.

3.2.2. Contaminants introduced in the ground above the water table due to Surface Impounds and Storage facilities

Liquid waste whether hazardous or non-hazardous is produced from a multitude of activities, and need is often be contained in surface impounds and storage facilities prior to treatment or as a disposal option.

Impounds are used to store waste from farming activities such as manure and dairy waste; as sewerage and water treatment plants; to store, process, treat or dispose of industrial waste and for mine water treatment or recycling, to name just a few.

Groundwater contamination occurs as a result of seepage and spillage from these impounds, with seepage being the prominent source.

Seepage of contaminates occurs primarily in unlined facilities and from facilities with inadequate lining or due to failures or leaks in the lining system. Spillages occur during high storm events, due to the discharge of overflow from the facilities or due to failures of the impounding walls. (*US EPA 1980 and US EPA 1983*).

3.2.3. Contaminants introduced in the ground above the water table due to Landfills

Solid waste produced by households and industries is disposed of in landfills and intermittently covered with soil or suitable material to reduce aesthetic effect, odour and health hazards. The material may be hazardous or non-hazardous with the leachate produced by the waste posing the greatest threat to groundwater.

Waste disposed of in a landfill undergoes aerobic and anaerobic decomposition. The infiltration of water and the reaction of water naturally contained within the waste when dumped may dissolve soluble substances and even react with the waste to produce leachate. The conditions governing the rate and quantity of leachate produced are; moisture content of the waste; temperature; type and permeability of cover material; rainfall; and type of waste. (*O'Leary et al 1986a*)

Leachate produced during aerobic decomposition generally contains volatile acids with low pH that perpetuate the dissolving of further contaminants in the waste. During anaerobic decomposition leachate is also accompanied by large volumes of methane gas. (*O'Leary et al 1986b*)

Only recently has regulations been set in place in South Africa to minimise the effect of leachate on groundwater. Waste must be classified as hazardous or non-hazardous and depending on this classification and the size of the facility, the appropriate liner and leachate collection facilities must be in place. Further more it is recognised that to ensure maximum protection of underlying aquifers, proper site selection must be done. It is envisaged that DRASTIC could play a key roll in the site selection process. Controlled operation and the correct closure of the facility are of utmost importance. These requirements have been set out in the "*Minimum requirements for waste disposal by landfill, and Minimum requirements for handling, classification and disposal of hazardous waste*".

Although these measures help protect the environment from new landfills, there are numerous older established landfills in South Africa that do not have these measures in place and pose a threat to groundwater everyday. Furthermore, many waste disposal sites are not licensed and no control exists on the type of waste being disposed in them.

3.2.4. Contaminants introduced in the ground above the water table due to waste disposal in excavations

As discussed by *Aller et al* the extraction of natural stones, sands and soils often results in large excavation sites that at the end of their life become illegal or unmonitored dumping sites.

Many of these excavations may be to a depth that is close to shallow aquifers or even contain groundwater due to seasonal risings of the water table.

By the dumping of waste in such sites, groundwater contamination is almost inevitable due to leaching of these contaminants by rainwater and/or groundwater. The severity of the contamination is directly connected to the type and amount of waste deposited in these sites.

Other source of groundwater contamination that originated in the soil above the water table is from leakages from underground pipelines and storage tanks and leachate from graveyards to name a few.

3.3. Contaminants introduced in the ground below the water table

3.3.1. Important DRASTIC Parameters

The DRASTIC parameters that are of most importance here are the same as those listed in section 3.2.1 above.

It is important to note thought net recharge will not be an important factor to consider for dry contaminates introduced below the water table, as these will be dissolved by the aquifer itself.

3.3.2. Contaminants introduced in the ground below the water table due to the disposal of waste in open excavations

Often mining activities occur on the surface in the form of open pits, strip mining and quarries that often extend below the water table. During the mining activities the groundwater seeping into the pits is pumped out, resulting in the lowering of the water table as well as in altering the flow path of the water table. Once mining activities have ceased these pits often fill with water until they are in equilibrium with the surrounding water table.

Material that has been excavated that is of mineral value to the mining company is commonly known as waste rock. Often when considering strip mining the waste rock excavated in one section is deposited in the previously excavated section (a type of cut and fill operation). Problems that may arise with such practises is the leaching of minerals out of the waste rock (now of a much larger surface area and possibly a different mineralogy to the rock originally in contact with the aquifer) directly into the aquifer and the oxidation of base metal sulphide compounds that leads to acid mine drainage.

Often after mining activities have ceased the open pits are not monitored and illegal dumping occurs. The water quality of the aquifer can be serious affected by this as the waste is in direct contact with the aquifer. Even contaminated runoff from the surrounding mine site that flows directly into the pit could contaminate the aquifer.

3.3.3. Contaminants introduced in the ground below the water table due to underground mining activities

Underground mining activities that intersect aquifers have much the same effect on groundwater quality as surface mining activities that intersect aquifers.

Groundwater contamination can occur when underground rock faces are exposed and come in contact with the aquifer, or when the mine stopes and shafts are refilled with waste material. In both instances acid mine drainage can occur as well as the leaching of minerals from the rocks, resulting in elevated levels of the minerals in the water to levels that could be toxic.

3.3.4. Contaminants introduced in the ground below the water table due to salt water intrusion

The excess pumping of groundwater in coastal areas often results in the intrusion of saltwater into the aquifer. Excessive pumping can be described in this instance as draining the aquifer at a faster rate than it is recharging.

This introduction of saltwater increased the total dissolved solid (TDS) concentration of the groundwater often to such levels that groundwater can no longer be considered suitable for human consumption.

Drought resulting in reduced surface flow can also cause the ingress of saltwater into aquifers. (*Bower, H*)

4. NATIONAL AND INTERNATIONAL EXPERIENCE WITH DRASTIC

4.1. The use of DRASTIC in the USA

In order to assess the soundness of the DRASTIC model, a range of counties in the USA with varying hydrogeological scenarios and with both an abundance and a scarcity of data in both rural and urban areas where selected for case studies. These counties were:

Cumberland County, Maine
Finney County, Kansa
Gillespie County, Texas
Greenville County, South Carolina
Lake County, Florida
Minidoka Country, Idaho
New Castle County, Delaware
Pierce County, Washington
Portage County, Wisconsin and
Yolo County, California

DRASTIC was tested on each in order to critique the methodology behind the system and make changes where deemed necessary. The 10 counties chosen have varying hydrogeological settings showing the extensive applicability of DRASTIC. In order to convey the wide spread applicability of DRASTIC the hydrogeological settings of each county has been summarised below.

4.1.1. Cumberland County, Maine

Sand and gravel aquifers form the major groundwater resources of Cumberland County, and the ability of supplying significant yields. The sand and gravel deposits are very permeable and the depth to water being shallow. Where these deposits where not present, igneous/metamorphic low yield aquifers were present. (*Caswell, B.W.*)

4.1.2. Finney County, Kansas

Two distinct groundwater regions are found in this county. The first region consist of aquifers formed of poorly- sorted unconsolidated sands and gravels, being extensively used for irrigation in the region, and subsequently resulting in decreasing water levels. An underlying consolidated chalky limestone is also present in this region.

The second region consists of the deep, confined Dakota Sandstone aquifer. An alluvial aquifer is also present in this region and is the only shallow groundwater source for the region. (*Meyer, M.E.*)

4.1.3. Gillespie County, Texas

The western region of Gillespie County is covered by a thick sequence of bedded dolomitic limestones, containing water in solution cavities and fractures. The central region is covered by unconsolidated sand and silts with the northeastern parts of the county being covered by igneous and metamorphic rocks that contain water in fractures and faults.

Save for the igneous and metamorphic aquifers, the county has a high yield of groundwater which provides water for both municipal and domestic use. (*Texas Department of Water Resources 1983.*)

4.1.4. Greenville County, South Carolina

The primary groundwater resources are from igneous and metamorphic rocks that provide moderate yields from fractures and faults. Overlaying these rocks is a layer of variable thickness of saprolite, in which unconfined groundwater accumulates that often acts as a recharge source for the underlying igneous/metamorphic aquifers. Overlying the saprolite are alluvial deposits of sand and gravel around rivers in the county. (*Paggett, G.G.*)

4.1.5. Lake County, Florida

The county is well known for its karst topography, numerous sinkholes, lakes and swampy areas with shallow water depths and highly permeable soils. Groundwater in the county is obtained either from the near surface sand aquifer of an underlying carbonate (limestone) rock aquifer. The two aquifers are hydraulically connected but separated by a confining layer of sand and clay.

The shallow sand aquifer due to the soils' permeability and shallowness is very susceptible to pollution. For the carbonate aquifer, its degree of susceptibility to contamination from the surface is governed by confinement of the limestone aquifer and the degree of recharge it receives from the surface soil aquifer. (*Furman et al*)

4.1.6. Minidoka County, Idaho

Deep unconfined highly permeable basalt deposits formed by individual lava events form the aquifers of Minidoka County. Some alluvial aquifers with hydraulic connection to the basalt aquifer are also present in the region. The deep basalt aquifers are developed for domestic, industrial and irrigation use. (*Young, H.W.*)

4.1.7. New Castle County, Delaware

New Castle County has two distinct aquifer regions, the first formed by igneous and metamorphic rock overlade by a variable thickness of saprolite. The second is comprises of thick layers of sand and gravel deposits that form an unconfined coastal aquifer. Underlying this aquifer is a series of deeper confined aquifers. (*Groot et al*)

4.1.8. Pierce County, Washington

Responsible for over 75% of this county's drinking water is a very thick sequence of interbedded glacial sands, gravels and silts that form a permeable shallow aquifer. Hydraulically connected to this aquifer are deeper sand and gravel aquifers that are recharges by the shallow aquifer.

In the eastern section of the county is the Cascade mountain range. Within this range, volcanic mudflows and igneous rocks form low yielding aquifers. (*Brown et al*)

4.1.9. Portage County, Wisconsin

Thick sequences of glacial outwash sands and gravels form this county's aquifers. They are characterised by highly permeable soils and shallow water depths. The north-west region of the county differs in that metamorphic and igneous rocks overlaid by a thin layer of glacial till form the aquifers. (*Otter et al*)

4.1.10. Yolo County, California

Yolo County is an alluvial basin. In the west one finds marine sandstones and shales yielding saline water and as one moves to the east older continental deposits, alluvial fans and river alluvium comprised of sands, silts and clays form the aquifers that provide significant yields. These aquifers are confined, but typically where they overlap they are hydraulically connected. (*California Department of Water Resources*)

Having confirmed with the above ten case studies that DRASTIC was in fact an acceptable and accurate tool in predicting an aquifer’s susceptibility to contamination, DRASTIC was used to map the entire United States for groundwater vulnerability.

One hundred and eleven different hydrogeological settings where identified in the USA and a nation groundwater vulnerability map based on 1: 2 000 000 data maps was produced.

4.2. Groundwater vulnerability to pesticides map for Indiana

In 1988 the EPA commissioned a National Survey of Pesticides in Drinking water. 1347 groundwater wells (563 community wells and 783 rural drinking wells) where tested for the presents of contamination due to pesticides. The results showed that over 0.8% of the wells tested contained pesticide residue higher than the acceptable Maximum Contaminant Level (MCL). Over 1.2% of the community wells and over 2.4% of the rural wells contained levels of nitrate well over the acceptable MCL.

The water quality analysis performed from this survey found that when compared with the National 1:2 000 000 DRASTIC maps, they did not correlate well. It was found that more detailed and accurate maps where required, if these maps are to be used in the implementation of pesticide management plans to prevent degradation of groundwater quality, implementation of groundwater quality monitoring programs and the zoning and other programs that influence new developments.

Thus a new study was commissioned in which maps for groundwater vulnerability to pesticides would be created using 1: 250 000 data maps and using both DRASTIC and SEEPAGE. The System for Early Evaluation of the Pollution Potential of Agricultural Environments (SEEPAGE) estimates contamination potential of groundwater using hydrologic factors in a similar manner to DRASTIC.

The hydrologic factors used in SEEPAGE are soil slope, depth to water table, vadose zone material, aquifer material, soil depth and attenuation potential. The attenuation potential further considers soil surface texture, subsoil texture, surface layer pH, organic matter content of surface, soil drainage class and soil permeability.

In conjunction to producing the 1: 250 000 DRASTIC and SEEPAGE maps, a pesticide use map was to be created from data of pesticide use in the state collected by the Indiana State Chemist. The use and overlay of the three maps together are expected to provide a map that shows both vulnerability and pesticide use for the region. This map will be the main tool in implementing pesticide management tools, monitoring tools and the in zoning new developments.

More recent studies involving the use of DRASTIC and GIS have been conducted in the United States. In 2000 *Fritch et al* performed a groundwater vulnerability assessment on the Paluxy aquifer in north-central Texas. They concluded that this methodology allowed an investigation of the potential for groundwater contamination on a regional, rather than site specific basis.

Evans et al. used a modified DRASTIC approach with GIS to evaluate the potential for regional groundwater pollution in southern Delaware. They replaced the DRASTIC parameters of net recharge, impact on the vadouse zone and aquifer media with land use/land cover and septic tank system density. The result was the ability to generate groundwater related information for large geographical areas that was sufficiently detailed for use by government bodies involved in groundwater protection.

4.3. *The use of DRASTIC in creating a vulnerability map for South-Africa*

In 1994, *Lynch et al,* began the process of developing a groundwater vulnerability map on a national scale for South Africa. This map can be found in Appendix 1 of this report.

They chose to use DRASTIC as the methodology for creating the map, as despite the fact that other vulnerability methodologies existed internationally, the 7 criteria considered in DRASTIC "*generally embodied the most significant factors controlling an aquifer's vulnerability to contamination*".

In creating this map, *Lynch et al* found the following limitations with the DRASTIC system:

- DRASTIC does not consider the impact of human activity on groundwater
- DRASTIC does not allow for natural or man-induced water quality problems (being intrinsically a vulnerability, as opposed to a risk assessment technique).
- DRASTIC does not take into account some physical parameters which have a strong influence on groundwater pollution such as:
    - Fracturing and faulting
    - The effect of precipitation duration and intensity
    - Soil reactivity
    - Differences in specific contaminant mobility

- Anisotropy and heterogeneity of the soil, Vadose zone and aquifer hydraulic conductivity
- DRASTIC does not consider dilution which could be a significant factor in the limited storage hard-rock aquifer conditions prevalent over much of South Africa.

Furthermore it was found that much of the information required as input data for creating the South African map was not available resulting in a number of assumptions having to be made in order to create the map. The parameter of hydraulic conductivity had been emitted from the analysis as very limited information was available on this parameter for South African aquifers. The input layer maps used in creating the South African Vulnerability map as well as the vulnerability map can be found in APPENDIX 1.

An important assumption was that the weighting system used in DRASTIC, which was developed for the United States of America, was applicable to South African conditions. The authors believed that this was acceptable as the map would be used for comparative purposes only.

It was further noted that no attempt had been made to validate the vulnerability map of South Africa and that further research was required before the map could be a tool that could be used by planners and decision makers.

The authors recommended that the national groundwater data base be populated at an accelerated rate and a list be made available of groundwater related data sets and of the organisations that have captured or are capturing hydro-geological data.

Subsequent to the development of the vulnerability map, the Department of Water Affairs and Forestry (DWAF) embarked on the development of a series of hydrogeological maps of South Africa. Of the envisaged 23 maps covering different regions of the country, 15 have been published to date.

The maps are on a scale of 1 in 500 000 and depict the groundwater occurrence (borehole yield and aquifer type) superimposed on a lithological background. Accompanying each of these maps are 4 insert maps. These are maps depicting

- the distribution of borehole data (Scale 1: 2 000 000)
- Elevation above sea level (Scale 1 : 2 000 000)
- Mean annual precipitation (Scale 1 : 2 000 000)
- Groundwater quality (Scale 1: 1 500 000)

Despite the fact that these maps cover many of the parameters used in the DRASTIC model, the use of these maps in creating a more reliable vulnerability map of South Africa is inappropriate given the large scale of the map.

Vegter, divided South Africa was into 64 groundwater regions based on the type of aquifer as well as the lithostratigraphy, physiograph and climate of the region. This large number depicts the diversity of South Africa's aquifers and simply re-iterates the fact that a more detailed, smaller scale analysis of these regions need to occur, in order for a meaningful and useful vulnerability map of South Africa to be created that can be used for planning and management purposes on a national and localised scale.

In 2004, *Jovanovc et al,* generated comprehensive inventory of groundwater contaminants, their properties and their associated sources in South Africa for the major metropolitan areas. From this they prioritized and development a risk assessment of these contaminants. Due to a lack of groundwater monitoring data the prioritization of the contaminates was based on types of industries and activities from which the occurrence of specific contaminants where deduced. A procedure using computer software was developed that allows the used to establish the priority contaminants for specific urban areas even with limited data available. This study further highlights the need of reliable groundwater monitoring data.

4.4. The European Union's experience on groundwater mapping

In February 1991 in a meeting held by the European Community Commission (EEC) it was agreed that a uniform method would need to be adopted by all member states to evaluate, rank and map groundwater pollution vulnerability. The reasoning and advantages of adopting a uniform system were stated by *Lobo Ferreire*[7] as being:

- *"Maps generated in one country are understandable by all;*
- *maps from different countries can be combined to cover cross-boundary and multinational regions;*
- *it facilitates the dialogue between professionals from different countries which allows form countries to benefit from the experience acquired by other countries;*
- *a compatible and coherent data base for all EEC member-states could be created."*

An important distinction was made by the EEC that being the difference between Vulnerability and Pollution Risk. Pollution risk does not only depend on the vulnerability of the aquifer but also on the pollution loading entering the subterranean environments. Thus it is possible to have high aquifer vulnerability and no risk of pollution if there is no significant pollution loading, and to have high pollution risk despite of low vulnerability if the pollution loading is extreme.

The EEC also recognized that the vulnerability of an aquifer is also dependant on the type of pollutant entering the system. Given this it would be more accurate to map the vulnerability of an aquifer in relation to a specific class of pollutants or in relation to a group of polluting activities such as agriculture or particular groups of industries.

Due to the fact that there rarely is sufficient information available to map specific vulnerability, a system would need to be adopted that would make best use of generally available data in a technically valid and useful way.

The system chosen was DRASTIC, and the first EEC member country to be mapped using DRASTIC was Portugal. The map developed was based on 1: 500 000 scale data maps.

After the application of DRASTIC to Portugal as a case study, Lobo-Ferreira, the head of Groundwater Research Group in Portugal was under the opinion that "*DRASTIC contains an excellent conceptual basis for the application of mathematical groundwater flow and mass transport models, also for salt-water intrusion assessment in coastal zones".*

The DRASTIC mapping of Portugal, found that the results followed the general pattern of results obtained from classical vulnerability assessment methods previously used in Portugal. Furthermore the DRASTIC mapping presented much greater zoning definition believed to be due to the fact that several relevant hydrogeological criteria had been taken into consideration by the DRASTIC model that where usually not considered by classical vulnerability assessment methods.

The groundwater vulnerability map created for Portugal can be found in APPENDIX 1 of this report.

4.5. New Zealand's applications of DRASTIC

New Zealand geographically is a latitudinally elongated and small land area. Within this small area a large variety of hydrogeological properties make up it's aquifer systems. The aquifers can be broadly grouped by the type and age of sediments and rocks in which they occur, these being; volcanic, sedimentary and metamorphic rocks, floodplain and river valley gravel, and sand and silt deposits.

The DRASTIC method for assessing contamination vulnerability of groundwater resources was used on an aquifer scale, on a regional scale as well as on a national scale in New Zealand.

Brown applied specifically modified DRASTIC factors to the confined aquifer system underlying the Heretaunga Plains, Hawkes Bay, to produce a GIS-based map for the Hawkes Bay Regional Council.

This map as stated by *Sheppard* was used by the Council to:

- *"review the Heretaunga Plains and adjacent areas groundwater quality monitoring network to make sure that there were monitoring wells sited in areas with high vulnerability to contamination (prioritization of monitoring);*

- *eliminate duplication of monitoring wells, especially where there was low vulnerability potential;*
- *identify areas where either additional or less stringent protection measures might be required;*
- *manage/design land-use practices such as pesticide application and septic tank density in vulnerable areas to reduce contamination risk.*
- *Prevent threatening practices such as bulk transport of particular lethal contaminants through a high vulnerability area or their storage in high vulnerability areas;*
- *Identify particular hydrogeologic settings where further reconnaissance might provide a better database for future groundwater resource assessments or another DRASTIC analyses".*

Brown et al. compiled a 1:500 000 scale map for the Wellington region, with the aim of the map being used to provide information for planning purposes to formulate policies on land-use activities that have potential of discharging contaminants on the land.

Close applied DRASTIC using the pesticide ranking system to compared 17 regions where significant amounts of pesticide were being used. The six highest ranked regions were then selected for groundwater sampling for pesticide analysis and more detailed study.

Hadfield et al. used DRASTIC to identify the most vulnerable regions with the Hauriki Plains to groundwater contamination from the land treatment of dairy industry waste. The DRASTIC evaluation depicted the distribution of contamination potential consistent with a previous study on the Hauriki Plains of the distribution of nitrate in the groundwater.

Following these studies, the authors had the following reservation on the use of DRASTIC:

- Close noted that *" for New Zealand it appears that the ranking of the top three regions is relatively insensitive to the weightings used".*

- *Brown* included the following disclaimer in his report "*this vulnerability map is designed for general use only. It shows the sensitivity of groundwater to contamination in a general way; local details have been generalized to fit the map scale. The map does not show areas that have been or will be contaminated, or areas that cannot be contaminated, and the map cannot be used for any site specific purpose. Detailed studies of individual areas may be necessary when specific information is needed. Characteristics of individual contaminants or the likelihood of contaminant release have not been taken into account when constructing the map."*

- *Brown(b)* in reviewing the application of DRASTIC to New Zealand floodplain aquifer system concluded, "*at present there is no clear answer as to whether vulnerability assessment and mapping (DRASTIC in particular) can represent the highly diversified hydrogeology of New Zealand alluvial plain aquifer system".*

4.6. Use of DRASTIC in India

DRASTIC was used in the assessment of the possible environmental impacts that a proposed landfill facility would have on the City of Jammu in India. Given the hydrogeological parameters of the area, the DRASTIC index number calculated for the proposed site was 162, indicating that the aquifer system was vulnerable to contamination from the proposed landfill on a micro-scale (local scale), and thus a high pollution potential.

From the results obtained from the DRASTIC model an Environmental Management plan was put in place for the project in order to miniminse groundwater contamination from the landfill. The management system introduced as detailed by *Nagar et al.* was:

- The installation of a drainage system to provide swift removal of rainwater.
- The installation of geosynthetic clay liner in sandwich layers between cement and other stabilising layers to prevent leachate from entering the groundwater.
- Permanent groundwater monitoring to detect any contamination caused by excessive leaching of heavy metals and other chemicals.

This is an excellent example of how DRASTIC can be utilized on a local scale – be it project by project, in order to assist in crucial decision making for the implementation of measures and the type of measures required to preserve groundwater resources.

4.7. Use of DRASTIC in China

DRASTIC was successfully applied to two case studies in China, the Guangxhou-Hauxin Basin and the Dalia Peninsula. It was found that with the hydrogeological data usually available in China, it was appropriate to use to DRASTIC to assess the groundwater vulnerability to pollution to coastal and inland regions of China.

The study lead on to the development of methodologies for the sustainable operation and strategic management of groundwater resources, that have already been applied to the Guangxhou-Hauxin Basin and the Dalia Peninsula.

The vulnerability maps created for the Guangxhou-Hauxin Basin and the Dalia Peninsula can be found in APPENDIX 1.

4.8. Use of DRASTIC in Jordan

There is a great need for groundwater vulnerability mapping in arid / desert countries in which water resources are scarce. In 2003, water consumption in Jordan exceeded their renewable freshwater resources by over 20%. Over 50% of their renewable resources is derived form groundwater.

Al-Adamat et al. utilised DRASTIC and GIS to create a groundwater vulnerability map for the Azraq Basin in Jordan showing 16% of the study area having low vulnerability and 84% a moderate vulnerability to contamination.

A land use map was created for the same basin with land uses being rated as follows:

LAND USE CATEGORY	RATING
Built up area	8
Irrigated field crops	8
Uncultivated land	5

Table 4-1 Land use rating - Azraq Basin

The land use map was converted to a raster grid, multiplied by a factor of 5 and added to the DRASTIC index. This resulted in the modified vulnerability map only increased the area having moderate vulnerability by 1%.

In order to investigate if there was a special relationship between land use and groundwater vulnerability the land use map was overlain on the original ground water vulnerability map. This was done in order to ascertain if any possible sources of contamination (farms and settlements) lay within the low and moderate vulnerability zones.

This exercise showed that less than 1% of the study area had a low vulnerability and possible source of contamination, that corresponded with the modified vulnerability map. Furthermore it showed that of the only 14% of the study area that had moderate vulnerability had possible sources of contamination and only 3% of the low vulnerability areas has possible sources of contamination.

This study highlights the fact that despite the vulnerability rating of the aquifer, the possibility of contamination is a very important factor to be considered when planning regional aquifer management. Area with low vulnerability but with high pollution potential, need to be given greater attention that even areas with high vulnerability but little pollution potential. This being said local area managers need to examine local aquifer conditions and rely purely on large scale regional vulnerability maps.

5. SOUTH AFRICAN LEGISTALION GOVERNING THE USE AND PROTECTION OF GROUND WATER WITHIN SOUTH AFRICA

As mentioned in Chapter 3 mining activities form a large sector of the South African economy, and is ranked as the largest Gross Domestic Product (GDP) creator of the resources sector. This having been said it stands to reason that due to the amount of mining activities taking place in our county their impact on South African groundwater resources will be significant.

Sources of groundwater contamination due to mining activities are many as detailed in Chapter 3. One of the greatest problems arise from the placement of tailings dams directly above dolomitic aquifers that results in the retained water within the dam draining vertically (seeping) into the aquifer. This has been the main contributor of the increased levels of sulphate in groundwater in South Africa, and has lead to the deterioration of groundwater quality.

In an effort to control the mining sectors effect on the water resources of the country laws and regulations as listed below have come into existence.

5.1. South African National Water act and related legislation

Section 24 of the *Constitution of the Republic of South Africa* ("the Constitution") provides that everyone has the right to an environment that is not harmful to their health or wellbeing and to have the environment protected for present and future generations by reasonable legislative measures that prevent pollution and ecological degradation, promote conservation, and secure ecologically sustainable development while promoting justified economic and social development.

Underneath the umbrella of the Constitution certain laws must be looked at in assessing a mines responsibility and legal requirements in terms of the conservation of groundwater resources.

5.1.1 National Water Act

Section 5 of the *National Water Act* requires the Minister to establish a national water resource strategy. As part of this strategy DWAF published a document referred to as "*Policy and strategy for groundwater quality management in South Africa*" ("Policy document"), dated 2000. In this Policy document the precautionary approach is adopted, in terms of which all groundwater will be assumed to be vulnerable unless it is shown otherwise. As a balance to the precautionary approach, the Policy document is sensitive to the fact that in the South African context where social and economic growth is important, it will be physically and economically impossible to protect all groundwater resources to the same degree. As a result groundwater resources will be grouped into aquifers and classified according to their importance. This classification will be based on potential yield and the level to which communities depend on the aquifer.

As part of the Policy document source directed strategies have been developed. In paragraph 4.1.4 of the source directed strategies it is stated that DWAF will place a general ban on waste disposal and other polluting activities within 200 meters of the recharge zone for major aquifers and sole-source aquifers.

Section 19 of the National Water Act ("Section 19") incorporates the Polluter Pays Principle (PPP). In terms of this principle the owner of land, person (including a juristic person) in control of land or a person who occupies or uses land on which an activity takes place (in the past, present and future) that has caused, is causing or is likely to cause pollution of a water resource must take all reasonable measures to prevent the pollution from occurring, continuing or reoccurring. In light of Section 19, the National Water Act and the associated considerations apply to the activity whether it was conducted in the past, is being conducted at present or will be conducted in the future.

Critical to the meaning of Section 19 is the definition of pollution as contained in Section 1(xv) of the National Water Act. In terms of this definition pollution means the alteration of a water resource so as to make it less fit for any beneficial purpose for which it may reasonably be expected to be used, or harmful or potentially harmful to human beings, aquatic and non-aquatic organisms, the resource quality and property.

The implications of Section 19 are that reasonable measures must be taken to prevent the pollution occurring. In interpreting the concept of 'reasonable measures' the provisions of Section 19(2) must be considered. Section 19(2) provides that these measures may include all of the following:

- Cease, modify or control the activity causing pollution;
- Compliance with any prescribed waste standard or management practice;
- Containment or prevention of the movement of pollutants;
- Elimination of the source of the pollution;

- Remedying the effects of the pollution; and
- Remedying the affects of any disturbance to the bed or banks of a watercourse.

The determination of which of these measures apply is left to the discretion of DWAF in the form of the relevant catchments management agency.

5.1.2 Government Notice Regulation 704

The following extract from *Government Notice Regulation 704* , stipulates the regulations on the use of water for mining and related activities aimed at the protection of water resources.

Regulation 4: Restrictions on locality states that

No person in control of a mine or activity may -

(a) locate or place any residue deposit, dam, reservoir, together with any associated structure or any other facility within the 1:100 year flood-line or within a horizontal distance of 100 metres from any watercourse or estuary, borehole or well, excluding boreholes or wells drilled specifically to monitor the pollution of groundwater, or on water-logged ground, or on ground likely to become water-logged, undermined, unstable or cracked;

(b) except in relation to a matter contemplated in regulation 10, carry on any underground or opencast mining, prospecting or any other operation or activity under or within the 1:50 year flood-line or within a horizontal distance of 100 metres from any watercourse or estuary, whichever is the greatest;

(c) place or dispose of any residue or substance which causes or is likely to cause pollution of a water resource, in the workings of any underground or opencast mine excavation, prospecting diggings, pit or any other excavation; or

(d) use any area or locate any sanitary convenience, fuel depots, reservoir or depots for any substance which causes or is likely to cause pollution of a water resource within the 1:50 year flood-line of any watercourse or estuary.

Regulation 5: Restrictions on use of material, states that:

No person in control of a mine or activity may use any residue or substance which causes or is likely to cause pollution of a water resource for the construction of any dam or other impoundment or any embankment, road or railway, or for any other purpose which is likely to cause pollution of a water resource.

Regulation 6: Capacity requirements of clean and dirty water systems, states that:

Every person in control of a mine or activity must -

(a) confine any unpolluted water to a clean water system, away from any dirty area;

(b) design, construct, maintain and operate any clean water system at the mine or activity so that it is not likely to spill into any dirty water system more than once in 50 years;

(c) collect the water arising within any dirty area, including water seeping from mining operations, outcrops or any other activity, into a dirty water system;

(d) design, construct, maintain and operate any dirty water system at the mine or activity so that it is not likely to spill into any clean water system more than once in 50 years; and

(e) design, construct, maintain and operate any dam or tailings dam that forms part of a dirty water system to have a minimum freeboard of 0.8 metres above full supply level, unless otherwise specified in terms of Chapter 12 of the Act.

(f) design, construct and maintain all water systems in such a manner as to guarantee the serviceability for flows up to and including those of the maximum flood with an average period of recurrence of once in 50 years.

Regulation 7: Protection of water resources, states that:

Every person in control of a mine or activity must take reasonable measures to-

(a) prevent water containing waste or any substance which causes or is likely to cause pollution of a water resource from entering any water resource, either by natural flow or by seepage, and must retain or collect such substance or water containing waste for use, re-use, evaporation or for purification and disposal in terms of the Act;

(b) design, modify, locate, construct and maintain all water systems, including residue deposits, in any area so as to prevent the pollution of any water resource through the operation or use thereof and to restrict the possibility of damage to the riparian or in-stream habitat through erosion or sedimentation, or the disturbance of vegetation, or the alteration of flow characteristics;

(c) cause effective measures to be taken to minimise the flow of any surface water or floodwater into mine workings, opencast workings, other workings or subterranean caverns, through cracked or fissured formations, subsided ground, sinkholes, outcrop excavations, audits, entrances or any other openings;

(d) design, modify, construct, maintain and use any dam or any residue deposit or stockpile used for the disposal or storage of mineral tailings, slimes, ash or other hydraulic transported substances, so that the water or waste therein, or falling therein, will not result in the failure thereof or impair the stability thereof;

(e) prevent the erosion or leaching of materials from any residue deposit or stockpile from any area and contain material or substances so eroded or leached in such area by providing suitable barrier dams, evaporation dams or any other effective measures to prevent this material or substance from entering and polluting any water resources;

(f) ensure that water used in any process at a mine or activity is recycled as far as practicable, and any facility, sump, pumping installation, catchment dam or other impoundment used for recycling water, is of adequate design and capacity to prevent the spillage, seepage or release of water containing waste at any time;

(g) at all times keep any water system free from any matter or obstruction which may affect the efficiency thereof; (h) cause all domestic waste, including wash-water, which cannot be disposed of in a municipal sewage system, to be disposed of in terms of an authorisation under the Act.

Regulation 8: Security and additional measures, states that:

Every person in control of a mine or activity must-

(a) cause any impoundment containing any poisonous, toxic or injurious substance to be effectively fenced-off so as to restrict access, and must erect warning notice boards at prominent locations so as to warn persons of the hazardous contents;

(b) ensure access control in any area used for the stockpiling or disposal of any residue or substance which causes, has caused or is likely to cause pollution of a water resource so as to protect any measures taken in terms of these regulations;

(c) not allow the area contemplated in paragraph (a) and (b) to be used for any other purpose, if such use causes or is likely to cause pollution of a water resource; and

(d) protect any existing pollution control measures or replace any existing pollution control measures damaged by the removing or reclaiming of materials from any residue deposit or stockpile, and establish additional measures for the prevention of pollution of a water resource which might occur, is occurring or has occurred as a result.

5.1.3 Minerals Act

Section 39 of the *Minerals Act* [19] ("Section 39") provides that for mines to conduct operations lawfully they must hold a mining authorisation and they must submit an Environmental Management Programme Report ("EMPR") for existing activities and an EMPR amendment whenever their activities extend beyond the scope of the existing EMPR.

From the above legislations it is clear that accurate analysis need to be conducted in order to assess the possibility and extent of contamination that a new mining activity would have on an underlying aquifer. Once the vulnerability of the aquifer is assessed, the mine can take the appropriate measures to ensure it's impact on the aquifer will be minimal. Such analysis and pollution prevention methods must be incorporated into the Environmental Management Program (EMPR) of the mine. This document must be submitted the Department of Water Affairs and Forestry (DWAF) for approval prior to any mining activities commencing.

It is envisaged that DRASTIC could be a valuable tool in assessing the possibility of contamination of the underlying aquifers from mining activities. The following case study has been undertaken in order to assess the effectiveness and applicability of DRASTIC to a localised situation and it's use as a management tool by DWAF for planning purposes.

6. THE USE OF DRASTIC ON A LOCALISED SCALE IN SOUTH AFRICA – CASE STUDY

6.1. Pering , the mine

Pering Mine was commissioned in 1985 to mine and process lead and zinc deposits. The mine is located in the North West Province of the Republic of South Africa approximately 140 km north-west of the province’s capital of Kimberley and about 80 km south west of the region's main commercial and administrative centre of Vryburg). It is situated on the Ghaap Plateau with an approximate altitude of 140mamsl.

The mine is situated in an arid environment where surface water is scarce resulting in groundwater being a vital resource in the area. The mine is situated on the regional dolomitic aquifer formed by the Ghaap Plateau Dolomite.

The mine was developed and operated by the Shell Group until 1994 when it was purchased by BHP Billiton. Mining activities stopped at the start of 2004 and the mine in currently undergoing closure.

During operations, the mining of the iron ore occurred from two open pits, namely the Main Pit and P24 Pit. The waste rock from these pits where stored in the “Waste Rock dumps” with the fine residue material being disposed of in the tailings dam, with the process water decanted off this dam being stored in the “Return water dam” in order to be returned to the plant for reuse.

Dewatering of the pits also took place during the operational phase of the mine.
Figure 4 below shows the general layout of the mine.

Pering mine was ideal for this case study as it was an established mine and the impacts of the mining activities on the underlying aquifer could already be seen and had been quantified.

In establishing a closure plan for the mine, BHP Billiton commissioned a full environmental investigation on the extent of the contamination of the underlying aquifer. The geohydrological assessment of the mine was carried out by *Southern African Geoconsultants (PTY) Ltd, (GeoCon)* [20] and the Mine Closure Plan by *Metago Environmental Engineers (PTY) Ltd* [21], who have generously allowed their investigational data to be used for this study.

In order to assess the aptness of DRASTIC in predicting the likelihood of mining activities at Pering to contaminate the underlying aquifer, each of the DRASTIC factors relevant to Pering have been analysed individually.

6.2. Aquifer Media

According to the South African Aquifer System Management Classification system (*Parsons* [22]), the regional dolomite aquifer can be classified as a *Major or even Sole Source Aquifer System* that contains large quantities of water, and is important in water supply to local communities, domestic purposes and agriculture for livestock

The regional dolomite aquifer boundaries are formed by the surface water catchment boundaries, which are the Kuruman Mountains in the west, and the Harts River in the east. Locally, the dyke and fault structures divide the Ghaap Plateau Dolomite into aquifer compartments. The compartment the mine is situated on is bounded in the west by the Scheurfontein Fault Zone, in the east by the Karikia Fault Zone, in the south by the Droogfontein Fault Zone and in the north-north-west by the Steekdoorns Fault Zone. These fault zones may be intruded by dykes. Figure 2 is a map showing the fault zones.

The compartment as defined here is 18.5 km from south to north and 13.5 km from west to east and covers a surface area of about 20 100 ha. The Ghaap Plateau Dolomite compartments are inter-linked with fracture/fault zones and are considered to be leaky compartments, allowing groundwater seepage across the compartment boundaries.

Figure 1: General Layout of Pering Mine

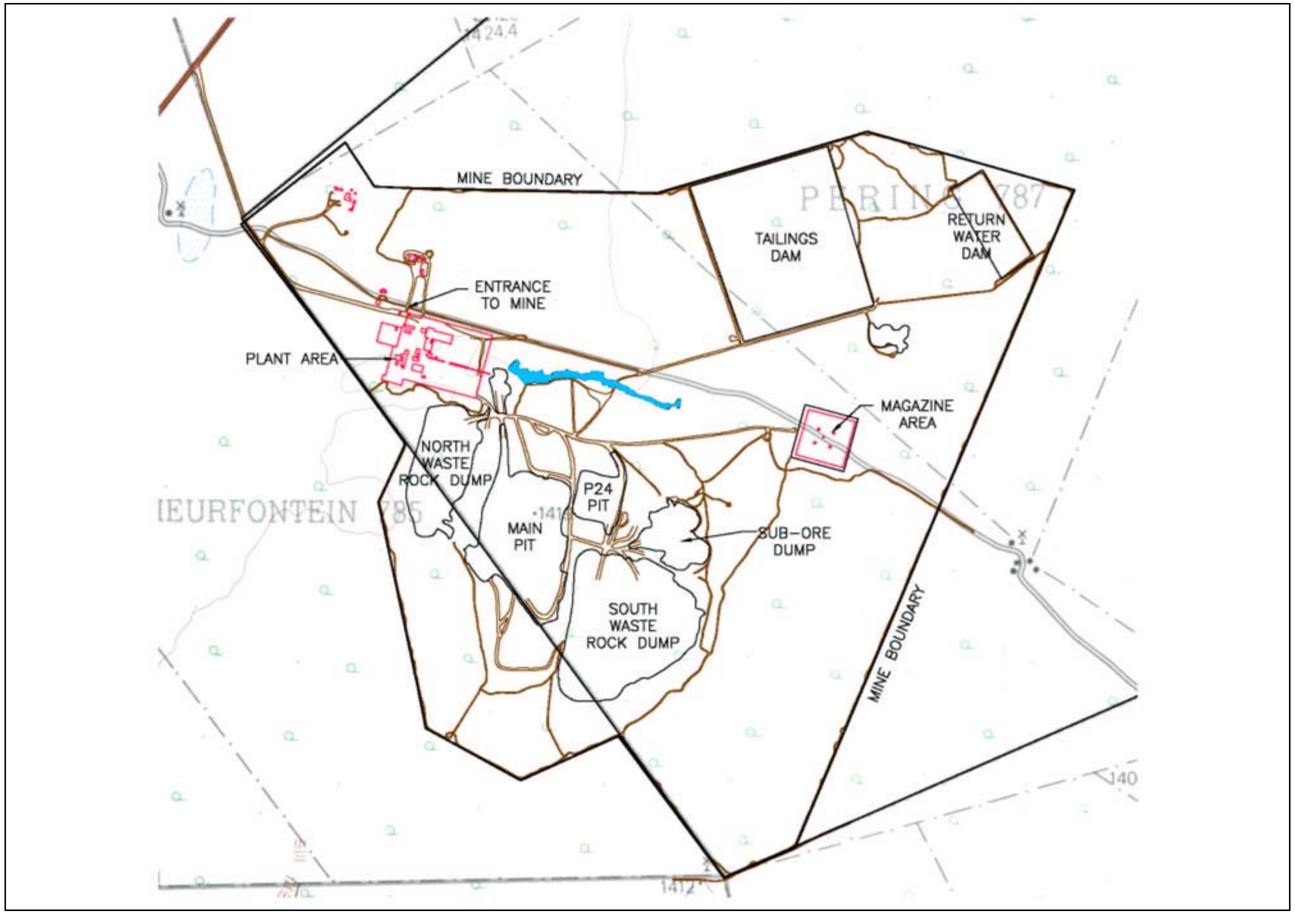
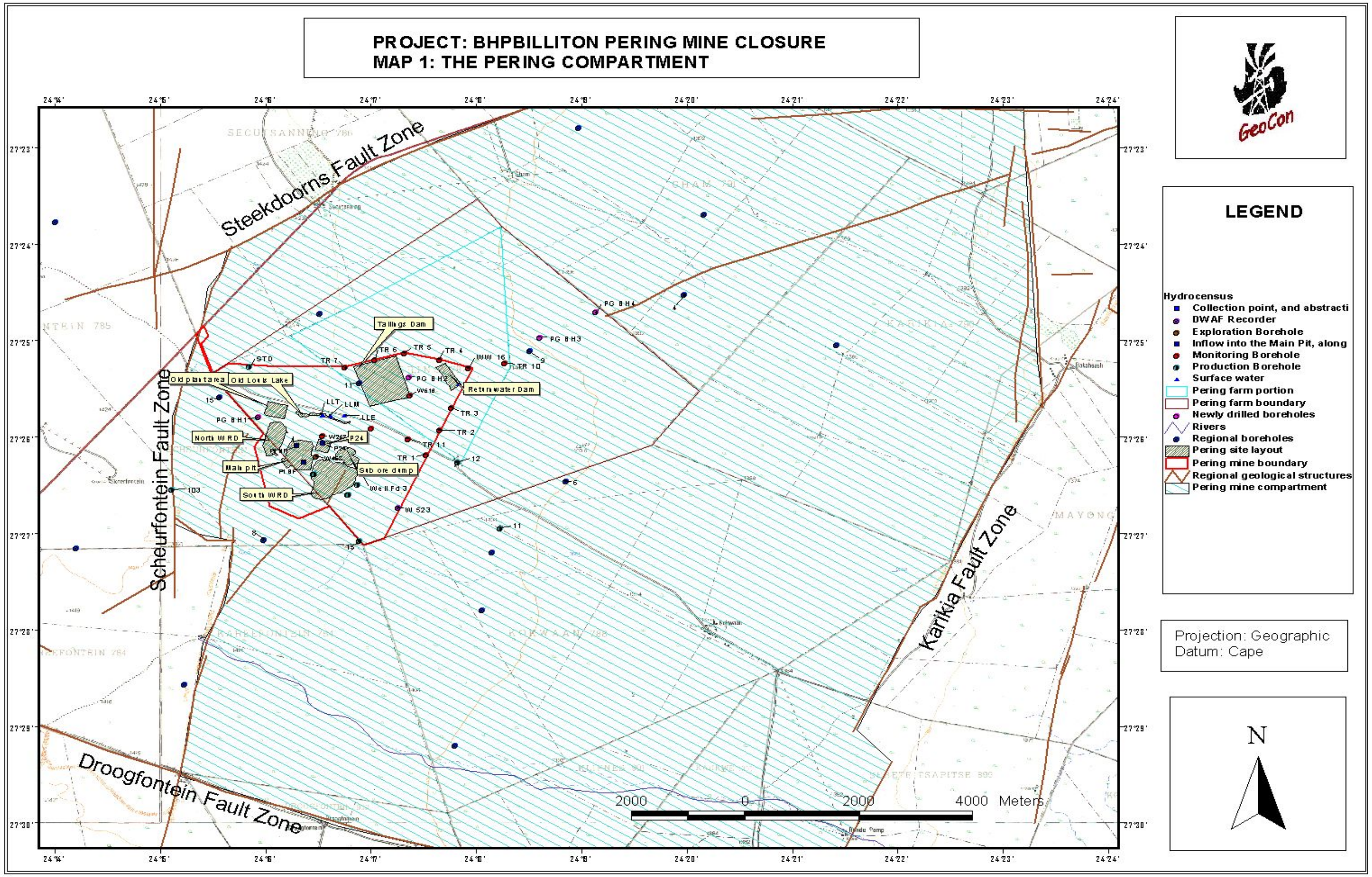


Figure 2: Fault zones of Ghaap Plateau



Using to the DRASTIC classification system the aquifer media the mine is situated above is “Massive Limestone” – consisting of consolidated limestone or dolomite bedrock which are characterised by thick deposits. The potential for contamination is increased by the degree of fracturing and the amounts of solution cavities in the bedrock.

6.3. Net Recharge

Pering Mine falls within an arid climatic region. Monthly climatic data was obtained from Taung Station (weather station No. 360483) for the period 1941-1998.

Rainfall occurs as storm events during summer, particularly from February to April. The rainfall influences the recharge to the aquifer and is an important factor in the groundwater balance determination. According to the data, the mean annual precipitation (MAP) is 525 mm. The standard deviation is 313 mm/year (59 % of the mean), indicating that the rainfall is highly variabile. The data indicates wet and dry cycles that lasts for 8-10 years. Table 6-1 below shows the mean monthly rainfalls based on the 57 years of records.

MONTH	AVERAGE MONTHLY RAINFALL (mm)	STANDARD DEVIATION (mm)
January	78.6	70.3
February	72.5	63.6
March	73.8	54.4
April	33.8	32.0
May	12.1	19.5
June	5.5	13.0

July	3.8	9.7
August	5.6	13.8
September	12.9	25.1
October	25.3	27.9
November	44.4	37.9
December	58.0	42.2

Table 6-1: Mean monthly rainfall data for Pering Mine

In order to predict the effect the mine would have/had on the groundwater, recharge of the aquifer, by mine activities must also be taken into account. The two facilities contributing most to the aquifer recharge were the Tailings Dam and Return Water Dam. Seepage from these two facilities during the mines operational were estimated as being 640m^3/day and 800m^3/day respectively.

Given the surface area of 494198m^2 for the Tailings Dam and 78954m^2 for the Return Water Dam, the seepage was equal to 473mm/year/m^2 and 3698mm/year/m^2 respectively.

Thus for the region of the aquifer surrounding the mine the annual recharge rate can be assumed to be the sum of the MAP and seepage losses from the Tailings and Return Water dam, amounting to 4696mm/year, resulting in a DRASTIC rating of 9 for Net Recharge.

6.4. Soil Media

The soils in the region of Pering Mine have been described as being discontinuous and consisting of fine to coarse quartzitic sand with wind blown manganese nodules. The soils are permeable and cannot be considered as an effective barrier between seepage sources and the underlying rock mass.

The soil cover over the site is very thin (<200 mm) and in outcrop areas is limited to joint and fracture openings. The soil is transported, being aeolian in origin and consists of slightly silty fine sand. The only areas where the soil is deeper are in pans and other slight depressions on calcrete ridges. The soil in the centre of the pans consists of clayey sands with the depth seldom exceeding 500 mm. This soil depth is generally insufficient for agricultural activity such as crop growth.

Given the description above, the soil present at Pering Mine would be considered as "Thin or Absent". As described in Chapter 2, if a soil layer is not present of if the layer is so thin as to be considered ineffective for contamination attenuation, the pollution potential is very high. Thin or absent should generally be chosen when the soil profile is 10 inches (< 25mm) or less in thickness.

Thus the given rating for a "Thin or Absent" soil media is 10.

6.5. Topography

The general area of the Ghaap Plateau is flat and grassy with a shallow topographic gradient of 1 in 323 (0.31%) falling to the east, with the gradient in the of Pering steepening slightly to 1 in 286 (0.35%). The only breaks in the flat topography are calcrete ridges formed over faults and shale bands. These can vary in height from less than a meter to several meters, depending on the width of the feature and extent of the dolerite intrusion.

Figure 3 below is an aerial photograph of the mine and the surrounding regions, in which the flatness of the region can clearly be seem.

Figure 3: Aerial Photograph of Pering

Given the gradient of 0.35% the assigned DRASTIC rating for Topography is 10.

6.6. Impact of the Vadose Zone Media

Below the 200mm thick soil zone lies a 0m to 5m thick vadous zone consiting primarily of calcrete. In general, the calcrete is permeable and would therefore act as a preferential zone for shallow groundwater flow.

This type of Vadoze Zone Media could be classified as either Limestome or Bedded Limestone, Sandstone Shale. The typical rating for both this Vadoze zone media is 6, thus making no difference which one is chosen.

6.7. Hydraulic Conductivity

The aquifer underlying Pering mine can be divided into three distinct zones all with varying hydraulic conductivities as listed below;

- The upper unsaturated zone between 0 m to 5 m with an estimated hydraulic conductivity of 0.5 m/day to 1.5 m/day.
- The main aquifer zone that consists of weathered/fractured shaly dolomite between 5 m and 60 m with an estimated hydraulic conductivity of 1.0 m/day to 1.5 m/day.
- The lower solid/fractured shaly dolomite aquifer zone from 60 m to 150 m with an estimated hydraulic conductivity of 0.1 m/day to 0.5 m/day. (No information is available below 150 m.)

The permeable fractured zones along regional faults and dyke-contact zones with a hydraulic conductivity in the order of 1 m/day to 10 m/day (50 m^2/day to 500 m^2/day).

The low permeability dyke zones that form the boundary between dolomite compartments with an estimated hydraulic conductivity value of 0.01-0.1 m/day. There could be cases where these dykes are weathered in the top 20 m and could therefore be permeable in the upper zones.

For the purpose of this study the hydraulic conductivity of the main aquifer zone will be used as it is this zone that comprises the largest portion of the aquifer thus having the greatest effect on the conductivity.

The hydraulic conductivity of 1.5m/day equates to 3.1 gal/day/$foot^2$ resulting in a DRASTIC rating of 1.

6.8. DRASTIC Index Value for Pering Mine's aquifer

Table 6-2 below summarises the allocated DRASTIC ratings for each DRASTIC Parameter for the Ghaap Plateau Dolomite, with the weighting of each factor also being given.

FACTOR	WEIGHT	ASSIGNED RATING
Depth to Water	5	7
Net Recharge	4	9
Aquifer Media	3	7
Soil Media	2	10
Topography	1	10
Impact on Vadose Zone Media	5	6
Hydraulic Conductivity of the Aquifer	3	1

Table 6-2: DRASTIC Index Value for Pering Mine

Thus given that the DRASTIC Index Value is the sum of all the weighting of each DRASTIC factor multiplied by its respective rating the DRASTIC Index is mathematically written as:

DRASTIC Index= $D_RD_W+R_RR_W+A_RA_W+S_RS_W+T_RT_W+I_RI_W+C_RC_W$

The DRASTIC Index for this case study is 155.

Given this high Drastic Index number, it is anticipated that the mining activities at Pering would have a great effect on the water quality of the aquifer, especially in the direct vicinity of the mine.

6.9. Groundwater Quality at Pering

The land use in the areas surrounding the mine is agriculture. The water quality parameters were compared against the DWAF water quality guidelines (1996) for domestic use and livestock watering. It is important to note that the majority of the neighboring farms relied on groundwater abstracted from boreholes on their properties as their primary source of water.

With the largest amount of contaminants entering the aquifer being due to seepage from the tailings dam and the return water dam, the water qualities of these two sources need to be examined.

DWAF classifies the suitability of water for consumptions into 5 classes according to the quality of the water. These classes and their possible impacts on humans have been summarised below in Table 6-3

CLASS	WATER QUALITY
0	Ideal- suitable for lifetime use
1	Good – suitable for use, rare instanced of negative effects
2	Marginal – conditionally acceptable. Negative effects may occur in some sensitive groups
3	Poor – unsuitable for use without treatment. Chronic effects may occur.
4	Dangerous – totally unsuitable for use. Acute effects may occur

Table 6-3: DWAF Water quality classes

During the operational phase of the mine, the water quality in the tailings dam was classified as Class 4 and exceeded the DWAF Target Water Quality Range for nitrate, chloride, sulphate, calcium, magnesium, electrical conductivity, iron, manganese, copper, zinc, lead and aluminium.

The water from the Return water dam was also classified as Class 4 and exceeded the DWAF Target Water Quality Range for chloride, sulphate, magnesium, electrical conductivity and lead.

Groundwater samples obtained from 31 boreholes in and around the mine site, showed that the water quality varied from Class 1 to Class 4, with all Class 4 boreholes exceeding the DWAF Target Water Quality Range for chloride, sulphate, calcium, magnesium and electrical conductivity.

Lead concentrations exceeded the DWAF Target Water Quality Range at all the boreholes on the mine property.

A summary of the most common groundwater contaminants that can arise from mining activities, along with their effects and maximum allowable limits in water used for domestic purposes, according to DWAF, can be found in APPENDIX 2 of this report.

Of all the contaminants present in the groundwater, sulphate was present in the largest quantities and had the furthest reaching effects. The sulphate where introduces by the leaching from the tailings dam and return water dam, with large concentrations also being leached out of the waste rock dumps by rainwater. The sulphate plumes arising from the waste rock dumps did not greatly affect the downstream water quality, as it was captured by the open pits which where dewatered.

The sulphate plume arising from the tailings and return water dams, after 20 years of mining operation was estimated at being 1.5km north-east of the return water dam (the 200mg/L sulphate contour line).

Figure 3 shows the modelled sulphate plume contours. The total area affected by the sulphate pollution plumes is estimated as being 950ha.

With the cessation of mining activities at Pering, the sulphate plume is expected to decrease as seepage from the Tailings and Return water dams will decrease as they dry out.

6.10. Conclusions and recommendations

Following discussions with GeoCon, it was established that the groundwater contamination at Pering is a severe case of contamination given the extent of the sulphate plume, when compared with other cases of mine activity groundwater contamination. GeoCon was under the opinion that the greatest reason for this is the vulnerability of the aquifer, that corresponds well with the finding of the application of DRASTIC to this case.

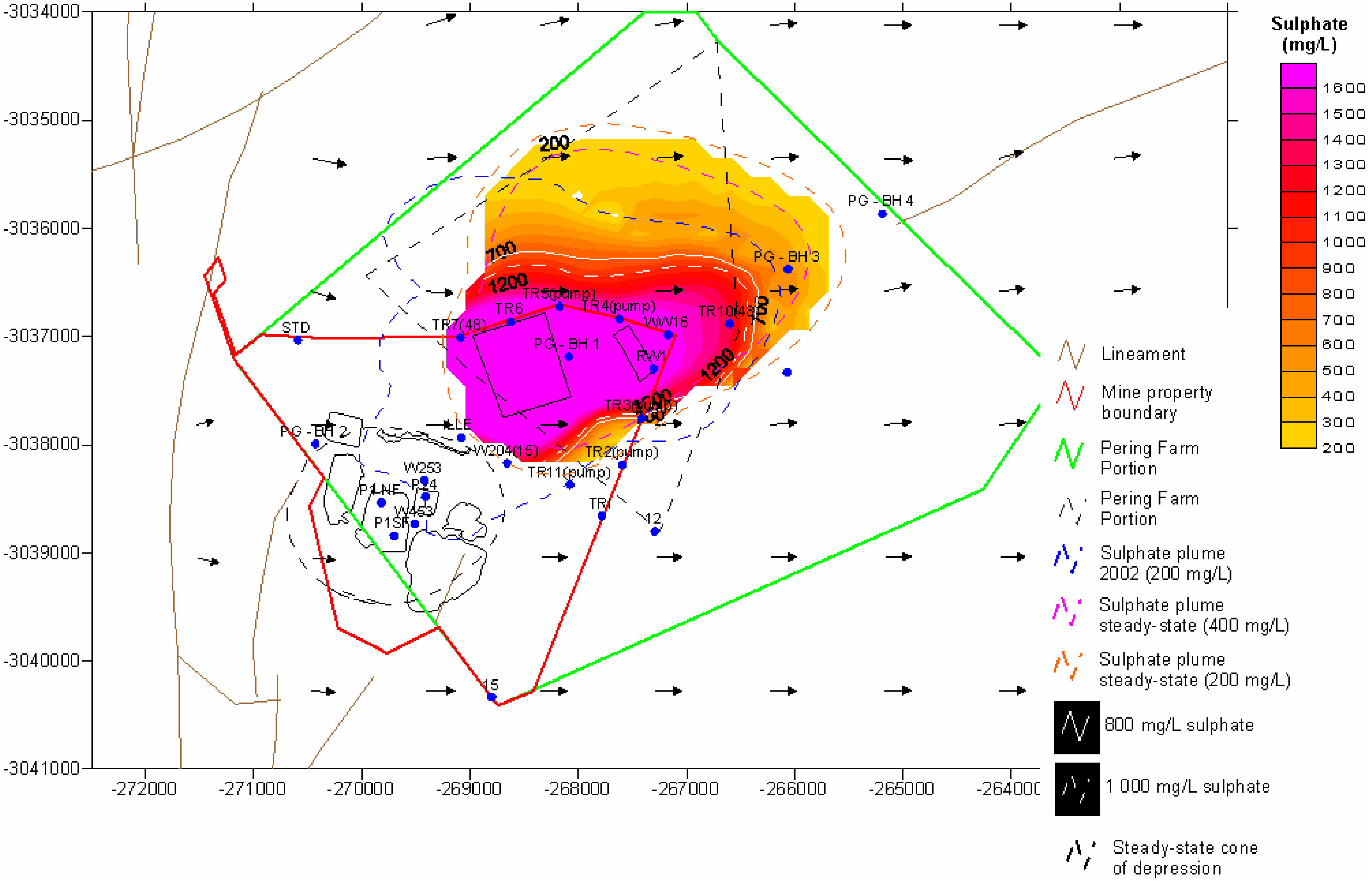
Had a study like DRASTIC been conducted prior to the development of the mine, the aquifers vulnerability to contamination would have been recognised. Thus the mine would have been able to create and implement an aquifer management system that would have helped retard the contamination of the aquifer.

The mine would have had a number of options they could have implemented in order to reduce groundwater contaminations such as:

- Lining of the tailings dam basin with a less/non permeable layer such as a clay layer or geosynthetic liner or an hdpe liner.
- Undertaken a site selection study involving the entire mine property in which groundwater contamination was considered a key factor thus choosing a less vulnerably site for the position of the tailings dam.
- Installing downstream de-watering boreholes in order to extract contaminated ground water and prevent it from entering the surrounding environment.

As the mine is in the final stage of closure, in order to minimise any further groundwater contamination, the tailings dam was rehabilitated by grading the side slopes to a 1V:3H and placing a 500mm topsoil layer over the entire dam and re-vegetating it. This is expected to reduce the amount of precipitation entering the dam and subsequently the water available for leaching and seeping into the aquifer from the tailings dam. Despite all mining activities coming to an end the Mine is still responsible for any environmental issues that may arise post closure.

Figure 4: Extent and contours of sulphate plume at Pering



7. CONCLUSIONS

DRASTIC was developed by the EPA with the aim of being a tool that could be used on a national scale for varying hydrogeological systems for the creation and implementation of aquifer management systems.

It has been acknowledge internationally as a system that incorporates the key factors that influence an aquifer's vulnerability to contamination. It has subsequently been used in numerous international applications and has successfully aided in the development of methodologies for the sustainable operation and strategic management of groundwater resources in China.

In Portugal it was found that the results obtained by DRASTIC correlated well with classical vulnerability assessment methods previously used in Portugal and provided greater zoning definition attributed to the fact that DRASTIC incorporated important hydrogeological criteria that classical method did not.

Furthermore, DRASTIC has proven to be a flexible tool. As shown by *Evans et al* and *Brown*, parameters may be replaced or altered for site specific application, and provide reliable results.

However limitations of the use of DRASTIC on national scales have been documented for both South Africa and New Zealand. It was found that in order to be a meaningful tool, small scale input data was necessary, and even them the maps created could not be used for site specific purposes but only as a general management tool for regional development.

It has been documented that the allocated ratings of each of the DRASTIC factors needs to be confirmed for each application and altered as deemed necessary. Factors if not available can be omitted but will yield less accurate results.

An issue raised by both *Al-Adamat et al* and EEC was that vulnerability and pollution risk are two separate concepts. They highlighted that by combining or overlapping vulnerability and land use/ pollution potential maps, regional planning and management of these regions would be easier as zones of high concern would be easily identified.

The use of DRASTIC on a localised scale was successfully applied in India. Having applied DRASTIC to a site destined to be a landfill, it was determined that the underlying aquifer was vulnerable to contamination, which lead to the development of an environmental management plan used to minimise groundwater contamination from the landfill.

The case study conducted in this report involved the assessment of the vulnerability of an aquifer overlain by a mine. The effect of the mine, operational for over 20 years, on the aquifer was established as being extensive with sulphate concentrations in the aquifer exceeding toxic levels extending in a 1.5km radius around the mine site.

The DRASTIC index for this aquifer was 155, indication the aquifer’s high vulnerability to contamination. The extent of the contamination as stated above is a clear indication that the DRASTIC index is appropriate in this instance and proves that DRASTIC could have been used effectively used by the mine prior to commencing operations to implement suitable aquifer management systems.

Having completed this study, I am of the opinion that DRASTIC can be used as a tool for the establishment of effective national management plans, provided that sufficient information is available for the study and that this information is available in relatively detailed scale. Furthermore for it to be a more reliable tool, land use/pollution potential will need to be taken into account as an additional parameter.

Base on the case study analysed and with the India landfill site, it is believed that DRASTIC is an effective tool for the development of aquifer management plans on localised scales. The level of information available for these studies are far greater than that available on national levels rendering more accurate and useful results.

As clearly shown by the extensive legislation relating to South Africa's aquifers, it is not merely up to government to protect these resources, but also the responsibility of industry and the entire private sector.

I am of the firm belief that by applying DRASTIC – a cost effective approach - to localised projects and implementing appropriate aquifer protection measures on these projects, the preservation of our aquifers on a regional scale will occur.

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APPENDIX 1 : DRASTIC MAP

Figure 5: South African National Depth to Ground Water DRASTIC Map

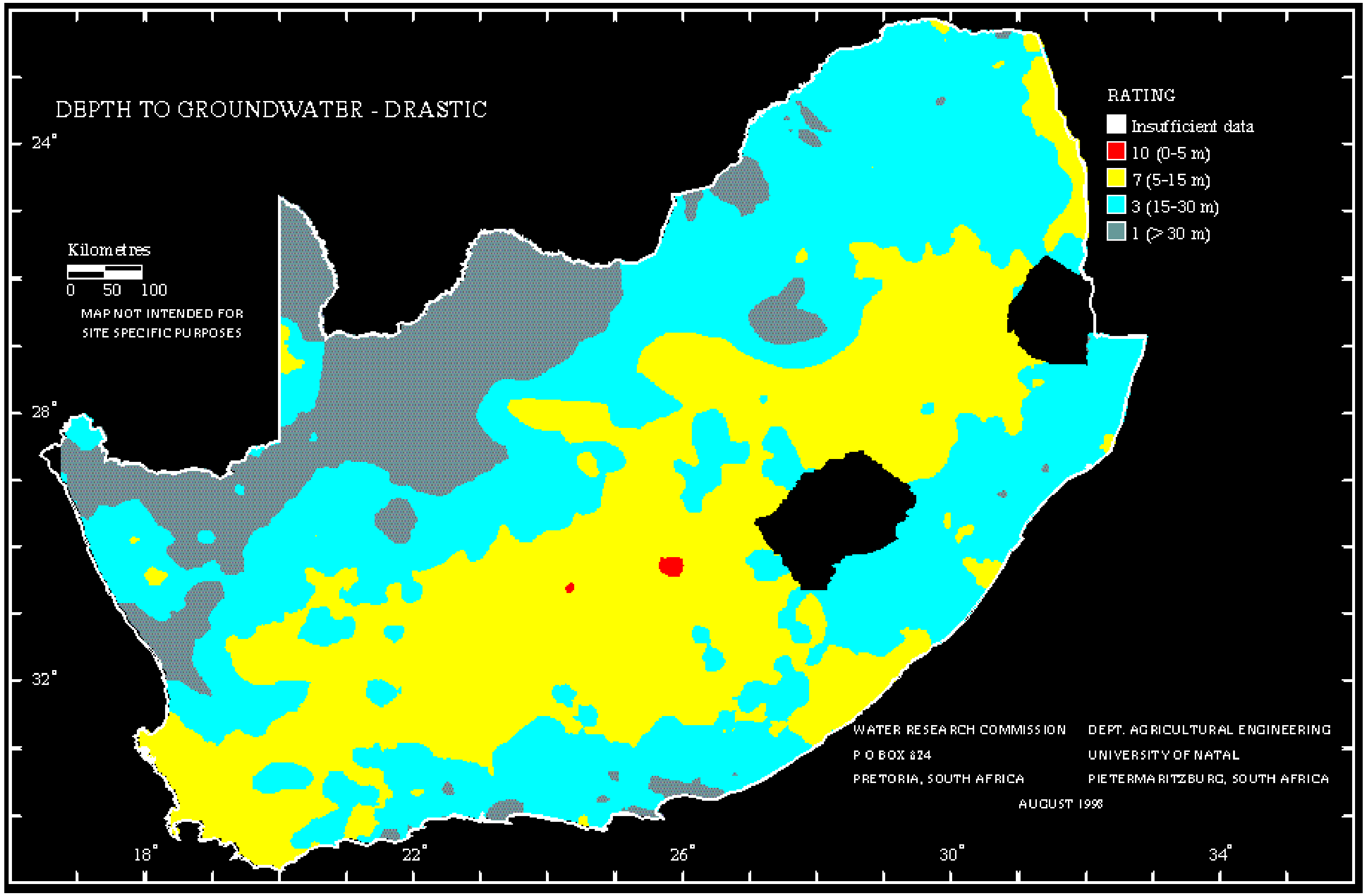


Figure 6: South African National Net Recharge DRASTIC Map

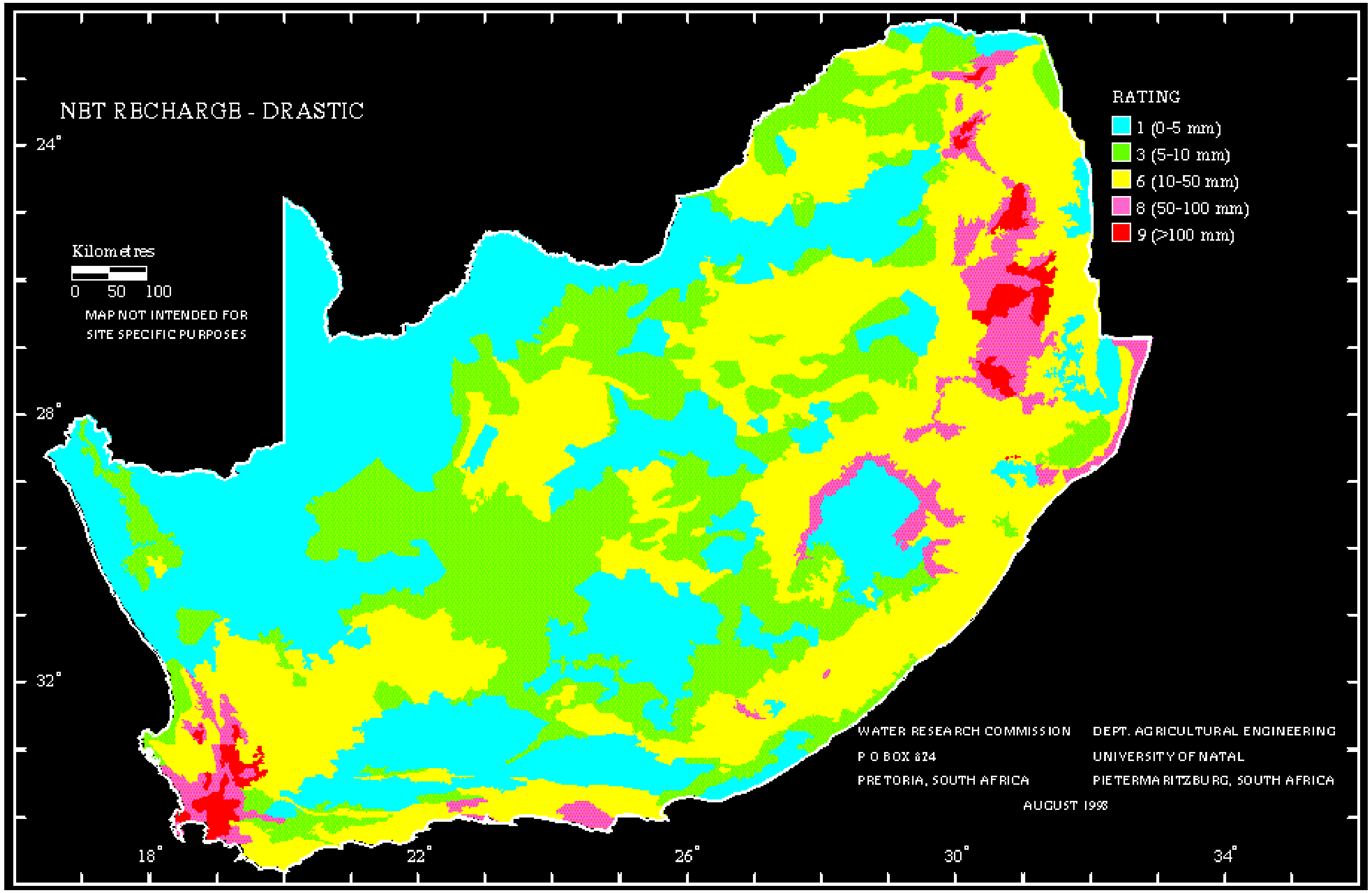


Figure 7: South African National Aquifer Media DRASTIC Map

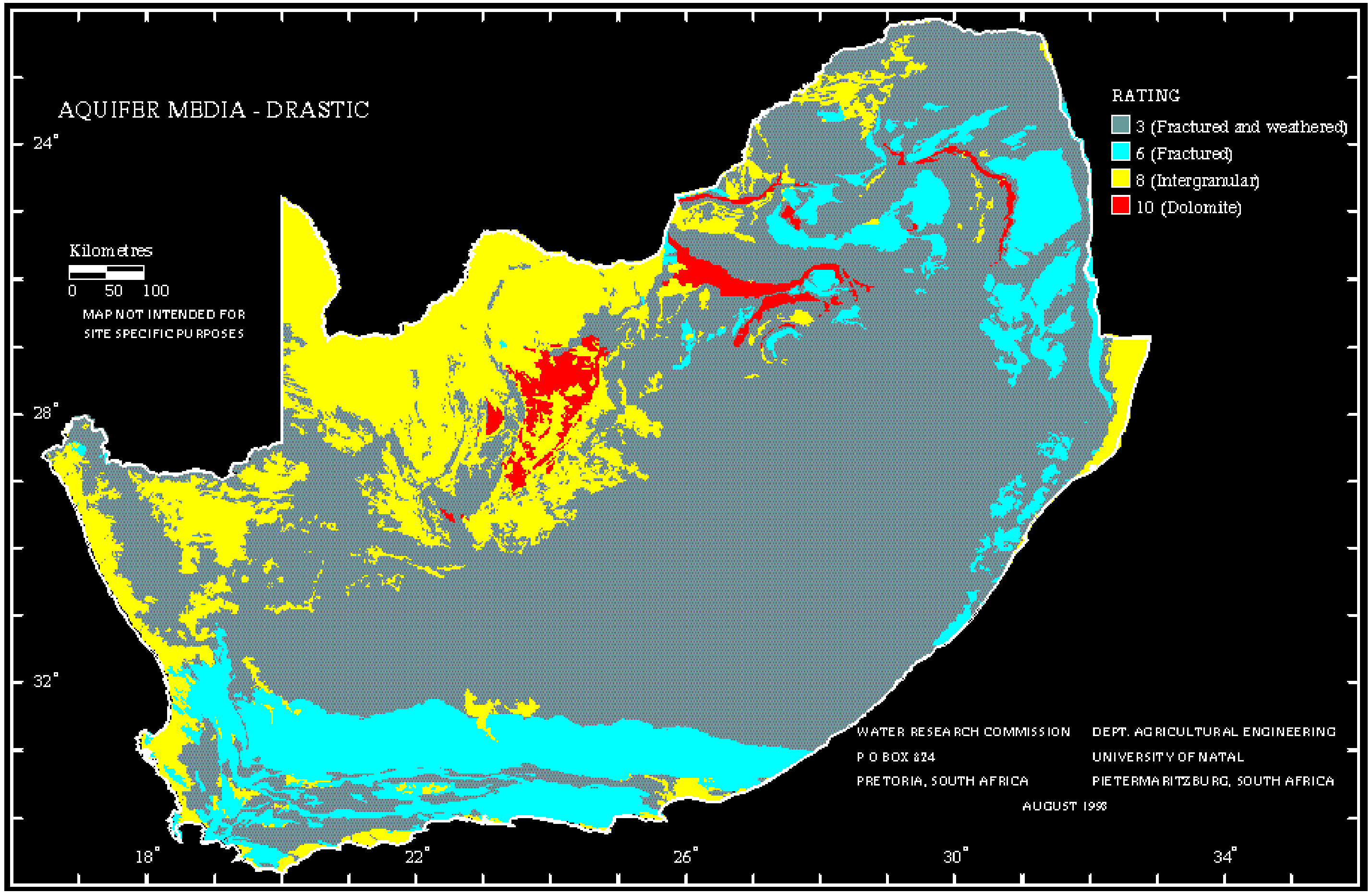


Figure 8: South African National Soil Media DRASTIC Map

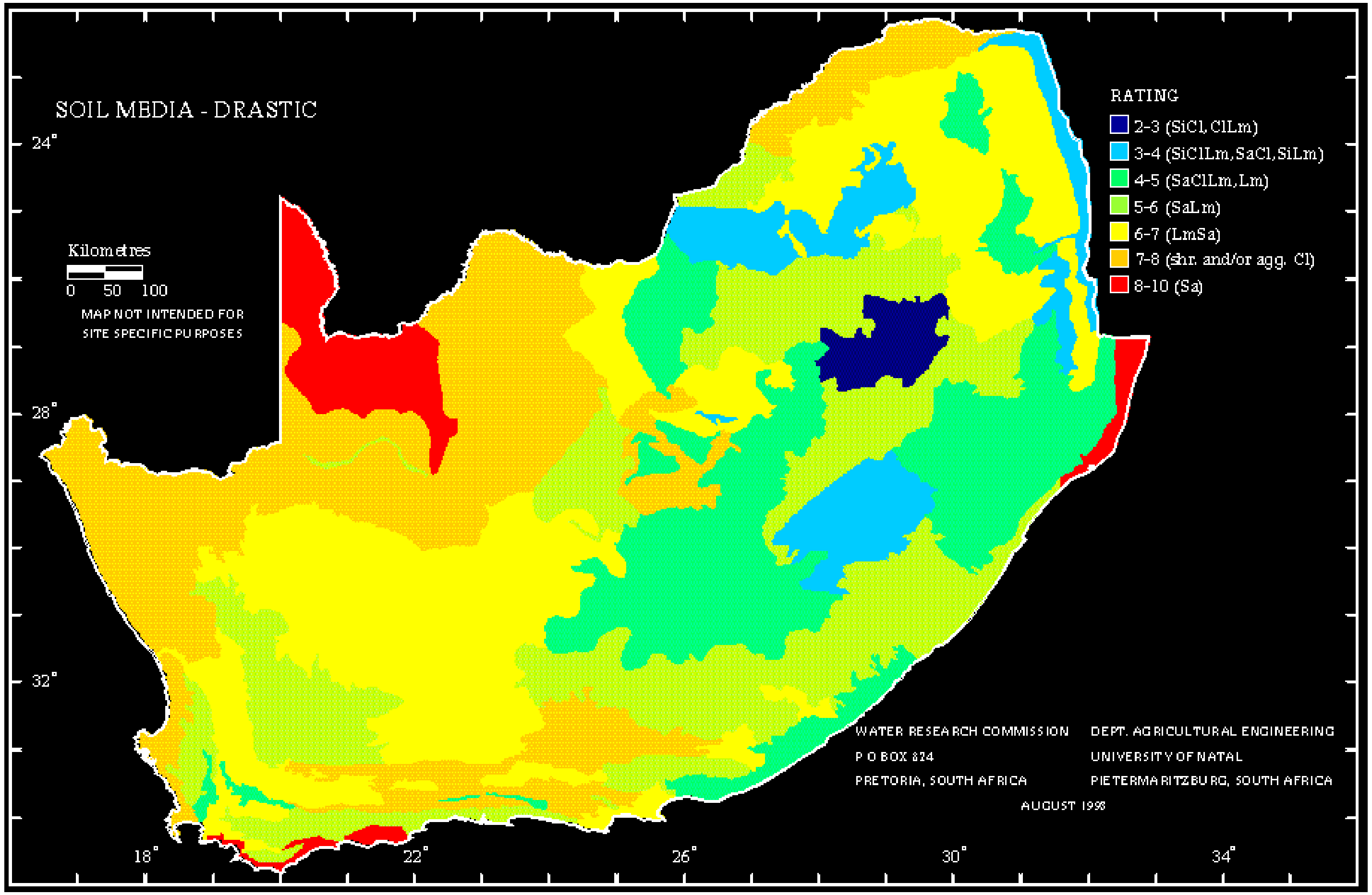


Figure 9: South African National Topographical DRASTIC Map

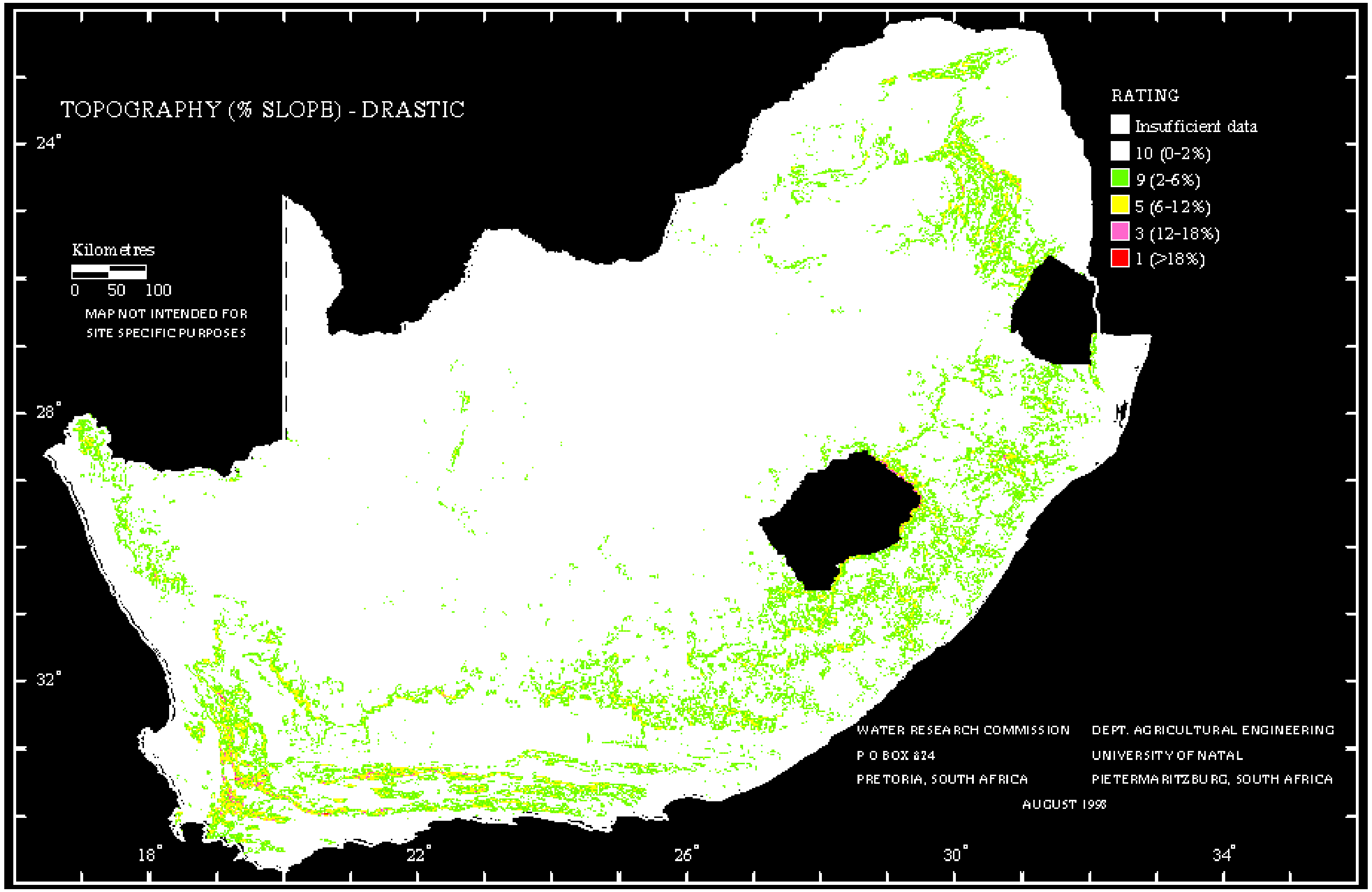


Figure 10: South African National Impact of Vadose Zone DRASTIC Map

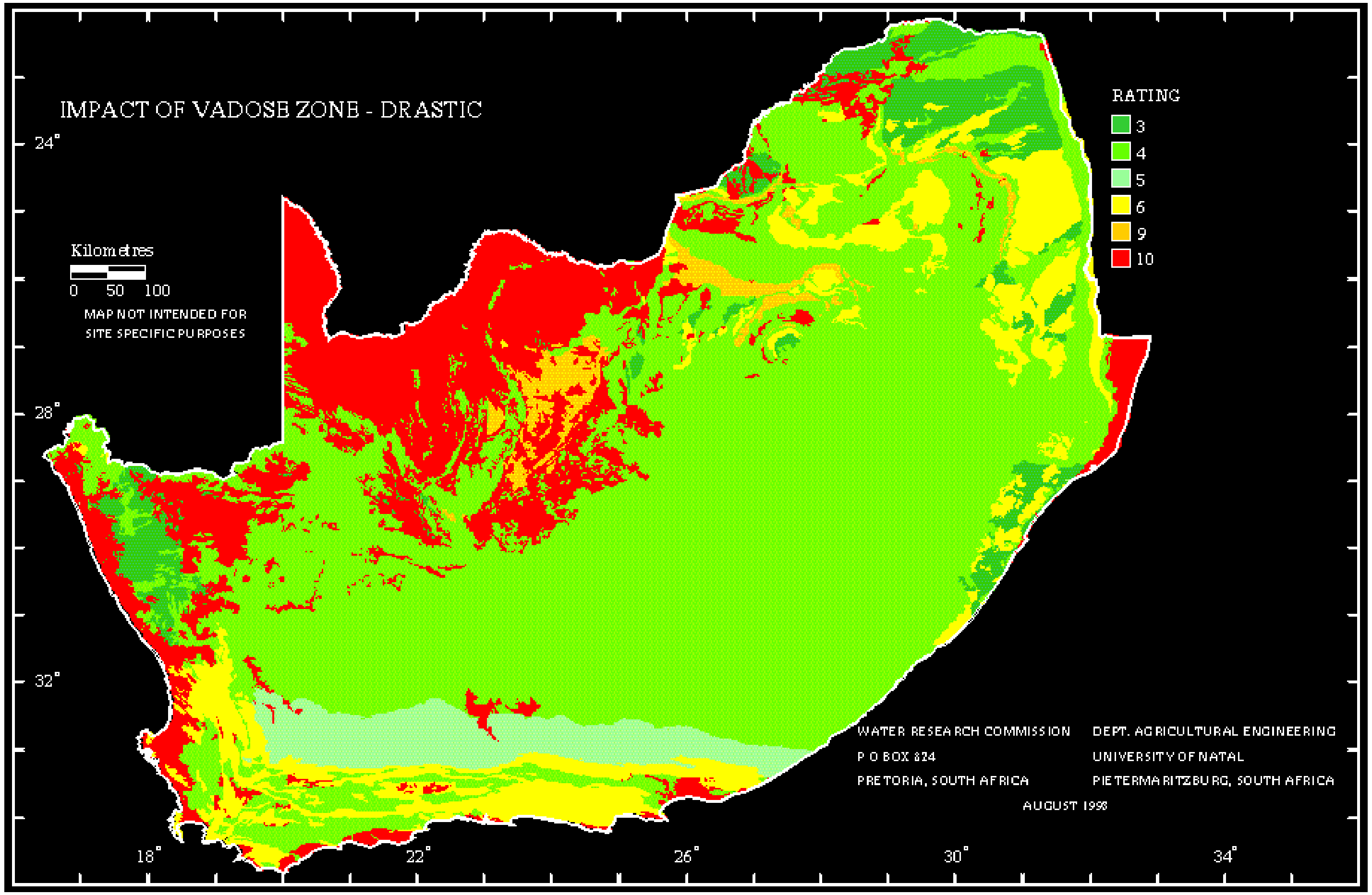


Figure 11: South African National Groundwater Vulnerability to Pollution –DRASTIC Map

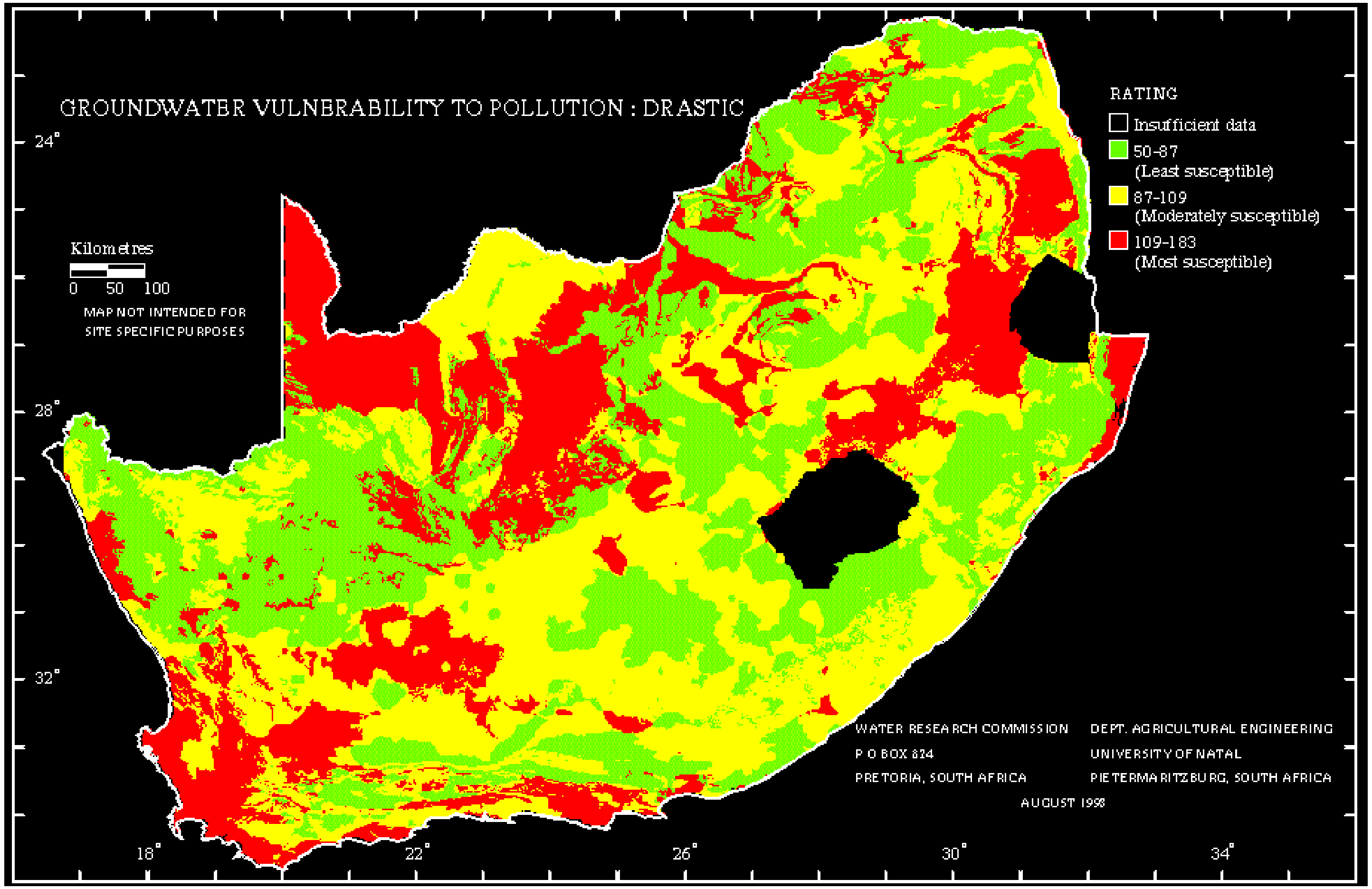


Figure 12: Groundwater Vulnerability Map for Portugal

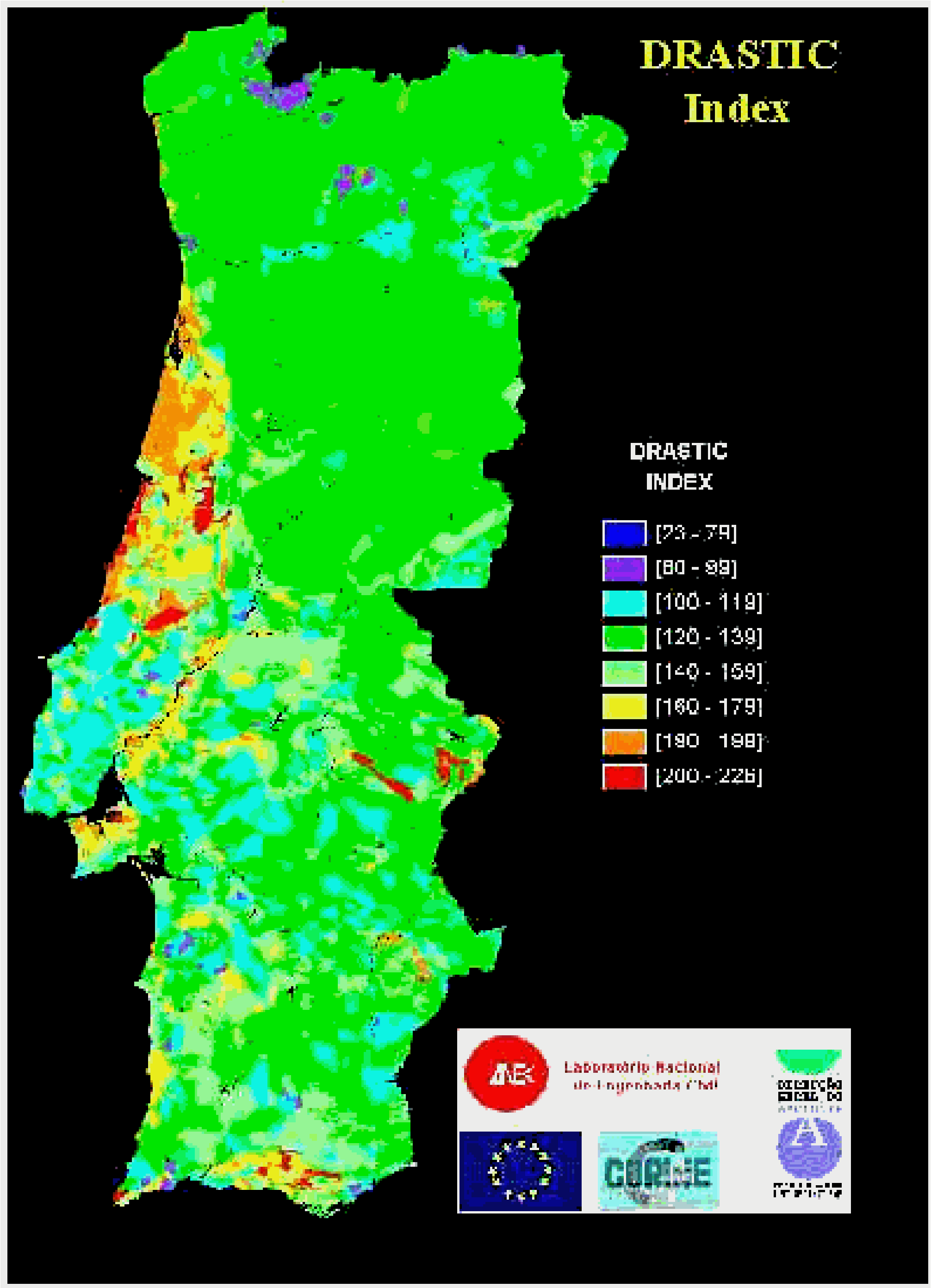


Figure 13: Groundwater Vulnerability Map for the Dalia Peninsula in China

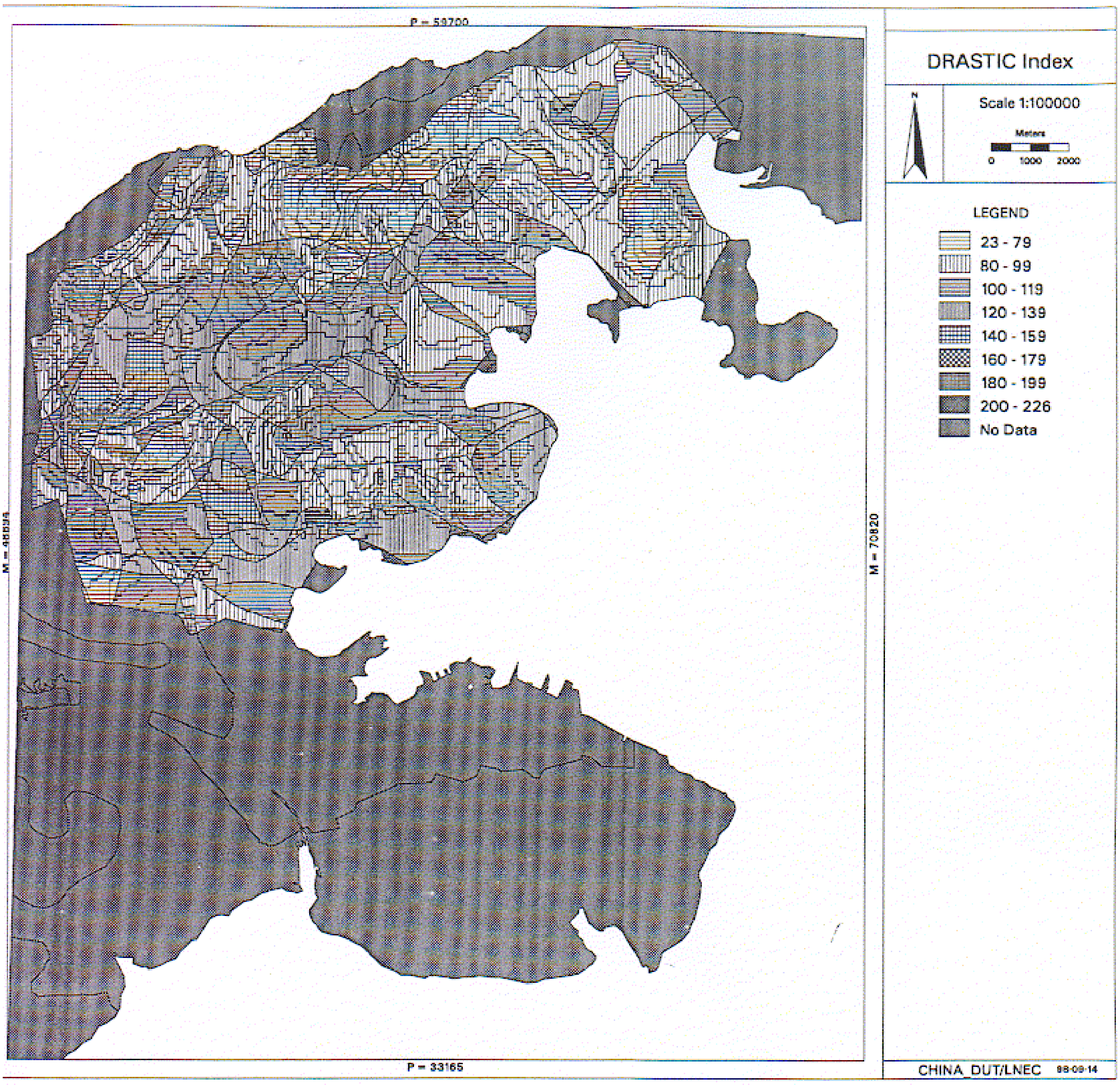
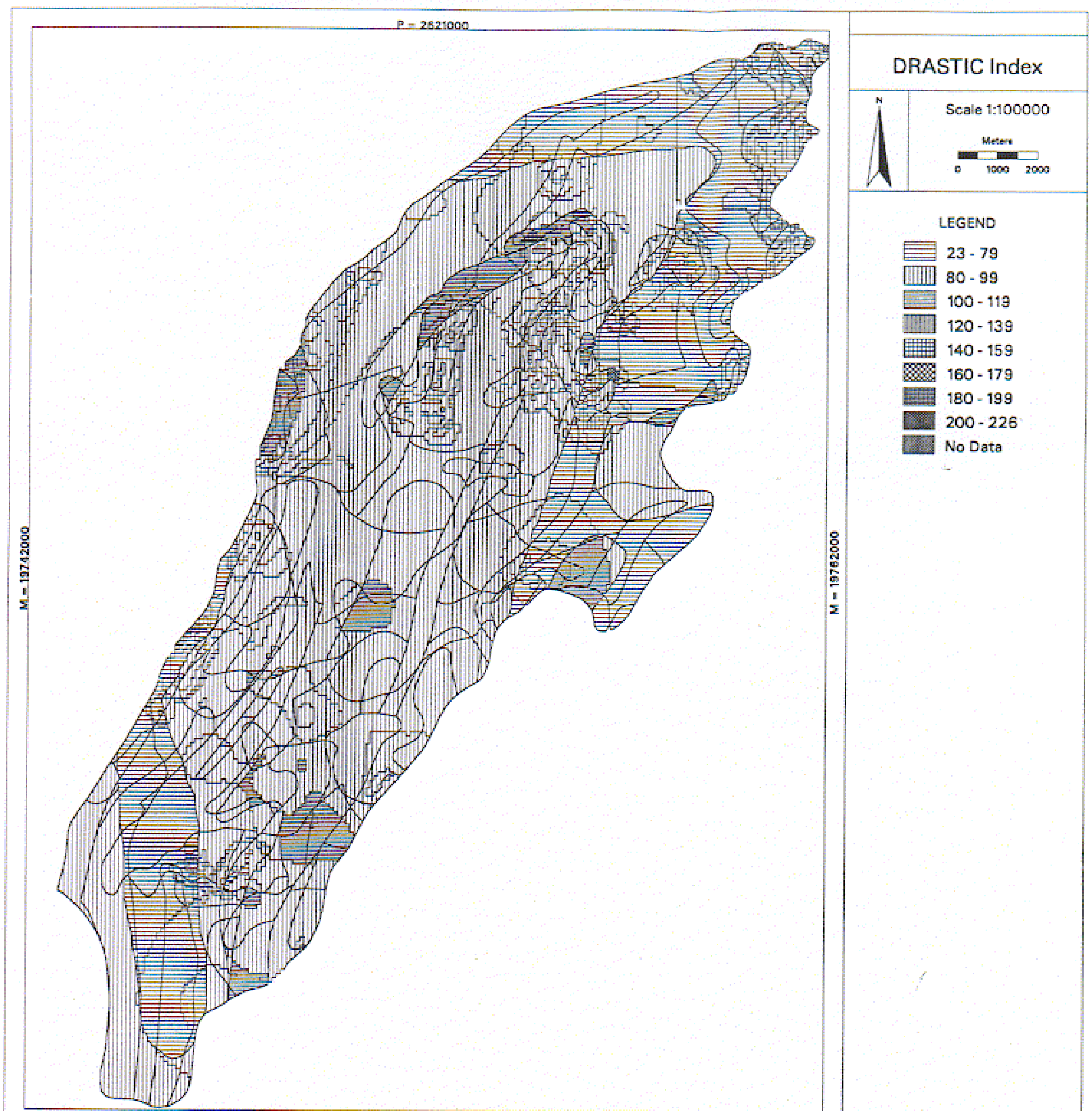


Figure 14: Groundwater Vulnerability Map for Guangxhou-Hauxin Basin in China



APPENDIX 2: SUMMARY OF SOUTH AFRICAN WATER QUALITY GUIDELINES FOR DOMESTIC USE

SOURCE: South African Water Quality Guidelines, Volume 1 Domestic Water Use, Second Edition 1996

Aluminium Range (mg/•)	Effects
Target Water Quality Range 0 - 0.15	***No acute or chronic health effects occur. Intake from water is < 5 % of the total dietary intake of aluminium. Generally, no adverse aesthetic effects occur. Very slight discolouration of water may become apparent when iron or manganese is present in association with aluminium at the upper limit of the range***
0.15 - 0.5	Intake from water may exceed 5 % of the total dietary intake, but no effects on health are expected. Noticeable adverse aesthetic effects (colour) occur when aluminium is present in association with iron or manganese
> 0.5	Intake from water exceeds 5 % of the total daily intake, but no acute health effects are expected except at very high concentrations. There may be long-term neurotoxic effects. ***This relationship has not been conclusively demonstrated.*** Severe aesthetic effects (discolouration) occur in the presence of iron or manganese

TableA-1: Effects of Alluminium on Aesthetics and Human Health

Ammonia Range (mg/• N)	Effects
Target Water Quality Range ***0 - 1.0***	*No health or aesthetic effects*
1.0 - 2.0	Possibility of taste and odour complaints from consumers
2.0 - 10.0	Consumer complaints of objectionable taste and odours likely. Disinfection by chlorine can be compromised
> 10.0	Unacceptable in domestic water. Danger of formation of nitrite. Likelihood of fish deaths in aquaria. Chlorination is severely compromised

TableA-2: Effects of Ammonia on Aesthetics and Human Health

Asbestos Fibre Count Range (Fibres/•)	Effects
Target Water Quality Range ***0 to 1 x 10^6***	*No adverse health effect expected*
1 x 10^6 - 1 x 10^7	Minimal health risk in drinking water, insignificant risk of cancer on inhalation
> 1 x 10^7	Increasing risk of cancer, but only after *inhalation* of the fibres in the water

TableA-3: Effects of Asbestos on Human Health

Arsenic Range (• g/•)	Effects
Target Water Quality Range 0 - 10	***No health effects expected; ideal concentration range***
10 - 200	Tolerable concentration, but low risk of skin cancer in highly sensitive individuals over long term
200 - 300	Increasing possibility of mild skin lesions over long term. Slight possibility of induction of skin cancer over long term
300 - 600	Possible adverse, chronic effects in sensitive individuals; brief exposure has no effect; skin lesions, including hyperpigmentation, will begin to appear on long-term exposure
600 - 1 000	Symptoms of chronic poisoning such as skin lesions, including hyperpigmentation, will appear on long-term exposure
1 000 - 10 000	Cancer or death will result from chronic poisoning
> 10 000	Death will result from acute poisoning

Note: **It is recommended that the concentration of arsenic in potable water should never exceed 200 • g/•, but ideally should not exceed the TWQR.**

TableA-4: Effects of Arsenic on Human Health

Cadmium Range (µg/•)	Effects
Target Water Quality Range 0 - 5	***No observable health effects***
As a precautionary measure, it is recommended that the TWQR not be exceeded because of the potentially acute and/or irreversible effects of cadmium on human health	
5 - 10	No observable health effects, unless zinc nutritional status is suboptimal, or in smokers, where there is a slight risk of subclinical effects on long-term exposure
10 - 20	Threshold for health damage with continuous exposure. Single incidence of exposure will not have observable effects
20 - 1 000	Danger of kidney damage with long-term exposure. Brief exposure, for less than one week should not cause any noticeable damage. Exposure should not exceed one week
> 1 000	Danger of acute cadmium poisoning, with the possibility of fatalities

TableA-5: Effects of Cadmium on Human Health

Calcium Range (mg/• as Ca)	Effects
Target Water Quality Range 0 - 32	***No health effects. No scaling evident. Possible corrosive effects < 16 mg/•***
32 - 80	No health effects. Increased scaling problems Lathering of soap impaired
> 80	No health effects. Severe scaling problems Lathering of soap severely impaired

TableA-6: Effects of Calcium on Personal Hygiene, Household Distribution Systems and Water Heating Appliances

Chloride Range (mg/•)	Effects
Target Water Quality Range 0 - 100	*No aesthetic or health effects. The threshold for corrosion acceleration in domestic appliances is at 50 mg/•*
100 - 200	No aesthetic or health effects. Possible increase in the corrosion rate in domestic appliances
200 - 600	Water has a distinctly salty taste, but no health effects Likelihood of noticeable increase in corrosion rates in domestic appliances
600 - 1 200	Water has objectionable salty taste and will not slake thirst Likelihood of rapid corrosion in domestic appliances
> 1 200	Water unacceptably salty. Nausea and disturbance of the electrolyte balance can occur, especially in infants, where fatalities due to dehydration may occur

TableA-7: Effects of Chloride on Aesthetics, Household Distribution Systems and Appliances and Human Health

Chromium(VI) Range (mg/•)	Effects
Target Water Quality Range 0 - 0.050	*Risk of cancer induction insignificant No toxic or aesthetic effects*
As a precautionary measure it is recommended that the TWQR not be exceeded due to the potentially acute and/or irreversible effects of chromium(VI) on human health	
0.05 - 1.0	Possible risk of induction of gastrointestinal cancer following long-term exposure
1.0 - 5.0	Undesirable taste, slight nausea, and increasing risk of cancer induction
> 5.0	Risk of acute toxicity

TableA-8: Effects of Chromium (VI) on Human Health

Copper Range (mg/•)	Effects
Target Water Quality Range 0 - 1	***No health or aesthetic effects***
1 - 3	No health effects. Astringent taste and staining of laundry and plumbing fixtures start appearing
3 - 30	No health effects. Severe taste and staining problems
30 - 200	Gastrointestinal irritation, nausea and vomiting. Severe taste and staining problems
> 200	Severe poisoning with possible fatalities. Severe taste and staining problems

Note: It is recommended that the concentration of copper in potable water should not exceed 30 mg/•, as this is the threshold for acute poisoning with nausea and vomiting.

TableA-9: Effects of Copper on Aesthetics and Human Health

Effects of Dissolved Organic Carbon and Human Health

Dissolved Organic Carbon Range (mg C/•)	Effects
Target Water Quality Range *0 - 5*	***No effect on health, aesthetics (taste, odour, colour) or THM formation during chlorination***
5 - 10	Slight risk of health effects, depending on the DOC composition. Slight aesthetic effects (taste, odour, colour). Some THM formation during chlorination
10 - 20	Risk of health effects, depending on the DOC composition. Significant aesthetic effects (taste, odour, colour). THMs formed during chlorination
> 20	Aesthetic effects (taste, odour, colour) and formation of THMs during chlorination. Marked health effects, depending on the composition of the DOC

TableA-10: Effects of Dissolved Organic Carbon on Human Health

Fluoride Range (mg/•)	**Effects**
Target Water Quality Range 0 - 1.0	***The concentration in water necessary to meet requirements for healthy tooth structure is a function of daily water intake and hence varies with annual maximum daily air temperature. A concentration of approximately 0.75 mg/• corresponds to a maximum daily temperature of approximately 26 • C - 28 • C. No adverse health effects or tooth damage occurs***
1.0 - 1.5	Slight mottling of dental enamel may occur in sensitive individuals. No other health effects are expected
1.5 - 3.5	***The threshold for marked dental mottling with associated tooth damage due to softening of enamel is 1.5 mg/•*** Above this, mottling and tooth damage will probably be noticeable in most continuous users of the water. No other health effects occur
3.5 - 4.0	Severe tooth damage especially to infants' temporary and permanent teeth; softening of the enamel and dentine will occur on continuous use of water. ***Threshold for chronic effects of fluoride exposure***, manifested as skeletal effects. Effects at this concentration are detected mainly by radiological examination, rather than overt
4.0 - 6.0	Severe tooth damage especially to the temporary and permanent teeth of infants; softening of the enamel and dentine will occur on continuous use of water. Skeletal fluorosis occurs on long-term exposure
6.0 - 8.0	Severe tooth damage as above. Pronounced skeletal fluorosis occurs on long-term exposure
> 8.0	Severe tooth damage as above. Crippling skeletal fluorosis is likely to appear on long-term exposure
> 100	Threshold for onset of acute fluoride poisoning, marked by vomiting and diarrhoea
> 2 000	The lethal concentration of fluoride is approximately 2 000 mg/•

TableA-11: Effect of Chloride on Aesthetics and Human Health

Iron Range (mg/•)	**Effects**
Water Quality Target Range 0 - 0.1	***No taste, other aesthetic or health effects associated with consumption and use***
0.1 - 0.3	Very slight effects on taste and marginal other aesthetic effects Deposits in plumbing with associated problems may begin to occur. No health effects; the water is generally well tolerated
0.3 - 1.0	Adverse aesthetic effects (taste) gradually increase as do possible problems with plumbing. No health effects
1 - 10	Pronounced aesthetic effects (taste) along with problems with plumbing. Slight health effects expected in young children, and sensitive individuals
10 - 30	Severe aesthetic effects (taste) and effects on the plumbing (slimy coatings). Slight iron overload possible in some individuals. Chronic health effects in young children and sensitive individuals in the range 10 - 20 mg/•, and occasional acute effects toward the upper end of this range
30 - 100	As above Long-term health effects gradually increase
100 - 300	As above Chronic health effects. Acute toxicity may begin to appear
300 - 3 000	As above Chronic and acute health effects. Accidental iron poisoning from water is rare
3 000 - 30 000	As above Lethal toxicity occurs

TableA-12: Effects of Iron on Aesthetics, Human Health and Household Distribution Systems

Lead Range (• g/•)	Effects
Target Water Quality Range 0 - 10	***No danger of any adverse effects by exposure from water***
It is recommended that the TWQR not be exceeded due to the potentially acute and/or irreversible effects of lead on human health	
10 - 50	No danger of any adverse health effects except for a slight risk of behavioural changes and possibility of neurological impairment, where the exposure to lead from other sources, such as food, is not minimised
50 - 100	Possible neurological damage where the nerve and brain tissues are developing, that is, in foetuses and young children. Young children and pregnant women should avoid exposure
100 - 300	Definite danger of neurological impairment in children Alternative water supply should be used by sensitive groups (children and pregnant women)
> 300	Symptoms of chronic lead poisoning are possible with continuous exposure

TableA-13: Effects of Lead on Human Heath

Magnesium Range (mg/• as Mg)	**Effects**
Target Water Quality Range 0 - 30	***No bitter taste. No scaling problems. No health effects***
30 - 50	No bitter taste. Slight scaling problems may occur. No health effects
50 - 70	No bitter taste; No health effects; Scaling problems
70 - 100	Slight bitter taste. Taste threshold for magnesium is • 70 mg/•. Scaling problems. Diarrhoea in sensitive users
100 - 200	Water aesthetically unacceptable because of bitter taste. Increased scaling problems. Diarrhoea in most new users if sulphate present
200 - 400	Severe scaling problems. Diarrhoea in all new users
> 400	Severe scaling problems. Diarrhoea in all new users. Health problems may occur

TableA-14: Effects of Magnesium on Aesthetics and Human Health

Effects of Manganese on Aesthetics and Human Health

Manganese Range (mg/•)	Effects
Target Water Quality Range 0 - 0.05	***No health or aesthetic effects; marginal aesthetic problems occasionally found in the 0.02-0.05 mg/• range***
0.05 - 0.10	Tolerable range, although slight staining may occur. No health effects
0.10 - 0.15	Threshold for significant staining and taste problems. No health effects
0.15 - 1.0	Increasingly severe staining and taste problems. No health effects
1.0 - 2.0	Very severe staining and taste effects. No health effects
2.0 - 5.0	Extreme staining, likely to be aesthetically unacceptable to a large proportion of users. No health effects
5 - 14	Unacceptable levels of aesthetic effects. Health effects rare
14 - 20	Very severe, aesthetically unacceptable staining. Domestic use unlikely due to adverse aesthetic effects. Some chance of manganese toxicity under unusual conditions
> 20	Domestic use unlikely due to extreme aesthetic effects Chronic toxicity; at high concentrations, possible acute effects

TableA-15: Effects of Manganese on Aesthetics and Human Health

Mercury Range (• g/•)	Effects
Target Water Quality Range 0 - 1	***No health effects expected***
It is recommended that the TWQR not be exceeded due to the potentially acute and/or irreversible effects of mercury on human health	
1- 5	At two • g/• water provides up to 13 % of the safe daily intake, and at five • g/• water provides 33 % of the safe daily intake. Risk to the general population is unlikely A very slight risk of neurotoxicity due to organic mercury may exist for sensitive individuals at the upper limit of this range
5 - 20	Brief, episodic exposure unlikely to have adverse effects Some risk of chronic neurotoxic effects due to organically complexed mercury
20 - 50	Risk of neurotoxicity with consequent serious disabilities with continuous exposure
50 - 1 000	Risk of neurotoxicity with continuous exposure, particularly to organic mercury compounds. Acute effects may occur, particularly with organic mercury compounds
1 000 - 10 000	Chronic effects; acute poisoning with damage to the nervous system and brain may occur with single exposure, and definitely with continuous exposure
> 100 000	Acute poisoning; permanent brain damage and/or death is possible

TableA-16: Effects of Mercury on Human Health

Nitrate/nitrite Range (as mg/• N)	Effects
Target Water Quality Range 0 - 6	***No adverse health effects***
6 - 10	Rare instances of methaemoglobinaemia in infants; no effects in adults. Concentrations in this range generally well tolerated
10 - 20	Methaemoglobinaemia may occur in infants. No effects in adults
> 20	Methaemoglobinaemia occurs in infants. Occurrence of mucous membrane irritation in adults

TableA-17: Effects of Nitrate/Nitrite on Human Health

Potassium Range (mg/•)	Effects
Target Water Quality Range 0 - 50	***No aesthetic (bitter taste) or health effects***
50 - 100	No aesthetic effects. No health effects in healthy adults. Undesirable concentration for infants or persons with renal disease
100 - 400	Bitter taste may be noticeable. Electrolyte disturbances may occur in sensitive individuals. Dangerous concentration for infants or persons with renal disease
> 400	Pronounced bitter taste. Occurrence of electrolyte disturbances with nausea, vomiting and irritation of mucous membranes. Dangerous concentration for infants or persons with renal disease

TableA-18: Effects of Potassium on Aesthetics and Human Health

Sodium Range (mg/•)	Effects
Target Water Quality Range 0 - 100	***No aesthetic or health effects***
100 - 200	Faintly salty taste. ***Threshold for taste*** No health effects
200 - 400	Slightly salty taste. Undesirable for persons on a sodium-restricted diet
400 - 600	Distinctly salty taste. No health effects in healthy adults with short-term use. Undesirable for infants or persons on a sodium-restricted diet
600 - 1 000	Very salty taste. Health effects may be expected. Very undesirable for infants or persons on a sodium-restricted diet
1 000 - 5 000	Highly salty taste. Likelihood of nausea and vomiting. Highly undesirable for infants or persons on a sodium-restricted diet
> 5 000	Extremely salty taste becoming bitter. Severe health effects with disturbance of electrolyte balance. Extremely undesirable for infants or persons on a sodium-restricted diet

TableA-19: Effects of Sodium on Aesthetics and Human Health

Sulphate Range (mg/• as $SO_4^{=}$)	Effects
Target Water Quality Range ***0 - 200***	***No health or aesthetic effects are experienced***
200 - 400	Tendency to develop diarrhoea in sensitive and some non-adapted individuals. Slight taste noticeable
400 - 600	Diarrhoea in most non-adapted individuals. Definite salty or bitter taste
600 - 1 000	Diarrhoea in most individuals. User-adaptation does not occur. Pronounced salty or bitter taste
> 1 000	Diarrhoea in all individuals. User-adaptation does not occur. Very strong salty and bitter taste

TableA-20: Effects of Sulphate on Aesthetics and Human Health

Vanadium Range (mg/•)	Effects
Target Water Quality Range 0 - 0.1	***No health effects. Suitable for continuous, long-term intake***
As a precautionary measure it is recommended that the TWQR not be exceeded due to the potentially acute and/or irreversible effects of vanadium on human health	
0.1 - 1.0	Suitable for short-term intake, but symptoms of vanadium toxicity such as growth suppression and respiratory symptoms may occur with long-term intake in sensitive individuals
> 1.0	Not suitable for drinking water use Symptoms of vanadium toxicity may appear

TableA-21: Effects of Vanadium on Human Health

Zinc Range (mg/•)	**Effects**
Target Water Quality Range 0 - 3	***No aesthetic or human health effects***
3 - 5	Slight opalescence or bitter taste. No health effects
5 - 10	Clearly discernable bitter taste and opalescence. No health effects
10 - 50	Bitter taste; strong opalescence. Some instances of chronic toxicity expected
50 - 700	Bitter taste; milky appearance. Acute toxicity with gastro-intestinal irritation, nausea and vomiting
> 700	Bitter taste; milky appearance. Severe, acute toxicity with electrolyte disturbances and possible renal damage

TableA-22: Effects of Zinc on Aesthetics and Human Health