THE PRIMARY SALINITY, SODICITY, AND ALKALINITY STATUS OF SOUTH AFRICAN SOILS

by

JOHANNES PETRUS NELL

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University of the Free State

Bloemfontein

Promoter: Prof CW Van Huyssteen
Co-Promoter: Dr PAL le Roux

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CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

Unequalled by any other region in the world, South Africa hosts some of the oldest known salt deposits in its geological material. The weathering of rocks is the primary source of soluble salts entering natural waters, sediments, and soils. Geological material is in most circumstances an important soil formation factor, but for salt-affected soils its effect is probably overshadowed in many areas by rainfall and position in the landscape. Rainfall in particular and fog seem to be a controlling factor often overriding lithological control in the development of salt-affected soils. Certain minerals and rocks are also more vulnerable to chemical reaction than others. Rhyolite with a low weathering potential is for example a non-extreme or non-active parent material and dolerite with a high weathering potential an active parent material. South African soils do not have a severe primary salinity and sodicity problems, the reason is probably that salts less soluble than gypsum such as calcium carbonate, which is commonly found in South African soils, are considered insoluble and hence are not considered to cause salinity and sodicity. Extremely high salinity, sodicity and alkalinity values occur along pans and riverbanks in arid areas in South Africa. The geological units resulting in most salt-affected soils are in declining order: Whitehill Formation ≈ Knersvlakte Subgroup >Gladkop Suite >Sundays River Formation >Enon Formation >Garies Subgroup >Kirkwood Formation >Port Nolloth Group >Nyoka Formation >Prince Albert Formation. The groundwater units resulting in most salt-affected soils are in declining order: Tanqua Karoo >Richtersveld >Knersvlakte >Ruensveld >Hantam >Namaqualand >Algoa Basin >Bushmanland Pan Belt >Bredasdorp Coastal Belt >Intermontane Tulbagh-Ashton Valley.

There is a strong relationship between rainfall, salt occurrence and salt movement. As rainfall increases the salinity, sodicity and alkalinity decreases because of the depletion of basic cations and anions. Salts predominantly move with water. The natural force is usually rainfall, mist, and fog. Regular and high rainfall in the eastern part of South Africa causes a continuous leaching and the transport of leached constituents out of the soil system into the ground water system. On the other hand, erratic and low rainfall combined with high evaporation in the west of South Africa result in the accumulation of salts in the soil profile. It should not be assumed that all salt-affected soils will always show definite and predictable associations with present day climate. The relationship between climate and salt-affected soils are made more difficult to determine, because practically all areas have suffered climates in the past different from those prevailing at present.

The three most important topographic conditions that have an influence on salt-affected soils in South Africa are probably pans (wetlands in arid areas), marine terraces, and Karst landforms. Topography can greatly affect the movement of water and salts through soil. This is, to a certain extent a result of gravity, which directly influences water and salt movement and partly as a result of topography's influence on soil development.

Nearly 60% of South African soils are non-saline, 23% slightly saline, 5.1% saline, 1.4% moderately saline, 0.4% strongly saline, 3.8% saline-sodic (non-alkaline), 6.3% saline-sodic (alkaline), and only 0.4% can be considered as sodic.

Transient salinity, or salinity not influenced by groundwater processes and rising water table, is the predominant salinity type in South Africa, and not dryland salinity. Saline and/or sodic soils in South Africa mostly occur only in relatively small areas due to localised factors, making the mapping on a national scale problematic.

Quartile values and not average values are best to use for salt-affected soils to present the data, because the majority of the data is strongly positively skewed, with large differences between median and average values. The use of the outlier definition in its statistical meaning for salt-affected soils is problematic. It is, therefore, better to use outlier in the sense that it means to be an observation that deviates markedly, but for obvious and/or explicable reasons, from the other members of the population and as such is representative of typical variability in a natural situation.

Keywords: Soil, salinity, sodicity, alkalinity, geology, topography, climate, salt-affected soil

CHAPTER 1: INTRODUCTION

1.1. MOTIVATION

No reliable primarily salinity, sodicity and alkalinity information is obtainable for South Africa, nor are there monitoring programs to track the salt-affected status of soils. Reliable baseline primary salinity, sodicity and alkalinity information are needed for various agricultural and environmental studies on a provincial and national scale, examples are the FAO's, Terrastat, Aquastat and Land Degradation Asessment in Dryland Areas (Lada) programmes, International Commission of Irrigation and Drainage (ICID) and South Africa's State of Environment reporting.

The problem of salt-affected soils (SAS) has gained ever-increasing importance in science, technology, ecology and economics alike during the last decades (Szabolcs, 1989). This is expected, given that more and more territories were found to be salt-affected in various regions and by the pressing demands for the production of foodstuffs and raw materials in many countries on the one hand and the conservation and production of the natural environment on the other. Salt-affected soils are closely associated with these, often conflicting requirements and has become a global problem. Salt-affected soils occur in all continents. Their distribution, however, is relatively more extensive in arid and semi-arid regions compared to the humid regions.

Natural geological, hydrological, geomorphological, and pedological processes have developed most salt-affected soils and some of them have existed for millennia. However, humans, interfering with natural processes, created salt-affected soils, resulting in a serious degradation and deterioration of land. It is well known that in ancient times large irrigated territories were turned into wastelands (in Mesopotamia, the valleys of the Yangtze and the Hwang Ho in China, the Nile Valley in Egypt etc.) due to improper methods of irrigation (Szabolcs, 1989).

Apart from irrigated areas, salt-affected soils pose a major management problem in areas where cropping is done under rain fed conditions. Dryland salinity is an acute management problem in Western Australia, the Great Plains region of North America and the prairie provinces of Canada. According to FAO (2001), dryland salinity is also said to occur in Iran, Afghanistan, Thailand, and India and it probably exists in other countries.

Generally, saline soils have received more attention than alkaline and sodic soils, because of the much larger areas of agricultural soils, which have been salinized throughout the world (Sumner, 1993). Salt-affected soils problems may exist over a spatial dimension as small as millimetres or as large as kilometres and may occur over a temporal scale that ranges from minutes to years.

1.2. HYPOTHESIS

The problems of soil salinity, soil sodicity and soil alkalinity are most widespread in the arid and semi-arid regions of South Africa, but salt-affected soils also occur extensively in sub-humid and humid climates, particularly in the coastal regions where atmospheric deposits of oceanic salts, the ingress of seawater through estuaries and rivers and through groundwater .

In South Africa where the rainfall is approximately five to ten times less than the potential evaporation, salts derived from rock weathering, bio-cycling, and atmospheric deposition may accumulate in the soil. Under higher rainfall conditions or poor or impeded soil drainage conditions, lateral leaching of dissolved solids in the groundwater along slopes may also result in bottomlands and pans being enriched in salts. Precipitation of salts is also visible under these conditions where a nick point in topography occurs. Some soils in South Africa are more prone to salt build-up than others. According to Nell and Bennie (1991), there is an increase in salt content with an increase in degree of structural development within the cutanic horizons.

Salts are a common and necessary component of soil and many salts are essential plant nutrients. The sustainable utilization and management of salt-affected soils, where, and when possible, firsts need a holistic approach, and a consideration of all major imminent aspects and properties. It is also important to consider the side effects of amelioration and the management of salt-affected soils on surrounding areas, water, air, and biosphere. The knowledge of primary salinity, sodicity, and alkalinity conditions is of primarily importance in the utilization and management of salt-affected soils.

Salinization and sodification are major factors in the deterioration of land and leads to a specific kind of degradation. Its environmental effect is much wider than that of a simple chemical processes, e.g., in case of soil contamination by chemicals. With increasing salt build-up in a soil, quality and quantity of salts determine practically all principal soil attributes: physical, chemical, biological, and even mineralogical.

For any long-term solution for the amelioration of salt-affected soils, it is necessary to first understand the mode of origin of salt-affected soils and to classify them, keeping in mind the physico-chemical characteristics, processes leading to their formation and the likely approaches for their reclamation and successful management.

1.3. OBJECTIVES

The purpose of this project was to determine the baseline salinity, sodicity, and alkalinity conditions for South African soils. The research objectives for the project were defined as follows:

- To describe and quantify the primary salinity, primary sodicity and primary alkalinity status of South African soils on a national scale in terms of the major geological formations, groundwater regions, rainfall, evaporation, aridity zones, elevation, slope, and the principal cyclic land surfaces
- To prepare a saline, saline-sodic and sodic soil map at a scale of 1:1 000 000 for South Africa.
- To develop an algorithm to quantify salt-affected soils from soil and climatic parameters.

1.4. METHODOLOGY

The analytical and morphological data used in the study were derived from soil survey reports for irrigation, environmental planning and the national land type survey undertaken by the ARC-Institute for Soil Climate and Water (ARC-ISCW). The minimum requirements set for inclusion in the data set was: (a) the profiles should have comprehensive chemical and physical analyses. Preference was given to data sets where soil analyses were done according to the methods of the Non-Affiliated Soil Analyses Working Group (1990) and where the analyses were done in the ARC-ISCW laboratory (b) accurate profile location information should be available (c) only primarily data could be used – no human-induced salinization or sodification (d) soil profile description should have been done according to Soil Classification: A Binomial System for South Africa (MacVicar *et al.,* 1977) or Soil Classification: A Taxonomic System for South Africa (Soil Classification Working Group, 1991).

Although data verification was done on most samples previously, much effort was devoted to data cleaning. Of the original more than 40 000 data points, only 22 404 data points were used due to the stringent cleaning protocol.

This study distinguished itself from other similar studies in South Africa in that a variety of soil types, locations and conditions were studied instead of concentrating on a particular soil group, condition and location alone (See section 2.2).

The distribution of the profile points is uneven, reflecting different and isolated objectives of data-collection programmes in the past (Figure 1.1). Sampling frequency of the various soil forms was not necessarily related to the occurrence or total area of each soil form. The data records also do not reflect a snapshot of a single representative period. The temporal changes in soil salinity, sodicity, and alkalinity could thus not be screened out, although it is probably not dramatic in non-irrigated areas in a relatively arid country such as South Africa. It is known that salts fluctuate from the topsoil to the subsoil during wet periods and from the subsoil to the topsoil during dry periods (Nell & Lea, 2004). The large dataset, however, lessen the effect of temporal variations.

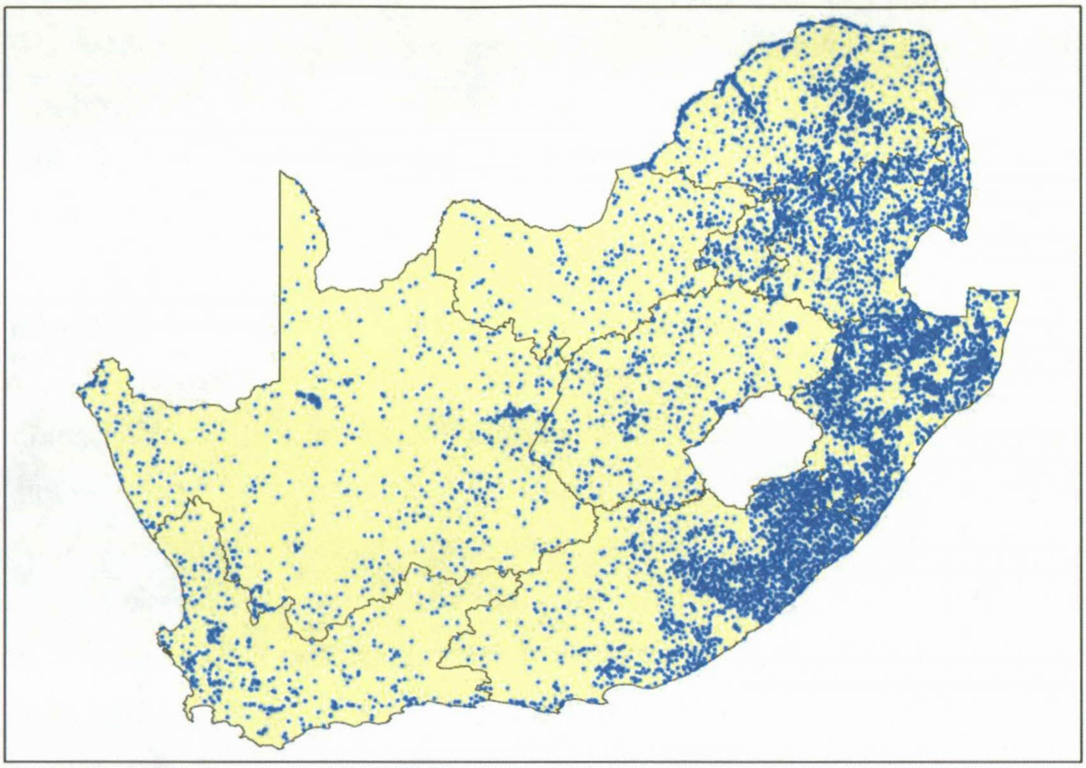

FIGURE 1.1 Distribution of soil sampling points.

The 73 soil forms were organised into 11 groups based on predominantly, a distinctive subsoil horizon or material. There is no single, best method to construct a key for the identification of salt-affected soils. The precedence given to one criterion over another depends on the perspective of the classifier (Fey, 2005). The classes were predominantly focused on the expression of a secondary accumulation of carbonates, structure development, and wetness.

The major geological formations (Vegter, 2001), terrain types (Kruger, 1983), rainfall, evaporation, aridity zones, elevation and slope (ARC-ISCW, 2004), as well as principal cyclic land surfaces (Partridge & Maud, 1987) were used to quantify primarily salinity, primarily sodicity, and primarily alkalinity for South Africa on a national scale.

Elementary statistical techniques (Statigraphics, 2005) were used to identify relationships between the soil, water, climate, topographic, geological, vegetation, and salt parameters.

1.5. THESIS STRUCTURE

The objectives, hypothesis and methodology are presented in Chapter 1, together with the outline of the report and definitions. Definitions were included in the first chapter, because no universally accepted definitions exist for the various salt parameters. Previous primary salt-affected soils work done in South Africa, is presented in Chapter 2, while Chapter 3 lists selected classes of salt-affected soils according to their chemical and morphological properties. Chapter 4 provides salinity, sodicity and alkalinity information for the different soil classification classes in South Africa. Parameters that have an influence on salt development in South African soils, such as geological formations, the different rainfall, evaporation, aridity zones, and principal cyclic land surfaces are discussed in Chapters 5 to 7. An algorithm to quantify salt-affected soils from soil texture and climatic parameters is provided in Chapter 8. In Chapter 9 the description and methodology of the salt-affected soil map for South Africa is presented. Chapter 10 consists of conclusions and Chapter 11 recommendations.

1.6. DEFINITIONS

There are many local names and terms for the different kinds of salt-affected soils (SAS) in the world which complex correlations, if any, between them. A few definitions that are relevant to discussions in this thesis are given in APPENDIX A.

The term "salinity" has become so ambiguous that its usefulness on a scientific scale has become seriously endangered. There is no universally accepted definition for saline soils, because the definition depends on the discipline and the type of measurement. For example, a soil scientist and geohydroligists distinguish primary and secondary salinity; plant scientists use the distribution of salt-tolerant plant species and/or the approximate range of electrical conductivity (EC) levels to distinguish slightly, moderately or severely affected soils and/or plants; and scientists in other disciplines may use measurements of pH (>9), presence of sodium carbonate and high EC to distinguish alkaline saline soils; while others use pH (<3.5), presence of sulphur and high EC to distinguish acid sulphate soils (Fitzpatrick, 2002).

Hall and Du Plessis (1984) used the word mineralization, a term they prefer to salinization and sometimes mineral content for salinity. They defined mineralization as the progressive accumulation of dissolved solids by surface water and groundwater in passing through the land phase of the hydrologic cycle.

The traditional division between saline and non-saline soils in Soil Science has been standardised on at a saturated electrical conductivity (EC) of 400 mS m^{-1}. According to Bresler *et al.* (1982), the terminology committee of the Soil Science Society of America has recommended that this limit be decreased to 200 mS m^{-1}, because of the large number of crops and ornamentals, which can be injured by salinity even in the saturated paste EC range of 200 to 400 mS m^{-1}. This recommendation was not accepted and they are still using the 400 mS m^{-1} value (SSSA, 2007).

The historical criterion to distinguish between sodic and non-sodic conditions has been an exchangeable sodium percentage (ESP) equal to 15% or more of the soil cation exchange capacity (CEC). Because of numerous potential errors in traditional CEC and ESP determinations, however, there are many situations where measured ESP values may be seriously in error. As a result, and to lessen the time and expense of diagnosis, some people use the sodium adsorption ratio (SAR) of the saturation extract for sodic soil characterization. Although ESP and SAR are not exactly equal numerically, an SAR value of 15 has been maintained for convenience as the dividing line between sodic and non-sodic (Bresler *et al.,* 1982). However, this assumption is seriously in error for South African conditions, because Nell (1991) found a 2:1 relationship between ESP and SAR for most South African conditions. Nell & Loock (2009) had indicated that the positive correlation coefficient between ESP and SAR for salinity classes between 10 and 800 mS m^{-1} changed to a negative correlation coefficient if salinity classes of 800, 1600 to 3200 mS m^{-1} were used. Therefore, the problem of defining what characteristics a sodic soil should possess has not yet been resolved satisfactorily to give a universally accepted definition. In some literature (Agassi *et al.,* 1985), the term sodic has even been applied to soils with low, but no fixed ESP or SAR. In view of the continuous effect of sodium, from low to high levels, on soil behaviour, the establishment of a critical level of ESP or SAR is very arbitrary and has caused considerable confusion. According to Sumner (1993), it would appear that the terms "sodic" and "sodicity" should become obsolete as their definition has become imprecise. Rather, soils should be described in terms of their behaviour.

The definition of alkalinity was previously also problematic, because it was considered synonymous with sodicity. Alkalinity is mostly expressed as a soil pH value greater than seven. For a soil to have a pH above seven, it must be calcareous, dolomitic, or sodic. The basic chemical definition of alkalinity is the sum of the bases that are titrable with strong acid. Descriptive terms commonly associated with certain ranges in soil pH measured in distilled water are: 7.4 to 7.8 mildly alkaline; 7.9 to 8.4 moderately alkaline; 8.5 to 9.0 strongly alkaline and more than 9.0 very strongly alkaline (Van der Walt & Van Rooyen, 1995).

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CHAPTER 2: LITERATURE STUDY OF PRIMARY SALINITY, SODICITY, AND ALKALINITY RESEARCH IN SOUTH AFRICA

2.1. INTRODUCTION

At the very first South African Irrigation Congress held in 1909, much concern was expressed at the extent of salt-affected soils and the sediment content of water supplies (Kanthach, 1909). At the National Irrigation Symposium 82 years later, Scotney and Van der Merwe (1991) had the same concerns and said that the long-term viability of soil and water resources are in jeopardy. Major threats to these resources result from among others, salinity and sodicity.

2.2. SOIL

Saline soils in South Africa do not occur in extensive areas forming a climatogenic soil zone, but are found in small to fairly big patches in several soil groups, due to localised factors (Van der Merwe (1962). These saline soils occur mainly, although not entirely, under arid conditions. Van der Merwe (1940) said that the saline patches cannot be mapped separately on a small-scale soil map, because they are so small. He also said that along the main watercourses of rivers of the Karoo the older alluvium, being rather clayey, is impregnated with an appreciable amount of soluble salts which form either a crust in the substratum or is evenly distributed throughout the soil mass with a maximum concentration of saline material in different horizons, depending on the time of the year and moisture conditions in the soil. When the salt impregnated clayey alluvial and colluvial soils are periodically inundated by floodwaters the soluble salts are leached from the surface horizons, producing an alkaline soil with solonetz morphology and a high soil reaction in the subsoil and upper layers of the lower strata. The above description of Van der Merwe (1940) is tipical of transient and riverbank salinity. According to Fey and De Clercq (2004) dryland salinity is widespread throughout semi-arid regions of the world and its occurrence in many river catchments of the Western Cape should therefore be considered quite normal, but according to their own data on "saline areas", only five out of thirty-two samples or 15.6% of the samples can be considered as saline. It is doubtful if large areas of dryland salinity exist in South Africa, because some researchers confuse dryland salinity with transient salinity and riverbank salinity. Even in Australia, only 16% of the area is likely to be affected by watertable-induced salinity or dryland salinity, while 67% of the area has a potential for transient salinity (Rengasamy, 2004).

Shallow calcareous lithosols (10 575 110 ha) and red apedal soils with a high base saturation (10 195 500 ha) occupy the largest area of the Karoo (Ellis, 1988). He also noted that the total soluble salt content increased from the A horizon to the underlying horizons and that the most important underlying materials in the Karoo are lime in the form of hardpan calcrete, calcic horizons, or rock with lime and dorbank. Netterberg (1969) described the effect of the five soil forming factors on the regional and local distribution of calcification in South Africa. According to him, the 550 mm isohyet (Figure 2.1.) is a good indication of the upper limit of hardpan occurrence, while the 800 mm isohyet is the upper limit of calcification in South Africa. Du Toit (1938) gave a figure of 625 mm and Van der Merwe (1962) a figure 650 mm, for the upper limit of calcrete occurrence in South Africa.

According to the National State of Environment Report (DEAT, 2001) soil salinity is not a major problem in South Africa and the 2006 report by DEAT (2006) did not even include it under the "Land Degradation and Desertification" section. Most of the State of the Environment Reports of the different provinces have very limited quantifiable data on salt-affected soils or on soil salinization specifically, because the majority of the provinces do not have the capacity to collect such data. Some provinces such as the Northern Cape Province simply used the data from a 1:1 000 000 scale map of Nell and Henning (2003) and the description of De Villiers *et al.* (2003) in their State of the Environment Report. Hoffman and Ashwell (2001) made a generalized statement that salinization is a major problem in croplands in South Africa, without actually quantifying it.

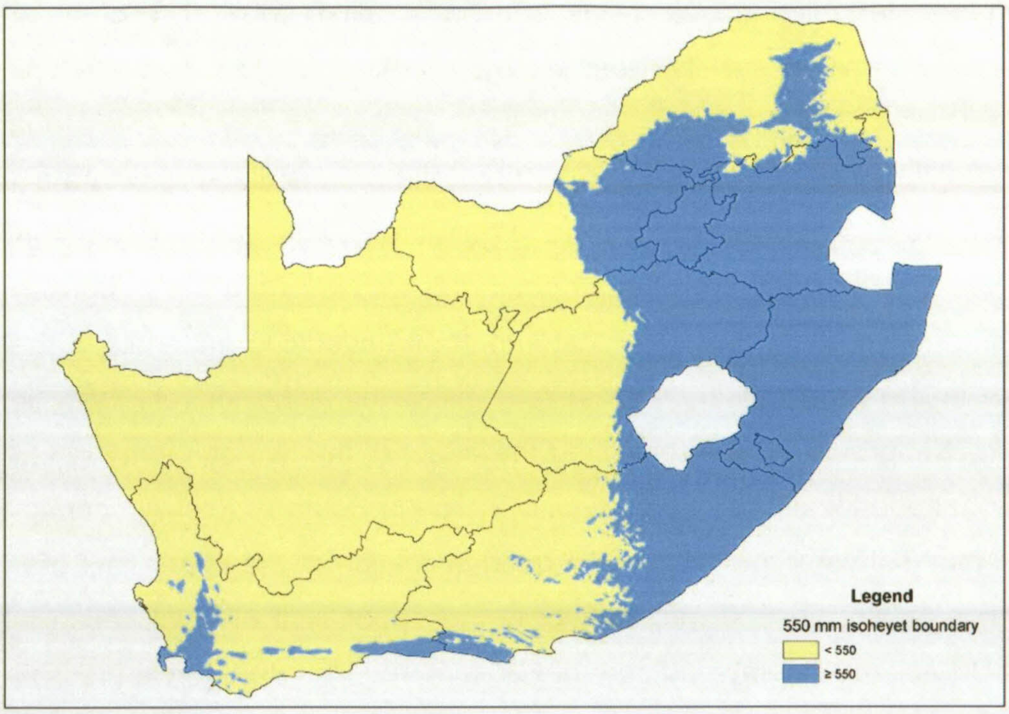

FIGURE 2.1 The 550 mm rainfall boundary for South Africa (Data from ARC-ISCW and SAWS weather stations with a recording period of 10 years or more were used).

Nell and Henning (2003) compiled a 1:1 000 000 scale salt-affected map for South Africa and quantified the salt-affected soils in the provinces (Table 2.1). The soils were classified as non-saline when EC was lower than 200 mS m^{-1}, slightly saline when the EC was between 200 and 400 mS m^{-1} and moderately saline when EC was between 400 and 800 mS m^{-1}. The area classifiable as severely saline was too small in extent to map. Only one class for sodic (EC lower than 400 mS m^{-1}, ESP higher than 15 and pH higher than 8.5) was used for the same reason. South Africa, in contrast to the FAO of the UN classification of saline-sodic soils (EC more than 400 mS m^{-1} and ESP more than 15), uses pH as distinction. When pH is higher than 8.5, the soil is classified as alkaline saline-sodic and when pH is lower than 8.5, as non-alkaline saline-sodic. The reason for this distinction is that the majority of the South African problematic soils fall in the alkaline saline-sodic class. Areas that can be considered as severely saline or very severely sodic are limited and occur in isolated areas.

TABLE 2.1 Salinity and sodicity status of South African soils in ha and % in parenthesis (Nell & Henning, 2003)

PROVINCE	Non-Saline (ha)	Slightly Saline (ha)	Moderately Saline (ha)	Saline-Sodic (Non-Alkaline) (ha)	Saline-Sodic (Alkaline) (ha)	Sodic (ha)
Eastern Cape	12 070 768 (71.1 %)	1 790 079 (10.5%)	2 720 327 (16.0%)	3 185 (0.02 %)	392 375 (2.3%)	10 228 (0.1%)
Free State	11 296 221 (87.0 %)	1 575 236 (12.1 %)	-	108 714 (0.8%)	-	-
Gauteng	1 699 258 (100 %	-	-	-	-	-
KwaZulu-Natal	8 452 759 (91.6 %)	249 251 (2.7 %)	-	529 055 (5.7 %)	-	-
Limpopo	9 417 086 (76.7 %)	2 412 651 (19.6 %)	452 612 (3.7 %)	-	-	-
Mpumalanga	7 014 923 (88.4 %)	-	89 668 (1.1%)	72 021 (0.9%)	-	-
North West	9 926 422 (85.4 %)	1 241 266 (10.7%)	-	449 033 (3.9%)	-	-
Northern Cape	17 696 226 (48.8 %)	4 879 977 (13.5%)	321 407 (0.9%)	5 165 931 (14.2%)	7 897 481 (21.8%)	313 678 (0.9%)
Western Cape	5 748 157 (44.4 %)	588 259 (4.5%)	1 935 175 (14.6%)	3 717 640 (28.7	961 768 (7.4%)	-
SOUTH AFRICA	83 321 820 (68.3%)	13 497 376 (11.1%)	5 519 189 (4.5%)	10 045 579 (8.2%)	9 251 624 (7.6%)	323 906 (0.3%)

The 1:5 000 000 scale soil map of South Africa by Van der Merwe (1940) indicate that approximately 3.6% or 4 360 000 ha of South African soils can be classify as Solonetic. According to the South African SOTER database (Samadi *et al.*, 1999) an estimated 0.62% (776 131 ha) of South African soils are strongly saline (Solonchaks and Arenosols) while soils with weak profile development, usually occurring on flood plains that can be saline, (Fluvisols, Cambisols, Luvisols, and Gleysols) comprise 1.16% (1 447 988 ha) (Barnard *et al.*, 2002; Samadi *et al.*, 1999). This finding does not agree with the area of salt-affected soils in South Africa, found by Nell and Henning (2003). According to them 83 321 820 ha (68.3%) is non-saline and non-sodic, 5 519 189 ha (4.5%) is moderately saline, 13 497 376 ha (11.1%) slightly saline, 10 045 579 ha (8.2%) is saline-sodic (non-alkaline), 9 251 624 ha (7.6%) is saline-sodic (alkaline) and 323 906 ha (0.3%) is sodic (Table 2.1). The difference in areas affected by salt-affected soils vary, because Nell and Henning (2003) used a much larger analytical database than Barnard *et al.* (2002) or Samadi *et al.* (1999).

MacVicar (1972) produced a sketch map giving a tentative appreciation of the occurrence of salt-affected soils in South Africa, without quantifying the area or the intensity of the problem. According to him, it is not possible at this scale to give meaningful statements about the associated salt-affected soils in each map unit.

The first maps showing the distribution of calcretes in South Africa was the 1:15 000 000 scale map of Mountain (1967) that was based on the soil maps of Van der Merwe (1940; 1962) and the 1: 5 000 000 scale map of Netterberg (1969).

The effect of sodicity on crusting, erosion, and infiltration were studied by several researches in South Africa (Van der Merwe, 1965; Levey & Van der Watt, 1988; Smith, 1990; Van der Merwe 1990). Du Plessis and Shainberg (1985), showed that infiltration of water can be reduced in soils with an ESP as low as 1 if the concentration of soluble salts is low enough and that sesquioxides tend to reduce the effects of sodicity on the dispersion of clay. The role of Mg in crust formation on South African soils have been studied by Nel (1989) and Van der Merwe (1965), who determined that low Ca:Mg ratios enhance dispersivity and cause structural instability. Bloem and Laker (1994) noted that soils most prone to crusting had at least one of the following properties: an ESP greater than 2, a clay fraction dominated by smectite, a Ca:Mg ratio smaller than 1, or an organic matter content below 2%.

Although salt-affected soils mostly have a negative undertone, it also has a positive effect on ecology in general. Khomo and Rogers (2005) indicate that primarily sodic patches in the Kruger National Park are ecologically important for nutrient accumulation, predator evasion and wallowing, but they are often perceived as derelict lands, because of vegetation denudation and low aesthetic quality. This negative perception, by both ecologists and tourists, often leads to ill-advised management and “rehabilitation” measures. Their results also imply a dynamic aspect of sodic patches, which have been previously viewed as static landscape features in pedogenic time scales.

2.3. GEOLOGY

Carbonate rocks are among the most widespread sedimentary rocks and account for up to 18 to 29% (v/v) of the lithosphere without the consideration of volcanic rock (Kuznetsov, 2002). Carbonate rock contains valuable and diverse information on the depositional settings and the conditions during past geological epochs. Unequalled by any other region in the world, South Africa hosts some of the oldest known salt deposits in its geological material. Of the oldest forms of calcium carbonate deposits on earth are found in the 3 500 million year old Barberton Supergroup in South Africa (Brandl *et al.*, 2006 and Lowe & Knauth, 1987). In the upper Black Reef formation with an age of 2 450 million years, even casts of cubic salts crystals, about 10 mm across are found (McCarthy & Rubidge, 2005). The Malmani and Cambellrand Subgroups are regarded as representing some of the earliest major platform carbonate successions (2 500 to 2 650 million years) that acted as sinks for the CO_2 that dominated the Archaean atmosphere (Moore *et al.*, 2001).

Martini and Wilson (1998) classified the various types of carbonate rock in South Africa into the following five categories:

(1) *Sedimentary carbonates* were deposited throughout much of South Africa's geological history and range from Swazian to Quaternary in age. The older members have generally been heated and metamorphosed to some extent, whilst the Cretaceous and younger members may be soft and poorly consolidated. Though of highly variable grade, the sedimentary carbonates constitute South Africa's major resource of limestone and dolomite. The economically significant resources are generally hosted within the following five sedimentary units: (a) the Malmani Subgroup and Campbell Rand Subgroup, both of which are of Vaalian age and are widely distributed, the former in Gauteng, the North West, Limpopo and Mpumalanga Province, and the latter in the Northern Cape Province; (b) the Mapumulo Group, which crops out at Marble Delta in southern KwaZulu-Natal; (c) the Malmesbury Group in the Western Cape; (d) the Nama group in the Vanrhynsdorp area of the Western Cape; and (e) Tertiary to Quaternary coastal limestone along the Cape coast.

(2) *Calcrete and dolocrete* have formed in the arid parts of the country and provide important resources of low-grade material for both the agricultural and cement manufacturing industries.

(3) *Travertine* has generally formed in small deposits, except at Ulco in the Northern Cape Province, where medium to high-grade limestone is mined on a large scale.

(4) *Cave limestone and vein deposits*, though very pure, occur only in small deposits and are generally of little economic significance.

(5) *Carbonatites* is a magmatic rock composed of more than 50% carbonate minerals, the most abundant being calcite, apatite and dolomite/ankerite. It is also of little limestone economic significance, but of the 350 documented carbonatite occurrences in the world, 43 occur in South Africa. The Phalaborwa carbonitite, unusual because it hosts significant copper deposits and the Pilansberg Alkaline Province are the best known in South Africa. Other important occurrences are the Salpeterskop, Schiel, Stukpan, Spitskop, Tweerivier, Kruidfontein, Nooitgedacht, Goudini, and Glenover carbontites (Schürmann, 1999; Cairncross, 2004).

In South Africa, gypsum deposits have formed mainly in surficial terrestrial environments, which are semi-arid to arid in nature (Botha, 1988). According to Oosterhuis (1998a) the gypsum forms in the topmost portion of the weathering profile in shales of the Ecca Group of the Karoo Supergroup or in salt pans under special conditions, namely: (a) where a suitable supply of calcium and sulphate are available, be they in the bedrock, ground water or in the atmosphere; (b) in a restricted drainage system conducive to the concentration and precipitation of salts upon evaporation; (c) where low rainfall and long dry periods occur with high evaporation rates; and (d) the presence of a clay layer in which the gypsum can form. The chief South African gypsum deposits are in low-lying areas northeast of Vanrhynsdorp and in the Bushmanland. According to Cairncross (2004) gypsum also occur in the Tugela Valley beyond Kranskop in the Greytown district in KwaZulu-Natal.

The salt (NaCl) industry is claimed to be one of the oldest industries in South Africa (Furguson & Juritz, *ca* 1925). Jan van Riebeeck, writing under the date of July 26th 1649 "the garrison would require no other supplies than bread, rice, oil and vinegar, as abundance of salt can be had there". Early travellers and pioneers, such as

Sparrman, Thunberg, Barrow, Lichenstein, Burchell, Chapman, Livingstone, and others, frequently mentioned the availability of salt in Southern Africa (Furguson & Juritz, *ca* 1925).

South Africa's salt resources are confined to underground brines associated with inland saltpans and seawater (Oosterhuis, 1998b). These brines are usually considered to be of secondary origin, having formed by the leaching of salt bearing sediments. The dominant salts encountered in pans are sodium and calcium sulphates, sodium chloride and sodium carbonate, mostly as efflorescence at the pan surface, or as a saline clay layer, as is the case at Soutpan, north of Bloemfontein (Shaw, 1988). Less common salts are nitrates, such as the salpetre deposits of Matsap in Griqualand. According to Oosterhuis (1998b), the majority of inland saltpans occur in a curved belt, 50 to 160 km wide, which is mostly underlain by rocks of the Karoo Supergroup. This belt extends from near Vryburg in the north to Hopetown in the south and Brandvlei in the west. Most of the pans have formed in the shales of the Dwyka Formation and Ecca Group. A considerable number of saltpans occur in the Kalahari region, north and northwest of Upington, also on shales of the Dwyka Formation. At Teviot near Hofmeyer, saltpans are underlain by sandstone and mudstone of the Beaufort Group and near Waterpoort, at the foot of the Soutpansberg, a saltpan occurs on basalt of the Lebombo Group. Several pans occur on Proterozoic granite gneiss south of Pofadder and also west of Vryburg. Most of the pans in the vicinity of Delareyville are underlain by lava of the Ventersdorp Supergroup. The crater-like Pretoria saltpan (Tswaiing), which was well known in the past for the production of sodium carbonate and bicarbonate, in addition to sodium chloride, occurs on granite of the Bushveld Complex. Coastal saltpans are found north and east of Cape Town, up to Mossel Bay, and in areas around Port Elizabeth, e.g. Koega. Some pans derive their saline constituents directly from the sea by periodic flooding or seepage, while others receive brines from older marine sediments. Some replenishment is derived from rainwater leaching from the surrounding salt-impregnated dunes (Oosterhuis, 1998b).

According to Du Toit (1938), the salts occurring in pans in South Africa have been brought in by surface run-off water and by hydrolysis of the minerals of the underlying rock through the accumulation of water. The easily soluble salts seem to have been leached from the surface horizons producing an alkaline soil. According to Day (1993), however, ions dissolving in surface waters must come either from the atmosphere in the form of rain, fog or wind-blown particles or from the substratum or the surrounding catchment area. Given the aridity of southern Africa, the atmosphere would seem to be a minor source of salt ions. This assumption may not be valid, though, given the following simple calculation. The rate of accumulation of Cl^- ions for, say, a closed-basin pan in the Northern Cape Province (rainfall 400 mm a^{-1}, $[Cl^-]$ in rain 11 mg L^{-1} (Bosman & Kemster, 1985), yields 156 g Cl^- m^{-2} in 1 000 years. For a pan 1 m deep, this is equivalent to an increase of 4.4 mg L^{-1} over 1 000 years. Lancaster (1979) has reported the existence of stromatolites (an indication of salinity and therefore possibility of aridity) from saline Kalahari lakes dated at 17 000 to 15 000 B.P. If arid conditions have indeed persisted for this long, then atmospheric precipitation could account for salinity of many pans. Clearly, this is an oversimplification in that even closed-basin pans can lose ions by deflation and seepage, but it does indicate that atmospheric precipitation should not be ignored as a potentially significant source of ions in arid areas.

2.4. WATER

The dissolved salt loads of South Africa's rivers are variable and reflect the underlying geology and climate (Walling, 1996). Rivers draining the strongly weathered basement rocks of the interior generally have low dissolved loads, whereas rivers draining the sedimentary rocks of the periphery of the continent have higher dissolved loads.

The Department of Water Affairs and Forestry have a National Chemical Monitoring Programme that illustrates the importance of consistent data collection over many decades. Hohls *et al.* (2002) have done a comprehensive study on the status of water quality in South Africa, reflected predominantly by the mineral salt composition. Various land uses, notably mining and agriculture and the degradation of land, modify the water quality in many parts of the country. At a national scale, however, land cover and geology have the predominant influence on water quality. Since the bulk of the country is still in a moderately natural state, it is only at a finer level of detail, such as the Water Management Area (WMA) level, that problem areas become more apparent. According to Du Plessis (1998), the quality of our surface water resources is largely within limits of acceptability for irrigation. The salinity of our surface waters furthermore compares favourably with the rest of the world judged against the 90th percentile of about 2 000 mg L^{-1} (320 mS m^{-1}) found by the US Salinity Laboratory for surface water samples which they obtained from around the world (Jurinak, 1990). According to Leske and Buckley (2003), however, elevated salt levels in surface waters and groundwaters in South Africa are a significant problem of national concern.

As early as the 1900's Juritz (1911) concluded that "the most saline waters appear to be those of the Uitenhage, Dwyka, and Bokkeveld formations and that the waters of the Malmesbury beds differ from those of the Table Mountain series in containing a larger all-round proportion of salts and in the more frequent presence of magnesium carbonate, and consequent absence of calcium sulphate". Eighty-four years later, Day and King (1995) studied the proportions of ions in rivers of South Africa. They used four broad categories of ionic proportions in water that show geographical distribution patterns linked to the geological and climatologically character of the country: Category 1 (dominant ions Ca^{2+}, Mg^{2+}, and HCO_3^-; Na^+ < 25% of cations) is restricted to the regions of the high altitude basalt cap of Lesotho/KwaZulu-Natal and the limestone, dolomites and chert of the Chuniespoort Group and the shales and quartzite's of the Pretoria Group both of the Transvaal Sequence. Category 2 (dominant ions Ca^{2+}, Mg^{2+}, and HCO_3^-; Na^+ >25% of cations) mostly encircles category 1 at lower altitudes; it occurs on Karoo and Waterberg sedimentary rocks and igneous rocks of the Basement Complex and the Bushveld Igneous Complex. Category 3 (Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^- more or less co-dominant) is widespread and apparently not associated with any particular geological formation. Category 4 (Na^+ and Cl^- dominant) occurs in the southwestern Cape on Table Mountain Sandstones, in the western arid regions on Karoo sediments and in the coastal KwaZulu-Natal on a variety of substrata. Waters in categories 1 and 2 are "rock dominated"; dilute waters in category 4 are "precipitation" dominated and concentrated waters in category 4 are evaporation-precipitation (crystallization) dominated.

Saline runoff conditions are experienced in several rivers, the more important of these being the Great Fish, Sundays, Berg, and Breede Rivers (Hall and Du Plessis, 1984). Greef (1994) reported that water analyses have shown that a few tributary streams, which drain the Bokkeveld Shale catchments, are responsible for the high salinity in the Breede River Valley.

The main water quality concerns throughout the country for domestic use relate to the widespread elevated salt levels (high TDS values) and elevated fluoride levels in certain locations (Hohls *et al.* (2002). TDS levels were especially elevated in the Lower Orange, Fish to Tsitisikamma and Gouritz WMA's. It would appear that these elevated levels are due to natural causes. From an irrigated agriculture use perspective, SAR, EC, pH, and Cl^- concentration were elevated in various regions of the country. There were high pH levels in the Levuvhu and Letaba, Crocodile (West) and Marico, Olifants, Usutu to Mhlatuze, Mzimvubu to Keiskama, Upper Orange and Lower Orange WMA's. The Fish to Tsitsikamma and Gouritz WMA had low pH values and high SAR, EC, and Cl^- values; making irrigated agriculture in these WMA's more challenging, and limiting crop selection to more salt- tolerant crops. The Thukela WMA had high pH values, while the Upper and Middle Vaal WMA's had high EC values. The South Western Cape (Breede and Berg WMA's) had low pH values evident in some cases and elevated SAR, EC and Cl^- values, again limiting the potential for growing salt sensitive crops.

There is an increase in salinity in ten out of the nineteen Water Management Areas from 1996 to 2001 (Godfrey *et al.*, 2002). The 2006 National State of Environment Report of South Africa (DEAT, 2006) indicates that for water salinity there is an increase (a deteriorating trend) in the case of 46% and a decrease (improvement) in 17% of the monitoring sites (Figure 2.2).

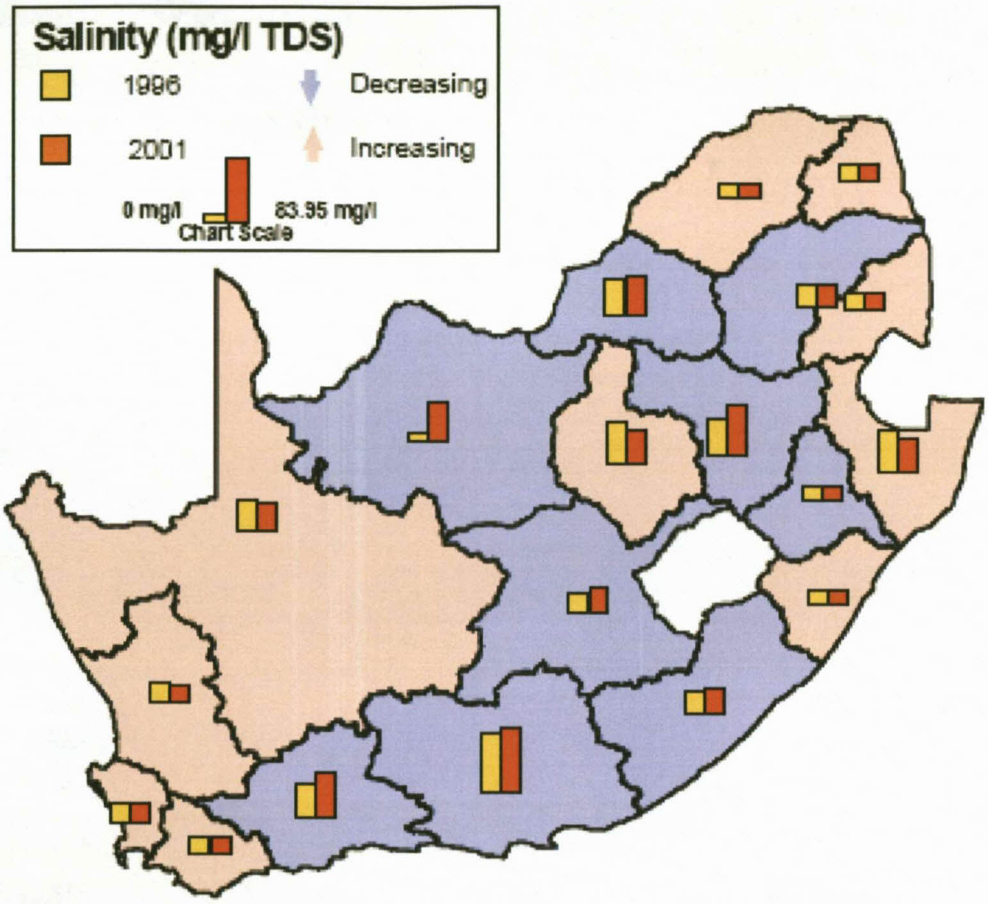

FIGURE 2.2 Spatial variation in surface water salinity per Water Management Area (Godfrey et al., 2003).

Van Niekerk *et al.* (2008) studied twenty-five sites on major rivers in South Africa that had sufficient continuous data for the estimation of salinity changes over a 25-year period and where statistically significant upward or downward trends occurred at 17 of the 25 sites. Twenty-five years is a relatively short period in terms of climatic cycles and some of the trends identified might be in reaction to an upward or downward period of a long-term wet-dry cycle. Most sites were also too far apart for detailed analyses of whole river systems, though an upward trend is apparent in the Lower Orange River and a downward trend in the Great Fish River. Van Niekerk *et al.* (2008) also indicate that in some rivers such as the Great Fish River, Vaal River and Berg River, external influences such as inter-basin water transfer schemes, extensive agriculture and large-scale industry can drastically alter the salinity in specific sections of a river.

The first attempt to study groundwater quality on a national scale is the one produced by Bond (1946). Van Noort and MacVicar (1958) conducted the second national attempt. This work was done for agricultural purposes and it was supposed to correlate geological formations and borehole waters. The dataset contained the results of 1 850 samples. The data was evaluated on a district basis (292 districts), but almost half of the districts were covered only by one sample. A series of simplified maps were produced with a very crude resolution. Bredenkamp *et al.* (1991) attempted to relate groundwater quality to average annual rainfall distribution. Point maps were produced depicting EC, nitrate, fluoride, chloride and sulphate. The thrust of the study was to find a correlation between rainfall and aforementioned parameters. This was found to be not straightforward and the other factors such as thickness of overburden and geology also had to be accounted for.

Most of the Karoo Basin groundwater has TDS in the range of 450 to 1 000 mg L^{-1}, which is not excessive by any standards (Woodford & Chevallier, 2002). High concentrations are limited to the westernmost and southernmost edges of the Karoo Basin, especially to groundwater in the Dwyka Formation. This water is partly of a connate origin. The relatively well defined picture of TDS may be skewed by the fact that fresh water related to dolerite structures was sampled most often. The groundwater quality in the sedimentary sequence is regarded as poorer due to longer residence time. Aquifers in the Karoo have in general a rather high pH, in the range of 8.0 to 8.5 (Woodford & Chevallier, 2002). Only a relatively small part of the Karoo Basin has ground water pH less than 7.5, limited to the east and north where rainfall (and carbonic acid activity) is comparatively higher than in other parts of the Karoo.

The source of salinity, in especially Karoo sediments, remains unresolved. Some researchers propose: a marine water body (Oelofsen & Araujo, 1987; Visser, 1992); a non-marine brackish water body with no connection to the world oceans (Veevers *et al.,* 1994); a huge freshwater lake that spanned much of south-western Gondwana and was characterised by algal blooms (Faure & Cole, 1999); and/or a sea-level high stand under restricted oceanic circulation (Visser, 1992; 1993).

2.5. CONCLUSION

Literature on the primary soil salinity and sodicity in South Africa is minimal and for primary alkalinity nearly non-existent, with the exception of the work done by Ellis

(1988) and Netterberg (1969). The effect of sodicity on crusting and erosion were studied by several researches in South Africa. Numerous water quality studies are also available.

Unequalled by any other region in the world, South Africa hosts some of the oldest known salt deposits in its geological material.

About 70% of South Africa's soil is non-saline and non-sodic. The same applies for most of the surface water. The reasonably favourable primarily salinity and primarily sodicity status of South African surface water and soil at present is no reason to be complacent, because water quality and soil quality continues to deteriorate as a result of industrial, municipal, and mining effluents, together with contributions from non-point sources. The former Department of Water Affairs and Forestry has a National Chemical Monitoring Programme that illustrates the importance of consistent data collection over many decades, combined with a rational distribution of monitoring sites, which enables them to draw useful conclusions regarding long-term changes in salinity, sodicity and alkalinity. The Department of Agriculture Forestry and Fisheries requires a similar programme to quantify and qualify salinity, sodicity, alkalinity, and other soil chemical parameters to make meaningful recommendations regarding the rehabilitation and use of problematic soils.

The dissolved salt loads of South Africa's rivers are variable and reflect the underlying geology and climate. The quality of our surface water resources is largely still within limits acceptable for irrigation. High salt concentrations in the groundwater are limited to the westernmost and southernmost edges of the Karoo Basin, especially to groundwater in the Dwyka Formation. High salt concentrations are also found in Bokkeveld Shale and in Quaternary deposits in the Kalahari Group and older Namaqua Metamorphic Complex.

South Africa's NaCl resources are confined to underground brines associated with inland saltpans and seawater. These brines are usually considered to be of secondary origin, having formed by the leaching of salt bearing sediments. In South

Africa, gypsum deposits formed mainly in surficial terrestrial environments, which are semi-arid to arid in nature.

The African continent south of about 23°S has few natural athalassic (inland) lakes, saline or freshwater. South Africa, however, is rich in temporary pans, many of which are saline and/or sodic.

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CHAPTER 3: CLASSIFICATION OF SALT-AFFECTED SOILS

3.1. INTRODUCTION

Salt-affected soils are widespread all over the world. There are many classification systems for salt-affected soils and numerous systems that group them for reclamation purposes. Some of these are incorporated into the generally accepted world soil classification systems, such as Soil Taxonomy, the soil classification systems of the FAO/UNESCO Soil Map of the World, Soil Map of Europe, and World Reference Base (FAO, 2006).

Based on the simplicity of the chemical characteristics of salt-affected soils, their classification would be expected to be a simple case. It is, indeed, relatively simple in national and international classification schemes. What makes it so variable is the difference in the approaches of classification, ranging from the standpoint of the pedologist to the standpoint of a soil chemist to the standpoint of the agronomist. This has arisen from limited understanding of the mechanisms involved in the development and behaviour of salt-affected soils. In many cases, saline and sodic soils are confused without any distinction made between them.

Salt-affected soils, is a pioneering branch of pedology, soil mapping, remote sensing, soil reclamation and soil utilization (Szabolcs, 1989). The fact that sodium was so frequently present in salt-affected land in Europe and Russia in fact aided the development of Soil Science and the recognition of soil as a colloidal medium. The basic principles of cation exchange grew out of salinity work (Hilgard, 1877). Letey (1984) provides an excellent review of the overall impact of salt-affected soils on the development of Soil Science itself.

The marriage of classical pedology with agronomy began with the work of E.W. Hilgard. His work began the application of agronomy to the natural science aspect of soils. Hilgard (1877) is one of the earlier references to be encountered that deals with problems of salinization of agricultural land. The other pioneer is Kelley. In his work in the 1930's (Kelley, 1937) describe "white alkali soils" what we now refer to as saline soils as and "black alkali soil" what we now refer to as sodic soils.

3.2. CHEMICAL CLASSIFICATION

The chemical classification of salt-affected soils reflects the types and amounts of salt present in the soil and hence the nature of resultant limitations to plant growth and land use.

The solubility of gypsum ($CaSO_4$) is commonly used as the standard for comparing solubilities of salts (Fitzpatrick *et al.*, 2003). Consequently, salts more soluble than gypsum are considered to be soluble and cause salinity such as sodium chloride (NaCl) and sodium sulphate (thenardite, Na_2SO_4). Salts less soluble than gypsum such as calcite (lime or calcium carbonate, $CaCO_3$), which is commonly found in soils are considered insoluble and do not cause salinity. Some common salts in soils and their solubility's in water are given in Table 3.1.

TABLE 3.1 Solubilities of selected salts in water at 25°C (Bresler *et al.*, 1982; Sumner, 2000)

Name	Formula	Solubility (mol L^{-1})
Halite	NaCl	6.15
Hexiihydrite	$MgSO_4 \cdot 6H_2O$	3.17
Epsomite	$MgSO_4 \cdot 7H_2O$	3.03
Soda	$Na_2CO_3 \cdot 10H_2O$	2.77
Mirabilte	$Na_2SO_4 \cdot 10H_2O$	2.74
Trona	$Na_3H(CO_3)_2 \cdot 2\ H_2O$	2.56
Bloedite	$Na_2\ Mg(SO_4)_2 \cdot 4H_2O$	2.31
Thernardite	Na_2SO_4	1.97
Nahocolite	$NaHCO_3$	1.22
Gypsum	$CaSO_4 \cdot 2H_2O$	0.005
Calcite	$CaCO_3$	0.0006

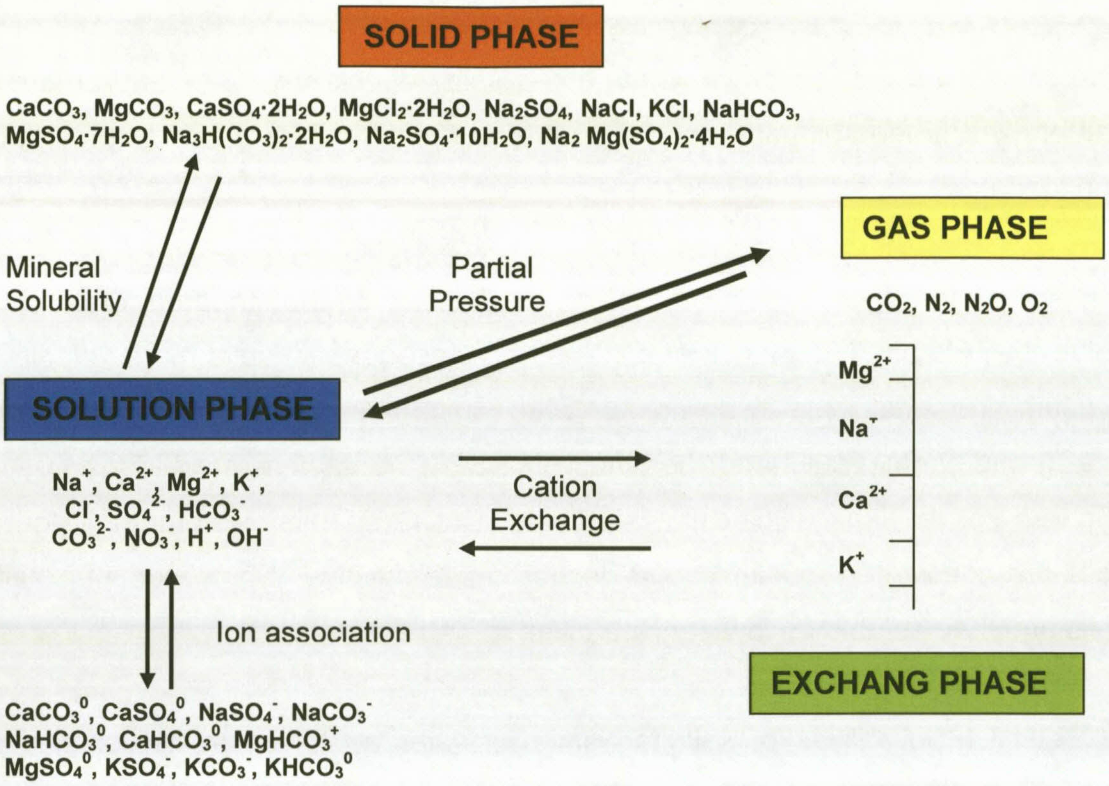

FIGURE 3.1 Interactive chemical reactions in soil- water systems (Tanjii, 1990).

Chemical classification of salts must bear in mind the complex chemical interactions that take place between the solution, solid, exchanger, and gas phases (Figure 3.1). The free ions and ion pairs are subject to transport by diffusion and convection, e.g., water movement. A change in soil water content by irrigation and rainfall or evapotranspiration by plants will cause the equilibrium to shift due to mineral precipitation or dissolution, association or dissociation of ion pairs, adsorption or desorption of cations and emission or absorption of gases (Paul *et al.*, 1966).

Traditionally it was thought that there are three potential hazards of salt-degraded soils to plants - salinity, sodicity and alkalinity (Richards, 1954). The first two hazards are used to classify soils as saline or sodic, or both, as described in Table 3.2. The alkalinity hazard, however, measured by the residual sodium carbonate (RSC) value is not usually applied directly to the classification of soils (McBride, 1994).

TABLE 3.2 Traditional chemical classifications of saline, saline-sodic and sodic soils

	EC mS m^{-1}	**ESP**	**SAR**	**pH**
Saline	>400	< 15	< 13	< 8.5
Saline-sodic	>400	>15	>13	< 8.5
Sodic	< 400	>15	>13	>8.5

In Table 3.3., a general picture is given, showing a practical grouping of some salt-affected soils developing under the influence of electrolytes and including some possibilities for the chemical composition of the salts and the main effect on production.

TABLE 3.3 Grouping of salt-affected soils (modified from Szabolcs, 1988; 1989)

TYPE OF SALT-AFFECTED SOILS	**ELECTROLYTE(S) CAUSING SALINITY AND/OR SODICITY**	**ENVIRONMENT**	**MAIN ADVERSE EFFECT ON PRODUCTION**
Saline soils	Sodium chloride and sulphate	Arid Semi-arid	High osmotic pressure of soil solution
Sodic soils	Sodium ions capable of alkaline hydrolysis	Arid Semi-arid Humid	Effect on water physical soil properties Toxic effect
Magnesium soils	Magnesium ions	Semi-arid Semi-humid	Toxic effect High osmotic pressure
Gypsiferous soils	Calcium ions (mainly $CaSO_4$)	Arid Semi-arid	High osmotic pressure of soil solution Toxic effect
Acid sulphate soils	Ferric and aluminium ions	Sea shores, lagoons with sulphur containing sediments	Strongly acidic Toxic effect

Salinity classification based on hydrogeology, surface water flow, geology, topography and soils, culminated in eight types of salinity recognized within the Province of Alberta, Canada: artesian salinity, contact/slope change salinity, coulee bottom salinity, depression bottom salinity, outcrop salinity, slough ring salinity, canal seepage and irrigation salinity (Kwiatkowski, 2004).

TABLE 3.4 Categorizing soils for management purposes based on their behaviour (Sumner, 1992)

	Flocculated	Flocculated	Dispersed	Dispersed
Saline natric	Saline non-natric	Non-saline non-natric	Spontaneous	Mechanical
ESP>6 EC>400 mS m^{-1}	ESP<6 EC>400 mS m^{-1}	ESP<6 EC>CFC*	ESP>6 EC<<CFC*	ESP<6 EC<CFC*
Saline-sodic	Saline	Non-saline Non-sodic	Sodic	?

* Critical flocculation concentration

As was indicated in Chapter 1, the terms sodic and sodicity should become obsolete as their definition has become imprecise (Sumner, 2000). Rather, soils should be described in terms of their behaviour and thus favoured terms might be 'spontaneously dispersive' and 'mechanically dispersive' (Table 3.4). At the bottom of the table, the presently used terminology is presented for each category. Many soils in the world and in South Africa that exhibit sodic behaviour may not fit into the classical sodic group, because typical morphological features including prismatic and columnar structure are not present. An ESP boundary limit of 15 is particularly problematic and even Richards (1954) said that this limit must be regarded as somewhat arbitrary and tentative.

Currently, general-purpose soil classification systems are not intended to distinguish between the causes of soil salinity, nor approaches to its management. Based on the Williams and Bullock (1989) system, a modified classification has been developed (Figure 3.2) by Fitzpatrick *et al.* (2003). In the new classification, saline soils are classified using hydrological, soil landscape features and dominant soil chemistry (type of soluble salt or sodicity). The important soil chemical indicators as defined by Isbell (1966) and used in the new classification are:

- Halitic (sodium chloride dominant)
- Gypsic (gypsum or calcium sulphate dominant)
- Sulfidic (pyrite dominant)
- Sulphuric (sulphuric acid dominant), and
- Sodic (high exchangeable sodium on clay surfaces)

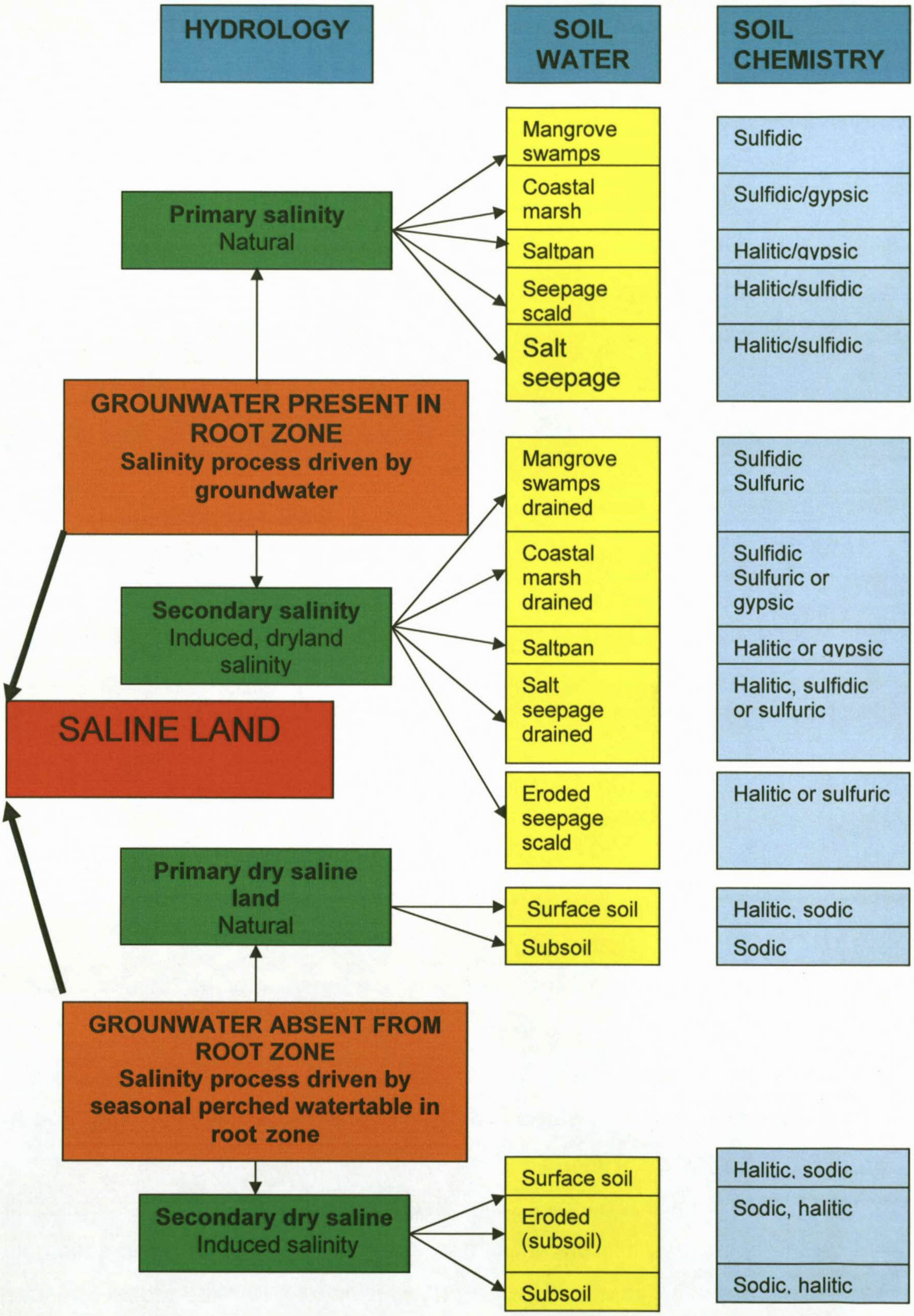

FIGURE 3.2 Categories of saline soils as defined by hydrology, soil water status and soil chemistry (Fitzpatrick, 2003).

According to Kust (1988), the term “degree of alkalinity” should not be utilised in soil classification, because every specific criterion usually used to determine general degree of soil alkalinity has its own value and sense. At the same time, each manifestation of alkalinity, either morphological, chemical or physical, can be scaled on its own degree.

The most extreme pH values, both acid and alkaline, occur in soils in nature associated with various groups of salt-affected soils. The various types of salt-affected soils cover the whole pH spectrum. Saline, magnesium, and gypsiferous soils tend to group in the middle, whereas sodic soils have the highest pH. The other extreme is represented by acid sulphate soils in the low pH range (Figure 3.3).

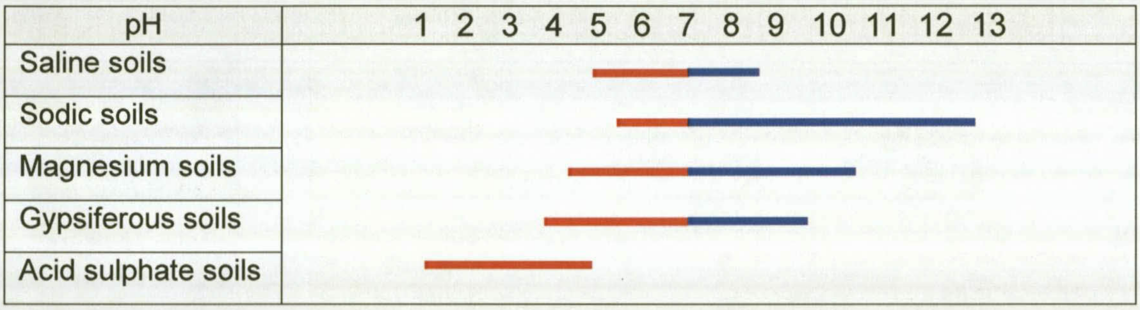

FIGURE 3.3 pH spectrum of different salt-affected soils (modified from Szabolcs, 1989).

3.3. MORPHOLOGICAL CLASSIFICATION

The international classification systems include terms such as salinity, alkali, sodic, solonetz, solonchak and solodized solonetz, and the complex inter-relationship between them makes comparison between salt-affected soils difficult. In different soil classification systems, salt-affected soils are presented differently and appear on different taxonomical levels. In many soil classification systems the term “salt-affected soils” is limited to those saline and sodic soils, where the neutral or alkaline hydrolyzing sodium salts dominate. It is true that most salt-affected soils belong to these two groups, but in a system aimed at casting light on the global importance of the problem, all soils which have developed under the dominating influence of electrolytes should be included (Szabolcs, 1989). According to Fitzpatrick *et al.* (1992) the following properties are common for salt-affected soils in most soil classification systems:

- Morphology of the soil profile (presence or absence of diagnostic horizons);
- Significant physical properties (mainly for sodic or Solonetz group);
- Chemical properties such as (a) content, composition and distribution of salt in the profile and, in some cases, also in the groundwater; (b) ESP and SAR; (c) pH conditions and the existence of sodium carbonate.

The Russian soil scientist (Kovda, 1965) cited by Chhamba (2005) classified salt-affected soils as Solonchaks (based on the percentage soluble salts) and Solonetz (based on ESP). Solonetz belongs to the family of salt-affected soils, in spite of the fact that some Solonetz soils, particularly in their upper horizons, the salt concentration is at present low or very low. Solonetz soils developed or are developing under the dominant influence of electrolytes which determined their morphology, physical, chemical and biological properties as well as their fertility. Evidently, the chemical composition and concentration of electrolytes influencing the soil forming processes can be diverse, and consequently various salt-affected soils may develop with different properties (Szabolcs, 1988). According to Szabolcs, the data available is not sufficient to give a precise ESP limit value as a criterion for the term "Solonetz" or even "alkali soils" in all regions. In many countries, soils with an ESP value of 15-20, or even more, do not manifest Solonetz morphological features, and may be fairly fertile, such as soils of the Valsrivier, Swartland, Addo and Etosha soil forms in the Lower Sundays River in the Eastern Cape Province, as were found by Nell (1991); Nell and Childs (1992). In other regions, a Solonetz profile may develop where the ESP value is less than 15 (such as soils near Queenstown and in the Tugela Basin in KwaZulu-Natal Province (Mac Vicar, 1972). According to Van der Eyk *et al.* (1969) the exchangeable magnesium is invariably high in such cases. It is not known whether the magnesium ion plays a role similar to that of sodium in the swelling process or whether cation occupation of the colloid has changed subsequent to the development of prismatic structure. Whatever the explanation, this apparent anomaly makes it impossible to set a quantitative lower limit to exchangeable sodium for diagnostic purposes. An accurate determination of ESP is also challenging. According to Nell and Loock (2009), for South African soils the relationship between ESP and SAR is much more sensitive to changes in salinity than soil pH_{water}. This appears contradictory, because the analysis of ESP depends on an accurate measurement of the CEC, which is a pH-dependent measurement. The reason for this anomaly is probably that if the soil is highly saline then the negative adsorption effects cause an over-correction for soluble sodium in the determination of exchangeable sodium. This causes the ESP values to be lower than the actual values.

According to Darab and Rédly (1988) the most important diagnostic features of Solonetz soils are: the presence of a compact horizon of accumulation with columnar and/or prismatic structure and the depth of the eluvial "A" horizon. The physical properties of the horizon of accumulation are determined by the accumulation of clay, the high dispersivity, and swelling ability of colloids.

Soil Survey Staff (1999) has classified salt-affected soils at the great group level as having nitric and/or salic subsurface horizons in soil orders of Alifisols, Aridisols, Inceptisols, Mollisols and Vertisols. The World Reference Base for Soil Resources (FAO, 1998 and 2006) classified these soils based on the EC for salic horizon as Solonchaks and ESP for nitric horizon as Solonetz. Solonchak soils are defined by an EC of 1 500 mS m^{-1}or of more than 800 mS m^{-1}if the pH_{water} (1:1) exceeds 8.5.

The following reference soil groups (RSG's) of the World Reference Base (WRB) for Soil Resources (FAO, 2006) are associated with salt-affected soils:

- Calcisols accommodate soils in which there is substantial secondary accumulation of lime.
- Gypsisols are soils with substantial secondary accumulation of gypsum ($CaSO_4 \cdot 2H_2O$).
- Solonchaks are soils that have a high concentration of soluble salts at some time in the year.
- Solonetz are soils with a dense, strongly structured, clayey horizon that has a high proportion of adsorbed Na and/or Mg ions.

The dominant WRB (FAO, 2006) second-level units that are associated with salt-affected soils are (specifiers not included):

- Alcalic are soils that have a pH (1:1 in water) of 8.5 or more throughout within 50 cm of the soil surface or to continuous rock or cemented or indurated layer, whichever is shallower.

- Arzic are soils that have sulphate-rich groundwater during some time in most years and containing 15% or more gypsum averaged over a depth of 100 cm.
- Calcaric material between 20 and 50 cm from the soil surface or between 20 cm and continuous rock or a cemented or indurated layer.
- Calcic are soils that have concentrations of secondary carbonates starting within 100 cm of the soil surface.
- Carbonatic having a salic horizon with a soil solution (1:1 in water) with a pH of 8.5 or more and $[HCO_3^-] > [SO_4^{2-}] >> [Cl^-]$.
- Chloridic having a salic horizon with a soil solution (1:1 in water) with $[Cl^-] >> [SO_4^{2-}] > [HCO_3^-]$.
- Gypsiric having a gypsic material between 20 and 50 cm from the soil surface.
- Gypsic having a gypsic horizon within 100 cm of the soil surface.
- Magnesic having an exchangeable Ca to Mg ratio of less than 1 in the major part within 100 cm of the soil surface or to continuous rock or indurated layer.
- Natric having a nitric horizon starting within 100 cm of the surface.
- Puffic having a crust pushed up by salt crystals.
- Salic having a salic horizon within 100 cm of the soil surface.
- Sodic having 15% or more exchangeable Na plus Mg on the exchange complex within 50 cm of the soil surface.

The presence of free carbonates, calcium carbonate or calcium-magnesium carbonate in soil has been used in the South African soil classification system (Soil Classification Working Group, 1991) to define diagnostic horizons and materials, and is used as a family criterion. There is a good correlation between the current South African soil classification system for the sixteen calcareous soils forms and international classification systems, such as the WRB system (FAO, 2006) (Table 3.5.), but not for the two sodium dominant soils, especially if the US Taxonomy Classification system is used.

TABLE 3.5 A broad correlation between South African soil classification system (Soil Classification Working Group, 1991) and the WRB system (FAO, 2006) for salt-affected soils

SOUTH AFRICAN SOIL CLASSIFICATION SYSTEM	WRB SOIL CLASSIFICATION SYSTEM
Addo	Haplic Calsisols
Askham	Petric Calsisols
Augrabies	Haplic Calsisols
Brandvlei	Hypercalcic Calsisols
Coega	Epipetric Calsisols
Estcourt	Haplic Solonetz
Etosha	Haplic Calsisols
Gamoep	Petric Calsisols
Immerpan	Epipetric Calsisols
Kimberley	Haplic Calsisols
Kinkelbos	Calcic Lixisols
Molopo	Haplic Calsisols
Montagu	Endogleyic Calsisols
Plooyesburg	Petric Calsisols
Prieska	Petric Calsisols
Steendal	Hypercalcic Calsisols
Sterkspruit	Haplic Solonetz
Trawal	Calcic Durisols

In the WRB (2006) soil classification system, sodic soils mainly occur in the Solonetz Reference Soil Group. However Solonetz soils may be associated with Histosols, Gleysols, Ghernozems, Kastonozems, Vertisols and Solonchaks (FAO, 2004a), and saline soils mainly in the Solonchaks Reference Soil Group. However, some other Reference Groups may also have a salic horizon such as Histosols, Vertisols and Fluvisols (FAO, 2004b).

3.4. CONCLUSION

In different soil classification systems, salt-affected soils are presented differently and appear on different taxonomical levels. It is difficult to establish a perfect method of conversion between the different classification systems. This cannot be expected in the near future either, because the salinity of soils is indicated at different levels in the taxonomical hierarchy of soil classification systems - in some classification systems at a high taxonomical level, and in others at a low level (Szabolcs, 1989). One of the general principles of soil classification, namely, that a universal system cannot accommodate all places, all scales, and all purposes, is probably also valid for salt-affected soils. Different systems should be applied when drawing a map on the distribution of salt-affected soils over a whole continent, South Africa, or when compiling a detailed soil map for a single farm.

The classification of salt-affected soils reflects the types and amounts of salt present in the soil and hence the nature of resultant limitations to plant growth and land use. The various types of salt-affected soils occur over the whole pH spectrum.

The solubility of gypsum is commonly used as the standard for comparing solubilities of salts. Consequently, salts more soluble than gypsum, such as sodium chloride and sodium sulphate are considered to be soluble and cause salinity. South African soils do not have a severe primary salinity problem, the reason is probably that salts less soluble than gypsum such as calcium carbonate, which is commonly found in South African soils, are considered insoluble and hence are not considered to cause salinity.

There is no agreement in the classification of salt-affected soils and various classification schemes are used in different countries. Some of the soil types and soil forming processes are still lacking precise diagnostics and are not sufficiently supported with acceptable numerical values, while others are well defined in regard of their morphology as well as physical and chemical properties. The definition of sodic and Solonetz soils are especially problematic, because both may develop where the ESP value is less than 15. The reason for this anomaly is probably due to the fact that if the soil is highly saline, negative adsorption effects cause an over-correction for soluble sodium in the determination of exchangeable sodium. Under these conditions the SAR-values are higher than the ESP-values.

There is a good correlation between the current South African soil classification system for the sixteen calcareous soils forms and international classification systems, but not for the two sodium dominant soil forms.

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CHAPTER 4: QUANTIFICATION OF THE SALT CONTENT OF SOUTH AFRICAN SOILS FOR DIFFERENT SOIL CLASSSES

4.1. INTRODUCTION

Salt-affected soils are represented differently in different soil classification systems and appear on different taxonomical levels (Szabolcs, 1998). Although sodium is not used, the presence of free carbonates, calcium carbonate, or calcium-magnesium carbonate in soil has been used in the South African soil classification system (Soil Classification Working Group, 1991) to define diagnostic horizons and materials and is also used as a family criterion.

Soils are inherently variable, both spatially and temporally in their physical and chemical characteristics. Usually the variability is much greater vertically than horizontally, resulting from the variability in the processes that originally formed the soils. The soil variability, in turn, will result in variability in the distribution of water and salts and in the ease with which they can be transported within, and removed from, the soil at a particular site. It is known that salts fluctuate from the topsoil to the subsoil during wet periods and from the subsoil to the topsoil during dry periods (Nell & Lea, 2004), complexing the quantification of salts per horizon, unless a large dataset is used to lessen the effect of temporal variations.

According to FAO (2001) salt-affected soils generally occur in regions that receive salts from other areas and water is the primary carrier. Although the weathering of rocks and minerals is the source of all salts, the salt-affected soils are rarely formed from in situ accumulation of salts. A well-developed profile in low rainfall areas usually carries at some point (usually in the C-horizon) a calcium carbonate accumulation greater than that of its parent material (Brady, 1990).

Van der Merwe (1940) said that saline soils in South Africa do not occur in extensive areas forming a climatogenic soil zone, but are found in small to fairly big patches in several soil groups, due to localised factors. He did, however, classify and map “Solonetzic Soils” as one soil group in his study on the “Soil Groups and Subgroups of South Africa”. According to him, this soil group, occurring in the south-central Free State, covers a fairly extensive area and lies between the Prairie Soils in the east, the Kalahari Sand on Limestone in the north-west and the Karoo or semi-desert soils in the west. The major portion of the soil group occurs in the Free State Province, with two comparatively small areas in the Eastern Cape Province. One area is confined to the Burgersdorp area and immediate surroundings, while the other has Queenstown as its centre.

4.2. METHODOLOGY

The application of pattern analysis to certain aspects of soil appears promising in theory, but in practice difficulties arise due to the layered or structured nature of soils. In attempting to cope with the structured nature of soils, a number of models have been proposed. Williams (1976) describes four such models: the soil as (1) an isotropic body; (2); a sequence of layers (3) a set of depth functions; and (4) an array of layer attributes. It was decided to regard the soil profile as an array of layer attributes and to consider the profiles as made up of layers equivalent in most cases to the traditional A (topsoil), B, and C (subsoil) horizons. Possible objections to such layer selection include the subjective choice of horizon designation, lack of comparative horizons in certain soils and the fact that depth differences within and between horizons are not considered. It was further decided to also consider the soil profile as an isotropic body and to use only the highest value in a profile, because of the dynamic nature of salt-affected soils.

Elementary statistical techniques such as median, lower quartile, upper quartile, and average were used to identify relationships between the soil classes (Statgraphics, 2005). The emphasis was, however, on the median, although mathematically it is more complex to use than the average value. The main advantage is that the median is not disturbed by the size of extreme values (outliers) or significant skewness. The values for EC and ESP were log-transformed to make their distribution to follow the normal distribution and to determine the significant differences between classes. The pH_{water} values were not transformed, because it is already in a log-transformed variable.

The 95% Bonferroni multiple comparison procedure was used to determine which means are significantly different from which others, because of the unequal sample sizes between the different soil classes. The Kruskal-Wallis test was also used to determine which medians were significantly different from which other, because of the known presence of outliers.

In this dissertation the term "outlier" is not being used in its statistical meaning, *i.e.* being "any observation that appears surprising or discrepant to the investigator" or "any observation that is not a realization from the target distribution" (Beckman & Cook, 1983). It is used here as meaning an observation that deviates markedly, for obvious and/or explicable reasons, from the other members of the population, and as such is representative of typical variability in a natural situation.

Coordinates of the soil profiles were imported into ArcView 9.2 to map the positions of the profiles on a national scale. As most of the points were captured by reading off the positions of the profiles from old 1:50 000 topo cadastral map sheets published in Cape datum, and before using GPS's and being aware of setting datum's, the assumption was made that all points were in Cape datum and defined as such in ArcView. The newly created point file was transformed to the WGS84 datum to be overlaid with other data.

Soluble salts occur in significant proportions in soils of arid and semi-arid areas where they accumulate because annual precipitation is insufficient to leach the salts. According to Netterberg (1969), hardpan and boulder calcretes generally only occur in areas receiving less than 550 mm of rainfall per year. It was therefore decided to divide South Africa into a high rainfall area (>550 mm) and a low rainfall area (<550 mm), as portrayed in Figure 2.1 in Chapter 2. An average annual rainfall value for each profile was obtained by overlaying the points with the modelled 1 km × 1 km average annual rainfall grid from the AgroMet databank at the ARC-Institute for Soil, Climate and Water. This was done by running the Extract Values to Point wizard in the Spatial Analyst module of ArcGIS. Regression analysis and spatial modelling were used during the development of the surface.

The 73 soil forms used by the Soil Classification Working Group (1991) were organized into 11 groups based on predominantly, a distinctive subsoil horizon or material (Table 4.1). The classes were predominantly focused on the expression of a secondary accumulation of carbonates, structure development, and wetness. The groups proposed by Fey (2005) were not used, although certain soils classes are nearly the same. The biggest difference between the two groupings occurs in Fey's Duplex soil group that was further divided into a neocutanic, prismacutanic, and pedocutanic and red structured classes. This was done because Nell (1991) and Nell & Bennie (1991) found that there were significant differences in salt content between these classes.

TABLE 4.1 Grouping of soil forms based on the presence of specific diagnostic horizons or materials

Soil Classes	Soil Form
Calcic	Montagu, Augrabies, Brandvlei, Coega, Addo, Prieska, Trawal, Plooyesburg, Etosha, Mollopo, Askham, Kimberley, Kinkelbos, Steendal, Immerpan, Gamoep
Alluvial and Aeolian	Dundee, Namib
Neocutanic	Tukulu, Oudtshoorn, Oakleaf, Sweetwater, Vilafontes
Pedocutanic and Red Structured	Sepane, Valsrivier, Swartland, Lusiki, Bonheim, Klapmuts, Shortlands
Prismacutanic	Sterkspruit, Estcourt
Vertic	Arcadia
Hydromorphic	Rensburg, Katspruit, Kroonstad, Thukulu, Champagne, Constantia, Pinedene, Willobrook
Plinthic	Longlands, Wasbank, Avalon, Dresden, Glencoe, Bainsvlei, Bloemdal, Sepane, Avalon, Westleigh
Apedal	Griffin, Clovelley, Garies, Hutton, Pinedene, Kranskop, Magwa, Inanada, Constantia, Fernwood
Lithosols	Mispah, Glenrosa, Mayo, Milkwood, Nomanci, Knersvlakte, Cartref
Podzolic	Lamotte, Concordia, Houwhoek, Groenkop, Pinegrove, Witfontein

Soil samples were analyzed in the laboratories of the ARC-ISCW for pH_{water}, electrical conductivity, and cation exchange capacity. In addition extractable- and soluble cations were both done to calculate the exchangeable cations using methods described by the Non-Affiliated Soil Analysis Work Committee (1991).

For the majority of the samples in the database, analysed between 1970 and 1980, the cation exchange capacity, sodium, calcium, and magnesium contents were determined by LiCl extraction. The LiCl solution served as extractant for exchangeable plus soluble cations and at the same time saturated the soil's exchange complex with Li. After removal of non-adsorbed Li with ethyl alcohol, the adsorbed Li was displaced from the Li-saturated soil with $Ca(NO_3)_2$ and then taken as an index of the CEC. Soluble cations were determined separately in soils containing significant quantities of soluble salts (electrical resistance <460 Ω). These were subtracted from the LiCl-extractable cations to obtain the exchangeable cations. The LiCl extracting solution (0.5 mol L^{-1} LiCl, buffered at pH 8) was used instead of the 0.25 mol L^{-1} $BaCl_2$ as recommended by Peech (1965). In soils containing lime or gypsum or those with a very high salt content, not all the water soluble salts were dissolved in the saturation extract (Land Type Survey Staff, 1987). In these cases, the sum of exchangeable cations is higher than the CEC. Less than 12% of samples used in this study were analysed by extraction with LiCl. These samples were also predominantly from the higher rainfall areas in South Africa and therefore largely non-saline and non-sodic. Any discrepancies in the results between the two methods are therefore expected to be negligible for the purpose of quantification of salinity and sodicity. Results obtained from the LiCl and NH_4OAc analyses were therefore pooled in this study.

Soil samples in the database from 1980 onwards were predominantly analysed for CEC and cations using NH_4OAc (1 mol dm^{-3}, pH7) as extractant. According to Land Type Survey Staff (1987) the correlation between CEC as determined by LiCl and NH_4OA_c extractants was good (R^2 of 0.95), with NH_4OA_c giving values on average 14% higher than LiCl. The individual cations extracted with these two solutions were in good agreement, with the exception of K. This implies very little difference between the sums of cations determined using the LiCl and NH_4OA_c extracting methods. This is somewhat contradictory to the remark made by the Non-Affiliated

Soil Analysis Working Committee (1990) that "the NH_4OA_c method does not give accurate results with respect to the exchangeable plus water soluble cation status". Saturation extractable cations were determined by filtration under suction of the water saturated soil paste. For the majority of the samples in the database that were analysed since 1980 the electrical resistance <460 Ω rule was not applied. Water saturation extractable cations (and electrical conductivity) were therefore determined on the majority of samples, including saline and non-saline soils.

Soil pH_{water} was determined using a 1:2.5 soil to water suspension.

4.3. RESULTS AND DISCUSSION

The large differences in the median and average values for salinity as indicated by electrical conductivity (Table 4.2 to Table 4.4) and sodicity, as indicated by the exchangeable sodium percentage (Table 4.5 to Table 4.7), are a clear indication of the variability and skewness of the data. To further divide soil classes into high and low rainfall classes does not remove the skewness from the salinity and sodicity data. Outliers with values several hundred percent higher than the lowest value were not unusual. As was previously stated, the term "outlier" is not being used in its statistical meaning, *i.e.* being "any observation that appears surprising or discrepant to the investigator" but rather "any observation that is not a realization from the target distribution". The small differences between the average and median pH_{water} values (Table 4.8 to Table 4.10) are indicative of a normal distribution pattern and a parameter that is buffered against large fluctuations. For that reason, the data for electrical conductivity and exchangeable sodium percentage were log-transformed and not the pH_{water} data to draw the Box and Wisker Plots (Figure 4.1 to 4.6).

Significant differences amongst the medians at the 95% confidence level for electrical conductivity in the topsoil and subsoil between rainfall classes within the calcic, alluvial/aeolian, neocutanic, lithosols, pedocutanic/red structured, hydromorphic, prismacutanic, apedal, and plinthic soil (in the subsoil) occur (Table 4.2 to Table 4.4). This is an indication of the importance of rainfall and leaching on salt movement, even within the same soil class. There is no statistically significant difference amongst the medians for the topsoil and subsoil at the 95% confidence level, between rainfall classes for vertic, podzolic and for the topsoil of the plinthic class. Possible reasons for this inconsistency are that the leaching potential for vertic soils is a great deal lower than that for other soil classes (because of the high clay content and resulting low infiltration rate). The podzolic soils are mostly found in areas where the annual rainfall is higher than 550 mm and for the plinthic class, because of the capillary movement of water and salts from the fluctuating watertable in the subsoil to the topsoil, which occurs under both low- and high rainfall conditions to the same degree.

There is a decrease in electrical conductivity for all the topsoil horizons, as indicated by the median value: vertic >alluvial/aeolian >calcic >neocutanic >pedocutanic/red structured >prismacutanic >lithosols >hydromorphic >plinthic >apedal >podzolic soil classes (Table 4.2). For the eleven soil classes, 27 different pairs show statistical differences at the 95% confidence level for the topsoil horizons (APPENDIX B.1). The alluvial/aeolian soil class is significantly different at the 95% confidence level from ten and the vertic soil class from three soil classes. If the log-transformed data in the Box and Wisker Plot is used, the vertic soil class is, however, clearly significantly different from all other soil classes (Figure 4.1).

Median electrical conductivity decreases for all the subsoil horizons (Table 4.3) from calcic >alluvial/aeolian >prismacutanic >neocutanic >pedocutanic/red structured >hydromorphic >lithosols >plinthic >apedal >podzolic. Electrical conductivity decreases in the order vertic >calcic >prismacutanic >alluvial/aeolian >neocutanic >pedocutanic/red structured >hydromorphic >lithosols >plinthic >apedal and podzolic if the highest value in a profile is used. For the neocutanic subsoils to have a higher salinity than the pedocutanic/ red structured subsoils is not typical. This irregularity can be ascribed to the high amount of samples from the high rainfall class (more leaching) for the pedocutanic / red structured soil class compared to the neocutanic soil class. If only median values from the low rainfall class are used, the sequence is calcic >alluvial/aeolian >prismacutanic >pedocutanic / red structured >neocutanic >lithosols >hydromorphic >apedal >podzolic. This is more in an agreement with the findings of Nell (1991) and Nell and Bennie (1991), that there is an increase in salt content with an increased degree of structural development (neocutanic to pedocutanic to prismacutanic). The apparent anomaly of the relatively high salt content values for the alluvial / aeolian soil class can be attributed to the position in the landscape of the alluvial soil in lower terrain units and the accompanying accumulation of salts and because most of the aeolian soils are found in the low rainfall areas. Pedogenetic changes have been minimal in transported alluvial and aeolian soils and it is reflected in the low degree of leaching of salts. The lowest electrical conductivity for the topsoil, subsoil and the highest value in a profile were found for soils in the plinthic-, apedal- and podzolic soil classes. This is an indication of good leaching conditions for salt out of these soils.

For the eleven soil classes, 31 different pairs showed statistical differences at the 95% confidence level for the subsoil horizons in terms of electrical conductivity. Soil of the alluvial/aeolian class was significantly different from all other soil classes, except for the subsoil horizons of soils in the vertic class (APPENDIX B.2). When the highest value in a profile was used, 35 different pairs showed differences at the 95% confidence level for electrical conductivity and again the alluvial/aeolian class was the only soil class that was significantly different from all other soil classes (APPENDIX B.3).

When the 400 mS m^{-1} threshold value was used to separate saline from non-saline soils, for the topsoil and subsoil horizons, in the < 550 mm annual rainfall class, only the alluvial/aeolian and hydromorphic classes tended to be saline, if the average values were used as an indicator and none if the median values were used (Table 4.2 and 4.3). When the highest value in a profile was used, soils of the neocutanic and calcic classes also tended to be saline in the < 550 mm annual rainfall class, together with soils of the alluvial/aeolian and hydromorphic classes, when the average values were used as an indicator of salinity, and again none if the median values were used (Table 4.4).

TABLE 4.2 Electrical Conductivity (mS m^{-1}) statistics for different topsoil horizons

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Vertic	<550	159	59	230	228	310	62
	>550	143	55	233	197	274	167
	All	**150**	59	230	205	284	229
Alluvial / Aeolian	<550	59	25	215	543*	1389	115
	>550	35	23	62	69*	110	52
	All	**51**	24	158	397	1173	167
Calcic	<550	47	30	98	233*	979	285
	>550	35	23	59	67*	156	90
	All	**41**	28	87	193	859	375
Neocutanic	<550	45	30	112	278*	970	547
	>550	26	17	41	42*	64	336
	All	**36**	23	70	188	772	883
Pedocutanic/ Red structured	<550	56	34	125	209*	588	333
	>550	36	25	59	63*	114	758
	All	**41**	27	78	108	345	1091
Prismacutanic	<550	41	21	80	111*	223	134
	>550	28	19	41	47*	74	261
	All	**28**	19	50	69	146	395
Lithosols	<550	38	26	68	120*	512	310
	>550	26	18	38	38*	88	1097
	All	**28**	18	42	56	254	1407
Hydromorphic	<550	26	15	137	522*	2067	105
	>550	25	15	49	68*	203	424
	All	**26**	15	53	158	953	529
Plinthic	<550	22	13	21	28	37	125
	>550	21	14	34	34	180	520
	All	**21**	14	34	33	57	645
Apedal	<550	25	16	41	78*	349	1016
	>550	17	12	26	24*	33	1962
	All	**20**	12.8	31	43	207	2978
Podzolic	<550	26	7	36	23	15	3
	>550	20	9	28	20	14	22
	All	**17**	9	28	20	13	25

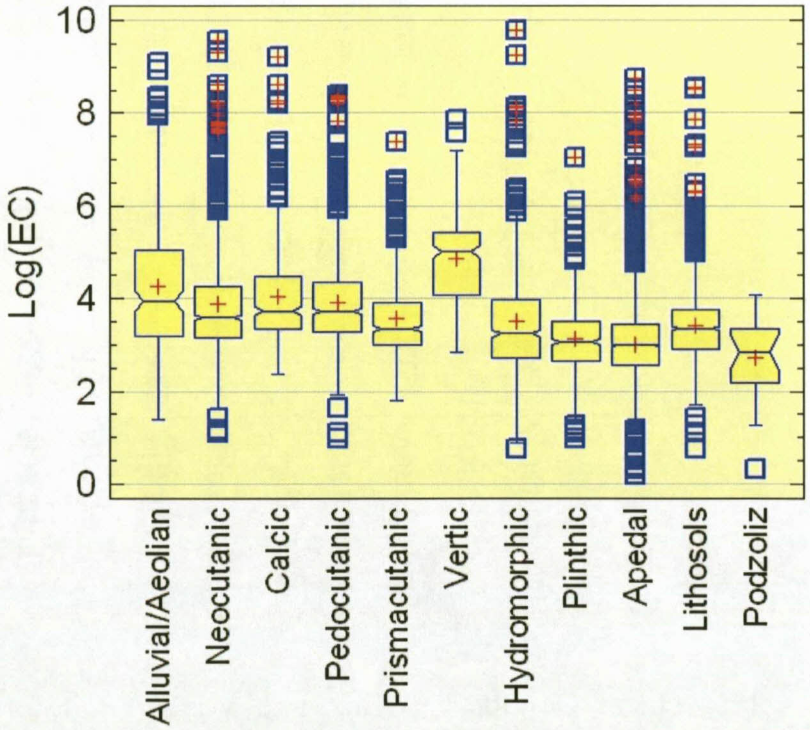

FIGURE 4.1 Electrical Conductivity Box and Wisker Plot for different topsoil horizons.

TABLE 4.3 Electrical Conductivity (mS m^{-1}) statistics for different subsoil horizons

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Calcic	<550	120	49	310	341*	693	369
	>550	83	41	186	185*	286	142
	All	**107**	43	275	298	612	511
Alluvial / Aeolian	<550	115	49	**489**	**680***	1370	107
	>550	30	11	48	51*	76.	47
	All	**71**	30	279	488	1178	154
Prismacutanic	<550	114	49	251	233*	397	208
	>550	49	28	140	134*	253	403
	All	**70**	33	178	168	313	611
Neocutanic	<550	100	45	350	**405***	855	930
	>550	26	15	49	61*	116.	463
	All	**59**	30	200	291	720	1393
Pedocutanic/ Red structured	<550	105	49	238	298*	679	479
	>550	41	26	87	98*	199	1031
	All	**54**	32	128	161	426	1510
Hydromorphic	<550	39	13	231	**599***	2087	155
	>550	26	12	59	63*	116	463
	All	**28**	12	72	197	1073	618
Lithosols	<550	67	36	147	382*	1566	121
	>550	21	15	38	37*	54	424
	All	**28**	17	52	113	751	545
Plinthic	<550	29	16	49	53*	140	230
	>550	18	11	32	33*	72	943
	All	**20**	12	36	37	90	1173
Apedal	<550	33	20	59	151*	475	1410
	>550	13	7	25	22*	36	3137
	All	**18**	9	36	62	273	4547
Podzolic	<550	15	7	28	18	12	7
	>550	12	4	18	16	18	48
	All	**12**	4	18	16	17	55

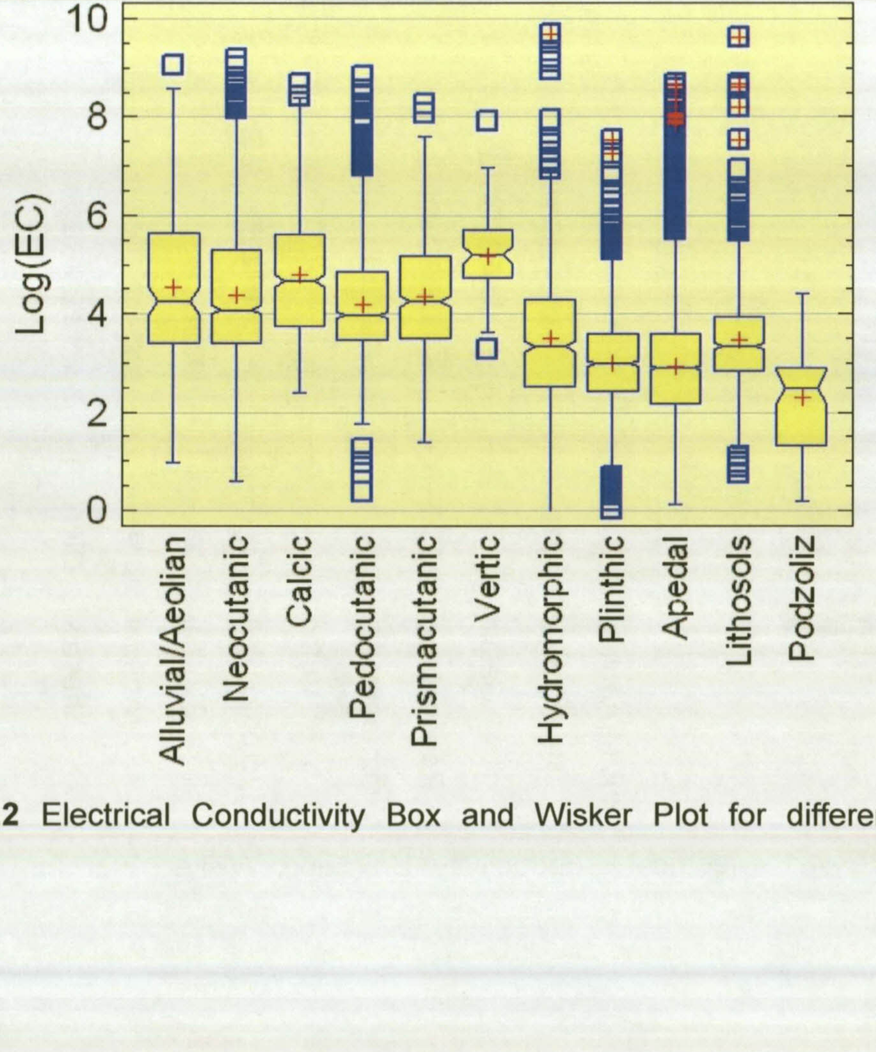

FIGURE 4.2 Electrical Conductivity Box and Wisker Plot for different subsoil horizons.

TABLE 4.4 Electrical Conductivity (mS m^{-1}) statistics for the highest value in a profile

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Vertic	<550	190	99	300	280	346	53
	>550	138	52	233	203	298	130
	All	**159**	59	252	225	313	183
Calcic	<550	108	41	315	412*	1063	306
	>550	87	41	224	206*	311	97
	All	**103**	41	290	362	938	403
Prismacutanic	<550	173	90	354	323*	478	136
	>550	59	34	165	157*	283	272
	All	**103**	40	232	213	368	408
Alluvial / Aeolian	<550	76	25	385	878*	1823	107
	>550	38	23	88	88*	132	44
	All	**60**	23	273	648	1573	151
Neocutanic	<550	115	45	412	514*	1183	594
	>550	28	18	52	88*	113	405
	All	**54**	28	203	331	937	999
Pedocutanic/ Red structured	<550	124	54	274	347*	750	346
	>550	41	28	87	96*	188	971
	All	**49**	32	126	162	431	1317
Hydromorphic	<550	84	26	323	706*	2330	104
	>550	30	17	64	80*	205	451
	All	**35**	17	92	197	1043	555
Lithosols	<550	42	28	89	203*	1013	318
	>550	27	18	41	41*	91	1129
	All	**28**	20	47	27	20	1447
Plinthic	<550	36	20	59	66	168	137
	>550	22	15	40	41	87	785
	All	**24**	15	43	45	103	922
Apedal	<550	36	22	59	150*	504	1161
	>550	18	11	30	28*	42	2971
	All	**22**	13	39	62	275	4132
Podzolic	<550	28	10	36	25	13	3
	>550	20	14	36	27	21	25
	All	**20**	13	36	26	20	28

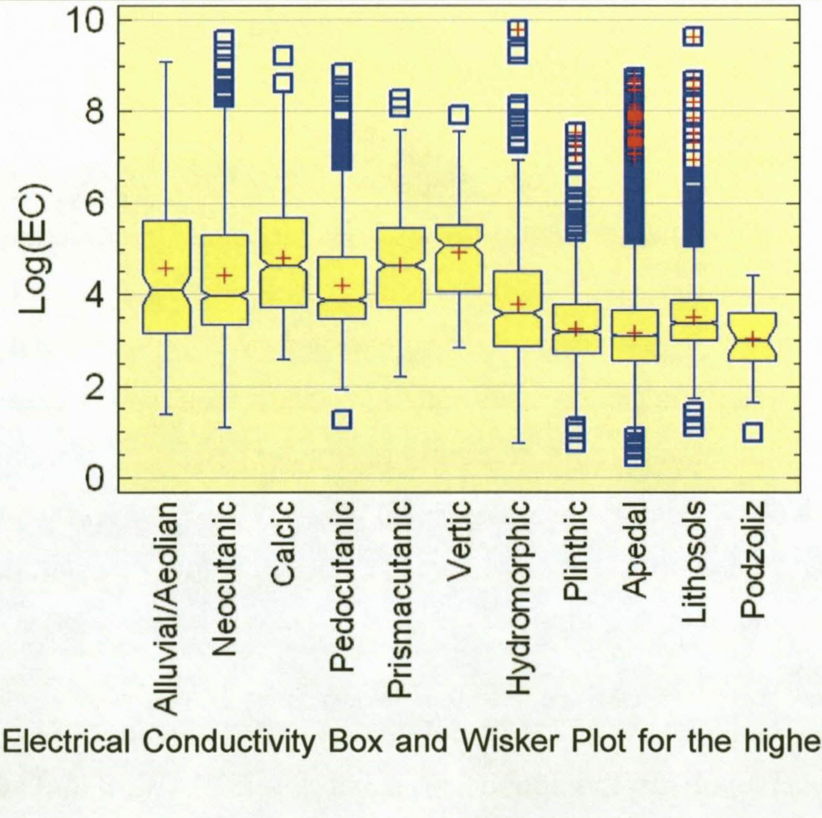

FIGURE 4.3 Electrical Conductivity Box and Wisker Plot for the highest value in a profile.

Significant differences amongst the medians at the 95% confidence level for ESP in the topsoil and subsoil between rainfall classes within the calcic, alluvial/aeolian, neocutanic, pedocutanic/red structured, hydromorphic, plinthic (in the subsoil), podzolic, prismacutanic, lithosols and apedal soil classes occur (Table 4.5 to Table 4.7). This is an indication of the importance of rainfall and leaching on the movement of salts in general, and on Na specifically, even within the same soil class. There is not a statistically significant difference amongst the medians for the topsoil and subsoil at the 95% confidence level, between rainfall classes for vertic and plinthic soil classes and if the highest value in a profile is used for the prismacutanic soil class. Possible reasons for this inconsistency are that the leaching potential for vertic soils is a great deal lower than other soil classes, because of the high clay content and the swelling properties (low infiltration rate when wet, and high water holding capacity). According to Bresler (1981), swelling of soil clay particles causes the size of larger soil pores to decrease. Dispersion and movement of clay platelets further block soil pores. The strong structure of vertic and prismacutanic soils are likely to cause the flow of water to be confined to macro-pore flow, which result in low leaching. The reason for the anomaly for the plinthic class is probably because of the capillary movement of water and salts from the fluctuating watertable in the subsoil to the topsoil, which occurs under both low- and high rainfall conditions.

There is a decrease in sodicity, as measured by the ESP for all topsoil horizons, as indicated by the median value from alluvial/aeolian >prismacutanic >hydromorphic >vertic >neocutanic >pedocutanic/red structured >calcic >lithosols >plinthic >apedal and podzolic (Table 4.5). The order for the subsoil horizons range from prismacutanic >calcic >hydromorphic >alluvial/aeolian >neocutanic >lithosols >vertic >pedocutanic/ red structured >plinthic >apedal and podzolic (Table 4.6), and for the highest value in a profile from prismacutanic >podzolic >hydromorphic >calcic >alluvial/aeolian >vertic >neocutanic >plinthic >pedocutanic/red structured >lithosols and apedal (Table 4.7).

For the 11 soil classes, 12 different pairs showed statistical differences at the 95% confidence level for the topsoil horizons for ESP, with the alluvial/aeolian and hydromorphic classes, both having statistical differences with four other classes

(APPENDIX C.1). For the subsoil horizons, 27 different pairs showed statistical differences at the 95% confidence level and with the alluvial/aeolian class that had statistical differences with all other classes, except with hydromorphic class (APPENDIX C.2). When the highest value in a profile was considered, 24 different pairs showed differences at the 95% confidence level (APPENDIX C.3) for ESP, with the alluvial/aeolian and neocutanic classes, both having statistical differences with four other classes.

For the 11 soil classes, soils of the plinthic, apedal and podzolic soil classes had the lowest median ESP-values in the topsoil (Table 4.5) and subsoil (Table 4.6), under all rainfall conditions. When the highest value in a profile was used, the podzolic soil class had the second highest median ESP-value. This anomaly was probably because some podzolic C horizons have a strong hydromorphic tendency, or the most likely scenario, that the podzolic soils are mostly found near coastal areas where there are atmospheric deposits of Na from the ocean and together with the low cation exchange capacity of podzolic soils resulting in relatively high ESP-values. Ellis and Van Laar (1999) established that soils with podzol B horizons have a higher reserve of Na, and that trees planted closer to the sea accumulate more Na on the leaves than those planted further away.

The prismacutanic soil class has the highest median ESP value (8.4) of the 11 soil classes for the subsoil horizons (Table 4.6), the highest median ESP value (10.1) when the highest value in a profile is used (Table 4.7) and the joint highest median value (2.9) for the topsoil horizons (Table 4.5). As was indicated in Chapter 3, an ESP boundary limit of 15 for sodic conditions is problematic and must be regarded as somewhat arbitrary and tentative, and that the classical concept of a solonetz B does not always apply for South African prismacutanic horizons. A reason for this is that certain prismacutanic horizons develop where the ESP values are less than 15, and in other circumstances soils with an ESP value of 15-20, or even more, do not manifest prismacutanic morphological features.

When 15 is used to separate sodic from non-sodic soils based on the median ESP values, for both the topsoil and subsoil horizons, none of the soil classes are sodic (Table 4.5 and 4.6).

When 15 is used to separate sodic from non-sodic soils based on the average ESP values, the topsoil of the hydromorphic and alluvial/aeolian soil classes are sodic when the annual rainfall is < 550mm, (Table 4.5). The subsoil of soils in the prismacutanic, hydromorphic, alluvial/aeolian, neocutanic and lithosols are sodic, when the annual rainfall is < 550 mm (Table 4.6). For the average highest value in a profile, soils of the prismacutanic, hydromorphic, alluvial/aeolian and neocutanic classes are sodic when the annual rainfall is < 550 mm and for prismacutanic even when the annual rainfall is >550 mm (Table 4.7).

When a value of 6 is used to separate sodic from non-sodic soils, based on the ESP median values, none of the topsoil classes are sodic. For the subsoil horizons soil of the prismacutanic (all rainfall conditions), calcic, hydromorphic, alluvial/aeolian and neocutanic soil classes are sodic (Table 4.6), and for the average highest value in a profile, soils of the prismacutanic, podzolic hydromorphic, calcic and neocutanic classes are sodic (Table 4.7) when the annual rainfall is < 550 mm.

When a value of 6 is used to separate sodic from non-sodic soils, based on the ESP average values, the topsoil's of the hydromorphic, prismacutanic, neocutanic, calcic and alluvial/aeolian soil classes are sodic when the annual rainfall is < 550mm, (Table 4.5). For the subsoil, most soil classes are sodic, except for soils of podzolic and plinthic classes, when the annual rainfall is < 550 mm (Table 4.6). For the average highest value in a profile, most soil classes are sodic, except for soils of podzolic (< 550 mm rainfall), pedocutanic/red structured, lithosols and apedal, when the annual rainfall is >550 mm (Table 4.7).

TABLE 4.5 Exchangeable sodium percentage statistics for different top soil horizons

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Alluvial / Aeolian	<550	4.7	1.7	12.5	**15.6***	34.5	121
	>550	1.8	0.8	3.4	2.4*	2.3	63
	All	**2.9**	1.3	7.2	11.1	28.7	184
Prismacutanic	<550	3.5	1.5	7.7	6.9*	11.1	137
	>550	2.8	1.6	5.0	4.5*	4.3	256
	All	**2.9**	1.6	6.0	5.1	7.5	393
Hydromorphic	<550	4.9	1.9	10.0	**27.6***	158.6	105
	>550	2.4	1.0	4.9	4.0*	6.3	416
	All	**2.7**	1.1	5.5	8.7	71.8	521
Vertic	<550	3.5	1.2	6.9	5.1	5.9	72
	>550	2.0	0.8	5.6	5.6	9.1	179
	All	**2.3**	0.9	6.0	5.5	8.3	251
Neocutanic	<550	2.6	1.3	7.0	10.5*	30.7	637
	>550	1.2	0.7	2.6	3.1*	7.1	396
	All	**2.0**	1.0	4.9	7.7	24.8	1033
Pedocutanic/ Red structured	<550	2.2	1.0	6.2	7.4*	17.6	409
	>550	1.5	0.8	3.3	3.4*	6.8	712
	All	**1.7**	0.8	4.1	4.9	12.1	1121
Calcic	<550	1.4	0.5	3.3	6.3*	17.0	130
	>550	1.7	1.1	3.6	5.2*	9.3	30
	All	**1.6**	0.7	3.3	6.1	15.9	160
Lithosols	<550	2.1	1.0	4.8	5.6*	17.6	299
	>550	1.5	0.9	2.5	2.2*	3.1	926
	All	**1.6**	0.9	2.9	3.1	9.2	1225
Plinthic	<550	2.2	0.6	2.6	2.2	2.5	125
	>550	1.6	0.6	2.9	2.8	5.5	530
	All	**1.6**	0.6	2.8	2.6	5.1	655
Apedal	<550	2.0	0.9	3.8	5.1*	20.6	1047
	>550	0.9	0.4	1.6	1.4*	2.7	1980
	All	**1.2**	0.5	2.2	2.7	12.4	3027
Podzolic	<550	1.8	0.8	2.8	1.8*	1.2	4
	>550	2.9	1.4	3.9	4.0*	4.7	23
	All	**2.9**	1.1	3.8	3.7	4.4	27

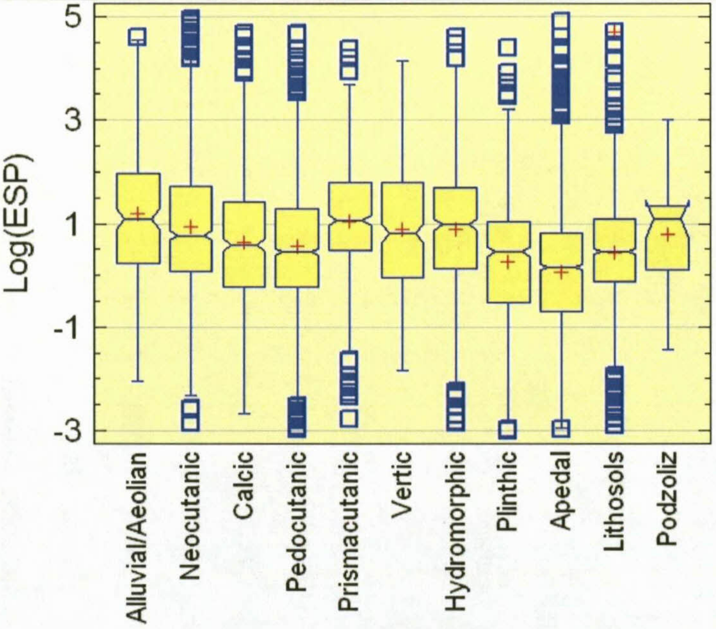

FIGURE 4.4 Exchangeable sodium percentage Box and Wisker Plot for different topsoil horizons.

TABLE 4.6 Exchangeable sodium percentage statistics for different subsoil horizons

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Prismacutanic	<550	9.1	4.7	**19.2**	**15.1***	18.3	211
	>550	8.0	4.2	**15.8**	12.2*	12.6	437
	All	**8.4**	4.4	**17.1**	13.1	14.7	648
Calcic	<550	5.3	2.0	**15.0**	14.0*	22.8	382
	>550	7.1	3.5	**15.9**	11.6*	11.8	142
	All	**6.1**	2.3	**15.2**	13.3	13.3	524
Hydromorphic	<550	7.7	3.5	**24.1**	**42.6***	130.7	151
	>550	4.1	1.8	8.8	6.9*	8.4	567
	All	**4.8**	2.0	10.0	14.4	61.9	718
Alluvial / Aeolian	<550	6.1	2.5	**30.8**	**32.7***	94.7	114
	>550	1.9	1.0	4.1	2.9*	2.6	68
	All	**4.0**	1.5	10.3	**21.6**	76.2	182
Neocutanic	<550	6.5	2.3	**18.4**	**17.9***	32.2	913
	>550	2.0	1.1	3.9	4.8*	11.0	466
	All	**3.5**	1.6	11.5	13.5	27.6	1379
Lithosols	<550	3.6	1.7	10.6	**15.9***	45.2	123
	>550	2.8	1.5	4.7	4.2*	5.3	469
	All	**3.0**	1.6	5.2	6.7	21.6	592
Vertic	550	3.4	0.2	1.2	5.1	5.9	72
	>550	2.0	0.8	5.6	5.6	9.0	179
	All	**2.6**	0.9	6.0	5.5	8.3	251
Pedocutanic/ Red structured	<550	3.4	1.5	13.5	11.5*	21.4	480
	>550	2.0	1.0	4.6	5.5*	15.0	1121
	All	**2.2**	1.1	6.5	7.3	17.4	1601
Plinthic	<550	2.1	1.1	4.3	4.4	9.7	224
	>550	2.2	1.1	4.2	4.0	6.8	1107
	All	**2.2**	1.1	4.2	4.1	7.4	1331
Apedal	<550	2.5	1.3	5.9	9.1*	22.8	1431
	>550	1.2	0.6	2.2	2.2*	19.5	3551
	All	**1.5**	0.7	2.8	4.1	20.7	4982
Podzolic	<550	1.5	0.4	2.3	1.5*	1.1	8
	>550	4.2	2.6	6.8	5.9*	5.7	50
	All	**3.6**	2.2	6.3	4.1	5.5	58

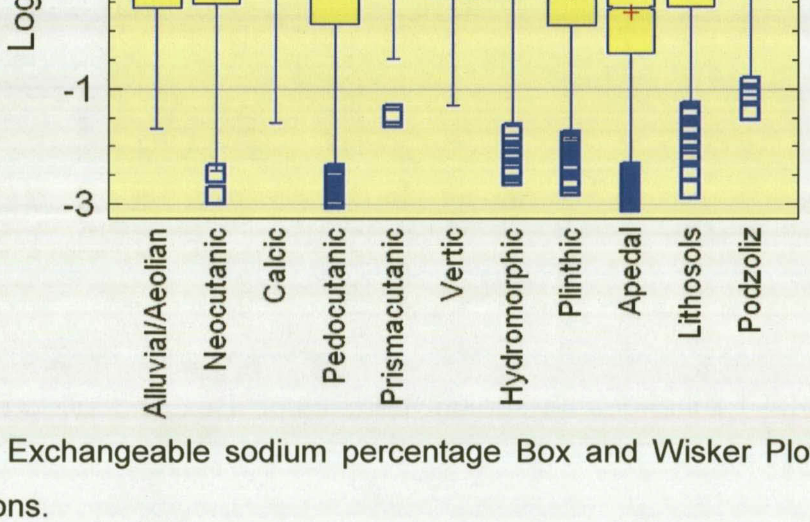

FIGURE 4.5 Exchangeable sodium percentage Box and Wisker Plot for different subsoil horizons.

TABLE 4.7 Exchangeable sodium percentage statistics for the highest value in a profile

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Prismacutanic	<550	**10.9**	4.7	**21.8**	**17.3**	18.9	135
	>550	**9.6**	4.3	**18.0**	**18.0**	13.3	267
	All	**10.1**	4.4	**19.6**	**17.7**	15.5	402
Podzolic	<550	**2.0**	1.1	2.8	2.0*	1.1	4
	>550	**5.8**	3.6	12.5	8.1*	7.3	26
	All	**5.3**	2.9	10.0	7.3	7.1	30
Hydromorphic	<550	**10.0**	5.0	**30.2**	**56.5***	198.0	105
	>550	**4.6**	2.2	10.0	8.0*	10.0	414
	All	**5.2**	2.4	12.0	17.8	91.1	519
Calcic	<550	**4.2**	1.4	12.7	13.1*	24.0	336
	>550	**6.9**	2.4	**16.2**	11.5*	16.1	104
	All	**4.9**	1.7	13.7	12.7	21.8	440
Alluvial / Aeolian	<550	**5.2**	1.9	**16.8**	**31.0***	96.8	114
	>550	**2.1**	1.2	4.2	3.5*	3.1	55
	All	**3.9**	1.6	10.0	22.0	80.4	169
Vertic	<550	**5.1**	2.0	9.7	7.0	6.5	60
	>550	**3.1**	1.4	8.6	8.1	11.4	126
	All	**3.8**	1.6	9.6	7.8	10.1	186
Neocutanic	<550	**7.5**	2.6	**23.0**	**22.2***	43.3	566
	>550	**2.1**	1.2	4.2	5.2*	11.6	395
	All	**3.7**	1.8	12.5	15.2	35.0	961
Plinthic	<550	**3.1**	1.6	5.9	5.7	1.6	136
	>550	**2.4**	1.3	4.4	4.6	8.2	792
	All	**2.5**	1.3	4.6	4.7	1.3	928
Pedocutanic/ Red structured	<550	**3.5**	1.6	14.5	12.8*	23.5	345
	>550	**2.0**	1.1	4.3	5.5*	16.1	960
	All	**2.2**	1.2	6.0	7.4	18.6	1305
Lithosols	<550	**2.3**	1.1	5.0	8.9*	31.1	308
	>550	**1.9**	1.1	3.6	3.1*	4.3	946
	All	**2.0**	1.1	3.9	4.5	16.0	1254
Apedal	<550	**2.8**	1.5	5.9	9.4*	27.9	1180
	>550	**1.4**	0.7	2.4	2.4*	21.1	3018
	All	**1.7**	0.8	3.0	4.4	23.4	4198

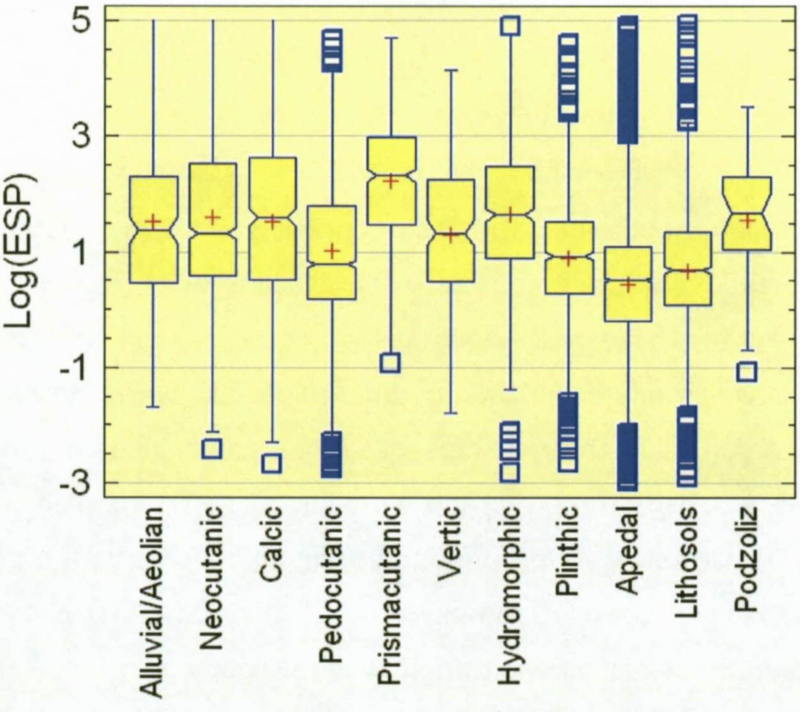

FIGURE 4.6 Exchangeable sodium percentage Box and Wisker Plot for the highest value in a profile.

The pH_{water} data is not skewed, with small differences between the median and average values (Table 4.8 to 4.10), which was not the case for ESP and electrical conductivity.

There was a decrease in pH_{water}, for all topsoil horizons (Table 4.8), as indicated by the median value, from the calcic >alluvial/aeolian >vertic >neocutanic >pedocutanic/ red structured >prismacutanic >lithosols >hydromorphic >plinthic >apedal to the podzolic soil class, for all the subsoil and highest value in a profile horizons from the calcic >alluvial/aeolian >neocutanic >prismacutanic >pedocutanic/ red structured >lithosols >hydromorphic >plinthic >apedal to the podzolic soil class (Table 4.9 and 4.10).

For the 11 soil classes, 46 different pairs showed statistical differences at the 95% confidence level for the topsoil and subsoil horizons, and 42 pairs if the highest value for pH_{water} in a profile was used (APPENDIX D.1 to 4.3).

Descriptive terms by Van der Watt and Van Rooyen (1995) commonly associated with ranges in pH_{water} are given in APPENDIX A. When the median pH_{water} in the topsoil was used, the calcic soil class was strongly alkaline, alluvial/aeolian, vertic, lithosols and neocutanic soil classes moderately alkaline and soils of the pedocutanic/red structured classes were mildly alkaline when the annual rainfall is < 550 mm (Table 4.8). When the median pH_{water} in the subsoil was used, calcic, alluvial/aeolian, neocutanic and prismacutanic soil classes were moderately alkaline and pedocutanic/red and lithosols mildly alkaline when the annual rainfall is < 550 mm (Table 4.9). When the median pH_{water} of the highest value in a profile was used calcic, alluvial/aeolian and neocutanic classes were strongly alkaline, vertic, prismacutanic and lithosols classes moderately alkaline and pedocutanic/red structured and hydromorphic classes mildly alkaline when the annual rainfall is < 550 mm (Table 4.10). Even under low rainfall conditions, the plinthic and podzolic soil classes are usually non-calcareous, and when the median values were considered, are classified as strongly acid to slightly acid.

TABLE 4.8 pHwater statistics for different topsoil horizons

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Calcic	<550	8.5	8.2	8.8	8.4	0.72	132
	>550	8.4	7.8	8.8	8.2	0.90	30
	All	**8.5**	8.1	8.8	8.4	0.76	162
Alluvial / Aeolian	<550	8.3	7.5	8.9	8.1*	0.97	124
	>550	7.1	6.2	8.1	7.1*	1.10	65
	All	**8.0**	7.1	8.6	7.8	1.13	189
Vertic	<550	8.1	7.9	8.6	8.1	0.61	62
	>550	7.7	7.0	8.3	7.6	0.90	212
	All	**7.9**	7.1	8.3	7.7	0.88	274
Neocutanic	<550	7.9	7.1	8.5	7.8*	0.95	667
	>550	6.3	5.8	6.9	6.4*	0.84	454
	All	**7.2**	6.3	8.1	7.2	1.12	1121
Pedocutanic/ Red structured	<550	7.5	6.8	8.2	7.5*	0.92	431
	>550	6.4	5.9	7.0	6.5*	0.84	796
	All	**6.7**	6.1	7.5	6.9	1.00	1227
Prismacutanic	<550	6.9	6.5	7.8	7.1*	0.85	141
	>550	6.2	5.8	6.7	6.3*	0.65	279
	All	**6.4**	6.0	7.0	6.6	0.82	420
Lithosols	<550	7.9	6.8	8.5	7.7	1.03	328
	>550	6.0	5.6	6.4	6.1	0.78	1181
	All	**6.2**	5.7	6.9	6.4	1.07	1509
Hydromorphic	<550	6.8	6.1	8.1	7.1*	1.23	111
	>550	6.1	5.5	6.8	6.3*	1.04	488
	All	**6.2**	5.6	7.1	6.4	1.12	599
Plinthic	<550	6.4	5.9	6.9	6.4	0.79	138
	>550	5.8	5.4	6.3	5.9	0.71	593
	All	**5.9**	5.5	6.4	6.0	0.76	731
Apedal	<550	7.2	6.3	8.1	7.2*	1.01	1087
	>550	5.5	5.1	6.1	5.7*	0.74	2176
	All	**5.9**	5.3	6.8	6.2	1.13	3263
Podzolic	<550	5.5	5.2	7.0	6.1	1.63	4
	>550	5.6	5.2	6.0	5.6	0.69	24
	All	**5.5**	5.2	6.0	5.7	0.86	28

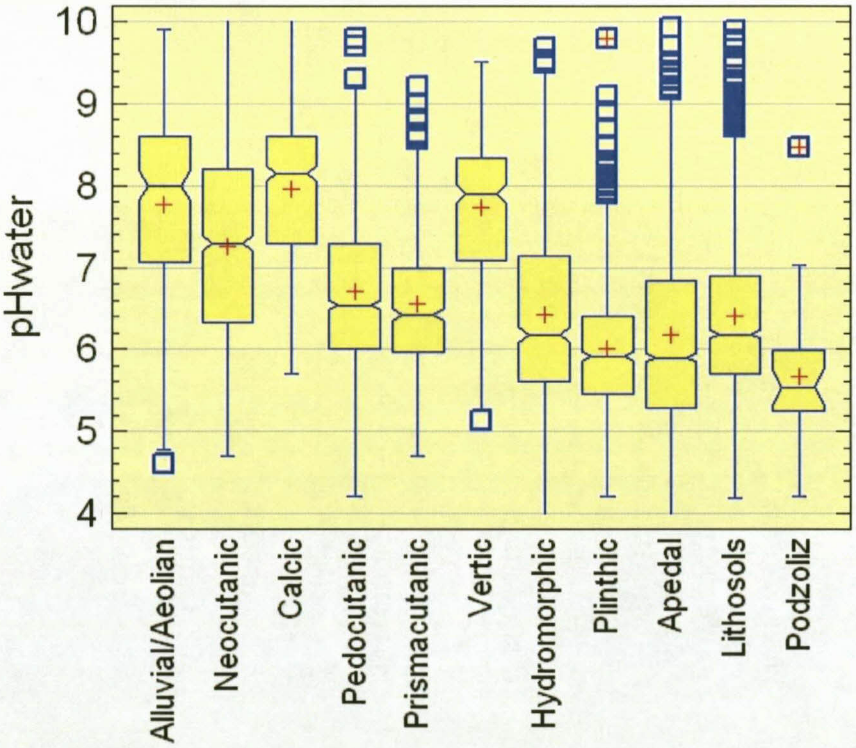

FIGURE 4.7 pH$_{water}$ Box and Wisker Plot for different topsoil horizons.

TABLE 4.9 pHwater statistics for different subsoil horizons

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Calcic	<550	8.3	7.9	8.7	8.3	0.66	388
	>550	8.3	8.0	8.7	8.4	0.64	148
	All	**8.3**	7.9	8.7	8.3	0.65	536
Alluvial / Aeolian	<550	8.3	7.5	8.6	8.1*	0.90	119
	>550	6.7	5.9	7.7	6.8*	1.03	61
	All	**8.0**	6.9	8.5	7.7	1.12	180
Neocutanic	<550	8.3	7.8	8.7	8.2*	0.90	932
	>550	6.8	6.0	7.6	6.8*	1.06	498
	All	**8.0**	7.0	8.5	7.7	1.14	1430
Prismacutanic	<550	7.9	7.1	8.4	7.8	1.02	215
	>550	7.1	6.4	8.0	7.2	1.04	423
	All	**7.4**	6.6	8.2	7.4	1.06	638
Pedocutanic/ Red structured	<550	7.6	6.9	8.3	7.6*	0.94	490
	>550	6.6	6.1	7.5	6.8*	0.96	1071
	All	**7.0**	6.3	7.8	7.1	1.02	1561
Lithosols	<550	7.4	6.7	8.2	7.4*	1.07	126
	>550	6.4	5.8	7.0	6.4*	0.89	454
	All	**6.5**	6.0	7.3	6.6	1.00	580
Hydromorphic	<550	7.0	6.2	8.0	7.1	1.18	161
	>550	6.5	5.7	7.4	6.6	1.16	527
	All	**6.5**	5.8	7.6	6.7	1.19	688
Plinthic	<550	6.4	5.8	6.9	6.4	0.92	239
	>550	5.9	5.4	6.4	6.0	0.82	1012
	All	**6.0**	5.4	6.6	6.1	0.86	1251
Apedal	<550	7.2	6.4	8.2	7.2*	1.15	1437
	>550	5.5	5.2	6.2	5.7*	0.75	3370
	All	**5.9**	5.3	6.8	6.2	1.13	4807
Podzolic	<550	5.7	5.2	5.9	5.9	1.15	8
	>550	5.7	5.3	6.1	5.7	0.60	50
	All	**5.7**	5.3	6.1	5.7	0.68	58

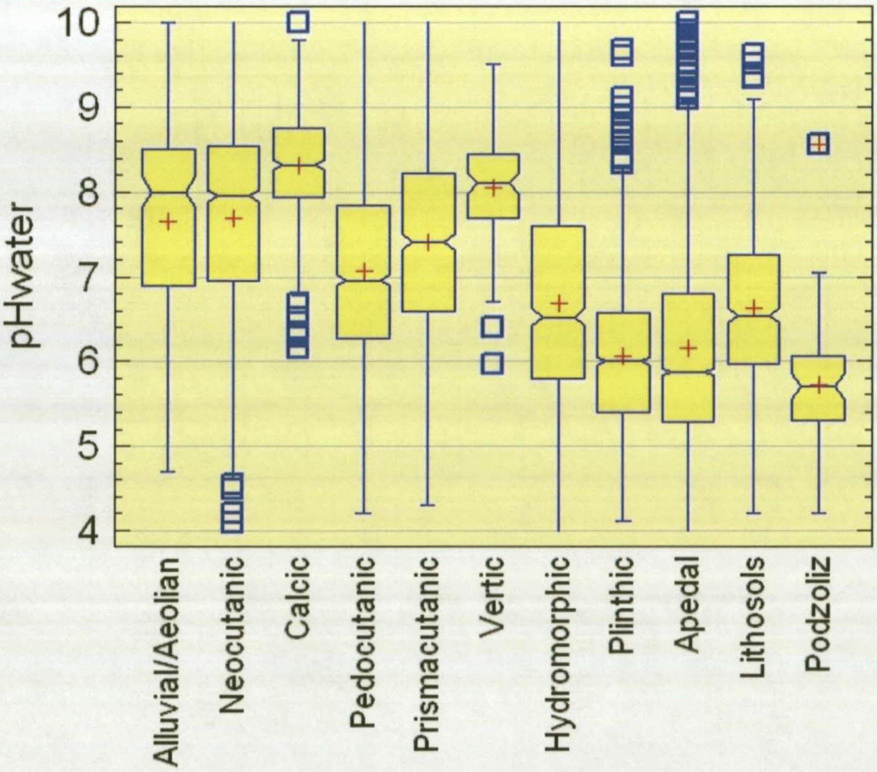

FIGURE 4.8 pH$_{water}$ Box and Wisker Plot for different subsoil horizons.

TABLE 4.10 pH$_{water}$ statistics for the highest value in a profile

Soil Class	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Calcic	<550	**8.6**	8.2	8.9	8.5	0.6	340
	>550	**8.5**	8.1	8.9	8.4	1.1	106
	All	**8.6**	8.2	8.9	8.5	0.7	446
Alluvial / Aeolian	<550	**8.6**	7.7	9.0	8.3*	0.9	117
	>550	**7.0**	6.3	8.2	7.0*	1.4	58
	All	**8.2**	7.1	8.8	8.2	1.3	175
Vertic	<550	**8.3**	7.9	8.7	8.2	0.6	52
	>550	**8.0**	7.1	8.4	7.8	0.9	160
	All	**8.1**	7.3	8.5	8.1	0.9	212
Neocutanic	<550	**8.5**	8.0	8.8	8.3*	0.9	597
	>550	**6.7**	6.0	7.6	6.8*	1.0	440
	All	**7.9**	6.8	8.6	7.7	1.2	1037
Prismacutanic	<550	**8.2**	7.4	8.6	8.0*	1.1	141
	>550	**7.3**	6.4	8.1	7.3*	1.1	289
	All	**7.6**	6.8	8.4	7.5	1.2	430
Pedocutanic/ Red structured	<550	**7.7**	7.0	8.4	7.7*	0.9	362
	>550	**6.5**	6.1	7.3	6.7*	1.2	1033
	All	**6.8**	6.2	7.7	6.9	1.2	1395
Hydromorphic	<550	**7.5**	6.5	8.5	7.5*	1.2	111
	>550	**6.4**	5.7	7.5	6.6*	1.3	508
	All	**6.5**	5.8	7.7	6.7	1.3	619
Lithosols	<550	**8.0**	6.9	8.5	7.7*	1.0	334
	>550	**6.1**	5.6	6.7	6.2*	0.9	1206
	All	**6.3**	5.8	7.2	6.5	1.2	1540
Plinthic	<550	**6.7**	6.1	7.4	6.8*	0.9	147
	>550	**5.9**	5.4	6.2	6.0*	1.1	855
	All	**6.0**	5.4	6.6	6.1	1.1	1002
Apedal	<550	**7.5**	6.6	8.4	7.5*	1.1	1194
	>550	**5.6**	5.2	6.2	5.8*	0.8	3194
	All	**6.0**	5.3	6.9	6.2	1.2	4388
Podzolic	<550	**5.9**	5.6	7.3	6.4	1.5	4
	>550	**5.7**	5.3	6.3	5.7	0.7	27
	All	**5.7**	5.4	6.3	5.8	0.8	31

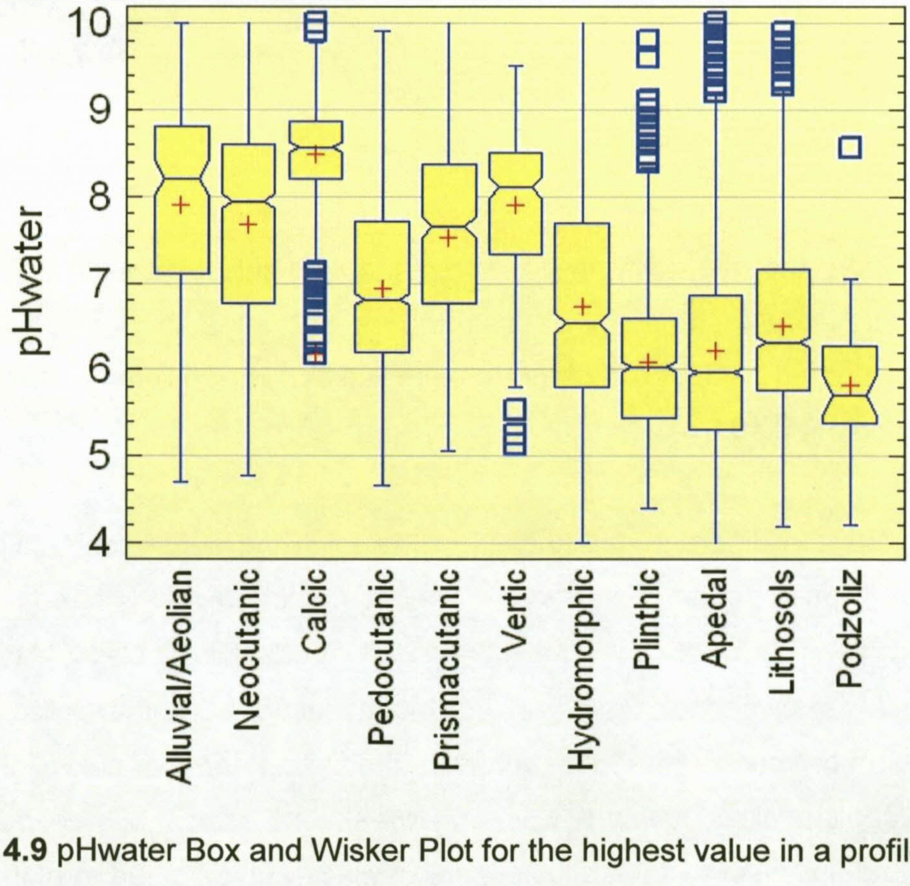

FIGURE 4.9 pHwater Box and Wisker Plot for the highest value in a profile.

TABLE 4.11 Soil classes affected by salts in declining order

Soil Class	**Geometric Mean**	**Median**
Calcic	9.30	10
Alluvial / Aeolian	9.24	10
Prismacutanic	7.95	9
Vertic	7.59	8
Pedocutanic/ Red structured	7.68	7
Neocutanic	7.45	8
Hydromorphic	5.62	5
Lithosols	4.39	5
Plinthic	3.20	3
Apedal	1.85	2
Podzolic	1.29	1

To establish which soil classes are most affected by salts, Table 4.2 to Table 4.10 were ranked from highest to lowest median value in terms of a combination of electrical conductivity, ESP, and pH_{water}. The soil classes with the highest median value in each of the nine tables were ranked 11 and the lowest median value one. The median and geometric mean were then calculated for each soil class (Table 4.11), but because some soil classes had the same median ratings, the geometric mean was used to rank the different soil classes (from the most likely to the least likely to be affected by salts).

Salt affects the different soil classes in the following sequence: calcic ≥ alluvial/ aeolian >prismacutanic >vertic >pedocutanic/red structured >neocutanic >hydromorphic ≥ lithosols >plinthic >apedal >podzolic (Table 4.11). As can be expected, the calcic soil class was the most likely to be salt-affected. There was, however, not much difference between the rating for the calcic class and the alluvial/aeolian class. There was only weak expression of pedogenesis in the arenic and fluvic soils of the alluvial/aeolian class and this lead to high salt content, because of minimum leaching of salts originally deposited. At the other extreme are prismacutanic soils that are in a mature stage of pedogenesis, which are strongly affected by sodicity and alkalinity in the B-horizon. The apedal and podzolic soil classes, which as a rule have a light texture, and where good leaching of salts naturally occurs, have the lowest ranking in terms of salt-affectedness.

4.4. CONCLUSION

Simple statements about salt-affected soil must be seen against the background of ever-present variation between and within soil classes, which must be taken into account in analyses. Quartile values and not average values are best to use for salt-affected soils to present the data, because the majority of the data is strongly positively skewed, with large differences between median and average values. The use of the outlier definition in its statistical meaning for salt-affected soils is problematic. It is, therefore, better to use outlier in the sense that it means to be an observation that deviates markedly, but for obvious and/or explicable reasons, from the other members of the population and as such is representative of typical variability in a natural situation. Extremely high salinity, sodicity and alkalinity values occur along pans and riverbanks in arid areas in South Africa.

There is a strong relationship between rainfall, salt occurrence and salt movement. As rainfall increases the salinity, sodicity and alkalinity decreases because of the depletion of basic cations and anions. Significant differences amongst the medians at the 95% confidence level for electrical conductivity, ESP, and pH_{water} in the topsoil and subsoil between rainfall classes within the calcic, alluvial/aeolian, neocutanic, pedocutanic/red structured, hydromorphic, plinthic (in the subsoil), prismacutanic, lithosols and apedal soil classes occurs.

Primary soil alkalinity (pH_{water} >7.4) and sodicity (ESP >6) are a bigger problem than primary salinity (EC >400 mS m^{-1}) in South Africa in terms of the different soil classes. None of the soil classes is saline, only the prismacutanic class is sodic, and the calcic, alluvial/aeolian, neocutanic and prismacutanic classes are alkaline when the median value of highest value in a profile was used as indicator for salt-affectedness.

An ESP boundary limit of 15 for sodic conditions is problematic and must be regarded as somewhat arbitrary and tentative. The classical concept of a solonetz

B does not always apply for South African prismacutanic horizons. A reason for this is that certain prismacutanic horizons develop where the ESP values are less than 15, and in other circumstances soils with an ESP value of 15-20, or even more, do not manifest prismacutanic morphological features. Sufficient data is not available, even for this relatively large dataset of 648 prismacutanic B-horizons, to proclaim a precise ESP value as a criterion for prismacutanic or solonetz soils in South Africa.

To establish which soil classes are most affected by salts, they were ranked from highest to lowest median value in terms of a combination of electrical conductivity, ESP, and pH_{water}. Salt-affected the different soil classes in the following sequence: calcic ≥ alluvial/aeolian >prismacutanic >vertic >pedocutanic/ red structured >neocutanic >hydromorphic ≥ lithosols >plinthic >apedal >podzolic.

For the 11 soil classes, 46 different pairs show statistical differences at the 95% confidence level for the topsoil and subsoil horizons and 42 pairs if the highest value in a profile is used for pH_{water}. When ESP is considered 12 pairs for the topsoil, 31 pairs for subsoil and 24 pairs for the highest value in a profile and for electrical conductivity 27 pairs in the topsoil, 31 pairs in the subsoil and 35 pairs if the highest value in a profile is used are statistical differences at the 95% confidence level.

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CHAPTER 5: QUANTIFICATION OF THE SALT CONTENT OF SOILS FOR DIFFERENT GEOLOGICAL CLASSES AND GROUNDWATER REGIONS

5.1. INTRODUCTION

The effect of geology as parent material is twofold, because it affects the physical aswell as the chemical composition of the soil. Before the advent of the climatic theories of soil formation, parent material was considered the major soil-forming factor (Jenny, 1941). According to Szabolcs (1989) the weathering of rocks is the primary source of soluble salts entering natural waters, sediments, and soils. The geochemistry of salts in any given place is determined by the mobility of the compounds formed and by the sequence of precipitation of the weathering products.

Weathering, soil formation, and surface processes, such as salinsation, sodification, and alkalinisation, are all to some extent controlled by the underlying rock types. However, it is difficult to make generalisations about potential salt levels in soils arising from different rock types. Much of the salt present may be derived from external sources (Isbell *et al.,* 1983). Woodford and Chevallier (2002) indicate for example that the coastal sections of the Karoo rocks in KwaZulu-Natal and the Eastern Cape show elevated sodium concentrations and this is most likely the impact of sea-born salts in which sodium dominates as the main cation. This is probably more so for the dry western part of South Africa. Anderson *et al.* (2004) indicate that chemostratigraphy is not an ideal approach for correlation in the Karoo Basin, since the geochemical signals have substantial statistical noise not easily related to lithology.

It is not possible to understand soil formation without some knowledge of weathering and weathering cannot be studied adequately without taking into account the soil zone at the top of the weathering profile (Clayton, 1969). De Villiers (1962) defined for example the term, pre-weathering, as the "weathering of hard and soft materials prior to the current cycle of soil formation". This term is usually applicable in the case of the older part of a binary parent material, since in single-parent material soils there is evidence of more than one cycle of soil formation (MacVicar, 1978). The parent material factor is complicated by the superficial addition of layers of different parent materials that can simulate soil horizons. It is therefore frequently a considerable problem to distinguish geological layering from pedogenic horizons.

Chemical composition alone is not a sure indication of weatherability and the different rates of weathering of minerals of the same composition demonstrate the futility of a too "chemical" approach to weathering (Clayton, 1969). The densest mineral is the most stable isomorph. Kynanite (Al_2SiO_5) is denser and more stable than silimanite and andulusite, but have the same composition. According to Clayton (1969), the rate of weathering of a mineral depends on several other factors besides its structure and composition. The main components are:

(1) *Crystal size.* Large minerals are harder to weather than small ones. This is because weathering can be regarded as a surface activity and many small crystals have a much greater surface area than a single large crystal of the same volume. If a grain 1 mm across is broken into particles of 0.1 mm across, the surface area increases at least a thousand fold. *Grain size* also has an effect on the rate of weathering. Birkeland (1984) established that coarser-grained igneous rocks commonly weather more rapidly than the finer grained rocks.

(2) *Crystal shape.* Platy crystals are more weatherable than chunky ones, as more of the crystal is near to a crystal face that is near to the weathering surface.

(3) *Crystal perfection.* Perfect crystals, i.e. those with a perfect geometrical lattice, are comparatively resistant to weathering, as each atom is securely in place.

(4) *Access of agent and removal of weathered product.* The more the weathering agent can get to a mineral, the more it will weather it. Thus, if a rock is porous and water can attack all grains, the weathering will be faster than if the rock is dense and compact as water can only penetrate from the rock surface, not from every mineral or grain surface. On a smaller scale, a mineral with good cleavage allows solutions to reach not only the mineral surface but also the cleavage planes and the greater ease of access allows more rapid weathering.

During the process of chemical weathering, which involves hydrolysis, hydration, solution, dissolution, oxidation-reduction, carbonation, and other processes, the salt constituents are gradually released and made soluble (FAO, 2001). The main source of all salts in the soil is primary minerals in the exposed layer of the earth's crust. The minerals mainly responsible for salt-affected soils are from four chemical groups namely carbonates, halides, sulphates, and borates. Klein and Hurlbut (1999) extensively discuss these mineral groups and their characteristics.

Geological materials are highly variable in their elemental composition and some materials are higher in salts than others are. Shale, especially those of marine origin, can supply large quantities of soluble salts when traversed by water (FAO, 2001). However, according to Gunn and Richardson (1979) not all marine sediments are high in salt content, as the saline water is generally not retained during the lithification process. The mean calcium, magnesium, and sodium composition of igneous and sedimentary rocks are given in Table 5.1. In most types of metamorphism, the rock undergoes little or no change in chemical composition through mineral recrystalisation. The elements originally present simply regroup themselves under conditions of higher temperatures and pressures to form new minerals that are stable in the new subsurface environment (Birkland & Larson, 1989). The chemical composition of slate will therefore be more or less similar to that of shale, quartzite to sandstone, marble to limestone, gneiss to granite, and hornfels to shale/mudstone (Meulenbeld, 2007). Sedimentary rocks cover 65%, igneous rocks 10%, and metamorphic 25% of the South Africa landscape (Snyman, 1996).

TABLE 5.1 Mean calcium, magnesium, and sodium composition (weight %) of igneous and sedimentary rocks (Brownlow, 1975; Hurlbut & Klein, 1977; Greensmith, 1978; Boggs, 1987; Marsh, 1987)

INGEOUS ROCKS									
Weight %	**Syenite**	**Rhyolite**	**Granite**	**Andesite**	**Basalt**	**Diorite**	**Gabbro**	**Peri-dotite**	**Dunite**
MgO	2.02	0.28	0.52	3.22	3.95	6.12	8.06	34.02	43.16
CaO	4.06	1.59	1.33	7.02	7.33	8.40	11.07	3.46	0.75
Na_2O	3.92	4.24	3.08	3.84	2.76	3.36	2.26	0.56	0.31
SEDIMENTARY ROCKS									
Weight %	**Quartz Arenite**	**Sand-stone**	**Shale**	**Boulder Clay**	**Iron-stone**	**Lime-stone**	**Clay**		
MgO	0.04	1.16	2.44	4.92	3.16	7.89	1.25		
CaO	1.60	5.50	3.11	6.38	1.78	42.57	0.07		
Na_2O	0.10	0.45	1.30	0.53	0.05	0.15	0.02		

There is considerable difficulty in finding a soil profile developed on a uniform parent material (Brewer, 1976). Jenny (1941) prefers to define parent material as the *initial state of the soil system* and thus avoid special reference to the strata below the soil, which may not be parent material. Statements by Schloemann, (1994), "the underlying geological material is the most important factor in determining the chemical composition of the investigated soils" is questionable and seems to be an oversimplified perspective for salt- affected soils and soils in different landscape positions. According to Netterberg (1969), however, the effect of the chemical composition of the parent material is marked in areas of essentially no calcification in the area between Potgietersrus and Thabazimbi is due to the non-calcareous Waterberg Sandstone. Similarly, the lack of calcrete in an apparently favourable climate in the southwestern Cape can also be attributed to non-calcareous parent material. Nell & Steenekamp (2006), conversely, found on predominantly non-calcareous parent material, such as the Nebo-Granite, small younger intrusions of diabase sills that have had a strong influence on the development of carbonate horizons that are uncharacteristic in a granite environment.

It is useful to distinguish between non-extreme and extreme parent materials (Clayton, 1969). Some parent materials are extreme, such as pure sand, ore bodies, or limestone and give rise to special soils very much dominated by the parent material. Others, such as granites, shales, and all rocks with a wide variability in chemical content, are non-extreme and on such rocks the influence of other factors is likely to be more important.

According to Hunt (1972), surface deposits are sediments weathered from bedrock in one area and transported by water, wind, or ice (and gravity) to another area. Thus not only are they much younger than the underlying bedrock, but they are mostly unrelated to it. A good definition of "transported soils" is provided by Brink (1985): "the unlithified sediments, which have been derived from residual soils or through the slow disintegration of rocks and which have been removed from their original locations within the landscape and deposited elsewhere by various geomorphic agencies".

It should not be expected that the geological classification of rocks would be ideal for the classification of soil parent rocks since, as Whiteside (1953) pointed out, the "test used by pedologists and geologist in evaluating a rock classification" are different. Geologists judge on the basis of whether the rock characteristics used in the classification are or are not basic to the understanding of the origin of the rocks. Soil scientists would like a rock classification system that would show the relationships between the major properties of the rocks so that by studying soils formed from a relatively few rocks it would be possible to predict what kinds of soils would be found on the related rocks when other soil formation factors are constant.

Variations in relief and climate in large basins are commonly great enough so that the effects of changes in rock type are small compared to changes in other parameters. However, in basins located entirely within plains, the lithology may be quite important (Blatt *et al.*, 1980). The macro-scale landscapes are a direct result of geological processes, while at a local or meso-scale landforms reflect the varying weathering and erosion rates of different rock types (Eriksson, 2000). The present-day landscape, which we may observe anywhere on the earth are temporary features (Strahler, 1981). This is probably more so for soils in general and salt-affected soils specifically.

Generalised statements on the salinity and sodicity status of the different formations of the Karoo Supergroup are not uncommon. The Karoo Supergroup dominates the geological map of South Africa, covering a very large proportion of the country (Fig 5.1). This reflects its relatively young age and the limited time there has been for its reduction by weathering and erosion (Eriksson, 2000). The Karoo Supergroup consists of a vast accumulation of mudrock and sandstone, with tillite at the bottom and basalt at the top (Brink, 1985) and ranges in age from Late Carboniferous to Middle Jurassic, with a total thickness of ~12 km in the south-eastern portion of the Main Karoo Basin towards the eastern end of the Karoo Trough (Johnson *et al.*, 2006). The sediments are capped by a 1.4 km thick unit of basaltic lava (Cole, 1992).

Rowsell and De Swardt (1976) estimated that at least 3 000 m of material was removed from the present surface of most of the Southern Karoo. Considering that this denudation started during the early Cretaceous period, approximately 140 to 100 million years ago, a denudation rate of approximately 0.02 to 0.03 mm per year over this period is calculated. They also calculated that each km^2 of the area, with a weathering rate of 0.03 mm per year, would release 8 250 kg dolerite, 18 750 kg sandstone, and 49 725 kg mudstone. A total amount of 5 490 kg km^{-2} year^{-1} of cations may therefore be released as a result of rock weathering in the area (Na = 1 283 kg km^{-2} year^{-1}, Ca = 1 424 kg km^{-2} year^{-1}, Mg = 969 kg km^{-2} year^{-1} and K = 1 815 kg km^{-2} year^{-1}).

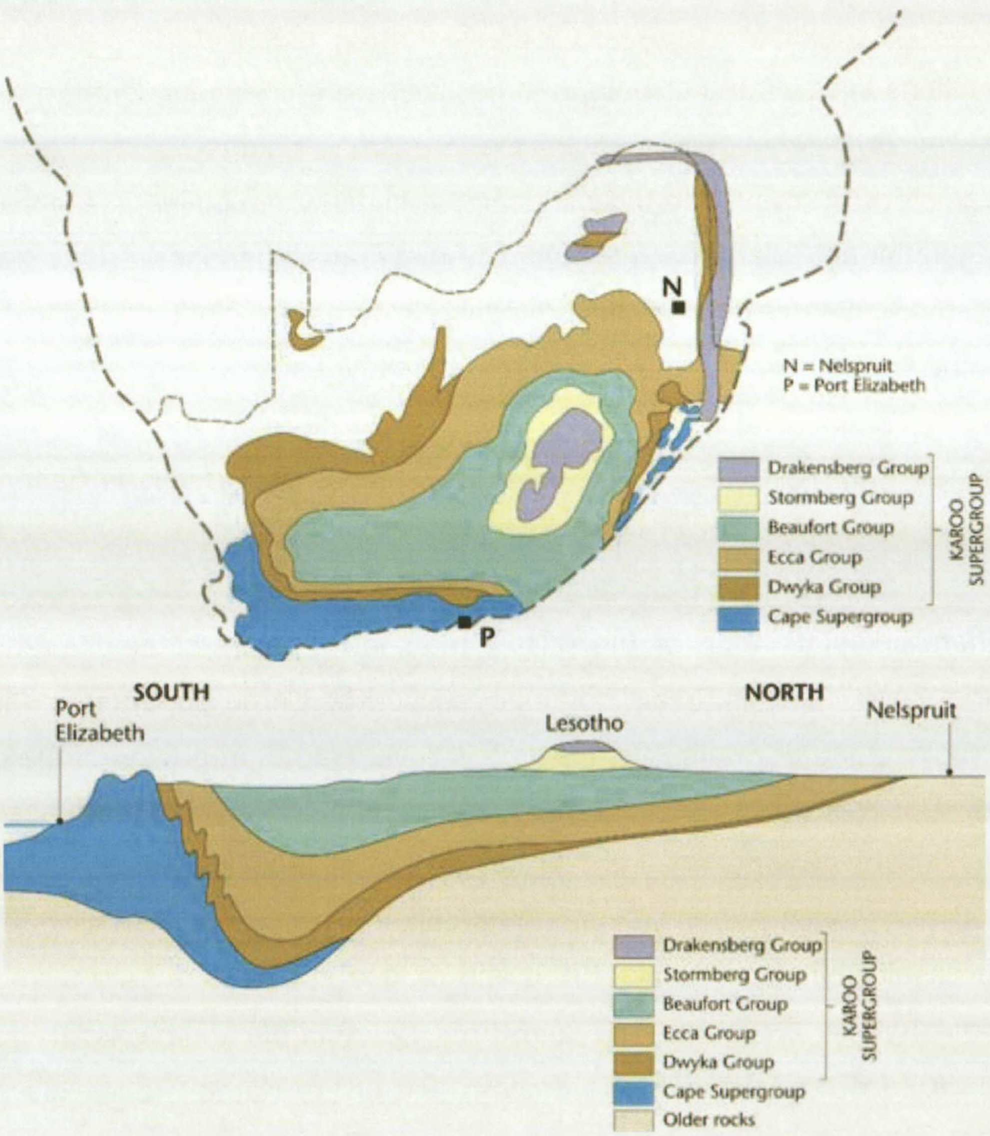


FIGURE 5.1 Stratigraphy of the Karoo Supergroup (McCarthy & Rubidge, 2005).

The depositional environments varied geographically in the Karoo Basin and ranged from marine to lacustrine for the Dwyka to lower Ecca Groups (Herbert & Compton, 2007). The lower Ecca Group shales (Prince Albert formation) are interpreted as marine basin or shelf deposits. However, in the eastern portion of the Main Karoo Basin, paleontological evidence (Anderson, 1970; Savage, 1970) suggests a fresh water periglacial environment for upper Dwyka deposits, while stable isotope analyses from sites along the northern and southern margins of the basin (Faure & Cole, 1999) indicate a brackish to fresh water depositional environment for the lower Ecca Group. The Ecca sedimentation graded upwards into the Beaufort Group, whose shales and sandstone were deposited on enormous semi-arid riverplains, is subject to strong seasonal variations in sedimentation (Smith *et al.*, 1993).

South Africa has a long and complex geological history, which dates back in excess of 3.6 billion years, but the present-day environment of southern Africa probably owes much of its origin to geological events in the post-Gondwana period (Fox & Rowntree, 2000). Since the fragmentation of Gondwana, large parts of the continent have been exposed to weathering and erosion, resulting in widespread denudation and sedimentation. Truswell (1977), Brink (1985), and Partridge and Maud (1987) provide a detailed description of the post-Gondwanaland geological history of South Africa. The geology in South Africa associated with salts such as carbonate, halite, and gypsum are given in paragraph 2.3.

5.2. METHODOLOGY

Soil sample analyses, statistical- and GIS procedures were undertaken in accordance with the methodology described in paragraph 4.2.

Digital geological data of nearly 300 geological units was obtained from the Council for Geoscience on a 1:1 000 000 and/or 1: 250 000 scale. Standard international stratigraphic terminology was used when referring to specific portions of the South African geological record namely *supergroup, group,* and *formation.* These terms, ranked in descending order of magnitude, reflect stacked successions of layered or stratified rocks of sedimentary and/or volcanic composition. Igneous intrusions are generally termed complexes, while assemblages of metamorphic rocks are known as *suites, complexes,* or, if very large *provinces.* The principles governing the naming of stratigraphic units are set out in the South African Code of Stratigraphic Terminology and Nomenclature (SACS, 1996).

The delineating of 65 groundwater regions by Vegter (2001) were use to obtain some degree of uniformity in respect of lithostratigraphy, physiography, and climate without creating an unmanageable number of regions. Vegter's groundwater regions were especially included for evaluation purposes, because it eliminates the dominant effect of rainfall over geology on a national scale to characterize salt-affected soils. This delineating was used in addition, because of the better explanation of basins, intermontane areas, and pan belts, where more salt accumulation in the soil is to be expected more. It should be noted that the subdivision was basically geological. In the case of 11 of the 16 major regions identified and delineated, a major lithostraigraphic unit and/or geologic structure was been the prime factor. Physiography was the main consideration in the case of three and a combination of physiography and geology in the remaining two cases (Vegter, 1990).

5.3. RESULTS AND DISCUSSION

As indicated in paragraph 4.3 the large differences in the median and average values for salinity as indicated by electrical conductivity (Table 5.2 to Table 5.4) and sodicity, as indicated by the exchangeable sodium percentage (Table 5.5 to Table 5.6), are a clear indication of the variability and skewness of the data. As was previously stated the term "outlier" is not being used in its statistical meaning, *i.e.* being "any observation that appears surprising or discrepant to the investigator" or "any observation that is not a realisation from the target distribution". It is rather used in the sense that it refers to an observation that deviates markedly, but for obvious and/or explicable reasons, from the other members of the population and as such is representative of typical variability in a natural situation, for example very high salinity and/or sodicity in basin, intermontane, or pan environments.

5.3.1. ELECTRICAL CONDUCTIVITY OF DIFFERENT GEOLOGICAL UNITS

The soil in the nearly 300 geological units (Appendix E) are predominantly non-saline and only 18 units have soil median electrical conductivity values higher than 100 mS m^{-1} (Table 5.2 and Figure 5.2). When the 400 mS m^{-1} threshold value was applied to separate saline from non-saline soils, only the Whitehill Formation, Knersvlakte Subgroup, and Hoogoor Suite geological units tended to be saline if the median values were used as an indicator of salinity. If the average values were used, the soil in the Gladkop Suite, Garies Subgroup, Prince Albert Formation, Enon Formation, Port Nolloth Group, and Bokkeveld Group also tended to be saline (Table 5.2).

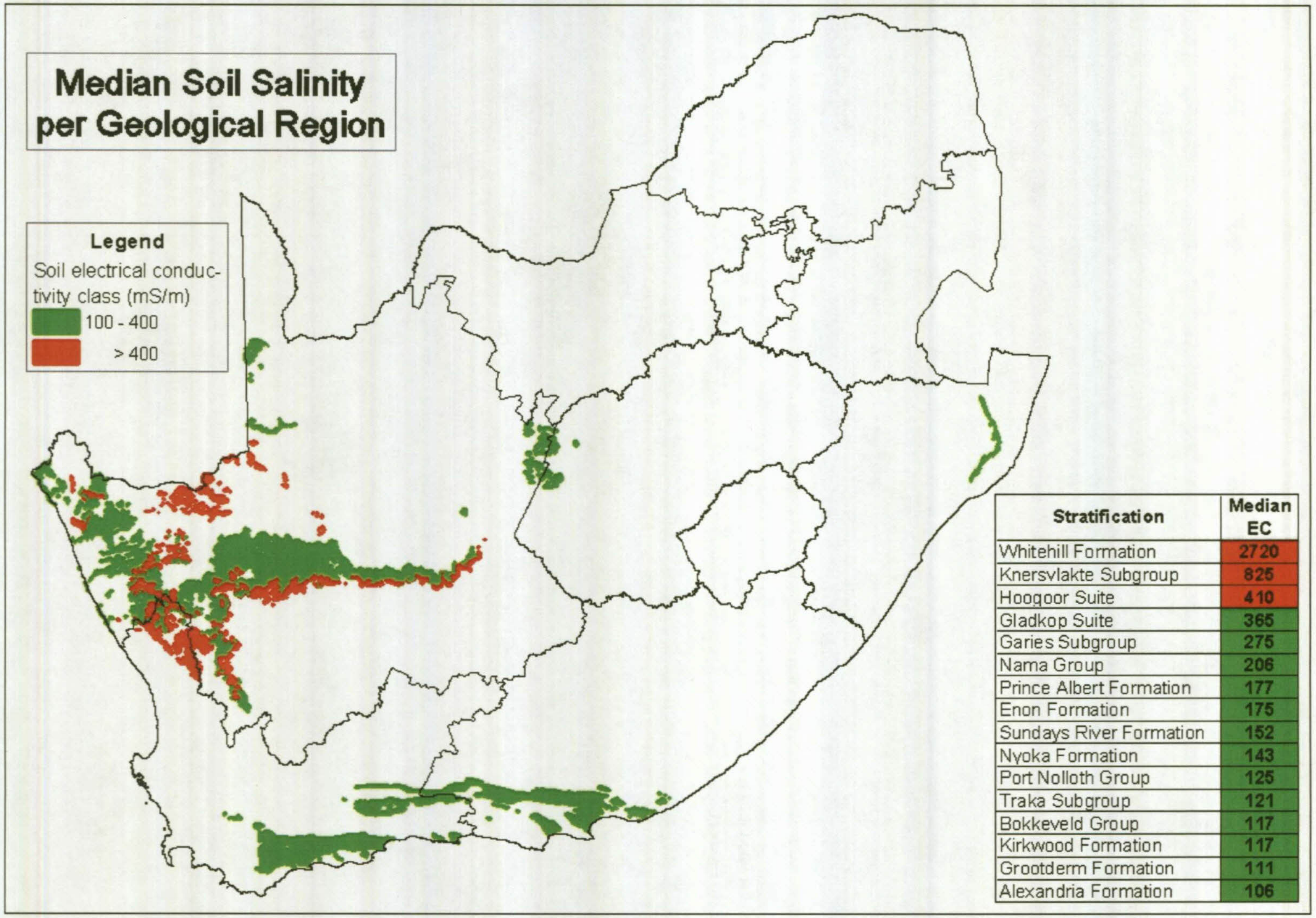
The soil of the Whitehill Formation in the Ecca Group is by far the most saline geological unit in South Africa (Table 5.2). The formation is considered to be marinate based due to its wide geographical distribution of approximately 150 000 km^2 (Christie, 1990). High electrical conductivities for the Whitehill Formation were first identified by *in situ* boreholes measurements during SOEKOR's regional oil exploration programme in the 1960's (Cole & McLachlan, 1994). Recently Van Zijl (2006) also found resistivity's as low as 1 Ωm (~ 1 000 mS m^{-1}) in the Whitehill Formation when he reviewed the results of deep electrical soundings. The black laminated carbonaceous shales, with chert and graphite lenses and pyrite stringers, of this formation were deposited largely by suspension settling in a young underfilled foreland basin under reducing (anoxic) bottom conditions (Cole & McLachlan, 1991; Visser, 1992; Branch *et al.,* 2007). The mudrocks of this formation weather white on the surface, making it a very useful marker unit (Johnson *et al.,* 2006). However, according to Branch *et al.* (2007) the formation appears white due to weathering of pyrite sulphide at the surface to sulphate (gypsum). The pyrite weathering is probably a major contributor to the high salinity of this formation. The Prince Albert Formation (seventh highest median soil electrical conductivity) is also characterized by black carbonaceous shales and pyrite bearing shale (Woodford & Chevallier, 2002). The black, organic-rich shales are thought to represent suspension-settling of mud under reducing conditions, but the salinity source remains unresolved with some researchers proposing: (i) a marine water body (Oelofsen & Araujo, 1987; Visser, 1992); (ii) a non-marine brackish water body with no connection to the world oceans (Veevers *et al.,* 1994), with a maximum water-depth of 80 m (i.e. within the photic zone), under anoxic conditions being restricted to the basin floor by benthic microbial mats (Cole & McLachlan, 1991); (iii) a huge freshwater lake that spanned much of south-western Gondwana and was characterized by algal blooms (Faure & Cole, 1999); and/or (v) a sea-level highstand under restricted oceanic circulation (Visser, 1986,1992).

Marine mudstone, siltstone, sandstone, conglomerate, and diamictite are the dominant sediments in the Knersvlakte Subgroup (Visser, 1989; Gresse, *et al.*, 2006 that has the second highest median electrical conductivity (Table 5.2). The Hoogoor Suite with the third highest soil electrical conductivity is characterized by red-weathered quartzo-feldspathic gneiss, often referred to as pink gneiss (Cornell *et al.,* 2006) and consist mainly of quarts, microline, albit-oligoclase, biotite, muscovite, and calci-silicate rocks (Visser, 1989).

The majority of the 20 highest median soil electrical conductivity values according to geological units are located in the arid western part of South Africa (Figure 5.2). The only exceptions are the Nyoka Formation (10th highest electrical conductivity) that primarily occur in the more humid part of the northern part of KwaZulu-Natal Province (Table 5.2). The Nyoka Formation consists predominately of red and purple mudstone with calcareous concretions. It is postulated that the formation was probably deposited on the floodplains of slow-flowing meandering rivers under arid conditions (Johnson *et al.,* 2006). A second exception is soils formed from the onshore Post-Karoo Mesozoic deposits of the Uitenhage Group in the Eastern Cape (Enon Formation 8th, Sundays River Formation 9th, and Kirkwood Formation 14th). The high soil electrical conductivity values of the Uitenhage Group is caused by the a combination of factors, the most important is probably that during Cretaceous (142 to 65 million years ago) three major episodes in world sea level rise occurred, covering the coastal plain with shallow marine deposits, that resulted in saline environments (McCarthy & Rubidge, 2005). The current influence by marine spray or salty rainwater can also have an influence on salinity.

TABLE 5.2 Soil electrical conductivity (mS m^{-1}) statistics for the 20 highest geological units according to median values.

Geological Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Whitehill Formation	2720	66	9950	4890	6330	15
Knersvlakte Subgroup	825	220	3610	1890	2240	10
Hoogoor Suite	410	115	676	394	287	5
Gladkop Suite	365	95	1500	796	800	9
Garies Subgroup	275	45	320	1060	1990	11
Nama Group	206	125	244	180	97	12
Prince Albert Formation	177	49	1680	1040	1610	57
Enon Formation	175	64	471	504	923	66
Sundays River Formation	152	75	374	349	483	57
Nyoka Formation	143	93	224	185	168	13
Port Nolloth Group	125	103	170	490	908	13
Traka Subgroup	121	61	360	186	151	6
Bokkeveld Group	117	40	241	625	1810	56
Kirkwood Formation	117	60	360	289	368	38
Grootderm Formation	111	75	125	227	292	9
Alexandria Formation	106	62	170	153	136	14
Waterford Formation	101	56	528	354	478	12
Villa Norra Anorthosite	99	59	170	138	177	25
Porterville Formation	91	26	261	163	178	59
Bloempoort Group	90	37	94	73	34.2	5



Stratification	Median EC
Whitehill Formation	2720
Knersvlakte Subgroup	825
Hoogoor Suite	410
Gladkop Suite	365
Garies Subgroup	275
Nama Group	206
Prince Albert Formation	177
Enon Formation	175
Sundays River Formation	152
Nyoka Formation	143
Port Nolloth Group	125
Traka Subgroup	121
Bokkeveld Group	117
Kirkwood Formation	117
Grootderm Formation	111
Alexandria Formation	106

FIGURE 5.2 Geological units with an electrical conductivity of more than 100 mS m^{-1}.

The Alexandria Formation (16th highest EC) that consists of calcareous sandstones deposited in shoreface, foreshore, infralittoral, and estuarine environments, that took place in response to a series of Middle Miocene to Pliocene marine transgression and regression cycles (Le Roux, 1987; Le Roux, 1990) are probably also accentuated by present day marine spray and salty rainwater.

5.3.2. ELECTRICAL CONDUCTIVITY OF DIFFERENT GROUNDWATER UNITS

Only the soil in the Tanqua Karoo groundwater unit is saline if soil median values were used as an indicator of salinity. If the soil averages values are use, the Richtersveld, Knersvlakte, Hantam, Ruensveld, Bushmanland Pan Belt, Western Great Karoo, Namaqualand, and Oudtshoorn Basin groundwater units are also saline (Table 5.3 and Figure 5.3).

Of the 20 highest groundwater regions, according to median soil electrical conductivity values, seven are from regions composed of Carbo-Triassic strata and nine of the highest groundwater regions occur in the arid western part of the Northern and Western Cape Province (Table 5.3, Figure 5.3, and Appendix F).

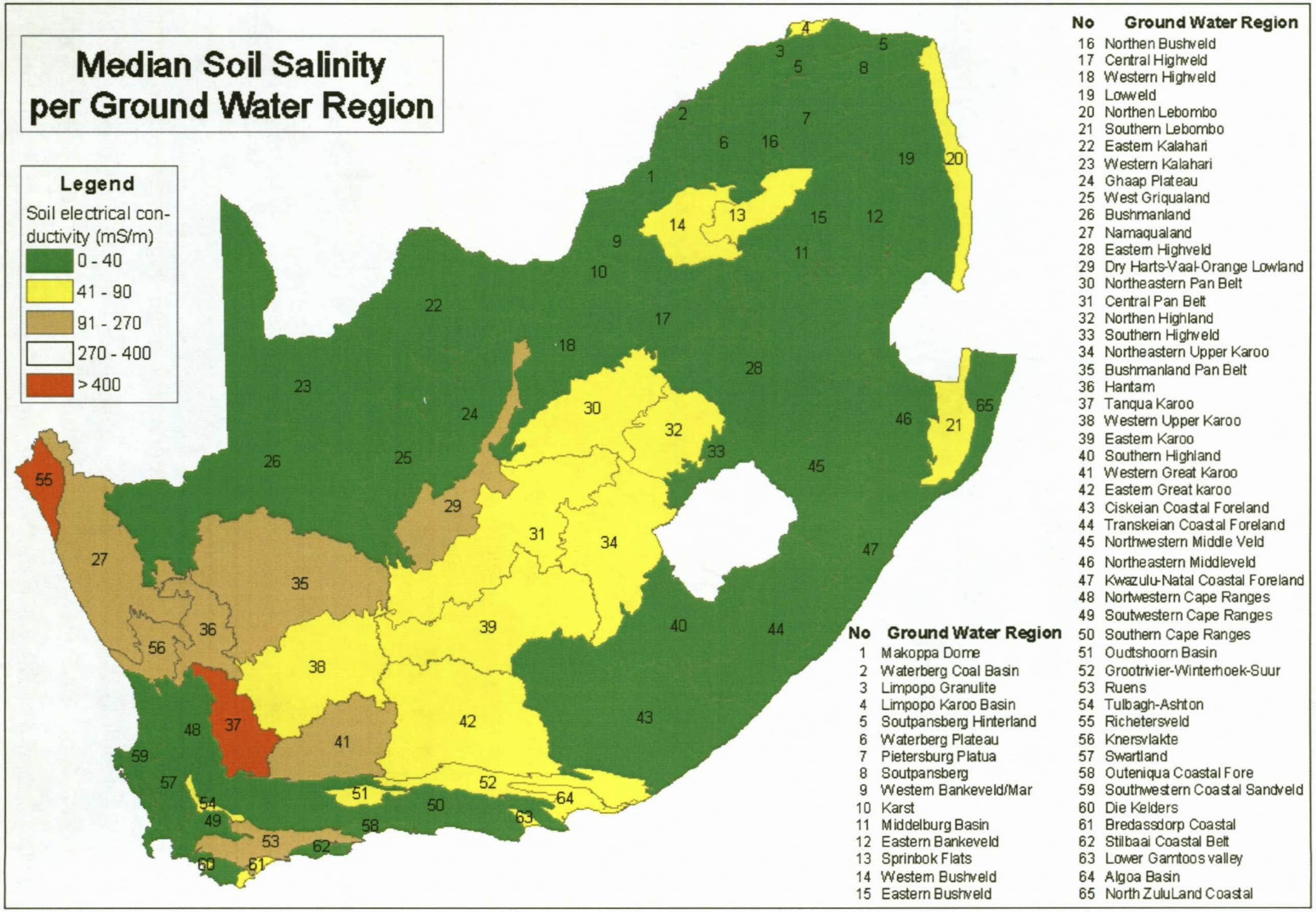
The soil in the Tanqua Karoo groundwater region is the most saline. The principal rock types in the Tanqua Karoo region are: Dwyka Formation tillite and shale; Prince Albert Formation shale; Whitehill Formation carbonaceous shale and pyrite; Tierberg Formation shale; and Waterford Formation shale and sandstone (Vegter, 2001). The Richtersveld (second highest EC) and Knersvlakte (third highest EC) ground-water regions (Table 5.3) consist mostly of Namibian Gariep Supergroup quartzite, arkose, arenite, limestone, dolomite, diamictite, phyllite, schist, amphibolite, and gneiss (Vegter, 2001). Cambrian Kuboos intrusive biotite granite, with tertiary raised beach deposits and alluvium occur in the Richtersveld. In the Knersvlakte, Cambrian Vanrhynsdorp Group shale, mudstone, conglomerate, flagstone, siltstone, limestone, dolomite and Tertiary to recent fluvial deposits occur (Vegter, 2001). The rock types in the Hantam (fourth highest EC) and Bushmanland Pan Belt (sixth highest EC) groundwater regions are predominately a succession of Dwyka Formation tillite and shale; and Prince Albert, Whitehill, and Tierberg Formation shale (Vegter, 2001). The Western Great Karoo (eighth highest EC) consists of tillite of the Dwyka Formation, shale and sandstone of the Ecca

Group and mudstone and sandstone of the Adelaide Subgroup, which underlies most of this groundwater region (Vegter, 2001). The Adelaide and Tarkastad Subgroup mudstone, shale and sandstone and Waterford Formation shale and sandstone are dominant in the Eastern Upper Karoo (13th highest EC).

Relatively closed basins, such as Tanqua Karoo (highest EC), the Algoa Basin (sixth highest EC), Oudtshoorn Basin (14th highest EC), and Limpopo Karoo Basin (18th highest EC) have a tendency to have high soil EC-values. Pan environment, such as the Bushmanland Pan Belt (sixth highest EC) and Central Pan Belt (16th highest EC) and Intermontane areas such as the Tulbagh-Ashton Valley (12th highest EC), also have a tendency to have high EC-values.

TABLE 5.3 Soil electrical conductivity (mS m^{-1}) statistics for the 20 highest groundwater units according to median values

Groundwater Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Tanqua Karoo	785	126	1890	1480	2090	83
Richtersveld	355	109	1720	1010	1330	88
Knersvlakte	161	28	1770	1070	1570	68
Hantam	119	45	589	438	713	36
Ruensveld	111	36	274	586	1840	146
Bushmanland Pan Belt	109	37	466	1060	2890	112
Dry Harts-Vaal-Orange	100	43	262	304	586	463
Western Great Karoo	96	54	230	447	997	60
Namaqualand	95	41	310	535	1380	197
Lower Gamtoos Valley	90	49	151	128	127	17
Algoa Basin	84	45	227	226	361	204
Intermontane Tulbagh-Ashton Valley	84	48	200	258	491	45
Eastern Great Karoo	76	41	139	224	445	162
Oudtshoorn Basin	76	36	560	709	1200	23
Southern Highveld	76	36	120	103	122	106
Central Pan Belt	59	36	128	355	900	304
Northern Lebombo	55	33	137	169	360	221
Limpopo Karoo Basin	54	36	269	316	776	237
Southern Lebombo	54	36	135	135	225	757
Grootrivier-Klein Winterhoek-Suurberg-Ranges	50	31	131	131	202	100



No	Ground Water Region
1	Makoppa Dome
2	Waterberg Coal Basin
3	Limpopo Granulite
4	Limpopo Karoo Basin
5	Soutpansberg Hinterland
6	Waterberg Plateau
7	Pietersburg Platua
8	Soutpansberg
9	Western Bankeveld/Mar
10	Karst
11	Middelburg Basin
12	Eastern Bankeveld
13	Sprinbok Flats
14	Western Bushveld
15	Eastern Bushveld
16	Northen Bushveld
17	Central Highveld
18	Western Highveld
19	Lowveld
20	Northen Lebombo
21	Southern Lebombo
22	Eastern Kalahari
23	Western Kalahari
24	Ghaap Plateau
25	West Griqualand
26	Bushmanland
27	Namaqualand
28	Eastern Highveld
29	Dry Harts-Vaal-Orange Lowland
30	Northeastern Pan Belt
31	Central Pan Belt
32	Northen Highland
33	Southern Highveld
34	Northeastern Upper Karoo
35	Bushmanland Pan Belt
36	Hantam
37	Tanqua Karoo
38	Western Upper Karoo
39	Eastern Karoo
40	Southern Highland
41	Western Great Karoo
42	Eastern Great karoo
43	Ciskeian Coastal Foreland
44	Transkeian Coastal Foreland
45	Northwestern Middle Veld
46	Northeastern Middleveld
47	Kwazulu-Natal Coastal Foreland
48	Nortwestern Cape Ranges
49	Soutwestern Cape Ranges
50	Southern Cape Ranges
51	Oudtshoorn Basin
52	Grootrivier-Winterhoek-Suur
53	Ruens
54	Tulbagh-Ashton
55	Richetersveld
56	Knersvlakte
57	Swartland
58	Outeniqua Coastal Fore
59	Southwestern Coastal Sandveld
60	Die Kelders
61	Bredassdorp Coastal
62	Stilbaai Coastal Belt
63	Lower Gamtoos valley
64	Algoa Basin
65	North ZuluLand Coastal

FIGURE 5.3 Soil electrical conductivity of the different groundwater regions in South Africa.

5.3.3. ELECTRICAL CONDUCTIVITY OF THE KAROO SUPERGROUP

Comparing the median soil electrical conductivity values of the different groups in the Karoo Supergroup, no real difference exist between the sedimentary rocks of the different groups and none of the groups can be considered as saline. The exception is the Dwyka and Ecca Formations which are saline and then only when the rainfall is less than 550 mm (Table 5.4). A palaeosalinity study by Zawada (1988), using trace elements Rb, B, Cu, V, and adsorbed Mg^{2+} and Ca^{2+} confirmed the absence of no difference in palaeosalinity between the Ecca and Beaufort Groups. If the average soil electrical conductivity values are considered it seems that there is a decline in electrical conductivity from the Dwyka Group, to the Ecca Group, to the Stormberg Group to the Beaufort Group (Table 5.4). Although clear differences between the groups are vague, highly statistically significant differences at the 99% confidence level occurs within a group between rainfall classes. The igneous rocks of the Lebombo and Drakensberg Groups show no significant difference between the two rainfall classes.

TABLE 5.4 Soil electrical conductivity (mS m^{-1}) statistics for the Karoo Supergroup

Group	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Dwyka	<550	49	28	422	634^{**}	1690	134
	>550	20	11	36	44^{**}	182	619
	All	22	12	41	149	764	753
Ecca	<550	61	36	168	426^{**}	1380	699
	>550	23	13	41	43^{**}	83	2577
	All	28	15	54	125	660	3276
Beaufort	<550	56	32	128	146^{**}	403	978
	>550	23	14	36	42^{**}	83	2971
	All	28	16	49	67	217	3949
Stormberg	<550	39	24	120	272^{**}	856	181
	>550	18	11	41	49^{**}	90	774
	All	22	12	49	91	390	955
Lebombo and Drakensberg	<550	49	30	99	161	425	142
	>550	48	23	129	157	334	425
	All	48	26	125	158	359	567

5.3.4. EXCHANGEABLE SODIUM PERCENTAGE OF DIFFERENT GEOLOGICAL UNITS

The soils in the nearly 300 geological units (Table 5.5, Figure 5.4, and Appendix G) are predominantly non-sodic and only the Whitehill Formation, Knersvlakte Subgroup, Gladkop Suite, and Malmesbury Group can be considered sodic if a median threshold ESP value of 15 is use as an indicator of sodicity. If the average values are use, the soils of the Nyoka, Enon, Waterford, Sundays River, Prince Albert, and Fort Brown Formations, Port Nolloth, Bredasdorp, and Bokkeveld

Groups, Bidouw and Garies Subgroups, and Spektakel Subgroups are also sodic if a median threshold ESP value of 15 is use as an indicator of sodicity.

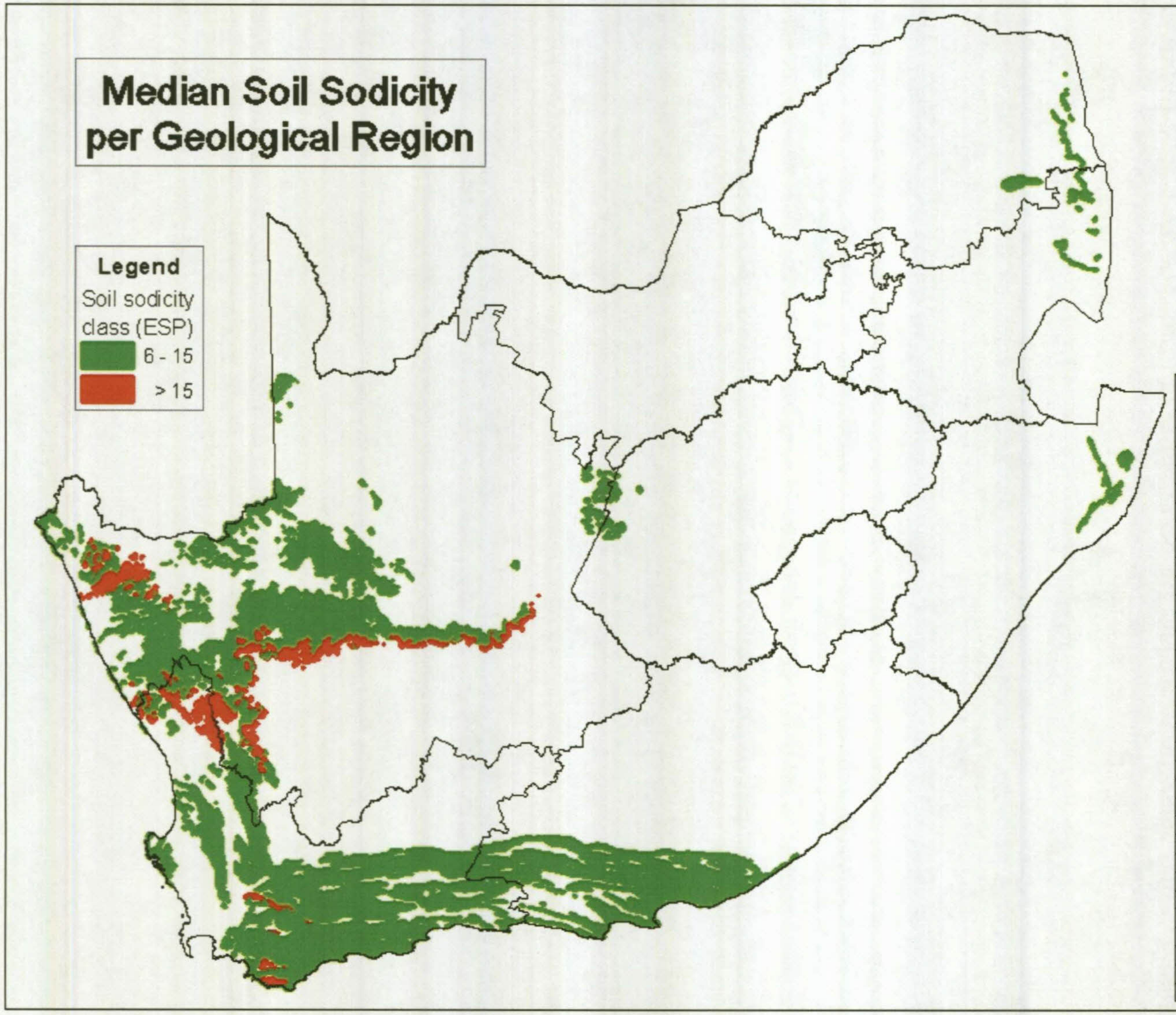
Most sodic soils (ESP>15), according to geological units are found in the arid areas of the Northern Cape and Western Cape Province. Relatively high sodic soils (ESP>6) are also found in the drier parts of the Eastern Cape, Free State, KwaZulu-Natal, Limpopo, and Mpumalanga Province (Figure 5.4, Table 5.5, and Appendix G). There is also a tendency for some of the most sodic soils to develop in geological units rich in granite and gneiss (Gladkop Suite, Spektakel Suite, Garies Subgroup, and Eendoorn Granite). Some of the most sodic soils developed on geological units with a predominately marine depositional environment and/or receive sodium rich coastal rainfall and/or fog (Port Nolloth, Bredasdorp, and Malmesbury Groups, Knersvlakte Subgroup, and Porterville, Sundays River, Kirkwood, Nanaga, and Alexandria Formations).

Mphepya *et al.* (2004) indicate that the composition of rainwater is affected by five sources: marine, terrigenous, nitrogenous, biomass burning, and anthropogenic sources. According to them, the marine source contributes 11% in Amersfoort (±300 km from the sea) and 23% in Louis Trichardt (± 450 km from the sea) to precipitation. The Na content of the rainfall at both sites were 9.3 mg L^{-1} and the annual wet deposition calculated by using the annual rainfall was 68.2 mmol m^{-2} yr^{-1} for Amersfoort and 56.1 mmol m^{-2} yr^{-1} for Louis Trichardt. The Na content of the rainfall was 8.9 mg L^{-1} and the annual wet deposition 20 mmol m^{-2} yr^{-1} for Skukuza (Mphepya *et al.*, 2006). The Na content of the rainfall in the Roodeplaat Dam catchment, near Pretoria was a very low at 0.4 to 1.5 mg L^{-1}, according to Bosman and Kempster (1985), an indication that not all rainfall has a high Na content. Fog is a major donor of salts and specifically Na to soils in the coastal and adjacent inland areas. In the Knersvlakte, non-rainfall may contribute up to 70 mm of water, or nearly 60 % of mean annual precipitation to the system (Brown *et al.*, 2008). In low-rainfall regions, fog transports moisture from the ocean up to 50 km inland (Van Zyl, 2003). Olivier (2004) suggested that around 88% of the water collected at Lepelfontein, about 5 km from the sea, originated from fog alone and only 12 % from rainfall. The measured Na content of the fog was 26.4 mg L^{-1} at Lepelfontein (Olivier, 2004) and 44 mg L^{-1} at Cape Columbine (Olivier, 2002).

TABLE 5.5 Exchangeable sodium percentage statistics for the geological units according to median values higher than ESP 6

Geological Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Whitehill Formation	79.8	3.0	118.0	72.9	70.2	15
Knersvlakte Subgroup	29.7	21.6	35.9	28.9	13.1	10
Gladkop Suite	21.6	12.6	45.7	32.6	24.2	9
Malmesbury Group	15.9	7.7	50.0	23.2	20.1	7
Nyoka Formation	13.8	2.9	32.8	17.6	16.2	9
Port Nolloth Group	13.8	9.2	22.0	33.8	49	13
Enon Formation	13.7	6.9	36.9	24.4	26.5	66
Waterford Formation	12.7	6.5	19.1	16.2	13.3	13
Sundays River Formation	10.9	4.9	25.5	17.9	16.1	57
Porterville Formation	10.7	4.4	17.1	13	10.8	63
Kirkwood Formation	9.7	5	25.0	19.2	22	38
Bredasdorp Group	9.2	4.6	20.0	18.6	23.6	18
Bokkeveld Group	8.5	3.6	13.1	54.5	241	50
Unnamed Granite and Gneiss	8.4	2.8	20.6	13.6	13.1	12
Bidouw Subgroup	8.0	5.0	19.8	16.3	18.9	32
Spektakel Suite	7.8	2.8	22.2	17.7	21.7	15
Prince Albert Formation	7.7	2.2	35.4	26.1	41	58
Muzi Formation	7.5	5.0	10.2	7.6	3.75	20
Piekenierskloof Formation	7.3	4.8	21.6	11.6	9.34	6
Garies Subgroup	7.0	5.2	26.0	19.5	23.8	11
Fort Brown Formation	6.8	3.3	16.8	18.1	29.5	78
Eendoorn Granite	6.7	3.3	13.5	16.8	27.1	39
Weltevrede Subgroup	6.7	3.7	11.5	11.4	27.4	78
Alexandria Formation	6.5	5.0	11.1	8.6	6.62	14
Ceres Subgroup	6.4	3.6	14.3	10.1	8.75	87
Nanaga Formation	6.3	3.6	10.0	7.9	6.04	78
Grootderm Formation	6.1	4.3	19.4	12.2	10.7	9

The halite crystals in the Whitehill Formation (Strydom, 1979; Van der Westhuizen *et al.,* 1981; Prinsloo, 1989), are probably a major cause of the high soil sodicity in this formation. In the Knersvlakte Subgroup, the most important cause of high soil sodicity is probably not the geological characteristics of the marine mudstone, siltstone, sandstone, conglomerate, and diamictite (Visser, 1989; Gresse, *et al.*, 2006), but the topographic position and climatic conditions under which the salts accumulated. From the geological data of Gresse (1992), the Na_2O content in the Knersvlakte Subgroup is only between 0.92% and 2.45% (m/m) in the sandstone and between 1.10% and 1.64% (m/m) in the shale. The Na_2O content of sea clay is in the order of 5.39% (m/m) according to Wedepohl (1971). The Malmesbury Group (fourth highest ESP) represents a predominately marine sedimentary assemblage with rocks, giving evidence of turbidite sedimentation in the west and marine shelf and possibly alluvial environments towards the east (Theron, 1983). The high soil sodicity in the Malmesbury Group is probably also not predominately from the marine shales of the Group alone, because the Na_2O content is only 1.5% (m/m) for the shales (Gresse, 1992). Dissolution of relict marine salt deposits occurs at coastal but not inland pans in the Darling area (Smith & Compton, 2004). They also indicated that the amount of Na released into solution by feldspar weathering from the granite in the area is relatively minor compared to the large contribution from coastal rainfall. Rainfall adjacent to the coast in the Western Cape has a chemical signature similar to seawater (Soderberg, 2003). The high soil sodicity in the Gladkop Suite (third highest ESP) is most likely the result of the weathering of the gneiss in this suite, because the range in Na_2O is from 2.58 to 5.40% (m/m) in the geological material (Reid *et al.,* 1983).



Stratification	Median ESP
Whitehill Formation	79.80
Knersvlakte Subgroup	29.70
Biesiesfontein Suite	26.60
Gladkop Suite	21.60
Malmesburry Group	15.90
Nyoka Formation	13.80
Port Nolloth Group	13.80
Enon Formation	13.70
Waterford Formation	12.70
Hoogoor Suite	11.40
Sundays River Formation	10.90
Porterville Formation	10.70
Kirkwood Formation	9.74
Bredasdorp Group	9.17
Bokkeveld Group	8.52
Timbavati Gabbro	8.45
Unnamed Granite and Gneis	8.36
Bidouw Subgroup	7.96
Spektakel Suite	7.84
Prince Albert Formation	7.71
Muzi Formation	7.46
Piekenierskloof Formation	7.27
Garies Subgroup	7.04
Fort Brown Formation	6.75
Eendoorn Granite	6.67
Harmony Granite	6.67
Weltevrede Subgroup	6.67
Alexandria Formation	6.53
Ceres Subgroup	6.43
Kaaimans Group	6.41
Nanaga Formation	6.25
Grootderm Formation	6.10

FIGURE 5.4 Median exchangeable sodium percentage of the geological units with an ESP higher than six.

5.3.5. EXCHANGEABLE SODIUM PERCENTAGE OF DIFFERENT GROUNDWATER UNITS

The soil in the 65 groundwater units (Table 5.6, Figure 5.5, and Appendix H) are predominantly non-sodic and only the Richtersveld and Tanqua Karoo groundwater units can be considered sodic if a median threshold ESP value of 15 is used as indicator of sodicity. If the average values are used soils of the Knersvlakte, Ruensveld, Intermontane Tulbagh-Ashton Valley, Oudtshoorn Basin, Namaqualand, and Bredasdorp Coastal Belt are also sodic.

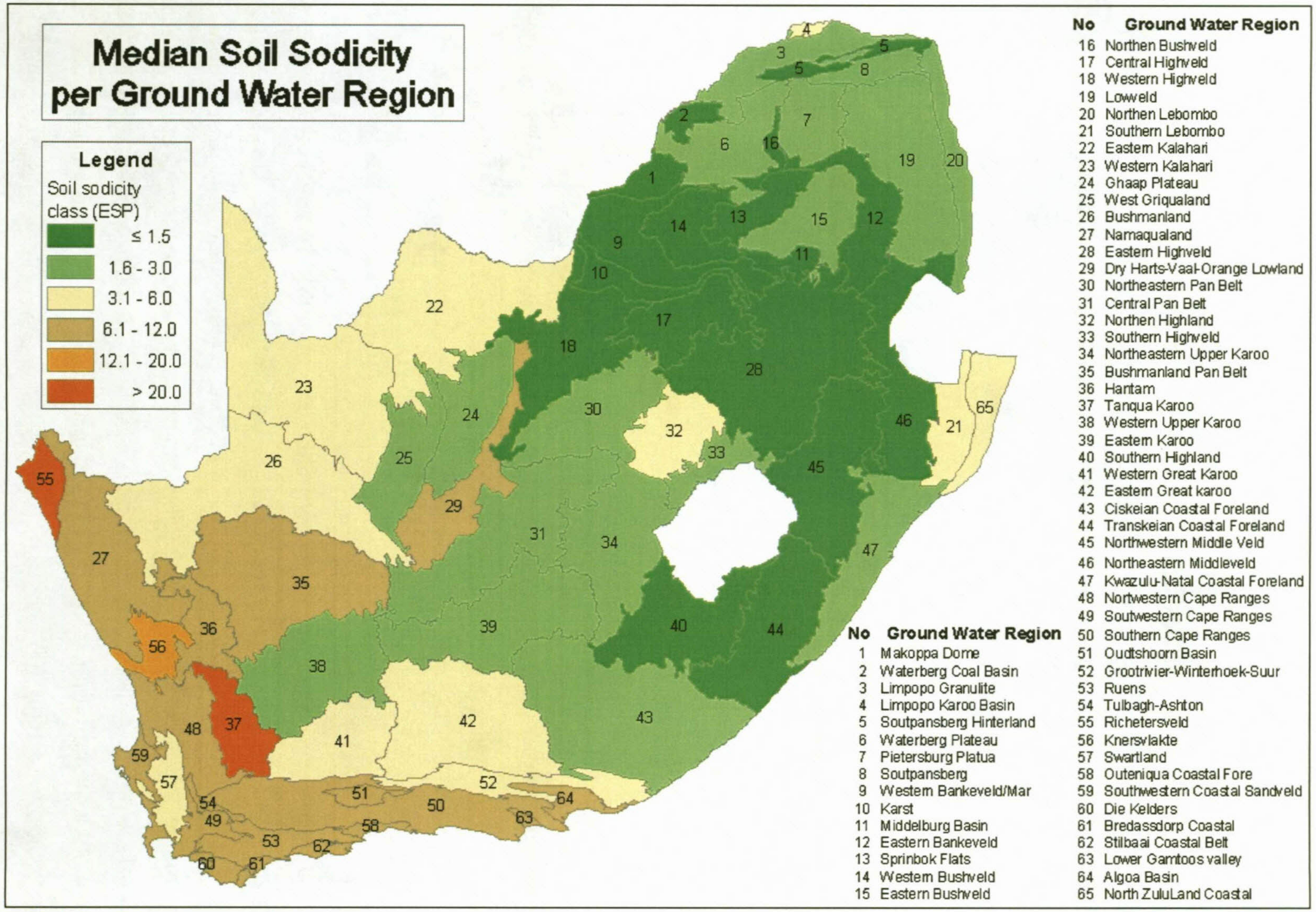
There is a tendency that the groundwater regions with the highest soil ESP occur in the more arid western part of South Africa, between intermontane areas such as the Tulbagh-Ashton valley, in groundwater regions that can be classified as relatively closed basins such as the Tanqua Karoo, Oudtshoorn Basin, and Algoa Basin, and areas where coastal rainfall and fog occurs such as the Richtersveld, Namaqualand, Bredasdorp Coastal Belt, Algoa Basin, Lower Gamtoos Valley, Outenikwa Coastal Foreland, Southwestern Coastal Sandveld, and Stilbaai Coastal Belt.

The Richtersveld groundwater unit with the highest median soil ESP of 27.6 consist mostly of Namibian and Cambrian Period material and is represented by rocks of the Richtersveld Suite, the Gariep Supergroup, and Nama Group (Vegter, 2001; Gresse *et al.*, 2006). Although the gneiss, granite, and tertiary raised beach deposits and alluvium contribute to high sodicity, the largest contribution is probably from coastal rainfall and fog, because geological weathering is expected to be very slow in this extremely arid groundwater unit.

The Tanqua Karoo groundwater region has the second highest soil ESP of 25.4 (Table 5.6). The geological material in the Tanqua Karoo groundwater region origin is mostly from the Whitehill, Prince Albert, and Waterford Formations. These formations are some of the most sodic geological units in South Africa (Table 5.5; paragraph 5.3.4). The Knersvlakte groundwater region (third highest median soil ESP of 14.5) consists mostly of sediments from the Knersvlakte Subgroup that is the second highest median soil ESP geological unit (Table 5.5; paragraph 5.3.). The fourth most sodic groundwater region is the Ruensveld with a median soil ESP of 11.2 (Table 5.6). The region consists of Ordo-Devonian material of predominately Bokkeveld Group shale, sandstone and siltstone, isolated occurrences of Table Mountain Group sandstone, and of Witteberg Group sandstone and shale (Vegter, 2001). The paleogeography data of Thamm and Johnson (2006) indicate that the Ruensveld groundwater region occurs on a paleo shallow marine shelf. According to Theron (1983), early Devonian marine life teemed in the shallow epeiric sea of the Bokkeveld Group, as reflected by the abundant fossilireous remains and feeding trails and tracks of infaunal bivalves, epifaunal brachiopods, and placoderm fish. The Bokkeveld Group comprise fine to medium-grained feldspathic wacke and arenite, mudrock, siltstone and minor sandstone (Thamm & Johnson, 2006).

TABLE 5.6 Exchangeable sodium percentage statistics for the groundwater units according to median values higher than ESP 6

Groundwater Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Richtersveld	27.6	7.9	78.5	59.8	90.7	88
Tanqua Karoo	25.4	10.6	50.0	59.3	125	83
Knersvlakte	14.5	4.6	35.0	22.1	22.1	71
Ruensveld	11.2	6.0	20.3	44.8	175	101
Intermontane Tulbagh-Ashton Valley	11.0	5.6	15.9	16.8	18.4	45
Oudtshoorn Basin	10.5	7.8	39.8	27.7	33.6	24
Namaqualand	10.2	4.3	26.2	18.6	22.6	198
Bredasdorp Coastal Belt	10.0	4.6	17.5	13.0	14.2	9
Algoa Basin	8.7	4.0	17.7	14.4	16	218
Hantam	8.3	3.0	16.1	14.4	19	33
Lower Gamtoos Valley	8.2	4.7	11.1	10.9	9.67	17
Northwestern Cape Ranges	7.1	2.5	16.5	20.8	46.9	152
Southwestern Cape Ranges	7.1	3.3	17.2	14.5	18.8	82
Southwestern Coastal Sandveld	6.7	3.7	15.2	14.6	21.3	81
Outenikwa Coastal Foreland	6.5	4.4	11.9	9.5	7.41	39
Southern Cape Ranges	6.5	3.7	12.5	9.9	10.2	233
Dry Harts-Vaal-Orange	6.3	2.3	16.0	12.3	15	466
Stilbaai Coastal Belt	6.3	4.9	8.3	6.2	3.21	5



No	Ground Water Region
1	Makoppa Dome
2	Waterberg Coal Basin
3	Limpopo Granulite
4	Limpopo Karoo Basin
5	Soutpansberg Hinterland
6	Waterberg Plateau
7	Pietersburg Platua
8	Soutpansberg
9	Western Bankeveld/Mar
10	Karst
11	Middelburg Basin
12	Eastern Bankeveld
13	Sprinbok Flats
14	Western Bushveld
15	Eastern Bushveld

No	Ground Water Region
16	Northen Bushveld
17	Central Highveld
18	Western Highveld
19	Lowveld
20	Northen Lebombo
21	Southern Lebombo
22	Eastern Kalahari
23	Western Kalahari
24	Ghaap Plateau
25	West Griqualand
26	Bushmanland
27	Namaqualand
28	Eastern Highveld
29	Dry Harts-Vaal-Orange Lowland
30	Northeastern Pan Belt
31	Central Pan Belt
32	Northen Highland
33	Southern Highveld
34	Northeastern Upper Karoo
35	Bushmanland Pan Belt
36	Hantam
37	Tanqua Karoo
38	Western Upper Karoo
39	Eastern Karoo
40	Southern Highland
41	Western Great Karoo
42	Eastern Great karoo
43	Ciskeian Coastal Foreland
44	Transkeian Coastal Foreland
45	Northwestern Middle Veld
46	Northeastern Middleveld
47	Kwazulu-Natal Coastal Foreland
48	Nortwestern Cape Ranges
49	Soutwestern Cape Ranges
50	Southern Cape Ranges
51	Oudtshoorn Basin
52	Grootrivier-Winterhoek-Suur
53	Ruens
54	Tulbagh-Ashton
55	Richetersveld
56	Knersvlakte
57	Swartland
58	Outeniqua Coastal Fore
59	Southwestern Coastal Sandveld
60	Die Kelders
61	Bredassdorp Coastal
62	Stilbaai Coastal Belt
63	Lower Gamtoos valley
64	Algoa Basin
65	North ZuluLand Coastal

FIGURE 5.5 Median soil sodicity of the different groundwater regions in South Africa.

5.3.6. EXCHANGEABLE SODIUM PERCENTAGE OF THE KAROO SUPERGROUP

None of the soils in the groups of the Karoo Supergroup can be classified as sodic if the median and average values are used and no real difference transpires between the groups (Table 5.7). The main reason for this anomaly is that the effect of rainfall and leaching is more dominant on sodium accumulation in a soil than the original parent material, especially if the groups of the Karoo Supergroup are not subdivided to formation level. Statistically significant differences at the 99% confidence level occur within a group between rainfall classes (Table 5.7). The highest soil median and average ESP values are encounted under low rainfall conditions in the Dwyka Group. Quartz, albite (sodium rich mineral), microcline, chlorite, and illite represent the main mineral phases in the glaciogenic Dwyka sediments (Scheffler *et al.,* 2006). The relatively high soil ESP values found in the Lebombo and Drakensberg groups are probably the result of high Na_2O that range from 2.14 to 2.51% (m/m) in the Drakensberg Group and from 1.6 to a high 6.92% (m/m) in the Lebombo Group (Duncan & Marsh, 2006).

TABLE 5.7 Exchangeable sodium percentage statistics for the Karoo Supergroup

Group	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Dwyka	<550	5.2	2.6	18.0	35.4**	132.0	135
	>550	1.6	0.7	3.2	3.0**	5.9	649
	All	1.9	0.8	3.8	8.6	56.2	784
Ecca	<550	2.6	1.4	8.8	12.9**	32.7	728
	>550	1.6	0.8	3.2	3.5**	9.9	2855
	All	1.8	0.9	3.7	5.5	17.6	3583
Beaufort	<550	2.8	1.3	6.9	7.3**	15.4	980
	>550	1.6	0.8	3.5	3.5**	6.1	3344
	All	1.8	0.9	4.1	4.4	9.2	4324
Stormberg	<550	3.2	1.5	8.0	7.7**	12.7	183
	>550	1.5	0.7	3.3	3.7**	7.0	723
	All	1.8	0.8	4.3	4.5	8.6	906
Lebombo and Drakensberg	<550	1.5	0.8	4.0	13.9**	64.0	120
	>550	1.8	0.8	3.8	5.8**	12.5	405
	All	1.7	0.8	3.9	7.7	32.6	525

In South Africa most of the dispersive clays encountered have been found in soils derived from the Molteno Formation, the Beaufort, Ecca, and Dwyka Groups (all part of the Karoo Supergroup), the Witteberg, Bokkeveld and Table Mountain Groups of the Cape Supergroup, the Malmesbury Group, the Cretaceous Enon, Kirkwood, and Sundays River Formations of the Uitenhage Group (Elges, 1985). He also indicates that soils developed on granite are especially prone to the development of high ESP values in low-lying areas. According to Brink (1985), dispersive soils develop in zones where the parent material of transported soil contains large quantities of illite and 2:1 clays with high ESP values. This situation is especially well represented in Cretaceous mudrocks and in mudrocks of the upper Beaufort Group and the Molteno Formation of the Karoo Supergroup in areas where climatic N-values range from 2 to 10.

The effect of sodicity on crusting, erosion, and infiltration were studied by several researches in South Africa on different geological material (Van der Merwe, 1965; Du Plessis & Shainberg, 1985; Levey & Van der Watt, 1988; Nel, 1989; Smith, 1990; Bloem & Laker, 1994).

5.3.7. SOIL ALKALINITY OF DIFFERENT GEOLOGICAL UNITS

The majority of alkaline soils according to geological units (Table 5.8, Figure 5.6, and Appendix I) occur in low rainfall areas in the Northern Cape Province, although extensive areas of alkaline soils are also found in the higher rainfall areas of the Limpopo Province that can be associated with geological units laden with granite, gneiss, anorthosite, and gabbronite. In the Eastern Cape Province, the alkaline soils can be associated with relatively young marine sediments.

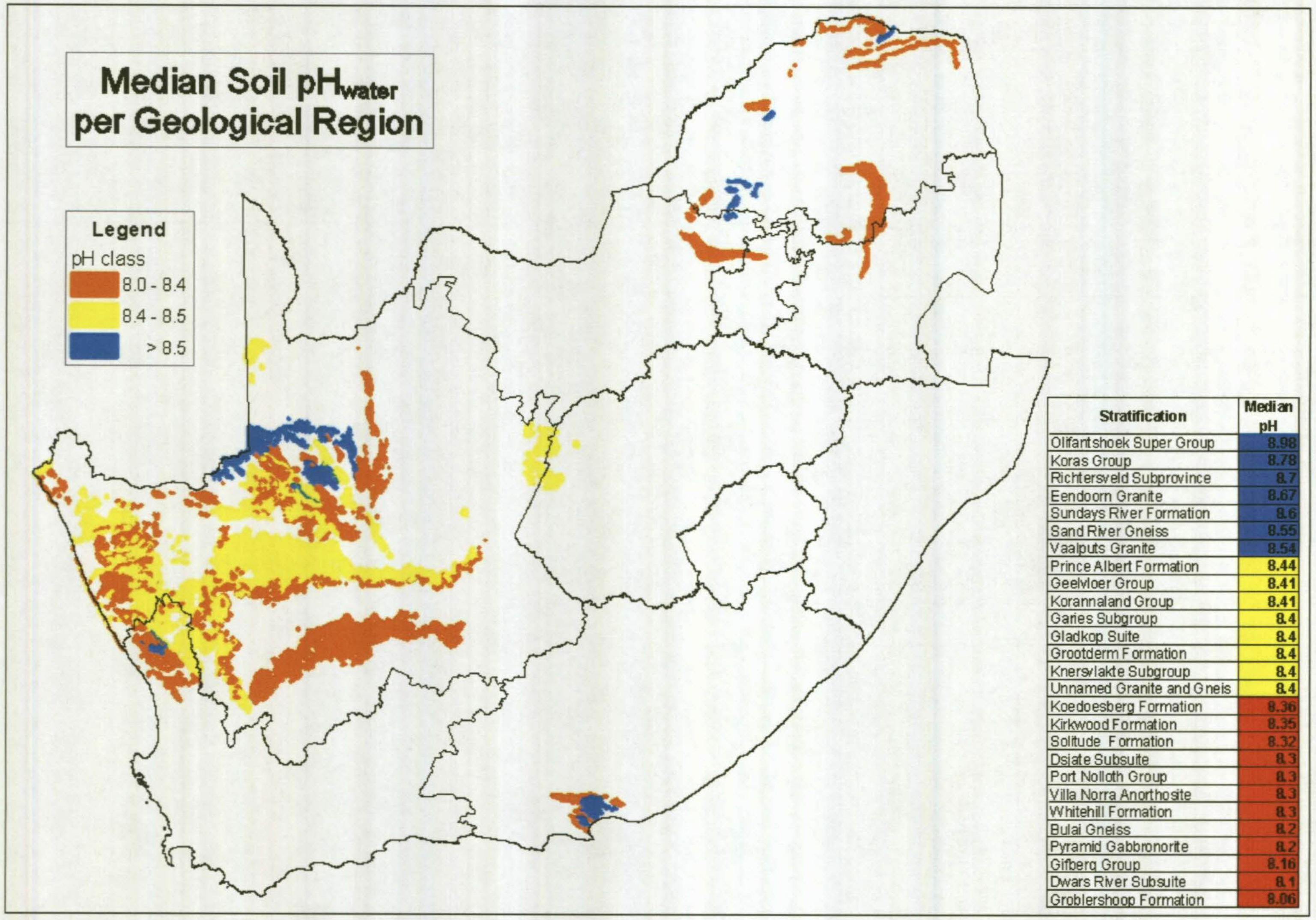
The most alkaline soil in geological units occur in the Richtersveld Subprovince and in the Eendoorn granite (Table 5.8), both occuring in the Namaqua Sector in the tectono-stratigraphic Namaqua-Natal Province (Cornell *et al.*, 2006) and both have a median soil pH_{water} of 8.7. Other geological units with high soil alkalinities that occur in the Namaqua Sector of the Namaqua-Natal Province are the Geelvloer Group (sixth highest median soil pH), Korannaland Group (seventh highest median soil pH), Garies Subgroup (eighth highest median soil pH) and Gladkop Suite (ninth highest median soil pH). These geological units are mostly characterised by granite, syenite, granodiorite, and gneiss. The Richtersveld Subprovince with the shared highest soil alkalinity comprises the 2 000 Ma old calc-alkaline volcanics of the Orange River Group and the 1 900-1 730 Ma intrusive Vioolsdrift granitoid batholith (Reid *et al.,* 1987; Eglington, 2006). The Eendoorn granite is rich in microcline, biotite, quartz, and plagioclase, with silmanite and cordierite as additional minerals (Visser, 1989). According to the mean geochemical analyses (m/m) in the Namaqualand metamorphic complex (Reid & Barton, 1983) for gneiss Na_2O = 3.8%, CaO = 1.4%, and MgO = 0.50%. For granodiorite the means are: Na_2O = is 3.0%, CaO 4.0%, and MgO = 2.2%. For granite the mean Na_2O = 3.1%, CaO = 1.3%, and MgO = 0.77%. The sediments in the Sundays River Formation (third highest median soil pH_{water}), Kirkwood Formation (14th highest median soil pH_{water}), and Port Nolloth Group (17th highest median soil pH_{water}) are all characterized by a marine origin. The Price Albert Formation, with a median pH_{water} of 8.4 that consists of mudstone, chert, carbonatic, phosphatic nodules, and lenses (Scheffler *et al.*, 2006) is the formation in the Karoo Supergroup with the highest soil alkalinity. The Geelvloer Group with a median soil pH_{water} of 8.4 consist of calc-silicate, biotite-chlorite schist, quartzite, and pyrite (Visser, 1989; Salt River Resources, 2009).

Netterberg (1969) described the effect of the five soil forming factors on the regional and local distribution of calcification in South Africa. According to him, the 550 mm isohyet (Figure 2.1.) is a good indication of the upper limit of hardpan (calcrete) occurrence, while the 800 mm isohyet is the upper limit of calcification in South Africa. Du Toit (1938) noted a figure of 625 mm and Van der Merwe (1962) a figure 650 mm, for the upper limit of calcrete occurrence in South Africa.

According to Martini and Wilson (1998), economically significant resources of carbonates are generally hosted within the following five sedimentary units: (a) the Malmani Subgroup, (b) the Campbell Rand Subgroup, (c) the Malmesbury Group, (d) the Nama group, and (e) Tertiary to Quaternary coastal limestone along the Cape coast. None of these sedimentary units have a median soil pH_{water} of more than 8.2 (Table 5.8 and Appendix I), an indication that the carbonates alone do not contribute to high alkaline conditions.

TABLE 5.8 pH_{water} statistics for geological units to according to median values for pH_{water} higher than 8.1.

Geological Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Richtersveld Subprovince	8.7	8.4	9.2	8.5	1.06	19
Eendoorn Granite	8.7	8.4	8.9	8.7	0.49	39
Sundays River Formation	8.6	8.3	8.8	8.5	0.58	57
Sand River Gneiss	8.6	7.7	8.7	8.3	0.68	18
Prince Albert Formation	8.4	8.0	8.8	8.4	0.60	58
Geelvloer Group	8.4	8.3	8.8	8.5	0.38	32
Korannaland Group	8.4	8.3	8.6	8.5	0.26	12
Garies Subgroup	8.4	6.6	8.8	8.1	1.19	11
Gladkop Suite	8.4	8.2	8.8	8.6	0.79	9
Knersvlakte Subgroup	8.4	7.9	9.5	8.5	0.77	10
Unnamed Granite and Gneiss	8.4	8.2	8.7	8.4	0.34	12
Koedoesberg Formation	8.4	7.8	8.6	8.1	0.52	9
Kirkwood Formation	8.4	8.0	8.7	8.3	0.68	38
Grootderm Formation	8.4	8.2	8.5	8.2	0.42	9
Solitude Formation	8.3	7.4	8.6	7.9	1.07	11
Dsjate Subsuite	8.3	7.2	8.6	7.9	0.92	81
Port Nolloth Group	8.3	7.9	8.5	8.2	0.55	13
Whitehill Formation	8.3	8.0	8.4	8.2	0.43	15
Villa Norra Anorthosite	8.3	7.4	8.4	8.0	0.99	25
Bulai Gneiss	8.2	7.3	8.6	8.1	0.98	26
Pyramid Gabbronorite	8.2	7.8	8.4	8.0	0.64	40
Gifberg Group	8.2	6.7	8.6	7.7	1.21	18



Stratification	Median pH
Olifantshoek Super Group	8.98
Koras Group	8.78
Richtersveld Subprovince	8.7
Eendoorn Granite	8.67
Sundays River Formation	8.6
Sand River Gneiss	8.55
Vaalputs Granite	8.54
Prince Albert Formation	8.44
Geelvloer Group	8.41
Korannaland Group	8.41
Garies Subgroup	8.4
Gladkop Suite	8.4
Grootderm Formation	8.4
Knersvlakte Subgroup	8.4
Unnamed Granite and Gneis	8.4
Koedoesberg Formation	8.36
Kirkwood Formation	8.35
Solitude Formation	8.32
Dsjate Subsuite	8.3
Port Nolloth Group	8.3
Villa Norra Anorthosite	8.3
Whitehill Formation	8.3
Bulai Gneiss	8.2
Pyramid Gabbronorite	8.2
Gifberg Group	8.16
Dwars River Subsuite	8.1
Groblershoop Formation	8.06

FIGURE 5.6 Soil alkalinity of geological units with a median pHwater higher than 8.1 per geological unit.

5.3.8. SOIL ALKALINITY OF DIFFERENT GROUNDWATER UNITS

The most alkaline soils occur in the Richtersveld-, Ghaap Plateau-, and Western Kalahari groundwater units with a median soil pH_{water} of 8.5 (Table 5.9, Figure 5.7, and Appendix J). Although the majority of the most alkaline soils are found in the western and northwestern groundwater regions of South Africa the exception to the rule is the Limpopo Karoo Basin groundwater region in the most northern part of South Africa with a median soil pH_{water} of 8.5 (Figure 5.7).

The Richtersveld groundwater region is composed principally of Namibian strata, rich in biotite granite, gneiss, quartzite, arkose, arenite, limestone, dolomite, diamictite, phyllite, and schist (Vegter, 2001). The Ghaap Plateau groundwater region is composed of Vaalian strata of the Campbell Rand and Schmidtsdrif Subgroups and Vryburg Formation, with limestone, dolomite, chert, andesite, and shale dominant (Vegter, 2001). The Western Kalahari groundwater region consists predominately of Kalahari Group, calcareous sand, sandstone, and clay; Brulpan Group muscovite, quartzite, and schist; Wildenhoutsdrif Group phyllite; Koras Group sandstone, and basalt; Dwyka Formation tillite; and Prince Albert Formation shale (Vegter, 2001). The Bushmanland Pan Belt, Tanqua Karoo, and Limpopo Karoo Basin groundwater units have all a median soil pH_{water} of 8.4 (fourth highest) and all have a parent material that is predominantly of Carbo-Triassic strata origin (Vegter, 2001).

TABLE 5.9 pHwater statistics for groundwater units according to median values for pHwater higher than 8.0

Groundwater Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Richtersveld	8.5	8.2	8.9	8.5	0.75	88
Ghaap Plateau	8.5	8.0	8.6	8.3	0.63	36
Western Kalahari	8.5	7.6	8.9	8.3	0.80	76
Bushmanland Pan Belt	8.4	8.0	8.8	8.4	0.59	113
Tanqua Karoo	8.4	8.0	8.8	8.4	0.67	83
Limpopo Karoo Basin	8.4	8.0	8.6	8.3	0.57	236
Algoa Basin	8.3	7.5	8.7	8.0	0.96	218
Dry Harts-Vaal-Orange	8.3	7.7	8.7	8.1	0.76	466
Bushmanland	8.3	7.8	8.7	8.2	0.65	421
Western Upper Karoo	8.3	7.6	8.8	8.2	0.83	72
Bredasdorp Coastal Belt	8.2	8.0	8.2	8.1	0.36	9
Eastern Upper Karoo	8.1	7.5	8.6	8.1	0.81	113
Hantam	8.1	7.6	8.6	8.0	0.70	36
Namaqualand	8.1	6.7	8.8	7.8	1.40	198
Western Great Karoo	8.1	7.3	8.5	7.9	1.10	63
Central Pan Belt	8.0	7.3	8.5	7.9	0.81	320
Eastern Great Karoo	8.0	7.5	8.5	8.0	0.84	162

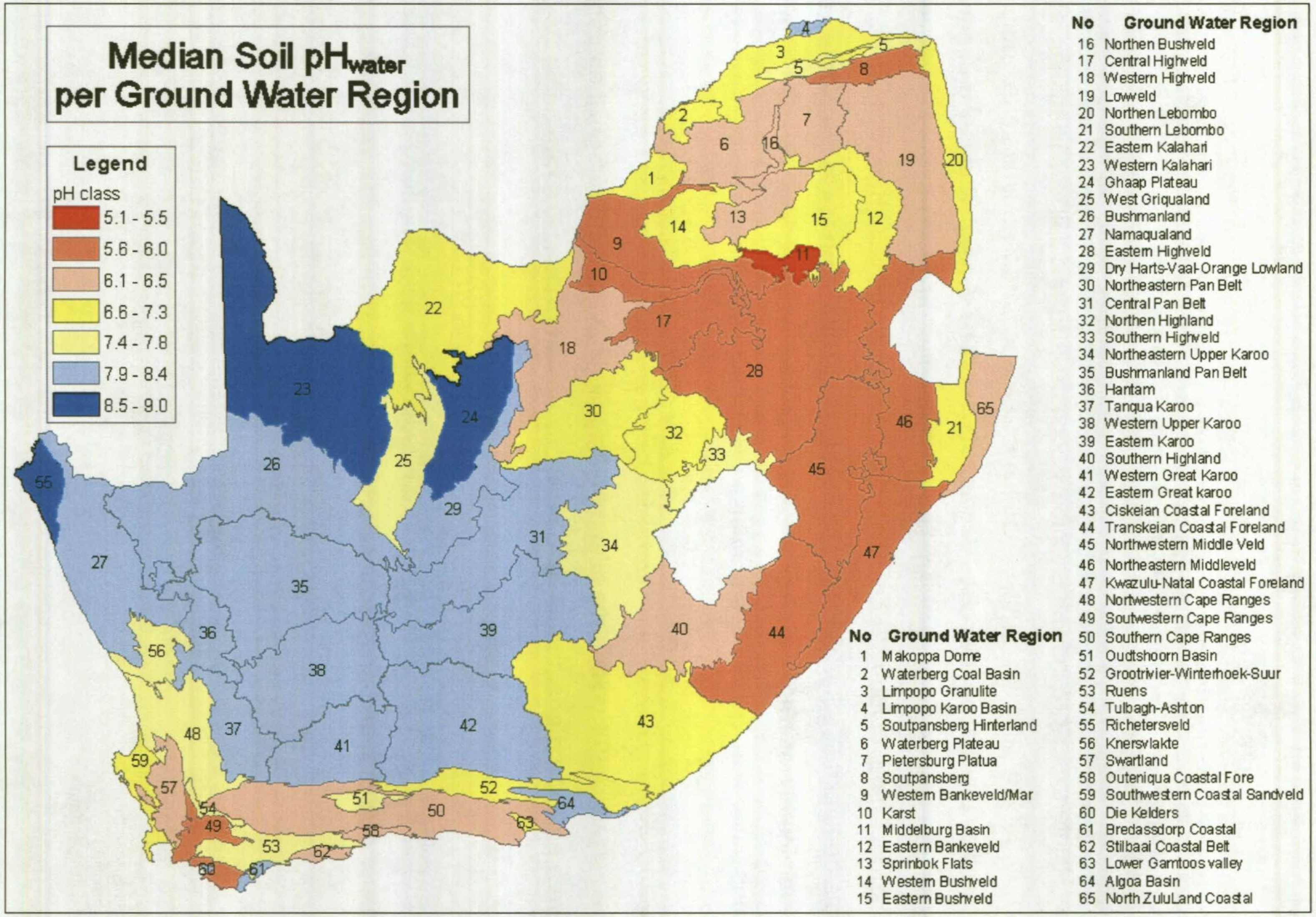


FIGURE 5.7 Soil pH_{water} of the different groundwater regions in South Africa.

5.3.9. SOIL ALKALINITY OF THE KAROO SUPERGROUP

Statistical significant differences at the 99% confidence level occur within a group between rainfall classes for soil pH_{water}, but this is not so clear between groups in the Karoo Supergroup (Table 5.10). The range in median soil pH_{water} in the low rainfall class is from 7.8 (Beaufort Group) to 8.0 (Dwyka Group), and in the high rainfall area from 5.7 (Dwyka group) to 6.4 (Lebombo and Drakensberg Group). The relatively high soil pH_{water} values found in the Lebombo and Drakensberg groups are probably the result of relatively high Na, Ca, and Mg values. The Na_2O weight percentage range from 2.14 to 2.51 in the Drakensberg Group and from 1.6 to a high 6.92 in the Lebombo Group, MgO ranges from 5.53 to 7.93 in the Drakensberg Group and from 0.39 to a very high 15.38 in the Lebombo Group, the range for CaO is from 10.16 to 10.95 in the Drakensberg Group and from 1.7 to 9.53 in the Lebombo Group (Duncan & Marsh, 2006). A network of dolerite dykes and sills also intrudes the Karoo Supergroup. Dolerite is rich in Ca and Mg, and to a lesser degree in Na, which can contribute to alkaline soil conditions. From the dolerite geochemical analyses of Le Roex and Reid (1978), Marsh and Mndaweni (1998), and Mitha (2006), the range in MgO is from 5.33 to 7.66% (m/m), CaO from 9.64 to 14.76% (m/m) and for Na_2O from 1.60 to 2.71% (m/m).

TABLE 5.10 Table 5.10. pH_{water} statistics for the Karoo Supergroup

Group	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Dwyka	<550	8.0	6.9	8.6	7.7**	1.06	136
	>550	5.7	5.2	6.3	5.8**	0.8	658
	All	6.0	5.3	6.7	6.2	1.1	794
Ecca	<550	7.9	7.1	8.5	7.8**	0.96	739
	>550	5.9	5.3	6.5	6.0**	0.95	2868
	All	6.1	5.4	7.2	6.4	1.19	3607
Beaufort	<550	7.8	7.0	8.4	7.7**	0.92	989
	>550	6.3	5.6	7.1	6.4**	1.07	3302
	All	6.6	5.8	7.6	6.7	1.17	4291
Stormberg	<550	7.9	6.9	8.4	7.7**	0.85	192
	>550	6.1	5.6	6.9	6.4**	1.07	789
	All	6.4	5.7	7.5	6.6	116	981
Lebombo and Drakensberg	<550	7.9	6.8	8.4	7.7**	0.93	132
	>550	6.4	5.7	7.2	6.5**	1.1	500
	All	6.6	6.0	7.7	6.8	1.16	632

The majority of the 9.25 million ha of alkaline saline-sodic soils (pH_{water},>8.5) in South Africa (Nell & Henning, 2003), developed on the Karoo Supergroup. The study of Ellis (1988) indicates that shallow calcareous lithosols (10.57 million ha) and red apedal soils with a high base saturation (10.19 million ha) occupy the largest area of the Karoo. He also noted that the total soluble salt content increases from the A horizon to the underlying horizons and that the most important underlying materials in the Karoo are lime in the form of hardpan calcrete, calcic horizons, or rock with lime and dorbank.

5.3.10. EXCHANGEABLE SODIUM, MAGNESIUM, AND CALCIUM OF THE DIFFERENT GEOLOGICAL UNITS

As expected, the soils with the highest median exchangeable Na content in the different geological units (Table 5.11 and Appendix K) are also those with highest ESP values (Table 5.5). The soils in the Whitehill Formation are by far the most Na rich, a major cause of the very high sodicity and salinity in this geological unit. The other soils high in Na in the different geological units are predominantly characterised by marine origin sediments and granite or gneiss parent material, an arid climate, and salty rainwater and/or fog from the sea.

The highest median soil exchangeable Mg values in soils is found predominantly in geological units rich in gabbro, gabbronorite, norite-anorthostite, olivine, and pyroxene. In this regard the Pyramid Gabbronorite, Dwars River Subsuite, and Dsjate Subsuite (Table 5.11 and Appendix L), all classified under the Rustenburg Layered Suite (Cawthorn *et al.,* 2006), are the most dominant parent material for Mg rich soils. The Hlobane Complex (4th highest soil Mg value) is also derived from gabbro (Visser, 1989) parent material. Two of the Lebombo Group formations, the Letaba and Jozini also produce soil rich in Mg. The Letaba Formation comprises picritic (olivine-rich) basalt and the Jozini Formation silicic rocks that are plagioclase-phyric rhyodacites and rhyolites (Duncan & Marsh, 2006). The average geological MgO value of the Letaba Formation is a relatively high 15.38% (m/m) and in the Jozini Formation a very low 0.40% (m/m) (Duncan & Marsh, 2006). The very low MgO content in the predominantly rhyolite parent material is in contradiction with the very high Mg content found in the soil. Relatively small intrusions of granorphyric gabbro occur in the Lebombo range with an MgO range of 0.85 to 8.6% (m/m) (Saggerson & Logan, 1988), but its effect on the high Mg values in the soil of the Jozini Formation must be localized. It was established that the rhyolite of the Jozini Formation is extremely resistant to weathering (Venter, 1990). On a geochemical basis, weathered rhyolite is less enriched in cations such as Ca and Mg compared to basalt (Meulenbeld, 2007). This is an example where the rhyolite is a non-extreme or non-active parent material and that the active parent material is probably the basalt of the bordering Letaba Formation.

TABLE 5.11 Summary statistics of the highest exchangeable Na, Ca, and Mg values per geological unit

Geological Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Na ($cmol_c\ kg^{-1}$)						
Whitehill Formation	6.6	0.3	12.3	7.0	7.2	15
Knersvlakte Subgroup	1.9	1.1	2.9	2.2	1.5	10
Gladkop Suite	1.7	1.1	3.1	2.3	1.9	9
Malmesbury Group	1.1	0.1	2.5	1.2	1.2	7
Sundays River Formation	1.1	0.5	2.9	2.0	2.0	57
Enon Formation	1.1	0.5	3.4	2.7	3.4	66
Kirkwood Formation	1.1	0.4	2.7	1.7	1.8	38
Prince Albert Formation	1.0	0.2	4.5	3.5	5.6	58
Waterford Formation	0.9	0.6	2.6	1.5	1.1	13
Alexandria Formation	0.8	0.4	1.2	1.0	0.8	14
Nyoka Formation	0.8	0.4	5.4	2.5	3.0	13
Port Nolloth Group	0.8	0.4	1.6	2.0	3.4	13
Mg ($cmol_c\ kg^{-1}$)						
Pyramid Gabbronorite	10.7	6.3	15.1	12.2	7.18	27
Dwars River Subsuite	9.6	3.6	18.9	11.1	8.13	65
Hlobane Complex	7.3	5.2	12.9	8.6	4.45	11
Nyoka Formation	7.2	5.4	9.7	7.7	2.59	13
Makwassie Formation	6.6	5.1	8.6	6.9	2.23	12
Jozini Formation	6.0	3.3	8.9	6.9	4.49	62
Letaba Formation	6.0	3.4	10.6	7.4	5.36	432
Dsjate Subsuite	5.9	3.2	10.0	7.9	6.61	99
Giyani Group	5.9	4.0	8.8	6.6	3.23	12
Pienaars River Subprovince	5.4	2.8	6.6	6.3	4.39	11
Ntabene Formation	5.3	3.5	8.2	6.0	3.86	28
Emakwezini Formation	5.0	3.2	7.2	5.3	2.72	130
Ca ($cmol_c\ kg^{-1}$)						
Pyramid Gabbronorite	19.1	12.7	27.7	20.2	9.56	27
Dsjate Subsuite	16.6	10.2	23.8	17.7	10.9	99
Whitehill Formation	14.7	11.2	60.0	32.9	28.1	15
Makwassie Formation	14.1	7.4	17.0	12.6	4.72	12
Timbavati Gabbro	12.9	9.9	15.2	11.5	5.85	9
Prince Albert Formation	12.3	8.0	21.2	16.0	15.6	58
Letaba Formation	10.8	5.1	19.7	13.5	10.9	432
Villa Norra Anorthosite	10.5	5.3	18.7	17.3	17.9	25
Koedoesberg Formation	9.0	6.4	14.7	10.5	5.98	9
Modipe Complex	8.9	3.6	11.8	8.6	5.4	13
Gaborone Granite	8.4	1.7	11.4	7.1	5.02	10
Sundays River Formation	8.3	6.6	10.6	9.4	7.18	57

The highest median exchangeable Ca values in soils (Table 5.11 and Appendix M) are mainly found in geological units rich in gabbro, gabbronorite, anorthosite, basalt, and pyroxene. In this regard the Pyramid Gabbronorite, Dsjate Subsuite, Timbavati Gabbro, Modipe Complex, Letaba Formation, and Villa Norra Anorthosite are the most important geological units. The Whitehill Formation (3rd highest Ca) and the Prince Albert Formation (6th highest Ca) of the Ecca Group both consist of black carbonaceous shales and pyrite-bearing shale (Woodford & Chevallier, 2002). The

Makwassie Formation in the Ventersdorp Supergroup has the fifth highest median soil Mg value and the fourth highest median soil Ca value of all geological units. The Makwasie Formation is classified as calc-alkaline dacites and rhyolites (Meintjies, 1998). The Koedoesberg Formation (9th highest median Ca) consists mostly of feldspathic sandstone and greywacke, with some limestone lenses (Viljoen, 1989), the latter probably resulting in relatively high soil Ca values.

5.3.11. EXCHANGEABLE SODIUM, MAGNESIUM, AND CALCIUM OF THE DIFFERENT GROUNDWATER UNITS

Soils with the highest median soil Na content in the different groundwater units (Table 5.12 and Appendix N) are also those with highest soil ESP values (Table 5.6). The exception is the Namaqualand groundwater region with a relatively high soil ESP value that was not detected in high soil Na per groundwater unit. This abnormality can be contributed to parent material rich in granite, gneiss, and quartzite that resulted in sandy soils with low cation exchange capacities and therefore high ESP values.

The soils in the Tanqua Karoo and Richtersveld groundwater units are by far the richest in Na, a major cause of the very high sodicity and salinity in these groundwater units. The soils high in Na in the different groundwater units are predominantly characterised by marine origin sediments, granite, or gneiss, an arid climate, the influence of salty rainwater and fog from the sea, and basin, pan, or intermontane surroundings. It is predictable that soils in the Northern Lebombo, Southern Lebombo, and Western Bushveld Complex groundwater units must have high Mg values, because the parent material is largely gabbro, gabbronorite, norite, anorthostite and pyroxene (Vegter, 2001), rich in Mg (Table 5.12 and Appendix O). It is, however, revealing that the North-Eastern Upper Karoo groundwater unit has the highest median soil Mg value of all groundwater units (Table 5.12). This groundwater unit consists predominantly of Adelaide and Tarkastad Subgroups mudstone, shale and sandstone (Vegter, 2001), with lower Mg values. Although the Tarkastad and Adelaide subgroups have been intruded by a network of dolerite dykes and sills (Visser, 1986), with relatively high Mg values, it cannot be explain with certainty that it is the only, or major cause of the high Mg content in the soil. Another explanation is that it is the result of weathering remnants of basalt from the

Drakensberg Group that also dominated the current groundwater unit in the past. Calcium (374 mg kg^{-1}) and magnesium (122 mg kg^{-1}) are dominant and sodium relatively low (21 mg kg^{-1}) in the sediments of the Caledon River (Slabbert, 2007) that forms part of the North-Eastern Upper Karoo groundwater region. The high Ca and Mg contents might therefore be an indication of additions to the soil from basalt and dolerite parent material.

TABLE 5.12 Summary statistics of the highest exchangeable Na, Ca, and Mg values per groundwater unit

Groundwater Unit	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
	Na (cmol_c kg^{-1})					
Tanqua Karoo	1.5	0.7	3.5	3.0	4.6	83
Richtersveld	1.2	0.4	3.2	3.0	4.5	88
Ruensveld	0.9	0.4	2.2	2.2	4.1	104
Knersvlakte	0.8	0.1	2.4	2.0	3.3	71
Algoa Basin	0.7	0.3	1.9	1.4	1.6	218
Bredasdorp Coastal Belt	0.7	0.1	1.2	1.0	1.3	9
Lower Gamtoos Valley	0.6	0.2	1.1	0.9	1.0	17
Hantam	0.6	0.3	3.4	2.2	2.4	33
Bushmanland Pan Belt	0.6	0.2	1.3	2.1	4.0	105
Dry Harts-Vaal-Orange	0.6	0.2	1.6	1.5	2.3	466
Oudtshoorn Basin	0.6	0.3	4.6	3.0	4.5	24
Intermontane Tulbagh-Ashton Valley	0.5	0.3	1.7	1.3	1.9	45
	Mg (cmol_c kg^{-1})					
North-Eastern Upper Karoo	5.5	4.7	4.7	6.3	4.7	378
Hantam	5.3	3.7	3.7	5.0	3.7	33
Northern Lebombo	5.2	3.6	3.6	5.6	3.6	221
Southern Lebombo	4.9	4.5	4.5	5.9	4.5	789
Southern Highveld	4.7	4.1	4.1	5.4	4.1	100
Dry Harts-Vaal-Orange	4.1	2.8	2.8	4.5	2.8	466
Western Bushveld Complex	4.1	6.6	6.6	6.7	6.6	229
Eastern Upper Karoo	3.7	2.8	2.8	4.7	2.8	110
Limpopo Karoo Basin	3.2	2.3	2.3	3.7	2.3	219
Central Pan Belt	3.0	3.1	3.1	3.9	3.0	320
Makoppa Dome	3.0	4.6	4.6	4.2	4.6	179
Western Upper Karoo	2.9	2.6	2.6	3.6	2.6	70
	Ca (cmol_c kg^{-1})					
Ghaap Plateau	13.0	7.1	17.7	12.8	6.7	36
Bushmanland Pan Belt	12.7	8.8	16.6	17.8	18.8	105
Hantam	11.0	8.2	20.1	13.7	9.4	33
Northern Lebombo	10.0	5.0	15.8	11.4	8.4	221
Eastern Upper Karoo	9.5	5.3	14.0	10.3	5.7	110
Limpopo Karoo Basin	9.1	6.2	12.3	10.0	5.8	219
Western Upper Karoo	8.6	6.1	13.6	9.9	5.2	70
Dry Harts-Vaal-Orange	8.6	5.4	11.6	9.0	5.5	466
Central Pan Belt	8.5	4.7	12.5	9.7	7.7	320
North-Eastern Upper Karoo	8.4	4.5	11.9	9.5	7.8	378
Tanqua Karoo	8.2	5.3	11.2	9.2	5.8	83
Eastern Great Karoo	7.8	5.5	10.2	8.1	3.3	160

The Ghaap Plateau groundwater region has the highest median exchangeable soil Ca content (Table 5.12 and Appendix P) of all 65 groundwater regions. The groundwater region on the Griqualand West Sequence is the only groundwater region in the ten highest soil Ca groundwater regions that did not develop in the

Karoo Supergroup. The Ghaap Plateau groundwater region is composed of Vaalian strata of the Campbell Rand and Schmidtsdrif Subgroups and Vryburg Formation, with limestone, dolomite, chert, andesite, and shale dominant (Vegter, 2001

To establish which geological and groundwater units are most affected by salts in general, the EC, ESP, pH_{water}, Ca, Mg, and Na values (Tables 5.2, 5.3, 5.5, 5.6, 5.8, 5.9, 5.11, and 5.12) were ranked from the highest to the lowest median value. The geological and groundwater units with the highest median value in each of the eight tables were given the rank of ten and the lowest median value a rank of one. The median was then calculated for each geological and groundwater unit, to rank the different units from the most likely to the least likely affected by salts (Table 5.13).

TABLE 5.13 Soil in geological and groundwater units affected by salts in declining order

Ranking	Geological Unit	Groundwater Unit
1	Knersvlakte Subgroup	Tanqua Karoo
2	Whitehill Formation	Richtersveld
3	Gladkop Suite	Knersvlakte
4	Sundays River Formation	Ruensveld
5	Enon Formation	Hantam
6	Garies Subgroup	Namaqualand
7	Kirkwood Formation	Algoa Basin
8	Port Nolloth Group	Bushmanland Pan Belt
9	Nyoka Formation	Bredasdorp Coastal Belt
10	Prince Albert Formation	Intermontane Tulbagh-Ashton Valley

The soils in the Knersvlakte Subgroup geological unit and Tanqua Karoo groundwater unit are most affected by salts (Table 5.13). Although the soils in the Whitehill Formation are by far the most saline (Table 5.3) and sodic (Table 5.5 and Table 5.11) of all geological units, it only ranks second in terms of salt-affected soils. The main reasons for this anomaly are the low Mg (Appendix M) and relatively low pH_{water} values (Table 5.11) of this geological unit. The rest of the ranking for the geological and groundwater units follows the same trend as was found for the various rankings of electrical conductivity, exchangeable sodium percentage, and pH_{water} already discussed.

5.4. CONCLUSION

Geological material is in most circumstances an important soil formation factor, but for salt-affected soils its effect is probably overshadowed in many areas by rainfall and position in the landscape. Rainfall in particular and fog seem to be a controlling factor often overriding lithological control in the development of salt-affected soils. Certain minerals and rocks are also more vulnerable to chemical reaction than others. Rhyolite with a low weathering potential is for example a non-extreme or non-active parent material and dolerite with a high weathering potential an active parent material.

The soil of the Whitehill Formation in the Ecca Group is by far the most saline and sodic geological unit in South Africa. The soil in the Tanqua Karoo groundwater unit is the most saline and the soils in the Richtersveld groundwater region the most sodic in South Africa. The soils of the Richtersveld Subprovince and the Eendoorn granite are the most alkaline geological units and the soils in the Richtersveld-, Ghaap Plateau-, and Western Kalahari groundwater units the most alkaline in South Africa.

The geological units resulting in most salt-affected soils are in declining order: Whitehill Formation ≈ Knersvlakte Subgroup >Gladkop Suite >Sundays River Formation >Enon Formation >Garies Subgroup >Kirkwood Formation >Port Nolloth Group >Nyoka Formation >Prince Albert Formation. The groundwater units resulting in most salt-affected soils are in declining order: Tanqua Karoo >Richtersveld >Knersvlakte >Ruensveld >Hantam >Namaqualand >Algoa Basin >Bushmanland Pan Belt >Bredasdorp Coastal Belt >Intermontane Tulbagh-Ashton Valley.

The highest median soil electrical conductivity values according to geological units in the arid western part of the Northern and Western Cape Province of South Africa. The only exceptions are the Nyoka Formation that primarily occurs in the more humid part of the northern part of KwaZulu-Natal Province and the Uitenhage Group in the Eastern Cape Province. For the groundwater regions, relatively closed basins, such as Tanqua Karoo, the Algoa Basin, Oudtshoorn Basin, and Limpopo Karoo

Basin have an inclination to have high EC values. Soils in a pan environment, such as the Bushmanland Pan Belt and Central Pan Belt and in intermontane areas such as the Tulbagh-Ashton Valley, also have high EC values.

The most sodic soils (ESP>15), according to geological units are found in the arid areas of the Northern Cape and Western Cape Province (see chapter 6). Relatively high sodic soils (ESP>6) are also found in the drier parts of the Eastern Cape, Free State, KwaZulu-Natal, Limpopo, and Mpumalanga Provinces. There is a tendency that the groundwater regions with the highest ESP occur in the more arid western and southern regions of South Africa, between intermontane areas such as the Tulbagh-Ashton valley, in groundwater regions that can be classified as relatively closed basins such as the Tanqua Karoo, Oudtshoorn Basin, and Algoa Basin, and in areas where coastal rainfall and fog occurs such as the Richtersveld, Namaqualand, Bredasdorp Coastal Belt, Algoa Basin, Lower Gamtoos Valley, Outenikwa Coastal Foreland, Southwestern Coastal Sandveld, and Stilbaai Coastal Belt. The Na content in certain coastal areas is about 10 mg L^{-1} in rainfall and about 45 mg L^{-1} in fog.

The most alkaline soil in geological units occurs in the Namaqua Sector of the Namaqua-Natal Province. The most alkaline soils in groundwater units occur in the Richtersveld-, Ghaap Plateau-, and Western Kalahari groundwater units. Although the majority of the most alkaline soils are in the western and northwestern groundwater regions of South Africa the exception to the rule is the Limpopo Karoo Basin groundwater region in the most northern part of South Africa.

Generalized statements on the salinity and sodicity status of different formations of the Karoo Supergroup are often made. None of the soils in the groups of the Karoo Supergroup can be classified as saline or sodic if the median and average values are used and no real difference transpires between the groups. The main reason for this anomaly is that the effect of rainfall and leaching is more dominant on salt accumulation in a soil than on the original parent material, especially if the groups in the Karoo Supergroup are not subdivided to formation level to eliminate the effect of rainfall. Statistical significant differences at the 99% confidence level occur within a group between rainfall classes.

There is a tendency that some of the most sodic and alkaline soils develop from geological units rich in granite, gneiss, and anorthosite (Gladkop Suite, Spektakel Suite, Garies Subgroup, Eendoorn Granite, and Villa Nora Anorthosite). Some of the most sodic and saline soils developed on geological units with a predominantly marine depositional environment characterised by mudstone, siltstone, and shale. Salt laden coastal rainfall and/or fog (Port Nolloth, Bredasdorp, and Malmesbury Groups, Knersvlakte Subgroup, and Porterville, Sundays River, Kirkwood, Nanaga, and Alexandria Formations) also contribute to salt accumulation in the soil. The Whitehill Formation in the Ecca Group is the most saline and sodic geological unit in South Africa consisting of black carbonaceous shales and pyrite-bearing shale.

The highest median exchangeable soil Mg values are mainly found in geological units rich in gabbro, gabbronorite, norite-anorthostite, olivine, and pyroxene. In this regard the Pyramid Gabbronorite, Dwars River Subsuite, and Dsjate Subsuite, all classified under the Rustenburg Layered Suite, are the most dominant parent material resulting in Mg rich soils. The highest median exchangeable soil Ca values are also mainly found in geological units rich in gabbro, gabbronorite, anorthosite, basalt, pyroxene, limestone, and dolomite.

The soils high in Na in the different groundwater units are predominantly characterised by marine origin sediments, granite or gneiss, an arid climate, the influence of salty rainwater from the sea, and a basin, pan, or intermontane surroundings. The North-Eastern Upper Karoo groundwater unit has the highest median Mg value of all groundwater units. The Adelaide and Tarkastad Subgroups mudstone, shale, and sandstone of the groundwater region are not usually associated with high Mg values. The intrusion by a network of dolerite dykes and sills, or the influence of remnants of basalt from the Drakensberg Group can also contribute to the high soil Mg values in this groundwater region. The Ghaap Plateau groundwater region has the highest median exchangeable soil Ca value. The groundwater region on the Griqualand West Sequence is the only groundwater region of the ten highest soil Ca groundwater regions that did not developed on the Karoo Supergroup.

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CHAPTER 6: QUANTIFICATION OF THE SALT CONTENT OF SOILS FOR DIFFERENT CLIMATE CONDITIONS

6.1. INTRODUCTION

The term climate is a composite concept and may be defined as the "long range pattern of weather (Kendrew, 1949). Taking into account not only prevailing weather conditions, but also the dynamic and intricate variations that occur diurnally, daily, monthly, seasonally and annually, and in addition allowing for the probability that the climate might vary from the norm (Schulze, 1997). The variability of climate over southern Africa has been reviewed extensively (Mason & Jury, 1997; Mason & Tyson, 1999; Tyson, 1986). Climatic variability within the instrumental record period is especially well documented (Meadows, 1988) and appears to have resulted in a regular cycle of relatively arid and humid phases with a length of approximately 10 to 11 years (Tyson *et al.,* 1975). Variations over periods of the order of 250 to 1000 years are thought to have taken place, during which climates have been markedly wetter and drier than those currently experienced (Van Zideren Bakker, 1976) and these, in turn, have been superimposed on relatively major fluctuations with intervals of tens of thousands of years, such as glacial and inter-glacial cycle (Goudie, 1977). Active research on especially rainfall variability is ongoing in South Africa. Debates as to whether South Africa has undergone desiccation, for example, date back at least 100 years (Wilson, 1865) and continue today (Tyson, 1986).

Through the whole debate about global warming and the greenhouse gas effect is an underling notion that the world's climate should stay exactly as it is. The geological record tells us that this is a vain and naïve hope. Instead, it tells us that dramatic change is inevitable. We may be contaminating the atmosphere in a way that could influence global climate, but there are other forces at work that we do not yet fully understand, which have caused major changes in climate in the past (McCarthy & Rubidge, 2005).

It is generally agreed that when the earth was formed about five thousand million years ago, high temperatures prohibited the formation of an atmosphere (Tyson & Preston-Whyte, 2004). As the earth began to cool, gases dissolved in the molten rock were released at the surface by the process of outgassing and were retained as an atmosphere by the earth's gravitational attraction. As the earth continued to cool, much of the water vapour condensed and accumulated to form the hydrosphere (oceans and lakes) and in so doing diminished the amount of water vapour in the atmosphere. Carbon dioxide reacted with calcium and magnesium to produce limestone and was precipitated as vast rock deposits into the sea. The carbon dioxide content of the atmosphere therefore became greatly reduced. It is estimated that by the end of the Precambrian period the carbon dioxide content was close to its present atmospheric level with some 99.83 % of the carbon stored in carbonate rocks, shales, and fossil fuels (Tyson & Preston-Whyte, 2004).

Sediments are complex archives of ancient climates and related environmental conditions (Sceffler *et al.*, 2006). South African research on the Transvaal Supergroup carbonate rocks has contributed significantly to internationally accepted models of early Precambrian atmospheric change, chemical sedimentation, and the evolution of early life (Eriksson, 2000). The literature study of Eriksson *et al.* (2006) indicates that the Transvaal Supergroup (Pretoria, Chuniespoort, Ghaap, and Postmasburg Groups) encompasses one of the world's earliest carbonate platform successions (Altermann & Wotherspoon, 1995; Beukes, 1987), with very well preserved and extensive stromatolites and an excellent record of cyanobacterial and bacterial evolution, recording the early history of life on earth (Altermann & Schopf, 1995; Klein *et al.*, 1987).

One of the most prominent climate changes during the Phanerozoic occurred during the Carboniferous-Permian on the Southern Hemisphere. Sceffler *et al.* (2003) indicated that frequent climate changes between stadial and interstadial phases during the Upper Carboniferous to Lower Permian in south Gondwana are documented by changes in geochemical composition of the sediments and carbon isotopy of the organic matter. The opening of the Drake Passage is probably the geological event in the resent past in the southern hemisphere that has the most dominant effect on salt-affected soils and climate change. The opening of the Drake Passage (Figure 6.1) and the resulting circum-polar circulation resulted in expansion of the Antarctic ice sheet and cooling of the Southern Ocean (McCarthy & Rubidge, 2005). The separation of South America from Antarctica is widely believed to have influenced Cenozoic cooling because these events enable the development of the Antarctic Circumpolar Current (Scher & Martin, 2006). In the atmosphere, a strong, semi-permanent high-pressure system established over the South Atlantic Ocean, producing offshore drift of water off the west coast of southern Africa. This gave rise to the Benguela up-welling system. From deep sea drilling cores Siesser (1980) suggested the time of initiation of the Benguela system at about 10 million years before the present. Cooling of the ocean water along the west coast radically changed the climate of southern Africa. Whereas previously, moist air was supplied to the subcontinent from both the Indian and Atlantic Oceans, producing relatively moist conditions on both sides of the continent, the up welling of cold water on the west coast cut off the moisture supply from the Atlantic. The west coast became very arid, the Namib Desert formed, and the rainfall gradient from the east to the west coast was established. Only the Orange River has remained a perennial river in this region since that time (McCarthy & Rubidge, 2005). Lower winter rainfall conditions in the western part of South Africa are of fairly recent origin (Bühmann *et al.*, 2004). These changes are partially preserved in deep weathering profiles, often capped by paleo- features that is out of phase with present day conditions, such as silcretes or ferricretes (Ellis, 1973; Summerfield, 1983; Ellis & Lambrechts, 1994; Francis, 2008). Bühmann *et al.* (2004) also indicate that kaolinite in Cape Granite was the dominant phyllosilicate alteration product, even in areas receiving as little as 122 mm annual precipitation at present. Kaolinite in

FIGURE 6.1 Drake Passage Google Earth image

these arid areas may well reflect much wetter possibly Cretaceous, paleoclimatic conditions as kaolinite formation from granite starts only at an annual precipitation >400 mm. However, Soderberg and Compton (2003) hypothesize an aeolian source for much of the kaolinite in the soil developed from the Peninsula Formation in the Western Cape.

There is considerable evidence for several humid cycles, with intervening arid episodes, during the latter part of the Pliocene and the Pleistocene. It was during such humid cycles that pedogenesis and bioturbation occurred within older colluvial or aeolian sediments to form transported sandy soils of mixed origin over large areas of South Africa (Brink, 1985). The more extensive fine-grained alluvial deposits of major rivers and pans may also be referred to periods that are more humid.

The mudbelt along the middle-inner shelf of the ocean that parallels the western shoreline of southern Africa provides a sediment record of unusually high resolution and the effect of Holocene climate change for southern Africa (Herbert & Compton, 2007). Terrestrial Holocene records also exist for South Africa from the Tswaing impact crater “Pretoria Saltpan” (Partridge *et al.,*1997; Partridge, 1999; Kristen *et al.,* 2007), Cango Caves (Talma & Vogel, 1992), Makapansgat caves (Holmgren *et al.,* 1999; Holmgren *et al.,* 2003), Cederberg region and west coast (Scott & Woodbourne, 2007).

Formerly it was considered that salt-affected soils were always related to arid conditions and statements to this effect may still be found in recent literature (Balba, 1995; Birkeland, 1984 & Gerrard, 1992). According to Szabolcs (1989), however, bearing in mind the diversity of the different types of salt-affected soils, it becomes obvious that they not only occur in desert and semi-desert areas but may develop in practically all the climatic zones of the world. It is, however, true that primary salt-affected soils are more extensive in arid than in non-arid areas and that South Africa is no exception to the rule. Salt-affected soils generally occur in regions that receive salts from other areas, with water the primary carrier. Although the weathering of rocks and minerals is the source of all salts, the salt-affected soils are rarely formed from the accumulation of salts *in situ* (FAO, 2001). The opinion of Laker (2000) is that rainfall and temperature are the dominant climatic factors affecting soil formation. Water provides the medium in which chemical reactions (transformations) can proceed, as well as for the translocation of dissolved or suspended substances and their leaching from the soil. The higher the rainfall or more correctly the higher the efficiency of the rainfall, the more advanced pedogenesis will be under otherwise identical conditions. According to Buol *et al.* (1973) soil is changed in response to changes in its environment so that only irreversible characteristics are likely to remain.

Water is essential for most chemical weathering and in so far as rainfall controls its abundance, an increase in rainfall leads to greater weathering. Thus, weathering is greatest in hot wet climates and becomes less as rainfall or temperature decreases. Water is the most important reactant in almost all forms of weathering and clearly its supply is a great factor in the amount and style of weathering (Clayton, 1969). If precipitation exceeds evaporation, there is largely a through movement of solutions, and continued removal of weathered products. If evaporation is dominant, there is periodic upward movement of water, drying out of soil, crystallisation of salts, and lack of removal of weathered products (Clayton, 1969). Weinert (1961) reported that weathering is apparently controlled largely by the precipitation-evaporation ratio. In the areas where Karoo dolerite is used for road construction, it is found that poorly weathered dolerite only occurs in the east where moisture aids its decomposition. In the west, it suffers more physical weathering. The boundary between poor weathering and advanced weathered dolerite rock appears to follow the line of 3.0 evaporation / precipitation ratio.

In Southern KwaZulu-Natal, with a mean annual precipitation between 618 and 1559 mm, the concentrations of exchangeable Ca and Mg were related in a highly significant, logarithmic manner to the various climatic indices (Donkin & Fey (1993). The distribution of sodic soils is generally related to the pattern of average annual rainfall in South Australia (Naidu *et al.,* 1995). Soils that are sodic throughout the profile seldom occur where average annual rainfall exceeds 500 mm. On the other hand, those soils with only sodic subsoils occur most frequently in areas with average annual rainfall ranging from 450 to 650 mm, but little sodicity persists where rainfall exceeds 900 mm (Naidu *et al.,* 1995). Shaw *et al.* (1995), however, indicate the occurrence of sodic soils in Queensland in Australia are related more to soil genetic factors of the past than to the current rainfall patterns.

Although salts, currently present in the oceans, originated primarily from mineral weathering in the earth's crust, the oceans now constitute a major and separate source of salts for arid and semi-arid areas (Bresler *et al.,* 1982). One mechanism for redistributing oceanic salts occurs when droplets of water from oceanic sprays and turbulence produce atmospheric aerosols of suspended salt crystals or salt droplets. The crystals can serve as condensation nuclei for subsequent raindrop formation. Sea salt aerosols are produced primarily by the bursting of air bubbles resulting from the entrainment of air induced by winds. Sea salt aerosols are estimated to be globally the second most abundant source of aerosols in the atmosphere (Gong *et al.,* 1997). The salts that are thus brought to an area in precipitation have been termed "cyclic salts" by Cope (1958) and Hutton (1958). The small, hygroscopic salt particles transported through the atmosphere following ocean surface turbulence can be removed from the air either as dry fall-out between storms or as "wash-out" or "rain-out" during storms. Dry fall-out is commonly neglected when assessing atmospheric salt accretions, but may constitute 25-50% of the atmospheric salts impinging on an inland area (Junge & Gustafson, 1957; Eriksson, 1960). Herold *et al.* (2001) indicate that aerosols are transferred to soil, vegetation, and water surfaces by precipitation (wet deposition), by cloud and fog (occult deposition), and by dry deposition. As maritime air masses move inland, the decrease in atmospheric salts is roughly exponential, because of wash-out and rain-out (Downes, 1961). A relatively uniform concentration of suspended atmospheric salts is generally reached at a distance of 50 to 150 km from the coast.

The first 5 mm of rainfall commonly removes a large percentage of the suspended salt particles from the lower atmosphere (Junge, 1963). Absolute Cl^- and Na^+ concentrations and the ratio of Cl^- to Na^+ in the rainfall commonly decreases with increasing distance from the sea, due to salt additions from terrestrial sources. Relative amounts of Ca^{2+} and SO_4^{2-} generally increase along the same transect (Junge, 1963). Much of the Mg^{2+} present in rainfall appears to arise from oceanic sources (Eriksson, 1952).

In South Africa, there is little information about the rainwater chemistry and the associated wet deposition, despite being one of the largest industrialized economies in the Southern hemisphere. Some information from Mphepya *et al.* (2004; 2006) and Oliver (2002; 2004) is, however, provided in section 5.3.4 for Lepelfontein, Cape Columbine, Skukuza, Louis Trichardt, and Amersfoort. The sum of marine contributions to the total ionic content of Skukuza was 25%, Amersfoort 11%, and for Louis Trichardt 23%. Tyson and Preston-Whyte (2004) provided the following summer (s) and winter (w) percentages contribution of marine aerosols to the detected background aerosol for Brand se Baai on the west coast (s=51% and w=69%), Ben MacDhui high-altitude site on the edge of the Lesotho massif in the Drakensberg mountains (s=0.2% and w=1.3%), Misty Mountain on the Escarpment (s= 16% and w=2%), and Ulushaba in the Lowveld (s=36% and w=8%). Seasonally, in both summer and winter, on the South African plateau and slopes below the Escarpment, aeolian dust is the major constituent of the background aerosol loading of the atmosphere, followed by industrial sulphur (Tyson & Preston-Whyte, 2004).

Investigations of fog chemistry and cloud physics have become very important during the last decades (Beiderwieden *et al.,* 2005). They found considerable higher ion concentrations in fog samples than in rain samples. A reason for the differences in the chemical characteristics between fog and rainwater may be the size of the droplets. Raindrops are much larger than fog droplets and may therefore be more diluted solutions than the fog drops. Fog is also a major donor of salts and Na specifically to soils in coastal and adjacent inland areas. In the Knersvlakte, non-rainfall may contribute up to 70 mm of water or nearly 60% of mean annual precipitation to the system (Brown *et al.,* 2008). In low-rainfall regions fog transports moisture from the ocean up to 50 km inland (Van Zyl, 2003). Olivier (2004) suggested that around 88% of the water collected at Lepelfontein, about 5 km from the sea, originated from fog alone and 12 % from rainfall. Measured Na content was 26.4 mg L^{-1} for Lepelfontein (Olivier, 2004) and 44 mg L^{-1} at Cape Columbine (Olivier, 2002).

The precipitation in the form of rainfall, mist, and fog of marine origin salts can lead to significant salt accumulations over time, especially in environments with low leaching (Bresler *et al.*, 1982; Simpson & Herczeg, 1994; Keywood *et al.*, 1997). In

Israel, Dan and Yaalon (1982) found a good correlation between salt distribution and age of pedomorphic surfaces, which supports the conclusion that the major sources of the salts are airborne ones blown in over a long period of time. Biggs (2004) also pointed out that atmospheric accessions of salts have long been identified as an important contribution to regolith salt stores in Australia.

South Africa receives only half the world's average rainfall. About 65% of the country receives less than 500 mm of rainfall annually, which is regarded as the minimum for dry-land farming. A high rate of evaporation results in only 8% of the country's total rainfall being carried off to the sea by rivers, while the world mean is 31 % (Van Zyl, 2003). Over the interior there is a distinct east-west trend in rainfall (Figure 6.2). Northeasterly airstreams affecting the eastern Highveld bring annual rainfall totalling around 800 mm, concentrated in the summer months. Rainfall totals decrease to below 125 mm in the arid west, bringing desert conditions to the Kalahari and southern Namibia (Vogel, 2000). Mountains impact especially on two climate regions of South Africa. The Cape Mountains deprive the Karoo of rain, by restricting rain to the ocean side of the mountains. The Drakensberg region benefits from rain on the ocean side of the Drakensberg mountains (Van Zyl, 2003). Walling (1996) notes the extremely high inter-annual variability of precipitation over southern Africa compared to that of the rest of the world. Only Australia shows similar variability. The coefficient of variability of mean annual runoff is just below 0.8, compared to 0.7 for Australia and between 0.25 and 0.40 for the rest of the world.

The temperatures over the interior of South Africa are strongly linked to the high-pressure field over the region. Subsiding air from the large semi-permanent cells of the subtropics, associated with the descending limb of the Hadley Cell of the general circulation, usually brings clear conditions for much of the year (Vogel, 2000). During the months from December to February, the highest near-surface temperatures occur in the tropics, when the thermal equator is in the southern hemisphere. Above average summer temperatures occur during anomalously dry years over the region (Hulme, 1996).

Mean annual evaporation in South Africa exceeds rainfall at all but the highest altitudes of the most south-westerly and north-easterly regions (Alexander, 1985). Mean annual potential evaporation are around 1400 mm in the Drakensberg and 1600-1800 mm along the eastern and southern coastal areas (Figure 6.2), with a general southeast-northwest increasing trend cumulating in highs exceeding 3000 mm per annum in the north west (Schulze, 1997).

The aridity index based on the ratio between annual precipitation to potential evaporation indicates that 0.8% of South Africa is hyper-arid, 36.9% arid, 44.3% semi-arid, 8.5% dry-subhumid, and only 9.4% humid (ARC-ISCW, 2004).

6.2. METHODOLOGY

Soil sample analyses, statistical, and GIS procedures were done according to the methodology described in paragraphs 4.2 and 5.2.

Data from the Agricultural Research Council (ARC) Institute for Soil Climate and Water and the South African Weather Service (SAWS) weather stations with a recording period of 10 years or more were used to determine the median annual rainfall for South Africa. Initially a trend surface was developed using monthly data. Subsequent regression analyses were used to relate the difference between station rainfall values and trend surface values for specific months to topographic indices such as rain shadow and aspect. These relationships and the trend surface were used to model the rainfall surface (1 x 1 km cells) from spatial topographic indices in ArcView (ARC-ISCW, 2004). It was decided to use the median annual rainfall and not the mean annual rainfall, because negative departures of annual rainfall (i.e. low rainfall years) are more numerous than positive ones (i.e. higher than average years) and annual rainfall values are therefore not normally distributed (i.e. they are positively skew). In South Africa mean annual rainfall is frequently inflated by a few very high annual totals from very wet years, especially in areas of low rainfall (Schulze, 1997). The natural availability of water across the country is highly uneven due to the poor spatial distribution of rainfall (Figure 6.2).

Because of a rather limited number of weather stations recording A-pan evaporation (Schulze, 1997), the development of a detailed national coverage also had to take a modelling route. Data were used from weather stations with records of five years or more with respect to A-pan evaporation, rainfall, and temperature. Monthly values for rainfall, maximum temperature, and the difference between maximum and minimum temperature were used in regression equations with the available A-pan evaporation values. The maximum and minimum temperature surfaces as well as the rainfall surfaces were used in ArcView to develop evaporation surface by means of the regression equations (ARC-ISCW, 2004). The annual evaporation for South Africa is depicted in Figure 6.3.

Aridity indices provide a simple way to express the ratio of precipitation to evaporation. The aridity index used is based on the ratio of annual precipitation to potential evapotranspiration (P/PET) and largely follows the classification used in a 1984 UESCO study to produce the Global Humidity Index Map (UNEP, 2009). The aridity indices data are produced by overlaying rainfall grids with PET grids released by the Department of Agricultural Engineering, University of KwaZulu-Natal (Schulze, 1994). Aridity was subsequently classified into four aridity classes and one humid class as follows:

Aridity zone	Aridity index (mm mm^{-1})
Hyper-Arid	<0.05
Arid	0.05 - 0.20
Semi-Arid	0.20 - 0.50
Dry-Sub-humid	0.50 - 0.65
Humid	>0.65

The aridity zones for South Africa are portrayed in Figure 6.4.

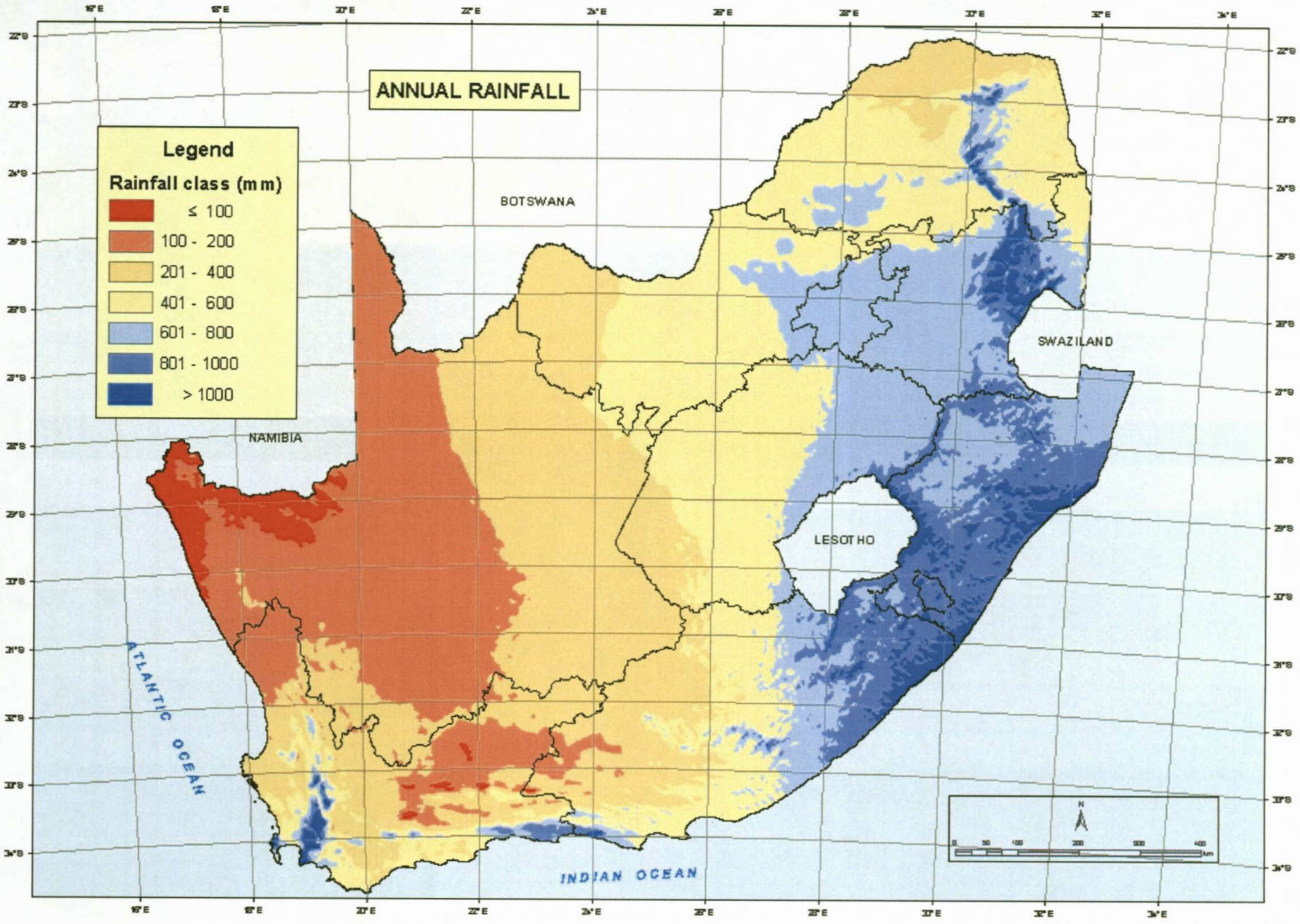

FIGURE 6.2 Annual rainfall interpolated from measured values at stations with more than 5 years data.

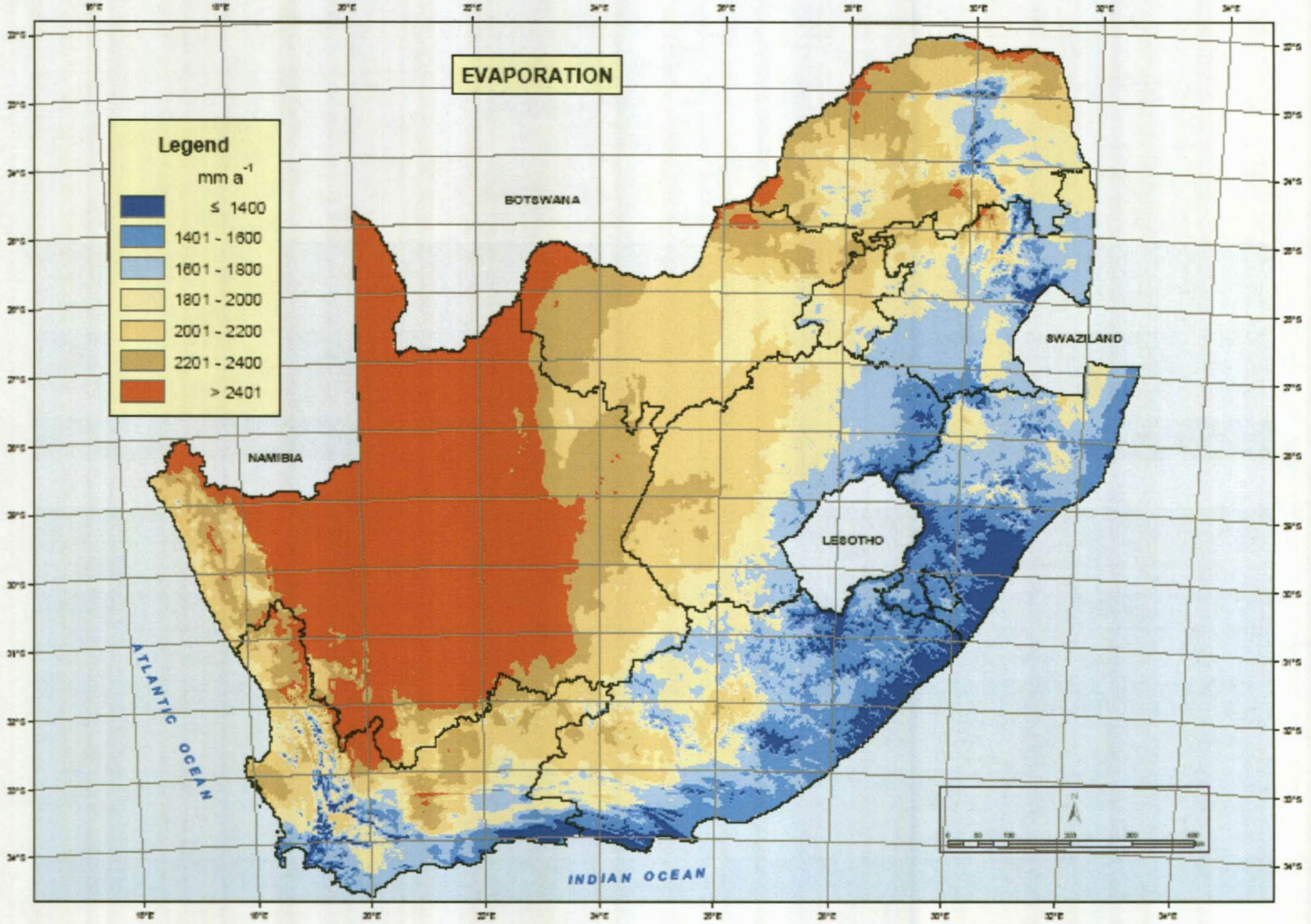

FIGURE 6.3 Annual evaporation calculated through regression from rainfall, maximum temperature, and the difference between maximum and minimum temperature.

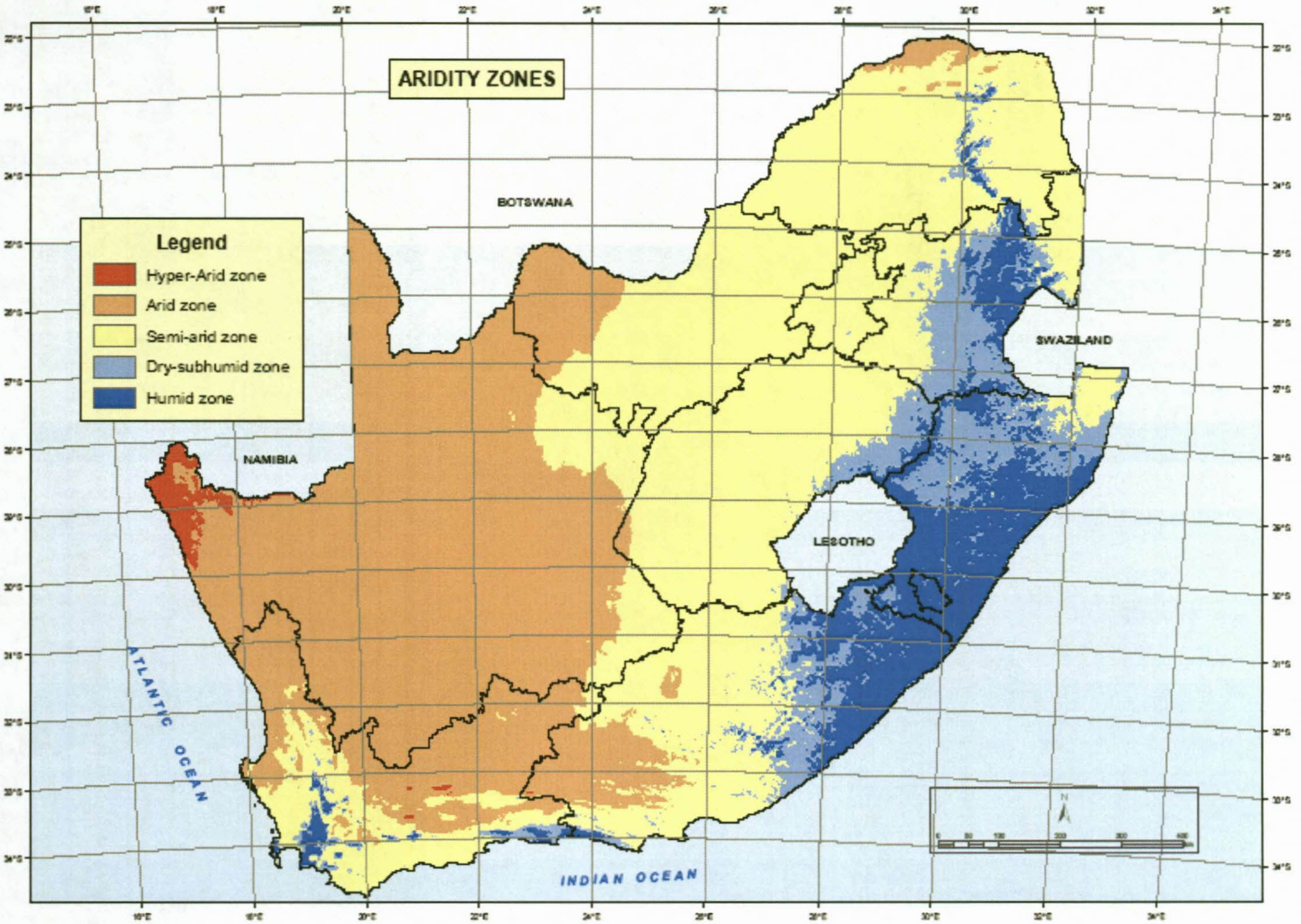

FIGURE 6.4 Aridity (P/PET) zones for the hyper-arid <0.05, arid 0.05-0.20, semi-arid zone 0.20-0.50, dry-sub-humid 0.50-0.65, and humid >0.65.

6.3. RESULTS AND DISCUSSION

As indicated in paragraph 4.3 and 5.3, the large differences in the median and average values for salinity as measured by electrical conductivity and sodicity, as designated by the exchangeable sodium percentage, are a clear indication of the variability and skewness of the data.

6.3.1. ELECTRICAL CONDUCTIVITY OF DIFFERENT RAINFALL, EVAPORATION, AND ARIDITY CLASSES

There is a clear decrease in electrical conductivity (EC) as indicated by the average value from the lowest annual rainfall class to the highest annual rainfall class. This is an indication of the importance of rainfall on the leaching or accumulation of salts in an environment. When considering the median values the tendency is not so clear, because the median values for the 101 to 200 mm class and the 201 to 400 mm class are both 49 mS m^{-1} (Table 6.1).

When using the 400 mS m^{-1} as a threshold value to separate saline from non-saline soils, the < 100mm and 101 to 200 mm rainfall classes tended to be saline if average values were used as indicator of salinity. None of the classes were saline when using the median value (Table 6.1).

There are no statistically significant differences at the 95% confidence level between the <100 mm and 101 to 200 mm annual rainfall classes. The same applies for the three rainfall classes between 601 to >1000 mm. For the seven rainfall classes 17 pairs show statistically significant differences at the 95% confidence level (Appendix Q).

TABLE 6.1 Soil electrical conductivity (mS m^{-1}) statistics for the different rainfall classes

Annual Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<100	158	59	492	606	1053	232
101-200	49	27	275	530	1532	934
201-400	49	28	157	262	745	2685
401-600	39	22	90	104	315	4652
601-800	27	15	49	60	142	5586
801-1000	20	11	32	36	97	4509
>1000	16	9	24	22	30	1484

There is an increase in electrical conductivity as indicated by the average value from the lowest annual evaporation class to the highest annual evaporation class (Table 6.2). When considering the median values the tendency is not so clear, because the median values for the 1601 to 1800 mm class and the 1801 to 2000 mm class are 29 and 30 mS m^{-1} respectively and for the 2001 to 2200 mm and 2201 to 2400 mm classes the median value is 45 mS m^{-1} for both classes. This is an indication that annual evaporation alone is not a good indicator of salt accumulation or it is a consequence of a rather limited number of weather stations recording A-pan evaporation.

There are no statistically significant differences at the 95% confidence level between the <1400 mm and 1401 to 1600 mm annual evaporation classes. The same applies for the annual evaporation classes between 1601 to 1800 mm and 1801 to 2000 mm, as well as 1801 to 2000 mm and 2001 and 2200 mm classes for EC. For the seven evaporation classes 18 pairs show statistically significant differences at the 95% confidence level (Appendix Q).

TABLE 6.2 Soil electrical conductivity (mS m^{-1}) statistics for the different evaporation classes

Annual Evaporation (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<1400	18	11	28	28	76	1980
1401-1600	21	12	36	46	122	4062
1601-1800	30	17	59	88	311	5197
1801-2000	29	15	64	96	401	2959
2001-2200	45	25	103	133	375	2261
2201-2400	45	23	125	231	676	2239
>2401	41	25	144	399	1295	1384

There is a drastic decrease in average EC from the hyper-arid to the humid aridity zones and to a lesser degree if the median values are considered (Table 6.3). This is a clear indication of the low leaching of salt in the hyper-arid areas that result in salt accumulation, compared to the high leaching of salts in the humid areas.

When using the 400 mS m^{-1} threshold value to separate saline from non-saline soils, only the hyper-arid zone is saline, if the average values are used as an indicator and none if the median values are used (Table 6.1).

There are no statistically significant differences at the 95% confidence level between the dry sub-humid and humid aridity zones. For the five aridity zones, nine pairs show statistically significant differences at the 95% confidence level (Appendix Q).

TABLE 6.3 Soil electrical conductivity (mS m^{-1}) statistics for the different aridity classes

Aridity Zones	P/PET)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Hyper-Arid	< 0.05	59	27	357	555	1507	677
Arid	0.05 – 0.20	49	26	132	265	805	3819
Semi-Arid	0.20 – 0.50	32	17	60	79	240	9901
Dry Sub-humid	0.50 – 0.65	21	12	36	41	99	3360
Humid	>0.65	16	9	26	23	63	2325

6.3.2. EXCHANGEABLE SODIUM PERCENTAGE OF RAINFALL, EVAPORATION, AND ARIDITY CLASSES

There is a decrease in exchangeable sodium percentage (ESP) as indicated by the average and median values from the lowest annual rainfall class of <100 mm to the 801 to 1000 mm annual rainfall class (Table 6.4). The maximum potential amount of Na leaching occurs between 801 to 1000 mm annual rainfall classes, with no further decrease in ESP when the annual rainfall is higher than 1000 mm. It can probably also be the result of low cation exchange capacities that are associated with kaolinitic soils in high rainfall areas.

When an ESP value of 15 is used to separate sodic from non-sodic soils based on the average values, the < 100 mm and 101 to 200 mm annual rainfall classes can be considered as sodic. If a value of six is used too separate sodic from non-sodic, based on the average ESP values, the annual rainfall class of 201 to 400 mm is also sodic. Only the annual rainfall class of <100 mm is sodic when using the median ESP of six to separate sodic from non-sodic soils (Table 6.4).

There are no statistically significant differences at the 95% confidence level among the three annual rainfall classes between <100 mm and 601 mm for ESP. For the seven rainfall classes, 18 pairs show statistically significant differences at the 95% confidence level (Appendix R).

TABLE 6.4 Exchangeable sodium percentage statistics for the different rainfall classes

Annual Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<100	14.5	5.8	37.9	34.2	61.5	232
101-200	5.9	2.5	15.5	19.1	55.9	952
201-400	3.7	1.6	10.3	12.7	31.5	2730
401-600	2.3	1.1	5.9	5.9	27.7	4913
601-800	1.7	0.7	3.9	4.0	7.5	5957
801-1000	1.5	0.8	2.7	2.9	8.0	4720
>1000	1.5	0.8	2.6	3.0	29.9	1498

There is no clear indication of an increase in ESP as indicated by the average or median values from the lowest annual evaporation class to the highest annual evaporation class (Table 6.5). There is, however, an observable increase in the average value from the 1401 to 1600 mm annual evaporation class to the >2401 mm class, and from the 1801 to 2000 mm to the >2401 mm class as indicated by the median value.

When an ESP value of 15 is used to separate sodic from non-sodic soils based on the median values, the annual evaporation class of >2400 mm can be considered as sodic. When using an ESP value of six to separate sodic from non-sodic based on the median values, the annual evaporation classes of 2001 to 2200 mm and 2201 to 2400 mm are also sodic (Table 6.5).

There are no clear statistically significant differences at the 95% confidence level for the four evaporation classes between <1400 and 2000 mm for ESP. For the seven evaporation classes, 15 pairs show statistically significant differences at the 95% confidence level (Appendix R).

TABLE 6.5 Exchangeable sodium percentage statistics for the different evaporation classes

Annual Evaporation (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<1400	1.7	0.9	3.3	3.7	25.6	2099
1401-1600	1.6	0.9	3.3	3.5	8.6	4363
1601-1800	2.1	1.0	4.9	5.5	25.6	5334
1801-2000	1.9	0.7	4.8	5.7	19.3	3044
2001-2200	2.1	1.0	5.6	6.8	19.9	2414
2201-2400	2.5	1.1	7.1	9.3	21.3	2355
>2401	3.6	1.6	10.6	17.3	55.2	1392

There is a drastic decrease in ESP values from the hyper-arid to the humid aridity zones as indicated by the average value and to a lesser degree if the median values are considered (Table 6.6).

When an ESP value of 15 is used to separate sodic from non-sodic soils based on the average values, the hyper-arid zone can be considered sodic. If a value of six is used to separate sodic from non-sodic based on the average ESP values the arid zone is also sodic and if the median value is used the hyper zone is also sodic (Table 6.6).

There are no statistically significant differences at the 95% confidence level between the dry sub-humid and humid aridity zones for ESP. For the five aridity zones nine pairs show statistically significant differences at the 95% confidence level (Appendix R).

TABLE 6.6 Exchangeable sodium percentage statistics for the different aridity classes

Aridity Zones	P/PET)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Hyper-Arid	< 0.05	8.0	3.2	22.6	27.6	72.5	677
Arid	0.05 – 0.20	3.2	1.4	10.0	11.3	28.8	3935
Semi-Arid	0.20 – 0.50	2.0	0.9	4.6	4.9	19.5	10397
Dry Sub-humid	0.50 – 0.65	1.6	0.8	2.9	3.2	6.1	3586
Humid	>0.65	1.4	0.8	2.6	2.9	23.7	2407

6.3.3. SOIL ALKALINITY OF DIFFERENT RAINFALL, EVAPORATION, AND ARIDITY CLASSES.

There is a clear decrease in pH_{water} as indicated by the average and median values from the lowest annual rainfall class of <100 mm to the highest rainfall class of >1000 mm (Table 6.7).

There are statistically significant differences at the 95% confidence level between all the rainfall classes for pH_{water}. For the seven rainfall classes, 21 pairs show statistically significant differences at the 95% confidence level (Appendix S).

TABLE 6.7 pH_{water} statistics for different rainfall classes

Annual Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<100	8.5	8.1	9.0	8.4	1.1	232
101-200	8.2	7.6	8.7	8.1	0.9	962
201-400	8.0	7.1	8.5	7.8	1.0	2713
401-600	7.0	6.3	7.6	7.1	1.1	4891
601-800	6.2	5.6	6.9	6.3	1.0	6273
801-1000	5.8	5.2	6.3	5.9	0.9	4745
>1000	5.5	5.2	5.9	5.6	0.7	1524

There is an increase in pH_{water} as indicated by the average and median values from the lowest annual evaporation class to the highest annual evaporation class (Table 6.8).

There are clear statistically significant differences at the 95% confidence level between the evaporation classes. For the seven evaporation classes, 21 pairs show statistically significant differences at the 95% confidence level (Appendix R).

TABLE 6.8 pH_{water} statistics for different evaporation classes

Annual Evaporation (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<1400	5.7	5.2	6.2	5.8	0.8	2157
1401-1600	5.9	5.3	6.5	6.0	0.9	4423
1601-1800	6.4	5.8	7.5	6.5	1.1	5355
1801-2000	6.5	5.5	7.3	6.6	1.2	3163
2001-2200	6.9	6.2	7.9	7.0	1.2	2521
2201-2400	7.7	6.7	8.4	7.5	1.1	2327
>2401	8.2	7.6	8.7	8.0	0.9	1394

There is an obvious decrease in pH_{water} as indicated by the average and median values from the hyper-arid to the humid zone (Table 6.9).

There are statistically significant differences at the 95% confidence level between the aridity zones. For the five aridity zones ten pairs show statistically significant differences at the 95% confidence level (Appendix S).

TABLE 6.9 pH_{water} **statistics** for different aridity classes

Aridity Zones	P/PET)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Hyper-Arid	< 0.05	8.4	7.9	8.8	8.3	0.8	677
Arid	0.05 – 0.20	7.9	7.0	8.5	7.7	1.1	3897
Semi-Arid	0.20 – 0.50	6.5	5.8	7.4	6.6	1.0	10751
Dry Sub-humid	0.50 – 0.65	5.8	5.3	6.4	6.0	0.9	3537
Humid	>0.65	5.5	5.2	6.0	5.6	0.7	2478

6.3.4. EXCHANGEABLE CALCIUM FOR DIFFERENT RAINFALL, EVAPORATION, AND ARIDITY CLASSES

There is a tendency to believe that with an increase in rainfall and a decrease in evaporation, or changing from hyper-arid to humid, that there is a decline in the exchangeable Ca content, due to increased leaching. Anomalies, however, occur at the two rainfall classes between 101 to 400 mm, the evaporation class of 1801 to 2000 mm, and in the arid aridity zone (Table 6.10). The main reason for these anomalies is that geological conditions in certain areas of South Africa overshadow the climatic conditions in terms of salt accumulation and leaching.

The highest median exchangeable Ca values in soils (Paragraph 5.3.10, Table 5.11, and Appendix M) are mainly found in geological units rich in gabbro, gabbronorite, anorthosite, basalt, and pyroxene. In this regard, the Pyramid Gabbronorite, Dsjate Subsuite, Timbavati Gabbro, Modipe Complex, Letaba Formation, Villa Norra Anorthosite, Whitehill Formation, and Sundays River Formation are the most important geological units. These geological units occur predominantly in the 200 to 600 mm annual rainfall classes, 1801 to 2200 mm annual evaporation classes, and therefore in the arid to semi-arid aridity zones. Marine strata of the late Tertiary are also well represented around the continental margin. Examples are the Alexandria and Bredasdorp Formations that are largely calcareous even under the relatively high annual rainfall conditions between 401 and 600 mm.

There are no clear statistically significant differences at the 95% confidence level between Ca, rainfall, evaporation, and aridity. For the seven rainfall classes 16 pairs, for the seven evaporation classes 20 pairs, and for the five aridity zones 10 pairs show statistically significant differences at the 95% confidence level (Appendix T).

TABLE 6.10 Exchangeable Ca of different rainfall, evaporation, and aridity classes ($\text{cmol}_c\ \text{kg}^{-1}$)

Annual Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<100	4.9	1.6	8.7	7.6	13.3	230
101-200	5.7	2.9	9.5	7.7	9.1	935
201-400	6.7	3.3	10.4	7.9	6.8	2587
401-600	4.5	2.0	9.0	7.0	7.6	4814
601-800	2.6	1.0	6.3	4.8	6.1	6995
801-1000	1.6	0.5	4.0	3.1	6.4	5103
>1000	0.7	0.3	2.3	2.0	3.0	1602
Annual Evaporation (mm)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
<1400	2.4	0.4	2.9	2.4	3.3	2219
1401-1600	3.5	0.6	4.5	3.5	6.9	4665
1601-1800	5.3	1.2	7.3	5.3	6.2	5669
1801-2000	4.8	0.8	6.7	4.7	6.0	3184
2001-2200	6.8	1.6	9.1	6.8	7.8	2442
2201-2400	8.0	2.3	10.4	8.0	8.6	2321
>2401	8.4	3.3	10.9	8.4	9.0	1366
Aridity Zones	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
Hyper-Arid	5.1	2.9	8.1	7.1	10.1	664
Arid	6.2	2.7	10.5	7.9	7.8	3798
Semi-Arid	3.2	1.2	7.4	5.5	6.6	10967
Dry Sub-humid	1.8	0.6	4.3	3.4	7.2	3879
Humid	0.9	0.3	2.5	2.1	3.2	2558

6.3.5. EXCHANGEABLE MAGNESIUM FOR DIFFERENT RAINFALL, EVAPORATION, AND ARIDITY CLASSES

There is a tendency to believe that with an increase in rainfall from 201 to >1000 mm, if the median values are considered and from 401 to >1000 mm if the average values are considered, that there is a decline in the exchangeable Mg content due to leaching (Table 6.11).

The exchangeable Mg values in the different evaporation classes are much more erratic than the exchangeable Ca values, with no real indication of an increase in Mg with an increase in evaporation, especially if the median value is used. The average exchangeable Mg values increase from 1801 mm annual evaporation class to >2400 mm class. A clear anomaly occurs in the 1601 to 1800 mm annual evaporation class.

There is a decline due to leaching in Mg from the arid to the humid aridity zones if the median value is used and from the semi-arid to humid, if the average values are being used (Table 6.11). The main reason for these anomalies is probably that geological conditions in certain areas of South Africa overshadow the climatic conditions in terms of Mg accumulation and leaching.

The highest median soil exchangeable Mg value in soils is predominantly found in geological units rich in gabbro, gabbronorite, norite-anorthostite, olivine, and pyroxene. In this regard, the Pyramid Gabbronorite, Dwars River Subsuite, and Dsjate Subsuite, Hlobane Complex, and Nyoka, Makwasie, Jozini, Ntabene, Emakezini Formations are the most important geological units (Paragraph 5.3.10; Table 5.11; Appendix M). These geological units occur predominantly in the 200 to 600 mm annual rainfall classes, 1801 to 2200 mm annual evaporation classes, and in the arid to semi-arid aridity zones.

There are no clear statistically significant differences at the 95% confidence level between Mg, rainfall, evaporation, and aridity. For the seven rainfall classes 16 pairs, for the seven evaporation classes 16 pairs, and for the five aridity zones nine pairs show statistically significant differences at the 95% confidence level (Appendix U).

TABLE 6.11 Exchangeable Mg of different rainfall, evaporation, and aridity classes (cmol$_c$kg^{-1})

Annual Rainfall (mm)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
<100	1.1	0.6	2.1	1.5	1.4	230
101-200	1.4	0.8	2.3	2.0	2.0	935
201-400	2.7	1.4	4.5	3.3	2.6	2585
401-600	2.1	1.0	4.8	3.6	4.1	4811
601-800	1.7	0.6	4.2	3.2	4.4	6595
801-1000	1.4	0.4	3.1	2.4	4.2	5109
>1000	0.8	0.1	2.4	1.7	2.4	1602
Annual Evaporation (mm)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
<1400	1.3	0.4	2.8	2.0	2.4	2219
1401-1600	1.4	0.5	3.1	2.5	4.2	4671
1601-1800	2.0	0.8	4.4	3.4	4.4	5668
1801-2000	1.6	0.4	4.0	3.0	3.9	3183
2001-2200	2.0	0.8	4.6	3.3	3.7	2442
2201-2400	2.2	1.0	4.5	3.4	3.7	2319
>2401	1.7	1.0	3.2	2.7	3.1	1365
Aridity Zones	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
Hyper-Arid	1.2	0.7	1.8	1.5	1.4	664
Arid	2.2	1.1	4.2	3.1	2.8	3795
Semi-Arid	1.9	0.7	4.4	3.4	4.2	10965
Dry Sub-humid	1.5	0.5	3.2	2.6	4.6	3885
Humid	1.0	0.2	2.5	1.8	2.3	2558

6.3.6. EXCHANGEABLE SODIUM FOR DIFFERENT RAINFALL, EVAPORATION, AND ARIDITY CLASSES

There is a decrease in exchangeable Na in the soil as indicated by the average and median values from the lowest annual rainfall class of <100 mm to the highest rainfall class of >1000 mm (Table 6.12), although the decline is not clear between the 101 to 400 mm rainfall classes. The decline in exchangeable Na is not so clear if the median value is considered. Possible reasons for this phenomenon are that the high Na content in soil has concentrated in patches that occur in all rainfall classes. The influence of Na rich rainfall near coastal areas that receive high precipitation and the influence of geological parent material with a high Na content that is strongly influenced by the transgression and regression of the sea level in the past can also result in anomalies that is not typical for a specific rainfall class. The Post-Karoo Mesozoic deposits of the Sundays River Formation, Alexandria Formation, Nanaga Formation, and Kirkwood Formation in the Eastern Cape are examples in this regard (paragraph 5.3.1 and 5.3.4). Both the west coast and Richtersveld areas are characterised by annual rainfall of less than 200 mm (Figure 6.2). The high Na content in these areas is probably not only the result of accumulation of Na due to low leaching, but also due to rainfall and especially mist with a high Na content (Chapter 5).

There is a tendency of an increase in exchangeable Na in the soil with an increase in evaporation when using the median Na value. This tendency is not observable when using the average Na value (Table 6.12). Possible reasons for this phenomenon are again that the high Na content in soil are concentrated in patches that occur in all evaporation classes and the influence of Na-rich precipitation near coastal areas that has high evaporation.

There is a clear decrease in exchangeable Na in the soil from the hyper-arid to the humid aridity zone when the average value is used (Table 6.12). Median values show no tendency for the Na to decrease from hyper-arid to the humid aridity zone. Marine spray and Na rich rainfall in humid coastal areas, as well as geological material rich in Na, and patches of high Na in the soil in all aridity classes are possible reasons for this irregularity.

TABLE 6.12 Exchangeable Na of different rainfall, evaporation, and aridity classes ($cmol_ckg^{-1}$)

Annual Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
<100	0.5	0.2	1.9	1.8	3.3	232
101-200	0.2	0.1	1.0	1.3	3.8	937
201-400	0.2	0.1	0.9	1.3	3.5	2665
401-600	0.2	0.1	0.4	0.7	2.0	4890
601-800	0.1	0.1	0.3	0.5	1.3	6660
801-1000	0.1	0.1	0.3	0.4	1.3	5110
>1000	0.2	0.1	0.3	0.2	0.6	1608
Annual Evaporation (mm)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
<1400	0.2	0.1	0.3	0.3	0.6	2223
1401-1600	0.2	0.1	0.3	0.4	1.3	4683
1601-1800	0.2	0.1	0.5	0.6	1.5	5744
1801-2000	0.1	0.0	0.3	0.6	1.7	3237
2001-2200	0.1	0.1	0.4	0.7	2.4	2506
2201-2400	0.2	0.1	0.6	1.0	2.5	2345
>2401	0.2	0.1	0.7	1.3	4.5	1364
Aridity Zones	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
Hyper-Arid	0.2	0.1	1.1	1.4	4.3	675
Arid	0.2	0.1	0.7	1.1	3.2	3875
Semi-Arid	0.1	0.1	0.4	0.6	1.5	11119
Dry Sub-humid	0.1	0.1	0.3	0.4	1.4	3887
Humid	0.2	0.1	0.3	0.2	0.6	2564

There are no clear statistically significant differences at the 95% confidence level between exchangeable Na, rainfall, evaporation, and aridity. For the seven rainfall classes 19 pairs, for the seven evaporation classes 17 pairs, and for the five aridity zones nine pairs show statistically significant differences at the 95% confidence level (Appendix V).

6.3.7. RELATIONSHIP OF SELECTED SALT PARAMETERS TO CLIMATIC PARAMETERS

The literature study of Hughes and Moolman (1986) indicates that a number of authors have referred to the skewed nature in the distribution of measured soil properties and that they recommend a natural logarithmic transformation of the data. It was, however, decided not to apply transformations such as square roots and logarithms to the data, because transformations are not of much value in cases where outliers are present (Daniel & Wood, 1980; Van Huyssteen, 1989). It was decided to rather use linear regression analyses, because of its simplicity, as well as the utilisation of different curvilinear analyses to predict salt parameters from climatic parameters.

There must be great awareness that significance in correlation coefficients does not necessarily imply causality, but such relationships are, however, useful for directing further research that may well be more practical orientated. Naturally, certain statistically significant correlation coefficients are meaningless and according to Van der Merwe (1973) if any significant correlation coefficient cannot be based upon scientific explanation, it must be ignored. A very low, arbitrary chosen r-value of 0.30 has been used as explanation, to predict salt parameters from climatic parameters, because the dataset is on a national scale, which can be associated with unpredictability. A national scale salt-affected soil assessment cannot always be expected to answer questions that require more detailed scales. It might, however, be able to put forward statically probable ranges of spatial distribution of salt-affected soils for a particular area or climatic condition.

Regression relationships for EC and ESP versus rainfall, evaporation, and aridity index show weak correlations on a national scale, particularly when using a linear model, with only the EC-rainfall with a r-value of -0.30 when using a linear model. Curvilinear models increase the r and R^2-values considerably for EC and ESP (Table 6.13). A probable explanation for the poor correlation is that in certain areas the geological material has a more dominant influence on salt accumulation or leaching than the existing climatic conditions. In some localised areas, the low salt content in the soil is out of phase with present day climatic conditions for example in relatively arid environments rich in silcretes, ferricretes, and kaolinite or salt patches in low lying areas in humid areas.

The log transformed pH_{water} values have a good linear correlation with evaporation (r of -0.51), aridity (r of -0.58), and rainfall (r of -0.61). The use of curvilinear models does not increase the r-values significantly for evaporation and rainfall to predict pH_{water}. There was, however, a slight increase when a square root-X model was applied to predict pH_{water} from aridity. To predict EC and ESP from rainfall, evaporation, and aridity is much better when curvilinear models are used and the only r-value lower than 0.30 is the r-value of 0.21 for ESP and evaporation (Table 6.13).

TABLE 6.13 Regression relationships between EC, ESP, and pH_{water} versus aridity, rainfall, and evaporation

EC-Aridity	**r**	**R^2**	**EC-Rainfall**	**r**	**R^2**	**EC-Evaporation**	**r**	**R^2**
Linear EC = 123.8 + 149.8*Aridity	-0.28	7.6%	*Linear* EC = 150.6+0.1321*Rain	-0.30	8.8%	*Linear* EC = -60.81+0.06923*Evap	0.22	4.7%
Logarithmic-Y square root-X EC= exp(4.959 - 2.53*sqrt(Aridity))	-0.39	15.4%	*Logarithmic-Y square root-X* EC= exp(5.984 - 0.09969*sqrt(Rain))	-0.44	19.3%	*S-curve* EC = exp(5.283-3232/Evap)	-0.31	9.5%
ESP-Aridity	**r**	**R^2**	**ESP-Rainfall**	**r**	**R^2**	**ESP-Evaporation**	**r**	**R^2**
Linear ESP = 12.96 + 17.15*Aridity	-0.15	2.1%	*Linear* ESP = 17.12+0.01684*Rain	-0.18	3.1%	*Linear* ESP = -9.395 + 0.008608*Evap	0.13	1.6%
Multiplicative ESP = exp(0.01543 - 0.6289*ln(Aridity))	-0.31	9.7%	*Square root-Y logarithmic-X* ESP = (8.992 - 1.122*ln(Rain))^2	-0.36	13.0%	Square root-Y squared-X ESP = (0.9909 + 2.526E-7*Evap^2)^2	0.21	4.4%
pH_{water}-Aridity	**r**	**R^2**	**pH_{water}-Rainfall**	**r**	**R^2**	**pH_{water} -Evaporation**	**r**	**R^2**
Linear $pH_{water =}$ 7.971+3.428*Aridity	-0.58	33.6%	*Linear* pH_{water} = 8.56+0.00298*Rain	-0.61	37.6%	*Linear* pH_{water} = 3.46+0.00174*Eva	0.51	25.8%
Square root-X pH_{water} = 9.155 - 4.207*sqrt(Aridity)	-0.60	36.2%	*Squared-Y square root-X* pH_{water} = sqrt(92.49-1.90*sqrt(Rain))	-0.61	37.6%	*Double squared* pH_{water} = sqrt(24.06+0.000006*Eva^2)	0.51	26.0%

On a national scale, a very poor correlation exists between Na, Ca, and Mg with aridity, rainfall, and evaporation. None of parameters has a linear r-value higher than 0.30 and only Ca has curvilinear r-values higher 0.30 when aridity, evaporation, and rainfall are considered (Table 6.14).

Although low correlation with poor significant differences between salt parameters and climatic parameters occurs on a national scale, the situation is different if a specific parameter such as soil type or geological unit is sub-divided into high and low rainfall classes. In this regard significant differences amongst the medians at the 95% confidence level for electrical conductivity and soil type (Table 4.2 to Table 4.4), ESP and soil type (Table 4.5 to Table 4.7) and pH_{water} and soil type (Table 4.8 to Table 4.10) were found. Statistical highly significant differences at the 99% confidence level occurs within a group in the Karoo Supergroup between rainfall classes and electrical conductivity (Table 5.4), ESP (Table 5.7), and pH_{water} (Table 5.10).

In terms of the salt parameters, pH_{water} has the highest R^2-value or the percentage of the variability that could be explained by a linear model in terms of rainfall (37.6%), aridity (33.6%), and evaporation (25.8%; Table 6.13). Exchangeable Mg has the lowest R^2-value if a linear model is used for rainfall (0.6%), aridity (1.0%), and evaporation (0.4%) (Table 6.14).

TABLE 6.14 Regression relationships between Na, Ca, and Mg versus aridity, rainfall, and evaporation

Na-Aridity	**r**	**R^2**	**Na-Rainfall**	**r**	**R^2**	**Na-Evaporation**	**r**	**R^2**
Linear Na = 1.172+1.391*Aridity	-0.14	2.1%	*Linear* Na = 1.447 +0.001264*Rain	-0.16	2.5%	*Linear* Na = -0.6299 + 0.0006903*Evap	0.12	1.5%
Square root-Y logarithmic-X Na = (0.3703 - 0.1652*ln(Aridity))^2	-0.20	4.1%	*Square root-Y logarithmic-X* Na = (2.027 - 0.2311*ln(Rain))^2	-0.22	4.8%	*Square root-X* Na = -1.893 + 0.05933*sqrt(Evap)	0.12	1.5%
Ca-Aridity	**r**	**R^2**	**Ca-Rainfall**	**r**	**R^2**	**Ca-Evaporation**	**r**	**R^2**
Linear Ca = 8.846 + 9.233*Aridity	-0.28	7.6%	*Linear* Ca = 10.13+0.007563*Rain	-0.27	7.5%	*Linear* Ca = -3.69 + 0.004895*Evap	0.25	6.2%
Square root-Y logarithmic-X Ca = (1.264 - 0.597*ln(Aridity))^2	-0.34	11.4%	*Square root-Y squared-X* Ca = (2.604 – 0.0000014*Rain^2)^2	-0.38	14.3	*Square root-Y logarithmic-X* Ca = (-13.33 + 2.039*ln(Evap))^2	0.32	10.5%
Mg-Aridity	**r**	**R^2**	**Mg-Rainfall**	**r**	**R^2**	**Mg-Evaporation**	**r**	**R^2**
Linear Mg = 3.698 + 1.881*Aridity	-0.10	1.0%	*Linear* Mg = 3.741+0.001207*Rain	-0.08	0.6%	*Linear* Mg = 1.681 + 0.000701*Evap	0.06	0.4%
Square root-Y squared-X Mg =	-0.19	3.5%	*Square root-Y squared-X* Mg = (1.706 - 5.224E-7*Rain^2)^2	-0.19	3.6%	*Squared-Y reciprocal-X* Mg = sqrt(36.9 - 2.233E4/Evap)	0.13	1.6%

6.4. CONCLUSION

The effect of rainfall, evaporation, and aridity on salt accumulation in the soil, on a national scale, is not straightforward and other factors such as geology, position in the landscape, and previous climatic conditions should to be accounted for. It should further not be assumed that all salt-affected soils will always show definite and predictable associations with present day climate. The relationship between climate and salt-affected soils are made more difficult to determine, because practically all areas have suffered climates in the past different from those prevailing at present.

The opening of the Drake Passage is probably the geological event in the resent past that has the most dominant effect on salt-affected soils and climate in southern Africa. This gave rise to the Benguela up welling system that radically changed the climate in southern Africa. Whereas previously, moist air was supplied to the subcontinent from both the Indian and Atlantic Oceans, the up welling of cold water on the west coast cut off the moisture supply from the Atlantic. Today the majority of salt-affected soils are found in the arid to hyper-arid western part of South Africa.

Salts originated primarily from mineral weathering, but the oceans also constitute a major source of salts. The mechanisms for redistributing of oceanic salts are through rainfall, mist, fog, and oceanic sprays. Dry fall-out is commonly neglected when assessing atmospheric salt accretions, but according to some literature it may constitute 25-50% of the atmospheric salts impinging on an in-land area.

Salts predominantly move with water. The natural force is usually rainfall, mist, and fog. Regular and high rainfall in the eastern part of South Africa causes a continuous leaching and the transport of leached constituents out of the soil system into the ground water system. On the other hand, erratic and low rainfall combined with high evaporation in the west of South Africa result in the accumulation of salts in the soil profile.

There is a clear decrease in EC, as indicated by the average values, but not always when using the median values, from the lowest annual rainfall class to the highest annual rainfall class; an increase in EC from the lowest annual evaporation class to the highest annual evaporation class; and a drastic decrease in EC from the hyper-arid to the humid aridity zones. This is an indication of the importance of rainfall and evaporation on the leaching or accumulation of salts in an environment.

There is a decrease in ESP as indicated by the average and median values from the lowest annual rainfall class of <100 mm to the 801 to 1000 mm annual rainfall class. The maximum potential amount of Na leaching occurs between 801 to 1000 mm annual rainfall classes, with no further decrease in ESP above an annual rainfall of 1000 mm. There is no clear indication of an increase in ESP as indicated by the average and median values from the lowest annual evaporation class to the highest annual evaporation class. There is, however, an increase in average ESP from the 1401 to 1600 mm annual evaporation class to the >2401 class and as in the median ESP from the 1801 to 2000 mm to the >2401 class. There is a drastic decrease in ESP values from the hyper-arid to the humid aridity zones as indicated by the average value and to a lesser degree when the median values are considered.

There is a clear decrease in pH_{water} as indicated by the average and median values from the lowest annual rainfall class of <100 mm to the highest rainfall class of >1000 mm. There is an increase in pH_{water} as indicated by the average and median values from the lowest annual evaporation class to the highest annual evaporation class. There is also a clear decrease in pH_{water} as indicated by the average and median values from the hyper-arid to the humid zone.

There is a tendency that with an increase in rainfall, decrease in evaporation, and a change from hyper-arid to humid, that there is a decline in the Ca content, due to leaching. Anomalies, however, occur at the two rainfall classes between 101 to 400 mm, the evaporation class of 1801 to 2000 mm, and in the arid aridity zone. The main reason for these anomalies is that geological conditions in certain areas of South Africa overshadow the climatic conditions in terms of salt accumulation and leaching for Ca and Mg, and to a lesser degree for Na. There is a tendency that with an increase in rainfall from 201 to >1000 mm, if the median values are considered and from 401 to >1000 mm if the average values are considered, that there is a decline in the Mg content due to leaching. The average Mg values increase from the 1801 mm annual evaporation class to >2400 mm class. A clear anomaly occurs between 1601 to 1800 mm annual evaporation classes. There is a decline in Mg due to leaching from the arid to the humid aridity zones if the median value is considered and from the semi-arid to humid, if the average values are being used. There is a decrease in Na in the soil as indicated by the average and median values from the lowest annual rainfall class of <100 mm to the highest rainfall class of >1000 mm, although the decline is not clear between the 101 to 400 mm rainfall classes. There is an increase in Na in the soil with an increase in evaporation when using the median value as indicator. The tendency is not observable when using the average value. There is a clear decrease in Na in the soil from the hyper-arid to the humid aridity zone if the average value is used. Median values show no tendency for the Na to decrease from hyper-arid to the humid aridity zone.

Regression relationships for EC and ESP versus rainfall, evaporation, and the aridity index show relatively weak correlations on a national scale, particularly when using a linear model. The same apply for Na, Ca, and Mg with aridity, rainfall, and evaporation. None of the parameters had a linear r-value higher than 0.30 and only Ca had curvilinear r-values higher 0.30 when aridity, evaporation, and rainfall were considered. The log transformed pH_{water} values had a good linear correlation with evaporation, aridity, and rainfall. In terms of the salt parameters, pH_{water} has the highest and Mg the lowest R^2-value or the percentage of the variability that could be explained by a linear model in terms of rainfall, aridity, and evaporation.

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CHAPTER 7: QUANTIFICATION OF THE SALT CONTENT OF SOILS FOR DIFFERENT TOPOGRAPHIC CONDITIONS

7.1. INTRODUCTION

The term “topography” refers to the configuration, the relief and contours, of the features that give variety to our landscape: our plains, plateaus, valleys, mountains, and other landforms (Hunt, 1972). FitzPatrick (1983) describes topography as the outline of the earth’s surface and as synonymous with relief. He indicates that topography is one of the chief factors which determine the spatial distribution or pattern of soils in the landscape. Topography affects soil formation (and salt movement) primarily by modifying climatic influences. Hausenbuiller (1985) indicates that by controlling runoff, topography influences the effectiveness of precipitation and the extent to which erosion removes the forming soil (and salts). Similarly, the effectiveness of solar radiation varies with the topography, for the direction and degree of slope determines how effectively the sun’s rays warm the soil. By affecting soil temperature and evaporation, topography alters the effectiveness of precipitation even after it has entered the soil.

The influence of topography is important because it controls the water to surface and to subsurface contact time (Andersson & Nyberg, 2008). Probably one of the most common types of changes occurs down slopes where variations in the water status are chiefly responsible for the variation in salt content. Generally, as water flows over the surface, varying amounts of soils and salts are picked up in suspension and either deposited lower down the slope or carried away by rivers.

The distribution of salts in soil landscapes is controlled primarily by subsurface hydrology and the balance between evapotranspiration and leaching (Sumner, 2000). In well-drained soils, where leaching is greater than evapotranspiration, salts do not accumulate because the constituent ions are leached to the groundwater. On the other hand, salts accumulate when leaching is minimal. Low leaching results from high evapotranspiration rates and/or low rainfall; convex topography, that disperses water flow; and soil conditions such as crusting that yield low infiltration rates (Sumner, 2000).

Many studies have shown that soil properties are related to gradient angle and to slope length (Gerrard, 1992). This is partly the result of the interaction between slope form and the process of erosion and deposition. The movement of both water and material is governed by the geometric configuration of the slope. Thus, these processes can selectively add or deplete the soil of certain physical or chemical characteristics (Gerrard, 1992).

Abtahi (1977) found that marked differences in the morphological, physical, chemical, and mineralogical properties of soil appear to be due to variations in topography and the depth of saline and alkaline ground water. Soils with salic horizons have formed on the flood plain with shallow ground water and soils with a natric horizon on the low terrace with deep ground water.

A very simple relationship between soil property and slope steepness was demonstrated by Norton and Smith (1930). They plotted angle of slope against thickness of A-horizon and, as might be expected, showed that the horizon is thickest on level topography and thinnest on steep slopes. Cooke and Warren (1973) have noted three factors which distinguish dry areas from more humid ones: first, the critical slope angle separating stable from unstable portions of the slope is generally more sharply defined in dry areas; secondly, where the water-table rises above a certain well-defined critical depth it will affect soil properties by capillary rise and salt-affected soils will result; and thirdly, these two factors often mean that soils on different slopes, and even on different portions of the same slope, may be of different ages (which will result in different salt content).

As was indicated in paragraph 1.2, in South Africa under higher rainfall conditions or poor or impeded soil drainage conditions, lateral leaching of dissolved solids in the groundwater along slopes may result in bottomlands and pans being enriched in salts. Precipitation of salts is also visible under these conditions where a nick point in topography occurs. This is in some way the same situation as what Ropin (2004) describes as "Slope Change Salinity", which occurs where the slope angle decreases. The reduced slope angle slows groundwater flow and results in build up of the water table. The salinity then expands in the upslope direction. Ropin (2004) also indicates that "Outcrop Salinity" occurs where a permeable, water-bearing layer, such as a sandy layer, or fractured bedrock layer, outcrops at or near the surface in rows along a slope at similar elevations.

Drainage is one of the most important factors influencing the development of calcretes (Netterberg, 1969). He indicates that in arid and semi-arid areas the best developed calcretes are almost invariably associated with drainage lines and pans, either fossil (paleo) or present day. On the whole, calcretes are prone to occur on flattish ground, as noted by Bond (1946), rather than on steep slopes. Younger calcretes are furthermore prone to occur in depressions, while older ones tend to form low rises and to outcrop when they are fossil (paleo). The reasons are fairly obvious. Depressions are poorly drained, tend to collect soluble material, and are likely to possess shallower perched or permanent water tables which then rises and thus are favourable sites for calcrete development (Netterberg, 1969).

Whittig and Janitzky (1963) related topographic position and landscape features to the development of sodic soils in the USA. These investigators demonstrated that lateral (throughflow) and upward water movement (discharge) coupled with SO_4 reduction produced a highly alkaline Na_2CO_3-enriched soil on the wetland edge. Processes similar to these have been identified in a number of duplex soils in Australia (Fitzpatrick *et al.*, 1992).

Salt-affected soils can be found at different altitudes from territories below sea level, e.g. the district of the Dead Sea, to mountains rising over 5000 meters, such as the Tibetan Plateau (Szabolcs, 1998). Geochemical studies down toposequences are very scarce (Schloeman, 1994) and geochemical studies on a national scale in terms of topography is non existing.

The three most important topographic conditions that have an influence on salt-affected soils in South Africa are probably pans (wetlands in arid areas), marine terraces, and Karst landforms. The distribution and characteristics of pans were discussed in detail in paragraph 2.3, see also the literature studies of Seaman *et al.* (1991), Allan *et al.* (1995), Cowan (1995), Shaw (1988), and Tooth and McCarthy (2007).

Dardis and Grindley (1988) indicate that tectonic events coupled with eustatic changes resulted in the coastal plain being subject to several transgression-regression cycles during the Tertiary and Pleistocene (see also Evans, 1979; Tankard *et al.* 1982; Jacobs 1986). A major transgression occurred during the Palaeocene, reaching a peak in the Eocene. Relict shoreline features occur intermittently along the southern African coastline, often at high levels (i.e. 100 m; Dardis & Grindley, 1988). Tertiary marine successions are preserved inland of the present shoreline at elevations up to approximately 300 m (Brink, 1985). Brink also pointed out that intervening marine transgressions, sometimes to above the present sea level, produced the important sequence of marine terraces preserved along much of the Namaqualand and Namibian coast. A widespread datum is provided in many areas by the 6-8 m terrace produced by the Eemian transgression of the last interglacial period between 100 000 and 130 000 years ago. The most recent (Flandrian) transgression, which began some 17 000 years ago, is responsible for the extensive elevation within incised river channels in the coastal hinterland (Brink, 1985).

Two percent of the southern Africa is underlain by carbonate rock (Marker, 1986). Karst landform assemblages are developed on the dolomitic limestones of the Proterozoic Malmani Subgroup (Transvaal Supergroup) and the Cambell Rand Subgroup (Ghaap Group) on the Highveld and on tertiary coastal limestones in KwaZulu-Natal, Eastern and Western Cape provinces (Marker, 1986; Martini, 2006). The famous Cango Valley karst is small and practically restricted to an area of late Precambrian shale and limestone 20 km long and two km wide (Martini, 2006). The Bredasdorp Formation karst forms are associated with benches at specific altitudes (Brink, 1985). Probably the best-developed paleokarst in South Africa and also one of the oldest in the world (~2400 Ma) is associated with the disconformity separating the Malmani subgroup from the overlying Pretoria group (Martini, 2006).

Topographically, South Africa consists of a high altitude basin (elevated plain), tilted downwards to the west and surrounded by mountains to the south and east. The seaward edge of the basin drops as a steep escarpment to a generally narrow coastal plain in the south and east. Thus, the rivers flowing to the south and southeast tend to be short with steep gradients. The wider coastal plain in the northeast results in rivers, which are longer, with less precipitous beds. The high altitude basin is drained largely by the Orange-Vaal River, the only permanent river flowing westwards between 17°S and 31°S (Day, 1993; Day & King, 1995).

Since the early years of the previous century the macroscale geomorphic evolution of southern Africa has aroused much controversy and has generated a relatively voluminous literature as can be seen in the literature studies of Wellington (1955), Dingle *et al.* (1983), and Partridge and Maud (1987; 1988). Africa is an ancient landmass. Evidence is accruing that the gross geomorphology of southern Africa is of considerable antiquity, with many landforms retaining elements from Mesozoic and early Cenozoic periods. The interior plateaux of southern Africa stand, altitudinally, above world average because of periodic uplift following the Jurassic disintegration of Gondwanaland and have had an extended subaerial evolution (Marker, 1984).

In an attempt to resolve the confusion that has arisen in the understanding of the geomorphology of southern Africa, Partridge and Maud (1987) have reinterpreted the macro-scale evolution of the subcontinent (Moon & Dardis, 1988). The surfaces identified by them have been named in accordance with those adopted by King (1967). The African surface is the highest and oldest erosion surface, although dissected highlands exist at greater elevations. The surface below the African in the interior has been named the Post-African surface. Seaward of the Great Escarpment, however, two surfaces of Post-African age have been developed and these are referred to as the Post-African I and Post African II, with the latter being the younger. Other features of the Partridge and Maud (1987) interpretation are the mountain regions rising to particular phases of erosion and extensive dissected tracts which exhibit marked structural control. Depositional landscapes are differentiated as Kalahari sediments and coastal marine and aeolian sediments dating to the Neogene.

The interpretation of the sub continental-scale geomorphology of southern Africa indicates that the development of the landscape at the macro-scale has occurred in discrete stages (Table 7.1). The existence of the surfaces related to these stages in the present landscape is evidence of landscape development progressive back-wearing and down-wearing (Moon & Dardis, 1988).

TABLE 7.1 Summary of the stages in the geomorphic development of southern Africa (Partridge & Maud (1987)

Date	Event	Geomorphology
Late Pliocene to Holocene	Climatic fluctuations, sea level changes small-scale tectonism	Maine benches, coastal dunes, river terraces
	Post-Africa II erosion	Post-Africa II surface formed (limited extent), incision of gorges
Late Pliocene (~2.5 Ma)	Major uplift (up to 900m)	Asymmetric uplift of continent, westward tilting
Early mid-Miocene to late Pliocene	Post-Africa I erosion	Post-Africa I erosion surface formed (imperfectly planed), major deposition in Kalahari basin
End of early Miocene (~18 Ma)	Moderate uplift (200-300m)	Interruption of African erosional phase, westward tilting of African surface
Late Jurassic/early Tertiary to end of early Miocene	African erosion	Large-scale planation of African surface (at different levels above and below escarpment) deep weathering on erosion surface
Late Jurassic/early Cretaceous	Fragmentation of Gondwanaland	New base levels formed, rapid erosion

7.2. METHODOLOGY

Soil sample analyses, statistical-, and GIS procedures were done according to the methodology described in paragraph 4.2, 5.2, and 6.2.

The land surfaces of Partridge and Maud (1987) were used to describe the salt-affected soils in terms of different erosion surfaces and time of inception of the different surfaces. A summary of principal geomorphic events in southern Africa since the Mesozoic is summarised in Table 7.1.

To create the slope classes, the 100 x 100 m DEM, was developed from spot data obtained from the Surveyor General (ARC-ISCW., 2004). The DEM data was subsequently projected into an Albers equal area projection with parameters central meridian 24°E, latitude of origin 0°S, 1st parallel -18°S, 2nd parallel -32°S. A raster with slope was made by running the SLOPE function of the Spatial Analyst mode of ArcMap, using PERCENT as output measurement and a cell size of 100 m (ARC-ISCW, 2004).

For creating the elevation classes digital elevation data (spot heights 200 m as part of the existing SOTER database) were manipulated in accordance with the SOTER methodology (ARC-ISCW, 2004).

7.3. RESULTS AND DISCUSSION

As was also indicated in paragraph 4.3, 5.3, and 6.3 the large differences in the median and average values for salinity as indicated by electrical conductivity and sodicity, as indicated by the exchangeable sodium percentage, are a clear indication of the variability and skewness of the data.

7.3.1. SOIL ELECTRICAL CONDUCTIVITY FOR DIFFERENT LAND SURFACES, ELEVATION, AND SLOPE CLASSES

There is a clear increase in electrical conductivity (EC) as indicated by the average and median values from the highest elevation class to the lowest elevation class. This is an indication of leaching and movement of salts from the higher elevation position and the accumulation of salts in the lower elevation position in an environment on a national scale (Table 7.2). Leaching is accentuated by higher rainfall conditions, coupled with a lower salt content, normally associated in mountains above 1500 m. These conditions especially occur along the eastern Great Escarpment.

Statistically significant differences at the 99% confidence level occur within an elevation class and between rainfall classes (Table 7.2). There are no statistically significant differences at the 95% confidence level between the >1999 m and 1500 to 1999 m elevation classes. For the five elevation classes eight pairs show statistically significant differences at the 95% confidence level (Appendix W).

TABLE 7.2 Soil electrical conductivity (mS m^{-1}) statistics for the elevation classes

Elevation Classes (m)	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
>1999	<550	-	-	-	-	-	-
	>550	18	9	27	20	15	171
	All	18	9	27	20	15	171
1500-1999	<550	23	14	47	66	165	168
	>550	21	11	39	40	68	2449
	All	21	11	40	42	78	2617
1000-1499	<550	26	13	54	92	361	2222
	>550	24	13	49	74	262	4475
	All	25	13	49	80	298	6697
500-999	<550	32	18	59	138	589	2779
	>550	28	17	49	121	663	3360
	All	29	17	54	129	631	6139
<500	<550	46	26	125	246	736	1635
	>550	40	21	100	177	577	2652
	All	41	23	111	203	643	4287

There is an increase in soil electrical conductivity as indicated by the average value from the steepest slope class of >20 % to the level slope class of < 1% on a national scale. When considering the median values the tendency is not so clear, because the median EC values for the >20% and the 10 to 19.9 classes are 21 and 20 mS m^{-1} respectively (Table 7.3). There is an accumulation of salts in the low relief areas. This situation occurs especially in the more arid pan environments in the Northern Cape, Free State, and Northwest Provinces.

Statistically significant differences at the 99% confidence level occur within a slope class between rainfall classes, except for the >20% class (Table 7.3). There are no statistically significant differences at the 95% confidence level between the >20%, 10 to 19.9%, and 5 to 9.9% slope classes. The same applies for the classes between 2.5 to 9.9%, 1.5 to 4.9%, 1 to 2.4%, and <1 to 1.4% classes for EC. For the seven slope classes 14 pairs show statistically significant differences at the 95% confidence level (Appendix W). The poor segregation between the classes can be expected on a national scale, because all the slope classes are found under high and low rainfall conditions.

TABLE 7.3 Soil electrical conductivity (mS m^{-1}) statistics for the slope classes

Slope Classes (%)	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
>20	<550	23	12	41	42	92	255
	>550	20	10	35	39	102	386
	All	21	10	36	40	98	641
10-19.9	<550	22	12	41	55	248	616
	>550	19	10	32	39	119	909
	All	20	11	38	45	182	1526
5.0-9.9	<550	27	16	53	103	451	991
	>550	22	12	41	73	419	1660
	All	24	13	45	84	431	2651
2.5-4.9	<550	35	16	76	133	500	1004
	>550	30	15	55	108	475	2100
	All	32	15	59	116	483	3104
1.5-2.4	<550	42	21	100	186	705	735
	>550	36	20	85	145	464	1387
	All	36	20	87	160	559	2122
1-1.4	<550	36	21	74	128	336	418
	>550	41	21	100	197	578	949
	All	39	21	91	176	517	1367
< 1	<550	50	24	177	262	762	333
	>550	41	21	103	207	943	996
	All	41	21	109	221	900	1329

When using 400 mS m^{-1} as a threshold value to separate saline from non-saline soils, the Structural Basin land surface class tended to be saline if the median values are used as indicator of salinity. The Structural Basin and Structural Bench land surface classes are saline when using the average value (Table 7.4).

There is no clear correlation between land surface age and electrical conductivity (EC), although there is a tendency, that land surfaces of Miocene and younger age have higher EC values. The high salt content, as indicated by EC, of the Structural Basin and Structural Bench in the western part of South Africa is probably not only the result of the aridity and geology of the area, but also due to less leaching of salts as the result of Pliocene uplift that was less intense in these areas than for example in the eastern part of South Africa. According to Partridge and Maud (1987), the uplift along the Ciskei-Swaziland axis varied from 600 to 900 m and to 100 m or less in the hinterland of the west coast.

The Structural Basin with the highest salt (EC) content predominantly occurs in the Tanqua Karoo (Table 7.3 and Figure 7.1). In the Tanqua Basin, five deep-water sand-rich submarine fans separated by fine-grained intervals overlie glacial deposits (Dwyka Group) and marine shales (Prince Albert, Tierberg, and Whitehill Groups). Submarine slope, deltaic, and fluvial deposits overlie the turbite system (Hodgson *et al.,* 2002). They also indicated that an up-section shift in paleoflow direction of >90° suggests deflection of turbidity currents against subtle confining topography. The orientation of abrupt lateral frontal pinchout and the deflection of turbidity currents imply a confining trending ~NNW-SSE. The early Karoo Basin of southwestern South Africa was segmented into the Tanqua and Laingsburg sub-basins through the growth of antiform/synform pairs oblique to the dominant shortening direction in the bounding Cape Fold Belt (Sixsmith *et al.*, 2002).

The Structural Bench with the second highest salt content (EC) occurs predominantly in the Hantam Karoo (Table 7.4 and Figure 7.1). This area is in the Northern (and to a smaller extent also in the Western) Cape Province. The geology is mostly glacial deposits (Dwyka Group) with smaller areas of marine shales (Prince Albert, Tierberg, and Whitehill groups). The groups are intruded by dykes and sills of the Jurassic Karoo Dolerite Suite (Vegter, 2001).

The Structural Basin and Bench is not described in detail in the original publication of Partridge and Maud (1987). They do, however, describe the Post-African I cycle with the 3rd highest soil salt content in detail. They indicate that the relatively short time-span of the Post-African I cycle is reflected in the absence of advanced weathering and kaolinization beneath it and the limited and localized development of duricrusts upon it. Although gradients are generally lower than on the African surface due to the lesser degree of deformation that it has suffered, planation is relatively imperfect in many areas. In these, structural influences are clearly apparent. Examples include the Ladysmith Basin and similar areas of incision in proximity to the base of the Great Escarpment and the Cape Middleveld to the south of the Orange River (Partridge & Maud, 1987).

TABLE 7.4 Soil electrical conductivity (mS m^{-1}) statistics for the different land surfaces

Cyclic Surfaces	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Structural Basin	540	115	1680	1225	1874	121
Structural Bench	136	96	423	406	699	23
Post-African 1 surface	59	34	149	190	375	756
African surface (lowered) Original surface on interfluves	47	27	102	92	307	958
Neogene marine and coastal aeolian sediment	43	28	78	111	196	40
Pre-Karoo Bench	41	24	95	93	133	87
Other dissected areas major structural control present	35	21	66	162	775	2716
Post-African surface (undifferentiated)	29	16	60	82	210	521
Cenozoic Kalahari sediments	29	21	107	68	76	52
African surface (partly planed)	28	15	51	94	337	1164
Post-African 1 surface (dissected)	26	16	49	100	360	9195
Mountainous areas above African surface	25	16	43	94	460	1236
African surface	24	11	48	144	794	1116
African surface (marine platform)	20	12	34	30	36	417
African surface (dissected)	19	13	28	28	34	118
Escarpment separating elevated interior	18	11	32	47	146.2	396
Post-African 2 surface (partly planed)	16	11	26	114	525.8	74
Post-African 1 surface (marine Platform)	16	8	34	76	333.5	857

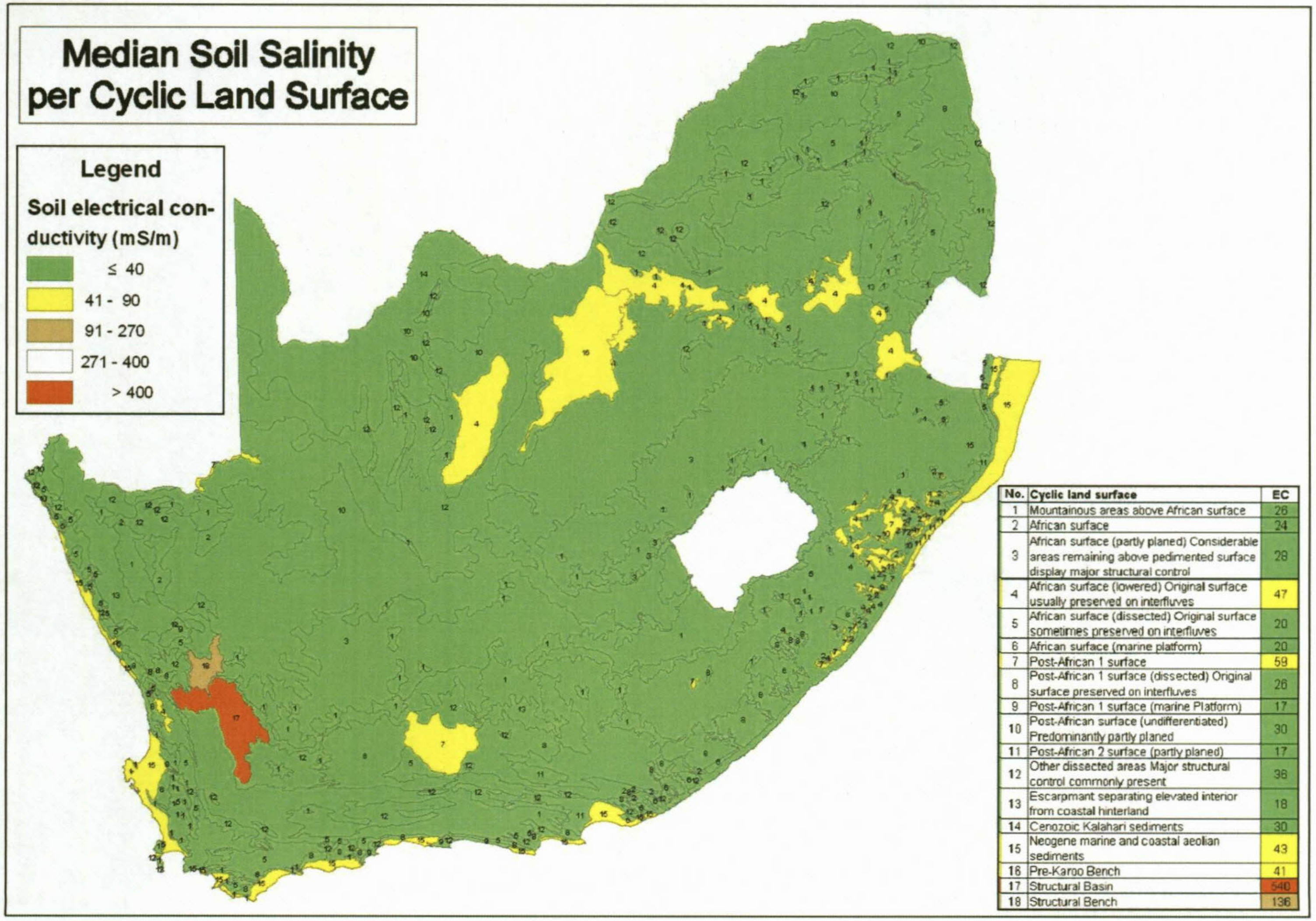
7.3.2. SOIL EXCHANGEABLE SODIUM PERCENTAGE FOR DIFFERENT LAND SURFACES, ELEVATION, AND SLOPE CLASSES

There is an increase in ESP as indicated by the average and median values from the highest elevation class to the lowest elevation class on a national scale. The lowest elevation class is by far the most sodic, not only because it is the lowest point in the landscape, but also because of marine sprays loaded in sodium that occurs in coastal areas and marine sediments that are also rich in sodium.

Statistical significant differences at the 99% confidence level occur within an elevation class for the 1500-1999 m and < 500 m classes, and between rainfall classes (Table 7.5). There are no statistically significant differences for ESP at the 95% confidence level between the >1999 m, 1500 to 1999 m, 1000 to 1499 and 500 to 999m elevation classes. For the five elevation classes only six pairs show statistically significant differences at the 95% confidence level (Appendix X).

TABLE 7.5 Soil exchangeable sodium percentage statistics for the elevation classes

Elevation Classes (m)	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
>1999	<550	-	-	-	-	-	-
	>550	1.0	0.5	1.8	1.6	2.0	162
	All	1.0	0.5	1.8	1.6	2.0	162
1500-1999	<550	1.7	0.9	4.3	3.7	5.3	165
	>550	1.1	0.4	2.4	2.7	23.1	2540
	All	1.2	0.5	2.4	2.8	22.4	2705
1000-1499	<550	1.5	0.7	3.2	4.3	10.7	2390
	>550	1.5	0.7	3.1	4.1	13.4	5107
	All	1.5	0.7	3.2	4.1	12.6	7497
500-999	<550	2.1	1.1	4.5	6.3	15.6	2832
	>550	1.9	1.0	4.0	6.1	26.1	3525
	All	2.0	1.1	4.3	6.2	22.1	6357
<500	<550	4.6	2.3	12.3	15.5	58.2	1505
	>550	4.3	2.2	10.5	11.4	27.6	2393
	All	4.5	2.2	11.1	13.0	42.1	3899



No.	Cyclic land surface	EC
1	Mountainous areas above African surface	26
2	African surface	24
3	African surface (partly planed) Considerable areas remaining above pedimented surface display major structural control	28
4	African surface (lowered) Original surface usually preserved on interfluves	47
5	African surface (dissected) Original surface sometimes preserved on interfluves	20
6	African surface (marine platform)	20
7	Post-African 1 surface	59
8	Post-African 1 surface (dissected) Original surface preserved on interfluves	26
9	Post-African 1 surface (marine Platform)	17
10	Post-African surface (undifferentiated) Predominantly partly planed	30
11	Post-African 2 surface (partly planed)	17
12	Other dissected areas Major structural control commonly present	36
13	Escarpmant separating elevated interior from coastal hinterland	18
14	Cenozoic Kalahari sediments	30
15	Neogene marine and coastal aeolian sediments	43
16	Pre-Karoo Bench	41
17	Structural Basin	540
18	Structural Bench	136

FIGURE 7.1 Median soil electrical conductivity per cyclic land surface.

TABLE 7.6 Soil exchangeable sodium percentage statistics for the different slope classes

Slope Classes (%)	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
>20	<550	1.7	1.0	2.8	3.0	4.3	242
	>550	1.6	1.0	2.7	2.6	4.1	366
	All	1.6	1.0	2.7	2.7	4.2	608
10-19.9	<550	1.7	1.0	3.3	3.8	11.3	608
	>550	1.6	0.8	3.1	2.9	4.9	903
	All	1.7	0.9	3.1	3.3	8.1	1512
5.0-9.9	<550	2.1	1.1	4.3	5.9	14.1	985
	>550	1.9	0.9	4.0	4.7	15.3	1588
	All	2.0	0.9	4.2	5.2	14.8	2573
2.5-4.9	<550	2.3	1.0	5.5	9.3	54.0	1008
	>550	2.1	0.9	4.9	6.7	33.1	2059
	All	2.2	1.0	5.0	7.6	41.2	3067
1.5-2.4	<550	2.6	1.2	6.7	8.1	18.3	727
	>550	2.6	1.1	6.3	8.1	24.3	1363
	All	2.6	1.1	6.3	8.1	22.4	2090
1-1.4	<550	2.2	1.0	5.0	6.8	14.9	425
	>550	2.5	1.1	6.7	9.1	20.7	957
	All	2.3	1.1	6.2	8.4	19.1	1372
< 1	<550	3.1	1.2	10.7	15.4	54.5	338
	>550	2.4	1.0	7.4	9.7	25.5	972
	All	2.5	1.0	7.7	11.2	35.5	1310

There is an increase in ESP as indicated by the average value from the steepest slope class of >20 % to the level slope class of < 1% on a national scale. When considering the median values the tendency is not so clear, because the median ESP values for the 1.5 to 2.4% and 1.0 to 1.4% classes are 2.6 and 2.0 respectively (Table 7.6). There is an accumulation of salts in the low relief areas. This situation occurs especially in the more arid pan environments in the Northern Cape, Free State, and Northwest Provinces.

There are no statistically significant differences at the 95% confidence level between the >20%, 10 to 19.9%, and 5 to 9.9% slope classes. The same applies for the classes between 1.5 to 9.9%, 1.5 to 4.9%, 1 to 2.4%, and <1 to 1.4% classes for ESP. For the seven slope classes 14 pairs show statistically significant differences at the 95% confidence level (Appendix W).

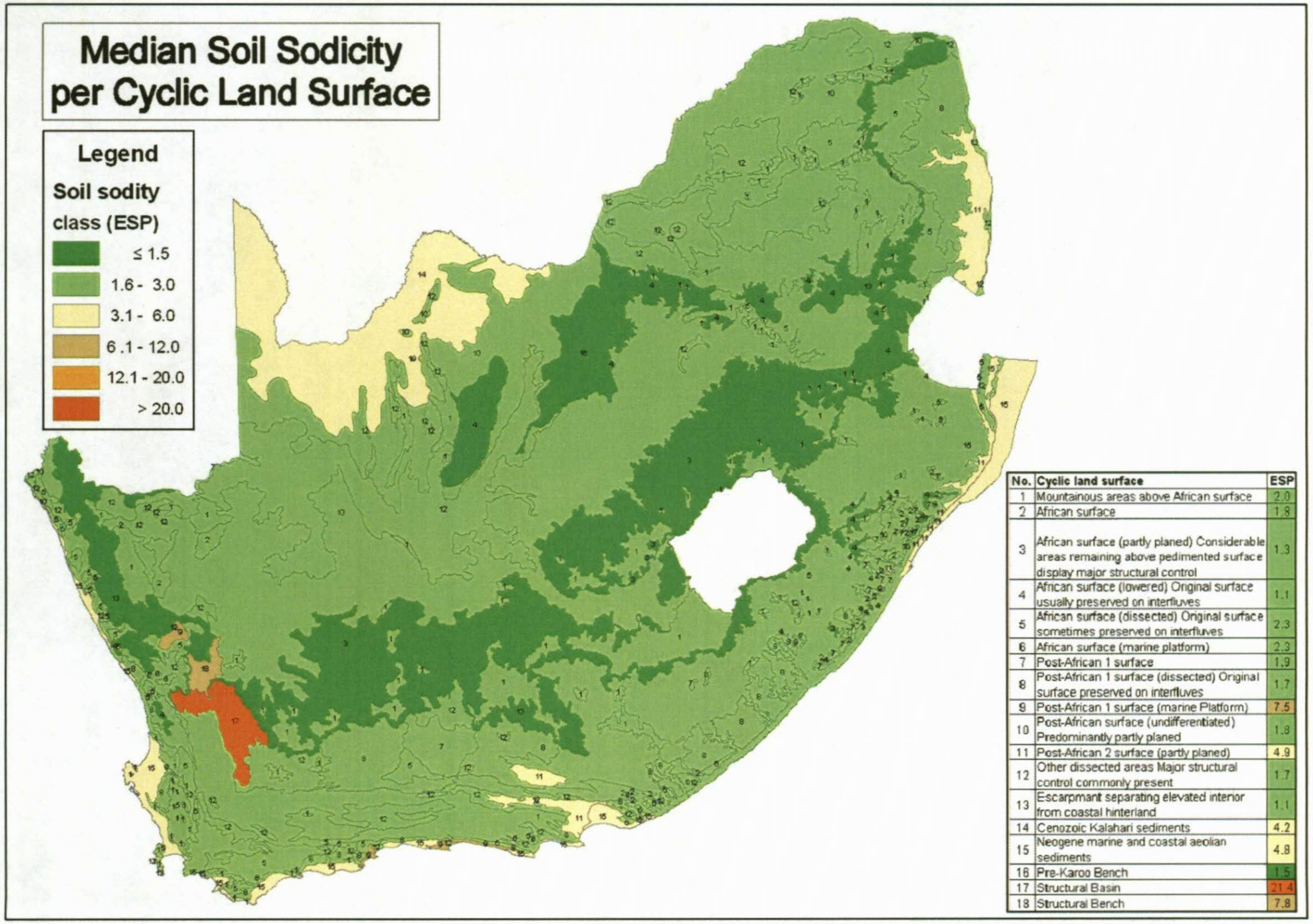
When a value of 15 is used to separate sodic from non-sodic soils, based on the median and average ESP values, the Structural Basin can be considered sodic. When using a value of six to separate sodic from non-sodic, based on the ESP median values, the Structural Bench and Post-African I Surface (Marine Platform) are also sodic. Nine of the 18 land surfaces are sodic if the average ESP values of six are use as an indicator of sodicity (Table 7.7).

The Structural Basin (1st) and Structural Bench (2nd) in the Tanqua and Hantam Karoo are the most sodic land surfaces (Table 7.7 and Figure 7.2). The Post-African 1 surface (Marine Platform) is the 3rd most sodic land surface. Moon and Dardis (1988) indicate that the Miocene uplift initiated the Post-Africa I erosional phase, lasted until the late Pliocene, when further uplift took place. They also highlighted the fact that the coastal (marine) platform of the southern Cape, although largely formed by marine planation, is also classified as a Post-Africa I surface. The planation that occurred during this phase is, in most instances, imperfect because of its relatively short duration. The dominant geology of the Post-African 1 surface (Marine Platform) is sediments of the Bredasdorp and Alexandria Formations. According to Brink (1985), the Bredasdorp Formation reaches elevations of about 150 m in the Riversdale area and about 75 m in the Bredasdorp area. He also indicates that the strata dip seaward across folded sedimentary rocks of the Table Mountain and Bokkeveld Groups.

A detail description of marine benches (platforms) of the southern Cape is provided by Marker (1987). She indicates that between Knysna and Robberg, west of Plettenberg Bay, the 200 m Coastal Platform terminates seaward in almost sheer cliffs ranging from 70 to 120 m in altitude. In gross form this coast is essentially linear and cut into resistant Cape Supergroup strata. Marine benches record fluctuations of sea level. There is evidence that the marine stillstands, now recorded as benches notched into rock, were progressively younger seawards, with the higher benches representing periods of tectonic uplift (subsequent to the dismemberment of the Gondwana continent) and changes in sea-floor configuration (Marker, 1987).

TABLE 7.7 Soil exchangeable sodium percentage statistics for the different land surfaces

Cyclic Surfaces	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Structural Basin	21.4	9.0	49.4	54.7	111.4	121
Structural Bench	7.8	4.2	15.4	10.2	8.1	23
Post-African 1 surface (Marine Platform)	7.5	2.8	15.2	10.3	9.5	40
Post-African 2 surface (partly planed)	4.9	2.6	14.1	12.8	19.6	652
Neogene marine and coastal aeolian sediment	4.8	2.7	10.2	10.6	31.7	484
Cenozoic Kalahari sediments	4.2	1.8	5.6	5.9	10.2	65
African surface (marine platform)	4.1	2.6	7.4	7.5	8.7	54
Post-African 1 surface (dissected)	2.0	1.2	5.3	8.1	55.3	1155
African surface (dissected)	2.3	1.2	5.7	6.7	16.3	1121
African surface (partly planed)	2.3	1.3	4.6	4.9	9.7	937
Mountainous areas above African surface	2.0	1.0	4.8	5.8	18.7	1103
Post-African 1 surface	1.9	1.1	3.5	3.3	7.3	426
African surface	1.8	1.1	3.1	3.0	3.6	118
Post-African surface (undifferentiated)	1.8	0.8	3.6	6.6	29.6	2875
Other dissected areas major structural control present	1.7	0.8	4.0	5.4	17.7	9899
Pre-Karoo Bench	1.5	0.3	3.1	4.7	14.1	92
Escarpment separating elevated interior	1.1	0.5	2.2	3.2	9.1	848
African surface (lowered) Original surface on interfluves	1.1	0.4	2.2	2.7	18.0	543



No.	Cyclic land surface	ESP
1	Mountainous areas above African surface	2.0
2	African surface	1.8
3	African surface (partly planed) Considerable areas remaining above pedimented surface display major structural control	1.3
4	African surface (lowered) Original surface usually preserved on interfluves	1.1
5	African surface (dissected) Original surface sometimes preserved on interfluves	2.3
6	African surface (marine platform)	2.3
7	Post-African 1 surface	1.9
8	Post-African 1 surface (dissected) Original surface preserved on interfluves	1.7
9	Post-African 1 surface (marine Platform)	7.5
10	Post-African surface (undifferentiated) Predominantly partly planed	1.8
11	Post-African 2 surface (partly planed)	4.9
12	Other dissected areas Major structural control commonly present	1.7
13	Escarpmant separating elevated interior from coastal hinterland	1.1
14	Cenozoic Kalahari sediments	4.2
15	Neogene marine and coastal aeolian sediments	4.8
16	Pre-Karoo Bench	1.5
17	Structural Basin	21.4
18	Structural Bench	7.8

FIGURE 7.2 Median soil exchangeable sodium percentage per cyclic land surface.

7.3.3. pH_{water} FOR DIFFERENT LAND SURFACES, ELEVATION, AND SLOPE CLASSES

There is an increase in pH_{water} as indicated by the average and median values from the highest elevation class to the lowest elevation class (Table 7.8). This is an indication of an accumulation of cations and anions in the low relief areas on a national scale.

TABLE 7.8 pH_{water} statistics for the elevation classes

Elevation Classes (m)	Rainfall (mm)	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
>1999	>550	5.4	5.1	5.8	5.5	0.5	69
	All	5.4	5.1	5.8	5.5	0.5	69
1500-1999	<550	6.3	5.5	7.2	6.4	1.1	172
	>550	5.7	5.2	6.4	5.9	0.9	2561
	All	5.7	5.2	6.4	5.9	0.9	2733
1000-1499	<550	6.4	5.5	7.6	6.6	1.3	2438
	>550	6.3	5.4	7.4	6.5	1.2	5056
	All	6.3	5.5	7.4	6.5	1.2	7503
500-999	<550	6.9	6.0	8.1	7.0	1.2	2941
	>550	6.5	5.9	7.7	6.8	1.2	3611
	All	6.7	5.9	7.9	6.7	1.1	6552
<500	<550	7.2	6.2	8.2	7.2	1.2	1696
	>550	6.6	5.7	7.6	6.8	1.2	2785
	All	6.8	6.0	7.9	6.9	1.2	4482

Statistically significant differences at the 99% confidence level occur within an elevation class for all the classes, between rainfall classes, except for the 1000 to 1499 m elevation class (Table 7.8). A possible reason for this anomaly is the occurrence of Rustenburg Layered Suite sediments rich in Ca and Mg in areas that receive more than 550 mm annual rainfall (paragraph 5.3 and Figure 5.6). There are statistically significant differences for pH_{water} at the 95% confidence level between all the elevation classes. For the five elevation classes, 10 pairs show statistically significant differences at the 95% confidence level (Appendix Y).

There is an increase in pH_{water} as indicated by the median value from the steepest slope class of >20 % to the level slope class of < 1% on a national scale. When considering the average value the tendency is not so clear, because pH_{water} value for the >20% and 10 to 19.9% slope classes are 6.1 and 6.9 respectively (Table 7.9).

Statistically significant differences at the 99% confidence level occur between slope class for all the classes, and between rainfall classes within a slope class except for the 1 to 1.4% slope class. There are no statistically significant differences at the 95% confidence level between the >20% and 10 to 19.9% as well as 1 to 1.4% and <1% slope classes. For the other classes there are statistically significant differences. For the seven slope classes, 19 pairs show statistically significant differences at the 95% confidence level (Appendix Y).

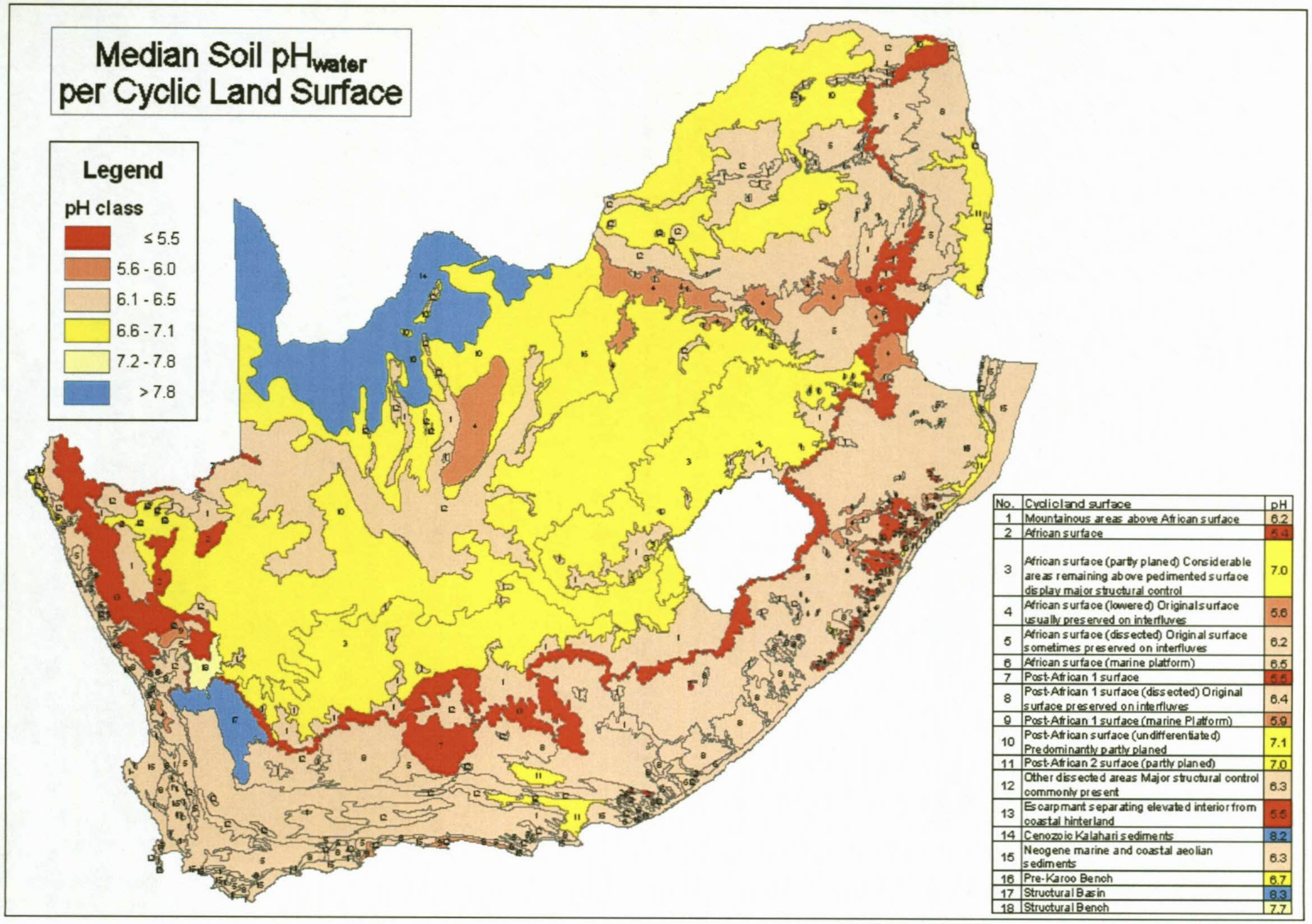
TABLE 7.9 Soil pH_{water} statistics for the different slope classes

Slope Classes (%)	**Rainfall (mm)**	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
>20	<550	6.0	5.4	6.7	6.2	1.0	271
	>550	5.8	5.3	6.5	6.0	1.0	391
	All	5.8	5.3	6.6	6.1	1.0	662
10-19.9	<550	6.0	5.4	6.7	6.2	1.0	645
	>550	5.8	5.3	6.4	5.9	0.9	939
	All	5.9	5.3	6.5	6.0	1.0	1584
5.0-9.9	<550	6.2	5.6	7.2	6.5	1.2	1065
	>550	6.0	5.4	6.7	6.2	1.1	1754
	All	6.1	5.4	6.9	6.3	1.1	2819
2.5-4.9	<550	6.8	5.9	7.9	6.9	1.2	1079
	>550	6.3	5.6	7.3	6.5	1.2	2235
	All	6.4	5.6	7.6	6.6	1.2	3314
1.5-2.4	<550	7.4	6.3	8.3	7.3	1.2	758
	>550	6.8	5.9	8.0	6.9	1.3	1475
	All	7.0	6.0	8.2	7.0	1.3	2233
1-1.4	<550	7.4	6.4	8.3	7.3	1.2	436
	>550	7.1	6.2	8.2	7.2	1.2	1016
	All	7.2	6.3	8.3	7.2	1.2	1452
< 1	<550	7.8	6.6	8.5	7.6	1.2	347
	>550	7.3	6.2	8.3	7.2	1.2	1045
	All	7.5	6.3	8.3	7.3	1.2	1392

TABLE 7.10 Soil pH_{water} statistics for the different land surfaces

Cyclic Surfaces	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Structural Basin	8.3	8.0	8.8	8.3	0.84	121
Cenozoic Kalahari sediments	8.2	6.6	8.7	7.8	1.13	75
Structural Bench	7.7	7.3	8.5	7.8	0.89	23
Post-African surface (undifferentiated)	7.1	6.3	8.1	7.2	1.11	2901
African surface (partly planed)	7.0	6.2	8.0	7.1	1.14	961
Post-African 2 surface (partly planed)	7.0	6.4	8.1	7.2	1.10	782
Pre-Karoo Bench	6.7	6.3	7.5	7.0	0.96	94
African surface (marine platform)	6.5	5.9	7.2	6.5	1.01	56
Post-African 1 surface (dissected)	6.4	6.0	7.2	6.6	0.98	1265
Other dissected areas major structural control present	6.3	5.5	7.6	6.6	1.26	10076
Neogene marine and coastal aeolian sediment	6.3	5.7	7.2	6.5	1.14	595
African surface (dissected)	6.2	5.6	7.0	6.4	1.08	1270
Mountainous areas above African surface	6.2	5.5	7.1	6.4	1.13	1073
Post-African 1 surface (marine Platform)	5.9	5.3	6.5	6.1	1.22	40
African surface (lowered) Original surface on interfluves	5.6	5.2	6.3	5.9	1.02	498
Escarpment separating elevated interior	5.5	5.1	6.3	6.0	1.20	893
Post-African 1 surface	5.5	5.2	6.2	5.8	0.95	433
African surface	5.4	5.2	6.0	5.7	0.80	120

The Structural Basin is the most salt-affected land surface. It is the most alkaline (Table 7.10 and Figure 7.3), most saline (Table 7.4), and the most sodic (Table 7.7). The Structural Bench has the second highest salinity and sodicity of the land surfaces, but it has the third highest alkalinity. The Cenozoic Kalahari sediments are the second most alkaline land surface. The Kalahari basin formed as a response to the down-warping of the interior of southern Africa, probably in the Late Cretaceous. The down-warping, along with possible uplift along epeirogenic axes, back-tilted rivers into the newly formed Kalahari basin and resulted in deposition of the Kalahari Group (Haddon & McCarthy, 2005). The authors also indicate that a period of relative stability during the mid-Miocene saw the silcretisation and calcretisation of the older Kalahari Group lithologies.



No.	Cyclic land surface	pH
1	Mountainous areas above African surface	6.2
2	African surface	5.4
3	African surface (partly planed) Considerable areas remaining above pedimented surface display major structural control	7.0
4	African surface (lowered) Original surface usually preserved on interfluves	5.6
5	African surface (dissected) Original surface sometimes preserved on interfluves	6.2
6	African surface (marine platform)	6.5
7	Post-African 1 surface	5.5
8	Post-African 1 surface (dissected) Original surface preserved on interfluves	6.4
9	Post-African 1 surface (marine Platform)	5.9
10	Post-African surface (undifferentiated) Predominantly partly planed	7.1
11	Post-African 2 surface (partly planed)	7.0
12	Other dissected areas Major structural control commonly present	6.3
13	Escarpmant separating elevated interior from coastal hinterland	5.5
14	Cenozoic Kalahari sediments	8.2
15	Neogene marine and coastal aeolian sediments	6.3
16	Pre-Karoo Bench	6.7
17	Structural Basin	8.3
18	Structural Bench	7.7

FIGURE 7.3 Median soil pH_{water} per cyclic land surface.

7.3.4. EXCHANGEABLE CALCIUM OF DIFFERENT ELEVATION, SLOPE AND LAND SURFACE CLASSES

There is a trend that, on a national scale, with a decrease in elevation and slope percentage there is an increase in the exchangeable Ca content, probably due to leaching of Ca from the higher and steeper positions in a landscape to lower elevations and lower relief areas (Table 7.11). However, inconsistency is apparent for the >20% and 10 - 19.9% slope classes, because the median Ca content is 2.1 and 1.7 $\text{cmol}_c\ \text{kg}^{-1}$ respectively. The higher Ca content in the >20% slope class is probably due to the high Ca content in the basalt of the Drakensberg Group (paragraph 5.3.8) where steep slopes are dominant.

The Structural Basin is by far the most Ca rich land surface with a median and average Ca content of 19.1 and 14.5 $\text{cmol}_c\ \text{kg}^{-1}$ respectively. The Structural Bench has the second and the Post-Africa I surface the third highest median Ca content of 7.4 and 6.6 $\text{cmol}_c\ \text{kg}^{-1}$ respectively (Table 7.11). The high Ca content of the Post-Africa I surface is surprising, because some of these surfaces are found in the relatively high rainfall areas of KwaZulu-Natal. A large area of Post-Africa I surface, however, also occur east of Beaufort West in the Karoo. The foremost geology of the Post-Africa I surface east of Beaufort West is Tertiary to Quaternary calcrete and alluvium (Johnson & Keyser, 1994), with a high Ca content.

7.3.5. EXCHANGEABLE MAGNESIUM OF DIFFERENT ELEVATION, SLOPE AND LAND SURFACES CLASSES

There is a trend, on a national scale, that with a decrease in elevation there is an increase in the median exchangeable Mg content, due to leaching of Mg from the higher positions in a landscape to lower elevations (Table 7.12). The trend is, however, not so apparent when the average value is used, because there is no distinct difference from the 500 to the 1999 m elevation classes, where the values only range from 2.8 to 2.9 $\text{cmol}_c\ \text{kg}^{-1}$. The tendency for Mg to increase with a decrease in slope is also not so apparent if average Mg is used. If the median values are used Mg increase from 1.5 $\text{cmol}_c\ \text{kg}^{-1}$ for the 10-19.9% slope class to 2.0 $\text{cmol}_c\ \text{kg}^{-1}$ for the <1% slope class.

The Structural Basin is by far the most Mg laden land surface with a median and average Mg content of 6.1 and 6.0 cmol $_c$ kg^{-1} respectively (Table 7.12). Partly planed surfaces are also rich in Mg, with the Post-Africa II surface that has the second highest Mg and the African surface the third highest Mg content. The large areas of the central Karoo and eastern Free State are described as planed. These planed areas, according to Vegter (2001), occur mostly in the North-Eastern Upper Karoo groundwater unit that has the highest median soil Mg value of all groundwater units (Table 5.12). This groundwater unit consists predominantly of the Adelaide and Tarkastad Subgroups mudstone, shale, and sandstone (Vegter, 2001), which has lower Mg values. Although the Tarkastad and Adelaide subgroups have been intruded by a network of dolerite dykes and sills (Visser, 1986), with relatively high Mg values, it cannot be explained with certainty that it is the only or major cause of the high soil Mg content. The African surface marine platform (fourth highest Mg) occurs at elevations up to about 300 m above present sea level, sloping down to about 30 m elevation in the area between Port Elizabeth and East London. The sediments of the African surface marine platform are mostly from the Algoa Group (Toerien & Hill, 1989; Johnson & Le Roux, 1979). Marker (1987) described the geology of the area as Tertiary limestone, basal marine overlain by aeolian beds. As a result of marine transgressions during the Tertiary Period, Uitenhage and Cape rocks were bevelled for several tens of kilometers inland (Toerien & Hill, 1989). On this wave-cut platform the marine Alexandria Formation was deposited during Neogene times, resting as a thin unconformable veneer on a remarkably level surface which display at least three steps (Engelbrecht *et al.*, 1962).

7.3.6. EXCHANGEABLE SODIUM OF DIFFERENT ELEVATION, SLOPE AND LAND SURFACES CLASSES

There is a trend that, on a national scale, with a decrease in elevation there is an increase in the average exchangeable Na content, due to leaching of Na from the higher positions in a landscape to lower elevations (Table 7.13). As was indicated in paragraph 7.3.2, the lowest elevation class is by far the most sodic, not only because it is lowest point in the landscape on a national scale, but also because of marine sprays rich in sodium occur in coastal areas. The trend is however not so apparent when the median value is used, because there is no distinct difference between the elevation classes, with the values ranging only from 0.1 to 0.2 cmol $_c$

kg^{-1}. The tendency for Na to increase with a decrease in slope is also not so apparent if the median Na value is used on a national scale. When median values are used, Na increase from 0.3 $cmol_c\ kg^{-1}$ for the>20% and 10-19.9% slope classes to 1.1 $cmol_c\ kg^{-1}$ for the <1% slope class.

As discussed previously, the Structural Basin and Structural Bench are the most saline (EC) and the most sodic (ESP) land surfaces (see paragraph 7.3.2; Tables 7.4 and 7.7). They also have the highest and second highest sodium content (Table 7.13). The Neogene marine and coastal aeolian sediment has the third highest exchangeable Na content, with a median Na value of 0.5 $cmol_c\ kg^{-1}$ and an average value of 0.8 $cmol_c\ kg^{-1}$. The Neogene sediments of the coastal regions consist of various marine and non-marine sediments, which can be described under three headings: the carbonate rocks of the southeast, south and southwest area (coastal limestone); the non-carbonate (locally phosphatic rocks) of the south-western Cape (Elandsfontein and Varswater formations); and the non-marine, and diamondierous, beach terraces of Namaqualand (Dingle *et al.*, 1983; Partridge & Maud, 1987). The sediments of eastern area are from the Maputaland Group (Sibayi, KwaMbonambi, Kosi Bay, and Uloa formations), with a maximum width of some 60 km, which constricts progressively southwards to Mtunzini (Roberts *et al.*, 2006). Although the marine sediments of the Neogene sediments of the coastal regions contribute to the relatively high Na content, marine spray, coastal rainfall, and mist high in Na must also supply substantially to the Na content in this land surface.

TABLE 7.11 Exchangeable Ca of different land surface, elevation, and slope classes ($cmol_c kg^{-1}$)

Cyclic Surfaces	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Structural Basin	19.1	5.4	20.4	14.5	8.6	23
Structural Bench	7.4	4.3	10.4	8.6	8.2	121
Post-African 1 surface	6.8	3.8	10.6	8.1	6.5	809
African surface (lowered)	5.9	2.6	10.7	7.5	6.8	932
Other dissected areas Major structural control present	4.4	2.0	9.3	7.2	8.7	2896
Pre-Karoo Bench	3.7	2.0	6.7	5.4	4.7	84
Cenozoic Kalahari sediments	3.7	2.5	5.5	4.7	3.7	58
Post-African 1 surface (dissected) I	3.0	1.0	6.9	5.0	7.0	10430
Mountainous areas above African surface	3.0	1.6	6.2	4.7	5.5	1292
African surface (partly planed)	1.8	0.8	4.3	3.8	5.4	1212
Post-African surface (undifferentiated)	1.6	0.6	5.1	3.8	5.3	611
African surface	1.5	0.3	5.5	4.4	7.7	1150
Post-African 2 surface (partly planed)	1.4	0.6	5.3	4.0	5.2	75
African surface (marine platform)	1.3	0.5	3.2	3.1	4.9	593
Neogene marine and coastal aeolian sediment	1.3	0.4	4.9	2.8	3.2	40
Post-African 1 surface (marine Platform)	1.0	0.3	3.7	3.0	4.7	908
Escarpment separating elevated interior	0.8	0.2	2.5	2.3	4.0	443
African surface (dissected)	0.8	0.3	1.6	1.6	2.2	125
Elevation Classes (m)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
>1999	0.4	0.2	1.1	2.2	5.3	168
1500-1999	1.7	0.5	4.7	4.1	6.7	2908
1000-1499	2.4	0.8	6.7	4.9	7.4	7746
500-999	3.5	1.6	7.4	5.6	6.6	6641
<500	4.1	1.4	8.1	5.9	6.9	4403
Slope Classes (%)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
>20	2.1	0.5	6.2	4.0	5.7	657
10-19.9	1.7	0.5	4.6	3.7	5.5	1639
5.0-9.9	2.1	0.7	5.2	3.9	5.1	2885
2.5-4.9	2.9	1.0	7.3	5.1	6.9	3387
1.5-2.4	4.5	1.5	8.5	6.2	6.9	2240
1-1.4	4.6	1.9	10.1	7.5	8.8	1449
< 1	4.9	1.87	9.7	7.3	7.9	1387

TABLE 7.12 Exchangeable Mg of different land surface, elevation, and slope classes ($\text{cmol}_c\text{kg}^{-1}$)

Cyclic Surfaces	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Structural Bench	6.1	3.1	8.5	6.0	3.1	23
Post-African 2 surface (partly planed)	4.0	2.0	6.6	5.0	4.2	809
African surface (partly planed)	3.0	1.6	6.7	4.6	4.1	932
African surface (marine platform)	2.3	1.4	3.7	2.8	2.1	58
Post-African 1 surface (dissected)	2.2	1.1	3.9	2.9	2.7	1290
Other dissected areas Major structural control	1.8	0.7	3.9	3.0	4.0	10435
Post-African surface (undifferentiated)	1.8	0.9	4.0	3.3	4.0	2895
Structural Basin	1.8	1.0	2.8	2.5	2.4	121
Post-African 1 surface (marine Platform)	1.6	0.8	3	2.0	1.6	40
Pre-Karoo Bench	1.6	0.9	2.8	2.4	2.4	84
African surface (dissected)	1.2	0.5	2.8	2.7	5.3	1212
Post-African 1 surface	1.1	0.3	2.2	1.7	2.0	443
Mountainous areas above African surface	0.9	0.1	2.9	2.4	3.8	1148
Neogene marine and coastal aeolian sediment	0.9	0.4	2.8	2.0	3.0	611
African surface (lowered) Original surface	0.8	0.3	2	1.9	3.2	594
Escarpment separating elevated interior	0.7	0.1	2.2	1.7	2.7	908
African surface	0.6	0.1	1.4	1.2	1.8	125
Cenozoic Kalahari sediments	0.6	0.3	1.1	0.8	0.7	75
Elevation Classes (m)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
>1999	0.2	0.0	0.8	1.2	2.6	168
1500-1999	1.0	0.3	2.9	2.8	4.9	2907
1000-1499	1.6	0.5	3.7	2.9	4.1	7752
500-999	1.9	0.9	3.7	2.9	3.5	6639
<500	2.4	0.9	4.5	3.4	3.6	4401
Slope Classes (%)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
>20	1.7	0.5	4.1	2.9	3.3	657
10-19.9	1.5	0.4	3.2	2.4	3.0	1639
5.0-9.9	1.5	0.5	3.5	2.7	3.7	2886
2.5-4.9	1.7	0.6	4.0	3.0	3.8	3387
1.5-2.4	2.1	0.8	4.4	3.3	3.9	2239
1-1.4	2.1	1.0	4.7	3.5	3.9	1448
< 1	2.0	0.8	4.6	3.3	3.8	1387

TABLE 7.13 Exchangeable Na of different land surface, elevation, and slope classes ($cmol_c kg^{-1}$)

Cyclic Surfaces	Median	Lower Quartile	Upper Quartile	Average	Standard Deviation	Sample Size
Structural Bench	1.6	0.4	3.4	2.3	2.1	23
Structural Basin	1.2	0.6	3.2	3.0	4.9	121
Post-African 1 surface	0.5	0.2	1.3	1.6	2.9	818
Neogene marine and coastal aeolian sediment	0.5	0.2	1.0	0.8	0.9	40
Cenozoic Kalahari sediments	0.4	0.2	1.2	0.9	1.3	58
African surface (lowered) Original surface	0.2	0.1	0.6	0.7	1.5	954
Mountainous areas above African surface	0.2	0.1	0.4	0.7	3.0	1293
African surface (dissected)	0.2	0.1	0.3	0.3	0.5	125
Post-African surface (undifferentiated)	0.2	0.1	0.5	0.6	1.6	624
Post-African 1 surface (dissected)	0.2	0.1	0.4	0.6	1.5	10490
Escarpment separating elevated interior	0.2	0.1	0.3	0.3	0.4	443
Pre-Karoo Bench	0.1	0.01	0.2	0.7	2.6	92
Other dissected areas Major structural control present	0.1	0.1	0.3	0.6	3.1	2926
African surface (partly planed)	0.1	0.1	0.3	0.5	1.5	1274
African surface	0.1	0.1	0.4	0.5	1.1	1187
Post-African 2 surface (partly planed)	0.1	0.1	0.1	0.5	2.3	65
African surface (marine platform)	0.1	0.01	0.2	0.3	2.5	594
Post-African 1 surface (marine Platform)	0.1	0.04	0.2	0.3	0.9	911
Elevation Classes (m)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
>1999	0.1	0.1	0.2	0.2	0.2	167
1500-1999	0.1	0.03	0.2	0.3	0.7	2933
1000-1499	0.1	0.1	0.3	0.5	1.8	7800
500-999	0.2	0.1	0.3	0.6	2.0	6646
<500	0.3	0.1	0.8	1.1	2.8	4556
Slope Classes (%)	**Median**	**Lower Quartile**	**Upper Quartile**	**Average**	**Standard Deviation**	**Sample Size**
>20	0.2	0.1	0.3	0.3	0.7	668
10-19.9	0.2	0.1	0.3	0.3	0.8	1644
5.0-9.9	0.2	0.1	0.3	0.5	1.2	2896
2.5-4.9	0.1	0.1	0.4	0.6	1.8	3412
1.5-2.4	0.2	0.1	0.5	0.8	2.1	2262
1-1.4	0.2	0.1	0.5	1.0	2.6	1462
< 1	0.2	0.1	0.6	1.1	3.8	1398

7.3.7. RELATIONSHIP OF SELECTED SALT PARAMETERS TO ELEVATION AND SLOPE PARAMETERS

As was indicated in paragraph 6.3.7, certain statistically significant correlation coefficients could be meaningless. According to Van der Merwe (1973) if any significant correlation coefficient cannot be based upon scientific explanation, it must be ignored. A very low, arbitrary chosen r-value of 0.30 has been used for explanation, to predict salt parameters from elevation and slope parameters, because the dataset is on a national scale, which can be associated with more unpredictability than on a local scale. A national scale salt-affected soil assessment cannot always be expected to answer questions that require investigation at more detailed scales. It might, however, be able to put forward statically probable ranges of spatial distribution of salt-affected soils for a particular area in terms of elevation, slope, geology, or climatic condition unpredictability

TABLE 7.14 Regression relationships between EC, ESP, and pH_{water} versus elevation and slope

EC-Elevation	**r**	**R^2**	**EC-Slope**	**r**	**R^2**
Linear			*Linear*		
EC = 228.4 - 0.1195*Elevation	-0.12	1.4%	EC = 156 - 5.743*Slope	-0.08	0.6%
*Exponential model: Y = exp(a + b*X)*			*Multiplicative model: Y = a*X^b*		
EC = exp(4.16 - 0.0006971*Elevation)	-0.27	7.3%	EC = exp(3.9 - 0.298*ln(Slope))	-0.25	6.0%
ESP- Elevation	**r**	**R^2**	**ESP- Slope**	**r**	**R^2**
Linear			*Linear*		
ESP = 13.29 - 0.007323*Elevation	-0.14	2.0%	ESP = 8.5 - 0.2719*Slope	-0.07	0.49%
*Logarithmic-Y square root-X model: Y = exp(a + b*sqrt(X))* ESP = exp(2.461 - 0.05935*sqrt(Elevation))	-0.38	14.7%	*Multiplicative model: Y = a*X^b* ESP = exp(1.014 -0.1808*ln(Slope))	-0.14	1.9%
pH_{water}- Elevation	**r**	**R^2**	**pH_{water}- Slope**	**r**	**R^2**
Linear			*Linear*		
pH_{water}= 7.252 - 0.0006556*Elevation	-0.26	6.6%	pH_{water}= 6.942 - 0.04673*Slope	-0.27	6.8%
*Reciprocal-Y squared-X: Y = 1/(a + b*X^2)*			Logarithmic-X model: Y = a + b*ln(X)		
pH_{water} = 1/(0.1455 + 9.268E-9*Elevation^2	0.30	8.7%	pH_{water}= 7.168 - 0.4046*ln(Slope)	-0.35	11.9%

Regression relationships for EC and ESP versus elevation and slope show weak correlations on a national scale, particularly when using a linear model. From these poor correlations, it is evident that other factors such as geology and climate have a much more dominant influence on EC and ESP than elevation and slope on a national scale. Curvilinear models increase the R^2-values considerably, although still low (Table 7.14).

The log transformed pH_{water} values have a relatively good linear correlation with elevation (r of -0.26), and slope (r of -0.27). The use of curvilinear models does increase the R^2-value, and when a reciprocal-Y squared-X model is used to predict pH_{water} from elevation the R^2-value is 8.7% and when a logarithmic-X model is model is used to predict pH_{water} from slope the R^2- value is 11.9% (Table 7.14).

On a national scale, a very poor correlation exists between Na, Ca, and Mg with elevation and slope. None of the parameters has a linear r-value higher than -0.13 (Table7.15). The highest r-value is -0.29 when an exponential model is used to predict Na from elevation.

TABLE 7.15 Regression relationships between Ca, Mg, and Na versus elevation and slope

Ca-Elevation	**r**	**R^2**	**Ca-Slope**	**r**	**R^2**
Linear Ca = 6.424 - 0.001302*Elevation	-0.09	0.8%	*Linear* Ca = 5.972 - 0.1157*Slope	-0.12	1.4%
Logarithmic-X model: Y = a + b*ln(X) Ca = 6.696 - 1.128*ln(Slope)	-0.17	2.8%	Logarithmic-X model: Y = a + b*ln(X) Ca = 6.696 - 1.128*ln(Slope	-0.18	3.1%
Mg-Elevation	**r**	**R^2**	**Mg-Slope**	**r**	**R^2**
Linear Mg = 3.403 - 0.0004733*Elevation	-0.06	0.3%	*Linear* Mg = 3.186 - 0.03166*Slope	-0.06	0.4%
Square root-Y squared-X model: Y = (a + b*X^2)^2 Mg = (1.609 - 1.399E-7*Elevation^2)^2	-0.14	2.0%	Square root-Y model: Y = (a + b*X)^2 Mg = (1.52 - 0.01059*Slope)^2	-0.08	0.6%
Na-Elevation	**r**	**R^2**	**Na-Slope**	**r**	**R^2**
Linear Na = 1.146 - 0.0005511*Elevation	-0.13	1.8%	*Linear* Na = 0.8008 - 0.02536*Slope	-0.10	0.8%
Exponential model: Y = exp(a + b*X) Na = exp(-0.9317 - 0.0009493*Elevation)	-0.29	8.6%	Logarithmic-X model: Y = a + b*ln(X) Na = 0.9382 - 0.2303*ln(Slope)	-0.12	1.5%

It is frequently assumed that meaningful relationships between slope form and soil properties will be the inevitable result of any properly conducted study. According to Gerrard (1992) realistic correlations will occur only if the processes of soil formation are in some sort of equilibrium with the surface and subsurface processes acting on the slope. No correlations should be expected if the landscape is morphologically very young or if erosive phases are extremely vigorous. Gerrard (1992) also pointed out that a change of climate or a change in the amount and type of vegetation cover will upset the equilibrium of the system. Thus a lack of significant correlations may be just as meaningful an indicator of landscape status as the highest statistical relationship.

7.4. CONCLUSION

Topography can greatly affect the movement of water and salts through soil. This is, to a certain extent a result of gravity, which directly influences water and salt movement and partly as a result of topography's influence on soil development. Topography affects the distribution of salt-affected soils in three ways on a local scale and to a certain degree also on a national scale: (i) It influences runoff and infiltration and therefore the potential of the salts to accumulate or to be leached. (ii) It creates microclimates different from the regional climate, especially on steeper slopes and different aspect positions. (iii) Together with geology and climate it determines the position, duration, and depth of watertables in the soil that has an influence on the precipitation and capillary movement of salts to the soil surface. In South Africa with predominantly transient and riverbank salinity and limited dryland salinity, the effect of watertables is less important.

Topographically, South Africa consists of a high altitude basin (elevated plain), tilted downwards to the west, and surrounded by mountains to the south and east. The seaward edge of the basin drops as a steep escarpment to a generally narrow coastal plain in the south and east. Rainfall which runs off sloping soil and landscapes are not usually available for leaching of salts out of the sloping areas. In South Africa the majority of sloping areas are, however, found in areas with the highest rainfall. Landscapes with steep slopes and well developed, well dissected, fast-flowing river systems that occur in the eastern part of South Africa. In such landscapes there is a good opportunity for salts to be leached out of the soils and the landscape in general. The high salt content of soils in the western part of South Africa is not only the result of the aridity and geology of the area, but also because of less leaching of salts due to the Pliocene uplift that was less intense in these areas, than in the eastern part of South Africa.

There is an increase on a national scale in electrical conductivity, exchangeable sodium percentage, and pH_{water} from the highest elevation class to the lowest elevation class. This is an indication of leaching and movement of salts from the higher elevation positions to the lower elevation position where accumulation of salts occur, even on a national scale. The lowest elevation class is the most sodic, saline, and alkaline not only because it is the lowest point in the landscape, but also because of salt laden marine sprays, rainfall, and mist that occur in coastal areas as well as the marine sediments.

There is a tendency, although not well defined, of an increase on a national scale in electrical conductivity, exchangeable sodium percentage, and pH_{water} from the steepest slope classes to the more level slope classes. There is accumulation of salts, especially in low relief areas, such as in pan environments that occur in the Northern Cape, Free State, and Northwest Province.

There is no clear correlation between age of land surface and electrical conductivity, exchangeable sodium percentage, and pH_{water}, although there is a tendency that land surfaces of Miocene and younger ages have higher salt contents. Land surfaces that occur at lower elevation positions also have an inclination to have higher salt contents. The Structural Basin and Structural Bench are by far the most sodic, saline, and alkaline. The Marine Platform of the Post-Africa 1 and Neogene marine and coastal sediment surfaces are also relatively sodic and the Cenozoic Kalahari sediments are relatively alkaline. The Post-African 1 surface has the third highest Ca content and the Post-African 2 surface the second highest Mg content of the 18 land surfaces.

Relationships are not sufficiently and indisputably established to enable the construction of efficient models to predict salt parameters on a national scale from elevation, slope, and land surfaces. Regression relationships for EC and ESP versus elevation and the slope index showed weak correlations on a national scale, particularly when using a linear model. When a logarithmic-Y square root-X model was used, the ESP versus elevation had a r-value of -0.38. Regression relationships for Na, Ca, and Mg with elevation and slope are very low. None of the parameters had a linear or non-linear r-value higher than 0.30. The log transformed pH_{water} values had a good non-linear correlation with elevation when the Reciprocal-Y squared-X was used, with an r-value of -0.30, and an r-value of -0.35 when the logarithmic-X was used for pH_{water} and slope.

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CHAPTER 8: REGRESION MODELS TO PREDICT ELECTRICAL CONDUCTIVITY, EXCHANGEABLE SODUIM PERCENTAGE, AND PH$_{\text{WATER}}$

8.1. INTRODUCTION

Hutson (1983) quoted Hillel who cautioned against the indiscriminate and blind use of models: "It must be remembered that simulation *per se* cannot solve a problem. It can only simulate a solution. Its results are predetermined by the input, although the full consequences of this determinism are often unforeseen for complex systems." Twenty-five years later, this is probably in a manner a simplified statement, because procedures that once required high-cost or specialised computers can now be performed on a standard desktop computer with low-cost or free programs.

Minasny and McBratney (2002) indicate that pedotransfer functions, or predictive functions of certain soil properties using easily, routinely, or cheaply measured properties, have recently become a popular topic to predict either physical or chemical properties of soil. Some pedotransfer functions and statistical models are very user unfriendly. More and more people are therefore using the Ockham razor principle. Ockham razor is a principle attributed to the 14$^{\text{th}}$ -century English logician and Franciscan friar William of Ockham (Ariew, 1976). The principle states that the explanation of any phenomenon should make as few assumptions as possible, eliminating those that make no difference in the observable predictions of the explanatory hypothesis or theory. He also indicated that the principle is often expressed in Latin as the *lex parsimonia*. Parsimony is one of the two pillars of science (StateMaster, 2009). The first pillar being falsification through experiment, the other taking the results and explaining it with the simplest theory with the best predictive power. Parsimony is also a factor in statistics. In general, mathematical models with the smallest number of parameters are preferred as each parameter introduced into the model adds some uncertainty to it. A useful method for simplifying the model is to perform a stepwise regression (Statgraphics, 2005). In a stepwise regression, variables are added or removed from a regression model one at a time, with the goal of obtaining a model that contains only significant predictors, but does not exclude any useful variables. According to Statgraphics (2005), Forward selection starts with a model containing only a constant and brings variables in one at a time if they improve the fit significantly. Backward selection starts with a model containing all of the variables and removes them one at a time until all remaining variables are statistically significant.

8.2. METHODOLOGY

Soil samples were analysed according to the methodology described in paragraph 4.2. The units for Na, Ca, and Mg are cmol$_c$ kg^{-1}, median annual rainfall in mm, and the aridity index were calculated according to the methodology described in paragraph 6.2. The goal of the regression analysis was to construct a model that contains no more X-variables than necessary to generate a good prediction. The latter consideration is referred to as parsimony. For simplicity it was decided to use only multiple linear regression and also not to log-transform the data. In paragraph 6.3.7 it was concluded that, transformations are not of much value in cases where outliers are present. A forward selection stepwise regression was therefor used to simplify the various models. In a stepwise regression, variables are added or removed from a regression model one at a time, with the goal of obtaining a model that contains only significant predictors, but does not exclude any useful variables (Statgraphics, 2005). The highest values are expressed first in the stepwise forward regression. The cation exchange capacity (CEC) was excluded from the regression equation for ESP, although it has the third highest relationship with ESP, because it is part of the calculation of ESP and because not all laboratories in South Africa are determing CEC on a routine basis.

8.3. RESULTS AND DISCUSSION

Regression relationships for EC, ESP, and pH$_{water}$ *versus* rainfall, evaporation, aridity index (Table 6.13), elevation and slope (Table 7.14) show weak linear correlations on a national scale. More complicated curvilinear models increased the r and R^2-values considerably, although these values were still relatively low.

Since the P-value is less than 0.05, there is a statistically significant relationship between the variables for the different rainfall classes at the 95% confidence level for EC. The R-squared statistic indicates that the model explains 58.28% of the variability in EC for the <550 mm rainfall class, only 38.66% for the >550 mm rainfall class, and 54.93% if no distinction is made between rainfall classes. The highest P-values for the independent variables are annual rainfall and pH_{water} for the <550 mm rainfall class and for the >550 mm rainfall class pH_{water} and exchangeable Ca have highest P-value (Table 8.1).

TABLE 8.1 Multiple linear regression relationships to predict EC for different rainfall classes.

Equation of the fitted model	R^2	Rainfall class	Sample size
$EC = 357.7 - 0.1472*Rain - 48.04*pH_{water} + 6.203*Ca + 139.7*Na + 9.299*Aridity$	54.93%	All	19016
$EC = 582.0 - 0.5615*Rain - 57.68*pH_{water} + 9.29*Ca + 155.6*Na + 4.82*Aridity$	58.28%	<550 mm	6695
$EC = 11.76 - 3.749*pH_{water} + 1.612*Ca + 67.56*Na + 10.68*Aridity$	38.66%	>550 mm	12320

Since the P-value is less than 0.05, there is a statistically significant relationship between the variables for the different rainfall classes at the 95% confidence level for ESP. The R-squared statistic indicates that the model as fitted explains a high 85.04% of the variability in ESP for the <550 mm rainfall class, only 52.04% for the >550 mm rainfall class, and 71.76% if no rainfall distinction is made. The highest P-value for the independent variables was found for exchangeable Na and EC for all the rainfall classes (Table 8.2).

TABLE 8.2 Multiple linear regression relationships to predict ESP for different rainfall classes

Equation of the fitted model	R^2	Rainfall class	Sample size
$ESP = 2.214 + 5.607*Na + 0.01615*EC + 0.1895*Aridity - 0.3308*pH_{water}$	71.76%	All	18207
$ESP = 0.05158 + 6.733*Na + 0.01028*EC + 0.2161*Aridity - 0.03307*pH_{water}$	85.04%	<550 mm	6726
$ESP = 3.306 + 1.156*Na + 0.06509*EC - 0.8513*Aridity - 0.2284*pH_{water}$	52.04%	>550 mm	11300

There is a statistically significant relationship between the variables for the different rainfall classes at the 95% confidence level for pH_{water}, since the P-value is less than 0.05. The R-squared statistic indicates that the model as fitted explains 34,40% of the variability in pH_{water} for the <550 mm rainfall class, 46.25% for the >550 mm rainfall class, and 55.80% if no distinction is made between rainfall classes. The highest P-value for the independent variables is for exchangeable Mg and annual rainfall for all the rainfall classes (Table 8.3).

Table 8.3 Multiple linear regression relationships to predict pH_{water} for different rainfall classes

Equation of the fitted model	R^2	Rainfall class	Sample size
$pH_{water} = 7.799 + 0.08394*Mg - 0.002368*Rain + 0.03244*Ca + 0.08664*Na - 0.004184*Clay$	55.80%	All	18834
$pH_{water} = 8.118 + 0.08887*Mg - 0.002991*Rain + 0.0371*Ca + 0.05102*Na - 0.006469*Clay$	34.40%	<550 mm	6390
$pH_{water} = 7.112 + 0.08067*Mg - 0.001592*Rain + 0.02846*Ca + 0.1961*Na - 0.003634*Clay$	46.25%	>550 mm	12443

8.4. CONCLUSION

The accuracy with which EC, ESP, and pH_{water} was predicted with stepwise multiple linear regression relationships on a national scale is surprising considering that the various models included all "outlier" values. The R-squared statistic indicated that the models as fitted explained the variability in EC and ESP much better for the low rainfall class (<550 mm annual rainfall), than for the high rainfall class (>550 mm annual rainfall). For EC the <550 mm annual rainfall class the model explains 58.28% and for the >550 mm annual rainfall class 38.66 % of the variability. Values for ESP are 85.04% for the <550 mm annual rainfall class and 52.04% for the >550 mm annual rainfall class. Multiple linear regression relationships were unable to predict pH_{water}, an indication that it would be better to log-transform the pH_{water} values or to use curvilinear models for the prediction.

The goal of the regression analysis was to construct models that contain no more X-variables than necessary to generate a good prediction. If the Ockham razor principle or parsimony is considered, it is probably better to use linear or stepwise multiple linear regression relationships, although more complicated models would have resulted in better R^2 values, especially for pH_{water}.

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CHAPTER 9: PRIMARY SALT-AFFECTED SOIL MAP FOR SOUTH AFRICA

9.1. INTRODUCTION

A wide variety of mapping and measurement techniques are available to map salt-affected soils. These technologies are derived from the disciplines of soil science, hydrology, geology, geomorphology, geophysics and remote sensing. The optimum strategy for mapping salt-affected soil depends on the scale and resources available. Users need to make best use of existing information and then integrate a range of the available mapping methods to that they best address their specific problem (Spies & Woodgate, 2005).

As was indicated in paragraph 2.2 saline, sodicic, and calcareous soils were mapped or described for South Africa in the past by Barnard *et al.*, (2002), Ellis (1988), MacVicar (1972), Mountain (1967), Nell and Henning (2003), Samadi *et al.* (1998), and Van der Merwe (1942).

9.2. METHODOLOGY

To compile the 1:1 000 000 scale primary salt-affected soil map of South Africa, the following maps were used: South African 1:1 000 000 scale topographical map as base map, South African 1:1 000 000 scale geological map; the South African 1: 1 000 000 scale mineral map, electronic inverse distance pH, ESP and EC maps on a 1:1 000 000 scale; and pH, ESP and EC maps in chapters 5, 6 and 7.

The soils were classified as *non-saline* when EC was lower than 200 mS m^{-1}, *slightly saline* when the EC was between 200 and 400 mS m^{-1}, *saline* when EC was between 400 and 800 mS m^{-1}, *moderately saline* when the EC was between 800 and 1600 mS m^{-1}, and *strongly saline* when the EC was more than 1600 mS m^{-1}. Only one class for sodic (EC lower than 400 mS m^{-1}, ESP higher than 15 and pH higher than 8.5) was used. In contrast to Richards (1954) and the FAO's (2001), classification of saline-sodic soils only as EC more than 400 mS m^{-1}, and ESP more than 15, pH was also used as distincton. When pH is higher than 8.5, the soil is classified as *alkaline saline-sodic* and when pH is lower than 8.5, as *non-alkaline saline-sodic.* The reason for this distinction is that the majority of the South African problematic soils fall in the alkaline saline-sodic class.

9.3. RESULTS AND DISCUSSION

Primary salt-affected soils do not occur extensively in South Africa. The majority of primarily salt-affected soils occur west of longitude 26° (Figure 9.1) in areas that can be considered mainly, although not entirely, as arid or hyper-arid (Figure 6.4).

Nearly 60% of South African soils are non-saline, 23% slightly saline, 5.1% saline, 1.4% moderately saline, 0.4% strongly saline, 3.8% saline-sodic (non-alkaline), 6.3% saline-sodic (alkaline), and only 0.4% can be considered as sodic (Table 9.1). The Gauteng Province is the least affected by primary salt-affected soils and the Northern Cape Province the most.

Provinces such as Gauteng, Mpumalanga, Eastern Cape, North West and Limpopo would probably have significant areas affected by secondary salinity and sodicity due to mining, industrial and agricultural activities.

TABLE 9.1 Salinity and sodicity status of South African soils in ha and percentages in parenthesis

PROVINCE	Non-Saline (ha)	Slightly Saline (ha)	Saline (ha)	Moderately Saline (ha)	Strongly Saline (ha)	Saline-Sodic (Non-Alkaline) (ha)	Saline-Sodic (Alkaline) (ha)	Sodic (ha)
Eastern Cape	8 414 831 **49.8%**	7 154 744 **42.4%**					1 322 885 **7.8%**	
Free State	8 976 688 **69.1%**	2 182 957 **16.8%**	1 104 427 **8.5%**			197 208 **1.5%**	521 234 **4.0%**	
Gauteng	1 605 555 **97%**	49 223 **3%**						
KwaZulu-Natal	8 375 592 **89.7%**	909 752 **9.7%**						47 336 **0.5%**
Limpopo	11 514 939 **91.6%**	913 589 **7.3%**					146 787 **1.2%**	
Mpumalanga	6 806 636 **89%**	750 971 **9.8%**					91 853 **1.2%**	
North West	10 059 460 **94.4%**	570 493 **5.4%**				21 258 **0.2%**		
Northern Cape	12 544 054 **33.6%**	10 778 830 **28.9%**	5131 117 **13.8%**	1 347 880 **3.6%**	448 350 **1.2%**	2 349 498 **6.3%**	4 272 864 **11.5%**	416 350 **1.1%**
Western Cape	4 468 902 **34.5%**	4 710 724 **36.4%**	13 237 **0.1%**	343 962 **2.7%**		2 080 370 **16.1%**	1 328 052 **10.3%**	
SOUTH AFRICA	72 766 657 **59.7%**	28 021 283 **23.0%**	6 248 781 **5.1%**	1 691 842 **1.4%**	448 350 **0.4%**	4 648 334 **3.8%**	7 683 675 **6.3%**	463 686 **0.4%**

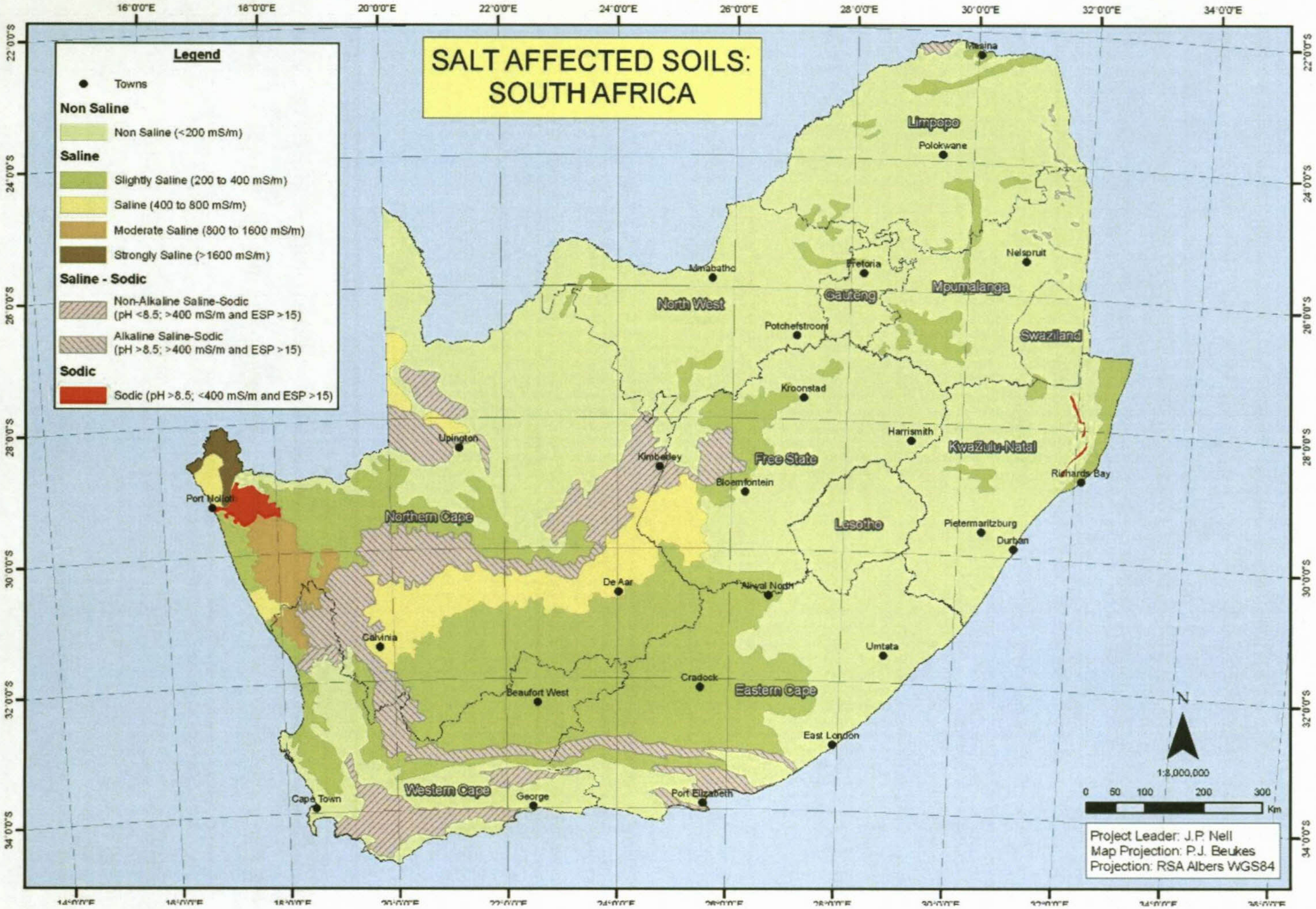

FIGURE 9.1 Salt-affected soils map of South Africa.

9.4. CONCLUSION

The relative area affected by primary salt-affected soils in South African is much more favourable, compared to countries such as Australia, Canada, Hungary, Israel, India, Namibia, and Pakistan. The main reason for this condition is probably the fact that the South African soils are mostly derived from geological material, such as shale, sandstone, dolerite, andesite, gabbro, and basalt that is Ca dominant and not Na dominant.

Soluble salts occur in significant proportions mostly in more arid areas of South Africa where the annual rainfall is less than 550 mm. Therefore, transient salinity, or salinity not influenced by groundwater processes and rising water table, is the predominant salinity type in South Africa, and not dryland salinity.

Saline and/or sodic soils in South Africa mostly occur only in relatively small areas due to localised factors, making the mapping on a national scale problematic.

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CHAPTER 10: CONCLUSIONS

All of the five natural soil-forming factors affect and are affected by water. The flux factors of soil formation (vegetation and climate) as well as the site factors (parent materials and topography) can be linked to landscape hydrology, which is further modified by the internal soil hydrological environment. Soil-forming processes such as transformation, translocation, additions and deletions that have a strong influence on the development of salt-affected soils, or the lack thereof, are all influenced by water to a significant degree.

Salts originated primarily from mineral weathering, but the oceans also constitute a major source of salts. The mechanisms for redistributing oceanic salts are through rainfall, mist, fog, and oceanic sprays. Inland areas such as the Richtersveld and Namaqualand not only receive coastal rainfall, but also mist and fog, that contribute substantially to salt accumulation in the soil. Dry fall-out is commonly neglected when assessing atmospheric salt accretions, but it may constitute a significant portion of the atmospheric salts impinging on an inland area.

Topography can greatly affect the movement of water and salts through soil. This is, to a certain extent, a result of gravity, which directly influences water and salt movement and partly as a result of topography's influence on soil development. Rainfall which runs off sloping soil is not available for leaching salt out of the sloping area. Landscapes with steep slopes and well developed, fast-flowing stream systems are well dissected. In such landscapes there is a good opportunity for salts to be leached out of the soils. In areas where the rainfall is high, the soil permeable and the landscape well dissected, there is no opportunity for salts to accumulate. Where rainfall is lower, the soil less permeable and the landscape less well dissected, salts accumulate in the least leached parts of the landscape. Relatively closed basins, such as Tanqua Karoo Basin, the Algoa Basin, Oudtshoorn Basin, and Limpopo Karoo Basin, pan environments such as the Bushmanland Pan Belt and Central Pan Belt, and Intermontane areas such as the Tulbagh-Ashton Valley, have a tendency to contain soils with a high salt content. The high salt content of soils in the western part of South Africa is not only the result of the aridity and geology of the area, but also because of less leaching of salts due to the Pliocene uplift that was less intense in these areas, than in the eastern part of South Africa.

There is an increase on a national scale in electrical conductivity, exchangeable sodium percentage, and pH_{water} from the highest elevation class to the lowest elevation class. This is an indication of leaching and movement of salts from the higher elevation positions to the lower elevation position where accumulation of salts occurs, even on a national scale. There is no clear correlation between age of land surface and electrical conductivity, exchangeable sodium percentage, and pH_{water}, although there is a tendency that land surfaces of Miocene and younger ages have higher salt contents. The Structural Basin and Structural Bench are by far the most sodic, saline, and alkaline. The Marine Platform of the Post-Africa 1 and Neogene marine and coastal sediment surfaces are also relatively sodic and the Cenozoic Kalahari sediments are relatively alkaline.

South Africa has a long and complex geological history, which dates back in excess of 3.6 billion years, but the present-day environment and soils of southern Africa probably owes much of its origin to geological events in the post-Gondwana period. Unequalled by any other region in the world, South Africa hosts some of the oldest known salt deposits in its geological material.

The minerals mainly responsible for salt-affected soils are from four chemical groups, namely carbonates, halides, sulphates, and borates. Geological material is in most circumstances an important soil formation factor, but for salt-affected soils its effect is probably overshadowed in many areas by rainfall and position in the landscape. It is also difficult to make generalizations about potential salt levels in a specific soil arising from different rock types, because much of the salt present may be derived from external transported sources. It is useful to distinguish between non-extreme and extreme parent materials. Certain minerals and rocks are more vulnerable to chemical reaction than others. Rhyolite (with a low weathering potential) is for example, a non-extreme or non-active parent material and limestone and dolerite (with a high weathering potential) an active parent material.

The soil in the Whitehill Formation in the Ecca Group is by far the most saline and sodic geological unit in South Africa. The soil in the Tanqua Karoo groundwater unit is the most saline and the soils in the Richtersveld groundwater region the most sodic in South Africa. The soils of the Richtersveld Subprovince and the Eendoorn granite are the most alkaline geological units and the soils in the Richtersveld-, Ghaap Plateau-, and Western Kalahari groundwater units the most alkaline in South Africa. The soils with the highest salt content, according to geological units, are found in the arid western part of the Northern and Western Cape Province of South Africa. The only exceptions are the Nyoka Formation that primarily occurs in the more humid part of the northern part of KwaZulu-Natal Province and the Uitenhage Group in the Eastern Cape Province.

There is a tendency that some of the most sodic and alkaline soils develop from geological units rich in granite, gneiss, and anorthosite (Gladkop Suite, Spektakel Suite, Garies Subgroup, Eendoorn Granite, and Villa Nora Anorthosite). Some of the most sodic and saline soils also developed on geological units with a predominately marine depositional environment characterised by mudstone, siltstone, and shale. Salt laden coastal rainfall and/or fog (Port Nolloth, Bredasdorp, and Malmesbury Groups, Knersvlakte Subgroup, and Porterville, Sundays River, Kirkwood, Nanaga, and Alexandria Formations) also contribute to salt accumulation in these soils. The Whitehill Formation in the Ecca Group, which is the most saline and sodic geological unit in South Africa, consists of black carbonaceous and pyrite-bearing shales.

Regular and high rainfall in the eastern part of South Africa causes a continuous leaching and the transport of leached constituents out of the soil system into the ground water system. On the other hand, erratic and low rainfall combined with high evaporation in the west of South Africa result in the accumulation of salts in the soil profile. It should not be assumed that all salt-affected soils will always show definite and predictable associations with present day climate. The relationship between climate and salt-affected soils is more difficult to determine, because practically all areas have experienced climates in the past different from those prevailing at present.

Salt affects the different soil classes in South Africa in the following sequence: calcic ≈ alluvial/aeolian >prismacutanic >vertic >pedocutanic/red structured >neocutanic >hydromorphic ≈ lithosols >plinthic >apedal >podzolic.

The geological units resulting in most salt-affected soils are in declining order: Whitehill Formation ≈ Knersvlakte Subgroup >Gladkop Suite >Sundays River Formation >Enon Formation >Garies Subgroup >Kirkwood Formation >Port Nolloth Group >Nyoka Formation >Prince Albert Formation.

The groundwater units resulting in most salt-affected soils are in declining order: Tanqua Karoo >Richtersveld >Knersvlakte >Ruensveld >Hantam >Namaqualand >Algoa Basin >Bushmanland Pan Belt >Bredasdorp Coastal Belt >Intermontane Tulbagh-Ashton Valley.

Nearly 60% of South Africa is non-saline, 23% slightly saline, 5.1% saline, 1.4% moderately saline, 0.4% strongly saline, 3.8% saline-sodic (non-alkaline), 6.3% saline-sodic (alkaline), and only 0.4% can be considered as sodic.

CHAPTER 11: RECOMMENDATIONS FOR FUTURE RESEARCH

Develop a salinity and sodicity risk index that measures the probability that an area has a certain level of salinity and sodicity.

Develop mechanistic models and geographic information systems to understand and spatially predict the processes that control salt-affected soils at point, toposequence, catchment, water management area, geological unit, provincial, and national scale.

The development of inferencing techniques based on remote sensing and digital terrain analysis to improve prediction of the likely occurrence of salt-affected soils.

Determine the impact of salt-affected soils on environmental issues such as silting up of dams, road engineering, and housing.

Improved database methodology to enable more efficient correlation of salt-affected soil properties with other properties of direct relevance to plant production and irrigable value of soils. Although databases at ARC-ISCW and some provincial departments are available, there is some doubt about the accuracy of historical data, especially when early methods of estimating exchangeable cations did not eliminate the effects of soluble cations.

Information on the nutrient interactions and cycling of nutrients in salt-affected soils is sparse and should be studied.

Standardise the methods for measurements and nomenclature relating to salt-affected soils in South Africa. Include anions in the analyses of salt-affected soils.

Develop a non-pedological salt-affected soil classification system for use by farmers, engineers, and soil scientists especially where new irrigation schemes are planned or rehabilitated.

The role of clay minerals in dispersion relative to ESP and/or SAR needs to be studied to enable an assessment of Na sensitivity of soils with varying mineralogy to provide a basis for the development of management techniques.

APPENDIX A: Definitions

ALGAL MAT: A layered communal growth of algae observed in fossils and in present-day tidal zones associated with carbonate sedimentation (Press & Siever, 1974).

ALKALI FELDSPAR: A mineral such as microcline, orthoclase, sanine, albite or perthite (Vegter, 2001).

ALKALINE SOIL: Any soil that has a pH greater than 7.0 (CanSIS, 2007).

ALKALI SOIL: (no longer used in SSSA publications) (i) A soil with a pH of 8.5 or higher or with an exchangeable sodium ratio greater than 0.15. (ii) A soil that contains sufficient sodium to interfere with the growth of most crop plants (SSSA, 2007).

ALKALINITY: The degree or intensity of alkalinity in a soil, expressed by a value >7.0 for the soil pH (SSSA, 2007).

ALKALINIZATION: The process whereby the exchangeable sodium content of a soil is increased (CanSIS, 2007).

ANDESITE: A dark-coloured fine-grained extrusive rock composed of sodium-rich plagioclase and mafic minerals such as hornblende, pyroxene, biote in a fine-grained groundmass (Vegter, 2001).

ARTESIAN SALINITY: Salinity that occurs where water from a pressurized aquifer rises to or near ground surface (Ropin, 2004).

BRINE: Sea water whose salinity has been increased by evaporation, or groundwater with an unusual concentration of salts(Press & Siever, 1974).

CALCARENITE: Consolidated calcareous sand (Vegter, 2001).

CALCAREOUS: A soil is considered calcareous from a chemical point of view when it is in equilibrium with excess of $CaCO_3$ at the partial pressure of the atmospheric CO_2 (Balba, 1995).

CALCAREOUS SOILS: Characterized by the presence of calcium carbonate in the parent material and be a calcic horizon, a layer of secondary accumulation of carbonates (usually Ca or Mg) in excess of 15% calcium carbonate equivalent and at least 5% more carbonate than an underlying layer FAO/AGL, 2004).

CALCIC POLDER: Under the influence of H_2SO_4 formed by the oxidation of sulphide, the Na^+ is eliminated, partial decarbonation of the complex by the Ca^{2+} ion occurs. (Duchaufour, 1912).

CALCRETE: A general term for strongly calcareous carbonate deposits or any material formed by the cementation and/or or partial or complete replacement of pre-existing soil by $CaCO_3$ (Netterberg, 1969).

CALC-SILICATE: Said of a metamorphic rock that consists mainly of calcite and calcium-bearing silicates such as dioside and wollastonite (Vegter, 2001).

CHEMICAL SEDIMENT: One that is formed at or near its place of deposition by chemical precipitation, usually from sea water (Press & Siever, 1974).

CONTACT/SLOPE CHANGE SALINITY: Is a saline seep that has water in its recharge areas, which percolate down through the soil profile beyond the root zoon. The groundwater moves to a lower position in the landscape and here through capillary rise, reaches the surface, resulting in a saline seep (Ropin, 2004).

DEPRESSION SALINITY: Occurs in depressions or drainage courses. Surface water flows slowly over and is trapped temporarily in the low-lying areas until the water drains off and/or infiltrates the soil (Ropin, 2004).

DRYLAND SALINITY:

(1) Occurs in non-irrigated areas. It is the build up of salt in the soil, as a result of a rising watertable (CRC, 2004).

(2) (On non-irrigated land) occurs when the concentration of soluble salts near the soil surface is sufficient to reduce plant growth. This is basically a water management problem: Increased recharge raises the watertable, bringing naturally stored salts from depth to the surface (State. West. Aus, 2006).

EVAPORITES: Residue of salts (including gypsum and all more soluble species) precipitated by evaporation (SSSA, 2007).

EXCHANGEABLE SODIUM PERCENTAGE (ESP):

(1) Exchangeable sodium fraction expressed as a percentage (SSSA, 2007).

(2) The percentage of cation exchange capacity of the soil that is occupied by sodium (van der Walt & van Rooyen, 1995).

EXCHANGEABLE SODIUM RATIO (ESR): The ratio of exchangeable sodium to all other exchangeable cations (SSSA, 2007).

GROUNDWATER ASSOCIATED SALINITY (GAS): Comprises salt-affected soils in rain fed areas that have direct or capillary contact with saline groundwater watertables and categories defined by the following hydrological and geochemical environments: (i) Primary (natural) or Secondary (anthropogenic), (ii) Alkaline (sodium carbonate dominant, pH >9), (iii) Halitic (sodium chloride dominant), (iv)

Gypsic (calcium sulphate dominant) and (v) Sodic (high exchangeable sodium percentage on clay surfaces (Fitzpatrick, 2009).

HALOMORPHIC SOIL: A suborder of the intrazonal soil order, consisting of saline and sodic soils formed under imperfect drainage in arid regions and including the great soil groups Solonchak or Saline soils, Solonetz soils, and Soloth soils (SSSA, 2007).

IRRIGATION SALINITY: Is mainly caused by over-irrigation of farmland, inefficient water use, poor drainage or irrigating on unsuitable soils (CRC, 2004).

KARST: A type of topography that is formed over limestone and dolomite by solution and that is characterized by closed depressions or sinkholes, caves and underground drainage (Vegter, 2001).

MARBLE: A metamorphic rock consisting predominantly of fine- to coarse-grained recrystallised calcite and or dolomite (Vegter, 2001).

MINERALIZATION: The progressive accumulation of dissolved solids by surface water and groundwater in passage through the land phase of the hydrological cycle (Hall & Du Plessis, 1984).

NON-GROUNDWATER ASSOCIATED SALINITY (NAS): Comprises salt-affected soils in rain fed areas that have no direct contact with saline groundwater watertables, and with categories defined by the following soil chemical environments: (i) Sodic (ESP ≥5) and (ii) Saline (EC_{se} ≥200 mS m^{-1}) conditions in the solum (A- and B- horizons, typically <1.2 m deep). (Fitzpatrick, 2009).

NONSALINE-ALKALINE SOILS: Soils for which the exchangeable sodium percentage is greater than 15 and the conductivity of the saturation extract is less than 400 mS m^{-1} at 25°C (Richards, 1954).

OUTCROP SALINITY: Occurs where a permeable, water-bearing layer, such as a sandy layer, or fractured bedrock layer, outcrops at or near the surface in rows along a slope at similar elevations (Ropin, 2004).

PRIMARY SALINITY: Where increases in salinity have occurred solely through natural processes (NAPTAS, 2007).

RIVER SALINITY: Water running from areas of dryland, irrigation and urban salinity may flow into rivers, raising their salinity (CRC, 2004).

SALIC HORIZON: A mineral soil horizon of enrichment with secondary salts more soluble in cold water than gypsum. A salic horizon is 15 cm or more in thickness, contains at least 20 g kg^{-1} salt, and the product of the thickness in centimetres and amount of salt by weight is >600 g kg^{-1} (SSSA, 2007).

SALINE POLDER: Aerated surface causing the partial oxidation of the sulphide and the formation of rusty patches (Duchaufour, 1912).

SALINE SOIL:

(1) A soil that contains sufficient soluble salts to impair its productivity (Richards, 1954).

(2) Soils containing sufficient neutral soluble salts to adversely affect the growth of most crop plants. The soluble salts are chiefly sodium chloride and sodium sulphate. But saline soils also contain appreciable quantities of chlorides and sulphates of calcium and magnesium (FAO, 2001).

(3) A non-sodic soil containing sufficient soluble salt to adversely affect the growth of most crop plants. The lower limit of saturation extract electrical conductivity of such soils is conventionally set at 400 mS m^{-1} (at 25 °C). Actually, sensitive plants are affected at half this salinity and highly tolerant ones at about twice this salinity (SSSA, 2007).

SALINE INTRUSION: Replacement of freshwater by saline water in an aquifer, usually as a result of groundwater abstraction (Parsons, 2004).

SALINIZATION:

(1) The process of accumulation of salts in soil (CanSIS, 2007).

(2) The process whereby soluble salts accumulate in the soil (Van der Watt and Van Rooyen, 1995).

SALINE-ALKALINE SOILS: Soils for which the conductivity of the saturation extract is greater than 400 mS m^{-1} at 25°C and the exchangeable sodium percentage is greater than 15. Under conditions of excess salts, the pH readings are seldom higher than 8.5 and the particles remain flocculated (Richards, 1954).

SALINE-ALKALI SOIL: (no longer used in SSSA publications) (i) A soil containing sufficient exchangeable sodium to interfere with the growth of most crop plants and containing appreciable quantities of soluble salts. The ESP is >15, the conductivity of the saturation extract >4 dS m^{-1}(at 25°C), and the pH is usually 8.5 or less in the saturated soil. (ii) A saline-alkali soil has a combination of harmful qualities of salts and either a high alkalinity or high content of exchangeable sodium, or both, so distributed in the profile that the growth of most crop plants is reduced (SSSA, 2007).

SALINITY:

(1) Is a measure of the total amount of soluble salt in the soil or soil solution (Bauder, 2004).

(2) The amount of soluble salts in a soil, expressed in terms of percentage, parts per million, or other convenient ratios (CanSIS, 2007).

(3) Is a state in which soil contains enough dissolved salts in the plant root zone to hinder plant growth. This condition is mainly controlled by the presence and movement of water in the soil (Eilers *et al.*, 1995).

SALT-AFFECTED SOILS:

(1) Soils that contain considerable amounts of soluble salts. Primary salt-affected soils can be broadly classified as saline soils and sodic soils (FAO/AGL, 2004).

(2) Soil that has been adversely modified for the growth of most crop plants by the presence of soluble salts, with or without high amounts of exchangeable sodium (SSSA, 2007).

(3) Soil that has been adversely modified for the growth of most crop plants by the presence of certain types of exchangeable ions or of soluble salts. It includes soils having an excess of salts, or an excess of exchangeable sodium, or both (CanSIS, 2007).

SALT BALANCE: The quantity of soluble salt removed from an irrigated area in the drainage water minus that delivered in the irrigation water (SSSA, 2007).

SALT FLATS: In Soil Survey a map unit that is a miscellaneous area, composed of undrained flats in arid regions that have surface deposits of secondary salt overlying stratified and strongly saline sediment (SSSA, 2007).

SALT TOLERANCE:

(1) The ability of plants to resist the adverse, non-specific effects of excessive soluble salts in the rooting medium (SSSA, 2007).

(2) The average soil salinity required to produce a specified decrease in plant yield or the ability, expressed qualitatively or quantitatively, of a plant species to withstand high salt concentrations in soil (SSSA)>

SCALDED AREAS: areas which are bare of vegetation due to extremely adverse growing conditions, such as being too saline or acidic (Fitzpatrick *et.al.*, 2003).

SECONDARY SALINITY: (or induced salinity) is where increases have occurred due to land use changes made by human activity (NAPTAS, 2007).

SLOPE CHANGE SALINITY: Occurs where the slope decreases. This reduced slope slows the groundwater and builds up the water table. The salinity expands in the upslope direction (Ropin, 2004).

SLOUGH RING SALINITY: Occurs as a ring of salt immediately adjacent to a permanent water body. Water from unsaturated flow and capillary rise from the watertable emerges at the surface where it evaporates, leaving salts at the edge of the slough (Ropin, 2004).

SODICATION: The process whereby the exchangeable sodium content of a soil is increased (Foth, 1984).

SODIC SOILS:

(1) Soils containing sodium salts capable of alkaline hydrolysis, mainly Na_2CO_3 (FAO, 2001).

(2) Soils with an ESP >6 in the upper B2 horizon or within 50 cm of the surface in profiles without B2 horizons (Doyle & Habraken, 1993).

(3) Soil with a low soluble salt content but sufficient adsorbed Na to have caused significant deflocculation. The exchangeable sodium percentage (ESP) is greater than 15. (Van der Watt & Van Rooyen, 1995).

SODICITY: Refers to soil exchange capacity and the degree to which sites are occupied by sodium ions, as compared to the more preferred calcium and magnesium ions (SSSA, 2007).

SODIUM ADSORPTION RATIO, ADJUSTED: The sodium adsorption ratio of a water adjusted for the precipitation or dissolution of Ca^{2+} that is expected to occur where water reacts with alkaline earth carbonates within a soil (SSSA, 2007).

SOIL pH (descriptive terms commonly associated with ranges in pH_{water}): (Van der Watt and Van Rooyen, 1995).

Extremely acid	<4.5
Very strongly acid	4.5-5.0
Strongly acid	5.1-5.5
Medium acid	5.6-6.0
Slightly acid	6.1-6.5
Neutral	6.6-7.3
Mildly alkaline	7.4-7.8
Moderately alkaline	7.9-8.4
Strongly alkaline	8.5-9.0
Very strongly alkaline	>9.0

SOIL SALINTY: The amount of soluble salts in a soil, expressed in terms of conductivity of the saturation extract, percentage, mg/kg or other convenient units (Van der Watt & Van Rooyen, 1995).

SOLONCHAK: A great soil group of the intrazonal order and halomorphic suborder, consisting of soils with grey, thin, salty crust on the surface, and with fine granular mulch immediately below being underlain with greyish, friable, salty soil; formed under subhumid to arid, hot or cool climate, under conditions of poor drainage, and under a sparse growth of halophytic grasses, shrubs, and some trees (SSSA, 2007).

TRANSIENT SALINITY:

(1) The seasonal and spatial variation of salt accumulation in the root zone not influenced by groundwater processes and rising water table (Rengasamy, 2002).

(2) Is the term used for salinity that is not associated with a permanent saline groundwater table (Fitzpatrick, 2002).

(3) Dry saline land subsurface and surface expressed - not hydrologically connected to a saline groundwater table (Fitzpatrick *et.al.*, 2003).

TRAVERTINE: A terrestrial deposit of limestone formed in caves and around hot springs where cooling, carbonate-saturated groundwater is exposed to the air (Press & Siever, 1974).

URBAN SALINITY: Salinity in towns and urban areas resulting from a combination of dryland salinity processes and over-watering of urban areas (CRC, 2004).

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APPENDIX B: MULTIPLE RANGE TESTS FOR ELECTRICAL CONDUCTIVITY.

2.1. Electrical conductivity per soil class for topsoil horizons

Method: 95.0 percent Bonferroni

Soil Class	***Count***	***Mean***	***Homogeneous Groups***
11 = Podzolic	25	20.0	X X XXX
8 = Plinthic	645	32.8	XX
9 = Apedal	2978	42.4	X
10 = Lithosols	1407	56.1	XX
5 = Prismacutanic	395	68.5	XXX
4 = Pedocutanic and Red Structured	1092	108.	XX X
7 = Hydromorphic	529	158.	XXX
2 = Neocutanic	883	188.	X
3 = Calcic	375	194.	XX
6 = Vertic	229	205.	XX
1 = Alluvial and Aeolian	167	396.	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	208.	130.
1 - 3	<*	202.	144.
1 - 4	<*	288.	128.
1 - 5	<*	327.	142.
1 - 6	<*	191.	157.
1 - 7	<*	238.	137.
1 - 8	<*	363.	134.
1 - 9	<*	353.	123.
1 - 10	<*	340.	126.
1 - 11	<*	376.	331.
2 - 3		-5.57	95.2
2 - 4	<*	80.5	69.9
2 - 5	<*	120.	93.4
2 - 6		-16.9	114.
2 - 7		30.3	84.9
2 - 8	<*	155.	80.0
2 - 9	<*	146.	59.2
2 - 10	<*	132.	66.3
2 - 11		168.	313.
3 - 4		86.1	92.4
3 - 5	<*	125.	111.
3 - 6		-11.3	129.
3 - 7		35.9	104.
3 - 8	<*	161.	100.
3 - 9	<*	151.	84.6
3 - 10	<*	138.	89.7
3 - 11		174.	319.
4 - 5		39.1	90.6
4 - 6		-97.5	112.
4 - 7		-50.2	81.8
4 - 8		74.7	76.7
4 - 9	<*	65.1	54.6
4 - 10		51.4	62.3
4 - 11		87.6	312.
5 - 6	<*	-137.	128.
5 - 7		-89.3	103.
5 - 8		35.7	98.6
5 - 9		26.0	82.7
5 - 10		12.3	87.9
5 - 11		48.5	318.
6 - 7		47.2	122.

6 - 8	<*	172.	119.
6 - 9	<*	163.	106.
6 - 10	<*	149.	110.
6 - 11		185.	325.
7 - 8	<*	125.	90.6
7 - 9	<*	115.	72.8
7 - 10	<*	102.	78.7
7 - 11		138.	316.
8 - 9		-9.62	67.0
8 - 10		-23.3	73.4
8 - 11		12.8	315.
9 - 10		-13.7	49.9
9 - 11		22.5	310.
10 - 11		36.2	311.

* denotes a statistically significant difference. An asterisk has been placed next to 27 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 6 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

2.2. Electrical conductivity per soil class for subsoil horizons

Method: 95.0 percent Bonferroni

Soil Class	***Count***	***Mean***	***Homogeneous Groups***
11 = Podzolic	55	16.3	XX
8 = Plinthic	1173	36.9	X
9 = Apedal	4547	62.0	X
10 = Lithosols	545	113.	XX
4 = Pedocutanic and Red Structured	1510	161.	X
5 = Prismacutanic	611	168.	X
7 = Hydromorphic	618	197.	X
6 = Vertic	69	276.	XXX
2 = Neocutanic	1393	291.	X
3 = Calcic	511	298.	X
1 = Alluvial and Aeolian	154	488.	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	197.	142.
1 - 3	<*	190.	154.
1 - 4	<*	326.	141.
1 - 5	<*	320.	151.
1 - 6		211.	242.
1 - 7	<*	291.	151.
1 - 8	<*	451.	143.
1 - 9	<*	426.	137.
1 - 10	<*	374.	153.
1 - 11	<*	471.	263.
2 - 3		-6.86	86.4
2 - 4	<*	129.	62.1
2 - 5	<*	123.	81.1
2 - 6		14.2	206.
2 - 7	<*	93.7	80.8
2 - 8	<*	254.	66.2
2 - 9	<*	229.	51.2
2 - 10	<*	177.	84.4
2 - 11	<*	274.	230.
3 - 4	<*	136.	85.5
3 - 5	<*	130.	100.
3 - 6		21.1	214.
3 - 7	<*	101.	99.9
3 - 8	<*	261.	88.6
3 - 9	<*	236.	78.0
3 - 10	<*	184.	103.

3 - 11	<*	281.	237.
4 - 5		-6.37	80.1
4 - 6		-115.	206.
4 - 7		-35.6	79.8
4 - 8	<*	124.	65.0
4 - 9	<*	99.3	49.6
4 - 10		48.0	83.5
4 - 11		145.	229.
5 - 6		-109.	212.
5 - 7		-29.3	95.3
5 - 8	<*	131.	83.4
5 - 9	<*	106.	72.0
5 - 10		54.3	98.5
5 - 11		151.	235.
6 - 7		79.4	212.
6 - 8	<*	240.	207.
6 - 9	<*	214.	203.
6 - 10		163.	214.
6 - 11		260.	302.
7 - 8	<*	160.	83.1
7 - 9	<*	135.	71.6
7 - 10		83.6	98.2
7 - 11		181.	235.
8 - 9		-25.1	54.7
8 - 10		-76.5	86.6
8 - 11		20.6	231.
9 - 10		-51.4	75.8
9 - 11		45.7	227.
10 - 11		97.1	236.

* denotes a statistically significant difference. An asterisk has been placed next to 31 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 4 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

2.3. The highest electrical conductivity in a profile per soil class

Method: 95.0 percent Bonferroni

Soil class	***Count***	***Mean***	***Homogeneous Groups***
11 = Podzolic	31	24.1	XXXX
8 = Plinthic	1044	39.4	X
9 = Apedal	4570	56.1	X
10 = Lithosols	1600	69.4	X X
4 = Pedocutanic and Red Structured	1460	146.	X
7 = Hydromorphic	655	167.	X
6 = Vertic	232	178.	XX
5 = Prismacutanic	440	197.	X
2 = Neocutanic	1050	315.	X
3 = Calcic	451	324.	X
1 = Alluvial and Aeolian	179	547.	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	232.	141.
1 - 3	<*	223.	154.
1 - 4	<*	401.	138.
1 - 5	<*	350.	154.
1 - 6	<*	369.	173.
1 - 7	<*	380.	147.
1 - 8	<*	507.	141.
1 - 9	<*	491.	132.
1 - 10	<*	477.	137.
1 - 11	<*	523.	338.

2 - 3		-8.82	97.9
2 - 4	<*	169.	70.3
2 - 5	<*	118.	98.7
2 - 6	<*	137.	126.
2 - 7	<*	148.	86.6
2 - 8	<*	275.	76.0
2 - 9	<*	259.	59.5
2 - 10	<*	245.	69.0
2 - 11		291.	317.
3 - 4	<*	178.	93.6
3 - 5	<*	127.	116.
3 - 6	<*	146.	140.
3 - 7	<*	157.	106.
3 - 8	<*	284.	98.0
3 - 9	<*	267.	85.8
3 - 10	<*	254.	92.7
3 - 11		300.	323.
4 - 5		-51.3	94.5
4 - 6		-31.8	123.
4 - 7		-20.9	81.8
4 - 8	<*	106.	70.5
4 - 9	<*	89.7	52.3
4 - 10	<*	76.4	62.9
4 - 11		122.	316.
5 - 6		19.5	141.
5 - 7		30.3	107.
5 - 8	<*	158.	98.8
5 - 9	<*	141.	86.8
5 - 10	<*	128.	93.6
5 - 11		173.	323.
6 - 7		10.9	133.
6 - 8	<*	138.	126.
6 - 9	<*	121.	117.
6 - 10		108.	122.
6 - 11		154.	332.
7 - 8	<*	127.	86.6
7 - 9	<*	111.	72.6
7 - 10	<*	97.3	80.6
7 - 11		143.	320.
8 - 9		-16.8	59.6
8 - 10		-30.1	69.2
8 - 11		15.3	317.
9 - 10		-13.3	50.5
9 - 11		32.0	313.
10 - 11		45.3	315.

* denotes a statistically significant difference. An asterisk has been placed next to 35 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 5 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

APPENDIX C: Multiple range tests for Exchangeable Sodium Percentage

3.1. ESP per soil class for topsoil horizons

Method: 95.0 percent Bonferroni

Soil Class	***Count***	***Mean***	***Homogeneous Groups***
8 = Plinthic	655	2.64	X
9 = Apedal	3027	2.68	X
10 = Lithosols	1225	3.09	X
11 = Podzolic	27	3.67	XX
4 = Pedocutanic and Red Structured	1062	4.53	X
5 = Prismacutanic	393	5.12	XX
6 = Vertic	251	5.48	XX
3 = Calcic	409	5.58	XX
2 = Neocutanic	843	8.62	X
7 = Hydromorphic	521	8.73	X
1 = Alluvial and Aeolian	184	11.1	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		2.44	6.04
1 - 3		5.49	6.58
1 - 4	<*	6.53	5.92
1 - 5		5.94	6.63
1 - 6		5.58	7.2
1 - 7		2.33	6.36
1 - 8	<*	8.42	6.19
1 - 9	<*	8.38	5.63
1 - 10	<*	7.97	5.86
1 - 11		7.39	15.3
2 - 3		3.05	4.47
2 - 4	<*	4.09	3.42
2 - 5		3.5	4.53
2 - 6		3.15	5.33
2 - 7		-0.111	4.13
2 - 8	<*	5.98	3.86
2 - 9	<*	5.94	2.89
2 - 10	<*	5.53	3.32
2 - 11		4.95	14.5
3 - 4		1.04	4.32
3 - 5		0.457	5.24
3 - 6		0.0986	5.95
3 - 7		-3.16	4.9
3 - 8		2.93	4.67
3 - 9		2.89	3.91
3 - 10		2.49	4.24
3 - 11		1.9	14.7
4 - 5		-0.586	4.38
4 - 6		-0.944	5.21
4 - 7	<*	-4.2	3.97
4 - 8		1.89	3.69
4 - 9		1.85	2.65
4 - 10		1.44	3.11
4 - 11		0.859	14.5
5 - 6		-0.359	5.99
5 - 7		-3.61	4.96
5 - 8		2.48	4.73
5 - 9		2.44	3.98
5 - 10		2.03	4.3
5 - 11		1.44	14.8

6 - 7		-3.26	5.7
6 - 8		2.84	5.51
6 - 9		2.79	4.87
6 - 10		2.39	5.14
6 - 11		1.8	15.0
7 - 8	<*	6.09	4.35
7 - 9	<*	6.05	3.52
7 - 10	<*	5.64	3.88
7 - 11		5.06	14.6
8 - 9		-0.0404	3.2
8 - 10		-0.448	3.59
8 - 11		-1.03	14.6
9 - 10		-0.408	2.51
9 - 11		-0.992	14.3
10 - 11		-0.584	14.4

* denotes a statistically significant difference. An asterisk has been placed next to 12 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 2 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

3.2. ESP per soil class for subsoil horizons

Method: 95.0 percent Bonferroni

Soil Class	*Count*	*Mean*	*Homogeneous Groups*
8 = Plinthic	1331	4.07	X
9 = Apedal	4982	4.14	X
11 = Podzolic	58	5.3	XXX
6 = Vertic	83	6.62	XXX
10 = Lithosols	592	6.67	XX
4 = Pedocutanic and Red Structured	1601	7.28	X
5 = Prismacutanic	648	13.1	X
3 = Calcic	524	13.3	X
2 = Neocutanic	1379	13.5	X
7 = Hydromorphic	718	14.4	XX
1 = Alluvial and Aeolian	182	21.6	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	8.08	6.81
1 - 3	<*	8.28	7.43
1 - 4	<*	14.3	6.76
1 - 5	<*	8.46	7.25
1 - 6	<*	15.0	11.4
1 - 7		7.14	7.17
1 - 8	<*	17.5	6.83
1 - 9	<*	17.4	6.52
1 - 10	<*	14.9	7.32
1 - 11	<*	16.3	13.0
2 - 3		0.2	4.43
2 - 4	<*	6.22	3.17
2 - 5		0.38	4.11
2 - 6		6.89	9.76
2 - 7		-0.938	3.98
2 - 8	<*	9.43	3.32
2 - 9	<*	9.36	2.63
2 - 10	<*	6.84	4.24
2 - 11		8.2	11.6
3 - 4	<*	6.02	4.35
3 - 5		0.18	5.07
3 - 6		6.69	10.2
3 - 7		-1.14	4.96
3 - 8	<*	9.23	4.45
3 - 9	<*	9.16	3.97

3 - 10	<*	6.64	5.18
3 - 11		8.0	12.0
4 - 5	<*	-5.84	4.02
4 - 6		0.667	9.72
4 - 7	<*	-7.16	3.88
4 - 8	<*	3.21	3.2
4 - 9	<*	3.14	2.48
4 - 10		0.618	4.15
4 - 11		1.98	11.5
5 - 6		6.51	10.1
5 - 7		-1.32	4.68
5 - 8	<*	9.05	4.14
5 - 9	<*	8.98	3.61
5 - 10	<*	6.46	4.91
5 - 11		7.82	11.8
6 - 7		-7.83	10.0
6 - 8		2.54	9.77
6 - 9		2.47	9.56
6 - 10		-0.0494	10.1
6 - 11		1.31	14.8
7 - 8	<*	10.4	4.0
7 - 9	<*	10.3	3.45
7 - 10	<*	7.78	4.8
7 - 11		9.14	11.8
8 - 9		-0.0739	2.67
8 - 10		-2.59	4.27
8 - 11		-1.23	11.6
9 - 10		-2.52	3.76
9 - 11		-1.16	11.4
10 - 11		1.36	11.9

* denotes a statistically significant difference. An asterisk has been placed next to 27 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 4 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

3.3. The highest ESP in a profile per soil class

Method: 95.0 percent Bonferroni

Soil Class	*Count*	*Mean*	*Homogeneous Groups*
10 = Lithosols	1600	3.54	X
9 = Apedal	4570	4.02	X
8 = Plinthic	1044	4.21	X
6 = Vertic	232	5.3	XX
4 = Pedocutanic and Red Structured	1460	6.62	X
11 = Podzolic	31	7.05	XXX
3 = Calcic	451	12.3	XX
5 = Prismacutanic	440	13.4	X
2 = Neocutanic	1050	13.9	X
7 = Hydromorphic	655	14.1	X
1 = Alluvial and Aeolian	179	20.8	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		6.94	7.89
1 - 3		8.47	8.62
1 - 4	<*	14.2	7.73
1 - 5		7.41	8.65
1 - 6	<*	15.5	9.71
1 - 7		6.72	8.23
1 - 8	<*	16.6	7.89
1 - 9	<*	16.8	7.43
1 - 10	<*	17.3	7.69

1 - 11		13.8	19.0
2 - 3		1.53	5.49
2 - 4	<*	7.26	3.95
2 - 5		0.468	5.54
2 - 6	<*	8.58	7.08
2 - 7		-0.216	4.86
2 - 8	<*	9.67	4.26
2 - 9	<*	9.86	3.34
2 - 10	<*	10.3	3.88
2 - 11		6.82	17.8
3 - 4	<*	5.73	5.26
3 - 5		-1.06	6.54
3 - 6		7.05	7.88
3 - 7		-1.74	5.97
3 - 8	<*	8.14	5.5
3 - 9	<*	8.33	4.82
3 - 10	<*	8.81	5.2
3 - 11		5.29	18.1
4 - 5	<*	-6.79	5.31
4 - 6		1.32	6.9
4 - 7	<*	-7.48	4.59
4 - 8		2.41	3.95
4 - 9		2.6	2.93
4 - 10		3.08	3.53
4 - 11		-0.436	17.7
5 - 6	<*	8.11	7.92
5 - 7		-0.684	6.01
5 - 8	<*	9.2	5.55
5 - 9	<*	9.39	4.87
5 - 10	<*	9.87	5.25
5 - 11		6.36	18.1
6 - 7	<*	-8.79	7.46
6 - 8		1.09	7.08
6 - 9		1.28	6.57
6 - 10		1.76	6.86
6 - 11		-1.75	18.7
7 - 8	<*	9.89	4.86
7 - 9	<*	10.1	4.08
7 - 10	<*	10.6	4.53
7 - 11		7.04	17.9
8 - 9		0.188	3.35
8 - 10		0.669	3.88
8 - 11		-2.85	17.8
9 - 10		0.481	2.83
9 - 11		-3.03	17.6
10 - 11		-3.52	17.7

* denotes a statistically significant difference. An asterisk has been placed next to 24 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 3 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

APPENDIX D: Multiple range tests for pH$_{(water)}$.

4.1. pH$_{water}$ per soil class for topsoil horizons.

Method: 95.0 percent Bonferroni

Soil Class	***Count***	***Mean***	***Homogeneous Groups***
11 = Podzolic	28	5.67	XX
8 = Plinthic	731	6.0	X
9 = Apedal	3263	6.17	X
10 = Lithosols	1509	6.41	X
7 = Hydromorphic	599	6.42	X
5 = Prismacutanic	420	6.55	XX
4 = Pedocutanic and Red Structured	1162	6.7	X
2 = Neocutanic	930	7.25	X
6 = Vertic	274	7.73	X
1 = Alluvial and Aeolian	189	7.77	X
3 = Calcic	418	7.96	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	0.527	0.278
1 - 3		-0.186	0.305
1 - 4	<*	1.08	0.273
1 - 5	<*	1.22	0.305
1 - 6		0.0462	0.329
1 - 7	<*	1.35	0.291
1 - 8	<*	1.77	0.284
1 - 9	<*	1.61	0.261
1 - 10	<*	1.37	0.269
1 - 11	<*	2.11	0.706
2 - 3	<*	-0.714	0.205
2 - 4	<*	0.548	0.153
2 - 5	<*	0.698	0.205
2 - 6	<*	-0.481	0.24
2 - 7	<*	0.827	0.183
2 - 8	<*	1.24	0.172
2 - 9	<*	1.08	0.13
2 - 10	<*	0.84	0.145
2 - 11	<*	1.58	0.668
3 - 4	<*	1.26	0.199
3 - 5	<*	1.41	0.241
3 - 6		0.233	0.271
3 - 7	<*	1.54	0.222
3 - 8	<*	1.96	0.214
3 - 9	<*	1.79	0.181
3 - 10	<*	1.55	0.193
3 - 11	<*	2.29	0.68
4 - 5		0.15	0.198
4 - 6	<*	-1.03	0.234
4 - 7	<*	0.279	0.175
4 - 8	<*	0.695	0.165
4 - 9	<*	0.531	0.119
4 - 10	<*	0.293	0.136
4 - 11	<*	1.03	0.666
5 - 6	<*	-1.18	0.271
5 - 7		0.129	0.222
5 - 8	<*	0.545	0.213
5 - 9	<*	0.381	0.181
5 - 10		0.143	0.192
5 - 11	<*	0.883	0.68
6 - 7	<*	1.31	0.254
6 - 8	<*	1.72	0.247
6 - 9	<*	1.56	0.219

6 - 10	<*	1.32	0.229
6 - 11	<*	2.06	0.691
7 - 8	<*	0.416	0.192
7 - 9	<*	0.251	0.155
7 - 10		0.0134	0.168
7 - 11	<*	0.753	0.674
8 - 9	<*	-0.165	0.143
8 - 10	<*	-0.403	0.157
8 - 11		0.337	0.671
9 - 10	<*	-0.238	0.108
9 - 11		0.502	0.661
10 - 11	<*	0.74	0.665

* denotes a statistically significant difference. An asterisk has been placed next to 46 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 6 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences

4.2. pH_{water} per soil class for subsoil horizons.

Method: 95.0 percent Bonferroni

Soil Class	*Count*	*Mean*	*Homogeneous Groups*
11 =Podzolic	58	5.71	X
8 = Plinthic	1251	6.07	X
9 = Apedal	4807	6.15	X
10 = Lithosols	580	6.63	X
7 = Hydromorphic	688	6.7	X
4 = Pedocutanic and Red Structured	1561	7.06	X
5 = Prismacutanic	638	7.42	X
1 = Alluvial and Aeolian	180	7.66	XX
2 = Neocutanic	1430	7.69	X
6 = Vertic	87	8.05	XX
3 = Calcic	536	8.31	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-0.0355	0.28
1 - 3	<*	-0.651	0.305
1 - 4	<*	0.597	0.278
1 - 5		0.243	0.298
1 - 6		-0.387	0.462
1 - 7	<*	0.963	0.296
1 - 8	<*	1.59	0.282
1 - 9	<*	1.51	0.269
1 - 10	<*	1.03	0.302
1 - 11	<*	1.94	0.534
2 - 3	<*	-0.616	0.179
2 - 4	<*	0.632	0.129
2 - 5	<*	0.279	0.168
2 - 6		-0.351	0.391
2 - 7	<*	0.999	0.164
2 - 8	<*	1.63	0.137
2 - 9	<*	1.54	0.107
2 - 10	<*	1.07	0.174
2 - 11	<*	1.98	0.474
3 - 4	<*	1.25	0.177
3 - 5	<*	0.894	0.207
3 - 6		0.264	0.409
3 - 7	<*	1.61	0.204
3 - 8	<*	2.24	0.183
3 - 9	<*	2.16	0.161
3 - 10	<*	1.68	0.212
3 - 11	<*	2.6	0.489
4 - 5	<*	-0.354	0.166

4 - 6	<*	-0.983	0.39
4 - 7	<*	0.366	0.162
4 - 8	<*	0.995	0.134
4 - 9	<*	0.91	0.103
4 - 10	<*	0.434	0.172
4 - 11	<*	1.35	0.473
5 - 6	<*	-0.63	0.404
5 - 7	<*	0.72	0.194
5 - 8	<*	1.35	0.172
5 - 9	<*	1.26	0.149
5 - 10	<*	0.788	0.203
5 - 11	<*	1.7	0.485
6 - 7	<*	1.35	0.402
6 - 8	<*	1.98	0.392
6 - 9	<*	1.89	0.383
6 - 10	<*	1.42	0.407
6 - 11	<*	2.33	0.6
7 - 8	<*	0.629	0.168
7 - 9	<*	0.544	0.144
7 - 10		0.0676	0.199
7 - 11	<*	0.982	0.484
8 - 9		-0.0849	0.112
8 - 10	<*	-0.561	0.178
8 - 11		0.353	0.475
9 - 10	<*	-0.476	0.155
9 - 11		0.438	0.467
10 - 11	<*	0.914	0.487

* denotes a statistically significant difference. An asterisk has been placed next to 46 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 6 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

4.3. The highest pH_{water} values in a profile per soil class

Method: 95.0 percent Bonferroni

Soil Class	***Count***	***Mean***	***Homogeneous Groups***
11 = Podzolic	31	5.82	XXX
8 = Plinthic	1044	5.84	X
9 = Apedal	4570	5.97	X
10 = Lithosols	1600	6.26	X
7 = Hydromorphic	655	6.36	X
4 = Pedocutanic and Red Structured	1460	6.63	X
6 = Vertic	232	7.21	X
5 = Prismacutanic	440	7.35	X
2 = Neocutanic	1050	7.58	X
1 = Alluvial and Aeolian	179	7.72	X
3 = Calcic	451	8.4	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		0.136	0.454
1 - 3	<*	-0.678	0.496
1 - 4	<*	1.09	0.445
1 - 5		0.372	0.498
1 - 6		0.508	0.559
1 - 7	<*	1.36	0.474
1 - 8	<*	1.88	0.455
1 - 9	<*	1.75	0.428
1 - 10	<*	1.46	0.443
1 - 11	<*	1.9	1.09
2 - 3	<*	-0.815	0.316
2 - 4	<*	0.955	0.227

2 - 5		0.235	0.319
2 - 6		0.372	0.408
2 - 7	<*	1.22	0.28
2 - 8	<*	1.74	0.246
2 - 9	<*	1.61	0.192
2 - 10	<*	1.33	0.223
2 - 11	<*	1.76	1.02
3 - 4	<*	1.77	0.303
3 - 5	<*	1.05	0.376
3 - 6	<*	1.19	0.454
3 - 7	<*	2.04	0.344
3 - 8	<*	2.55	0.317
3 - 9	<*	2.43	0.277
3 - 10	<*	2.14	0.3
3 - 11	<*	2.58	1.04
4 - 5	<*	-0.72	0.306
4 - 6	<*	-0.584	0.397
4 - 7	<*	0.265	0.264
4 - 8	<*	0.785	0.228
4 - 9	<*	0.656	0.169
4 - 10	<*	0.372	0.203
4 - 11		0.808	1.02
5 - 6		0.136	0.456
5 - 7	<*	0.985	0.346
5 - 8	<*	1.5	0.319
5 - 9	<*	1.38	0.28
5 - 10	<*	1.09	0.302
5 - 11	<*	1.53	1.04
6 - 7	<*	0.849	0.429
6 - 8	<*	1.37	0.408
6 - 9	<*	1.24	0.378
6 - 10	<*	0.956	0.395
6 - 11	<*	1.39	1.07
7 - 8	<*	0.52	0.28
7 - 9	<*	0.39	0.235
7 - 10		0.107	0.261
7 - 11		0.543	1.03
8 - 9		-0.129	0.193
8 - 10	<*	-0.412	0.224
8 - 11		0.0234	1.02
9 - 10	<*	-0.283	0.163
9 - 11		0.153	1.01
10 - 11		0.436	1.02

* denotes a statistically significant difference. An asterisk has been placed next to 42 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level. At the top of the page, 5 homogenous groups are identified using columns of X's. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences.

APPENDIX E: GEOLOGICAL UNITS ELECTRICAL CONDUCTIVITY (mS m^{-1})

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Alexandria Formation	14	153	106	136	62	170
Allanridge Formation	80	57	32	96	22	58
Alldays Gneiss	305	105	27	294	16	49
Alluvium Sand and Calcrete	1595	321	59	882	25	196
Alma Formation	10	8	8	3	7	9
Amsterdam Formation	5	18	16	6	14	20
Augrabies Gneiss	46	49	24	89	20	32
Barberton Supergroup	77	35	32	24	23	41
Baderoukwe Granite	1	54	54		54	54
Bandelierskop Complex	16	58	34	89	17	52
Basement Complex	456	33	19	53	11	36
Beaufort Group	1987	81	29	286	18	65
Berea Formation	66	21	17	13	11	26
Bidouw Subgroup	54	155	58	397	26	108
Bierkraal Magnetite Gabbro	90	60	49	45	36	59
Black Reef Formation	16	35	32	27	17	38
Bloempoort Group	5	73	90	34	37	94
Bokkeveld Group	56	625	117	1810	40	241
Bosbokpoort Formation	10	18	18	7	16	20
Bothaville Formation	11	24	13	23	4	41
Brandwacht Formation	7	65	27	56	20	129
Bredasdorp Group	17	185	45	294	15	225
Bulai Gneiss	26	117	40	222	28	49
Bumbeni Complex	19	79	41	111	15	79
Cape Granite Suite	102	301	32	922	12	70
Central Rand Group	5	39	34	21	34	50
Ceres Subgroup	123	151	49	331	17	159
Clarens Formation	200	269	41	817	20	152
Clermont Formation	9	15	7	16	6	12
Croydon Subsuite	40	78	39	115	12	63
Cunning Moor Tonalite	43	47	26	85	13	39
Dabreek Formation	2	11	11	0.4	11	12
Damwal Formation	17	17	14	11	10	20
Daspoort Formation	8	24	23	17	9	39
Dennilton Formation	3	28	26	7	22	36
Dominion Group	6	34	32	21	32	38
Drakensberg Group	156	35	22	40	11	37
Dsjate Subsuite	48	59	43	46	29	71
Duitschland Formation	2	59	59	-	59	59
Dwars River Subsuite	22	101	71	81	38	140
Dwyka Group	753	149	22	764	12	41
Ecca Group	463	104	23	420	16	41
Eendoorn Granite	39	188	45	381	28	100
Elliot Formation	153	31	17	41	12	27
Emakwezini Formation	129	98	41	149	32	87
Enon Formation	66	504	175	923	64	471
Fig Tree Group	9	39	28	42	16	39
Fort Brown Formation	78	257	70	530	36	167
Franschhoek Formation	2	26	26	16	15	37
Fundudzi Formation	7	20	14	16	13	25
Gaborone Granite	10	168	39	298	19	59
Gamtoos Group	6	12	12	2	11	12
Garies Subgroup	11	1060	275	1990	45	320
Geelvloer Group	32	88	28	118	21	87
Ghaap Group	27	23	22	14	12	31
Gifberg Group	16	144	31	321	18	53
Giyani Group	10	72	41	59	41	125
Gladkop Suite	9	796	365	800	95	1500
Godwan Group	3	13	14	5	6	17

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Goudplaats Gneiss	357	84	28	262	15	45
Government Subgroup	10	65	11	120	8	26
Grasvally Norite-Anorthosite	43	21	14	20	11	24
Gravelotte Group	7	50	39	47	16	74
Groblershoop Formation	4	44	44	8	37	51
Grootderm Formation	9	227	111	292	75	125
Gumbu Group	13	388	39	1190	28	59
Halfway House Granite	3	28	20	21	12	51
Harmony Granite	3	1780	27	3050	18	5300
Hebron Pluton	4	12	7	12	5	18
Hekpoort Formation	95	35	21	62	13	32
Hlobane Complex	11	93	81	38	69	94
Hoogoor Suite	5	394	410	287	115	676
Hospital Hill Subgroup	5	24	14	16	13	41
Hout River Gneiss	120	82	28	341	19	43
Irrigasie Formation	19	153	28	394	16	67
Jeppestown Subgroup	9	75	36	80	34	54
Jozini Formation	60	246	76	503	42	187
Kaaimans Group	4	33	39	20	18	49
Kaap Valley Tonalite	31	20	16	16	8	23
Kalahari Group	190	69	22	331	12	40
Kameeldoorns Formation	4	29	30	11	21	37
Kango Group	2	39	39	16	28	50
Karoo	203	114	32	298	11	60
Karoo Dolerite Suite	940	55	23	119	13	41
Kirkwood Formation	38	289	117	368	60	360
Klipriviersberg Group	15	31	18	22	16	40
Knersvlakte Subgroup	10	1890	825	2240	220	3610
Koedoesberg Formation	9	58	33	60	27	40
Kookfontein Formation	4	89	83	50	55	122
Korannaland Group	12	36	35	10	30	40
Koras Group	3	33	23	23	16	59
Kraaipan Group	2	28	28	10	21	35
Lake Mentz Subgroup	21	404	49	797	32	157
Lakenvalei Formation	10	30	19	27	12	36
Lebowa Granite Suite	210	62	29	142	18	50
Lekkersmaak Granite	5	343	34	703	24	49
Leococratic Biotite Granite	12	8	8	3	6	11
Letaba Formation	352	197	62	394	36	169
Leucocratic Biotite Granite	45	24	20	21	12	26
Leucocratic Biotite Granite	2	47	47	40	19	76
Leydsdorp Formation	5	46	39	13	36	59
Little Namaqualand Suite	205	366	32	1240	23	59
Loskop Formation	10	16	17	5	11	18
Magaliesberg Formation	36	75	30	142	20	50
Makeckaan Subgroup	6	19	15	16	7	28
Makwassie Formation	11	59	59	13	54	59
Malala Drift Group	284	118	32	396	23	45
Malmani Subgroup	161	37	20	71	12	32
Malmesbury Group	7	121	59	168	2	310
Mapumulo Group	202	33	22	53	13	36
Mashashane Suite	5	25	28	10	18	28
Matlabas Subgroup	119	60	27	111	12	49
Matok Granite	7	24	24	8	14	30
Mbotyi Formation	1	18	18	0	18	18
Meinhardskraal Granite	3	12	12	1	11	12
Messina Suite	34	110	34	310	18	41
Metanorite-Gabbro	35	34	23	39	11	45
Modipe Complex	13	144	30	276	28	59
Molteno Formation	552	40	18	72	11	36
Moodies Group	14	41	35	26	22	54
Moorreesburg Formation	38	194	60	251	15	310

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Mount Dowe Group	86	46	32	77	23	45
Mozaan Group	192	72	28	148	20	45
Mpluze Granite	150	25	12	60	6	19
Mulati Formation	8	51	40	33	33	58
Muzi Formation	25	45	28	38	16	70
Mzimkulu Group	1	13	13	0	13	13
Nama Group	12	180	206	97	125	244
Nanaga Formation	74	59	36	64	23	61
Nardouw Subgroup	162	101	26	255	13	49
Natal Group	384	27	17	72	10	26
Nelspruit Suite	87	29	16	76	9	28
Ngoye Complex	12	69	59	24	51	83
Nondweni Group	9	23	18	17	11	41
Nsuze Group	67	42	30	37	16	49
Ntabene Formation	27	148	75	138	64	194
Nyoka Formation	13	185	143	168	93	224
Nzhelele Formation	9	115	53	140	39	131
Olifantshoek Super Group	3	11	13	4	6	13
Ongeluk Formation	14	419	37	1140	30	59
Onverwacht Group	27	124	45	251	30	76
Palala Granite	8	67	59	33	54	71
Palmietfontein Granite	3	10	10	2	8	12
Penge Formation	4	74	79	46	35	113
Peninsula Formation	59	31	18	50	9	34
Piekenierskloof Formation	1	24	24	0	24	24
Pienaars River Subprovince	11	61	58	21	49	90
Pietermaritzburg Formation	569	55	28	108	14	49
Pietersburg Group	36	34	30	25	15	45
Piketberg Formation	11	58	20	89	13	67
Pilanessberg Complex	6	38	37	26	15	54
Porseleinberg Formation	9	40	36	27	22	38
Port Durnford Formation	3	11	9	3	9	13
Port Nolloth Group	13	490	125	908	103	170
Porterville Formation	59	163	91	178	26	261
Post-Transvaal Diabases	59	39	26	47	20	36
Pretoria Group	66	26	18	29	12	27
Prince Albert Formation	57	1040	177	1610	49	1680
Pyramid Gabbronorite	34	105	89	66	50	168
Rashoop Granophyre Suite	31	21	17	12	10	30
Raytonn Formation	14	58	39	50	32	59
Richtersveld Subprovince	18	509	68	1220	41	159
Rietgat Formation	8	33	21	28	18	40
Rooiwater Complex	3	52	41	21	39	76
Roossenkal Subsuite	91	79	45	105	28	103
Salisbury Kop Pluton	15	110	45	262	19	70
Sand River Gneiss	18	90	34	146	17	41
Schiel Alkaline Complex	4	21	21	5	18	23
Schrikkloof Formation	1	16	16	0	16	16
Selons River Formation	38	26	23	16	13	36
Silverton Formation	101	46	32	58	20	49
Solitude Formation	11	71	41	78	21	59
Soutpansberg Group	34	32	33	20	20	45
Spektakel Suite	15	338	82	624	34	132
Spitskop Complex	2	50	50	16	39	61
Steenkampsberg Formation	19	14	12	9	7	19
Strubenkop Formation	3	38	34	24	17	64
Sundays River Formation	57	349	152	483	75	374
Swaershoek Formation	8	12	10	6	7	17
Syenite	13	75	36	130	26	45
Tarkastad Subgroup	1822	51	23	107	14	40
Tierberg Formation	6	100	85	63	49	120
Timbavati Gabbro	9	219	51	518	28	54

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Timeball Hill Formation	108	36	23	38	12	41
Traka Subgroup	6	186	121	151	61	360
Tugela Group	55	49	36	42	17	67
Turffontein Subgroup	7	47	60	24	24	67
Turfloop Granite	46	44	30	50	19	41
Tygerberg Formation	9	48	41	39	20	49
Uloa Formation	5	52	35	32	32	60
Unnamed Granite and Gneiss	12	296	69	548	35	220
Usushwana Complex	5	11	12	4	9	12
Utrecht Granite	2	8	8	0	8	8
Vaalkoppies Group	5	78	26	88	18	113
Vaalputs Granite	4	32	30	17	18	46
Vaalwater Formation	11	14	13	7	7	20
Ventersdorp Supergroup	30	176	26	382	15	67
Vermont Formation	18	32	22	28	14	40
Villa Norra Anorthosite	25	138	99	177	59	170
Vlakfontein Subsuite	26	86	43	81	23	147
Volksrust Formation	795	147	38	503	20	84
Vryheid Formation	1292	47	23	87	12	41
Waterberg Group	99	56	21	157	10	41
Waterford Formation	12	354	101	478	57	528
Weltevrede Subgroup	76	187	43	668	26	121
Whitehill Formation	15	4890	2720	6330	66	9950
Wilge River Formation	123	17	10	38	4	18
Witwatersrand Supergroup	2	12	12	1	12	13
Wolkberg Group	8	13	9	11	7	16
Wyllies Poort Formation	48	42	12	79	6	35
Zoetveld Subsuite	2	17	17	6	13	21
Zululand Group	126	133	54	247	29	100

APPENDIX F: GROUNDWATER REGIONS ELECTRICAL CONDUCTIVITY (mS m^{-1})

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Algoa Basin	204	226	84	361	45	227
Bredasdorp Coastal Belt	9	137	45	250	22	67
Bushmanland	408	143	32	416	22	55
Bushmanland Pan Belt	112	1060	109	2890	37	466
Central Highveld	169	41	25	60	15	45
Central Pan Belt	304	355	59	900	36	128
Ciskeian Coastal Foreland and Middleveld	1431	78	32	144	21	66
Dry Harts-Vaal-Orange	463	304	100	586	43	262
Eastern Bankeveld	515	46	24	79	12	44
Eastern Bushveld Complex	430	53	33	76	19	54
Eastern Great Karoo	162	224	76	445	41	139
Eastern Highveld	811	56	30	78	17	59
Eastern Kalahari	87	25	16	27	10	32
Eastern Upper Karoo	113	128	49	258	36	107
Ghaap Plateau	34	45	24	76	20	36
Grootrivier-Klein Winterhoek-Suurberg	100	131	50	202	31	131
Hantam	36	438	119	713	45	589
Intermontane Tulbagh-Ashton Valley	45	258	84	491	48	200
Karst Belt	59	52	23	85	14	36
Knersvlakte	68	1070	161	1570	28	1770
KwaZulu-Natal Coastal Foreland	940	35	20	102	12	36
Limpopo Granulite Gneiss Belt	927	98	32	313	20	49
Limpopo Karoo Basin	237	316	54	776	36	269
Lower Gamtoos Valley	17	128	90	127	49	151
Lowveld	770	61	22	268	12	39
Makoppa Dome	174	69	36	121	23	59
Middelburg Basin	274	13	8	27	3	15
Namaqualand	197	535	95	1380	41	310
Northeastern Middleveld	1466	40	20	123	12	36
Northeastern Pan Belt	180	113	41	234	25	93
Northeastern Upper Karoo	404	94	49	110	30	120
Northern Bushveld Complex	18	28	17	29	12	36
Northern Highland	138	56	30	54	16	80
Northern Lebombo	221	169	55	360	33	137
Northern Zululand Coastal Plain	369	103	32	270	17	79
Northwestern Cape Ranges	192	263	24	749	11	145
Northwestern Middleveld	1430	29	17	45	9	32
Oudtshoorn Basin	23	709	76	1200	36	560
Outenikwa Coastal Foreland	42	143	40	353	27	70
Pietersburg Plateau	312	69	28	238	17	45
Richtersveld	88	1010	355	1330	109	1720
Ruensveld	146	586	111	1840	36	274
Southern Cape Ranges	220	105	36	267	19	80
Southern Highland	688	36	18	65	11	32
Southern Highveld	106	103	76	122	36	120
Southern Lebombo	757	135	54	225	36	135
Southwestern Cape Ranges	85	163	28	396	13	134
Southwestern Coastal Sandveld	67	148	28	328	11	96
Soutpansberg	102	46	24	72	9	45
Soutpansberg Hinterland	49	190	32	622	20	49
Springbok Flats	158	111	44	193	23	141
Stilbaai Coastal Belt	5	25	15	24	13	23
Swartland	184	166	37	563	13	111
Tanqua Karoo	83	1480	785	2090	126	1890
Transkeian Coastal Foreland and Middleve	2035	25	17	60	11	26
Waterberg Coal Basin	87	131	36	325	12	50

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Waterberg Plateau	333	50	22	112	10	45
West Griqualand	36	175	22	720	13	37
Western Bankeveld and Marico Bushveld	217	37	26	38	17	41
Western Bushveld Complex	205	81	49	119	36	90
Western Great Karoo	60	447	96	997	54	230
Western Highveld	152	108	32	308	20	59
Western Kalahari	76	530	24	1920	14	41
Western Upper Karoo	72	263	39	1060	30	57

APPENDIX G: Geological units ESP

Geological Units	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Alexandria Formation	14	8.59	6.53	6.62	4.95	11.10
Allanridge Formation	82	3.63	1.09	13.30	0.27	2.00
Alldays Gneiss	305	7.38	1.85	21.10	0.98	2.94
Alluvium Sand and Calcrete	1618	15.10	4.84	36.60	1.71	13.80
Alma Formation	10	2.21	0.92	2.36	0.67	5.00
Amsterdam Formation	5	1.67	1.34	0.93	1.18	1.39
Augrabies Gneiss	46	4.04	1.63	9.86	0.79	3.56
Barberton Supergroup	77	1.76	1.52	1.64	0.78	2.38
Bandelierskop Complex	16	2.96	2.84	1.51	1.61	3.71
Basement Complex	384	4.58	1.72	15.40	0.90	3.23
Beaufort Group	2305	4.59	2.04	10.20	1.06	4.26
Berea Formation	51	5.17	3.45	4.82	2.70	6.25
Bidouw Subgroup	32	16.30	7.96	18.90	5.04	19.80
Bierkraal Magnetite Gabbro	90	2.65	0.97	5.18	0.66	2.04
Black Reef Formation	18	1.67	1.45	1.13	0.82	2.82
Bloempoort Group	4	2.03	2.05	0.73	1.50	2.56
Bokkeveld Group	50	54.50	8.52	241.00	3.62	13.10
Bosbokpoort Formation	10	2.50	2.63	1.36	1.62	3.23
Bothaville Formation	11	1.07	0.59	1.16	0.32	1.33
Brandwacht Formation	7	4.43	1.75	4.34	0.94	9.17
Bredasdorp Group	18	18.60	9.17	23.60	4.55	20.00
Buffelsfontein Group	3	1.18	0.61	1.13	0.45	2.48
Bulai Gneiss	26	16.00	2.04	33.30	1.54	5.56
Bumbeni Complex	13	9.12	5.41	9.44	2.86	11.80
Cape Granite Suite	107	12.10	4.35	25.10	2.30	10.00
Central Rand Group	5	2.53	0.73	2.84	0.59	4.80
Ceres Subgroup	87	10.10	6.43	8.75	3.60	14.30
Chuniespoort Group	2	0.96	0.96	0.19	0.83	1.10
Clarens Formation	198	7.58	2.39	14.30	0.99	6.76
Clermont Formation	9	1.92	0.44	2.99	0.39	0.56
Croydon Subsuite	40	5.54	2.50	9.19	1.04	4.47
Cunning Moor Tonalite	21	4.33	2.86	4.17	1.59	5.88
Dabreek Formation	2	1.59	1.59	0.11	1.52	1.67
Damwal Formation	17	2.00	1.59	2.29	0.31	2.13
Daspoort Formation	8	3.66	4.35	2.13	1.73	5.44
Dennilton Formation	2	5.24	5.24	3.48	2.78	7.69
Dominion Group	6	2.74	2.86	1.42	1.96	3.92
Drakensberg Group	153	1.34	1.05	1.04	0.69	1.67
Dsjate Subsuite	92	2.95	0.90	6.80	0.46	1.96
Duitschland Formation	2	1.70	1.70	1.41	0.70	2.70
Dwars River Subsuite	56	2.19	0.62	4.22	0.32	1.71
Dwyka Group	784	8.60	1.93	56.20	0.83	3.82
Ecca Group	475	5.35	1.79	15.30	1.14	3.15
Eendoorn Granite	39	16.80	6.67	27.10	3.33	13.50
Elliot Formation	138	2.86	1.48	3.87	0.75	2.77
Emakwezini Formation	122	10.80	4.42	14.20	2.67	9.00
Enon Formation	66	24.40	13.70	26.50	6.88	36.90
Fig Tree Group	8	1.38	1.30	0.47	1.00	1.78
Fort Brown Formation	78	18.10	6.75	29.50	3.33	16.80
Franschhoek Formation	4	3.15	2.83	1.65	1.97	4.34
Fundudzi Formation	7	1.33	1.15	0.84	0.81	1.35
Gaborone Granite	10	10.80	3.30	16.60	1.18	10.80
Gamtoos Group	6	2.74	1.60	2.78	1.59	2.38
Garies Subgroup	11	19.50	7.04	23.80	5.17	26.00
Geelvloer Group	32	13.10	4.17	24.80	2.74	7.37
Ghaap Group	29	2.06	1.76	1.62	0.65	3.33
Gifberg Group	18	17.60	3.96	27.90	1.61	18.50

Geological Units	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Giyani Group	10	5.59	1.60	10.00	1.19	2.06
Gladkop Suite	9	32.60	21.60	24.20	12.60	45.70
Godwan Group	3	1.82	1.14	1.27	1.04	3.28
Goudplaats Gneiss	374	5.65	2.24	12.80	1.37	4.22
Government Subgroup	12	1.80	0.22	3.71	0.13	0.48
Grasvally Norite-Anorthosite	43	1.31	0.61	1.93	0.17	1.31
Gravelotte Group	7	1.25	1.52	0.58	0.63	1.64
Groblershoop Formation	4	0.91	0.91	0.03	0.89	0.94
Grootderm Formation	9	12.20	6.10	10.70	4.27	19.40
Gumbu Group	12	4.07	2.81	4.90	1.50	4.29
Halfway House Granite	49	2.17	1.55	3.17	0.99	2.18
Harmony Granite	3	31.70	6.67	44.10	5.88	82.60
Hebron Pluton	3	2.51	2.86	1.04	1.33	3.33
Hekpoort Formation	101	1.16	0.72	1.80	0.38	1.18
Hlobane Complex	11	5.18	4.27	3.34	2.94	6.19
Hoogoor Suite	5	19.40	11.40	13.00	9.31	31.80
Hospital Hill Subgroup	5	0.34	0.21	0.25	0.18	0.50
Hout River Gneiss	113	5.28	2.00	13.70	1.14	3.57
Irrigasie Formation	23	5.18	2.04	8.72	0.94	3.71
Jeppestown Subgroup	15	1.98	1.04	2.75	0.20	2.00
Jozini Formation	36	14.40	5.03	25.50	3.00	18.30
Kaimans Group	4	5.44	6.41	3.18	3.16	7.73
Kaap Valley Tonalite	26	1.98	1.60	1.58	1.16	2.94
Kalahari Group	194	3.90	2.56	6.62	0.91	4.87
Kameeldoorns Formation	4	0.80	0.63	0.76	0.19	1.41
Kango Group	2	2.30	2.30	0.51	1.94	2.67
Karoo	200	3.72	1.45	7.08	0.71	3.49
Karoo Dolerite Suite	1014	3.86	1.33	36.30	0.70	2.60
Kirkwood Formation	38	19.20	9.74	22.00	5.00	25.00
Klipriviersberg Group	13	1.09	0.63	1.07	0.15	1.53
Knersvlakte Subgroup	10	28.90	29.70	13.10	21.60	35.90
Koedoesberg Formation	9	3.75	0.88	7.18	0.43	2.99
Kookfontein Formation	4	4.35	4.63	1.13	3.55	5.14
Korannaland Group	12	0.74	0.74	0.53	0.47	0.82
Kraaipan Group	2	1.45	1.45	0.28	1.25	1.65
Lake Mentz Subgroup	22	10.40	4.55	15.60	2.32	6.43
Lakenvalei Formation	9	1.17	1.14	0.76	0.46	1.56
Lebowa Granite Suite	254	3.13	2.02	5.72	1.27	3.00
Lekkersmaak Granite	5	7.70	3.57	10.40	3.13	3.80
Leococratic Biotite Granite	12	1.10	1.15	0.97	0.13	1.63
Letaba Formation	338	9.78	2.02	39.50	0.90	5.42
Leucocratic Biotite Granite	51	1.38	1.30	0.97	0.72	1.85
Leydsdorp Formation	5	2.88	2.24	1.73	2.06	4.58
Little Namaqualand Suite	205	16.20	3.80	30.10	1.40	10.30
Loskop Formation	11	2.16	0.37	4.65	0.23	1.10
Magaliesberg Formation	36	3.36	1.34	6.86	0.56	2.34
Makeckaan Subgroup	6	2.07	1.04	2.18	0.64	4.67
Makwassie Formation	12	1.57	1.54	1.05	0.90	1.65
Malala Drift Group	275	8.59	2.17	22.70	1.21	3.61
Malmani Subgroup	173	1.35	0.90	1.95	0.25	1.75
Malmesbury Group	7	23.20	15.90	20.10	7.69	50.00
Malmesbury Group	2	3.48	3.48	2.76	1.53	5.42
Mapumulo Group	218	3.61	2.30	6.80	1.40	4.27
Mashashane Suite	5	2.26	2.70	1.20	1.43	3.23
Matlabas Subgroup	119	4.39	1.79	8.80	0.59	4.17
Matok Granite	7	2.82	3.02	1.54	1.83	3.70
Meinhardskraal Granite	3	1.63	0.50	2.05	0.39	4.00
Messina Suite	33	10.50	1.56	23.00	1.30	3.57
Metanorite-Gabbro	34	1.71	0.99	1.76	0.46	2.33
Modipe Complex	13	8.21	2.56	12.60	1.54	6.70

Geological Units	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Molteno Formation	525	3.41	1.54	5.59	0.67	3.57
Moodies Group	14	1.35	1.16	0.53	0.97	1.59
Moorreesburg Formation	43	9.80	5.04	10.60	2.11	16.00
Mount Dowe Group	85	2.71	2.08	2.17	1.33	3.23
Mozaan Group	178	5.02	2.07	8.34	1.29	4.04
Mpluze Granite	148	1.96	0.30	6.77	0.13	0.74
Mulati Formation	6	1.27	1.23	0.29	1.09	1.44
Muzi Formation	20	7.62	7.46	3.75	4.95	10.20
Mzimkulu Group	2	4.68	4.68	2.22	3.11	6.25
Nama Group	12	5.45	2.08	5.72	1.09	9.72
Nanaga Formation	78	7.91	6.25	6.04	3.57	9.97
Nardouw Subgroup	155	8.65	5.88	9.12	2.94	12.30
Natal Group	409	2.52	1.68	3.04	0.97	3.11
Nelspruit Suite	71	3.68	2.17	7.26	1.10	4.13
Ngoye Complex	12	4.21	3.42	2.44	2.64	4.41
Nondweni Group	12	3.02	1.97	3.01	1.26	3.43
Nsuze Group	70	1.71	1.14	2.01	0.81	1.69
Ntabene Formation	26	8.70	5.03	7.63	2.06	15.00
Nyoka Formation	9	17.60	13.80	16.20	2.86	32.80
Nzhelele Formation	8	1.46	0.96	1.44	0.72	1.36
Olifantshoek Super Group	3	0.98	0.32	1.14	0.32	2.29
Ongeluk Formation	14	2.16	1.58	3.14	0.24	2.17
Onverwacht Group	22	5.82	1.63	8.42	1.12	8.04
Palala Granite	8	2.48	2.37	1.24	1.47	3.29
Palmietfontein Granite	3	1.75	1.08	1.19	1.06	3.13
Penge Formation	4	15.20	1.99	27.50	0.42	29.90
Peninsula Formation	62	6.77	4.12	7.12	2.45	8.42
Piekenierskloof Formation	6	11.60	7.27	9.34	4.80	21.60
Pienaars River Subprovince	11	3.42	2.73	1.94	1.94	4.17
Pietermaritzburg Formation	532	3.05	1.75	6.03	1.04	2.91
Pietersburg Group	36	2.54	2.25	1.67	1.45	3.28
Piketberg Formation	13	5.11	4.82	2.71	3.51	6.98
Pilanessberg Complex	8	1.53	1.44	0.78	0.87	2.33
Porseleinberg Formation	12	3.61	3.24	1.85	2.32	5.00
Port Durnford Formation	3	0.43	0.37	0.14	0.33	0.59
Port Nolloth Group	13	33.80	13.80	49.00	9.20	22.00
Porterville Formation	63	13.00	10.70	10.80	4.35	17.10
Post-Transvaal Diabases	67	1.70	1.01	2.86	0.10	1.84
Pretoria Group	67	2.40	1.69	2.76	0.97	2.63
Prince Albert Formation	58	26.10	7.71	41.00	2.19	35.40
Pyramid Gabbronorite	40	4.18	2.00	6.16	0.83	4.21
Rashoop Granophyre Suite	26	1.86	1.60	1.43	0.77	2.50
Raytonn Formation	16	1.25	1.16	0.79	0.66	1.80
Richtersveld Subprovince	19	9.31	5.88	7.69	3.37	14.20
Rietgat Formation	8	0.86	0.80	0.58	0.36	1.39
Rooiwater Complex	3	1.28	1.26	0.37	0.92	1.65
Roossenkal Subsuite	106	2.33	1.90	2.28	0.81	2.86
Salisbury Kop Pluton	15	5.27	1.11	10.70	0.46	2.92
Sand River Gneiss	18	3.80	3.45	1.91	2.38	4.62
Schiel Alkaline Complex	4	1.05	1.09	0.32	0.81	1.29
Selons River Formation	34	1.26	0.76	1.32	0.44	1.87
Silverton Formation	82	1.00	0.85	0.99	0.15	1.28
Solitude Formation	11	4.48	2.50	6.42	1.82	3.58
Soutpansberg Group	33	1.68	1.61	1.21	0.98	1.94
Spektakel Suite	15	17.70	7.84	21.70	2.84	22.20
Spitskop Complex	3	1.26	0.82	0.94	0.62	2.34
Steenkampsberg Formation	14	1.20	0.32	1.68	0.16	1.72
Sundays River Formation	57	17.90	10.90	16.10	4.88	25.50
Swaershoek Formation	8	2.33	0.83	3.31	0.45	2.94
Syenite	15	3.72	1.59	5.19	1.14	3.85

Geological Units	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Tarkastad Subgroup	1886	3.68	1.42	7.14	0.64	3.43
Tierberg Formation	6	2.17	2.38	0.53	1.56	2.59
Timbavati Gabbro	4	60.60	8.45	110.00	0.57	121.00
Timeball Hill Formation	105	1.26	0.93	1.11	0.43	1.93
Traka Subgroup	7	2.57	2.04	1.67	1.90	2.22
Tugela Group	69	2.51	2.02	2.12	1.54	2.67
Turffontein Subgroup	7	3.45	4.21	3.29	0.32	5.60
Turfloop Granite	52	13.60	2.05	49.70	1.22	4.30
Tygerberg Formation	15	5.97	3.64	5.92	1.11	8.05
Unnamed Granite and Gneiss	12	13.60	8.36	13.10	2.76	20.60
Usushwana Complex	5	1.25	1.18	0.65	0.81	1.41
Utrecht Granite	2	0.42	0.42	0.11	0.34	0.49
Vaalkoppies Group	5	2.47	2.86	1.27	2.70	3.17
Vaalputs Granite	4	2.45	2.79	1.75	1.03	3.88
Vaalwater Formation	11	3.68	3.13	3.79	0.39	7.14
Ventersdorp Supergroup	31	7.84	1.69	15.70	0.80	3.77
Vermont Formation	13	0.86	0.25	1.41	0.14	0.89
Villa Norra Anorthosite	25	9.27	0.79	25.50	0.36	1.47
Vlakfontein Subsuite	20	2.83	1.48	4.89	0.82	2.54
Volksrust Formation	933	5.88	1.69	24.60	0.95	3.36
Vryheid Formation	1484	3.88	1.65	6.87	0.70	3.64
Waterberg Group	106	3.39	1.80	7.16	0.50	3.57
Waterford Formation	13	16.20	12.70	13.30	6.49	19.10
Weltevrede Subgroup	78	11.40	6.67	27.40	3.66	11.50
Whitehill Formation	15	72.90	79.80	70.20	2.97	118.00
Wilge River Formation	131	3.63	0.56	13.00	0.33	1.67
Witwatersrand Supergroup	2	3.79	3.79	0.30	3.57	4.00
Wolkberg Group	8	1.05	1.38	0.78	0.15	1.59
Wyllies Poort Formation	51	4.39	1.22	14.30	0.82	2.38
Zoetveld Subsuite	2	0.56	0.56	0.14	0.47	0.66
Zululand Group	109	7.47	4.17	8.66	2.22	9.74

APPENDIX H: Groundwater Regions ESP

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Algoa Basin	218	14.40	8.74	16.00	3.96	17.70
Bredasdorp Coastal Belt	9	13.00	10.00	14.20	4.55	17.50
Bushmanland	417	11.30	3.28	23.70	1.06	7.14
Bushmanland Pan Belt	105	20.80	5.71	41.20	2.33	12.20
Central Highveld	236	1.61	0.97	2.52	0.25	2.06
Central Pan Belt	320	12.30	2.00	37.00	1.12	6.51
Ciskeian Coastal Foreland and Middleveld	1563	5.75	2.37	10.70	1.15	5.85
Dry Harts-Vaal-Orange	466	12.30	6.34	15.00	2.33	16.00
Eastern Bankeveld	488	2.20	1.09	4.68	0.52	2.02
Eastern Bushveld Complex	529	2.55	1.77	4.23	0.78	2.83
Eastern Great Karoo	160	10.30	4.28	20.70	2.02	9.42
Eastern Highveld	802	2.90	1.52	4.37	0.55	3.34
Eastern Kalahari	88	3.44	3.50	2.35	1.36	5.43
Eastern Upper Karoo	110	7.30	1.65	19.30	0.73	3.43
Ghaap Plateau	36	2.03	0.77	3.61	0.14	2.25
Grootrivier-Klein Winterhoek-Suurberg	104	7.86	5.41	7.17	3.23	9.55
Hantam	33	14.40	8.33	19.00	2.97	16.10
Intermontane Tulbagh-Ashton Valley	45	16.80	11.00	18.40	5.62	15.90
Karst Belt	72	1.78	1.00	2.64	0.25	2.05
Knersvlakte	71	22.10	14.50	22.10	4.55	35.00
KwaZulu-Natal Coastal Foreland	1059	3.14	2.08	5.17	1.20	3.45
Limpopo Granulite Gneiss Belt	914	6.76	1.97	18.80	1.15	3.33
Limpopo Karoo Basin	233	8.95	4.02	14.00	2.13	8.82
Lower Gamtoos Valley	17	10.90	8.16	9.67	4.73	11.10
Lowveld	697	5.28	2.00	16.40	1.19	3.56
Makoppa Dome	179	2.82	1.39	6.08	0.73	2.38
Middelburg Basin	312	1.99	0.51	8.58	0.36	0.83
Namaqualand	198	18.60	10.20	22.60	4.33	26.20
Northeastern Middleveld	1444	2.76	1.42	5.99	0.74	2.51
Northeastern Pan Belt	205	3.36	1.89	4.55	1.04	3.37
Northeastern Upper Karoo	405	5.29	2.50	8.21	1.33	6.33
Northern Bushveld Complex	18	3.01	2.49	2.88	0.43	3.94
Northern Highland	134	3.20	2.02	3.80	1.35	3.13
Northern Lebombo	170	11.20	2.38	51.10	1.18	5.26
Northern Zululand Coastal Plain	271	7.90	4.17	12.50	2.55	9.09
Northwestern Cape Ranges	152	20.80	7.14	46.90	2.48	16.50
Northwestern Middleveld	2190	3.73	1.42	26.60	0.76	2.74
Oudtshoorn Basin	24	27.70	10.50	33.60	7.77	39.80
Outenikwa Coastal Foreland	39	9.51	6.45	7.41	4.35	11.90
Pietersburg Plateau	311	6.19	2.22	22.80	1.10	4.00
Richtersveld	88	59.80	27.60	90.70	7.92	78.50
Ruensveld	101	44.80	11.20	175.00	5.97	20.30
Southern Cape Ranges	233	9.92	6.45	10.20	3.68	12.50
Southern Highland	647	2.76	1.35	4.49	0.65	2.83
Southern Highveld	100	6.62	4.14	6.44	2.28	9.37
Southern Lebombo	514	10.00	4.35	13.30	2.31	11.30
Southwestern Cape Ranges	82	14.50	7.13	18.80	3.33	17.20
Southwestern Coastal Sandveld	81	14.60	6.67	21.30	3.72	15.20
Soutpansberg	105	3.03	1.20	10.10	0.90	2.04
Soutpansberg Hinterland	44	9.26	0.92	37.40	0.34	1.84
Springbok Flats	224	3.42	1.31	6.22	0.60	2.86
Stilbaai Coastal Belt	5	6.23	6.25	3.21	4.88	8.33
Swartland	220	9.08	4.46	14.00	2.30	10.60
Tanqua Karoo	83	59.30	25.40	125.00	10.60	50.00
Transkeian Coastal Foreland	2039	2.22	1.25	3.80	0.64	2.23
Waterberg Coal Basin	87	6.42	1.25	19.00	0.50	2.83
Waterberg Plateau	344	3.23	1.73	5.83	0.59	3.48
West Griqualand	36	2.37	1.84	2.37	0.72	3.33

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Western Bankeveld and Marico Bushveld	220	1.40	0.78	3.37	0.19	1.70
Western Bushveld Complex	234	3.58	1.31	8.11	0.66	2.66
Western Great Karoo	63	18.60	5.26	34.10	2.91	15.40
Western Highveld	157	4.16	1.25	12.40	0.31	2.50
Western Kalahari	66	34.70	3.22	148.00	1.27	5.39
Western Upper Karoo	70	6.00	2.69	12.60	1.15	5.26

APPENDIX I: Geological units soil $\mathrm{PH}_{\mathrm{water}}$

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Alexandria Formation	14	7.81	7.90	0.82	7.30	8.20
Allanridge Formation	84	6.99	6.60	0.92	6.37	7.40
Alldays Gneiss	305	7.02	6.90	1.12	6.20	7.90
Alluvium Sand and Calcrete	1689	7.61	7.90	1.21	6.76	8.59
Alma Formation	10	5.56	5.30	0.81	4.90	6.50
Amsterdam Formation	5	5.48	5.30	0.46	5.30	5.60
Augrabies Gneiss	46	7.78	7.80	0.61	7.37	8.13
Barberton Supergroup	77	6.56	6.60	0.78	6.00	7.03
Baderoukwe Granite	1	6.76	6.80	0.00	6.76	6.76
Bandelierskop Complex	16	6.04	6.20	0.71	5.49	6.47
Basement Complex	479	6.05	5.90	0.94	5.31	6.57
Beaufort Group	2243	6.66	6.50	1.17	5.78	7.41
Berea Formation	73	5.89	5.80	0.87	5.30	6.30
Bidouw Subgroup	54	7.41	7.50	1.03	6.45	8.30
Bierkraal Magnetite Gabbro	90	6.51	6.30	0.86	6.00	6.70
Biesiesfontein Suite	1	7.64	7.60	0.00	7.64	7.64
Black Reef Formation	19	6.36	6.10	0.98	5.69	6.86
Bloempoort Group	5	6.53	6.90	0.64	6.18	6.90
Bokkeveld Group	64	7.13	7.50	1.16	6.05	8.13
Bosbokpoort Formation	10	7.24	7.30	0.73	6.64	7.80
Bothaville Formation	11	5.96	5.80	0.79	5.30	6.10
Brandwacht Formation	7	5.34	5.10	0.39	5.10	5.60
Bredasdorp Group	18	7.71	7.90	0.86	7.47	8.20
Buffelsfontein Group	3	7.28	6.60	1.14	6.62	8.60
Bulai Gneiss	26	8.12	8.20	0.98	7.25	8.65
Bumbeni Complex	19	6.36	6.20	0.90	5.78	6.96
Cape Granite Suite	108	6.38	6.10	1.09	5.60	7.00
Central Rand Group	5	5.44	5.30	1.09	4.44	6.35
Ceres Subgroup	127	6.68	6.50	1.24	5.60	7.70
Chuniespoort Group	2	6.44	6.40	0.42	6.14	6.74
Clarens Formation	218	7.30	7.60	1.20	6.30	8.35
Clermont Formation	9	6.07	5.50	1.45	5.10	5.90
Croydon Subsuite	42	7.30	7.10	0.91	6.62	7.99
Cunning Moor Tonalite	43	6.58	6.50	0.95	5.78	7.34
Dabreek Formation	2	6.14	6.10	0.18	6.01	6.27
Damwal Formation	18	5.62	5.50	0.41	5.30	6.00
Daspoort Formation	9	5.73	5.80	0.61	5.65	5.90
Dennilton Formation	3	6.46	6.60	0.47	5.95	6.86
Dominion Group	6	6.27	6.10	0.72	5.70	7.10
Drakensberg Group	157	5.82	5.50	0.88	5.19	6.30
Dsjate Subsuite	81	7.94	8.30	0.92	7.29	8.57
Duitschland Formation	2	7.90	7.90	0.42	7.60	8.20
Dwars River Subsuite	67	7.63	8.10	1.26	6.62	8.60
Dwyka Group	794	6.16	6.00	1.10	5.29	6.66
Ecca Group	535	6.39	6.10	1.17	5.46	7.12
Eendoorn Granite	39	8.69	8.70	0.49	8.44	8.89
Elliot Formation	154	6.20	6.00	0.99	5.50	6.62
Emakwezini Formation	129	7.43	7.40	1.04	6.57	8.23
Enon Formation	66	7.53	7.60	1.10	6.70	8.34
Fig Tree Group	9	5.91	6.20	0.62	5.48	6.17
Fort Brown Formation	78	7.74	7.90	1.15	7.00	8.50
Franschhoek Formation	4	6.32	6.30	0.20	6.18	6.46
Fundudzi Formation	5	6.19	6.20	0.11	6.20	6.23
Gaborone Granite	10	7.42	7.40	1.22	6.20	8.78
Gamtoos Group	6	5.70	5.70	0.18	5.60	5.80
Garies Subgroup	11	8.08	8.40	1.19	6.60	8.80
Geelvloer Group	32	8.46	8.40	0.38	8.25	8.79

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Ghaap Group	29	7.73	7.70	0.87	7.27	8.50
Gifberg Group	18	7.67	8.20	1.21	6.71	8.60
Giyani Group	11	7.63	7.40	1.08	6.75	8.61
Gladkop Suite	9	8.56	8.40	0.79	8.20	8.80
Godwan Group	3	5.89	5.90	0.29	5.60	6.17
Goudplaats Gneiss	378	6.48	6.40	0.94	5.88	6.86
Government Subgroup	12	5.74	5.30	1.29	4.82	6.18
Grasvally Norite-Anorthosite	43	7.00	6.80	0.70	6.40	7.50
Gravelotte Group	6	5.26	5.00	0.90	4.60	5.50
Groblershoop Formation	4	8.06	8.10	0.17	7.91	8.21
Grootderm Formation	9	8.23	8.40	0.42	8.20	8.50
Gumbu Group	12	7.23	7.70	1.26	5.83	8.27
Halfway House Granite	49	6.31	6.30	0.75	5.87	6.72
Harmony Granite	3	7.22	5.90	3.22	4.89	10.90
Hebron Pluton	4	5.48	5.30	0.50	5.15	5.81
Hekpoort Formation	42	6.13	6.30	0.98	5.58	6.75
Hoogoor Suite	5	7.62	8.00	1.35	6.40	8.86
Hospital Hill Subgroup	5	5.28	4.80	0.86	4.59	6.18
Hout River Gneiss	134	6.41	6.20	0.99	5.78	6.76
Irrigasie Formation	24	6.74	6.30	1.16	5.92	7.98
Jeppestown Subgroup	15	5.64	5.60	0.83	4.86	6.30
Jozini Formation	62	6.77	6.60	0.82	6.10	7.55
Kaaimans Group	4	5.95	6.00	0.55	5.55	6.35
Kaap Valley Tonalite	31	5.64	5.40	0.65	5.20	6.00
Kalahari Group	204	7.68	7.70	1.01	6.95	8.52
Kameeldoorns Formation	4	6.20	6.30	0.60	5.79	6.61
Kango Group	2	7.00	7.00	0.14	6.90	7.10
Karoo	209	6.51	6.50	1.18	5.50	7.33
Karoo Dolerite Suite	998	6.19	6.00	1.11	5.33	6.74
Kirkwood Formation	38	8.29	8.40	0.68	8.00	8.70
Klipriviersberg Group	15	6.13	5.90	0.68	5.70	6.10
Knersvlakte Subgroup	10	8.51	8.40	0.77	7.90	9.50
Koedoesberg Formation	9	8.19	8.40	0.52	7.80	8.64
Kookfontein Formation	4	7.98	7.90	0.24	7.80	8.15
Korannaland Group	12	8.48	8.40	0.26	8.29	8.60
Koras Group	3	8.93	8.80	0.33	8.70	9.30
Kraaipan Group	2	6.40	6.40	0.14	6.30	6.50
Lake Mentz Subgroup	23	6.99	7.00	0.97	6.10	7.60
Lakenvalei Formation	12	5.93	5.80	0.53	5.54	6.29
Lebowa Granite Suite	281	6.64	6.50	1.02	5.89	7.36
Lekkersmaak Granite	5	6.61	6.30	0.83	5.98	6.86
Leococratic Biotite Granite	12	5.21	5.10	0.44	4.95	5.30
Letaba Formation	414	7.14	7.00	1.09	6.32	8.10
Leucocratic Biotite Granite	51	5.90	5.90	0.66	5.49	6.37
Leuocratic Biotite Granite	2	6.00	6.00	1.41	5.00	7.00
Leydsdorp Formation	5	6.14	6.10	0.27	5.98	6.20
Little Namaqualand Suite	205	7.93	8.00	0.83	7.47	8.54
Loskop Formation	15	5.88	5.90	0.56	5.49	6.39
Magaliesberg Formation	38	7.40	7.90	1.32	6.40	8.50
Makeckaan Subgroup	6	6.88	7.10	1.31	5.40	8.04
Makwassie Formation	12	7.05	7.10	0.78	6.30	7.60
Malala Drift Group	277	7.52	7.50	0.87	6.93	8.05
Malmani Subgroup	173	6.12	5.90	1.09	5.30	6.83
Malmesbury Group	9	6.19	6.10	0.52	5.80	6.20
Mapumulo Group	215	5.70	5.70	0.58	5.29	6.07
Mashashane Suite	16	6.12	6.00	0.51	5.73	6.52
Matlabas Subgroup	119	6.85	6.80	1.11	6.00	7.70
Matok Granite	7	6.23	6.40	0.62	5.58	6.66
Meinhardskraal Granite	3	6.17	6.20	0.06	6.10	6.20
Messina Suite	33	7.41	7.40	1.05	6.47	8.40
Metanorite-Gabbro	35	6.21	6.20	0.77	5.80	6.70
Modipe Complex	13	6.71	6.90	1.31	5.80	7.70

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Molteno Formation	559	6.39	6.20	1.05	5.63	7.00
Moodies Group	14	6.34	6.50	0.56	5.80	6.76
Moorreesburg Formation	43	6.42	6.10	0.95	5.70	6.89
Mount Dowe Group	85	7.53	7.70	1.06	6.70	8.49
Mozaan Group	192	6.87	6.60	0.97	6.26	7.40
Mpluze Granite	153	5.48	5.30	0.76	5.00	5.72
Mulati Formation	8	6.46	6.10	0.87	5.95	6.85
Muzi Formation	25	6.06	6.10	0.85	5.38	6.37
Mzimkulu Group	2	5.70	5.70	0.44	5.38	6.01
Nama Group	12	6.73	6.60	1.84	5.25	8.22
Nanaga Formation	78	6.98	6.70	1.12	6.20	8.10
Nardouw Subgroup	168	6.13	5.90	1.11	5.40	6.51
Natal Group	423	5.44	5.30	0.56	5.09	5.68
Nelspruit Suite	97	6.06	6.00	0.71	5.58	6.44
Ngoye Complex	3	6.01	5.90	0.60	5.48	6.66
Nondweni Group	9	5.37	5.40	0.38	4.99	5.58
Nsuze Group	67	6.11	6.10	0.79	5.40	6.57
Ntabene Formation	27	7.47	7.70	1.24	6.48	8.13
Nyoka Formation	13	6.99	6.80	0.92	6.27	7.65
Nzhelele Formation	7	7.37	7.50	1.09	7.24	8.21
Olifantshoek Super Group	3	8.46	9.00	0.91	7.41	8.98
Ongeluk Formation	14	7.66	7.60	0.58	7.20	7.90
Onverwacht Group	27	6.78	6.90	0.94	6.25	7.30
Palala Granite	8	7.40	7.50	0.80	7.05	8.00
Palmietfontein Granite	3	4.73	4.70	0.06	4.70	4.80
Penge Formation	4	8.13	7.80	1.08	7.46	8.80
Peninsula Formation	62	5.69	5.50	0.87	5.20	5.92
Piekenierskloof Formation	6	6.17	6.10	0.92	5.46	7.04
Pienaars River Subprovince	11	7.74	7.90	0.54	7.54	8.10
Pietermaritzburg Formation	584	6.08	6.00	0.94	5.38	6.57
Pietersburg Group	44	6.52	6.40	0.60	6.22	6.87
Piketberg Formation	13	7.25	7.40	0.81	6.40	7.90
Pilanessberg Complex	8	6.76	6.70	0.71	6.25	7.10
Porseleinberg Formation	12	6.23	6.50	0.79	5.53	6.86
Port Durnford Formation	3	6.67	6.50	0.38	6.40	7.10
Port Nolloth Group	13	8.19	8.30	0.55	7.90	8.50
Porterville Formation	63	6.70	6.60	1.22	5.90	7.95
Post-Transvaal Diabases	67	6.35	6.30	0.70	5.78	6.66
Pretoria Group	18	6.77	6.50	1.36	5.40	8.26
Prince Albert Formation	58	8.42	8.40	0.60	8.00	8.78
Pyramid Gabbronorite	40	8.03	8.20	0.64	7.77	8.43
Rashoop Granophyre Suite	35	6.14	5.80	0.99	5.49	6.67
Raytonn Formation	16	6.98	7.40	1.01	6.34	7.73
Richtersveld Subprovince	19	8.45	8.70	1.06	8.37	9.20
Rietgat Formation	8	6.25	6.20	0.38	5.95	6.45
Rooiwater Complex	3	6.37	6.40	0.49	5.88	6.86
Roossenkal Subsuite	109	7.51	7.60	0.91	6.57	8.33
Salisbury Kop Pluton	15	6.69	6.70	1.13	5.50	8.04
Sand River Gneiss	18	8.25	8.60	0.68	7.74	8.71
Schiel Alkaline Complex	4	6.00	6.00	0.09	5.93	6.07
Selons River Formation	42	5.62	5.50	0.51	5.20	5.87
Silverton Formation	101	6.31	6.20	0.98	5.68	6.70
Solitude Formation	11	7.90	8.30	1.07	7.37	8.64
Soutpansberg Group	31	6.00	5.80	0.83	5.40	6.57
Spektakel Suite	15	6.88	6.50	1.12	6.10	8.00
Spitskop Complex	3	6.78	7.60	1.42	5.14	7.63
Steenkampsberg Formation	19	5.34	5.30	0.30	5.10	5.40
Strubenkop Formation	3	6.03	6.50	1.27	4.60	7.00
Sundays River Formation	57	8.46	8.60	0.58	8.30	8.80
Swaershoek Formation	8	5.48	5.20	0.95	4.75	6.53
Syenite	17	6.53	6.50	0.44	6.17	6.86
Tarkastad Subgroup	1908	6.70	6.60	1.17	5.71	7.60

Geological Unit	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Tierberg Formation	6	7.69	7.70	0.26	7.50	7.90
Timbavati Gabbro	8	7.50	7.00	1.28	6.52	8.26
Timeball Hill Formation	105	6.04	5.80	1.09	5.29	6.50
Traka Subgroup	7	7.93	7.90	0.76	7.47	8.68
Tugela Group	49	5.93	5.90	0.70	5.40	6.17
Turffontein Subgroup	7	5.76	5.70	1.27	4.53	7.18
Turfloop Granite	66	6.31	6.40	0.93	5.90	6.86
Tygerberg Formation	15	7.05	6.60	1.03	6.40	8.20
Uloa Formation	5	6.40	6.60	0.78	5.64	6.74
Unnamed Granite and Gneiss	12	8.41	8.40	0.34	8.15	8.70
Usushwana Complex	5	5.61	5.40	0.35	5.38	5.90
Utrecht Granite	2	5.86	5.90	0.23	5.69	6.02
Vaalkoppies Group	5	7.80	7.60	0.76	7.30	7.70
Vaalputs Granite	4	8.49	8.50	0.14	8.40	8.59
Vaalwater Formation	11	5.56	5.50	0.38	5.19	5.90
Ventersdorp Supergroup	24	6.23	6.00	1.38	5.48	6.81
Vermont Formation	18	5.88	5.60	0.80	5.29	6.18
Villa Norra Anorthosite	25	7.96	8.30	0.99	7.40	8.41
Vlakfontein Subsuite	26	7.38	7.20	1.07	6.50	8.00
Volksrust Formation	897	6.85	6.90	1.26	5.79	7.90
Vryheid Formation	1432	6.01	5.80	0.99	5.29	6.47
Waterberg Group	103	5.99	5.70	1.32	4.99	6.80
Waterford Formation	13	8.20	7.80	0.84	7.60	8.80
Weltevrede Subgroup	88	6.53	6.40	1.10	5.80	7.13
Whitehill Formation	15	8.24	8.30	0.43	8.00	8.40
Wilge River Formation	147	5.37	5.10	0.66	4.89	5.74
Witwatersrand Supergroup	2	5.95	6.00	0.07	5.90	6.00
Wolkberg Group	8	5.24	5.20	0.72	4.94	5.74
Wyllies Poort Formation	49	5.98	5.70	1.18	5.14	6.33
Zoetveld Subsuite	2	7.01	7.00	0.47	6.68	7.34
Zululand Group	149	6.46	6.40	0.95	5.80	6.96

APPENDIX J: Groundwater units soil PH$_{\text{water}}$

Groundwater Region	**Count**	**Average**	**Median**	**Standard deviation**	**Lower quartile**	**Upper quartile**
Algoa Basin	218	8.01	8.30	0.96	7.50	8.70
Bredasdorp Coastal Belt	9	8.14	8.20	0.37	8.00	8.20
Bushmanland	421	8.23	8.29	0.65	7.80	8.70
Bushmanland Pan Belt	113	8.36	8.40	0.59	8.00	8.80
Central Highveld	229	6.03	6.00	0.94	5.35	6.69
Central Pan Belt	320	7.92	8.00	0.81	7.30	8.51
Ciskeian Coastal Foreland and Middleveld	1568	7.08	7.00	1.04	6.30	7.87
Dry Harts-Vaal-Orange	466	8.13	8.30	0.77	7.70	8.70
Eastern Bankeveld	415	6.66	6.47	1.28	5.50	7.80
Eastern Bushveld Complex	576	6.92	6.76	1.21	5.89	8.10
Eastern Great Karoo	162	7.99	8.00	0.85	7.50	8.50
Eastern Highveld	809	6.00	5.88	0.96	5.31	6.40
Eastern Kalahari	88	7.17	7.05	0.96	6.35	8.11
Eastern Upper Karoo	113	8.05	8.10	0.81	7.50	8.60
Ghaap Plateau	36	8.25	8.50	0.63	8.04	8.64
Grootrivier-Klein Winterhoek-Suurberg-Ka	112	6.66	6.50	1.03	5.96	7.40
Hantam	36	8.04	8.10	0.70	7.55	8.60
Intermontane Tulbagh-Ashton Valley	45	7.21	7.60	1.26	6.15	8.20
Karst Belt	69	6.23	6.10	0.92	5.60	6.72
Knersvlakte	71	7.50	7.70	1.43	6.40	8.69
KwaZulu-Natal Coastal Foreland	1032	5.69	5.58	0.68	5.19	6.07
Limpopo Granulite Gneiss Belt	916	7.33	7.33	1.06	6.54	8.16
Limpopo Karoo Basin	236	8.28	8.37	0.57	8.00	8.64
Lower Gamtoos Valley	17	6.96	6.80	1.03	6.10	7.80
Lowveld	828	6.34	6.27	0.93	5.71	6.82
Makoppa Dome	179	6.84	6.80	1.06	6.00	7.62
Middelburg Basin	350	5.33	5.10	0.63	4.89	5.54
Namaqualand	198	7.76	8.10	1.35	6.70	8.80
Northeastern Middleveld	1428	5.86	5.69	0.84	5.20	6.30
Northeastern Pan Belt	212	7.13	7.01	0.85	6.44	7.70
Northeastern Upper Karoo	409	7.40	7.36	0.90	6.68	8.10
Northern Bushveld Complex	17	7.12	7.20	0.95	6.30	7.88
Northern Highland	134	6.53	6.39	0.78	6.00	7.00
Northern Lebombo	204	7.12	6.87	0.91	6.51	7.85
Northern Zululand Coastal Plain	404	6.24	6.17	0.94	5.56	6.78
Northwestern Cape Ranges	204	6.79	6.51	1.36	5.50	8.10
Northwestern Middleveld	1798	5.91	5.68	0.96	5.19	6.40
Oudtshoorn Basin	24	7.65	7.50	1.06	7.20	8.65
Outenikwa Coastal Foreland	42	6.59	6.50	0.99	5.80	7.10
Pietersburg Plateau	365	6.43	6.30	0.92	5.88	6.81
Richtersveld	88	8.47	8.50	0.75	8.20	8.90
Ruensveld	146	7.27	7.42	1.25	6.30	8.30
Southern Cape Ranges	234	6.44	6.20	1.25	5.60	7.20
Southern Highland	702	6.36	6.24	1.00	5.61	6.96
Southern Highveld	102	7.39	7.40	0.88	6.70	8.20
Southern Lebombo	776	6.91	6.69	1.03	6.07	7.80
Southwestern Cape Ranges	85	6.03	5.82	0.83	5.60	6.20
Southwestern Coastal Sandveld	81	7.16	7.20	1.13	6.20	7.84
Soutpansberg	101	6.14	6.01	1.10	5.38	6.60
Soutpansberg Hinterland	41	7.57	7.74	0.86	6.80	8.30
Springbok Flats	245	7.03	7.00	1.19	6.10	8.20
Stilbaai Coastal Belt	5	6.62	6.50	0.75	6.10	6.80
Swartland	220	6.48	6.30	1.06	5.70	7.16
Tanqua Karoo	83	8.36	8.38	0.67	8.00	8.86
Transkeian Coastal Foreland	2227	5.96	5.84	0.88	5.31	6.43
Waterberg Coal Basin	87	7.02	7.10	1.30	5.70	8.20
Waterberg Plateau	341	6.41	6.20	1.20	5.50	7.30

Groundwater Region	**Count**	**Average**	**Median**	**Standard deviation**	**Lower quartile**	**Upper quartile**
West Griqualand	36	7.45	7.40	0.98	7.00	8.00
Western Bankeveld and Marico Bushveld	228	6.13	6.07	0.93	5.60	6.57
Western Bushveld Complex	260	7.15	7.00	1.03	6.30	8.05
Western Great Karoo	63	7.89	8.10	1.06	7.30	8.50
Western Highveld	159	6.94	6.60	1.02	6.20	7.44
Western Kalahari	76	8.28	8.50	0.81	7.58	8.90
Western Upper Karoo	72	8.18	8.28	0.84	7.65	8.82

APPENDIX K: GEOLOGICAL REGIONS EXCHANGABLE SODIUM ($cmol_ckg^{-1}$)

Geological Formation	**Count**	**Average**	**Median**	**Standard deviation**	**Lower quartile**	**Upper quartile**
Alexandria Formation	14	1.00	0.80	0.81	0.40	1.20
Allanridge Formation	82	0.58	0.10	2.41	0.01	0.14
Alldays Gneiss	305	0.83	0.10	3.04	0.10	0.20
Alluvium Sand and Calcrete	1668	1.14	0.25	2.47	0.10	1.00
Alma Formation	10	0.04	0.01	0.04	0.01	0.10
Amsterdam Formation	5	0.08	0.07	0.02	0.07	0.08
Augrabies Gneiss	46	0.14	0.04	0.26	0.02	0.12
Barberton Supergroup	77	0.14	0.10	0.22	0.10	0.13
Bandelierskop Complex	16	0.21	0.20	0.14	0.10	0.20
Basement Complex	480	0.40	0.10	1.72	0.05	0.20
Beaufort Group	2390	0.56	0.20	1.32	0.10	0.44
Berea Formation	79	0.11	0.10	0.11	0.03	0.10
Bidouw Subgroup	37	1.04	0.70	1.20	0.30	1.10
Bierkraal Magnetite Gabbro	88	0.37	0.10	0.75	0.10	0.20
Black Reef Formation	19	0.13	0.14	0.08	0.04	0.17
Bloempoort Group	5	0.25	0.20	0.15	0.20	0.40
Bokkeveld Group	55	1.79	0.70	4.72	0.22	1.30
Bosbokpoort Formation	10	0.07	0.08	0.04	0.04	0.10
Bothaville Formation	11	0.05	0.01	0.06	0.01	0.10
Brandwacht Formation	7	0.42	0.14	0.47	0.10	1.07
Bredasdorp Group	18	0.84	0.30	1.16	0.10	1.20
Buffelsfontein Group	3	0.18	0.03	0.26	0.03	0.48
Bulai Gneiss	26	1.14	0.15	2.40	0.10	0.40
Bumbeni Complex	19	0.80	0.18	1.31	0.10	1.10
Cape Granite Suite	107	0.77	0.12	1.74	0.10	0.40
Central Rand Group	3	0.04	0.02	0.05	0.01	0.10
Ceres Subgroup	124	0.81	0.30	1.28	0.10	1.00
Chuniespoort Group	2	0.07	0.07	0.01	0.06	0.07
Clarens Formation	214	0.88	0.20	1.97	0.10	0.60
Clermont Formation	9	0.12	0.01	0.22	0.01	0.01
Croydon Subsuite	42	0.71	0.12	1.58	0.09	0.30
Cunning Moor Tonalite	43	0.59	0.10	1.72	0.08	0.31
Dabreek Formation	2	0.10	0.10	0.00	0.10	0.10
Damwal Formation	18	0.11	0.10	0.12	0.01	0.10
Daspoort Formation	9	0.13	0.10	0.08	0.10	0.20
Dennilton Formation	3	0.11	0.10	0.09	0.03	0.20
Dominion Group	6	0.12	0.10	0.07	0.10	0.20
Drakensberg Group	157	0.31	0.20	0.32	0.10	0.30
Dsjate Subsuite	99	0.80	0.18	2.44	0.06	0.39
Duitschland Formation	2	0.15	0.15	0.07	0.10	0.20
Dwars River Subsuite	65	0.54	0.13	1.16	0.06	0.30
Dwyka Group	826	0.63	0.20	3.50	0.10	0.30
Ecca Group	537	0.51	0.21	1.42	0.10	0.34
Eendoorn Granite	39	0.52	0.20	0.82	0.10	0.50
Elliot Formation	153	0.31	0.10	0.59	0.05	0.28
Emakwezini Formation	130	1.80	0.68	2.69	0.30	1.28
Enon Formation	66	2.65	1.05	3.41	0.46	3.37
Fig Tree Group	9	0.13	0.10	0.07	0.10	0.10
Fort Brown Formation	78	1.21	0.60	1.47	0.22	1.40
Franschhoek Formation	4	0.07	0.07	0.02	0.05	0.09
Fundudzi Formation	7	0.15	0.14	0.04	0.11	0.19
Gaborone Granite	10	1.91	0.12	3.44	0.10	1.80
Gamtoos Group	6	0.13	0.10	0.05	0.10	0.20
Garies Subgroup	11	1.37	0.50	1.67	0.27	2.90
Geelvloer Group	32	0.26	0.10	0.38	0.10	0.23
Ghaap Group	29	0.10	0.10	0.06	0.04	0.14
Gifberg Group	18	0.86	0.20	1.96	0.11	0.54
Giyani Group	12	1.18	0.17	2.74	0.14	0.24
Godwan Group	3	0.13	0.10	0.06	0.10	0.20

Geological Formation	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Goudplaats Gneiss	389	0.71	0.20	2.75	0.10	0.30
Government Subgroup	10	0.01	0.01	0.01	0.00	0.01
Grasvally Norite-Anorthosite	43	0.21	0.05	0.60	0.01	0.16
Gravelotte Group	7	0.20	0.20	0.06	0.20	0.20
Groblershoop Formation	4	0.20	0.20	0.00	0.20	0.20
Grootderm Formation	9	1.06	0.50	1.45	0.40	1.00
Gumbu Group	12	0.45	0.10	1.01	0.10	0.30
Halfway House Granite	49	0.10	0.08	0.11	0.06	0.11
Harmony Granite	3	3.70	0.10	6.24	0.10	10.90
Hebron Pluton	4	0.08	0.10	0.03	0.07	0.10
Hekpoort Formation	106	0.12	0.10	0.16	0.02	0.10
Hlobane Complex	11	0.97	0.60	1.01	0.30	1.30
Hoogoor Suite	5	0.51	0.43	0.13	0.43	0.60
Hospital Hill Subgroup	5	0.04	0.01	0.04	0.01	0.05
Hout River Gneiss	126	0.73	0.10	3.20	0.03	0.20
Irrigasie Formation	24	0.68	0.10	2.01	0.08	0.15
Jeppestown Subgroup	13	0.08	0.10	0.05	0.01	0.11
Jozini Formation	62	2.07	0.75	3.59	0.23	1.91
Kaaimans Group	4	0.50	0.50	0.44	0.16	0.85
Kaap Valley Tonalite	29	0.11	0.10	0.07	0.10	0.10
Kalahari Group	194	0.26	0.10	1.34	0.03	0.11
Kameeldoorns Formation	4	0.08	0.08	0.08	0.01	0.15
Kango Group	2	0.30	0.30	0.14	0.20	0.40
Karoo	209	0.57	0.14	1.39	0.08	0.40
Karoo Dolerite Suite	1073	0.39	0.13	0.76	0.10	0.30
Kirkwood Formation	38	1.85	1.05	1.83	0.40	2.70
Klipriviersberg Group	15	0.07	0.04	0.08	0.01	0.12
Knersvlakte Subgroup	10	2.20	1.87	1.52	1.10	2.90
Koedoesberg Formation	9	0.37	0.10	0.59	0.05	0.40
Kookfontein Formation	4	0.60	0.70	0.27	0.45	0.75
Korannaland Group	12	0.05	0.05	0.03	0.03	0.06
Kraaipan Group	2	0.08	0.08	0.00	0.08	0.08
Lake Mentz Subgroup	24	1.31	0.48	1.72	0.21	2.15
Lakenvalei Formation	12	0.08	0.10	0.05	0.03	0.10
Lebowa Granite Suite	278	0.29	0.10	1.28	0.07	0.16
Lekkersmaak Granite	5	0.54	0.20	0.82	0.10	0.30
Leococratic Biotite Granite	12	0.07	0.10	0.04	0.01	0.10
Letaba Formation	432	1.94	0.33	5.50	0.13	0.80
Leucocratic Biotite Granite	51	0.13	0.10	0.12	0.10	0.20
Leydsdorp Formation	5	0.32	0.30	0.23	0.20	0.30
Little Namaqualand Suite	205	0.75	0.10	1.82	0.04	0.40
Loskop Formation	15	0.09	0.02	0.21	0.01	0.05
Magaliesberg Formation	38	0.64	0.10	2.17	0.04	0.20
Makeckaan Subgroup	6	0.05	0.06	0.04	0.01	0.07
Makwassie Formation	12	0.36	0.20	0.38	0.10	0.40
Malala Drift Group	272	0.65	0.10	2.00	0.10	0.20
Malmani Subgroup	170	0.07	0.08	0.07	0.01	0.10
Malmesbury Group	7	1.16	1.10	1.23	0.10	2.50
Malmesbury Group	2	0.25	0.25	0.20	0.11	0.39
Mapumulo Group	218	0.29	0.20	0.31	0.10	0.30
Mashashane Suite	16	0.06	0.03	0.06	0.02	0.10
Matlabas Subgroup	119	0.29	0.10	0.83	0.01	0.20
Matok Granite	7	0.11	0.10	0.07	0.06	0.20
Meinhardskraal Granite	3	0.04	0.01	0.05	0.01	0.10
Messina Suite	33	1.18	0.12	2.90	0.10	0.23
Metanorite-Gabbro	35	0.13	0.10	0.30	0.01	0.10
Modipe Complex	13	1.17	0.14	1.84	0.10	1.20
Molteno Formation	557	0.47	0.10	1.16	0.06	0.33
Moorreesburg Formation	43	0.67	0.21	1.01	0.04	0.95
Mount Dowe Group	85	0.17	0.10	0.17	0.10	0.20
Mozaan Group	195	0.78	0.20	1.67	0.10	0.36
Mpluze Granite	152	0.19	0.02	0.84	0.01	0.06

Geological Formation	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Mulati Formation	6	0.15	0.10	0.08	0.10	0.20
Muzi Formation	27	0.43	0.20	0.51	0.06	0.60
Mzimkulu Group	2	0.14	0.14	0.06	0.10	0.18
Nama Group	12	0.60	0.35	0.59	0.03	1.20
Nanaga Formation	78	0.53	0.30	0.68	0.10	0.53
Nardouw Subgroup	165	0.50	0.20	0.73	0.10	0.60
Natal Group	431	0.20	0.10	0.29	0.10	0.20
Nelspruit Suite	97	0.21	0.10	0.96	0.03	0.13
Ngoye Complex	12	0.48	0.40	0.22	0.40	0.50
Nondweni Group	12	0.27	0.20	0.15	0.20	0.40
Nsuze Group	70	0.21	0.10	0.33	0.10	0.20
Ntabene Formation	28	1.46	0.50	1.70	0.25	2.95
Nyoka Formation	13	2.51	0.80	2.95	0.42	5.40
Nzhelele Formation	8	0.20	0.16	0.12	0.09	0.30
Olifantshoek Super Group	3	0.04	0.01	0.05	0.01	0.09
Ongeluk Formation	14	0.12	0.10	0.15	0.01	0.10
Onverwacht Group	27	0.76	0.20	1.49	0.10	0.49
Palala Granite	8	0.28	0.35	0.15	0.10	0.40
Palmietfontein Granite	3	0.13	0.10	0.06	0.10	0.20
Penge Formation	4	1.40	0.11	2.60	0.08	2.71
Peninsula Formation	62	0.30	0.20	0.38	0.10	0.30
Piekenierskloof Formation	6	0.62	0.12	0.85	0.09	1.21
Pienaars River Subprovince	11	0.42	0.29	0.28	0.24	0.50
Pietermaritzburg Formation	605	0.60	0.20	1.53	0.10	0.40
Pietersburg Group	46	0.16	0.10	0.14	0.10	0.20
Piketberg Formation	13	0.22	0.06	0.38	0.03	0.17
Pilanessberg Complex	8	0.16	0.14	0.08	0.10	0.20
Porseleinberg Formation	12	0.17	0.15	0.08	0.12	0.20
Port Durnford Formation	3	0.01	0.01	0.00	0.01	0.01
Port Nolloth Group	13	2.02	0.80	3.36	0.40	1.60
Porterville Formation	63	0.99	0.48	1.15	0.10	1.72
Post-Transvaal Diabases	67	0.21	0.10	0.30	0.01	0.20
Pretoria Group	68	0.18	0.10	0.29	0.10	0.10
Prince Albert Formation	58	3.49	1.00	5.64	0.23	4.50
Pyramid Gabbronorite	32	1.15	0.59	1.42	0.27	1.35
Rashoop Granophyre Suite	35	0.11	0.09	0.12	0.02	0.11
Raytonn Formation	16	0.18	0.16	0.14	0.06	0.34
Richtersveld Subprovince	19	0.61	0.40	0.63	0.20	1.10
Rietgat Formation	8	0.06	0.06	0.05	0.01	0.10
Rooiwater Complex	3	0.17	0.20	0.06	0.10	0.20
Roossenekal Subsuite	1	0.20	0.20	0.00	0.20	0.20
Roossenkal Subsuite	121	0.39	0.13	1.07	0.10	0.23
Salisbury Kop Pluton	15	0.42	0.10	1.00	0.01	0.40
Sand River Gneiss	18	0.19	0.10	0.13	0.10	0.30
Schiel Alkaline Complex	4	0.10	0.10	0.00	0.10	0.10
Selons River Formation	42	0.09	0.08	0.11	0.01	0.10
Silverton Formation	99	0.14	0.10	0.21	0.01	0.20
Solitude Formation	11	0.40	0.18	0.68	0.10	0.30
Soutpansberg Group	33	0.19	0.20	0.10	0.10	0.20
Spektakel Suite	15	1.10	0.40	1.82	0.13	0.80
Spitskop Complex	3	0.14	0.15	0.05	0.07	0.18
Steenkampsberg Formation	19	0.06	0.04	0.05	0.01	0.10
Sundays River Formation	57	1.95	1.10	1.97	0.50	2.90
Swaershoek Formation	8	0.04	0.01	0.05	0.01	0.10
Syenite	17	0.34	0.11	0.77	0.10	0.20
Tarkastad Subgroup	1944	0.46	0.12	1.00	0.06	0.34
Timbavati Gabbro	9	4.43	0.14	12.10	0.09	0.42
Timeball Hill Formation	112	0.11	0.10	0.12	0.02	0.10
Traka Subgroup	7	0.26	0.16	0.22	0.10	0.40
Tugela Group	69	0.30	0.30	0.16	0.20	0.40
Turffontein Subgroup	3	0.02	0.02	0.01	0.00	0.03
Turfloop Granite	69	0.85	0.10	3.41	0.03	0.20

Geological Formation	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Tygerberg Formation	15	0.49	0.12	0.83	0.08	0.24
Uloa Formation	5	0.10	0.05	0.11	0.05	0.08
Unnamed Granite and Gneiss	12	1.87	0.66	2.11	0.10	3.67
Usushwana Complex	5	0.09	0.10	0.03	0.08	0.10
Utrecht Granite	2	0.01	0.01	0.00	0.01	0.01
Vaalkoppies Group	5	0.53	0.13	0.66	0.10	0.89
Vaalputs Granite	4	0.13	0.15	0.09	0.06	0.20
Vaalwater Formation	11	0.06	0.10	0.05	0.01	0.10
Ventersdorp Supergroup	37	0.57	0.10	1.20	0.01	0.20
Vermont Formation	18	0.06	0.04	0.06	0.01	0.10
Villa Norra Anorthosite	25	1.64	0.10	4.46	0.10	0.20
Vlakfontein Subsuite	20	0.55	0.10	1.26	0.10	0.47
Volksrust Formation	952	0.83	0.20	3.60	0.10	0.40
Vryheid Formation	1668	0.39	0.10	1.00	0.08	0.22
Waterberg Group	106	0.34	0.10	1.32	0.01	0.11
Waterford Formation	13	1.49	0.90	1.12	0.60	2.60
Weltevrede Subgroup	89	0.94	0.40	1.16	0.20	1.10
Whitehill Formation	15	6.99	6.60	7.17	0.30	12.30
Wilge River Formation	150	0.16	0.01	0.80	0.01	0.08
Witwatersrand Supergroup	2	0.10	0.10	0.00	0.10	0.10
Wolkberg Group	8	0.07	0.10	0.05	0.01	0.10
Wyllies Poort Formation	51	0.40	0.10	1.30	0.06	0.12
Zoetveld Subsuite	2	0.08	0.08	0.04	0.06	0.11
Zululand Group	155	1.01	0.30	2.19	0.10	0.80

APPENDIX L: GEOLOGICAL REGIONS EXCHANGABLE MAGNESIUM (cmol$_c$kg^{-1})

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Alexandria Formation	14	2.87	3.00	1.29	2.20	3.80
Allanridge Formation	78	3.20	2.00	4.24	1.10	3.40
Alldays Gneiss	305	2.05	1.30	1.94	0.70	2.80
Alluvium Sand and Calcrete	1639	3.09	2.00	3.44	0.75	4.41
Alma Formation	10	0.07	0.00	0.11	0.00	0.10
Amsterdam Formation	5	0.17	0.10	0.19	0.10	0.16
Augrabies Gneiss	46	1.44	1.15	1.02	0.81	1.61
Barberton Supergroup	77	2.48	1.90	2.02	0.93	3.30
Bandelierskop Complex	16	2.45	1.95	1.69	1.20	3.70
Basement Complex	480	1.72	0.78	2.65	0.20	2.17
Beaufort Group	2389	3.53	2.30	4.57	1.20	4.45
Berea Formation	73	0.77	0.60	0.66	0.32	0.91
Bidouw Subgroup	37	2.71	2.30	2.45	1.30	3.28
Bierkraal Magnetite Gabbro	86	4.08	2.90	3.01	2.40	5.10
Black Reef Formation	19	2.27	1.40	2.27	0.59	3.52
Bloempoort Group	5	4.50	6.10	2.48	2.21	6.40
Bokkeveld Group	46	2.24	1.53	2.20	0.68	3.30
Bosbokpoort Formation	10	0.62	0.62	0.25	0.43	0.83
Bothaville Formation	11	1.29	0.70	1.79	0.30	1.00
Brandwacht Formation	5	1.30	0.70	1.83	0.00	1.40
Bredasdorp Group	18	1.02	0.55	1.09	0.20	1.50
Buffelsfontein Group	3	2.02	1.36	1.23	1.25	3.44
Bulai Gneiss	26	2.73	2.40	1.28	1.70	3.60
Bumbeni Complex	19	3.19	2.30	2.80	1.00	4.10
Cape Granite Suite	103	1.10	0.54	1.47	0.20	1.30
Central Rand Group	3	2.21	0.20	3.63	0.01	6.40
Ceres Subgroup	123	2.12	1.10	2.55	0.25	2.93
Chuniespoort Group	2	0.95	0.95	0.19	0.81	1.08
Clarens Formation	214	3.91	2.60	3.83	1.50	5.03
Clermont Formation	9	0.60	0.10	1.08	0.00	0.30
Croydon Subsuite	42	3.78	3.78	2.68	1.61	5.59
Cunning Moor Tonalite	43	5.06	1.00	8.12	0.53	4.39
Dabreek Formation	2	1.55	1.55	0.35	1.30	1.80
Damwal Formation	18	0.60	0.35	0.73	0.00	1.00
Daspoort Formation	9	1.75	0.80	1.93	0.50	1.92
Dennilton Formation	3	0.74	0.80	0.10	0.63	0.80
Dominion Group	6	0.98	0.90	0.76	0.40	1.80
Drakensberg Group	155	5.14	2.50	6.60	0.60	8.40
Dsjate Subsuite	99	7.87	5.91	6.61	3.17	10.00
Duitschland Formation	2	2.95	2.95	0.64	2.50	3.40
Dwars River Subsuite	65	11.10	9.58	8.13	3.63	18.90
Dwyka Group	823	2.25	1.50	3.12	0.40	2.87
Ecca Group	529	3.14	2.40	2.82	1.29	4.00
Eendoorn Granite	39	1.25	1.20	0.76	0.60	1.88
Elliot Formation	154	2.40	1.38	2.98	0.70	2.60
Emakwezini Formation	130	5.26	4.99	2.72	3.21	7.20
Enon Formation	38	3.16	2.70	2.77	1.50	3.60
Fig Tree Group	9	2.72	2.00	2.87	0.00	4.50
Fort Brown Formation	78	2.75	2.15	1.58	1.60	3.40
Franschhoek Formation	4	0.52	0.40	0.32	0.31	0.73
Fundudzi Formation	7	3.79	3.86	1.79	2.09	5.50
Gaborone Granite	10	3.96	3.55	3.15	0.96	7.60
Gamtoos Group	6	1.00	0.95	0.54	0.70	1.50
Garies Subgroup	11	1.74	1.79	1.72	0.41	2.10
Geelvloer Group	32	1.19	1.05	0.60	0.80	1.60
Gifberg Group	18	1.93	1.90	1.49	0.80	3.30
Giyani Group	12	6.64	5.89	3.23	4.05	8.76
Gladkop Suite	9	2.72	1.80	2.97	1.10	3.70
Godwan Group	3	1.33	1.40	0.31	1.00	1.60

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Goudplaats Gneiss	387	2.78	2.03	2.82	1.10	3.50
Government Subgroup	10	0.42	0.10	0.69	0.00	0.34
Grasvally Norite-Anorthosite	43	2.29	1.55	2.55	0.99	2.41
Gravelotte Group	7	3.39	2.30	3.48	1.10	3.80
Groblershoop Formation	4	4.65	4.65	0.27	4.42	4.88
Grootderm Formation	9	2.44	1.80	1.87	1.30	2.90
Gumbu Group	12	1.64	1.35	1.45	0.35	2.67
Halfway House Granite	49	0.93	0.64	0.97	0.49	0.93
Harmony Granite	3	0.17	0.10	0.12	0.10	0.30
Hebron Pluton	4	0.20	0.00	0.40	0.00	0.40
Hekpoort Formation	106	2.03	0.24	4.15	0.00	2.20
Hlobane Complex	11	8.55	7.30	4.45	5.20	12.90
Hoogoor Suite	5	0.74	0.90	0.36	0.40	1.04
Hospital Hill Subgroup	5	1.74	0.11	2.54	0.10	2.64
Hout River Gneiss	126	2.18	1.50	2.18	0.70	2.60
Irrigasie Formation	24	1.89	1.05	2.36	0.58	2.10
Jeppestown Subgroup	13	1.12	0.84	0.73	0.53	1.40
Jozini Formation	62	6.93	6.01	4.49	3.33	8.90
Kaaimans Group	4	1.90	0.90	2.49	0.55	3.25
Kaap Valley Tonalite	29	2.20	1.00	5.09	0.00	2.00
Kalahari Group	204	1.36	0.70	2.82	0.40	1.24
Kameeldoorns Formation	4	1.63	1.30	1.03	1.00	2.26
Kango Group	2	3.15	3.15	1.48	2.10	4.20
Karoo	209	2.97	1.60	3.65	0.50	4.38
Karoo Dolerite Suite	1068	3.60	2.03	5.55	0.77	4.07
Kirkwood Formation	38	3.64	3.10	2.07	1.90	4.80
Klipriviersberg Group	15	2.40	1.67	2.47	0.74	2.60
Knersvlakte Subgroup	10	2.64	2.08	1.76	1.70	3.40
Koedoesberg Formation	9	2.35	2.28	0.80	1.62	3.00
Kookfontein Formation	4	3.65	4.10	1.30	2.75	4.55
Korannaland Group	12	1.29	1.40	0.57	0.75	1.64
Lake Mentz Subgroup	24	3.11	2.76	2.02	1.85	3.22
Lakenvalei Formation	12	0.97	0.52	1.01	0.10	1.99
Lebowa Granite Suite	278	1.46	0.86	1.77	0.46	1.80
Lekkersmaak Granite	5	1.68	0.90	1.99	0.40	2.00
Leococratic Biotite Granite	12	0.07	0.00	0.16	0.00	0.00
Letaba Formation	432	7.40	6.01	5.36	3.41	10.60
Leucocratic Biotite Granite	47	1.46	0.90	1.58	0.30	2.20
Leydsdorp Formation	5	3.62	3.30	1.63	2.80	5.20
Little Namaqualand Suite	205	1.70	1.30	1.54	0.99	1.92
Loskop Formation	15	0.73	0.50	0.73	0.33	0.90
Magaliesberg Formation	38	3.41	2.32	3.18	1.15	4.62
Makeckaan Subgroup	6	0.64	0.60	0.47	0.20	0.98
Makwassie Formation	12	6.90	6.65	2.23	5.10	8.60
Malala Drift Group	272	2.33	2.00	1.35	1.23	3.10
Malmani Subgroup	170	1.53	0.80	2.31	0.22	2.07
Malmesbury Group	7	1.20	1.40	1.12	0.10	2.20
Malmesbury Group	2	1.86	1.86	1.31	0.93	2.78
Mapumulo Group	218	1.77	1.20	2.02	0.40	2.30
Mashashane Suite	16	1.16	0.79	1.23	0.41	1.58
Matlabas Subgroup	119	1.82	1.00	1.87	0.50	2.40
Matok Granite	7	1.14	1.07	0.41	0.80	1.40
Meinhardskraal Granite	3	0.43	0.50	0.12	0.30	0.50
Messina Suite	33	2.44	2.23	1.56	1.01	3.60
Metanorite-Gabbro	35	1.52	0.80	1.73	0.42	2.10
Modipe Complex	13	3.92	3.26	2.76	1.90	4.40
Molteno Formation	538	3.13	1.43	4.02	0.63	4.05
Moodies Group	13	3.82	3.00	2.99	1.40	6.10
Moorreesburg Formation	39	1.30	0.64	2.22	0.20	1.37
Mount Dowe Group	85	2.35	2.20	1.47	1.30	3.20
Mozaan Group	195	4.47	3.36	3.65	2.00	6.00
Mpluze Granite	152	0.97	0.21	2.39	0.08	0.59

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Mulati Formation	6	3.45	3.80	2.08	2.20	4.60
Muzi Formation	27	1.77	1.20	1.73	0.40	3.10
Mzimkulu Group	2	0.47	0.47	0.52	0.10	0.84
Nama Group	12	3.25	2.60	3.01	0.39	5.85
Nanaga Formation	78	1.49	1.11	1.52	0.30	2.70
Nardouw Subgroup	160	1.01	0.30	1.65	0.10	1.30
Natal Group	431	0.99	0.55	1.44	0.10	1.30
Nelspruit Suite	97	1.03	0.51	1.99	0.20	1.10
Ngoye Complex	12	4.73	4.65	0.67	4.30	5.15
Nondweni Group	12	0.67	0.20	1.10	0.00	0.85
Nsuze Group	70	2.38	2.05	1.97	1.00	3.60
Ntabene Formation	28	6.02	5.25	3.86	3.45	8.23
Nyoka Formation	13	7.73	7.20	2.59	5.40	9.73
Nzhelele Formation	8	6.01	3.70	5.16	2.92	9.50
Olifantshoek Super Group	3	0.85	1.15	0.52	0.26	1.15
Ongeluk Formation	14	2.58	2.05	1.52	1.49	3.30
Onverwacht Group	27	4.22	3.80	3.36	0.82	7.60
Palala Granite	8	3.09	2.90	1.82	1.85	4.50
Palmietfontein Granite	3	0.00	0.00	0.00	0.00	0.00
Penge Formation	4	4.88	5.87	2.69	3.05	6.71
Peninsula Formation	60	0.68	0.40	0.86	0.10	0.86
Piekenierskloof Formation	6	0.90	0.38	0.98	0.22	2.04
Pienaars River Subprovince	11	6.26	5.41	4.39	2.83	6.60
Pietermaritzburg Formation	605	3.23	2.30	3.19	0.70	4.90
Pietersburg Group	46	2.78	2.25	2.06	1.10	3.80
Piketberg Formation	6	1.56	0.87	2.00	0.00	2.51
Pilanessberg Complex	8	2.86	2.41	1.61	1.62	4.35
Porseleinberg Formation	12	1.29	1.02	1.03	0.50	1.87
Port Durnford Formation	3	0.37	0.40	0.06	0.30	0.40
Port Nolloth Group	13	2.15	1.50	1.79	1.00	3.10
Porterville Formation	27	2.28	1.10	3.34	0.20	2.50
Post-Transvaal Diabases	67	4.28	3.00	3.46	2.20	5.00
Pretoria Group	68	0.71	0.10	1.71	0.05	0.60
Prince Albert Formation	58	3.05	1.56	3.39	1.05	3.77
Pyramid Gabbronorite	27	12.20	10.70	7.18	6.34	15.10
Rashoop Granophyre Suite	35	1.78	0.67	2.75	0.20	1.40
Raytonn Formation	16	3.95	4.19	2.45	1.48	6.09
Richtersveld Subprovince	17	1.35	1.10	1.23	0.60	1.48
Rietgat Formation	8	1.64	1.60	0.97	0.68	2.40
Rooiwater Complex	3	3.30	2.90	1.73	1.80	5.20
Roossenkal Subsuite	121	3.73	2.30	3.42	1.37	5.00
Salisbury Kop Pluton	15	1.48	1.60	1.17	0.50	2.80
Sand River Gneiss	18	1.84	1.75	0.74	1.20	2.60
Schiel Alkaline Complex	4	1.08	1.05	0.21	0.90	1.25
Selons River Formation	42	1.83	0.75	3.01	0.44	2.00
Silverton Formation	99	4.08	3.30	3.78	1.37	5.50
Solitude Formation	11	3.56	2.90	2.81	1.30	4.60
Soutpansberg Group	33	2.80	2.30	2.18	1.40	4.10
Spektakel Suite	15	1.44	1.00	1.34	0.58	1.80
Spitskop Complex	3	3.40	4.40	2.61	0.44	5.36
Steenkampsberg Formation	19	0.79	0.18	2.63	0.00	0.40
Strubenkop Formation	1	0.14	0.14	0.00	0.14	0.14
Sundays River Formation	57	3.45	3.10	1.72	1.90	4.90
Swaershoek Formation	8	0.46	0.35	0.49	0.00	0.90
Syenite	17	2.21	1.85	1.53	1.68	2.65
Tarkastad Subgroup	1917	3.16	1.70	4.70	0.83	4.12
Tierberg Formation	6	4.23	4.10	1.56	2.90	5.59
Timbavati Gabbro	9	4.82	2.77	4.39	1.79	8.65
Timeball Hill Formation	112	1.79	0.76	3.03	0.20	2.25
Traka Subgroup	7	2.19	1.90	1.39	1.20	3.39
Tugela Group	69	3.45	3.30	2.64	1.20	4.60
Turffontein Subgroup	3	0.36	0.13	0.49	0.03	0.92

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Turfloop Granite	67	1.74	1.30	1.34	0.80	2.65
Tygerberg Formation	14	1.00	0.50	1.24	0.20	1.20
Uloa Formation	5	1.50	0.74	1.75	0.67	1.09
Unnamed Granite and Gneiss	6	1.59	1.60	0.64	1.07	1.90
Usushwana Complex	5	0.47	0.60	0.32	0.16	0.70
Utrecht Granite	2	0.47	0.47	0.15	0.36	0.57
Vaalkoppies Group	5	6.95	1.10	9.14	1.10	9.53
Vaalputs Granite	4	1.14	1.13	0.53	0.78	1.50
Vaalwater Formation	11	0.19	0.00	0.26	0.00	0.40
Ventersdorp Supergroup	37	2.93	2.40	2.63	1.00	4.40
Vermont Formation	18	3.71	1.34	5.53	0.50	4.04
Villa Norra Anorthosite	24	3.55	2.75	2.53	1.55	4.99
Vlakfontein Subsuite	18	7.09	3.64	8.20	2.20	7.31
Volksrust Formation	952	3.60	2.25	3.75	1.00	5.13
Vryheid Formation	1668	2.44	1.20	3.73	0.30	3.18
Waterberg Group	106	1.53	0.65	2.22	0.20	1.90
Waterford Formation	13	3.42	3.30	1.38	2.40	4.20
Weltevrede Subgroup	89	2.48	1.60	4.25	0.90	2.80
Whitehill Formation	15	4.87	3.90	3.61	2.30	7.30
Wilge River Formation	150	0.63	0.30	1.76	0.10	0.50
Witwatersrand Supergroup	2	0.40	0.40	0.00	0.40	0.40
Wolkberg Group	8	0.49	0.15	0.66	0.00	0.90
Wyllies Poort Formation	51	2.33	0.70	4.68	0.30	1.59
Zoetveld Subsuite	2	3.56	3.56	0.44	3.25	3.87
Zululand Group	140	3.74	2.87	3.38	1.02	5.27

APPENDIX M: GEOLOGICAL REGIONS EXCHANGABLE CALCIUM ($cmol_ckg^{-1}$)

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Alexandria Formation	14	8.57	7.80	3.27	6.30	10.50
Allanridge Formation	78	5.89	3.50	5.95	2.10	7.00
Alldays Gneiss	305	4.87	3.40	4.15	1.80	6.80
Alluvium Sand and Calcrete	1641	7.09	5.56	7.73	1.70	9.90
Alma Formation	10	0.51	0.40	0.48	0.20	0.60
Amsterdam Formation	5	0.13	0.10	0.17	0.00	0.16
Augrabies Gneiss	46	5.27	3.63	3.75	2.94	7.48
Barberton Supergroup	77	4.02	2.90	2.87	2.10	5.20
Bandelierskop Complex	16	3.14	2.60	2.33	1.60	4.60
Basement Complex	480	2.92	1.21	3.95	0.50	3.75
Beaufort Group	2389	5.90	3.60	9.40	1.75	7.90
Berea Formation	73	1.15	0.75	1.69	0.30	1.40
Bidouw Subgroup	37	5.39	3.99	5.00	1.80	7.40
Bierkraal Magnetite Gabbro	86	6.86	5.80	3.63	4.80	8.10
Black Reef Formation	19	4.12	2.40	4.37	1.49	4.72
Bloempoort Group	5	7.33	9.80	4.08	3.75	10.30
Bokkeveld Group	46	6.23	2.56	14.90	1.08	4.80
Bosbokpoort Formation	10	1.77	1.70	0.63	1.27	2.31
Bothaville Formation	11	2.67	1.00	4.41	0.60	1.50
Brandwacht Formation	5	0.34	0.20	0.24	0.20	0.60
Bredasdorp Group	18	4.19	3.05	4.14	1.60	5.20
Buffelsfontein Group	3	10.90	2.53	14.60	2.40	27.80
Bulai Gneiss	26	7.93	7.50	3.75	4.90	11.40
Bumbeni Complex	19	6.26	2.96	8.72	1.30	10.30
Cape Granite Suite	104	3.99	1.20	15.10	0.70	3.05
Central Rand Group	3	1.09	0.64	1.34	0.02	2.60
Ceres Subgroup	123	3.06	1.90	3.65	0.50	4.20
Chuniespoort Group	2	2.81	2.81	0.99	2.11	3.51
Clarens Formation	214	8.56	6.70	7.18	3.28	11.60
Clermont Formation	9	1.78	0.40	2.88	0.20	0.60
Croydon Subsuite	42	5.14	3.84	5.49	1.55	6.67
Cunning Moor Tonalite	43	5.76	2.48	6.66	1.17	9.40
Dabreek Formation	2	3.45	3.45	0.50	3.10	3.80
Damwal Formation	18	0.99	0.70	0.88	0.30	1.20
Daspoort Formation	9	2.88	1.00	2.74	0.70	4.44
Dennilton Formation	3	1.44	1.20	0.48	1.13	2.00
Dominion Group	6	1.40	1.60	0.61	1.40	1.80
Drakensberg Group	155	7.57	2.90	9.95	0.50	10.80
Dsjate Subsuite	99	17.70	16.60	10.90	10.20	23.80
Duitschland Formation	2	13.30	13.30	4.38	10.20	16.40
Dwars River Subsuite	65	13.60	7.14	13.20	3.55	19.70
Dwyka Group	823	3.19	1.50	4.43	0.60	3.80
Ecca Group	529	4.81	2.95	5.14	1.20	7.10
Eendoorn Granite	39	6.46	6.60	2.87	4.40	7.70
Elliot Formation	154	5.08	2.68	8.35	1.13	6.50
Emakwezini Formation	130	8.13	6.71	5.23	4.16	10.40
Enon Formation	38	6.75	4.20	13.90	2.40	6.40
Fig Tree Group	9	2.65	1.60	3.56	0.20	2.30
Fort Brown Formation	78	6.89	6.35	3.42	4.80	8.80
Franschhoek Formation	4	0.85	0.76	0.33	0.60	1.10
Fundudzi Formation	7	5.89	7.19	3.04	3.30	7.78
Gaborone Granite	10	7.12	8.35	5.02	1.72	11.40
Gamtoos Group	6	0.53	0.40	0.37	0.20	1.00
Garies Subgroup	11	5.22	3.30	4.73	2.31	7.45
Geelvloer Group	32	4.94	4.05	2.65	3.00	6.60
Ghaap Group	29	8.32	5.68	7.56	1.60	13.20
Gifberg Group	18	5.50	2.65	6.35	0.72	9.52
Giyani Group	12	8.96	5.09	7.93	4.40	11.90
Gladkop Suite	9	4.43	4.20	2.27	2.40	6.50

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Godwan Group	3	0.27	0.20	0.31	0.00	0.60
Goudplaats Gneiss	387	4.50	3.10	4.82	1.60	5.80
Government Subgroup	10	1.10	0.58	1.39	0.40	0.88
Grasvally Norite-Anorthosite	43	5.67	2.90	7.65	1.89	6.53
Gravelotte Group	7	3.34	2.30	3.18	0.50	5.40
Groblershoop Formation	4	0.68	0.68	0.29	0.43	0.93
Grootderm Formation	9	8.50	7.40	5.60	4.50	9.50
Gumbu Group	12	10.80	6.35	11.70	1.15	20.00
Halfway House Granite	49	3.13	1.73	4.95	1.14	2.79
Harmony Granite	3	1.27	0.90	0.72	0.80	2.10
Hebron Pluton	4	0.52	0.15	0.86	0.00	1.05
Hekpoort Formation	106	2.83	0.40	5.03	0.20	3.46
Hlobane Complex	11	6.60	7.10	1.58	5.20	7.80
Hoogoor Suite	5	7.78	2.10	8.48	2.10	17.00
Hospital Hill Subgroup	5	2.12	0.61	2.40	0.47	4.72
Hout River Gneiss	126	3.29	2.17	3.42	1.20	3.90
Irrigasie Formation	24	5.45	3.72	4.84	1.14	9.80
Jeppestown Subgroup	13	2.60	2.31	1.27	1.74	3.08
Jozini Formation	62	9.96	7.96	7.30	4.62	13.00
Kaaimans Group	4	1.87	1.10	2.13	0.55	3.20
Kaap Valley Tonalite	29	2.18	0.50	3.84	0.00	1.80
Kalahari Group	204	4.92	2.03	5.96	0.98	6.70
Kameeldoorns Formation	4	2.32	1.85	1.10	1.71	2.93
Kango Group	2	7.55	7.55	2.62	5.70	9.40
Karoo	209	5.09	3.40	5.40	0.80	7.50
Karoo Dolerite Suite	1067	4.85	2.62	6.01	0.90	6.48
Kirkwood Formation	38	6.99	6.55	3.41	5.10	8.20
Klipriviersberg Group	15	2.84	2.16	2.19	1.40	2.70
Knersvlakte Subgroup	10	7.26	7.69	2.61	5.50	8.80
Koedoesberg Formation	9	10.50	9.00	5.98	6.35	14.70
Kookfontein Formation	4	9.10	9.75	2.79	6.90	11.30
Korannaland Group	12	6.94	4.83	4.05	4.41	10.30
Lake Mentz Subgroup	24	6.14	5.90	3.37	3.43	8.34
Lakenvalei Formation	12	1.84	1.54	2.53	0.15	2.20
Lebowa Granite Suite	278	4.54	2.13	6.13	1.00	5.00
Lekkersmaak Granite	5	2.02	0.90	1.91	0.60	4.00
Leococratic Biotite Granite	12	0.34	0.10	0.60	0.00	0.25
Letaba Formation	432	13.50	10.80	10.90	5.07	19.70
Leucocratic Biotite Granite	47	2.77	1.60	3.36	0.80	3.70
Leydsdorp Formation	5	4.28	4.90	1.49	3.50	5.00
Little Namaqualand Suite	205	5.34	4.10	6.20	2.55	6.80
Loskop Formation	15	1.20	0.75	1.15	0.46	1.42
Magaliesberg Formation	38	6.59	4.15	6.42	1.40	9.90
Makeckaan Subgroup	6	3.82	2.05	5.64	0.30	3.31
Makwassie Formation	12	12.60	14.10	4.72	7.45	17.00
Malala Drift Group	272	5.56	4.90	2.94	3.40	7.35
Malmani Subgroup	170	3.28	1.43	4.75	0.50	3.90
Malmesbury Group	7	1.04	0.70	1.02	0.20	2.10
Malmesbury Group	2	4.54	4.54	2.56	2.73	6.35
Mapumulo Group	218	2.16	0.90	2.97	0.30	3.20
Mashashane Suite	16	2.42	1.29	2.67	0.94	3.05
Matlabas Subgroup	119	4.20	2.00	4.59	1.00	6.00
Matok Granite	7	2.19	2.30	0.74	1.50	3.00
Mbotyi Formation	1	0.32	0.32	0.00	0.32	0.32
Meinhardskraal Granite	3	0.63	0.60	0.15	0.50	0.80
Messina Suite	33	6.63	6.00	3.83	3.31	8.40
Metanorite-Gabbro	35	2.89	2.00	2.93	1.00	4.10
Modipe Complex	13	8.56	8.90	5.40	3.60	11.80
Molteno Formation	538	4.78	2.40	7.62	1.00	5.80
Moodies Group	13	5.18	3.70	5.18	1.80	5.10
Moorreesburg Formation	39	1.77	1.00	2.56	0.46	2.31
Mount Dowe Group	85	5.22	4.90	2.68	3.10	7.60

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Mozaan Group	195	5.67	4.60	4.42	2.30	8.20
Mpluze Granite	152	1.32	0.38	3.21	0.17	0.87
Mulati Formation	6	4.72	4.40	1.22	4.10	5.50
Muzi Formation	27	1.97	1.10	2.01	0.40	2.90
Mzimkulu Group	2	0.60	0.60	0.56	0.20	0.99
Nama Group	12	6.85	1.40	9.48	0.89	11.30
Nanaga Formation	78	5.05	2.91	5.57	1.10	7.00
Nardouw Subgroup	160	1.48	0.52	2.20	0.27	1.65
Natal Group	431	1.15	0.50	2.05	0.20	1.10
Nelspruit Suite	97	2.54	1.03	6.30	0.47	2.28
Ngoye Complex	12	4.81	4.75	1.62	3.50	6.05
Nondweni Group	12	1.07	0.40	1.49	0.20	1.25
Nsuze Group	70	4.05	2.40	4.60	0.80	5.30
Ntabene Formation	28	8.79	7.05	6.51	3.80	10.40
Nyoka Formation	13	11.10	6.40	8.15	5.50	16.10
Nzhelele Formation	8	10.70	7.95	7.98	6.13	16.50
Olifantshoek Super Group	3	2.88	3.92	1.80	0.80	3.92
Ongeluk Formation	14	5.51	4.95	2.45	3.80	6.60
Onverwacht Group	27	5.20	5.60	3.68	2.13	8.50
Palala Granite	8	8.94	7.95	5.08	5.05	13.10
Palmietfontein Granite	3	0.00	0.00	0.00	0.00	0.00
Penge Formation	4	8.76	8.56	5.52	4.15	13.40
Peninsula Formation	60	0.62	0.35	0.97	0.15	0.75
Piekenierskloof Formation	6	1.03	0.82	0.74	0.48	1.78
Pienaars River Subprovince	11	7.06	5.45	3.95	3.72	9.85
Pietermaritzburg Formation	605	4.71	2.60	5.56	0.60	6.90
Pietersburg Group	46	3.53	2.95	2.92	1.40	4.80
Piketberg Formation	6	3.07	2.20	2.27	1.46	4.50
Pilanessberg Complex	8	6.06	5.16	3.17	4.19	8.70
Porseleinberg Formation	12	1.96	1.68	0.85	1.31	2.52
Port Durnford Formation	3	1.30	1.30	0.10	1.20	1.40
Port Nolloth Group	13	7.58	6.60	5.56	4.80	9.30
Porterville Formation	27	2.00	2.00	1.59	0.60	2.50
Post-Transvaal Diabases	67	5.65	4.60	3.82	3.30	6.60
Pretoria Group	68	1.74	0.30	3.37	0.20	0.97
Prince Albert Formation	58	16.00	12.30	15.60	8.02	21.20
Pyramid Gabbronorite	27	20.20	19.10	9.56	12.70	27.70
Rashoop Granophyre Suite	35	3.53	1.48	4.69	0.40	5.99
Raytonn Formation	16	6.66	7.14	4.21	2.67	9.70
Richtersveld Subprovince	17	7.94	6.30	5.35	3.70	11.30
Rietgat Formation	8	2.43	2.60	0.87	1.60	3.05
Rooiwater Complex	3	5.97	5.10	1.68	4.90	7.90
Roossenkal Subsuite	121	12.60	6.99	12.50	3.59	19.70
Salisbury Kop Pluton	15	5.02	1.40	5.77	0.60	10.40
Sand River Gneiss	18	5.55	5.80	2.53	3.50	7.60
Schiel Alkaline Complex	4	2.25	2.30	0.33	2.05	2.45
Selons River Formation	42	2.32	1.10	2.90	0.50	3.47
Silverton Formation	99	5.77	4.15	5.96	1.06	8.00
Solitude Formation	11	6.71	4.71	4.03	2.50	10.20
Soutpansberg Group	33	4.65	4.00	3.48	2.60	6.40
Spektakel Suite	15	2.93	1.32	4.95	0.80	2.30
Spitskop Complex	3	12.60	16.10	10.50	0.82	21.00
Steenkampsberg Formation	19	1.10	0.30	3.53	0.10	0.60
Sundays River Formation	57	9.38	8.30	7.18	6.60	10.60
Swaershoek Formation	8	0.46	0.35	0.42	0.15	0.80
Syenite	17	3.96	3.40	2.44	2.20	5.40
Tarkastad Subgroup	1915	4.72	2.86	5.24	1.32	6.42
Tierberg Formation	6	9.73	10.60	2.14	8.90	11.00
Timbavati Gabbro	9	11.50	12.90	5.85	9.86	15.20
Timeball Hill Formation	112	3.74	1.40	6.08	0.40	4.47
Traka Subgroup	7	8.42	6.91	4.29	5.90	9.87
Tugela Group	69	5.12	3.80	4.49	1.40	7.90

Geological Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Turffontein Subgroup	3	1.81	0.42	2.76	0.01	4.99
Turfloop Granite	68	2.89	2.10	2.59	1.23	3.70
Tygerberg Formation	14	2.18	2.06	1.42	0.80	3.35
Uloa Formation	5	10.10	2.62	11.30	1.89	18.40
Unnamed Granite and Gneiss	6	5.65	4.50	2.88	3.90	8.10
Usushwana Complex	5	0.50	0.20	0.54	0.18	0.80
Utrecht Granite	2	0.77	0.77	0.08	0.71	0.83
Vaalkoppies Group	5	19.60	13.10	23.80	1.60	22.30
Vaalputs Granite	4	4.02	4.03	0.65	3.60	4.43
Vaalwater Formation	11	0.39	0.30	0.37	0.10	0.50
Ventersdorp Supergroup	37	5.09	3.70	4.13	2.29	6.30
Vermont Formation	18	3.42	1.10	4.91	0.20	3.30
Villa Norra Anorthosite	25	17.30	10.50	17.90	5.30	18.70
Vlakfontein Subsuite	18	6.15	2.05	6.85	1.50	10.80
Volksrust Formation	949	6.18	4.31	6.28	1.60	9.40
Vryheid Formation	1668	3.22	1.60	4.24	0.50	4.40
Waterberg Group	106	3.98	0.98	7.34	0.30	3.80
Waterford Formation	13	6.58	5.50	4.79	3.70	7.30
Weltevrede Subgroup	89	4.29	3.20	4.80	1.31	5.10
Whitehill Formation	15	32.90	14.70	28.10	11.20	60.00
Wilge River Formation	150	1.09	0.58	1.77	0.32	1.00
Witwatersrand Supergroup	2	0.80	0.80	0.28	0.60	1.00
Wolkberg Group	8	1.00	0.30	1.30	0.20	1.70
Wyllies Poort Formation	51	3.93	0.90	7.14	0.40	2.53
Zoetveld Subsuite	2	7.10	7.10	1.25	6.21	7.98
Zululand Group	140	5.83	4.35	6.08	1.30	8.00

APPENDIX N: GROUNDWATER REGIONS EXCHANGABLE SODIUM $(\text{cmol}_c\text{kg}^{-1})$

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Algoa Basin	218	1.44	0.70	1.75	0.30	1.90
Bredasdorp Coastal Belt	9	0.97	0.70	1.32	0.10	1.20
Bushmanland	417	0.44	0.10	1.02	0.04	0.25
Bushmanland Pan Belt	105	2.06	0.60	3.98	0.20	1.30
Central Highveld	238	0.14	0.08	0.42	0.01	0.11
Central Pan Belt	320	1.70	0.20	5.46	0.10	0.75
Ciskeian Coastal Foreland and Middleveld	1560	0.69	0.25	1.30	0.11	0.66
Dry Harts-Vaal-Orange	466	1.47	0.60	2.28	0.18	1.60
Eastern Bankeveld	540	0.26	0.10	0.90	0.06	0.14
Eastern Bushveld Complex	600	0.33	0.10	1.22	0.06	0.20
Eastern Great Karoo	160	0.81	0.47	1.06	0.20	0.95
Eastern Highveld	930	0.34	0.10	0.73	0.03	0.23
Eastern Kalahari	88	0.14	0.10	0.19	0.06	0.10
Eastern Upper Karoo	110	1.10	0.20	3.00	0.10	0.50
Ghaap Plateau	36	0.21	0.09	0.57	0.01	0.12
Grootrivier-Klein Winterhoek-Suurberg-Ka	120	0.94	0.40	1.22	0.20	1.05
Hantam	33	2.15	0.61	2.44	0.30	3.40
Intermontane Tulbagh-Ashton Valley	45	1.28	0.54	1.86	0.28	1.70
Karst Belt	68	0.08	0.09	0.08	0.01	0.12
Knersvlakte	71	2.01	0.79	3.32	0.13	2.40
KwaZulu-Natal Coastal Foreland	1099	0.28	0.20	0.36	0.10	0.30
Limpopo Granulite Gneiss Belt	907	0.63	0.10	2.29	0.10	0.20
Limpopo Karoo Basin	219	0.93	0.30	1.60	0.12	0.81
Lower Gamtoos Valley	17	0.91	0.63	0.96	0.21	1.10
Lowveld	836	0.58	0.10	2.58	0.10	0.20
Makoppa Dome	179	0.43	0.10	1.26	0.10	0.20
Middelburg Basin	356	0.08	0.01	0.53	0.01	0.02
Namaqualand	198	1.23	0.40	2.33	0.20	1.10
Northeastern Middleveld	1501	0.29	0.10	0.78	0.09	0.20
Northeastern Pan Belt	199	0.42	0.10	0.87	0.06	0.20
Northeastern Upper Karoo	407	0.86	0.30	1.57	0.16	1.00
Northern Bushveld Complex	18	0.44	0.14	0.89	0.03	0.23
Northern Highland	134	0.43	0.20	0.79	0.10	0.40
Northern Lebombo	221	1.57	0.30	5.67	0.18	0.60
Northern Zululand Coastal Plain	433	0.82	0.14	2.15	0.09	0.52
Northwestern Cape Ranges	204	1.09	0.14	2.98	0.04	0.77
Northwestern Middleveld	2219	0.42	0.10	1.65	0.10	0.30
Oudtshoorn Basin	24	2.96	0.60	4.47	0.30	4.55
Outenikwa Coastal Foreland	41	0.76	0.30	0.98	0.20	0.70
Pietersburg Plateau	362	0.60	0.10	2.64	0.04	0.20
Richtersveld	88	2.99	1.20	4.45	0.40	3.15
Ruensveld	104	2.20	0.90	4.06	0.40	2.15
Southern Cape Ranges	233	0.66	0.30	0.95	0.13	0.70
Southern Highland	698	0.37	0.10	0.79	0.06	0.30
Southern Highveld	100	1.14	0.50	1.34	0.19	1.70
Southern Lebombo	789	1.48	0.40	2.76	0.20	1.10
Southwestern Cape Ranges	82	0.98	0.30	1.77	0.10	0.98
Southwestern Coastal Sandveld	81	0.55	0.13	0.85	0.07	0.70
Soutpansberg	105	0.31	0.10	0.93	0.10	0.20
Soutpansberg Hinterland	44	1.84	0.10	8.09	0.01	0.12
Springbok Flats	239	0.77	0.10	2.10	0.04	0.30
Stilbaai Coastal Belt	5	0.16	0.10	0.15	0.10	0.20
Swartland	220	0.53	0.12	0.90	0.07	0.49
Tanqua Karoo	83	2.95	1.53	4.56	0.70	3.50
Transkeian Coastal Foreland and Middleve	2233	0.26	0.13	0.61	0.07	0.24
Waterberg Coal Basin	87	0.80	0.10	2.15	0.01	0.30
Waterberg Plateau	344	0.25	0.10	0.84	0.01	0.20
West Griqualand	36	0.10	0.10	0.10	0.02	0.10
Western Bankeveld and Marico Bushveld	220	0.13	0.10	0.21	0.01	0.12

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Western Bushveld Complex	238	0.61	0.19	1.56	0.10	0.41
Western Great Karoo	63	1.27	0.50	2.37	0.20	0.90
Western Highveld	157	0.59	0.10	2.21	0.01	0.14
Western Kalahari	66	2.79	0.10	11.70	0.08	0.13
Western Upper Karoo	70	0.71	0.26	1.31	0.10	0.65

APPENDIX O: GROUNDWATER REGIONS EXCHANGABLE MAGNESIUM (cmol$_c$kg^{-1})

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Algoa Basin	218	2.75	2.40	1.87	1.32	3.80
Bredasdorp Coastal Belt	9	1.29	0.60	1.38	0.20	2.10
Bushmanland	409	1.43	1.19	1.18	0.80	1.70
Bushmanland Pan Belt	105	2.70	2.06	2.24	0.90	3.70
Central Highveld	238	1.94	0.92	2.85	0.45	2.12
Central Pan Belt	320	3.94	3.03	3.07	1.70	5.09
Ciskeian Coastal Foreland and Middleveld	1555	3.61	2.55	3.29	1.40	4.57
Dry Harts-Vaal-Orange	466	4.53	4.10	2.83	2.40	5.97
Eastern Bankeveld	540	2.57	1.20	3.92	0.10	3.70
Eastern Bushveld Complex	600	3.32	1.49	4.58	0.60	4.23
Eastern Great Karoo	160	3.40	2.70	1.99	2.00	4.48
Eastern Highveld	928	3.56	1.22	6.46	0.44	3.67
Eastern Kalahari	88	1.12	0.65	1.41	0.37	1.20
Eastern Upper Karoo	110	4.67	3.69	2.81	2.56	6.19
Ghaap Plateau	36	1.76	1.01	1.91	0.58	1.83
Grootrivier-Klein Winterhoek-Suurberg-Ka	120	2.57	1.70	3.84	0.90	3.10
Hantam	33	5.03	5.30	3.67	1.30	8.00
Intermontane Tulbagh-Ashton Valley	25	1.81	1.57	1.53	0.40	3.20
Karst Belt	68	2.07	1.10	4.42	0.50	1.82
Knersvlakte	71	2.46	1.89	2.60	0.55	3.40
KwaZulu-Natal Coastal Foreland	1099	2.06	1.23	2.47	0.40	2.70
Limpopo Granulite Gneiss Belt	906	2.22	1.70	1.73	0.90	3.00
Limpopo Karoo Basin	219	3.74	3.18	2.29	2.10	5.00
Lower Gamtoos Valley	9	1.70	1.30	1.16	0.70	2.79
Lowveld	828	2.25	1.30	3.09	0.52	2.75
Makoppa Dome	179	4.19	2.97	4.58	1.20	5.15
Middelburg Basin	356	0.48	0.20	1.27	0.00	0.42
Namaqualand	198	1.60	1.04	1.73	0.46	2.00
Northeastern Middleveld	1501	2.01	1.10	3.09	0.16	2.70
Northeastern Pan Belt	199	2.96	1.70	3.18	0.93	3.80
Northeastern Upper Karoo	378	6.29	5.50	4.66	2.20	9.10
Northern Bushveld Complex	18	2.76	1.72	3.61	1.10	2.41
Northern Highland	114	3.13	2.12	3.39	0.75	4.00
Northern Lebombo	221	5.58	5.23	3.59	2.82	7.60
Northern Zululand Coastal Plain	412	3.11	1.30	3.78	0.45	4.69
Northwestern Cape Ranges	198	1.43	0.40	2.34	0.12	2.00
Northwestern Middleveld	2220	2.60	1.30	4.66	0.30	3.20
Oudtshoorn Basin	24	2.10	1.75	1.62	0.85	3.25
Outenikwa Coastal Foreland	41	1.77	1.10	1.84	0.60	1.80
Pietersburg Plateau	362	2.41	1.60	2.72	0.82	3.02
Richtersveld	88	1.66	1.30	1.36	0.70	2.20
Ruensveld	78	2.82	2.05	2.94	0.97	3.70
Southern Cape Ranges	227	1.72	1.00	1.99	0.30	2.60
Southern Highland	700	3.76	1.69	4.78	0.76	4.80
Southern Highveld	100	5.44	4.70	4.09	1.90	8.10
Southern Lebombo	789	5.90	4.90	4.49	2.89	7.77
Southwestern Cape Ranges	69	0.87	0.30	1.14	0.10	1.40
Southwestern Coastal Sandveld	77	0.81	0.36	1.12	0.10	0.70
Soutpansberg	105	3.02	1.80	4.00	0.40	4.10
Soutpansberg Hinterland	44	2.69	1.51	2.74	0.77	3.36
Springbok Flats	239	4.81	2.53	5.28	1.27	7.91
Stilbaai Coastal Belt	5	0.60	0.20	0.85	0.20	0.40
Swartland	166	1.14	0.50	1.95	0.20	1.25
Tanqua Karoo	83	2.58	1.98	2.20	1.30	3.16
Transkeian Coastal Foreland and Middleve	2233	2.66	1.72	4.13	0.80	3.31
Waterberg Coal Basin	87	2.72	1.60	2.97	0.50	3.60
Waterberg Plateau	344	1.79	0.80	2.33	0.30	2.20
West Griqualand	36	1.59	1.18	1.37	0.68	2.05
Western Bankeveld and Marico Bushveld	220	3.62	2.60	4.35	0.68	4.40

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Western Bushveld Complex	229	6.69	4.10	6.59	2.20	8.98
Western Great Karoo	63	2.33	2.00	1.50	1.30	2.68
Western Highveld	149	2.09	1.50	1.97	0.80	2.66
Western Kalahari	76	0.88	0.64	0.79	0.41	1.11
Western Upper Karoo	70	3.56	2.89	2.64	1.62	4.30

APPENDIX P: GROUNDWATER REGIONS EXCHANGABLE CALCIUM ($\text{cmol}_c\text{kg}^{-1}$)

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Algoa Basin	218	7.84	7.00	5.77	4.50	9.90
Bredasdorp Coastal Belt	9	5.71	3.80	5.14	2.90	5.60
Bushmanland	409	5.26	4.34	3.68	2.69	7.00
Bushmanland Pan Belt	105	17.80	12.70	18.80	8.79	16.60
Central Highveld	238	3.35	2.29	3.84	1.11	4.16
Central Pan Belt	320	9.69	8.45	7.74	4.70	12.50
Ciskeian Coastal Foreland and Middleveld	1556	6.26	4.52	6.29	2.32	7.76
Dry Harts-Vaal-Orange	466	8.96	8.60	5.52	5.38	11.60
Eastern Bankeveld	540	4.66	1.31	6.60	0.20	6.92
Eastern Bushveld Complex	600	8.37	4.08	10.10	1.20	12.40
Eastern Great Karoo	160	8.10	7.80	3.32	5.58	10.20
Eastern Highveld	928	4.38	2.04	6.03	0.76	5.09
Eastern Kalahari	88	3.15	1.45	3.67	0.80	4.75
Eastern Upper Karoo	110	10.30	9.51	5.70	5.33	14.00
Ghaap Plateau	36	12.80	13.00	6.76	7.05	17.70
Grootrivier-Klein Winterhoek-Suurberg-Ka	120	4.90	3.75	4.54	2.00	6.55
Hantam	33	13.70	11.00	9.39	8.20	20.10
Intermontane Tulbagh-Ashton Valley	25	2.66	2.10	2.47	0.60	3.30
Karst Belt	68	4.05	1.86	5.69	1.10	4.02
Knersvlakte	71	5.61	3.00	6.77	0.80	8.80
KwaZulu-Natal Coastal Foreland	1099	2.32	0.99	3.34	0.30	2.90
Limpopo Granulite Gneiss Belt	907	5.74	4.60	5.20	2.53	7.80
Limpopo Karoo Basin	219	9.98	9.06	5.81	6.20	12.30
Lower Gamtoos Valley	9	3.18	3.60	1.70	1.80	4.50
Lowveld	829	3.92	2.39	4.85	1.00	5.07
Makoppa Dome	179	7.14	5.10	6.18	2.40	10.10
Middelburg Basin	356	0.87	0.45	1.38	0.30	0.84
Namaqualand	198	4.96	2.21	7.75	0.92	6.50
Northeastern Middleveld	1501	2.28	1.10	2.98	0.38	3.00
Northeastern Pan Belt	199	5.20	2.80	5.82	1.71	6.70
Northeastern Upper Karoo	378	9.53	8.37	7.84	4.50	11.90
Northern Bushveld Complex	18	7.23	3.70	10.90	2.04	6.49
Northern Highland	114	7.54	4.06	11.60	2.12	9.40
Northern Lebombo	221	11.40	10.00	8.42	5.00	15.80
Northern Zululand Coastal Plain	412	4.61	1.91	6.32	0.59	6.55
Northwestern Cape Ranges	198	3.19	0.78	6.78	0.25	3.14
Northwestern Middleveld	2214	3.60	1.70	8.74	0.50	4.70
Oudtshoorn Basin	24	8.77	5.40	17.30	3.10	7.35
Outenikwa Coastal Foreland	41	2.30	1.90	1.76	1.01	3.50
Pietersburg Plateau	362	3.61	2.30	4.15	1.22	4.30
Richtersveld	88	11.20	6.60	19.70	3.80	9.60
Ruensveld	78	5.02	3.00	11.60	1.02	4.76
Southern Cape Ranges	227	3.04	1.40	3.97	0.40	4.20
Southern Highland	700	5.91	2.91	8.18	1.17	7.28
Southern Highveld	100	7.35	6.65	5.30	2.70	10.00
Southern Lebombo	789	8.33	6.90	6.40	3.70	11.30
Southwestern Cape Ranges	69	0.89	0.50	1.60	0.30	0.90
Southwestern Coastal Sandveld	79	2.48	1.20	3.52	0.50	2.60
Soutpansberg	105	4.89	3.00	6.13	0.56	6.90
Soutpansberg Hinterland	44	7.49	4.00	8.71	2.30	10.40
Springbok Flats	239	11.50	5.89	12.50	2.39	18.20
Stilbaai Coastal Belt	5	2.28	1.10	2.96	1.00	1.60
Swartland	167	1.78	1.13	2.04	0.60	2.35
Tanqua Karoo	83	9.18	8.16	5.85	5.30	11.20
Transkeian Coastal Foreland and Middleve	2232	3.24	2.03	3.62	0.90	4.00
Waterberg Coal Basin	87	6.57	4.70	6.06	0.90	11.00
Waterberg Plateau	344	4.08	1.61	5.96	0.60	5.35
West Griqualand	36	4.32	2.95	4.53	1.46	5.56
Western Bankeveld and Marico Bushveld	220	4.95	3.35	6.38	1.27	6.20

Groundwater Region	Count	Average	Median	Standard deviation	Lower quartile	Upper quartile
Western Bushveld Complex	229	9.86	6.30	9.63	3.80	11.10
Western Great Karoo	63	8.92	7.60	5.93	4.80	11.00
Western Highveld	149	5.19	3.20	4.97	1.80	6.70
Western Kalahari	76	5.23	2.75	5.68	1.00	8.22
Western Upper Karoo	70	9.91	8.62	5.18	6.10	13.60

APPENDIX Q: Rainfall, evaporation and aridity class: Electrical Conductivity

Multiple Range Tests for Electrical Conductivity (mS m^{-1}) by Rainfall Class (mm)

Method: 95.0 percent Bonferroni

Rainfall Class	*Rain nr*	*Count*	*Mean*	*Homogeneous Groups*
>1000	7	1484	21.73	X
801-1000	6	4509	36.31	X
601-800	5	5586	59.67	X
401-600	4	4652	104.0	X
201-400	3	2685	262.3	X
101-200	2	934	530.5	X
<100	1	232	606.1	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		75.6	106.1
1 - 3	<*	343.8	99.02
1 - 4	<*	502.0	97.34
1 - 5	<*	546.4	96.95
1 - 6	<*	569.8	97.41
1 - 7	<*	584.4	102.2
2 - 3	<*	268.2	54.97
2 - 4	<*	426.4	51.88
2 - 5	<*	470.8	51.15
2 - 6	<*	494.2	52.02
2 - 7	<*	508.8	60.44
3 - 4	<*	158.2	35.07
3 - 5	<*	202.6	33.98
3 - 6	<*	226.0	35.27
3 - 7	<*	240.6	46.81
4 - 5	<*	44.37	28.72
4 - 6	<*	67.74	30.24
4 - 7	<*	82.32	43.14
5 - 6		23.36	28.97
5 - 7		37.95	42.26
6 - 7		14.59	43.3

* denotes a statistically significant difference.

An asterisk has been placed next to 17 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Electrical Conductivity (mS m^{-1}) by Evaporation Class (mm)

Method: 95.0 percent Bonferroni

Evaporation Class	*Evap nr*	*Count*	*Mean*	*Homogeneous Groups*
<1400	1	1980	27.93	X
1401-1600	2	4062	45.5	X
1601-1800	3	5197	88.08	X
1801-2000	4	2959	96.22	XX
2001-2200	5	2261	132.8	X
2201-2400	6	2239	231.3	X
>2401	7	1384	399.4	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-17.57	40.31
1 - 3	<*	-60.15	38.85
1 - 4	<*	-68.3	42.71
1 - 5	<*	-104.9	45.27
1 - 6	<*	-203.4	45.38
1 - 7	<*	-371.5	51.53

2 - 3	<*	-42.58	30.8
2 - 4	<*	-50.72	35.55
2 - 5	<*	-87.32	38.59
2 - 6	<*	-185.8	38.72
2 - 7	<*	-353.9	45.78
3 - 4		-8.145	33.87
3 - 5	<*	-44.74	37.06
3 - 6	<*	-143.3	37.18
3 - 7	<*	-311.4	44.49
4 - 5		-36.6	41.09
4 - 6	<*	-135.1	41.2
4 - 7	<*	-303.2	47.9
5 - 6	<*	-98.52	43.85
5 - 7	<*	-266.6	50.2
6 - 7	<*	-168.1	50.29

* denotes a statistically significant difference.
An asterisk has been placed next to 18 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Electrical Conductivity (mS m^{-1}) by Aridity zone
Method: 95.0 percent Bonferroni

Aridity zone	*Aridity Nr*	*Count*	*Mean*	*Homogeneous Groups*
Humid	5	2325	22.91	X
Dry Sub-humid	4	3360	40.68	X
Semi-Arid	3	9901	78.59	X
Arid	2	3819	264.5	X
Hyper-Arid	1	677	554.6	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	290.1	56.15
1 - 3	<*	476.0	53.49
1 - 4	<*	513.9	56.73
1 - 5	<*	531.7	58.81
2 - 3	<*	185.9	25.65
2 - 4	<*	223.8	31.85
2 - 5	<*	241.6	35.42
3 - 4	<*	37.92	26.89
3 - 5	<*	55.68	31.03
4 - 5		17.76	36.33

* denotes a statistically significant difference.
An asterisk has been placed next to 9 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APPENDIX R: Rainfall, evaporation and aridity classes ESP

Multiple Range Tests for ESP by Rainfall Class (mm)

Method: 95.0 percent Bonferroni

Rainfall Class	*Rain nr*	*Count*	*Mean*	*Homogeneous Groups*
801-1000	6	4720	2.922	X
>1000	7	1498	3.047	X
601-800	5	5957	3.998	X
401-600	4	4913	5.93	X
201-400	3	2730	12.68	X
101-200	2	952	19.13	X
<100	1	232	34.21	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	15.09	5.378
1 - 3	<*	21.53	5.023
1 - 4	<*	28.28	4.935
1 - 5	<*	30.21	4.915
1 - 6	<*	31.29	4.939
1 - 7	<*	31.17	5.182
2 - 3	<*	6.442	2.765
2 - 4	<*	13.2	2.601
2 - 5	<*	15.13	2.564
2 - 6	<*	16.2	2.61
2 - 7	<*	16.08	3.044
3 - 4	<*	6.755	1.753
3 - 5	<*	8.687	1.698
3 - 6	<*	9.763	1.766
3 - 7	<*	9.638	2.362
4 - 5	<*	1.932	1.416
4 - 6	<*	3.008	1.497
4 - 7	<*	2.883	2.168
5 - 6		1.076	1.431
5 - 7		0.9511	2.123
6 - 7		-0.1249	2.178

* denotes a statistically significant difference.

An asterisk has been placed next to 18 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level

Multiple Range Tests for ESP by Evaporation Class (mm)

Method: 95.0 percent Bonferroni

Evaporation Class	*Evap nr*	*Count*	*Mean*	*Homogeneous Groups*
1401-1600	2	4364	3.503	X
<1400	1	2099	3.673	XX
1601-1800	3	5334	5.503	XX
1801-2000	4	3044	5.697	XX
2001-2200	5	2414	6.789	X
2201-2400	6	2355	9.298	X
>2401	7	1392	17.32	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		0.1693	1.975
1 - 3		-1.83	1.916
1 - 4		-2.025	2.11
1 - 5	<*	-3.116	2.219
1 - 6	<*	-5.625	2.232
1 - 7	<*	-13.64	2.57
2 - 3	<*	-1.999	1.518
2 - 4	<*	-2.194	1.756
2 - 5	<*	-3.285	1.886
2 - 6	<*	-5.794	1.901

2 - 7	<*	-13.81	2.289
3 - 4		-0.1947	1.689
3 - 5		-1.286	1.824
3 - 6	<*	-3.795	1.84
3 - 7	<*	-11.81	2.238
4 - 5		-1.091	2.027
4 - 6	<*	-3.6	2.041
4 - 7	<*	-11.62	2.406
5 - 6	<*	-2.509	2.154
5 - 7	<*	-10.53	2.503
6 - 7	<*	-8.018	2.514

* denotes a statistically significant difference.
An asterisk has been placed next to 15 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for ESP by Aridity zone
Method: 95.0 percent Bonferroni

Aridity zone	*AridNr*	*Count*	*Mean*	*Homogeneous Groups*
Humid	5	2407	2.884	X
Dry Sub-humid	4	3586	3.231	X
Semi-Arid	3	10397	4.856	X
Arid	2	3935	11.28	X
Hyper-Arid	1	677	27.59	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	16.31	2.831
1 - 3	<*	22.73	2.699
1 - 4	<*	24.36	2.851
1 - 5	<*	24.7	2.96
2 - 3	<*	6.422	1.273
2 - 4	<*	8.047	1.571
2 - 5	<*	8.394	1.76
3 - 4	<*	1.626	1.318
3 - 5	<*	1.972	1.539
4 - 5		0.3467	1.793

* denotes a statistically significant difference.
An asterisk has been placed next to 9 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APENDIX S: Rainfall, evaporation and aridity classes-pH$_{WATER}$

Multiple Range Tests for PH_H2O by Rainfall Class (mm)

Method: 95.0 percent Bonferroni

Rainfall Class	*Rain nr*	*Count*	*Mean*	*Homogeneous Groups*
>1000	7	1524	5.6	X
801-1000	6	4745	5.89	X
601-800	5	6273	6.319	X
401-600	4	4891	7.09	X
201-400	3	2713	7.771	X
101-200	2	962	8.102	X
<100	1	232	8.376	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	0.2741	0.2165
1 - 3	<*	0.6055	0.2025
1 - 4	<*	1.286	0.1989
1 - 5	<*	2.058	0.1979
1 - 6	<*	2.486	0.1991
1 - 7	<*	2.777	0.2086
2 - 3	<*	0.3313	0.1111
2 - 4	<*	1.012	0.1044
2 - 5	<*	1.783	0.1025
2 - 6	<*	2.212	0.1047
2 - 7	<*	2.502	0.1219
3 - 4	<*	0.6806	0.07087
3 - 5	<*	1.452	0.06803
3 - 6	<*	1.881	0.07126
3 - 7	<*	2.171	0.09477
4 - 5	<*	0.7715	0.05647
4 - 6	<*	1.2	0.06032
4 - 7	<*	1.491	0.08685
5 - 6	<*	0.4286	0.05696
5 - 7	<*	0.7191	0.08455
6 - 7	<*	0.2904	0.08717

* denotes a statistically significant difference.

An asterisk has been placed next to 21 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for PH_H2O by Evaporation Class (mm)

Method: 95.0 percent Bonferroni

Evaporation Class	*Evap nr*	*Count*	*Mean*	*Homogeneous Groups*
<1400	1	2157	5.788	X
1401-1600	2	4423	6.031	X
1801-2000	4	3163	6.487	X
1601-1800	3	5355	6.631	X
2001-2200	5	2521	7.008	X
2201-2400	6	2327	7.543	X
>2401	7	1394	8.043	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	-0.243	0.08493
1 - 3	<*	-0.8429	0.08248
1 - 4	<*	-0.6993	0.09031
1 - 5	<*	-1.22	0.09486
1 - 6	<*	-1.755	0.09666
1 - 7	<*	-2.255	0.1111
2 - 3	<*	-0.5999	0.06571
2 - 4	<*	-0.4564	0.07531
2 - 5	<*	-0.9766	0.08071
2 - 6	<*	-1.512	0.08282
2 - 7	<*	-2.012	0.09934

3 - 4	<*	0.1435	0.07253
3 - 5	<*	-0.3767	0.07812
3 - 6	<*	-0.9124	0.0803
3 - 7	<*	-1.412	0.09724
4 - 5	<*	-0.5202	0.08635
4 - 6	<*	-1.056	0.08833
4 - 7	<*	-1.556	0.104
5 - 6	<*	-0.5357	0.09297
5 - 7	<*	-1.036	0.1079
6 - 7	<*	-0.4999	0.1095

* denotes a statistically significant difference.

An asterisk has been placed next to 21 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for PH_H2O by Aridity zone

Method: 95.0 percent Bonferroni

Aridity Zone	*AridNr*	*Count*	*Mean*	*Homogeneous Groups*
Humid	5	2478	5.645	X
Dry Sub-humid	4	3537	5.976	X
Semi-Arid	3	10751	6.604	X
Arid	2	3897	7.669	X
Hyper-Arid	1	677	8.282	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	0.6132	0.1199
1 - 3	<*	1.677	0.1141
1 - 4	<*	2.305	0.1208
1 - 5	<*	2.636	0.1249
2 - 3	<*	1.064	0.05386
2 - 4	<*	1.692	0.0669
2 - 5	<*	2.023	0.07401
3 - 4	<*	0.628	0.05584
3 - 5	<*	0.9591	0.06419
4 - 5	<*	0.3311	0.07546

* denotes a statistically significant difference.

An asterisk has been placed next to 10 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APPENDIX T: RAINFALL, EVAPORATION AND ARIDTITY CLASS CALCIUM ($cmol_c kg^{-1}$)

Multiple Range Tests for Ca ($cmol_c$ kg^{-1}) by Rainfall Class (mm)

Method: 95.0 percent Bonferroni

Rainfall Class	*Rain nr*	*Count*	*Mean*	*Homogeneous Groups*
>1000	7	1602	1.922	X
801-1000	6	5103	3.13	X
601-800	5	6595	4.763	X
401-600	4	4814	6.958	X
<100	1	230	7.545	XX
101-200	2	935	7.688	XX
201-400	3	2587	7.879	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-0.143	1.506
1 - 3		-0.3346	1.408
1 - 4		0.5869	1.381
1 - 5	<*	2.782	1.372
1 - 6	<*	4.415	1.379
1 - 7	<*	5.623	1.442
2 - 3		-0.1915	0.7806
2 - 4		0.7299	0.7311
2 - 5	<*	2.925	0.7148
2 - 6	<*	4.558	0.7277
2 - 7	<*	5.766	0.8419
3 - 4	<*	0.9215	0.4987
3 - 5	<*	3.117	0.4745
3 - 6	<*	4.75	0.4937
3 - 7	<*	5.958	0.6503
4 - 5	<*	2.195	0.3878
4 - 6	<*	3.828	0.411
4 - 7	<*	5.036	0.59
5 - 6	<*	1.633	0.3814
5 - 7	<*	2.841	0.5698
6 - 7	<*	1.208	0.5858

* denotes a statistically significant difference.

An asterisk has been placed next to 16 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Ca ($cmol_c$ kg^{-1}) by Evaporation Class (mm)

Method: 95.0 percent Bonferroni

Evaporation Class	*Evap nr*	*Count*	*Mean*	*Homogeneous Groups*
<1400	1	2219	2.368	X
1401-1600	2	4665	3.521	X
1801-2000	4	3184	4.751	X
1601-1800	3	5669	5.248	X
2001-2200	5	2442	6.804	X
2201-2400	6	2321	8.028	X
>2401	7	1366	8.385	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	-1.153	0.5303
1 - 3	<*	-2.88	0.515
1 - 4	<*	-2.383	0.5687
1 - 5	<*	-4.436	0.6031
1 - 6	<*	-5.66	0.6106

1 - 7	<*	-6.017	0.7072
2 - 3	<*	-1.727	0.4065
2 - 4	<*	-1.231	0.4727
2 - 5	<*	-3.283	0.5136
2 - 6	<*	-4.508	0.5224
2 - 7	<*	-4.864	0.6326
3 - 4	<*	0.4966	0.4554
3 - 5	<*	-1.556	0.4978
3 - 6	<*	-2.78	0.5068
3 - 7	<*	-3.137	0.6198
4 - 5	<*	-2.053	0.5532
4 - 6	<*	-3.277	0.5613
4 - 7	<*	-3.634	0.6651
5 - 6	<*	-1.224	0.5961
5 - 7	<*	-1.581	0.6948
6 - 7		-0.3567	0.7013

* denotes a statistically significant difference.
An asterisk has been placed next to 20 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Ca ($\text{cmol}_c\ \text{kg}^{-1}$) by Aridity Zone

Method: 95.0 percent Bonferroni

Aridity Zone	*AridNr*	*Count*	*Mean*	*Homogeneous Groups*
Humid	5	2558	2.065	X
Dry Sub-humid	4	3879	3.441	X
Semi-Arid	3	10967	5.471	X
Hyper-Arid Arid	1	664	7.077	X
Arid	2	3798	7.88	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	-0.8026	0.8003
1 - 3	<*	1.606	0.7604
1 - 4	<*	3.637	0.799
1 - 5	<*	5.012	0.8286
2 - 3	<*	2.408	0.3582
2 - 4	<*	4.439	0.4343
2 - 5	<*	5.815	0.4866
3 - 4	<*	2.031	0.3554
3 - 5	<*	3.407	0.4177
4 - 5	<*	1.376	0.4846

* denotes a statistically significant difference.
An asterisk has been placed next to 10 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APPENDIX U: RAINFALL, EVAPORATION AND ARIDITY CLASS MAGNESIUM (cmol$_c$kg^{-1})

Multiple Range Tests for Mg (cmol $_c$ kg^{-1}) by Rainfall Class (mm)

Method: 95.0 percent Bonferroni

Rainfall Class	*Rain nr*	*Count*	*Mean*	*Homogeneous Groups*
<100	1	230	1.524	X
>1000	7	1602	1.724	X
101-200	2	935	2.025	XX
801-1000	6	5109	2.404	X
601-800	5	6595	3.242	X
201-400	3	2585	3.257	X
401-600	4	4811	3.627	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-0.5012	0.8667
1 - 3	<*	-1.733	0.8103
1 - 4	<*	-2.103	0.7948
1 - 5	<*	-1.718	0.7899
1 - 6	<*	-0.8799	0.7937
1 - 7		-0.2	0.8303
2 - 3	<*	-1.232	0.4494
2 - 4	<*	-1.602	0.4209
2 - 5	<*	-1.216	0.4115
2 - 6		-0.3787	0.4189
2 - 7		0.3012	0.4846
3 - 4	<*	-0.3694	0.2872
3 - 5		0.01578	0.2733
3 - 6	<*	0.8535	0.2842
3 - 7	<*	1.533	0.3744
4 - 5	<*	0.3852	0.2233
4 - 6	<*	1.223	0.2366
4 - 7	<*	1.903	0.3397
5 - 6	<*	0.8377	0.2195
5 - 7	<*	1.518	0.328
6 - 7	<*	0.6799	0.3372

* denotes a statistically significant difference.

An asterisk has been placed next to 16 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Mg (cmol $_c$ kg^{-1}) by Evaporation Class (mm)

Method: 95.0 percent Bonferroni

Evaporation Class	*Evap nr*	*Count*	*Mean*	*Homogeneous Groups*
<1401	1	2219	2.018	X
1601-1800	2	4671	2.464	X
>2401	7	1365	2.67	XX
1801-2000	4	3183	2.98	X
2001-2200	5	2442	3.33	X
2201-2400	6	2319	3.406	X
1601-1800	3	5668	3.42	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	-0.4466	0.305
1 - 3	<*	-1.402	0.2962
1 - 4	<*	-0.9625	0.3271
1 - 5	<*	-1.312	0.3469
1 - 6	<*	-1.388	0.3513
1 - 7	<*	-0.6523	0.4069
2 - 3	<*	-0.9553	0.2338

2 - 4	<*	-0.5159	0.2719
2 - 5	<*	-0.8658	0.2954
2 - 6	<*	-0.9411	0.3005
2 - 7		-0.2057	0.364
3 - 4	<*	0.4394	0.262
3 - 5		0.08952	0.2863
3 - 6		0.01415	0.2916
3 - 7	<*	0.7496	0.3566
4 - 5	<*	-0.3498	0.3182
4 - 6	<*	-0.4252	0.323
4 - 7		0.3102	0.3827
5 - 6		-0.07536	0.343
5 - 7	<*	0.6601	0.3998
6 - 7	<*	0.7354	0.4035

* denotes a statistically significant difference.
An asterisk has been placed next to 16 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Mg (cmol $_c$ kg^{-1}) by Aridity Zone

Method: 95.0 percent Bonferroni

Aridity zone	*AridNr*	*Count*	*Mean*	*Homogeneous Groups*
Hyper-Arid Arid	1	664	1.532	X
Humid	5	2558	1.813	X
Dry Sub-humid	4	3885	2.619	X
Arid	2	3795	3.067	X
Semi-Arid	3	10965	3.38	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	-1.536	0.4584
1 - 3	<*	-1.849	0.4355
1 - 4	<*	-1.087	0.4576
1 - 5		-0.2814	0.4746
2 - 3	<*	-0.3129	0.2052
2 - 4	<*	0.4486	0.2487
2 - 5	<*	1.254	0.2788
3 - 4	<*	0.7615	0.2035
3 - 5	<*	1.567	0.2393
4 - 5	<*	0.8057	0.2775

* denotes a statistically significant difference.
An asterisk has been placed next to 9 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APPENDIX V: RAINFALL, EVAPORATION AND ARIDTY CLASS SODIUM (cmol$_c$kg^{-1})

Multiple Range Tests for Na (cmol $_c$ kg^{-1}) by Rainfall Class (mm)

Method: 95.0 percent Bonferroni

Rainfall Class	*Rain nr*	*Count*	*Mean*	*Homogeneous Groups*
>1000	7	1608	0.2416	X
801-1000	6	5110	0.3546	X
601-800	5	6660	0.4934	X
401-600	4	4890	0.677	X
101-200	2	937	1.249	X
201-400	3	2665	1.253	X
<100	1	232	1.841	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	0.5923	0.4436
1 - 3	<*	0.5885	0.4141
1 - 4	<*	1.164	0.4065
1 - 5	<*	1.348	0.404
1 - 6	<*	1.487	0.4061
1 - 7	<*	1.599	0.4248
2 - 3		-0.003798	0.2297
2 - 4	<*	0.5718	0.2157
2 - 5	<*	0.7553	0.2111
2 - 6	<*	0.8942	0.215
2 - 7	<*	1.007	0.2486
3 - 4	<*	0.5756	0.1457
3 - 5	<*	0.7591	0.1387
3 - 6	<*	0.898	0.1445
3 - 7	<*	1.011	0.191
4 - 5	<*	0.1835	0.1139
4 - 6	<*	0.3224	0.121
4 - 7	<*	0.4354	0.1739
5 - 6	<*	0.1389	0.1125
5 - 7	<*	0.2519	0.1681
6 - 7		0.113	0.173

* denotes a statistically significant difference.

An asterisk has been placed next to 19 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Na (cmol $_c$ kg^{-1}) by Evaporation Class (mm)

Method: 95.0 percent Bonferroni

Evaporation Class	*Evap nr*	*Count*	*Mean*	*Homogeneous Groups*
<1400	1	2223	0.2811	X
1401-1600	2	4683	0.4095	X
1801-2000	4	3237	0.5735	X
1601-1800	3	5744	0.614	X
2001-2200	5	2506	0.6942	X
2201-2401	6	2345	0.9609	X
>2401	7	1364	1.33	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-0.1283	0.1567
1 - 3	<*	-0.3329	0.152
1 - 4	<*	-0.2923	0.1676
1 - 5	<*	-0.4131	0.1773

1 - 6	<*	-0.6798	0.1801
1 - 7	<*	-1.048	0.2093
2 - 3	<*	-0.2046	0.1198
2 - 4	<*	-0.164	0.1391
2 - 5	<*	-0.2847	0.1506
2 - 6	<*	-0.5514	0.1539
2 - 7	<*	-0.9201	0.1872
3 - 4		0.04057	0.1337
3 - 5		-0.08016	0.1457
3 - 6	<*	-0.3469	0.1491
3 - 7	<*	-0.7156	0.1833
4 - 5		-0.1207	0.1619
4 - 6	<*	-0.3875	0.165
4 - 7	<*	-0.7562	0.1964
5 - 6	<*	-0.2667	0.1748
5 - 7	<*	-0.6354	0.2048
6 - 7	<*	-0.3687	0.2072

* denotes a statistically significant difference.

An asterisk has been placed next to 17 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Na (cmol $_c$ kg^{-1}) by Arid Zones

Method: 95.0 percent Bonferroni

Aridity Zone	*AridNr*	*Count*	*Mean*	*Homogeneous Groups*
Humid	5	2564	0.2555	X
Dry-Sub-humid	4	3887	0.3966	X
Semi-Arid	3	11119	0.5622	X
Arid	2	3857	1.125	X
Hyper-Arid	1	675	1.403	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	0.278	0.2339
1 - 3	<*	0.8404	0.2222
1 - 4	<*	1.006	0.2338
1 - 5	<*	1.147	0.2425
2 - 3	<*	0.5624	0.1048
2 - 4	<*	0.728	0.1274
2 - 5	<*	0.8691	0.1428
3 - 4	<*	0.1656	0.1045
3 - 5	<*	0.3067	0.1228
4 - 5		0.1411	0.1426

* denotes a statistically significant difference.

An asterisk has been placed next to 9 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APPENDIX W: Elevation and slope electrical conductivity

Multiple Range Tests for Electrical Conductivity for different elevation classes

Method: 95.0 percent Bonferroni

Elevation Classes	*Elevation Class No*	*Count*	*Mean*	*Homogeneous Groups*
>1999	1	171	20	XX
1500-1999	2	2617	42	X
1000-1499	3	6697	80	X
500-999	4	6139	129	X
<500	5	4287	203	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-21.7	109.1
1 - 3		-59.88	107.0
1 - 4	<*	-108.8	107.2
1 - 5	<*	-183.0	107.8
2 - 3	<*	-38.18	31.87
2 - 4	<*	-87.08	32.27
2 - 5	<*	-161.3	34.29
3 - 4	<*	-48.9	24.42
3 - 5	<*	-123.1	27.04
4 - 5	<*	-74.17	27.51

* denotes a statistically significant difference. An asterisk has been placed next to 8 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for Electrical Conductivity for different Slope Classes

Method: 95.0 percent Bonferroni

Slope Classes	*Slope Class No.*	*Count*	*Mean*	*Homogeneous Groups*
>20	1	641	40	X
10-19.9	2	1526	45	X
5.0-9.9	3	2651	84	XX
2.5-4.9	4	3104	116	XX
1.5-2.4	5	2122	160	XX
1-1.4	6	1367	176	XX
< 1	7	1329	221	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-5.092	73.71
1 - 3		-43.82	68.93
1 - 4	<*	-76.32	67.94
1 - 5	<*	-119.5	70.58
1 - 6	<*	-135.8	74.97
1 - 7	<*	-181.0	75.31
2 - 3		-38.73	50.32
2 - 4	<*	-71.23	48.96
2 - 5	<*	-114.4	52.56
2 - 6	<*	-130.7	58.32
2 - 7	<*	-175.9	58.76
3 - 4		-32.51	41.42
3 - 5	<*	-75.72	45.62
3 - 6	<*	-91.94	52.15
3 - 7	<*	-137.2	52.64
4 - 5		-43.21	44.11
4 - 6	<*	-59.43	50.84
4 - 7	<*	-104.6	51.34
5 - 6		-16.23	54.31
5 - 7	<*	-61.44	54.78
6 - 7		-45.21	60.33

* denotes a statistically significant difference. An asterisk has been placed next to 14 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APPENDIX X: Elevation and slope -

Multiple Range Tests for ESP by elevation class

Method: 95.0 percent Bonferroni

Elevation Class	*Elevation No*	*Count*	*Mean*	*Homogeneous Groups*
>1999	1	162	1.6	XX
1500-1999	2	2705	2.8	X
1000-1499	3	7497	4.1	X
500-999	4	6357	6.2	X
<500	5	3899	13.0	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-1.161	5.605
1 - 3		-2.535	5.503
1 - 4		-4.567	5.513
1 - 5	<*	-11.42	5.556
2 - 3		-1.374	1.554
2 - 4	<*	-3.405	1.591
2 - 5	<*	-10.25	1.734
3 - 4	<*	-2.031	1.181
3 - 5	<*	-8.881	1.368
4 - 5	<*	-6.849	1.41

* denotes a statistically significant difference.

An asterisk has been placed next to 6 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for ESP by Slope Class

Method: 95.0 percent Bonferroni

Slope Class	*Slope No*	*Count*	*Mean*	*Homogeneous Groups*
>20	1	608	2.7	X
10-19.9	2	1512	3.3	X
5.0-9.9	3	2573	5.2	X
2.5-4.9	4	3067	7.6	X
1.5-2.4	5	2090	8.1	X
1-1.4	6	1372	8.4	XX
< 1	7	1310	11.2	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		-0.552	3.925
1 - 3		-2.463	3.685
1 - 4	<*	-4.851	3.628
1 - 5	<*	-5.405	3.766
1 - 6	<*	-5.657	3.982
1 - 7	<*	-8.418	4.01
2 - 3		-1.911	2.648
2 - 4	<*	-4.299	2.568
2 - 5	<*	-4.853	2.759
2 - 6	<*	-5.105	3.047
2 - 7	<*	-7.866	3.085
3 - 4	<*	-2.388	2.185
3 - 5	<*	-2.942	2.407
3 - 6	<*	-3.194	2.732
3 - 7	<*	-5.955	2.774
4 - 5		-0.5543	2.318
4 - 6		-0.806	2.654
4 - 7	<*	-3.567	2.697
5 - 6		-0.2518	2.84
5 - 7	<*	-3.013	2.88
6 - 7		-2.761	3.157

* denotes a statistically significant difference.

An asterisk has been placed next to 14 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

APPENDIX Y: elevation and slope - pH$_{water}$

Multiple Range Tests for pH$_{water}$ by Elevation Class

Method: 95.0 percent Bonferroni

Elevation No	*Elevation Class*	*Count*	*Mean*	*Homogeneous Groups*
1	>1999	69	5.5	X
2	1500-1999	2733	5.9	X
3	1000-1499	7503	6.5	X
4	500-999	6552	6.9	X
5	<500	4482	6.9	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2	<*	-0.437	0.4068
1 - 3	<*	-1.007	0.4036
1 - 4	<*	-1.362	0.4039
1 - 5	<*	-1.434	0.4048
2 - 3	<*	-0.5698	0.07456
2 - 4	<*	-0.9248	0.07599
2 - 5	<*	-0.9972	0.08099
3 - 4	<*	-0.355	0.05643
3 - 5	<*	-0.4274	0.063
4 - 5	<*	-0.07234	0.06469

* denotes a statistically significant difference.
An asterisk has been placed next to 10 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.

Multiple Range Tests for pH$_{water}$ by Slope Class

Method: 95.0 percent Bonferroni

Slope No	*Slope Class*	*Count*	*Mean*	*Homogeneous Groups*
2	10-19.9	1584	6.0	X
1	>20	662	6.1	X
3	5.0-9.9	2819	6.3	X
4	2.5-4.9	3314	6.6	X
5	1.5-2.4	2233	7.0	X
6	1-1.4	1452	7.2	X
7	< 1	1392	7.3	X

Contrast	*Sig.*	*Difference*	*+/- Limits*
1 - 2		0.03631	0.1643
1 - 3	<*	-0.2244	0.1534
1 - 4	<*	-0.5559	0.1512
1 - 5	<*	-0.9758	0.1571
1 - 6	<*	-1.151	0.1665
1 - 7	<*	-1.252	0.1677
2 - 3	<*	-0.2607	0.1115
2 - 4	<*	-0.5922	0.1085
2 - 5	<*	-1.012	0.1167
2 - 6	<*	-1.187	0.129
2 - 7	<*	-1.289	0.1305
3 - 4	<*	-0.3315	0.09098
3 - 5	<*	-0.7514	0.1006
3 - 6	<*	-0.9265	0.1147
3 - 7	<*	-1.028	0.1163
4 - 5	<*	-0.42	0.09722
4 - 6	<*	-0.595	0.1118
4 - 7	<*	-0.6964	0.1134
5 - 6	<*	-0.175	0.1197
5 - 7	<*	-0.2764	0.1213
6 - 7		-0.1013	0.1332

* denotes a statistically significant difference. An asterisk has been placed next to 19 pairs, indicating that these pairs show statistically significant differences at the 95.0% confidence level.