

Geological and anthropogenic impacts on inorganic water quality at rural clinics in the
Limpopo province, South Africa

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Abstract

This study gives insight to the origin of pollution in the water resources of the Limpopo province of South Africa. The Limpopo province is the largest rural province in South Africa. Up to 40% of the total population does not have access to sufficient water supply, resulting in adverse health effects. The purpose of this study is to determine (1) the degree of inorganic pollution of borehole water; (2) to identify the pollution sources, and (3) to determine whether the pollution is inherited from the surface water that recharges the groundwater or is caused on site near the bore holes. In order to achieve these objectives, surface water quality data (14 675 samples) and borehole water data (340 samples) at health facilities were analysed. A pollution index, defined by the following ratio:

$$\text{Pollution index (\%)} = 100 \times ([\text{Cl}^-] + 2[\text{SO}_4^{-2}] + [\text{NO}_3^-] + 3[\text{PO}_4^{-3}]) \div ([\text{Cl}^-] + 2\text{SO}_4^{-2} + [\text{NO}_3^-] + [\text{PO}_4^{-3}] + [\text{HCO}_3^-])$$

was used to determine the percentage of contribution of each chemical species towards pollution. This ratio is based on the fact that bicarbonate is released during chemical weathering of rocks whereas sulphate, nitrate, chloride, and phosphate are anthropogenic in origin. The pollution index shows that 6% of the surface waters and 21% of the borehole water is severely polluted. The pollution of the surface water is characterized by high concentrations of sulphate whereas the pollution of the borehole water is characterized by high concentrations of chloride. This indicates that the pollution of the borehole water is not so much the result of the infiltration of polluted surface water, but rather the result of on-site pollution on the surface near the bore holes.

Key words: Limpopo, Pollution index, inorganic pollution, borehole water, surface water

Opsomming

Die navorsing wat in hierdie verhandeling weergegee word, is uitgevoer om die oorsprong van besoedeling in die waterbronne van landelike gesondheidsfasiliteite in die Limpopo-provinsie van Suid-Afrika na te speur. Die Limpopo-provinsie is die grootste landelike provinsie in Suid-Afrika. Tot 40% van die totale bevolking het nie toegang tot voldoende en geskikte water nie, wat beduidende nadelige gevolge vir die gesondheid van die bevolking inhou. Die doel van hierdie studie was:

- om die graad van anorganiese besoedeling van boorgatwater by landelike gesondheidsfasiliteite in Limpopo te bepaal;
- vas te stel of die waarskynlike besoedelingsbronne natuurlik of antropogenies van aard is; en
- om te bepaal of die besoedeling van grondwaterbronne afkomstig is van infiltrerende oppervlakwater of deur lokale besoedeling op die grondoppervlakte naby die boorgate.

Om die gestelde doelwitte te bereik is die oppervlakwater gehalte in Limpopo (14 675 monsters) vergelyk met die grondwater gehalte (340 monsters) in die onmiddellike omgewing van die landelike gesondheidsfasiliteite. 'n Besoedelingsindeks wat deur die volgende vergelyking beskryf word:

$$\text{Besoedeling indeks (\%)} = 100 \times ([\text{Cl}^-] + 2[\text{SO}_4^{-2}] + [\text{NO}_3^-] + 3[\text{PO}_4^{-3}]) \div ([\text{Cl}^-] + 2\text{SO}_4^{-2} + [\text{NO}_3^-] + [\text{PO}_4^{-3}] + [\text{HCO}_3^-])$$

is gebruik om die graad van besoedeling te bepaal. Hierdie verhouding is gebaseer op die feit dat bikarbonate vrygestel word gedurende die chemiese verwerking van rotse, terwyl sulfate, nitrate, chloriede en fosfate van antropogeniese oorsprong is.

Die besoedelings indeks dui aan dat 6% van die oppervlakwater en 21% van die

boorgatwater in Limpopo erg besoedel is. Die oppervlakwater word hoofsaaklik besoedel deur sulfate, terwyl die boorgatwater deur hoë konsentrasies van chloriede besoedel word. Dit dui daarop aan dat die besoedeling van die boorgatwater merendeels afkomstig is van plaaslike besoedeling op die grondoppervlakte naby die boorgate, en dat grondwatergehalte dus nie beduidend deur die infiltrasie van oppervlakwater beïnvloed word nie. Hierdie bevinding verskaf duidelike riglyne vir remediërende maatreëls wat getref behoort te word om skoon, veilige water te verskaf aan landelike gesondheidsfasiliteite in Limpopo.

Sleutelwoorde: Limpopo, Besoedeling indeks, anorganiese besoedeling, boorgatwater, oppervlakwater

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List of abbreviations

AGES	Africa Geo-Environmental Services
DDT	Dichlorodiphenyltrichloroethane
ERWAT	East Rand Water Care Company
PBT	Persistent Bioaccumulative Toxic
PCB	Polychlorinated biphenyls
POP	Persistent Organic Pollutants
PVC	Polyvinyl chlorides
SCB	Stoichiometric charge balance
TDS	Total Dissolved Solids
VIP	Ventilated Improved Pit
WHO	World Health Organization

Chapter 1

Introduction

1.1. Current water situation in South Africa

The Constitution of South Africa (1996), states that everyone has a right to a safe environment which is not harmful to their health or well-being. Safe drinking water is not only essential to health but also a basic human right and a component of human health protection (Prüss- Üstun, 2008).

South Africa is a semi-arid to arid country with an average rainfall of 450 mm per year, which is below the world's average of 860 mm per year (M'Marete, 2003; Bosman & Kidd, 2009; Burger, 2009). According to the Department of Water Affairs and Forestry, South Africa is classified as a water scarce country (M'Marete, 2003; Bosman & Kidd, 2009). The current water prediction is that South Africa will experience absolute water scarcity by 2025, if drastic measures are not taken (Mara, 2003; FLOW, 2010; CSIR, undated). In addition to the limited resources, South Africa's water quality is vulnerable due to factors such as climate variability; degradation of water resources as a result of poor management; transboundary water issues which result in complications for downstream users; intensive irrigation, erosion and pollution (Mafuta *et al*, 2008; Bosman & Kidd, 2009;). The major sources of surface water pollution in South Africa are agricultural wash-off, urban wash-off, industries, mining activities and inadequate sanitation services. Groundwater pollution mostly originates from mining activities, informal settlements and leachate from landfills. The biggest challenges concerning water pollution in South Africa are eutrophication, nitrification, microbiological contamination, increased salinity and acid mine drainage (Bosman & Kidd, 2009):

- Eutrophication occurs when water resources are enriched with nutrients like nitrates and phosphates. The nutrients lead to excessive growth of macrophytes and microscopic plants, causing a depletion of oxygen in the water (e.g., Hartbeespoort Dam) (DWEA, 2008; Bosman & Kidd, 2009);
- Nitrification refers to elevated nitrate levels in water resources. Nitrification is caused by inadequate sewage treatment, poor sanitation and poor agricultural practices like excessive use of fertilizers (Fortuna *et al*, 2003; Bosman & Kidd, 2009);
- Microbiological contamination (e.g., E-coli) is caused through inadequate sanitation and ineffective water treatment (Ashbolt, 2004; Bosman & Kidd, 2009).
- Increased salinity which is often associated with mining and industrial activities (Sardinha *et al*, 2003; DEA, 2007; Bosman & Kidd, 2009)
- Acid mine drainage, the acidification of water due to oxidation of pyrite . The exposure of pyrite to oxygen and water is caused by mining activities. Typically, natural waters affected by acid mine drainage have low pH levels, elevated salinity levels and high concentrations of sulphate, iron, aluminium and manganese (Bosman & Kidd, 2009; Jacobs *et al*, 2010).

1.2. Problem statement: Potable water quality in the Limpopo province

The Limpopo Province seems to have significant water challenges in the rural areas, especially since only 40% of the entire province has access to safe drinking water (M'Marete, 2003; Hope *et al*, 2004; Busari, 2008). The Department of Health initiated a water supply project at health facilities in 1999. According to the study, issues regarding water quality at health facilities raised concerns. In 2003, water samples from various health facilities were sampled to determine the water quality of boreholes supplying these health facilities with potable water (Stander, 2010). The study concluded that more than 40% of the boreholes did not comply with the South African Bureau of Standards standard or the Water Quality Guidelines issued by the Department of Water Affairs and Forestry for potable water quality (Vivier, 2006).

A comprehensive survey was subsequently conducted of the water quality at the Health Facilities in the rural areas in 2005. The biggest part of the hydrological census was conducted between March 2006 and July 2006, although all data sampled between 2003 and 2010 was also included in the dataset. The survey was done at each health facility and included a land-use survey in a radius of 100 meters around every health facility. The aim of this survey was to document the following (Vivier, 2006):

- The current surface- and groundwater usage
- The status of existing on-site sanitation systems
- Cleansing material used
- Willingness of health facility staff to perform operational and maintenance tasks regarding sanitary facilities as well as water treatment facilities

- Assessment of the staff and patient's most and least preferred sanitation options (Vivier, 2006)

The results obtained from this survey can be summarized as follows:

Forty nine percent of the 266 health facilities that were surveyed were dependent on boreholes for water supply. Of these, only 63% of the boreholes were located within the health facilities yard and 37% were located outside the yard, but no further than 100 meters from the facility. The water obtained from the boreholes were mainly used for potable water, sanitation, irrigation, and washing at facilities and nearby communities. The water supply was reported to be irregular and unreliable at 21% of the facilities and approximately 90% of facilities with their own water supply did not treat the water prior to using it (Vivier, 2006).

The sanitation infrastructures at the health facilities consisted of 34% septic tanks, 23% Ventilated Improved Pit Toilets (VIP), 15% pit latrines, 13% off-site waterborne systems, 7% on-site waterborne systems, 4% conservancy tanks, 3% eco-toilets and 1% with no form of sanitation. The operation and maintenance of the facilities were found to be not up to standard, with 22% of the facilities in a poor condition. The operational and maintenance problems ranged from broken toilet doors to overflowing pits and leaking pipes. All in all it can be concluded that the water quality at these facilities was unacceptable. Various intervention strategies have since been implemented, but the main source of the water contamination (groundwater as well as surface water), remains to be determined (Vivier, 2006).

The purpose of this study is:

- To qualify and quantify water pollution at health facilities in the Limpopo province.
- To identify possible sources of pollution by investigating the inorganic chemistry of surface and groundwater sources in detail.
- To compare the results with the known surface and ground water chemistry of the Limpopo province in order to determine whether observed pollution is caused by surface water pollution that recharges the groundwater or pollution on the surface near or above groundwater resources.

1.3. Organization of this thesis

Chapter 1 gives an overview of the water situation in South Africa as well as factors that contribute to the vulnerability of the water sources. It also discusses the background and purpose of the study. Chapter 2 gives an overview of the Limpopo province's geology and land use activities while Chapter 3 describes the datasets and the methods used to analyse the datasets of both the surface and groundwater. Chapter 4 is an important chapter since it describes the water chemistry in Limpopo, giving a better understanding of the inorganic parameters and pollution that might be present in the water. It also describes the pollution index that is used to determine which inorganic species contribute most towards the pollution index, in order to identify the source of pollution. Chapter 5 contains all the results of both the surface and groundwater analyses, with detailed maps and figures to illustrate and compare the results. Chapter 6 is the synthesis, containing the conclusions, recommendations, outstanding questions and further research.

Chapter 2

Study area: the Limpopo Province

2.1. Introduction

This chapter gives an overview of the climate, geology and land use activities in the Limpopo Province. This information is critical in order to evaluate the surface and groundwater quality in the Limpopo Province.

2.2. General information about the Limpopo province of South Africa

The Limpopo province consists of 10.2% of the country's total land surface and 11.2% of the total population. It is the biggest rural province in South Africa of which the rural communities make up about 90% of the total population in the province (Hope *et al*, 2004; Sikhwari, 2008; Busari, 2008).

The elevation varies from 600 m to 1700 m above sea level. The average annual rainfall in the Limpopo Province varies from approximately 300 mm in the west to more than 600 mm in parts of the northeast with up to 2000 mm in the mountain regions (M'Marete, 2003; Sikhwari, 2008; Busari, 2008). It is a subtropical rainfall region with hot humid summers and mild frost-free winters with temperatures on average between 4°C and 20°C in the winter and between 17°C and 27°C in the summer, however temperatures sometimes reach as high as 45°C (M'Marete, 2003; Sikhwari, 2008). The Limpopo region is affected by droughts as result of infrequent and low precipitation, combined with high evaporation rates (Busari, 2008).

2.3. The geology of the Limpopo Province

The geology of the Limpopo Province is illustrated in Figure 2.1. The four most important geological terrains found in the Limpopo province include the Kaapvaal Craton, the Limpopo Belt, the Bushveld Complex and the Waterberg Group. The Kaapvaal Craton, which is the oldest of the three terrains, is a typical granitoid-greenstone terrain, comprising granitic rocks of which the most important minerals include quartz, feldspar, and mica. The greenstones comprise a variety of rocks including siliciclastic sediments, mafic and felsic volcanic. Both the granites and greenstones are cut by younger dolerite dykes. The metamorphic grade of the Kaapvaal Craton is low to medium grade (Kramers *et al*, 2006).

Between the Kaapvaal Craton and the Zimbabwe Craton a broad zone of high-grade metamorphic rocks occurs; the Limpopo Belt. The Limpopo Belt is subdivided into three domains namely, the Central Zone, the Southern Marginal Zone and the Northern Marginal Zone. The rock types that form part of the Limpopo Belt includes meta-sediments e.g., banded iron-formations, marbles, metapelites and quartzites, and intrusive granitoids of varying ages. The Limpopo Belt is to a great extent covered by younger sedimentary and volcanic formations of the Soutpansberg Trough and the Karoo-age Tuli Trough (Kramers *et al*, 2006).

The Bushveld Complex mafic and ultramafic and felsic intrusive rocks, well known for its Platinum Group Element deposits, cover a large zone within the province. The Bushveld Complex is emplaced into the older Transvaal Supergroup (Cawthorn *et al*, 2006).

The youngest of the three terrains in the Limpopo Province, the Waterberg Group covers the Transvaal Supergroup, the Bushveld Complex and the Archaen gneiss

and granite formations of the Kaapvaal Craton. The rock formations of the Waterberg Group mainly consist of coarse siliciclastic rocks (Callaghan *et al*, 1991). The Waterberg Group can be divided into three subgroups, namely the Nylstroom, Matlabas and Kransberg Subgroups (De Kock *et al*, 2006; Baker *et al*, 2006). The subgroups consist of rudites (conglomerates consisting of carbonate, chert and sandstone clast) and arenites at the base and lutites and arenites at the top (Baker *et al*, 2006).

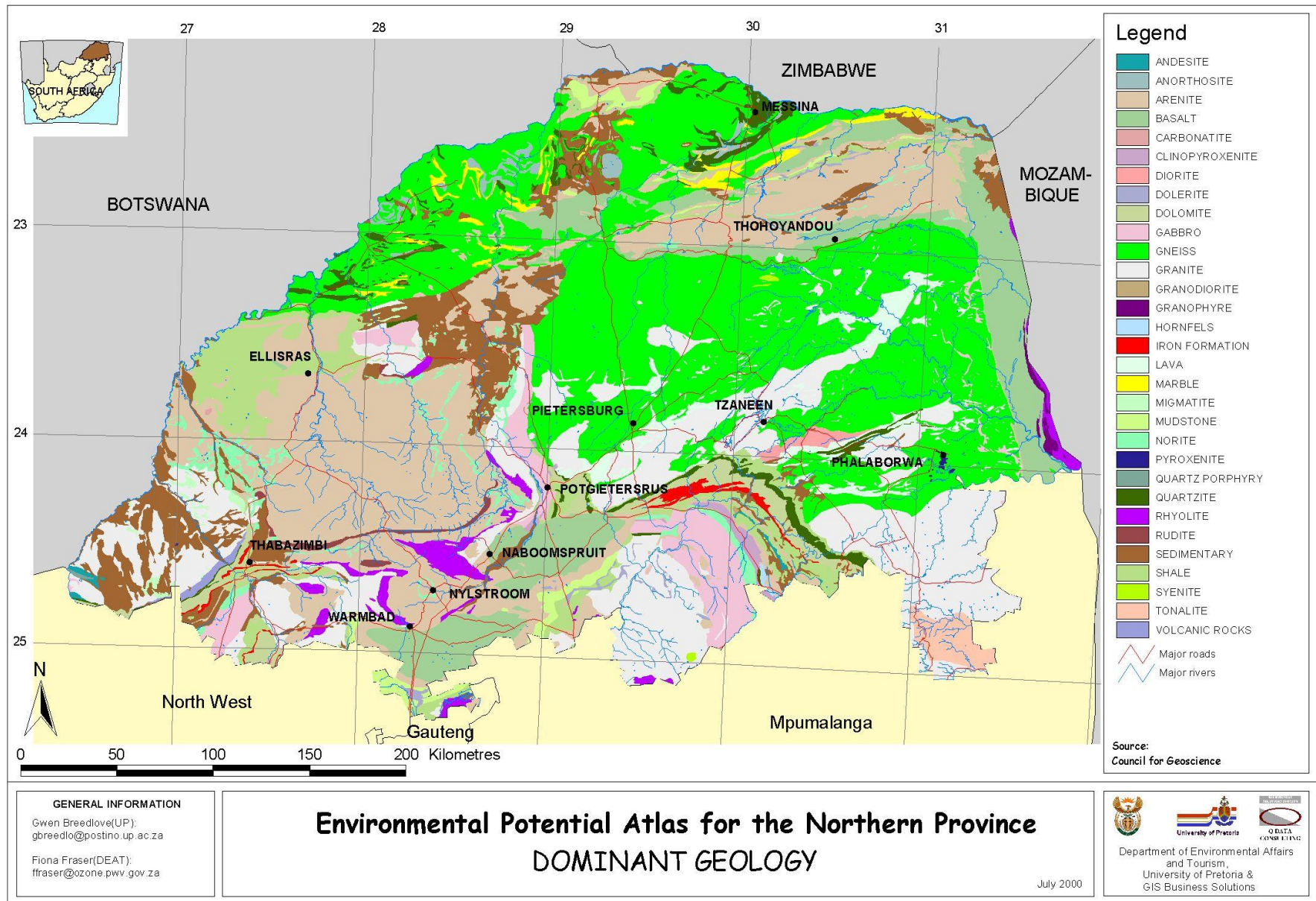


Figure 2.1: The general geology of the Limpopo Province. The Kaapvaal Craton consists of granite, granodiorite and volcanic rocks; the Limpopo Belt consists of migmatite and tonalite, the Bushveld Complex consists of anorthosite, clinopyroxenite, gabbro, norite and pyroxenite and the Waterberg Group is made up of sedimentary formations (DEAT *et al*, 2000).

2.4. Different types of land use activities in Limpopo

The land use activities and land cover of the Limpopo Province is illustrated in Figure 2.2 and 2.3. Land use can be defined in terms of human activities such as agriculture, mining, industrialization, forestry, construction as well as social and economic activities that revise land surface processes including hydrology, biodiversity and biogeochemistry (Ellis, 2010). Therefore land use has a great influence on the productivity and condition of land and its biodiversity (Fig 2.2) (DEAT, 2008). Land cover includes vegetation, soil, water and artificial structures (Fig 2.3) (IWR, 1997; Ellis, 2010).

The Limpopo Province has various agricultural- industrial- and mining activities (Busari, 2008). The climate allows the province to produce a wide variety of agricultural products from cereals like cotton, groundnuts, tobacco, wheat and maize to tropical fruit such as mangoes as well as vegetables like onions and tomatoes (M'Marete, 2003; Sikhwari, 2008; Busari, 2008; LDA, 2010). The province also has a wide variety of game and cattle ranching (M'Marete, 2003). Due to the characteristics of the climate, soil and topography, agricultural land use can be divided into the following proportions:

1. 37,7% appropriate for cultivated farming
2. 50,1% appropriate for pasturage
3. 12,2% appropriate for wildlife.

The Limpopo province is rich in mineral resources, giving rise to mining and industrial activities. Mining and industrial activities include the production of platinum,

diamonds, chrome, silicon, copper, granite and coal. Mining activities currently account for 22% of the provincial Gross Domestic Product (Busari, 2008).

The province also has vast areas occupied with subsistence farming (Fig 2.2 and Fig 2.3), since 90% of the province live in rural communities (as mentioned in chapter 1) (Busari, 2008).

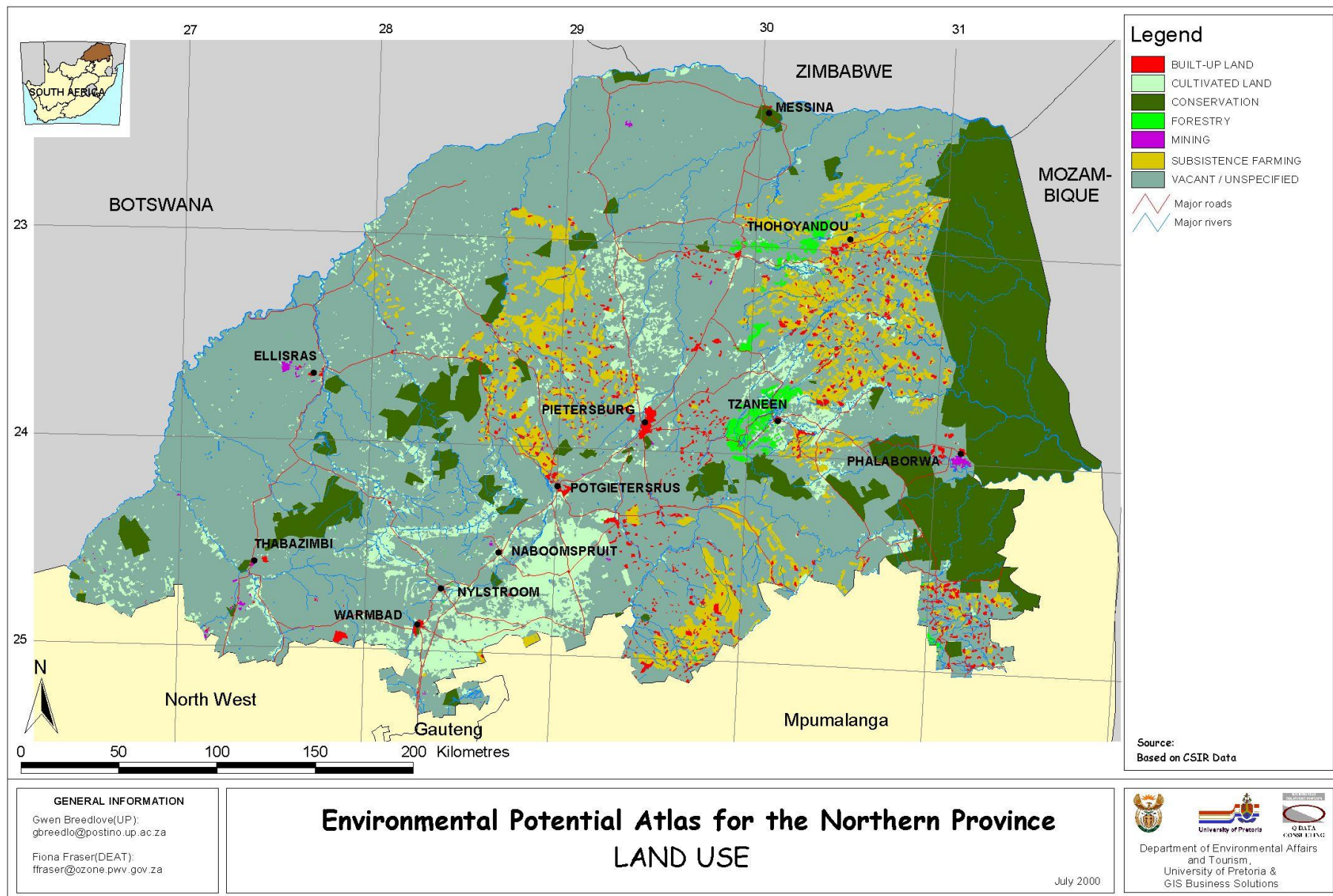


Figure 2.2: General land use activities in the Limpopo Province (DEAT *et al*, 2000).

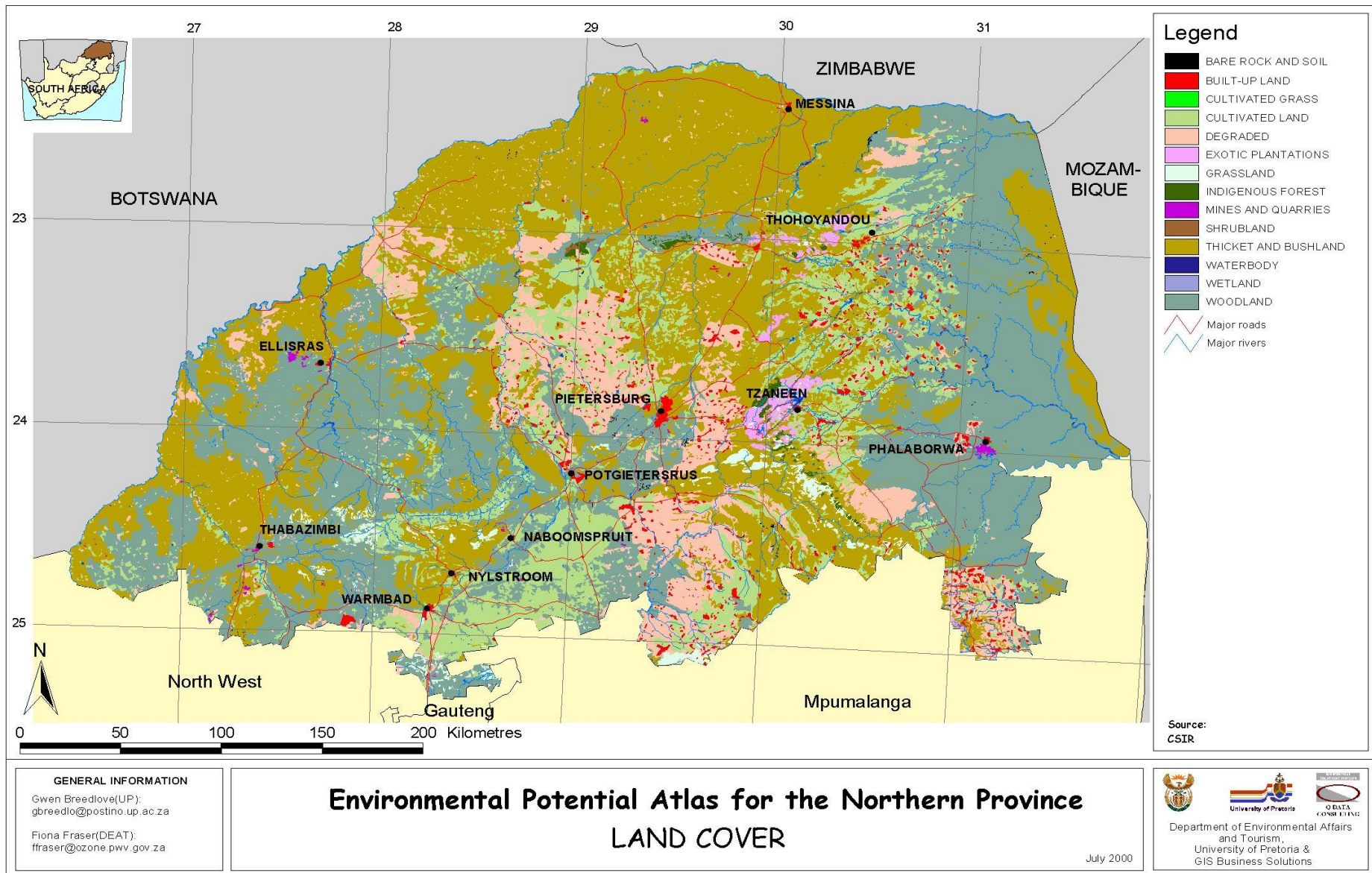


Figure 2.3: General land cover in the Limpopo Province (DEAT *et al*, 2000).

Chapter 3

Datasets and methodology

3.1. Introduction

This chapter describes the datasets of both the surface and borehole water used in this study. Before the data can be used, some significant modifications of the datasets are required to ensure an accurate water quality dataset. The chapter will also give an overview of the methods used to analyse the data.

3.2. Surface water data

Surface water data were used to determine the geological and anthropogenic influences on surface water and to establish whether there is any association between surface- and groundwater pollution in the Limpopo province as the groundwater reservoirs are recharged by surface waters.

The surface water quality data were obtained from the compact disk, Water Quality on Disc (CSIR Environmentek and DWAF, 1999). The water quality compact disk contains water quality data for the entire country from the 1970's up to 1999. Surface water quality data from 2000 to 2008 were received from the Department of Water Affairs and Forestry on request. Unfortunately the available data for 2009 and 2010 is incomplete and could not be used. The sample monitoring station numbers in the Limpopo province were gathered in order to make a data set for the Limpopo province only. Surface water quality data from 94 sampling stations throughout Limpopo were used to support the objectives (Table 3.1).

Table 3.1: Number of surface water sampling stations per municipality.

Municipality	Number of surface sampling stations
Bohlabela	16
Capricorn	2
Mopani	17
Sekhukhune	13
Vhembe	18
Waterberg	28

The sample stations (Appendix 1) are found in the Limpopo (A) and Olifants (B) primary catchment areas. The original data was in a dBase format and was converted to an Excel format for the purpose of this study. Incomplete water analyses were removed from the dataset. The entire dataset includes 24 921 complete analyses.

The water chemical data include pH, total alkalinity (measured as CaCO_3 in mg/L), electrical conductivity and the concentrations of the following major chemical species (all in mg/L): sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), ammonium (NH_4^+), silica (Si), fluoride (F), orthophosphate (PO_4^{3-}), chloride (Cl), sulphate (SO_4^{2-}), nitrate (NO_3^-) and the total dissolved solids (TDS). The carbonate and bicarbonate concentrations were calculated from the pH and the total alkalinity using the procedure described in Appelo and Postma (2005).

The quality of this dataset was screened by calculating the stoichiometric charge balance (SCB). The SCB was calculated according to the following equation (Appelo and Postma (2005).:

$$\text{SCB (\%)} = 100 \times \frac{\sum [\text{cations}] - \sum [\text{anions}]}{\sum [\text{cations}] + \sum [\text{anions}]}$$

in which the concentration of the anions and cations are expressed in milli-equivalent per litre as absolute values. According to Appelo and Postma's (2005),

the acceptable stoichiometric charge balance has to be within a $\pm 5\%$ range in order for the analysis to be accurate. After this quality check, 14 675 samples could be used from the original 24 921 (i.e., 59%). All the data handling was performed in Excel.

3.3. Groundwater data

Two hundred and seventy four health facilities were assessed within the Capricorn, Mopani, Sekhukhune, Vembe and Waterberg district municipalities of the Limpopo Province. Of the 274 health facilities only 183 facilities had accurate water quality data and these were used to determine whether geology or anthropogenic activities were mainly responsible for pollution in Limpopo (Table 3.2). The majority of these health facilities rely on groundwater for potable and general purposes. The water is mostly obtained from boreholes which are on site or commune sources in the vicinity. Water samples from these boreholes were collected and analysed, and simultaneously a hydrological census was done to determine the sanitation regime and surrounding land-use at each health facility. Groundwater samples from the utility sources at each health facility have been sampled on a monthly basis by Africa Geo-Environmental Services (AGES) during and after 2005, until present (Appendix 2).

Table 3.2 : Number of health facilities per municipality of which water quality data was obtained.

Municipality	Number of health facilities
Bohlabela	2
Capricorn	38
Mopani	40
Sekhukhune	34
Vhembe	43
Waterberg	26

All the samples were analysed by ERWAT laboratory for the same chemical parameters as the surface water samples. However, not all samples were analysed for nitrate, phosphate, and silica. These samples were not excluded from the dataset (654 samples), in order to make the dataset bigger, for more accurate results. The instruments and analytical procedures used by ERWAT are shown in Table 3.3.

Table 3.3: PERKIN ELMAR, optima 5000 series ICP Optical Emission, Operator's Manual for the analysis of the borehole water at health facilities in Limpopo (Nel, 2010.)

Determinants	Instrument used and Analytical procedure	Concentration units	Measurements range (mg/L)
Calcium	ICP - OES	mg/L	0.1 – 100
Potassium	ICP – OES	mg/L	0.1 – 50
Magnesium	ICP - OES	mg/L	0.1 - 100
Ammonia nitrogen	Colorimetric FIA (Salicylate)	mg/L	0.1 - 100
Nitrate + nitrite nitrogen	Colorimetric FIA Cd reduction	mg/L	0.1 - 40
Orthophosphate	Colorimetric – FIA (Potassium antimony tartrate)	mg/L	0.1 - 40
Chloride	Colorimetric – FIA (Mercuric Thyocyanate)	mg/L	2 - 400
Sulphate	Turbidimetric FIA (5) (Bariun Sulphate)	mg/L	10 - 400
Alkalinity	Titration	mg/L (CaCO ₃)	> 0
Silicate	Unknown	Unknown	Unknown

The concentrations of nitrate and phosphate are generally small and silica is not an important chemical species for this type of study (Huizenga, 2010). Similar to the surface waters, a SCB check was done on the groundwater analyses. Using a $\pm 5\%$ charge balance error as a limit, only 222 samples were accurate enough. This reduces the dataset significantly and may reduce the validity of the interpretation of the data, due to the wide distribution of the surface and borehole water stations in Limpopo. Therefore, a charge balance error of $\pm 10\%$ was used instead, which still represents reasonable accuracy, in order to enlarge the dataset of the groundwater

to a more acceptable number of 340 samples. All the data manipulation was performed in Excel 2007.

The locations of the health facilities and surface water stations are shown in (Fig 3.1):

Map of monitoring stations

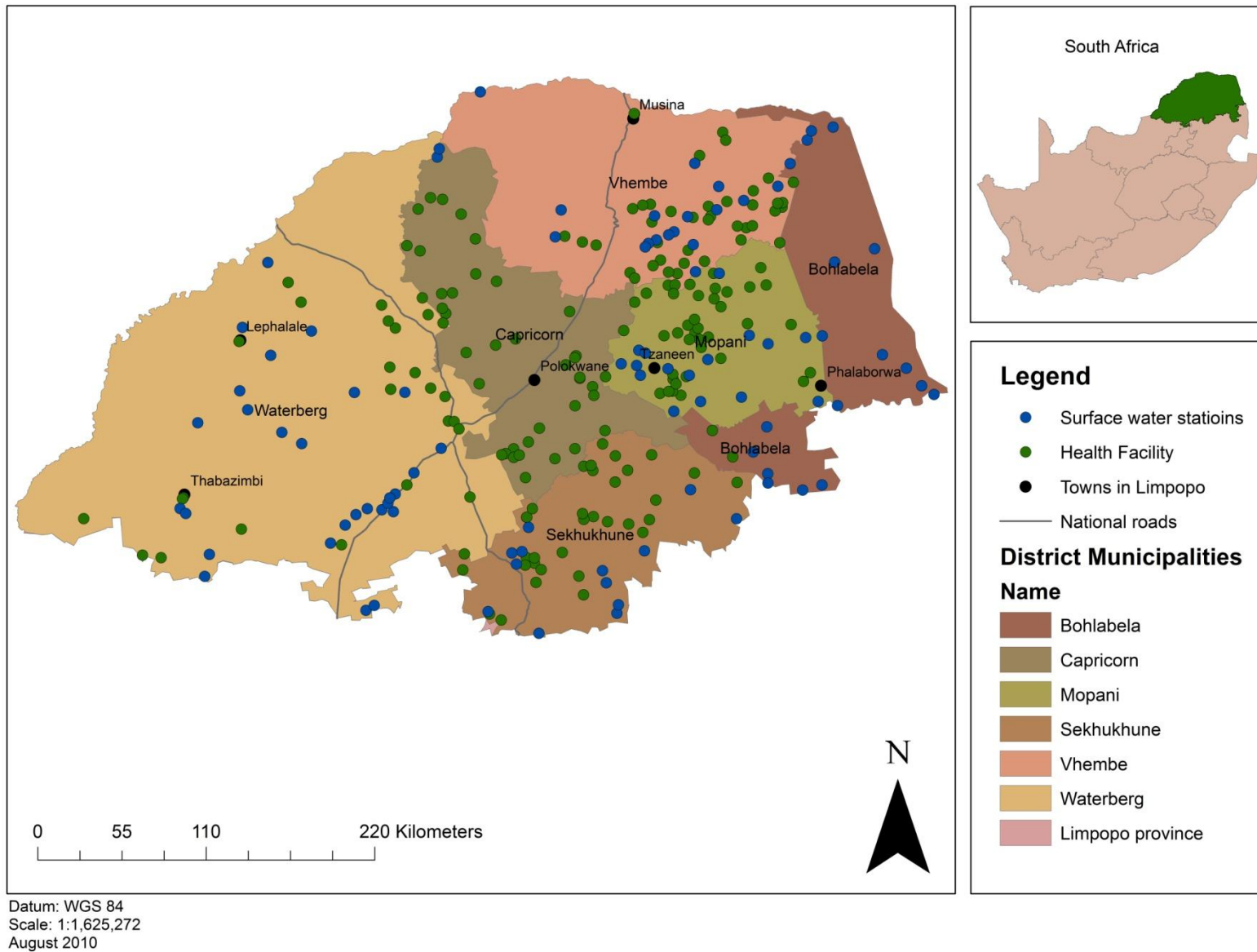


Figure 3.1: The locations of both the surface - and borehole water sites in the Limpopo Province.

Chapter 4

Controlling factors of water chemistry in the Limpopo Province

4.1. Introduction

This chapter will describe and discuss the factors that control the inorganic water chemistry, which is complicated due to the unique climatic-geological conditions of the Limpopo Province. The province is dry with relatively high temperatures throughout the year, and little soil has been developed (M'Marete, 2003). It can, therefore, be expected that the concentrations of major cations and anions are relatively high (Fig 4.1.).

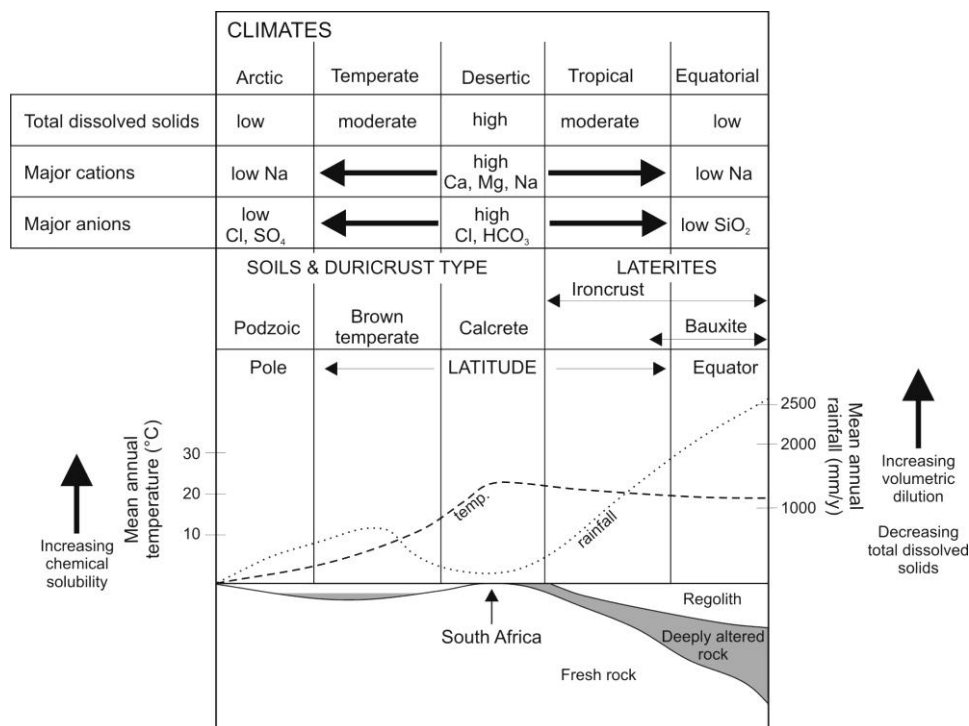


Figure 4.1: The relationship between climate factors and water chemistry (adapted from Plant *et al*, 2001).

The high concentrations of cations and anions may be perceived as contamination from anthropogenic sources. For example, the total dissolved solids (TDS)

concentrations are one of the criteria that are usually used to quantify pollution (Table 4.1) (Bosman & Kidd, 2000).

Table 4.1: The components and weightings of the South African Water Quality Index (Bosman & Kidd, 2000).

Variable	Weight
Total dissolved solids	0.27
Ecoli	0.21
Dissolved oxygen	0.16
Chlorophyll – alpha	0.13
pH	0.12
Turbidity	0.11

Figure 4.1 however, shows that the TDS concentrations of rivers in South Africa tend to be high due to climatic conditions, i.e. it can thus not be used as an indicator for pollution.

In order to distinguish between polluted and non-polluted water, a modified pollution index described by Van der Weijden and Pacheco (2006) has therefore been used.

$$\text{Pollution index (\%)} = 100 \times ([\text{Cl}^-] + 2[\text{SO}_4^{-2}] + [\text{NO}_3^-] + 3[\text{PO}_4^{-3}]) \div ([\text{Cl}^-] + 2\text{SO}_4^{-2} + [\text{NO}_3^-] + [\text{PO}_4^{-3}] + [\text{HCO}_3^-]) \quad (4.1)$$

This equation uses the charge corrected concentration (mol/L), and is based on the fact that chemical weathering of rock formations results in bicarbonate ions, due to similar or dissimilar weathering of carbonates and silicates (Appelo and Postma, 2005; van der Weijden & Pacheco, 2006). Chloride, sulphate, phosphate and nitrate on the other hand cannot be derived from chemical weathering and can only be obtained from anthropogenic sources. Through this understanding it is clear that bicarbonates and cations, like calcium and magnesium, are primarily derived from chemical weathering and that chloride, sulphate, nitrate and phosphate originate from anthropogenic and atmospheric sources (van der Weijden & Pacheco, 2006).

It is noteworthy that water pollution and water quality are fundamentally different concepts. Water pollution is the discharge of pollutants through anthropogenic and natural activities and sources, respectively, whereas water quality is determined through the water quality guidelines issued by the Department of Water Affairs and Forestry for each purpose (DWAF, 1996; vanLoon and Duffy, 2005). The pollution index as defined in Equation (4.1) is thus an objective measurement whereas water quality is based on man-made targets and thus subjective. The pollution index is expressed as a percentage indicating how much of the overall water chemistry is derived from anthropogenic and atmospheric sources (Van der Weijden and Pacheco, 2006).

Using data from Gaillardet *et al* (1999); the minimum lower limit for the pollution index for polluted water is defined as 70% and maximum lower limit is set at 30% for non-polluted rivers. The available dataset for surface waters in the Limpopo Province can now be subdivided into polluted waters ($PI \geq 70\%$), non-polluted waters ($PI \leq 30\%$), and intermediate polluted waters ($30\% < PI < 70\%$). In this chapter, the data will only be used to illustrate that chemical weathering is the main natural process controlling the water chemistry in the Limpopo Province.

4.2. Chemical weathering

Weathering is responsible for most of the soils, clays, and dissolved substances found in water resources. The two ways in which rock formations weather are chemical weathering and physical weathering, of which chemical weathering is dominant in South Africa (Press *et al*, 2004). Chemical weathering is basically the process through which residual materials form as result of rock formations that are dissolved, disintegrating or loosened by chemical processes (Press *et al*, 2004;

Ritter, 2010). Chemical weathering also weakens rock formations, which make them more subject to fracturing (Press *et al*, 2004). As mentioned previously, chemical weathering is most likely the main factor that controls the water chemistry of non-polluted rivers in the Limpopo Province. In this section, different geochemical techniques will be used to determine to what extent chemical weathering controls the water chemistry and which rocks in particular dominate this process. For this purpose non-polluted surface waters will be used. The Gibbs diagram, Figure 4.2 shows that the inorganic chemistry of non-polluted surface water is concentrated in the rock dominance field, confirming that the chemical quality of surface waters are controlled by chemical weathering. According to Gibbs (1970), the two major cations that characterize surface water are Ca^{+2} and Na^{+} . Fresh water bodies are characterized by Ca^{+2} , whereas Na^{+} is found in high saline water. Gibbs (1970) plotted $\text{Na}^{+} \div (\text{Na}^{+} + \text{Ca}^{+2})$ against TDS in order to separate rivers into three classes. The classes include precipitation dominated, rock dominated and evaporation dominated and non-polluted river compositions should plot against the shaded area shown in the diagram.

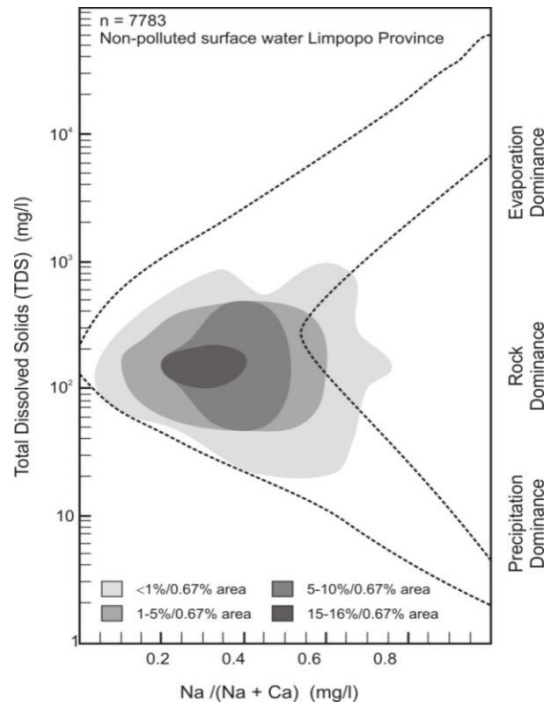


Figure 4.2: Gibbs diagram for non-polluted surface water (modified from Gibbs, 1970).

A second diagram introduced by Gaillardet *et al* (1999) can be used to determine which rock types are responsible for chemical weathering. The diagram shows the end-member compositions of rivers draining silicates, carbonates and evaporates (Fig 4.3). The diagram uses sodium normalised concentrations of bicarbonate and calcium. Sodium is a conservative element, i.e. normalisation against sodium will filter out the effects of increasing concentrations in dry periods due to evaporation. The diagram (Fig.4.3) clearly shows that the surface water chemistry in the Limpopo Province is solely controlled by the chemical weathering of silicate rocks and to a lesser extent carbonate rocks.

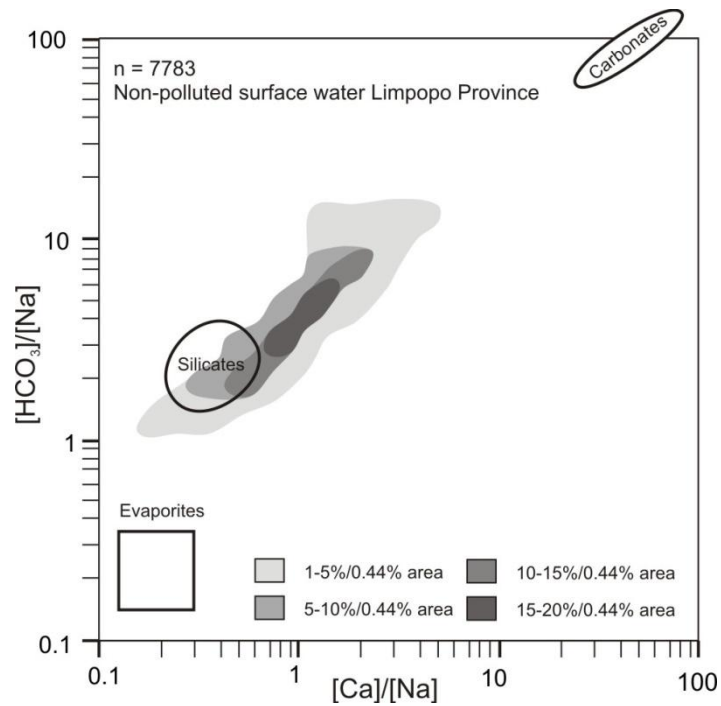


Figure 4.3: Correlation between non-polluted surface water and silicates, carbonates and evaporites. (Density contouring was used due to the large dataset) (modified from Gaillardet *et al*, 1999).

Chemical weathering of silicate and carbonate rocks typically add Ca, Mg, Na, K, Si, and HCO_3^- to the surface water in the Limpopo Province as elaborated upon in (Table 4.2).

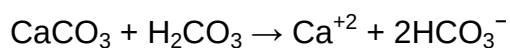
Table 4.2: Major elements in water and their natural - and anthropogenic sources (Appelo & Postma, 2005).

Element	General	Sources
Carbon	Major element for all life forms. Variable oxidation state from +4 to +2. Occurs as H_2CO_3 , HCO_3^- or CO_3^{2-} in natural water, depending on the pH. It is measured as alkalinity.	<i>Natural:</i> atmosphere, mineral weathering, organic material.
Calcium	Most abundant alkali earth metal, essential element for plant and animal life forms. Only one oxidation state (+2). Large, divalent ion holds strongly onto mineral surfaces.	<i>Natural:</i> Pyroxenes, amphiboles, Ca-feldspars, carbonate minerals (calcite, aragonite, and dolomite), gypsum, anhydrite, and fluorite.
Magnesium	Alkaline earth metal, essential in plant and animal nutrition. Smaller than Ca or Na ions and, therefore, more hydrated. Only one oxidation state (+2).	<i>Natural:</i> Pyroxenes, olivine, amphiboles, micas, chlorite, serpentine, magnesite, dolomite.
Sodium	Most abundant of the alkali metals. Larger, less hydrated ion. Always found in +1 oxidation state.	<i>Natural:</i> Atmosphere, Na-feldspars, clay minerals such as kaolinite or illite. In sodium salts formed from evaporation (thenardite, halite). <i>Anthropogenic:</i> Industrial waste.
Potassium	Alkali metal, essential for plants and animals. Found in 1+ oxidation state. In natural waters it has a much lower concentration than Na. Once in solution, there is a tendency to be reincorporated into solid weathering products.	<i>Natural:</i> K-feldspars, micas, illite, dry plant material, ash.
Silicon	Second only to oxygen in abundance on Earth, often extracted by organisms for shells and skeletons. The Si – O bond is strong. It only occurs in oxide form (SiO_2). The hydrated form is H_4SiO_4 .	Silicate minerals.
Sulphur	Non metal occurring in oxidation states from S^{2-} to S^{6+} . Normally occurs in oxidised SO_4^{2-} (in water and minerals) or reduced form S^{2-} (minerals only).	<i>Natural:</i> metallic sulphides and evaporates (gypsum), volcanoes, geothermal sources. <i>Anthropogenic:</i> burning of fuels, smelting of ores, acid mine drainage.

Chloride	Most abundant of halogens. Many compounds readily soluble. It has a low concentration in rocks compared to other elements. ~75% of all chloride occurs in the oceans.	<i>Natural:</i> atmosphere, evaporates and sedimentary rocks (halite, sodalite, apatite). Found in cementing material and marine deposits. <i>Anthropogenic:</i> industrial and domestic waste.
Fluoride	Lightest element of halogen group. Most electronegative element. F ⁻ ion in solution. Essential for bones and teeth.	<i>Natural:</i> fluorite, apatite, amphiboles, micas.
Nitrogen	Oxidation states N ³⁻ to N ⁵⁺ . In water it occurs as NO ₂ ⁻ , NO ₃ ⁻ , NH ₄ ⁺ . ~70% of the Earth's atmosphere is nitrogen. Nitrogen is of vital importance for plant and animal nutrition.	<i>Natural:</i> biologically converting N in atmosphere to chemical compounds available in lithosphere and hydrosphere. <i>Anthropogenic:</i> fertilizers, combustion of fossil fuels, waste disposal (cyanide, CN ⁻), explosives, sewerage
Phosphorus	Major nutrient for biota. Low solubility of P when in the form of inorganic compounds. It has variable oxidation states (P ³⁻ to P ⁵⁺). In water it mainly occurs as orthophosphate (PO ₄ ³⁻).	<i>Natural:</i> apatite, phosphorites. <i>Anthropogenic:</i> fertilizers, sewerage, insecticides.

4.2.1. Chemical weathering of carbonates

Typical minerals that occur in carbonate rocks are calcite (CaCO₃) and dolomite (CaMg(CO₃)₂). The amount of carbonate minerals that dissolves depends on the amount of CO₂ in the atmosphere, which dissolves in the river water and forms carbonic acid. Calcite weathers relatively easily and results in high concentrations of Ca⁺ and HCO₃⁻. Dolomite, on the other hand, is less soluble (Appelo & Postma, 2005). Calcite dissolves in the presence of carbonic acid (and the dissolved components) according to the reaction (Press *et al*, 2004):



4.2.2. Chemical weathering of silicates

Chemical weathering of silicate minerals, even for the most soluble silicate minerals, is much slower than the chemical weathering process of carbonate minerals (Press *et al*, 2004; Appelo & Postma, 2005). Although silicates dissolve slowly it still contributes to 45% of the total dissolved loads in rivers worldwide. Minerals like olivine that form at relatively high temperatures and pressures are more prone to chemical weathering than minerals that form under low pressure and temperatures. Most silicate weathering reactions reduce acid and increase the pH level of water sources as bicarbonate is released during the weathering process. The weathering of silicates results in the formation of minerals like kaolinite and gibbsite as described by the following equations using Na-feldspar (albite) as an example (Appelo & Postma, 2005):

- $2\text{Na(AlSi}_3\text{)O}_8 + 2\text{H}^+ + 9\text{H}_2\text{O} \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{Na}^+ + 4\text{H}_4\text{SiO}_4$ (albite resulting in kaolinite)
- $\text{Na(AlSi}_3\text{)O}_8 + \text{H}^+ + 7\text{H}_2\text{O} \rightarrow \text{Al(OH)}_3 + \text{Na}^+ + 3\text{H}_4\text{SiO}_4$ (albite resulting in gibbsite)

Generally, for reactions between minerals and water the weathering reaction is as follows (Appelo & Postma, 2005):

- $\text{Mineral (silicate)} + \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{weathering residue} + \text{cations} + \text{HCO}_3^- + \text{H}_4\text{SiO}_4$

Summarising, chemical weathering is the only natural process that controls the surface water chemistry in the Limpopo Province. Typically, these waters will be supplied with Ca, Mg, K, Na, and Si as cations, and HCO_3^- as the only anion. The pH

of the surface waters is normally around 8.5. (Huizenga, 2010) The buffer capacity of the surface waters themselves is very low because HCO_3^- is the only anion and the concentration of CO_3 is very low (Huizenga, 2010). However, if the river drains carbonate rocks, the pH is buffered by the carbonate weathering reaction. In silicate terranes, this buffer is far less effective due to the slow reaction kinetics of the silicate weathering reaction (Huizenga, 2010).

4.3. Impacts of land use on water quality

Environmental and anthropogenic factors affect the quality of water resources such as streams, lakes, rivers and groundwater through spilling, improper disposal of waste, leaking and intentional application of chemicals such as pesticides, which contaminate streams and groundwater (IWR, 1997; Rank, 2010). Anthropogenic activities contribute greatly to the pollution of water resources which can be quantified in terms of the intensity of the type of land use, population density and the type and quantity of livestock in the area (Rank, 2010). As mentioned in Chapter 2 the Limpopo province has abundant agricultural, industrial and mining activities as well as urban and rural built up areas. It is likely that mining, industrial and agricultural activities contribute to pollution in water resources; however rural activities are dominant in the area. The following activities can, therefore, be associated with the above mentioned activities in the province and therefore relate to pollution in water resources (Table 4.3)

Table 4.3: Sources activities and impacts that affect the quality of water sources in the Limpopo Province (modified after Bosman & Kidd, 2009).

Sources and Activity	Impact
Mining	
Discard dumps (coal mining activities Waterberg Complex)	Increased salinity, SO ₄ , Cl
Return water dams (platinum mines)	Cl, SO ₄ and low oxygen
Ash dumps (coal mining)	High pH
Slimes disposal (mining activities in the Bushveld Complex)	Fe, Ni, SO ₄
Stock piling (platinum mines)	
Dewatering (coal and diamond mining)	Increased salinity, Ni,Co, Na, Cl
Underground or opencast mining areas (Bushveld Complex)	SO ₄ , Fe, Al, Co
Urban sector	
Sewage effluent	NO ₃ , PO ₄
Sludge drying beds	NO ₃ and acidity
Landfills and dumps	SO ₄ , Cl, Mg, Na
Storm water	Added fertilizers and chemicals
Leaking sewers	NO ₃ , PO ₄ , Cl
Informal housing (on-site sanitation)	Domestic waste and sewage
Industrial sector	
Industrial effluent	Na; Cl, SO ₄ , Na, Al, K
Storage of chemicals	Leakage and spillage
Solid waste	Cl,
Agriculture	
Irrigation (return flow)	NO ₃ , PO ₄ , K
Fertilizer application	NO ₃ , PO ₄ , K
Pesticide usage	Cl, DDT
Extensive stock farming (kraals)	PO ₄ , NO ₃
Intensive animal feeding units	PO ₄ , NO ₃
Groundwater over-abstraction	Increased salinity

4.4. Summary

Based on the geology in the province and the above mentioned, typical water chemistry in Limpopo should consist of silica and added cations such as, magnesium, potassium and sodium as result of silicate weathering and calcium and magnesium as result of carbonate weathering. Bicarbonate is the only anion obtained from chemical weathering. Naturally this results in increased pH levels of the surface water. The concentrations of these species may increase as a result of the dry, warm climate, on the other hand land use activities add other chemical species, including nitrate, phosphate, chloride, and sulphate. The Limpopo Province will most likely be affected by anthropogenic activities that originate from mainly rural activities and to a lesser extent mining and industrial activities. Chemical weathering and land use activities are thus the most likely factors that control the chemistry of both the surface and groundwater in the Limpopo Province.

Chapter 5

Surface and borehole water chemistry in the Limpopo Province: Results

5.1. Introduction

This chapter presents the results of the interpretation of the inorganic chemistry of the surface and borehole waters. The median pollution index and inorganic contribution towards the pollution index was determined for both datasets and illustrated with representative graphs. The data is interpreted for the whole of the Limpopo Province, because the sampling stations are not distributed evenly over all district municipalities.

5.2. Surface water chemistry results

As mentioned in Chapter 4, the pollution index determines whether water resources are polluted ($\geq 70\%$) or non-polluted ($\leq 30\%$). Figure 5.1 illustrates the distribution of the surface water stations and the median of the pollution index for each of the stations.

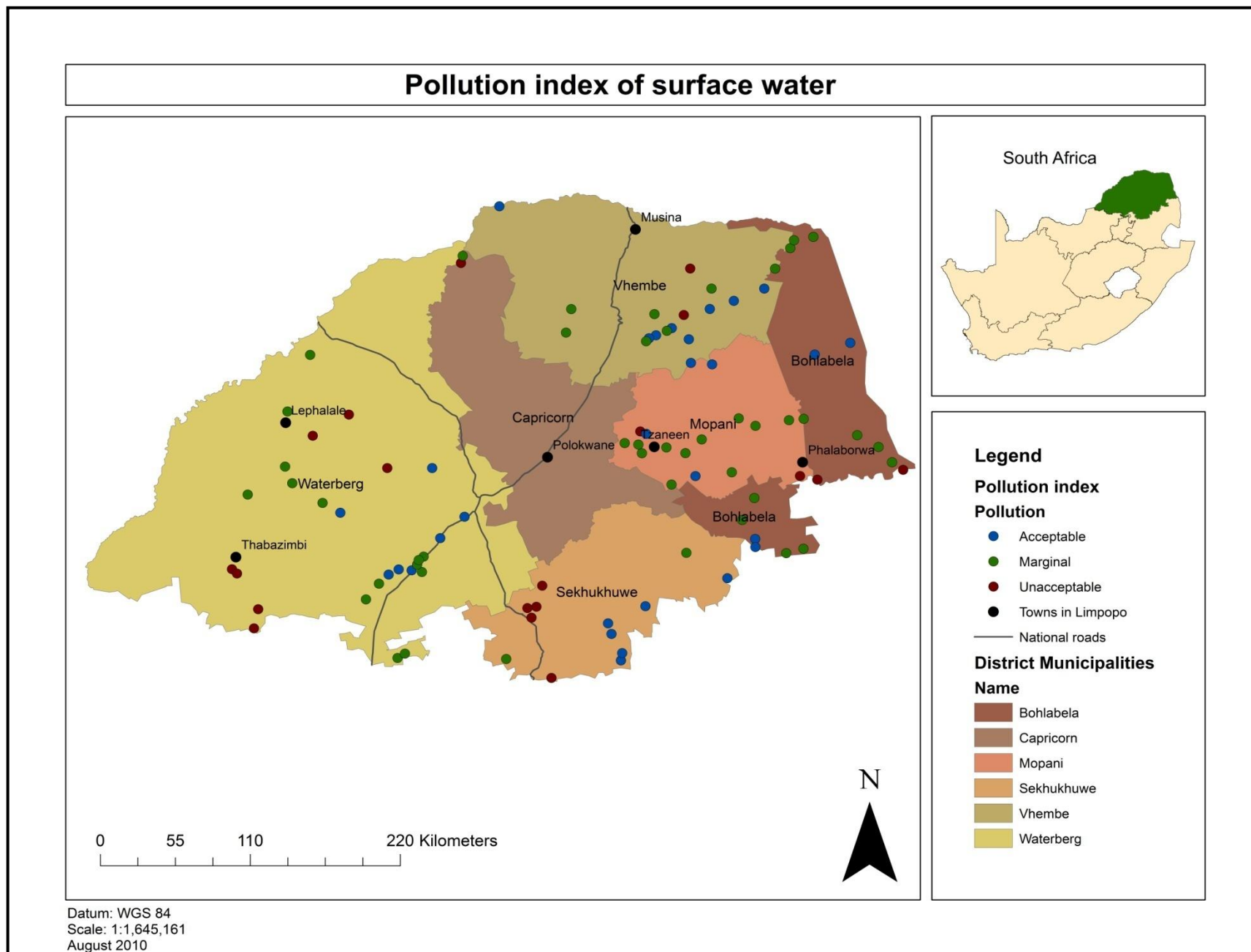


Figure 5.1: Median pollution index at each surface water station.

The pollution index for the surface water shows that 36% of the water samples have a pollution index below 30% and 6% of the water samples have a pollution index greater than 70% (Fig 5.2).

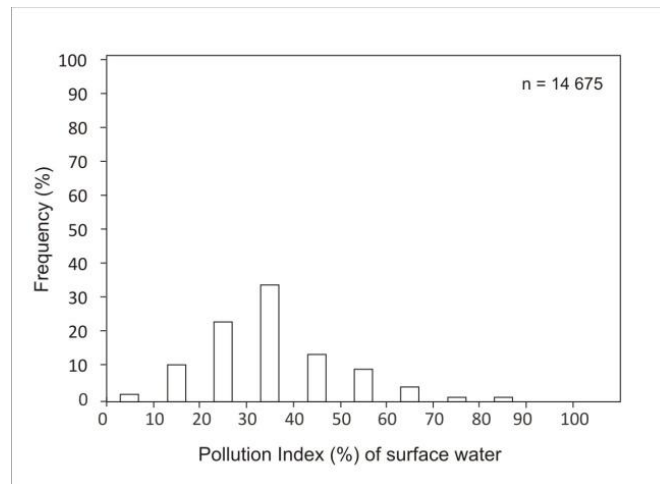


Figure 5.2: The pollution index of the surface water in Limpopo.

A further evaluation of the pollution can be done by determining the relative contribution of chloride, sulphate, phosphate, and nitrate towards the polluted index. This is particularly useful because each of these chemical species is associated with typical anthropogenic sources, i.e. identifying the contribution of each chemical species leads automatically to the identification of pollution sources (refer to table 4.2 and 4.3). The four species are typically associated with the following anthropogenic activities:

- Sulphate is typically associated with acid mine drainage and fertilizers, (Gimeno-Garcia *et al*, 1996; van der Weijden & Pacheco, 2006; Jennings *et al*, 2008; Oelofse, 2008)
- Nitrate is associated with sewage pollution and fertilizer use (Gimeno-Garcia *et al*, 1996; Wakida & Lerner, 2005; van der Weijden & Pacheco, 2006),
- Phosphate is associated with fertilizer use (Gimeno-Garcia *et al*, 1996), and

- Chloride is associated with industrial activities, fertilizers and domestic waste (Gullett *et al*, 2001; Kakareka, 2002; van der Weijden & Pacheco, 2006).

The results of this evaluation are shown in Figure 5.3 illustrating that the two most important chemical species that contribute to the pollution index are chloride and sulphate. Phosphate and nitrate contributions are relatively small.

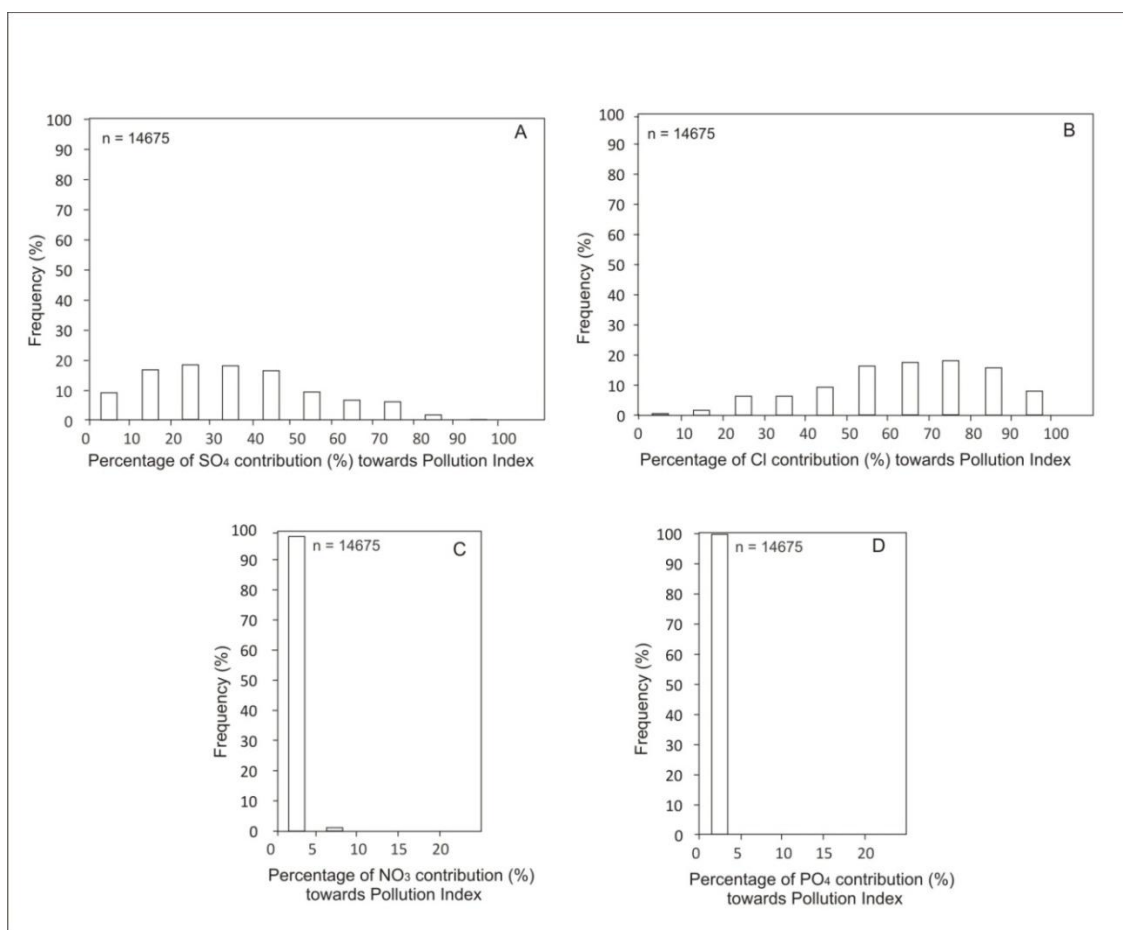


Figure 5.3: The pollution contribution of sulphate (A), chloride (B), nitrate (C) and phosphate (D) towards the pollution index of surface water.

To obtain more accurate results a further evaluation of the pollution can be done by determining the relative contribution towards the pollution index for the polluted samples only. There are 780 polluted samples confirming that sulphate and chloride are the major sources of pollution, however, the main source of pollution is sulphate and to a lesser extent chloride (Fig 5.4). Approximately 75% of the water samples

show a 60-100% sulphate contribution towards the pollution index, whereas approximately 75% of the water samples show a 0-40% chloride contribution towards the pollution index. Nitrate and phosphate still have relatively small contributions towards the pollution index.

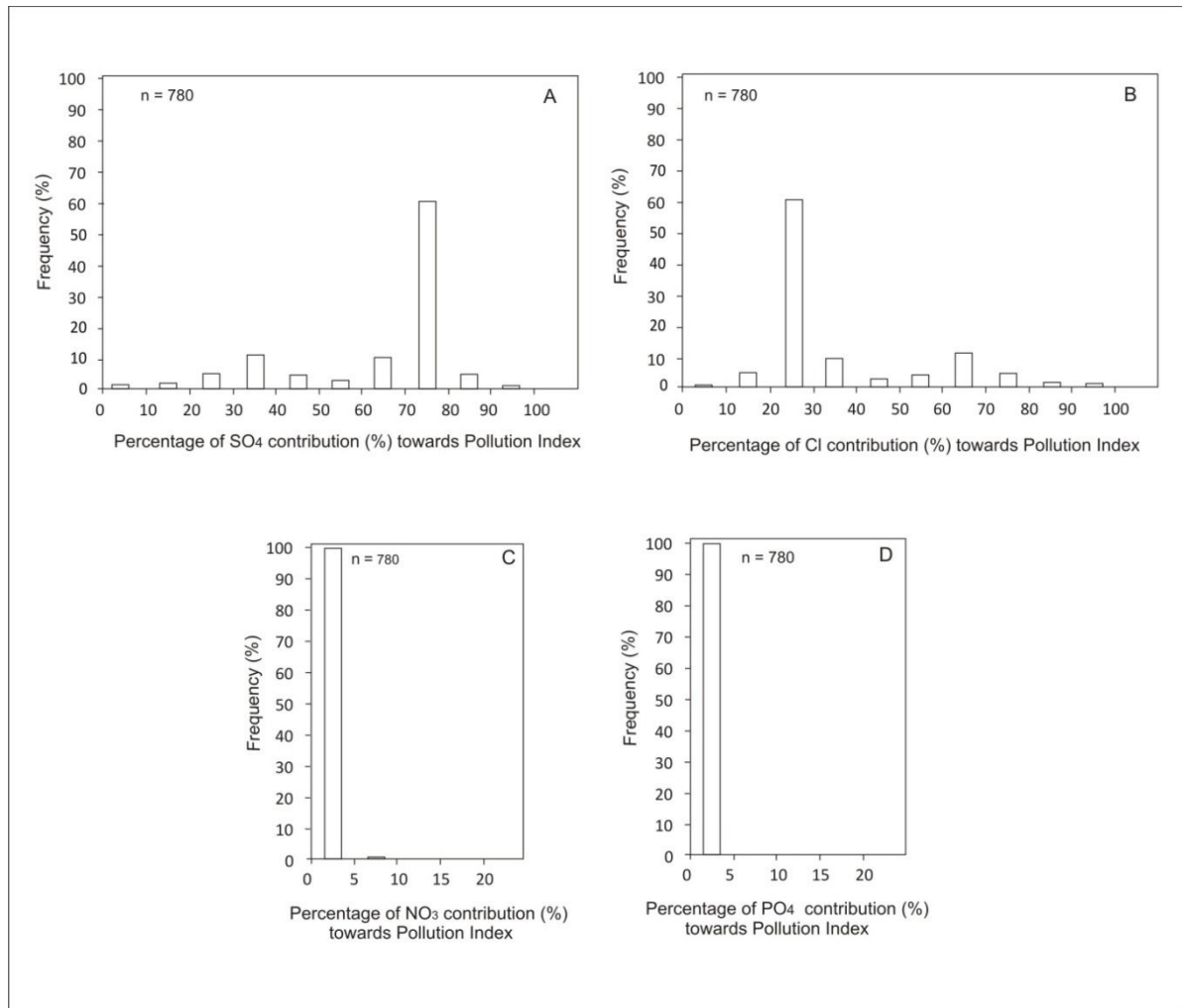


Figure 5.4: The pollution contribution of sulphate (A), chloride (B), nitrate (C) and phosphate (D) towards the pollution index of surface water (polluted samples only).

The pollution index and sulphate and chloride contribution towards the pollution index for polluted water sources were used to determine whether the levels of chloride and sulphate as well as the pollution index differ according to between sampling years in order to determine whether any given year was influenced by specific phenomena's in that period (Fig 5.5). A minimal differentiation was found

between the pollution indexes for the various years whereas the concentration of chloride decreases as the sulphate increases, with an increase of chloride and decrease in sulphate levels from 1999 to 2008.

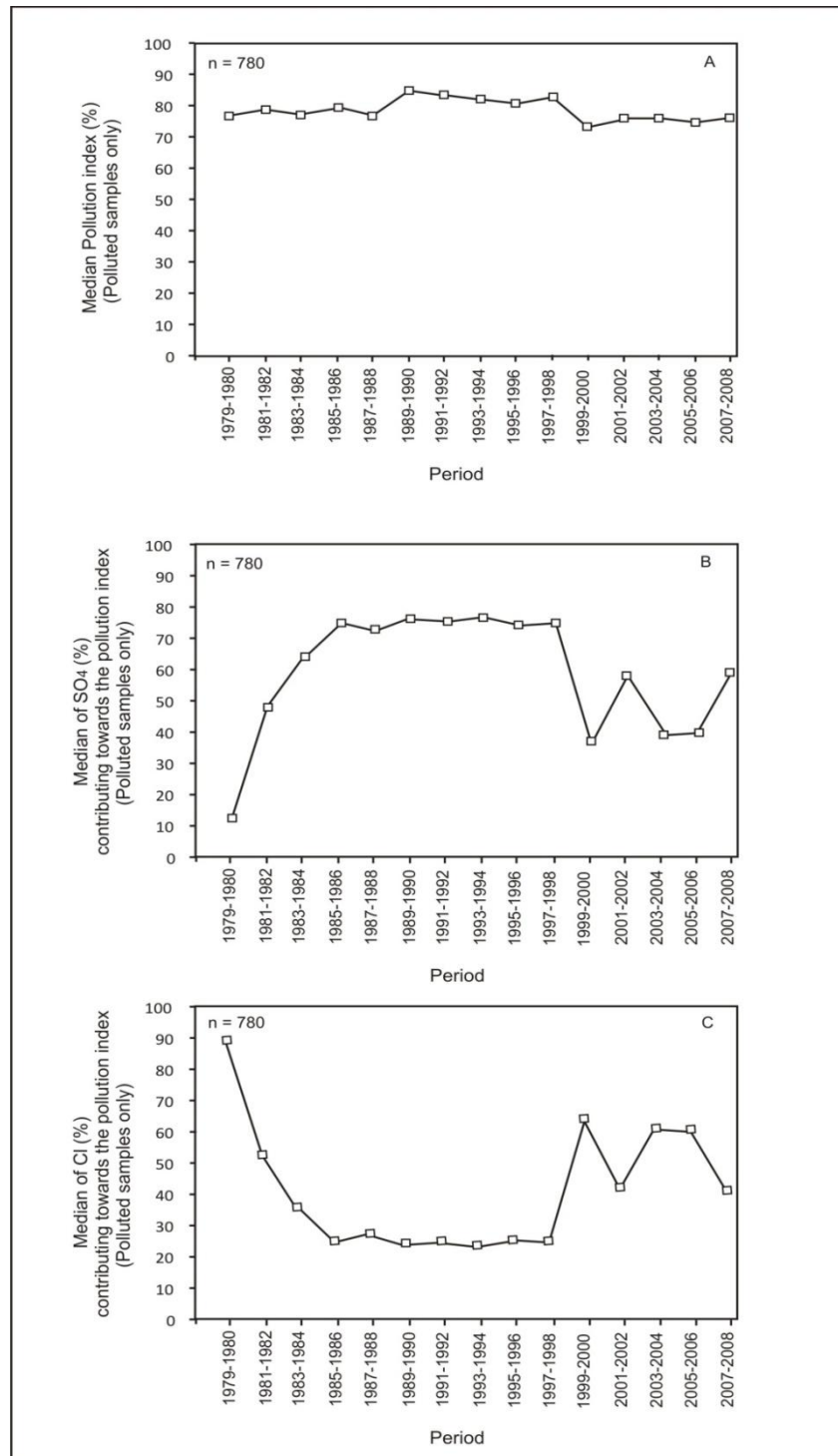


Figure 5.5: The median pollution index (A) and sulphate (B) and chloride (C) contribution towards the pollution index (for polluted samples only).

5.3. Borehole water chemistry results

Figure 5.6 illustrates the distribution of the borehole stations and the median of the pollution index for each of the boreholes for 2003 to 2010.

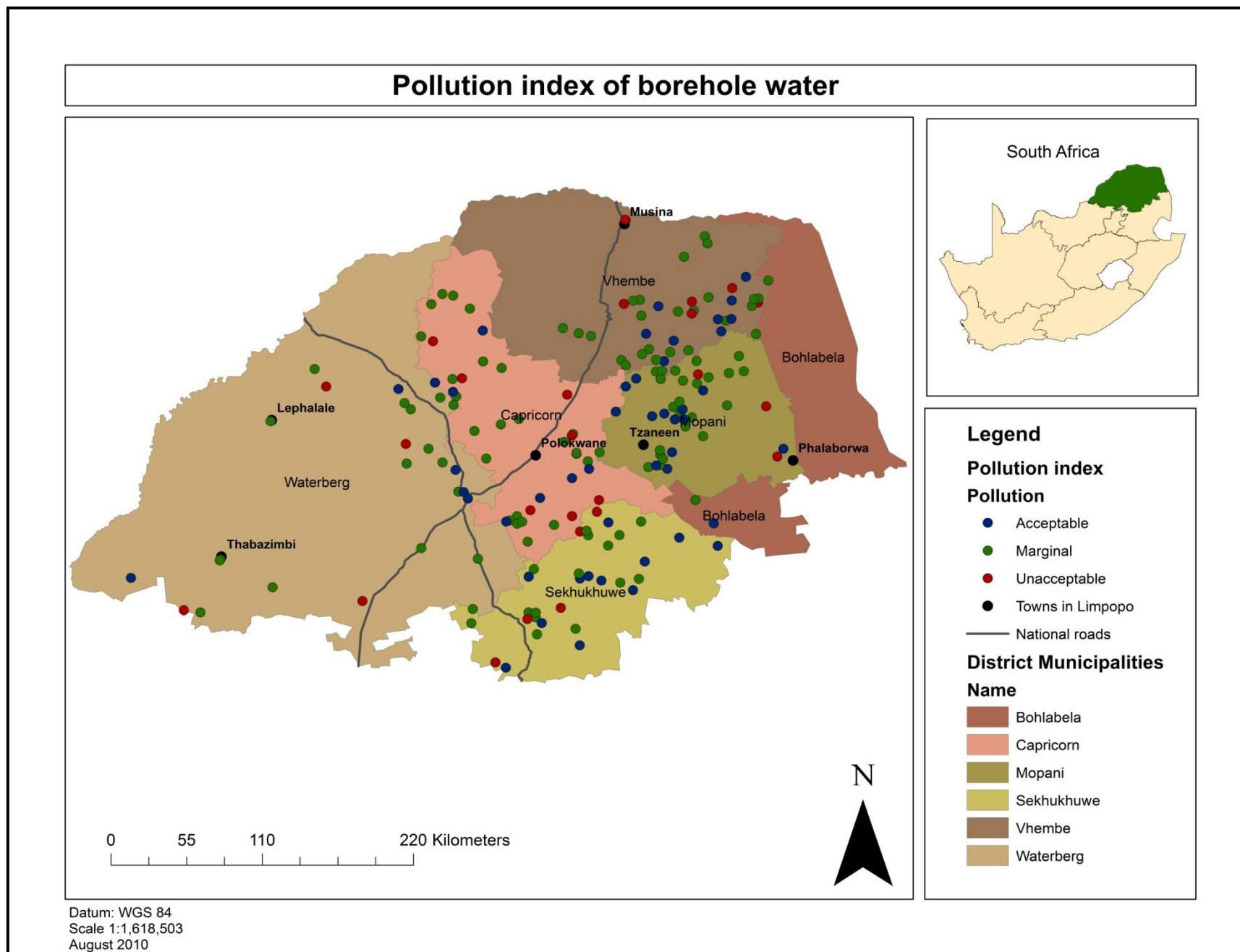


Figure 5.6: Median pollution index at each borehole sampling point.

The pollution index of the groundwater indicates that 26% of the water sample data have a pollution index below 30% and 21% of the total dataset has a pollution index greater than 70% (Fig 5.7).

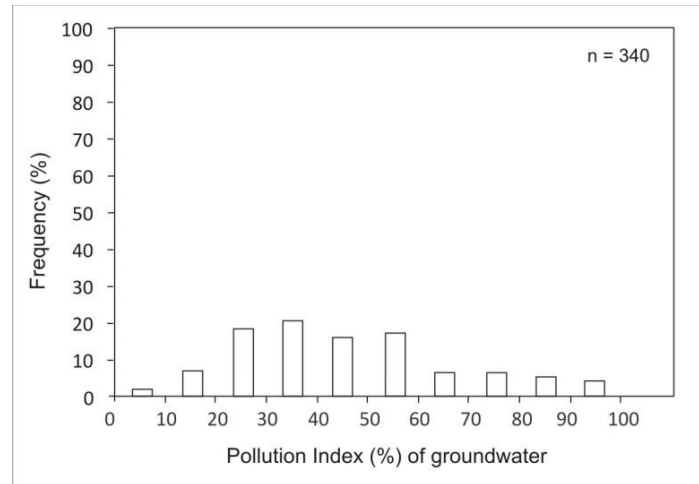


Figure 5.7: The pollution index of the borehole water at health facilities.

As for surface water, the contribution of chloride, sulphate, phosphate and nitrate was determined towards the pollution index for the borehole water. The results of the evaluation are shown in Figure 5.8 and indicate that the prevailing pollution sources are chloride and to a lesser extent sulphate. Phosphate and nitrate have relatively small contributions towards the pollution index.

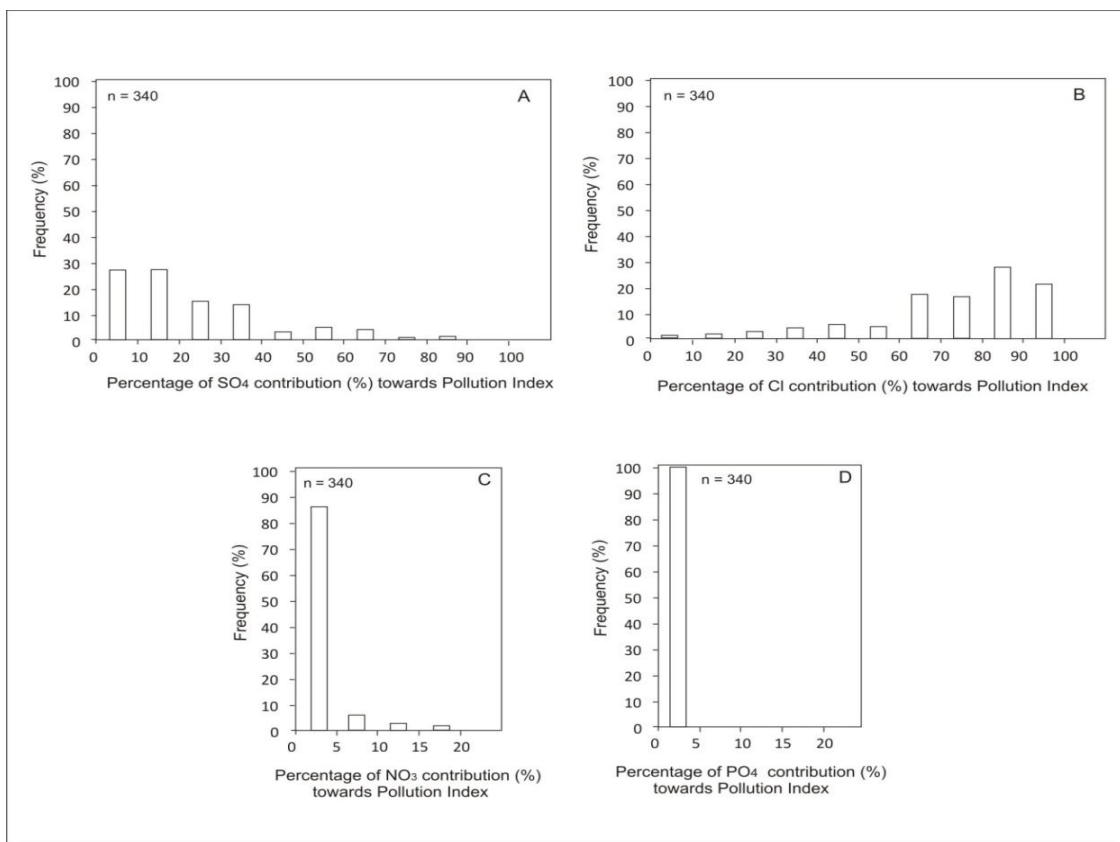


Figure 5.8: The pollution contribution of sulphate, chloride, nitrate and phosphate towards the pollution index of borehole water.

Similarly to the surface water a further evaluation of the polluted borehole water samples were done by determining the relative contribution towards the pollution index. The 45 polluted samples (Fig 5.9) confirm the previous results, indicating that the prevailing pollution sources are chloride and to a lesser extent sulphate. Approximately 70% of the water samples show a 0-40% sulphate contribution towards the pollution index, whereas approximately 73% of the water samples show a 60-100% chloride contribution towards the pollution index. Nitrate and phosphate have relatively small contributions towards the pollution index.

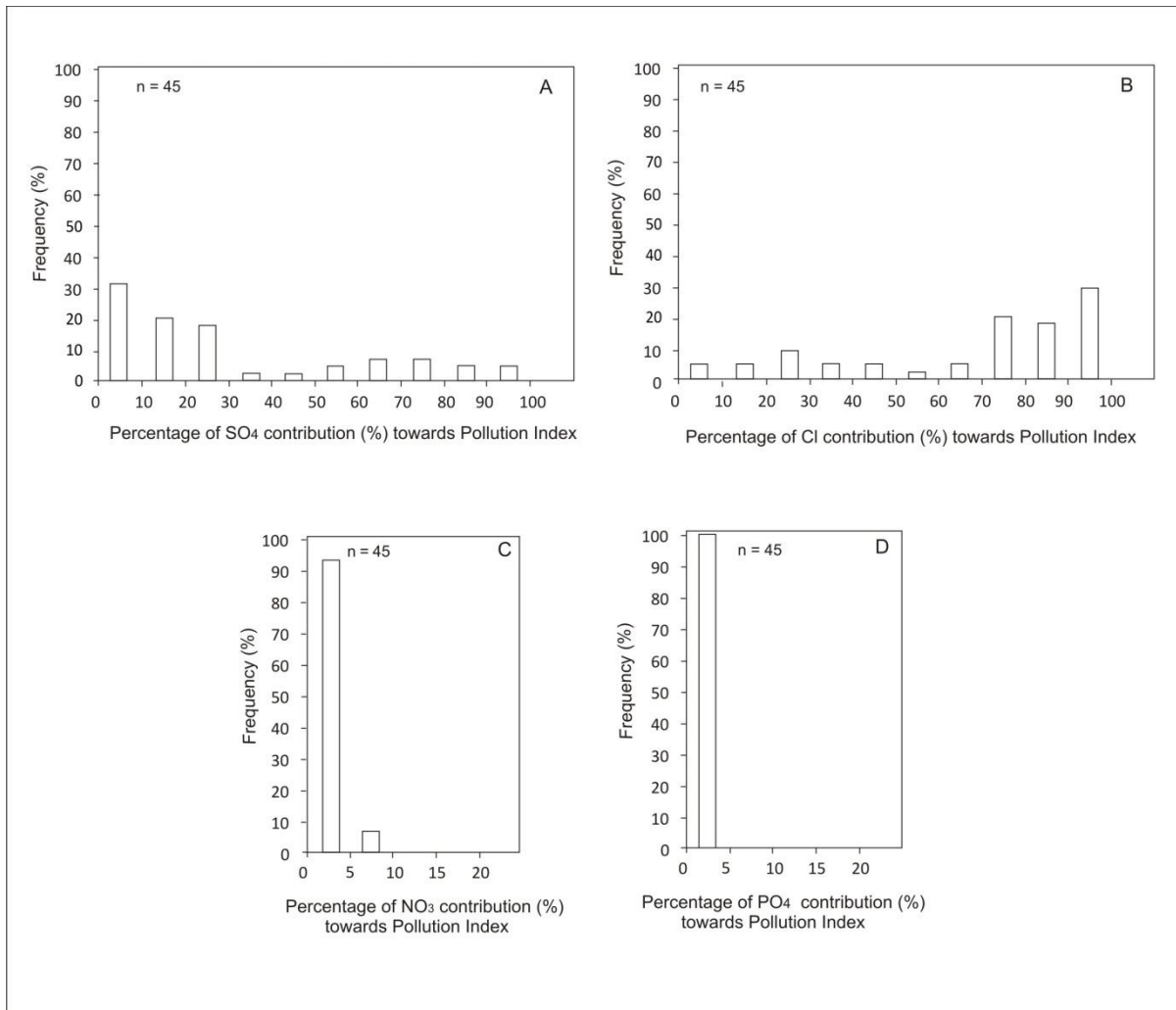


Figure 5.9: The pollution contribution of sulphate, chloride, nitrate and phosphate towards the pollution index of borehole water.

Similarly to the surface water, the median pollution index and sulphate –and chloride contribution towards the pollution index for polluted water sources were used to conclude whether levels of these species differ between sampling years (Fig 5.10). The figure shows that the overall borehole water pollution index is high, mostly due to high levels of chloride.

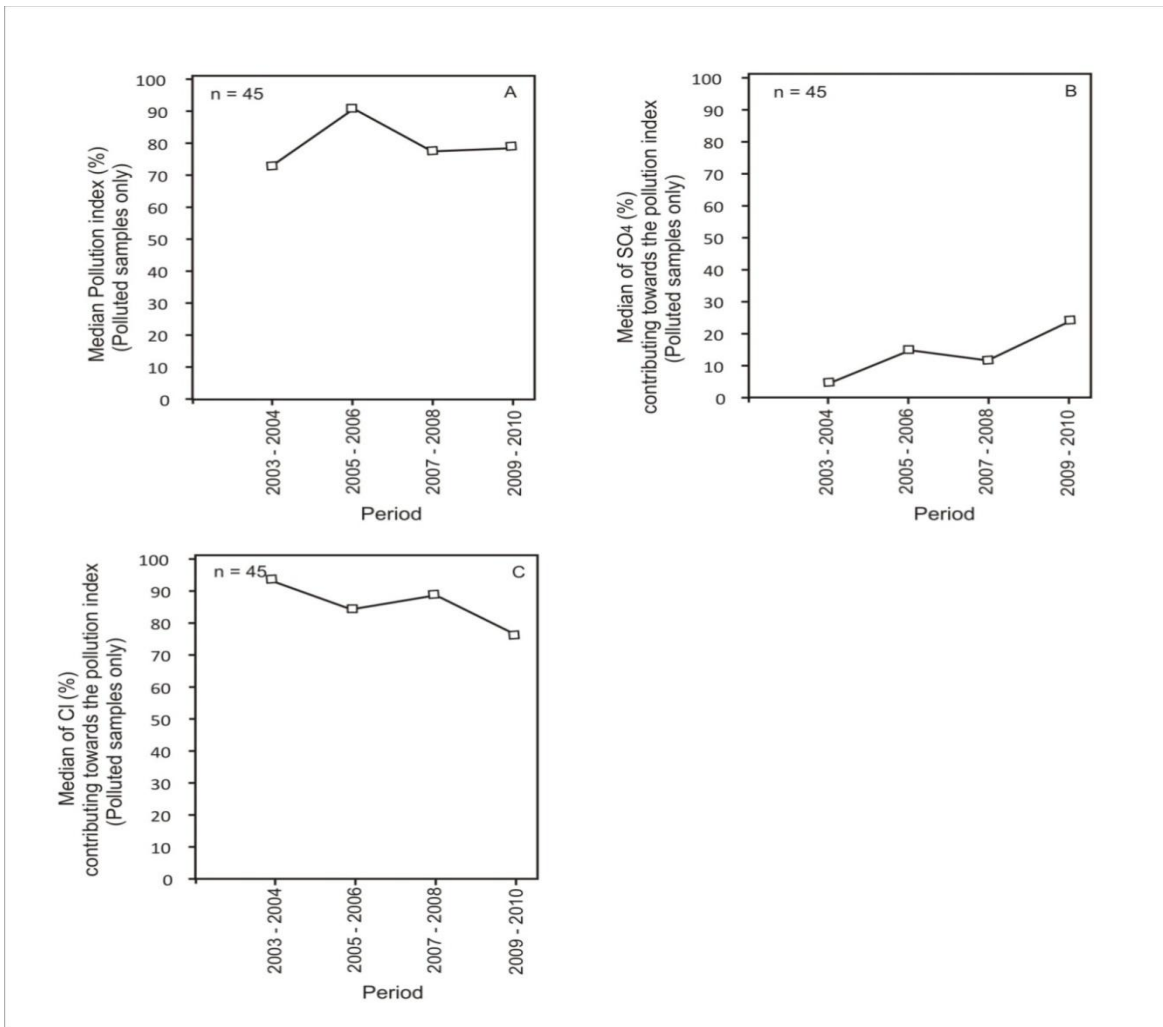


Figure 5.10: The median pollution index (A) and sulphate (B) -and chloride (C) contribution towards the pollution index for each sampling year (polluted samples only).

5.4. Discussion

Only 6% of the surface water in Limpopo is polluted according to the pollution index. The results indicate that chloride and sulphate are the dominant sources of pollution, with sulphate contributing 38% and chloride 86% to the 6% overall pollution. The pollution index for the borehole water shows that 21% of the boreholes in Limpopo are polluted. Sulphate contributes 16% and chloride contributes 91% to the polluted borehole water resources. Both the surface and borehole water results indicate contributions from chloride and sulphate towards the pollution index. However the

polluted surface water indicates a higher sulphate contribution towards the pollution index, whereas the borehole water is dominated by chloride pollution. Table 4.2 and 4.3 illustrates the possible sources of sulphate and chloride pollution.

5.5. Summary

As mentioned in Chapter 2 and 4, the geology of the Limpopo province mostly consists of silicate rocks and to a lesser extent carbonate rock formations. Typically, these rocks comprise the main rock-forming minerals including quartz, feldspar, pyroxenes, amphibole and mica (Appelo & Postma, 2005; Dyar *et al*, 2008). The carbonate rock formations consist of dolomite and calcite (Mayo *et al*, 2000; Appelo & Postma, 2005; Dyar *et al*, 2008). It is obvious that the geology cannot release any chloride or sulphate during chemical weathering.

The surface water is less polluted than the groundwater in Limpopo, indicating a higher concentration of the pollutant sources near the borehole sites. This might be due to the fact that surface water has a residue time of about two weeks and groundwater has a residue time of hundreds to thousands of years. Therefore, groundwater pollution is detected more easily than surface water pollution, especially in cases of solitary pollution incidents (Bosman & Kidd, 2009).

Based on the results presented in this chapter, only sources contributing to chloride and sulphate pollution will be discussed.

Chloride, which is the main source of pollution, originates mostly from industrial activities and domestic waste (Gullett *et al*, 2001; Kakareka, 2002; van der Weijden & Pacheco, 2006). Chloride is found in chlorinated building materials which are classified as persistent organic pollutants (POP's) or persistent bio-accumulative toxic chemicals

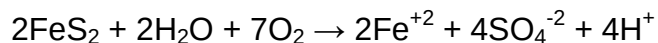
(PBT's). POP's are harmful to the environment and can be placed in three categories namely, pesticides, industrial chemicals and by-products. Chlorinated building materials occur in all three of the categories for example (Kakareka, 2002):

- Pesticides like chlordane, DDT and hexachlorobenzene (Jones & de Voogt, 1999).
- Industrial chemicals such as polychlorinated biphenyls (PCB's) (Rank, 2010) and polyvinyl chlorides (PVC) which are used to manufacture plastic products, building materials, paint, transformers, paper and pipes, wall covering and cable sheathing (Jones & de Voogt, 1999; Kakareka, 2002), and
- By-products of industrial processes like polychlorinated dibenzofurans, which are called dioxin, furan and co-planar of PCB's, are also present in plastic products (Jones & de Voogt, 1999; Kakareka, 2002).

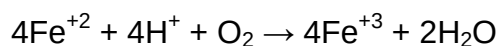
In addition, domestic waste (industrial manufactured products) and the application of fertilizers can also contribute to higher levels of chloride in water resources (Gullett *et al*, 2001; Kakareka, 2002; van der Weijden & Pacheco, 2006).

As mentioned earlier, sulphate is typically associated with acid mine drainage and fertilizers but other factors such as burning fuels also contribute to sulphate pollution in the environment (Table 4.2) (van der Weijden & Pacheco, 2006; Oelofse, 2008; Tayanç, 2000; Reddy & Venkataraman, 2002; Carbonell *et al*, 2007). Acid mine drainage is produced through the oxidation of sulphide minerals. It is a chemical reaction which takes place when water flows over or through sulphur-bearing materials forming solutions of net acidity. Pyrite oxidation creates sulphuric acid along with ferrous and ferric sulphates (Mohan & Chander, 2006; Jennings *et al*, 2008; Bosman & Kidd, 2009;

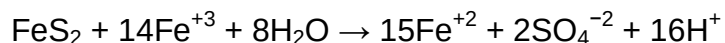
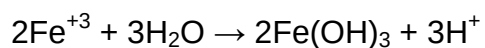
Pérez-López *et al*, 2010). The reactions involved in acid mine drainage is given below (Mayo *et al*, 2000; Ríos *et al*, 2008):



The oxidation of ferrous iron to ferric iron:



Ferric iron reacts in the following ways:



Fossil fuels contain sulphur which is released in the form of sulphur dioxide during combustion and then subsequently precipitates as sulphuric acid. However fossil fuels mostly contribute to air pollution (Tayanç, 2000; Reddy & Venkataraman, 2002; Carbonell *et al*, 2007) and therefore acid mine drainage is more likely to cause sulphate pollution in water resources than fossil fuels.

Chapter 6

Synthesis

6.1. Conclusion

The aim of this study was to determine the likely source(s) of inorganic contamination of the water supplied to rural clinics in the Limpopo Province. It must be noted that the data presents only a snapshot in time, and that ongoing programs coordinated and funded by the Department of Health are in place in order to improve the quality of water supplied to health facilities in Limpopo. As such, the situation has improved significantly since the data was collected and the Department of Health is to be commended on their continuing efforts.

The objectives of this study, as stated in Chapter 1, were as follows:

- To qualify and quantify water pollution at health facilities in the Limpopo Province
- To identify possible sources of pollution by investigating the inorganic chemistry of surface and groundwater sources in detail.
- To compare the results with the known surface and ground water chemistry of the Limpopo province in order to determine whether observed pollution is caused by surface water pollution that recharges the groundwater or pollution on the surface near or above groundwater resources.

The water quality of both the surface and groundwater in the Limpopo Province has been qualified and quantified in Chapter 5. It can be concluded that chloride and sulphate are the main pollutants in water resources in the Limpopo province. It was found that chemical weathering of silicate and carbonate rocks could not have

contributed to increased concentrations of sulphate and chloride in the Limpopo province.

Anthropogenic sources in the Limpopo Province that are therefore likely to contribute to the contamination of surface and ground water include mining activities (i.e., acid mine drainage) causing elevated sulphate levels, as well as domestic- and industrial wastes such as pesticides and plastic products, which results in higher concentrations of chloride.

The fact that chloride is the main pollutant for the groundwater and sulphate is the main pollutant for the surface water indicates that pollution of surface water has little effect on the pollution status of the groundwater. This implies that groundwater pollution must have a local origin.

6.2. Recommendations

As mentioned in Chapter 1, most of the potable water resources of health facilities are located within a hundred meter radius of such facilities. The poor water quality and the fact that the pollution originates from anthropogenic activities show that the water resources are situated too close to these activities. It is however difficult to determine a universal acceptable minimum safe distance between water sources and potentially polluting activities according to the World Health Organization (WHO, 1997). It is therefore recommended that borehole water sources should preferably not be sited near rural villages or rural anthropogenic activities. The travel time of any pollutants, through the soil and rock types in the vicinity, has to be determined in order to establish a minimum safe distance for each borehole (WHO, 1997).

6.3. Outstanding questions and further research

This study focused on whether geology or anthropogenic activities were responsible for the poor water quality in the Limpopo province, and it was clearly demonstrated that the latter was the culprit. The results of the study however raised a further question which is beyond the focus of this study, namely what types of anthropogenic activities can be responsible for the high levels of chloride and to a lesser extent sulphate in the water in the Limpopo province?

It is recommended that (1) further studies be done on the existing dataset, and if necessary the dataset be extended in order to positively identify those anthropogenic activities, (2) on-site investigations are done to identify under what conditions borehole water is obtained, how the borehole facilities are maintained, etc. so that on-site pollution can be minimized, and (3) what remedial action need to be taken to prevent further contamination of potable water resources at health facilities in rural Limpopo.

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Appendices

Appendix 1

Table (I): Identification numbers and coordinates of the surface water sampling stations in Limpopo

A2H025Q01	-24.9333	27.54833
A2H037Q01	-24.6636	27.37583
A2H060Q01	-25.0622	27.52111
A2H097Q01	-24.8672	28.26
A2H116Q01		
A4H002Q01	-24.2822	28.09028
A4H004Q01	-24.1594	27.47972
A4H005Q01	-24.0828	27.77306
A4H007Q01	-23.7631	27.90861
A4H008Q01	-24.2158	27.97361
A4H010Q01	-23.9714	27.72639
A4H013Q01	-23.5992	27.74194
A5H004Q01	-23.9811	28.4
A5H005Q01	-23.6203	28.14722
A5H008Q01	-23.2169	27.89167
A6H002Q01	-24.6825	28.62889
A6H006Q01	-24.6992	28.40917
A6H009Q01	-22.5972	28.88639
A6H010Q01	-24.5781	28.64
A6H011Q01	-24.7611	28.34556
A6H012Q01	-24.6647	28.47556
A6H020Q01	-24.6708	28.56083
A6H021Q01	-24.6328	28.59694
A6H022Q01	-24.6014	28.60778
A6H023Q01	-24.4536	28.75
A6H024Q01	-24.3094	28.90972
A6H034Q01	-22.2144	29.13944
A6H035Q01		
A6H036Q01	-23.9806	28.69611
A7H001Q01	-22.9083	29.61417
A7H003Q01	-23.0667	29.57917
A8H010Q01	-22.6344	30.39894
A8H011Q01	-22.9422	30.16278
A9H001Q01	-23.1117	30.38972
A9H002Q01	-22.9072	30.52833

A9H004Q01	-22.7703	30.53917
A9H005Q01	-23.0847	30.17333
A9H006Q01	-23.0369	30.27694
A9H007Q01	-23.055	30.245
A9H008Q01	-22.6356	30.95861
A9H009Q01	-22.4972	31.05861
A9H010Q01	-22.4436	31.08333
A9H011Q01	-22.4217	31.21111
A9H012Q01	-22.7697	30.88694
A9H017Q01		
A9H020Q01	-23.1258	30.10808
A9H024Q01	-22.9481	30.35639
A9H025Q01	-22.8528	30.68639
B3H001Q01	-24.9167	29.38417
B3H003Q01	-25.2622	28.4675
B3H005Q01	-24.9906	29.35139
B3H007Q01	-25.2694	29.18472
B3H013Q01	-25.2333	28.51667
B3H019Q01		
B3H021Q01	-24.9253	29.32444
B4H003Q01	-25.0289	29.85667
B4H009Q01	-24.9125	30.10333
B4H011Q01	-24.5528	30.37333
B4H016Q01	-25.2792	29.94167
B4H017Q01	-25.2292	29.95
B4H020Q01	-25.1	29.87917
B5H004Q01	-24.7744	29.42222
B6H005Q01	-24.5139	30.82889
B6H007Q01	-24.7242	30.64389
B7H002Q01	-24.0919	30.27528
B7H004Q01	-24.5553	31.03222
B7H007Q01		
B7H008Q01	-24.0092	30.67278
B7H009Q01	-24.3312	30.74164
B7H010Q01	-24.035	30.43333
B7H015Q01	-24.0589	31.23722
B7H018Q01	-23.9931	31.80333
B7H019Q01	-24.0342	31.12361
B7H022Q01	-24.525	31.14583

B8H008Q01	-23.6581	31.05
B8H009Q01	-23.8803	30.36694
B8H014Q01	-23.8806	30.07972
B8H017Q01	-23.6456	30.71861
B8H018Q01	-23.8386	31.64083
B8H022Q01	-23.7333	30.06972
B8H024Q01	-23.8417	30.24167
B8H025Q01	-23.7875	30.475
B8H027Q01	-23.6958	30.82917
B8H028Q01	-23.6486	31.14722
B8H029Q01	-23.7592	31.50083
B8H030Q01	-23.9417	31.73056
B8H033Q01	-23.281	30.54306
B8H043Q01	-23.75	30.10833
B8H045Q01	-23.8222	30.05694
B8H053Q01	-23.8125	29.96667
B8H054Q01	-23.2717	30.40306
B9H002Q01	-23.2153	31.22
B9H003Q01	-23.1361	31.45472

Appendix2

Table (II): Facilities and coordinates of borehole sampling points

Facility Name	Longitude	Latitude
Abbotspoort	28.08689	-23.4505
Ambergate	28.93679	-23.5167
Bakenberg	28.75603	-23.8648
Basani	30.51917	-23.3693
Bavaria	28.83294	-23.5241
Bele Bela New	28.32427	-24.8766
Bellevue	30.42064	-23.4121
Ben Farm	31.03731	-23.9161
Bergplaats (Vhambelani)Maelula	30.14747	-22.9793
Bismark	30.50194	-24.2047

Bochabelo	30.51278	-23.4305
Bokwalakwala	28.95136	-24.1491
Boschkloof	30.09358	-24.8041
Bungeni	30.19752	-23.203
Carlotta	30.31733	-23.998
Charlie Rangane	30.55219	-23.4771
Chuene	29.48597	-24.1914
Dan Village	30.27156	-23.9044
Davhana	30.45625	-23.2097
Dichoeng New	29.88629	-24.7408
Dikgalaopeng	29.45714	-24.9854
Dilokong	30.17049	-24.6142
Dithabaneng	29.57765	-24.3705
Donal fraser	30.47902	-22.8865
Dwaalboom	26.81012	-24.7231
Dzumeri	30.7086	-23.5764
Eerstegeluk New	30.13215	-24.7293
Elandskraal New	29.41113	-24.7148
Elandskraal old	29.41202	-24.7142
Ellisras 1	27.72298	-23.6815
Folofhodwe	30.42727	-22.5882
Fondwe	30.25919	-22.9176
Ga Manamela New	29.22935	-23.7028
Goedertrou	28.91244	-23.4008
Goedgedacht	29.71783	-25.0607
Grace Mugobeni	30.4365	-23.7165
Grootdraai	28.70778	-23.1178

Groothoek (DR Machupe)	29.335	-24.3126
Helderwater (Hlangenani)	30.29619	-23.2819
Hele Franz	29.11313	-23.2838
Homulani	31.06017	-23.8751
Hlaneki	30.50933	-23.2814
Indermark	29.11073	-23.0786
Iteleng	30.11417	-23.3981
Jakhalskuil	28.60781	-23.8332
Kganya (Boyne)	29.79861	-23.9472
Kgapane	30.21861	-23.6478
Kibi	28.84697	-22.8364
Klipfontein (Mokamole)	28.61325	-23.9628
Kranzplaas	28.91639	-23.4862
Kromhoek	29.02653	-22.9327
Kuruleni	30.35966	-23.1456
Kutama	29.63544	-23.0632
Kwarrielaagte	29.2619	-25.3195
Lambani	30.83168	-22.7212
Leboeng (Swaranang)	30.64733	-24.51
Ledwaba	29.42183	-24.2724
Lekhureng	28.92033	-23.5733
Lenyenye Old	30.26783	-23.9742
Lenynenye New	30.26783	-23.9742
Lephephane	30.1945	-23.9868
Letaba	30.26933	-23.8742
Lulekani	31.07726	-23.8646
Lesfontein (Sekhung)	28.78547	-23.1493

Madimbo	30.56282	-22.4518
Madombidzha	29.8194	-23.1148
Madumane	30.39964	-23.6294
Makakhulele	30.91166	-22.8924
Makanye (calais)	29.72392	-23.8982
Makepsvlei	29.04581	-24.9304
Makgato	29.66342	-23.5056
Makhado	30.03442	-22.9008
Makhuva	30.96467	-23.5822
Makotopong New	29.64143	-23.8184
Makuleke	30.91454	-22.8652
Malamulele	30.701	-23.0132
Mamaila	30.24269	-23.3511
Mamone	29.803	-24.711
Mamushi	29.69539	-24.0595
Mankotswana (Mooiplaas)	29.74728	-24.4149
Mankuwe	28.55959	-23.4678
Mankweng	29.72422	-23.892
Manyima	30.01833	-23.2764
Mapayeni	30.81833	-23.3491
Mapela	28.84756	-23.9558
Marishane	29.74683	-24.7274
Mariveni	30.34878	-23.8875
Marseilles New	30.33668	-23.222
Marulaneng	29.41017	-24.9515
Masakona	30.24417	-23.2736
Mashabela	30.00483	-24.4387

Mashamba	30.15349	-23.2355
Mashashane	29.13306	-23.93
Mashite New	29.69467	-24.3117
Matamanyane	29.34658	-23.6664
Mathabatha New	29.87133	-24.2057
Matiyani	30.97781	-22.7461
Matlala Capricorn	29.05611	-23.7464
Matsepe Old	29.49703	-25.0234
Matsheka	30.73908	-22.8787
Matswi	30.35767	-23.5858
Mattanau	28.79839	-23.4249
Mavambe New	30.64894	-23.0037
Mavele	30.42594	-23.6685
Mawani	30.55194	-23.7808
Mmotoaneng	29.62081	-24.9223
Mmutlane	30.14586	-24.3478
Moeding	29.4575	-24.9535
Moganyaka	29.40283	-24.9963
Mogodi (Wurtsdorp)	29.23472	-23.3276
Mogoto New	29.28796	-24.341
Mogoto Old	29.26489	-24.3484
Mohlaba	30.28911	-23.931
Moime (Motjeneng)	30.24553	-23.9757
Mokopane	28.98611	-24.1521
Moletlane New	29.33569	-24.3631
Mookgaphong	28.70833	-24.5248
Morapalala	30.41778	-23.6032

Morutji	30.36711	-23.6703
Motetema New	29.46608	-25.0983
Motsepe	29.85747	-24.2836
Mphambo	30.67062	-23.0841
Mphephu	30.13825	-22.8748
Msengi	30.37014	-23.3456
Mtititi	30.898	-23.1017
Mukula	30.58778	-22.8583
Mulima	30.04608	-23.3091
Musina	30.04502	-22.3436
Mussina	30.04285	-22.3417
Nchabaleng	29.80071	-24.4401
Ndlovu Private Medical HC	29.19363	-25.284
Ngobe (Nguve)	30.7215	-23.3615
Nkoana New	29.78969	-24.4098
Northam	27.26433	-24.9526
Ntlhaveni C	30.87044	-22.9146
Ntlhaveni D	30.88506	-22.8693
Nyavana (Shihoko)	30.47828	-23.6559
Olifantshoek	30.28338	-23.3478
Phaahla New	29.73968	-24.6932
Pheeha	30.0464	-23.4506
Phiphidi	30.38817	-22.9525
Rabali	30.09326	-22.8802
Rakgoatha	29.3685	-24.3495
Regorogile 2	27.39531	-24.5988
Roedtan	29.07898	-24.5963

Rooiberg	27.73632	-24.7851
Rotterdam	30.27447	-23.4007
Schoonoord	30.01017	-24.7548
Sebayeng New	29.70164	-23.7663
Sebayeng Old	29.69433	-23.7768
Segole	28.64022	-23.6024
Sehlale	29.80628	-23.9984
Sekgopo	29.98153	-23.6177
Selepe	29.93258	-24.3544
Senobela	30.39731	-23.5512
Seroka	29.931	-24.508
Shihoko	30.47833	-23.6556
Shimange	30.58787	-23.39
Shingwedzi	30.73722	-23.0014
Shotong	30.29853	-23.631
Sibasa	30.49146	-22.9465
Spitskop	29.87444	-23.8883
Swartklip	27.15589	-24.9378
Taaiboschgroet	28.91726	-22.8461
Taung	30.39633	-24.4552
Thabazimbi LA	27.39007	-24.6064
The Willows	30.62144	-24.36
Thohoyandou	30.47799	-22.966
Thomo	30.78614	-23.248
Toverfontein	28.77442	-22.9031
Tshaulu	30.743	-22.7958
Tshilwavhusiku	29.73847	-23.0967

Tshiungani	30.58042	-22.4986
Uitkyk	28.9751	-23.396
Vaalkop	28.93253	-24.0051
Valdezia	30.17971	-23.1001
Van Der Merweskraal	29.44483	-24.6644
Voortrekker	29.01405	-24.1962
Weltevreden	28.59906	-23.5608
Witfontein (Mamaneng)	29.03596	-25.0243
Witpoort	28.01118	-23.3345
Zaaiplaats	29.74566	-25.1711
Zebediela	29.40445	-24.4819