THE CONTENT AND BEHAVIOUR OF NATURAL RADIONUCLIDES IN BASEMENT-HOSTED GROUNDWATER FROM VAALPUTS, NAMAQUALAND, SOUTH AFRICA

by

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This thesis is dedicated to my wonderful, loving parents (both teachers) who inspired and encouraged me right from the beginning. To my mom, Elica, for her curiosity, sparking my interest in science, and to my dad, Jan, for his exemplary hard work and determination.

Declaration

I, Huibrecht Catharina Florina Pretorius, declare that the dissertation hereby submitted for the qualification: M.Sc Geology, at the University of the Free State, is my own independent work and I have not previously submitted the same work for a qualification at/in another university or faculty.

_____ 27 January 2012

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Abstract

Vaalputs, the South African radioactive waste disposal facility, is currently licensed to dispose only low and intermediate level radioactive waste. The repository has been disposing radioactive waste since 1986; however, up until May 2011 no long-lived uranium containing waste has been delivered to Vaalputs. The Nuclear Energy Corporation of South Africa (Necsa) has foreseen this disposal and so ordered this study to establish a baseline for the behaviour of naturally occurring radionuclides from the uranium and thorium decay chains in the groundwater of Vaalputs. This baseline will be used to monitor the groundwater below Vaalputs for possible anthropogenic additions to the environmental radioactivity.

This baseline was established by studying a unique dataset of 25 years of analysis of activities of man-made and naturally occurring radionuclides as well as cation and anion concentrations in the groundwater at Vaalputs. This database is the result of annual monitoring of the groundwater from a confined set of boreholes on and around the facility as part of the regulatory requirements of radioactive disposal.

The analytical results of radionuclides in groundwater from 13 annually and 3 quarterly sampled boreholes have been evaluated during this study. Cation and anion concentrations were measured respectively by inductively coupled plasma optical emission spectrometry and ion chromatography. In routine analyses the activities of the long-lived radionuclides ^{238}U and ^{232}Th were measured by instrumental neutron activation analysis, while the short-lived radionuclide ^{226}Ra was detected by γ-ray spectrometry. The overall radioactivity hazard from total α and β radiation levels were measured by gas flow proportional counting. On occasion groundwater samples have been analysed by α-spectrometry to determine the activities of α-emitting radionuclides from the decay chains of ^{238}U, ^{235}U and ^{232}Th. These analytical results have been integrated in order to evaluate trends in activities of radionuclides, the relative contributions of individual radionuclides to total radiation levels and how these are influenced by groundwater conditions.

^{238}U levels show a natural anomaly in the near-field of the disposal site, attributed to basement rocks anomalously enriched in uranium located close to the disposal trenches. This should be taken into consideration when monitoring the groundwater for possible additions of uranium. One set of duplicate samples from 2009 has been analysed by alpha spectrometry, determining an average activity ratio of $^{234}U/^{238}U$ in the groundwater of Vaalputs as 4.1. This average ratio has been used in the rest of the study for comparison of the contribution of ^{234}U to total α radiation with the contribution of the other α-emitting radionuclides. However, it is suggested that a more extensive experiment should be carried out to determine a statistically representative activity ratio for the different areas at Vaalputs.

High levels of ^{226}Ra, unsupported by ^{238}U, have been found in groundwater from certain boreholes, mostly boreholes lying closely together on the western side of the property. This groundwater also yielded low activity ratios for $^{234}U/^{238}U$, lower pH and stronger oxidizing conditions than that of the rest of the area. The distinct host of Namaqualand rocks with the absence of overlaying sedimentary rocks has been suggested as the key to the different geochemical conditions of the groundwater of these boreholes.

^{232}Th and its daughter radionuclides yielded levels far below the guideline of 1 $Bq.l^{-1}$ given by the World Health Organisation, as is expected from the known low mobility of thorium.

A peak in total α radiation levels was seen in 2000 in the near-field area. Assessing the cumulative contributions of the various radionuclides it was very clear that the greatest factor in producing α radiation is ^{234}U. However, no data is available for the levels of ^{234}U in 2000. It is suggested that future occurrences of elevated total α radiation levels should be investigated either by performing alpha spectrometry on a duplicate sample or on a sample collected as soon as possible after the original sampling.

Analysis of total β radiation levels were found to be unreliable up to 2005, and since the analysis of β-emitting radionuclides was not part of the scope of this study, no conclusions with regard to the contributors to total β radiation could be made. It is suggested that the elevation of total β radiation levels of specific beta-emitting radionuclides, especially ^{40}K, should be determined.

Opsomming

Vaalputs, die Suid-Afrikaanse radioaktiewe afvalbergingsfasiliteit, is tans slegs gelisensieer om lae- en mediumvlak radioaktiewe afval te stoor. Alhoewel die storingsplek sedert 1986 radioaktiewe afval huisves, is die eerste langlewende uraanbevattende afval eers in Mei 2011 by Vaalputs afgelewer. Die Kernenergie Korporasie van Suid-Afrika (Necsa) het in beplanning vir die verwikkeling besluit om hierdie studie te doen ter opstelling van ‘n basisvlak vir die optrede van natuurlike radionukliede in die uraan- en torium-vervalkettings. Die basisvlak sal gebruik word om die grondwater van Vaalputs te monitor vir moontlike antropogeniese byvoegings tot die omgewingsradioaktiwiteit.

Die basisvlak is opgestel deur die bestudering van ‘n unieke datastel van 25 jaar se analises van grondwater vir die aktiwiteite van mensgemaakte en natuurlike radionukliede sowel as katioon- en anioonkonsentrasies. Hierdie databasis is die gevolg van jaarlikse monitering van die grondwater vanuit ‘n bepaalde stel boorgate op en rondom Vaalputs as deel van die regulerende vereistes vir radioaktiewe berging.

Die aktiwiteite van radionukliede in grondwater van 13 jaarliks en 3 kwartaalliks geanaliseerde boorgate word in die studie geëvalueer. Katioon- en anioonkonsentrasies is onderskeidelik bepaal

deur induktief gekoppelde plasma optiese emissie spektrometrie en ioonchromatografie. Met roetine analises is die aktiwiteite van die langlewende radionukliede ^{238}U en ^{232}Th gemeet deur instrumentele neutronaktiveringsanalise, terwyl die kortlewende radionukliede ^{226}Ra bepaal is deur γ-straal spektrometrie. Die algehele radioaktiewe risiko vanaf totale α en β straling is gemeet deur gasvloei proporsionele telling. Per geleentheid is grondwater monsters geanaliseer deur α-spektrometrie vir die bepaling van die aktiwiteite van α-uitstralende radionukliede in die vervalkettings van ^{238}U, ^{235}U en ^{232}Th. Hierdie analitiese resultate is geïntegreer vir die evaluering van neigings in die aktiwiteite van radionukliede, die relatiewe bydraes van individuele radionukliede tot die totale straling en die invloed daarop deur grondwater toestande.

^{238}U vlakke wys ‘n natuurlike anomalie in die nabyveld van die bergingsplek, wat toegeskryf kan word aan anomale uraan-ryke fondasiegesteentes wat naby die bergingslote geleë is. Hierdie anomalie moet in gedagte gehou word vir monitering van grondwater vir moontlike toevoegings van uraan. Een stel duplikaat-monsters van 2009 is geanaliseer deur α-spektrometrie en daardeur is die gemiddelde aktiwiteitsverhouding van $^{234}U/^{238}U$ in die grondwater van Vaalputs as 4.1 bepaal. Hierdie gemiddelde verhouding is tydens die res van hierdie studie gebruik vir die vergelyking van die bydrae van ^{234}U tot die totale α straling teenoor die bydrae van die ander α-uitstralende radionukliede. Daar word egter voorgestel dat ‘n meer ekstensiewe eksperiment uitgevoer sal moet word om ‘n statisties verteenwoordigende aktiwiteitsverhouding vir die verskillende areas in die grondwater van Vaalputs te bepaal.

Hoë vlakke van ^{226}Ra, wat nie deur ^{238}U ondersteun word nie, is in die grondwater van sekere boorgate gevind. Hierdie boorgate is hoofsaaklik gekonsentreer in ‘n klein area aan die westekant van die fasiliteit en bevat grondwater wat lae aktiwiteitsverhoudings vir $^{234}U/^{238}U$, laer pH en sterker oksiderende toestande as die res van die area getoon het. Die onderskeidende gasheer van Namakwaland gesteentes met die afwesigheid van oorliggende sedimentêre gesteentes word as die sleutel tot die verskil in die geochemiese toestande van die grondwater van hierdie boorgate aangedui.

^{232}Th en sy dogter radionukliede het vlakke ver onder die riglyn van 1 $Bq.l^{-1}$ wat die Wêreld Gesondheidsorganisasie daargestel is, soos te wagte van die bekende lae mobiliteit van torium.

‘n Piek in die totale α radiasie vlakke kan gesien word in 2000 in die naby-veld area. Na assessering van die kumulatiewe bydraes van die verskeie radionukliede is dit duidelik dat ^{234}U die grootste faktor is in die produsering van α-straling. Geen data is egter beskikbaar vir die vlakke van ^{234}U in 2000 nie. Dit word voorgestel dat toekomstige gevalle van verhoogde totale α-stralingsvlakke ondersoek sal word deur alpha spektrometrie-analise op ‘n duplikaat monster of ‘n monster wat so spoedig moontlik na die oorspronklike monster geneem word.

Analise van totale β stralingsvlakke is onbetroubaar bevind tot en met 2005. Aangesien analises van β-uitstralende radionukliede nie deel uitgemaak het van hierdie studie nie, kon geen gevolgtrekkings gemaak word met betrekking tot die bydraers tot β-straling nie. Daar word voorgestel dat monsters met verhoogde vlakke van totale β-straling geanaliseer word vir spesifieke β-uitstralende radionukliedes, veral ^{40}K.

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List of Abbreviations

- AEB: Atomic Energy Board
- AEC: Atomic Energy Corporation
- BBC: British Broadcasting Commission
- EW: Exempt waste (non-radioactive waste, exempt from regulatory controls)
- HLW: High level radioactive waste
- IAEA: International Atomic Energy Agency
- ICRP: International Commission on Radiological Protection
- ILW: Intermediate level radioactive waste
- KNPS: Koeberg Nuclear Power Station
- LILW: Low and intermediate level radioactive waste
- LLW: Low level radioactive waste
- m.a.m.s.l. metres above mean sea level
- MAP: Mean annual precipitation
- MDA: Minimum detectable activity5
- Necsa: South African Nuclear Energy Corporation
- NIMBY: Not In My Back Yard
- NNR: National Nuclear Regulator (South African)
- NORM: Naturally occurring radioactive material
- TDS: Total dissolved solids
- TRU: Transuranium elements
- TRUW: Transuranium containing waste
- UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation
- VLLW: Very low level radioactive waste
- VSLW: Very short lived radioactive waste
- WHO: World Heatlh Organisation
- WIPP: Waste Isolation Pilot Plant
- WNA: World Nuclear Association
- WWII: The Second World War
- USA: United States of America
- USEPA: United States Environmental Protection Agency
- USSR: Union of Soviet Socialist Republics

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1 Introduction

1.1 Background

Environmental radioactivity can be defined as radioactivity present in natural systems as a result of natural processes or anthropogenic activities. Natural radioactivity contributes most of the environmental radioactivity and has two main sources, the first being cosmogenic radionuclides such as ^{35}S, ^{10}Be and ^{22}Na. Cosmogenic radionuclides are generated during interaction between cosmic ray particles such as low energy protons, neutrons and muons, and the nuclei of atmospheric N, O and Ar (Yamamoto *et al*., 2006; Jasiulionis and Wershofen, 2005). The second important source of natural radioactivity is the decay of primordial radionuclides still present in the earth's crust since its origin (Dragović *et al*., 2006). These primordial radionuclides are mainly ^{238}U, ^{232}Th, and ^{40}K and they are present in trace amounts in rocks, soil, water, food and ultimately the human body. ^{235}U, with a half-life of 703.8 Ma, is a primordial radionuclide that was abundant more than 2 Ga ago, but is now almost extinct, making up only 0.72% of natural uranium.

NORM is an acronym for 'naturally occurring radioactive material' which refers to radioactive material occurring naturally with the potential to expose humans to radiation. This definition has however led to widespread debate, as most natural materials contain some natural radionuclides. According to a report from the International Atomic Energy Agency (IAEA) (2008), the definition should only include material that is subject to regulatory control due to its level of radioactivity.

According to Hu *et al*. (2010), man-made additions to the total environmental radioactivity began to accumulate since the Second World War (WWII) in the 1940s, firstly with programs of nuclear weapon production and testing. After the war, there was also an increase in the use of nuclear power to generate electricity, and to produce radioactive isotopes for medicine and other industries. The mining and reprocessing of nuclear fuels, as well as nuclear accidents further contribute to the global environmental radioactivity. One of the biggest concerns of nuclear scientists is to ensure that these anthropogenic additions to the environmental radioactivity are kept as limited as possible.

The concern over exposure of humans to radioactivity is an important driving factor behind the studies of environmental radiation and natural radioactivity levels. This exposure occurs as a result of γ-radiation from decaying radionuclides in the environment (external exposure), as well as radiation generated by α-decay of radionuclides that were ingested and/or inhaled (internal exposure) (Mahur *et al*., 2008). According to the United Nations Scientific Committee on the Effects of Atomic Radiation, (UNSCEAR, 2000), natural cosmic and terrestrial radiation contribute a major proportion of the collective dose received by the world's population. The average natural radiation levels in the environment result in an 'effective dose' of 2.4 mSv per annum, per capita. With regards to anthropogenic additions to this 'effective dose', it is recommended by the

International Commission on Radiological Protection (ICRP, 1991) that planned exposures to the general public should not exceed 1 mSv per annum, per capita.

Radioactive materials have been encountered by mankind centuries before it was discovered in the mid 1900s, how energy from the nuclei of atoms could be released and exploited in different ways (Eisenbud, 1973). In medieval times high fatality rates amongst European silver mine workers were raising much debate. Mine workers believed it was bad luck brought by the dark rocks they called pitchblende, an unwanted rock associated with the silver ore (Mould, 2007). Only in 1789, the same year that the element uranium was discovered, cancer of the lungs was identified as the fatal disease crippling the industry. However, uranium (or its radiation) was not yet the suspect, as radioactivity was only discovered more than a century later in 1896 by Antoine-Henri Becquerel (Blaufox, 1996). Almost another half a century later Lorenz (1944) was able to make the link. He made a connection from the uranium in pitchblende, to the highly radioactive atmosphere of the European silver mines, to the lung cancer which caused an estimated 43% of fatalities amongst the mine workers. Although Lorenz might not have yet made this further connection, radon, an inert radioactive gas and decay product of uranium, and other short-lived daughter elements have also been found to contribute to the development of lung cancer in humans due to indoor and underground exposure (Lubin & Boice, 1997).

After its discovery, uranium became very popular as a yellow, green and orange colouring agent and was commercially used in tinting of glassware, glazing of porcelain as well as for paintings and wallpaper. Thorium was used in similar applications as well as in gaslights, due to its incandescent properties, while radium was injected into patients for varying reasons and mixed into paints creating luminescent timepieces (Eisenbud, 1973). Natural radioactivity has been advertised since early in the 20^{th} century for its health benefits such as laxative properties of radioactive spring water, curing arthritis by drinking water bubbled with radon and destroying cancerous cells by visiting radioactive spas, some of these inside old mines with high concentrations of radon (Eisenbud, 1973).

Bodansky (2004) reports how, after the discovery of radioactivity, scientists such as E. Rutherford and L. Szilard where intrigued by the structure of atoms, the heat produced during decay of radium, and by the possibility of finding ways to control the release of the large amounts of energy stored inside the nucleus. As early as 1913 the British novelist, H.G. Wells, predicted the discovery of artificially induced radioactivity and that this would be important for the military as well as for industrial uses. In 1932 James Chadwick discovered the neutron and a year later Frederic Joliot (later the son-in-law of Pierre and Marie Curie) discovered artificial radioactivity. Only in 1938 however, scientists were able to recognize and start explaining the fission of uranium, and soon a team of Italian physicists, led by Enrico Fermi (all living in America at the time) was able to demonstrate how neutrons, emitted during fission, were able to produce a self-sustainable chain

reaction. This research led to the first nuclear reactor in 1942 in Chicago, and to the first atomic test bomb that was detonated at a New Mexico air base in 1945.

Being in the midst of WWII, the military applications of this newly discovered energy were much more the focus of the nuclear research, and soon large reactors were constructed for the purpose of producing plutonium-239 (^{239}Pu) for use in fission bombs (Bodansky, 2004). Two types of nuclear bombs have been developed, the first being the atomic bomb (or A-bomb) whose energy is derived from nuclear fission of heavy elements such as plutonium or enriched uranium into lighter nuclei. Years later E. Teller developed the hydrogen bomb (or H-bomb) which uses an A-bomb device to fuse ^{2}H or ^{3}H nuclei into ^{4}He - the same reaction that delivers energy in the sun and many stars. The United States eventually detonated the first atomic bombs in 1945, near the end of WWII, at Hiroshima and Nagasaki in Japan (Malik, 1985), after which France, China, the USSR and Britain also started their own nuclear weapons programs (Bodansky, 2004). The two atomic bombs of 1945, however, turned out to be the only nuclear bombs to have ever been used as offensive weapons, although up to 1980 over 500 more nuclear bombs were detonated into the atmosphere during nuclear weapons testing in these countries (Beck & Bennet, 2002). After proposals and initial agreements, starting from 1953, the Non-Proliferation Treaty was brought into force in 1970, discouraging the military applications of nuclear energy while promoting the peaceful applications thereof. There are however still some countries, including India, North Korea and Pakistan, who has openly disagreed to the treaty, with Israel applying a policy of deliberate ambiguity with regard to their possession and testing of nuclear weapons resulting in widespread speculation (Bodansky, 2004).

Development in the nuclear science was largely sped up by the pressures of WWII, but although in the background, scientists were still excited about the possibilities of this new source of energy. They have been waiting for the opportunities to generate electricity from nuclear power and to use radioactivity for medical, industrial and scientific purposes. In 1951 the first electricity was generated on the Experimental Breeder Reactor I in Idaho, USA, followed by Britain and Russia later in the 1950s. Countries such as France, Japan, South Africa and China joined them slightly later in the century (Bodansky, 2004; Meyer *et al*., 2006). Development of civilian nuclear power technology was still in a large part driven by military programs, when the USA and Russian navies very successfully started using nuclear power for the propulsion of their vessels. Eisenbud (1973) further describes the heavy increase in electricity usage and the cost of fossil fuels in the USA and how, during this time, uncertainties regarding the long-term availability of fossil fuels and the contribution to air pollution from traditional electricity generation became national concerns. The economic viability of nuclear was demonstrated and as a consequence using nuclear power became more and more favourable.

The applications of nuclear power began to grow and scientists developed more ways to use radioactivity and radioactive isotopes in medicine, research, industry and agriculture. As a result there was also an inevitable increase in the amounts of nuclear waste, including spent fuel. Radioactive waste is a product of all the different steps in the nuclear fuel cycle, starting from mining and processing of uranium and/or thorium bearing minerals and rocks Furthermore waste is produced during the enrichment of uranium with fissionable ^{235}U, fabrication of fuel rods to the generation of nuclear power and decommissioning these power plants (Giusti, 2009). According to Kugo *et al*. (2008) the general public is often not aware that nuclear power plants produce radioactive waste and that this waste needs to be disposed safely. An example is given by the Korean government who had the full support of the public in developing the nuclear program, but when it came to the waste management program communities had a very strong negative reaction (Hwang *et al*., 2003). The phenomenon of a negative image and resulting social rejection towards environmental intervention and management is defined by Pol *et al*. (2006) as the NIMBY (Not in My Back Yard) effect. The initial public attitude of tolerance has been replaced by a phobia towards radioactivity and this has been an obstacle in many countries in further development of the nuclear power industry and the effective management and disposal of radioactive waste (Beghin, 1997). Research towards socially acceptable and technically proven solutions for the disposal of this waste has thus been enjoying the undivided attention of nuclear scientists and engineers for many years.

Several possible nuclear disposal solutions have been proposed, some less feasible than others, for example: ocean and sub-seabed disposal, dumping on remote islands or in outer space, reprocessing or transmutation of waste, burial below ice sheets, in deep boreholes or geological repositories. Studying natural systems for radioactive waste disposal has delivered some insight into the possible permanent disposal of nuclear waste. Natural analogues are found in the long-term geological confinement of concentrated uranium deposits such as at Cigar Lake, Canada, as well as of the natural nuclear reactors and its fission products at Okélobondo, Gabon (Rempe, 2007). Over time, weighing all the advantages and disadvantages, the international consensus is towards disposal of high level radioactive waste in deep geological repositories (Rogers, 2009).

The pace of the development of solutions towards the final disposal of spent fuel, the main high level waste product of the nuclear fuel cycle, is however of great international concern. At this point in time it is common practice to leave this high-level radioactive waste on the reactor site, or placed in interim facilities until a long-term solution is found (Rogers, 2009). Pickard (2010) reports about the decision of USA President Barack Obama in 2009 that the high level radioactive waste repository at Yucca Mountain, Nevada, would never be operated as such. This waste disposal facility has been in development for the past 20 years, but after Obama's announcement, he established the Blue Ribbon Commission to find an alternative repository location for a permanent solution. Broomby (2009) reports of the difficulties that the United Kingdom experiences in finding a

suitable disposal area with their voluntarism policy, where the decision is based on volunteering local governments, rather than geology. Rogers (2009) mentions how, since the early years of nuclear energy development, the general attitude was that the waste issues will be dealt with at a later time and in the process delaying the development of sound solutions for nuclear waste disposal. While politicians, scientists and communities have a 'wait and see' approach, radioactive waste is stored on the surface, vulnerable to natural disasters, terrorist incidents, human errors (Pickard, 2010) and societal changes (Madsen, 2009).

There is, however, some progress towards disposal of spent fuel being made in countries such as Finland and Sweden, planning to have operational geological disposal facilities by 2020, and France preparing a repository for waste from fuel reprocessing to be ready at around 2025 (Chapman, 2009). Finland is in the lead, currently constructing the Onkalo high level waste repository site near the Olkiluoto nuclear power plant. Posiva, the company responsible for constructing the large system of underground tunnels to a depth of 420m, is planning to have the facility licensed by 2020 (Broomby, 2009). The site is excavated from an ancient (1,8 to 1.9 Ma) Pre-Cambrian shield with the bedrock consisting of migmatitic-gneiss and relatively undeformed granite and granodiorite intrusions (Hudson *et al*., 2011). The first deep geological repository to be actively used for the disposal of radioactive waste is however found at Carlsbad in New Mexico. The Waste Isolation Pilot Plant (WIPP) has been operational as a disposal site since 1999. This repository is however only licensed to dispose transuranium (TRU) waste generated by past nuclear defence activities in the USA (Lucchini *et al*., 2007; Thakur & Mulholland, 2011).

One of the main concerns with the disposal of radioactive waste in continental geological repositories is the possibility of contaminating groundwater reserves. According to Suksi *et al*. (2006) natural radionuclides in groundwater are the result of normal recharge, adding cosmogenic radionuclides, and the interaction of water with rocks containing radionuclides from the natural decay series. However, Coetzee *et al*. (2008) made an interesting conclusion after studying the migration of radionuclides in groundwater at two naturally anomalous areas: the Karoo Uranium Province, and the Bushmanland-Namaqualand area. They have found that the content of radionuclides in groundwater did not simply correlate with the geological unit nor with the chemical analytical results of the rocks where-in the boreholes were drilled. According to Coetzee *et al*. (2008) consideration should also be given to groundwater usage habits, redox chemistry, localised mineralized zones in the aquifer or recharge area, the residence time of groundwater (natural recharge) and the ratio of bulk water to rock-surface area (fracturing) and to how all these factors influence each other.

The World Health Organisation (WHO), (2004), recommends that the contribution to the effective annual dose from the consumption of drinking water should not exceed 10% of the total recommended limit of anthropogenic radiation. This limit is 1 mSv per annum, thus 0.1 mSv of

radiation is allowed from one year's consumption of drinking water. In South Africa, doctors at a hospital in Cape Town had noted that a significant number of patients from the Pofadder area in the Northern Cape Province later suffered from haematological abnormalities related to leukaemia. Toens *et al*. (1999) later confirmed a correlation between these abnormalities and high levels of uranium and arsenic in the groundwater of the area. In 2010 Nair *et al*. applied a mathematical model to a hypothetical uranium tailings pond in order to calculate the radiological impact from ^{238}U decay chain radionuclides in groundwater. In this study it was calculated that 99.75% of the total effective dose should be contributed by ^{222}Rn, ^{210}Po, ^{210}Pb and ^{226}Ra, while only 0.25% would come from all other radionuclides, including long-lived ^{238}U. This clearly shows the importance of monitoring daughter radionuclides along with their parents.

1.2 Context of the study

In order to fully understand contribution of man-made radio-isotopes to the total environmental radioactivity at a particular site and to keep the addition to a minimum, it is important to monitor on an ongoing basis the levels of natural radioactivity in that environment.

Vaalputs, the only radioactive waste disposal site in South Africa, has been licensed to dispose low and intermediate level radioactive waste (LILW) since it received the first delivery of radioactive waste from the Koeberg Nuclear Power station (KNPS) in 1986. Until recently, the radioactive waste disposed of at Vaalputs contained only short-lived radionuclides including ^{60}Co, ^{90}Sr, ^{137}Cs and ^{134}Cs (a full list of radionuclides will be shown in chapter three). Since 11 May 2011, long lived LILW containing small amounts of U (and traces of its daughter elements) from Necsa's research facilities in Pelindaba, 25km from Pretoria, is also being disposed of at Vaalputs. In 2008, foreseeing this disposal of U-containing waste, it was considered a valuable precaution to determine a pre-operational baseline of the natural occurrence and behaviour of U and its daughter elements in the basement-hosted groundwater at Vaalputs. According to Ainslie *et al*. (2003) groundwater has been identified in Vaalputs safety studies as the most important pathway of transporting radioactivity to humans. This happens both via direct ingestion of borehole drinking water by humans, as well as via the food-chain of plants and animals using the same water.

A unique opportunity for establishing such a baseline presents itself in the wealth of environmental, radiometric and geologic data Necsa obtained from the environmental monitoring at Vaalputs over the past 25 years. Among others, one of the licensing conditions prescribes that Necsa routinely monitors, and reports to the National Nuclear Regulator (NNR), the levels of dissolved radioactive elements in the groundwater below and surrounding the waste disposal site. Because of the above directives, the groundwater at Vaalputs is routinely analysed for a number of radionuclides, some of which are man-made and could be released into the environment, only occurring in the waste disposed, as well as those occurring naturally in the groundwater.

1.3 Purpose of this study

The objective of this study is to establish a radiological baseline in the groundwater of Vaalputs for the content and behaviour of naturally occurring radionuclides. As discussed above, this baseline will be of great assistance in monitoring the radiation levels when man-made waste products are introduced into the natural system. In order to establish this baseline, the following aims were set:

- Determine the content and behaviour of the naturally occurring long-lived radionuclides ^{238}U and ^{232}Th in the groundwater of Vaalputs;
- Determine the content and behaviour of naturally occurring short-lived daughters of ^{238}U, namely ^{234}U and ^{226}Ra;
- Determine and evaluate the overall hazard of the groundwater by measuring the total α and β particles; and
- Determine how the individual radionuclides contribute to the total activity in the groundwater.

1.4 Structure of the thesis

The principles of environmental radioactivity will be explained in the second chapter, followed by a description of the classification, types, production and disposal of radioactive waste and of the Vaalputs radioactive waste disposal site. The study area is described in chapter four with regards to physiography, hydrogeology and geology. Chapter five gives the methodology used for sampling, analyses, calculations and data refining and statistical treatment of the data. The results are presented in next the two chapters: chapter six shows a groundwater level map for the study site, recharge estimations and water geochemistry results and short discussion thereof. Chapter seven contains radio-analytical results, the main results for this study. The results from chapter seven will be discussed separately in chapter eight after which the conclusions and recommendations will be made in chapter nine.

2 Principles of radioactivity

Environmental radioactivity is a field that has been and still is studied extensively (eg: Eisenbud, 1973; Baxter, 1993; Yamamoto *et al*., 2006; Hu *et al*., 2010). One important aspect that receives special attention is the determination of the impact of anthropogenic additions to the total environmental radioactivity. However, what is crucial in these studies is to understand first the natural radioactivity of the environment in order to be able to draw conclusions on the influence of human involvement on environmental radioactivity. In this chapter, firstly an introduction will be given to radioactive terminology and concepts, this will be followed by a summary of the principles of natural radioactivity and naturally occurring radionuclides, and in conclusion a few notes on anthropogenic radioactivity.

2.1 Radioactivity terminology and concepts

2.1.1 Radionuclides

A radionuclide is often also referred to as a radioactive isotope, which is an unstable isotope of a chemical element. These radionuclides can be naturally occurring, i.e.: unstable isotopes that arise from the decay of primordial radionuclides uranium and thorium (more on this in section 2.2), or radionuclides that are artificially manufactured in nuclear accelerators or reactors and do not exist in nature. Examples of artificial radionuclides are ^{99}Tc, ^{123}I, ^{11}C, ^{32}P, ^{201}Tl, ^{67}Ga and ^{51}Cr – all radionuclides that are commonly used in nuclear medicine (Duggirala *et al*., 2010; Newman, 2008).

2.1.2 Radioactive decay, rate of decay and types of decay

According to the Collins English Dictionary (2009) and Duggirala *et al*. (2010) radioactive decay is defined as the disintegration of an unstable nucleus that occurs spontaneously while emitting energy in the form of ionizing particles and electromagnetic radiation (gamma rays). The charge and mass of the unstable atomic nucleus change during decay to form a new nucleus.

All radio-isotopes decay continuously at a specific constant rate, therefore the same fraction of atoms will disintegrate in any particular time period. The decay constant describes the fraction of atoms that undergo decay per unit of time (Shapiro, 2002). Another useful way to express the rate of decay is the half-life: the time in which half (50%) of the atoms of a specific radionuclide are transformed through radioactive decay (Shapiro, 2002).

There are three main types of radioactive decay (Zumdahl & DeCoste, 2010; Duggirala *et al*., 2010):

- α decay is the emission of α particles, which can also be described as a double-ionized helium atom.

- β decay is the emission of a β particle, either an electron (e-) which can be emitted by both natural and artificial radionuclides; or a positron (e+) which can only be emitted by artificial radionuclides.
- γ decay refers to any decay resulting in the emission of gamma rays (electromagnetic radiation). Gamma rays can be emitted with α or β particles during the transition of a nucleus from an excited state to the ground state.

In addition, another interesting type of decay is the spontaneous fission that occurs in ^{238}U. The majority of ^{238}U however undergoes α decay and spontaneous fission is mostly neglected during calculations of decay rates and radiation emitted.

2.1.3 Activity of radionuclides

The activity of a radionuclide represents the amount of radioactive material in which one spontaneous nuclear transformation (or disintegration) takes place per second. The SI unit for activity is the Becquerel (Bq), given as 1 Bq = 1 s^{-1} (IAEA, 1996; Durham, 2007; Podgorsak, 2010).

Specific activity is defined as activity per unit mass, with the SI unit: Bq/kg. The specific activity *a* of a radioactive atom depends on the decay constant *λ* and on the atomic mass number *A* of the radioactive atom:

$$\text{Specific activity } (a) = \frac{\text{activity}}{M} = \frac{\lambda N}{M} = \frac{\lambda N_A}{A},$$

where N_A is the Avogadro number (6.022×10^{23} mol^{-1}) (Podgorsak, 2009).

2.1.4 Radiation dose

According to the IAEA (1996), the absorbed radiation dose (or just absorbed dose), is the term commonly used to quantify the amount of energy absorbed by a unit mass of a substance from the radiation to which it is exposed. The absorbed dose unit is joule per kilogram, but is given the name gray (Gy). This however does not account for the relative sensitivities of the different human tissue to different types of ionizing radiation.

To take account of the varying negative health effects of the different types of radiation, the absorbed dose averaged over a tissue or organ is multiplied by a *radiation weighting factor* to obtain a quantity named the equivalent dose. The equivalent dose to each organ and tissue can then be multiplied by a *tissue weighting factor* to take account of the organ's radio-sensitivity. The weighted equivalent doses for all exposed tissues in a specific human are totalled to obtain the effective dose. Both equivalent and effective dose has the unit of joule per kilogram, but the name sievert (Sv) is used for these quantities.

The effective dose therefore depends on the activity concentration of the radioactive material (measure in Becquerel per litre - $Bq.l^{-1}$), the energy of the emitted radiation, the time of exposure,

the organ exposed, the age of the individual exposed, as well as on the distance from the radiation source.

2.2 Natural radioactivity

Natural radioactivity is a result of both the decay of radionuclides occurring in all living and non-living substances on Earth, as well as of ionizing radiation bombarding the earth from outside of its boundaries (Eisenbud, 1973).

Table 2.1: Sources of exposure to natural radioactivity and contributions to the annual effective dose (data: after UNSCEAR, 2000).

Source of exposure	Annual effective dose (mSv)	
	Average	Typical range
Cosmic radiation		
Directly ionizing and photon component	0.28	
Neutron component	0.1	
Cosmogenic radionuclides	0.01	
Total cosmic and cosmogenic radiation	**0.39**	0.3 - 1.0[a]
External terrestrial radiation		
Outdoors	0.07	
Indoors	0.41	
Total external terrestrial radiation	**0.48**	0.3 - 0.6[b]
Inhalation exposure		
^{238}U, ^{235}U and ^{232}Th series	0.006	
^{222}Rn	1.15	
^{220}Rn (Thoron)	0.1	
Total inhalation exposure	**1.26**	0.2 - 1.0[c]
Ingestion exposure		
^{40}K	0.17	
^{238}U, ^{235}U and ^{232}Th series	0.12	
Total ingestion exposure	**0.29**	0.2 - 0.8[d]
TOTAL	**2.4**	1 - 10

a Range from sea level to high ground elevation.
b Depending on radionuclide composition of soil and building materials.
c Depending on indoor accumulation of radon gas.
d Depending on radionuclide composition of foods and drinking water.

Table 2.1 gives the sources of natural radiation and annual effective dose in mSv received from each of these sources, with the average total exposure to natural radiation to the average adult as 2.4 mSv and the typical range for individuals being 1 to 10 mSv.

Table 2.2 shows how Eisenbud (1973) divides the natural radionuclides that contribute to the environmental radiation into three groups: singly occurring cosmogenic radionuclides, singly occurring terrestrial radionuclides and terrestrial radionuclides that are part of one of three decay chains (Figure 2.1).

Table 2.2: The three groups of natural radionuclides (adapted from Eisenbud, 1973).

Cosmogenic radionuclides	^{3}H, ^{7}Be, ^{10}Be, ^{14}C, ^{22}Na, ^{24}Na, ^{32}Si, ^{32}P, ^{33}P, ^{35}S, ^{36}Cl, ^{38}S, ^{38}Cl, ^{39}Cl
Terrestrial radionuclides: singly occurring	^{40}K* (and ^{50}V, ^{87}Rb, ^{115}In, ^{123}Te, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{148}Sm, ^{146}Sm, ^{152}Gd, ^{156}Dy, ^{174}Hf, ^{176}Lu, ^{180}Ta, ^{187}Re, ^{190}Pt)
Terrestrial radionuclides: decay chains	^{238}U, ^{235}U and ^{232}Th and their daughter radionuclides (See Figure 2.1)

** The only singly occurring terrestrial radionuclide with significant contribution to environmental radioactivity.*

Eighteen radionuclides of terrestrial origin do not form chains of radionuclides through decay, i.e.: they are neither decay products of other radionuclides nor do they form radionuclides as a result of their own decay. Most of these radionuclides are of little relevance in producing radioactivity due to their very low concentrations in the earth's crust and their half-lives being very long. The exception is ^{40}K a rare isotope of potassium, with a relative isotopic abundance of 0.012%, which means that this is the percentage of ^{40}K relative to the total amount of potassium isotopes occurring on earth (Eisenbud, 1973). The abundance factor is called the relative isotopic abundance. Potassium-40 has a long half life of 1.26×10^{9} years and it decays to the two stable isotopes ^{40}Ca and ^{40}Ar by β decay and electron capture, respectively (Faure, 1998). With potassium having a weight abundance in the earth's crust of 2.6% (Lutgens and Tarbuck, 2000) ^{40}K is present in the earth's crust at about 30ppm, which amounts to a significant contribution to the total environmental radioactivity.

Table 2.3 below gives the relative isotopic abundance, half-life and decay constant of each of the naturally occurring radionuclides of U and Th that are important for this study. These properties are all useful when making calculations of concentrations and activities of these radionuclides.

Table 2.3 : Abundances, half-lives and decay constants of the most important naturally occurring isotopes of uranium and thorium (adapted from Faure, 1998).

Isotope	Relative isotopic abundance (%)	Half-life (years)	Decay Constant y^{-1}
^{238}U	99.2743	4.468×10^{9}	1.55125×10^{-10}
^{235}U	0.72	7.038×10^{8}	9.8485×10^{-10}
^{234}U	0.0057	2.47×10^{5}	2.806×10^{-6}
^{232}Th	~100	14.010×10^{9}	4.9475×10^{-11}
^{226}Ra	~100	1601	1.373×10^{-11}

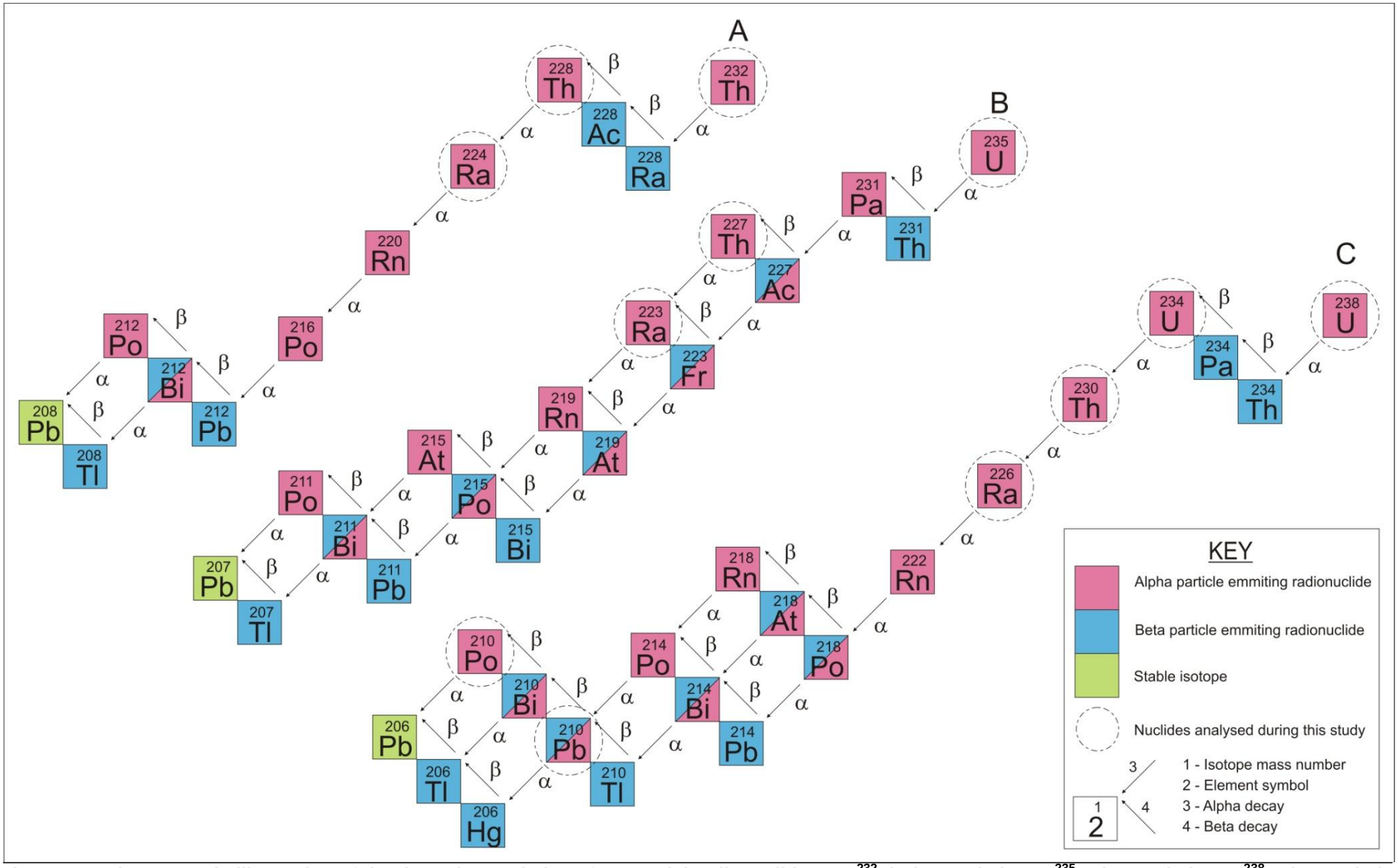


Figure 2.1: Diagrammatic illustration of the three decay chains of terrestrial radionuclides. A: ^{232}Th decay chain; B: ^{235}U decay chain; C: ^{238}U decay chain (adapted from Faure, 1998).

2.3 Anthropogenic radioactivity

Human activities and human-made sources (such as medical radiology and industrial use of radionuclides) can result in an addition to the total environmental radioactivity. Table 2.4 shows how Choppin *et al*. (2002) summarises the findings from UNSCEAR (2000) on the contributions of each of the different anthropogenic sources of radioactivity to the total radioactivity released.

Table 2.4: Summary of total radioactivity released from several important anthropogenic sources (data, adapted, from: Choppin *et al*., 2002).

Source of anthropogenic radioactivity	Total radioactivity released (EBq)
Atmospheric nuclear weapons tests (details in Table 2.5)	~2600
Nuclear reactors	~3.9
Nuclear fuel reprocessing plants	~3.4 (up to 1998)
The Chernobyl nuclear accident	~2

The Fukushima Daiichi nuclear accident of March 2011 released an estimated radioactivity of 0.37 EBq on 12 April 2011, approximately one month after the incident (BBC, 2011). Events such as these accidents seem to have had a minor contribution to the total environmental radioactivity compared to that from the atmospheric testing of nuclear weapons. Table 2.5 shows all the anthropogenic radionuclides that have been added to the environmental radioactivity during atmospheric nuclear testing carried out at locations such as Nevada, the Pacific Islands, Kazakhstan, the Russian Arctic and Australia. Of these, the following radionuclides, mostly generated at Koeberg, are currently being deposited at Vaalputs: ^{14}C, ^{137}Cs, ^{144}Ce, ^{3}H, ^{54}Mn, ^{90}Sr, and $^{239, 240, 241}$Pu (as part of transuranium elements - TRU).

Table 2.5: Half-lives and estimated total of radionuclides released during atmospheric nuclear testing (data: adapted from UNSCEAR, 2000).

Radionuclide	Half-life	Estimated release total (EBq)	Radionuclide	Half-life	Estimated release total (EBq)
^{3}H	12.33 y	186	^{125}Sb	2.73 y	0.741
^{14}C	5730.0 y	0.213	^{131}I	8.02 d	675
^{54}Mn	312.3 d	3.98	^{137}Cs	30.07 y	0.948
^{55}Fe	2.73 y	1.53	^{140}Ba	12.75 d	759
^{89}Sr	50.53 d	117	^{141}Ce	32.50 d	263
^{90}Sr	28.78 y	0.622	^{144}Ce	284.9 d	30.7
^{91}Y	58.51 d	120	^{239}Pu*	24110.0 y	0.00652
^{95}Zr	64.02 d	148	^{240}Pu	6560.0 y	0.00435
^{103}Ru	39.26 d	247	^{241}Pu	14.36 y	0.142
^{106}Ru	1.023 y	12.2	**TOTAL**		**2566.09**

** Release values of plutonium radionuclides were estimated from their ratios to ^{90}Sr in global deposition. Red: Radionuclides are amongst the radionuclides in waste deposited at Vaalputs (see Table 3.2 and Table 3.3).*

From the amounts of radioactivity released from various sources, as shown in Table 2.4, an estimate was made and published in WHO (2004) of the average annual effective radiation dose per person during the year 2000 for some important sources (Table 2.6).

Table 2.6: Summary of average annual effective radiation dose per person during the year 2000 for some important sources of radioactivity (data: adapted from WHO, 2004).

Source of radioactivity	Average radiation dose (mSv)
Natural background radiation	2.4
Medical diagnostic examinations & therapeutic treatments	0.4
Nuclear weapons tests	0.005
Chernobyl	0.002
Nuclear fuel cycle (mining, generating power, waste disposal)	0.0002
Total	2.81

Considering the large amount of radioactivity released from nuclear weapons tests (Table 2.4), its corresponding average radiation dose for 2000 appears very low compared to the total radiation dose experienced by the average person (Table 2.6). The reason for this is that the dose contribution from this source has reached a peak in 1963, with an annual average effective dose of 0.11 mSv, which has since decreased to 0.005 mSv as these tests were ceased in 1980 (UNSCEAR, 2000). Of the anthropogenic sources most have an insignificant contribution to the total annual effective dose compared to that from the natural background radiation, with medical exposures being the highest, but still low in comparison.

3 Principles of radioactive waste management

Generating electricity from nuclear power has become an increasingly attractive alternative to conventional fossil fuel electricity. Nuclear power has no contribution to global warming, no air pollutants are emitted and it is efficient and reliable. In 2008, nuclear power accounted for approximately 15% of all electricity produced world-wide (Rogers, 2009; Abu-Khader, 2009). However, according to IAEA (2007), more than 10 000 tons of highly radioactive spent fuel is produced every year. The safe disposal of this waste and its possible negative environmental effects has been a much debated topic for many years.

Over the past 60 years the establishment of nuclear regulatory bodies by countries such Canada, the USA and Korea has shown the importance of monitoring radioactive waste disposal facilities for possible environmental impact. In 1946 the Canadian government established what is now called the Canadian Nuclear Safety Commission (Canadian Nuclear Safety and Control Act, 1997); the United States has the US Nuclear Regulatory Commission, previously the Atomic Energy Commission, from 1954 (USA Energy Reorganization Act, 1974); and the Korean Nuclear Safety Center, now the Korea Institute of Nuclear Safety, was established in 1981 (Korean Atomic Energy Act, 1958).

In South Africa, the Atomic Energy Board (AEB), later the Atomic Energy Corporation (AEC), was established by the Atomic Energy Act of 1948. The AEC was later restructured by the South African Nuclear Energy Act (1999) into the South African Nuclear Energy Corporation (Necsa) with its objective set on developing the nuclear industry. Necsa's activities includes: the production of nuclear fuels and medical isotopes (such as Mo-99) at their nuclear reactor in Pelindaba, North West Province, as well as the management of the disposal of radioactive waste. Also in 1999, the National Nuclear Regulator (NNR) was established under the South African National Nuclear Regulatory Act (1999) for the independent regulatory control over nuclear safety. In 2008, the National Radioactive Waste Disposal Institute was established as the body with the responsibility of management of the radioactive waste disposal (South African National Radioactive Waste Disposal Institute Act, 2008).

Among the responsibilities of these regulators is to give guidelines as to the appropriate ways in which different types of radioactive waste must be treated and disposed. In the following section some background is given on the different sources of radioactive waste, the classification of radioactive waste and correct ways of disposal of each class. Finally, a summary of the radioactive waste disposed of at the Vaalputs waste disposal facility is given.

3.1 Sources of radioactive waste

3.1.1 Mining

Natural uranium is the key raw material used for the sustainable production of nuclear energy, with nuclear power reactors and research reactors that use mostly fissile ^{235}U (obtained from the enrichment of ^{nat}U) as fuel (Ganguly, 2005). The first step in producing nuclear energy is therefore the mining of uranium (and thorium to a lesser extent) ores. During mining of uranium ores two streams of radioactive waste is produced: firstly the mine tailings, which constitutes low-grade material removed and accumulated as waste piles, and secondly the mill tailings namely the residues left after the processing of high-grade material in order to extract radionuclides such as ^{238}U, ^{232}Th, and ^{226}Ra. India has recently started extracting ^{232}Th for the use as fuel in experimental Th-^{233}U cycle based reactors (Anantharaman *et al*., 2008). Radioactive waste is also commonly produced during mining of phosphate minerals, mineral sands, gold ores, coal and hydrocarbons when these are hosted in rocks enriched in NORMs (IAEA, 2009).

3.1.2 Nuclear fuel production

Radioactive waste of various types and classes is generated during various stages in the production of electricity from nuclear energy (IAEA, 2009):

- During manufacturing of nuclear fuel, waste is generated by the purification, conversion and enrichment of uranium. Furthermore spent fuel could be reprocessed into 'fresh' nuclear fuel, producing waste that usually contains uranium and often also plutonium.
- During the operation of nuclear power plants and nuclear propelled marine and sub-marine vessels, the waste produced includes a) spent nuclear fuel, b) water used for cooling, c) chemicals used to decontaminate equipment and d) waste from routine maintenance of the facilities.
- During decommissioning of nuclear power facilities, waste is produced in the process of clearing the facility from the need of further nuclear regulatory control.

3.1.3 Nuclear medicine

Nuclear medicine uses radionuclides in the diagnosis and treatment of various health conditions. ^{99m}Tc is a metastable, short lived nuclear isomer of technetium-99 that decays to ^{99}Tc, which in turn has a long half-life of 211 000 years. ^{99m}Tc is produced from ^{99}Mo and is the most widely used radioisotope in this field, followed by ^{123}I, ^{18}F, ^{201}Tl and ^{67}Ga. These isotopes are mostly used in diagnosis during examinations and imaging of organ function, blood flow and bone condition. Radiotherapy is used in the control or elimination of cancerous growth; some isotopes used for this application are ^{131}I, ^{153}Sm, ^{192}Ir and ^{90}Y. Medical radioactive waste, typically with significant levels of ^{99}Mo as a waste product in producing ^{99m}Tc, is mostly classified as very low or low level (see section 3.2) radioactive waste (Woolridge *et al*., 2008, www.ansto.gov.au, 2011)

3.1.4 Industrial isotopes

Radionuclides are becoming increasingly important in various industries, i.e.: mining and exploration, materials manufacturing and food processing industries, as well as in environmental management (WNA, 2010). Table 3.1 gives a summary of important industrial and environmental applications of radioisotopes.

Table 3.1: Industrial and environmental applications of radioactive isotopes (adapted from WNA, 2010).

Radioisotopes	Industrial applications
^{3}H, ^{14}C, ^{36}Cl, ^{210}Pb*	Water, soil and sand age determinations
^{241}Am, ^{137}Cs, ^{60}Co	Density and fill height detectors and switches
^{137}Cs, ^{57}Cr, ^{198}Au, ^{99m}Tc, ^{3}H	Radiotracers in studies such as: soil, coastal sand and riverbed erosion, factory waste tracing, sewage & liquid waste movements
^{60}Co, ^{140}La, ^{46}Sc, ^{198}Au, ^{110m}Ag	Used collectively to determine resident times in blast furnaces and in measurements of furnace performance
^{60}Co, ^{192}Ir, ^{75}Se, ^{169}Yb	Gamma sterilisation, gamma radiography (eg. locating flaws in metal components), non-destructive testing
^{241}Am, ^{85}Kr, ^{90}Sr, ^{204}Tl, ^{63}Ni	Industrial, thickness and backscatter gauges, borehole logging
^{54}Mn, ^{65}Zn	Predict behaviour of heavy metal components in mining waste water effluents

3.1.5 Nuclear weapons

Radioactive waste generated by nuclear defence programmes and production of nuclear weapons are mostly high level (see section 3.2) waste currently being stored for future geological disposal. However, some of the highly enriched uranium, and/or plutonium are reprocessed into nuclear fuel used for peaceful purposes such as generating nuclear power (IAEA, 2009).

3.1.6 Radioactive residues in the environment

Residues from testing of nuclear weapons, nuclear accidents and un- or badly regulated past uranium mining operations are still being deposited onto the surface of the Earth. These residues constitute radioactive waste and should be either managed or correctly disposed (IAEA, 2009). The Steenkampskraal Monazite Deposit, about 150km south of Vaalputs, was actively mined from 1952 to 1963, when the mine was abandoned, leaving spoil heaps on the surface. New mining activities are due to start, which should result in rehabilitation of the site which has up to now been a source of extensive dispersion of Th and U-bearing monazite ore into the environment (Andreoli, 2011; Andreoli *et al*., 1994; Read *et al*., 2002).

3.2 Classification and disposal of radioactive waste

Figure 3.1 is a simplistic conceptual illustration of the scheme for classification and disposal options for radioactive waste (IAEA, 2009). This scheme is based on the activity content and the half-lives of radionuclides in the waste. The activity content considers both the amount of total activity and the activity concentration in determining the waste class applicable. This scheme is much generalised and determining the class of waste depends on factors such as the radiological properties of the specific radionuclides, whether it is artificial (mostly short-lived) or natural (mostly longer lived) radionuclides and the specifications of proposed disposal facilities. Generic limit specifications are not available and decisions for classifying waste are generally made on a case-by-case basis and greatly depend on the controls of the regulatory bodies of each country (IAEA, 2009).

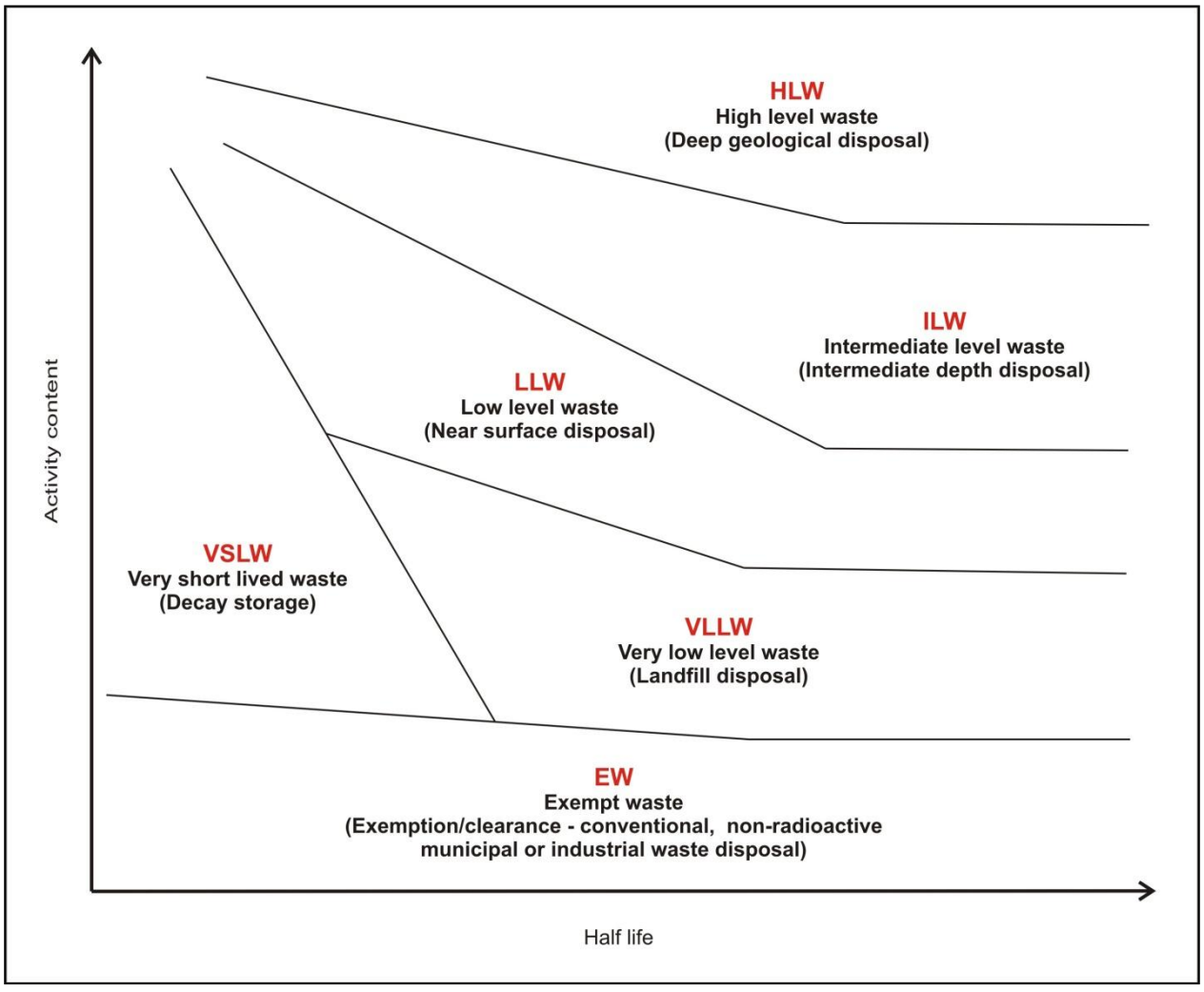


Figure 3.1: Conceptual illustration of the classification and disposal of nuclear waste according to activity concentration and half life (adapted after IAEA, 2009.

The procedures for the disposal of radioactive waste are based on the classification scheme derived by the IAEA (2009) (Figure 3.1). This scheme divides waste from the various nuclear operations into six classes:

3.2.1 Exempt waste (EW):

Exempt waste is non-radioactive waste generated at nuclear operations, which can be disposed or recycled with other industrial or municipal waste after being cleared from regulatory control. The activity concentration of radionuclides in this waste is so low that no provision for protection against radiation is required (IAEA, 2009). The IAEA (2004) reported the limits for activity concentration for each radionuclide which is used in determining the exclusion, exemption or clearance of radioactive waste, based on adding less than 0.01 mSv to the annual dose to members of the public. For natural radionuclides the limits are 10 $Bq.g^{-1}$ for ^{40}K and 1 $Bq.l^{-1}$ for all other natural radionuclides, while the exemption limits of 257 artificially produced radionuclides can be seen in Appendix A: Table A-1. In the case of mixtures of different radionuclides certain calculations has to be made based on these limits, these formulas and guidelines are described in detail in the report from the IAEA, (2004).

3.2.2 Very short lived waste (VSLW):

Radionuclides in this waste mostly have very short half-lives and are often derived from industrial and medical procedures, for example the use of ^{192}Ir and ^{99m}Tc in medicine. This waste can be cleared from regulatory control after storage time long enough to allow waste to decay below the levels for clearance – decaying into the exempt waste class. The limit in half-life of this type of waste varies depending on the storage time and initial activity concentration of the radioactive waste, but in general radionuclides that have half-lives in the order of 100 days or less are stored as VSLW (IAEA, 2009).

3.2.3 Very low level waste (VLLW):

VLLW is waste with activity concentrations only slightly above clearance levels that have to be isolated and contained for up around 300 years in specially engineered surface landfill facilities. 300 years is the duration of time for which reliance on institutional controls is assumed according to IAEA, 2009. This waste may have relatively high activity concentration levels, but has low concentrations of long lived radionuclides (IAEA, 2009). Generic limits of activity content for this type of waste is not available, but the guideline for waste containing short lived artificial radionuclides is that activity concentration levels can be one or two orders of magnitude higher than the criteria for exempt waste. For the waste containing longer lived naturally occurring radionuclides, lower levels of activity concentration are expected in order to qualify as VLLW (IAEA, 2009). Typical waste that will fall in the class of VLLW is mine and mill tailings from uranium mining and mineral processing (Abu-Khader, 2009; IAEA, 2009). This class of waste is also generated at nuclear installations, together with higher classes of radioactive waste (IAEA, 2009).

3.2.4 Low level waste (LLW):

Low level waste contains significant amounts of long lived radionuclides and needs to be isolated for periods longer than can be controlled by institutions (longer than 300 years). This waste is

disposed in what is called near surface disposal facilities, buried at varying depths up to 30m from the surface. The determination of whether a specific waste package falls in the class of VLLW or LLW is based on estimating the expected possible dose an individual may be subjected to if exposed after 300 years of disposal. In a previous classification system of the IAEA (1994) low and intermediate level waste (LILW) was classified together and subdivided into: short lived waste (LILW-SL) and long lived waste (LILW-LL). LILW-SL was restricted to contain <4000 $Bq.g^{-1}$ per individual package of waste and an overall average of 400 $Bq.g^{-1}$ per waste package and could be disposed in near surface facilities. LILW-LL contains concentrations of long lived radionuclides higher than LILW-SL and is to be disposed of in geological disposal facilities. In this classification scheme LILW was restricted to emitting thermal power lower than about $2kW/m^3$. Vaalputs is currently only licensed to dispose LILW-SL (Van Blerk, 2006). At Vaalputs, LLW is buried in near surface trenches contained in metal drums. LLW typically contain low activity solidified resin and trash such as contaminated gloves, cloths, clothing, broken laboratory equipment deriving from the medical and industrial use of radionuclides (Abu Khader, 2009; Truter, 2010).

3.2.5 Intermediate level waste (ILW):

This type of waste typically contains a significant amount of long lived radionuclides and therefore needs to be disposed in a more secure way, at greater depths, than LLW (IAEA, 2009). The period of significant risk to the environment and lives of humans of this type of waste is in the range of a few 100 to more than 100 000 years (Stewart, 2002). The disposal site has to have natural and engineered barriers that provide long-term isolation from the environment and human intrusion when institutional controls might no longer be in place. Disposal requirements and classification is determined on a case-by-case basis, depending on the safety case and its assessment (IAEA, 2009). ILW usually includes chemical sludge, metal reactor fuel cladding, solidified concentrates, filters, plastic and non-compactable waste set in concrete (Abu-Khader, 2009; Truter, 2010).

3.2.6 High level waste (HLW):

Waste that has very high activity concentration levels and/or high concentrations of long lived radionuclides, with typical activity levels between 5×10^4 and 5×10^5 TBq/m^3 (IAEA, 1994; 2009). This type of waste is highly toxic and hazardous and remains so for several 100 000 years of decay; additionally large amounts of heat is produced during the decay of this waste (more than about $2kW/m^3$ according to the IAEA's 1994 classification scheme), requiring storage to include cooling mechanisms for up to 50 years in order for the waste to cool down to temperatures found in the subsurface (Stewart, 2002). HLW consist of spent fuel rods containing fission products and transuranium elements produced in the core of nuclear reactors (Abu-Khader, 2009).

Abu Khader, (2009), describes an additional class of radioactive waste:

3.2.7 Transuranic waste (TRUW)

Waste that is significantly contaminated with α-emitting transuranium radionuclides (eg. ^{239}Pu, ^{241}Am and ^{237}Np) that has half-lives longer than 20 years and activity concentrations of over 3.7 MBq/kg, excluding waste that belongs to the class of HLW (Abu-Khader, 2009; Lucchini *et al*., 2007). This waste is also designated for deep geological disposal, such as the mined repository near Carlsbad in New Mexico, disposing TRU at a depth of 655m below the surface in a semi arid region. This waste is typically generated during the production of nuclear weapons (Thakur & Mulholland, 2011).

3.3 The Vaalputs radioactive waste disposal site

The Vaalputs waste disposal site has been selected after various in depth studies of potential effects of radioactive waste on the environment, as well as effects of the environment (eg. tectonics) on the safe disposal of radioactive waste. Some of the factors that contribute to Vaalputs being seen as an attractive choice for such a facility are (Ainslie *et al*., 2003):

- the semi-arid to arid climate, lowering possibilities of contaminating water resources,
- low population density,
- sparse agricultural activities,
- low potential for economic mineral exploitation,
- the area is locally elevated, reducing flooding potential,
- long-term geological and geomorphological stability (Andreoli *et al*., 1986; Levin, 1988).

Figure 3.2: Air photo of the Vaalputs radioactive waste disposal facility (photo courtesy of Andreoli & Van Blerk, 2006).

3.3.1 Type of waste disposed locally

The KNPS has been in use since 1985 and its decommissioning and decontamination was originally planned for 2035 (Meyer *et al*., 2006). Since 1986 Necsa (previously the AEC) is in charge of the disposal of short lived low- and intermediate level radioactive (LILW) at Vaalputs, the specially designed facility located in the north west of the Northern Cape Province. This waste, the bulk of which is generated by Eskom at the Koeberg Nuclear Power station near Cape Town, is disposed in metal (LLW) and concrete (ILW) drums buried and capped in near-surface (10m deep) trenches. Until 11 May 2011 the radioactive waste disposed of at Vaalputs contained only short-lived radionuclides including ^{60}Co, ^{90}Sr, ^{137}Cs and ^{134}Cs, which means it was free of the long-lived U- and its daughter elements. From this date on long lived low level waste (LLW-LL) that was previously stored at Pelindaba, has been delivered to Vaalputs in metal drums. High level spent fuel is stored on the site of KNPS in reactor pools, since Vaalputs currently does not hold a licence for the disposal of HLW.

The drums from Koeberg currently disposed at Vaalputs typically contain the following waste (Truter, 2010):

LLW (steel drums)	low activity solidified resin, slightly compacted solid waste consisting of trash such as contaminated gloves, cloths, clothing, broken laboratory equipment, etc.
ILW (concrete drums)	solidified evaporator concentrates, solidified resin concentrates, filters, plastic, non-compactable waste set in concrete.

The LLW-LL arriving from Pelindaba since 2011 is placed in two types of steel drums. These steel drums contain the following waste:

210 litre steel drums	Contain compacted waste: 6 to 8 compacted 100 or 160 litre drums containing trash such as in the Koeberg steel drums are placed inside and further solidified by filling with concrete.
100 litre steel drums	Contain evaporator concentrates solidified with concrete.

Every year an average of 210 concrete containers and 600 steel drums are delivered to Vaalputs from the Koeberg Nuclear Power Station. Delivery of waste from the Pelindaba reactor started recently and it is planned that 6000 210 litre steel drums and 3000 100 litre steel drums will be delivered every year (Truter, 2010). Table 3.2 and Table 3.3 are inventories of the isotopes in LILW waste that has been delivered to Vaalputs from 1986 to 2011, showing the total activity of waste received and the amount left to decay as on the 9th of November 2011.

Table 3.2: Low- and intermediate-level waste received (GBq*) from the KNPS for disposal at the Vaalputs site as at November 2011 (data: adapted from Necsa, 2011a).

Isotope	LLW (Trenches A01-A04)		ILW (Trenches B01-B04)	
	Received	Amount left to decay	Received	Amount left to decay
Ag-110	2.66E-04	2.66E-04	1.04E+03	1.02E+03
C-14	1.12E-02	-	2.16E+02	-
Co-60	1.72E+04	1.38E+04	6.58E+04	6.09E+04
Cs-134	3.19E-02	3.18E-02	4.99E+03	4.28E+03
Cs-137	4.04E+03	1.19E+03	5.35E+04	7.41E+03
Ce-144	-	-	2.52E+03	2.40E+03
H-3	3.56E+02	2.22E+02	1.09E+04	4.62E+03
I-129	9.62E-08	-	1.83E-01	-
Mn-54	1.47E-02	1.47E-02	1.62E+03	1.60E+03
Sr-90	2.33E-04	7.80E-05	2.44E+02	4.07E+01
Tc-99	4.49E-08	-	1.40E+01	-
TRU**	7.68E-06	-	5.78E+00	-
TOTAL	**2.16E+04**	**1.52E+04**	**1.41E+05**	**8.23E+04**

** GBq = Gigabequerel; ** TRU: Transuranium elements, i.e.: plutonium*

Table 3.3: Other KNPS waste packages delivered to the Vaalputs site (data: adapted from Necsa, 2011a).

	Carpets	Crates	Fuel Racks	Other packages	TOTAL	Amount left to decay
Ag-110			2.91×10^{4}		2.91×10^{4}	2.91×10^{4}
Co-60		1.08×10^{-1}	1.43×10^{5}	9.00×10^{-8}	1.43×10^{5}	8.88×10^{4}
Cs-137	8.35		1.65×10^{2}		1.73×10^{2}	2.94×10^{1}
TOTAL	**8.35**	**1.08×10^{-1}**	**1.72×10^{5}**	**9.00×10^{-8}**	**1.72×10^{5}**	**1.18×10^{5}**

3.3.2 Containment vessels and lining

All waste delivered to Vaalputs must be in a solid form. Most waste would therefore either be compacted or immobilised by concrete inside the containers. Low level waste is stored in steel drums (Figure 3.3A), whereas intermediate level waste is vitrified within high-density concrete containers, lined with a metal casing and a second outer concrete casing (Figure 3.3B) (Truter, 2010). The disposal procedure differs from the proposed disposal options given by the IAEA (see Figure 3.1), since at Vaalputs, both LLW and ILW are disposed in similar near surface trenches, the only difference in disposal is therefore on the part of the type of containers used.

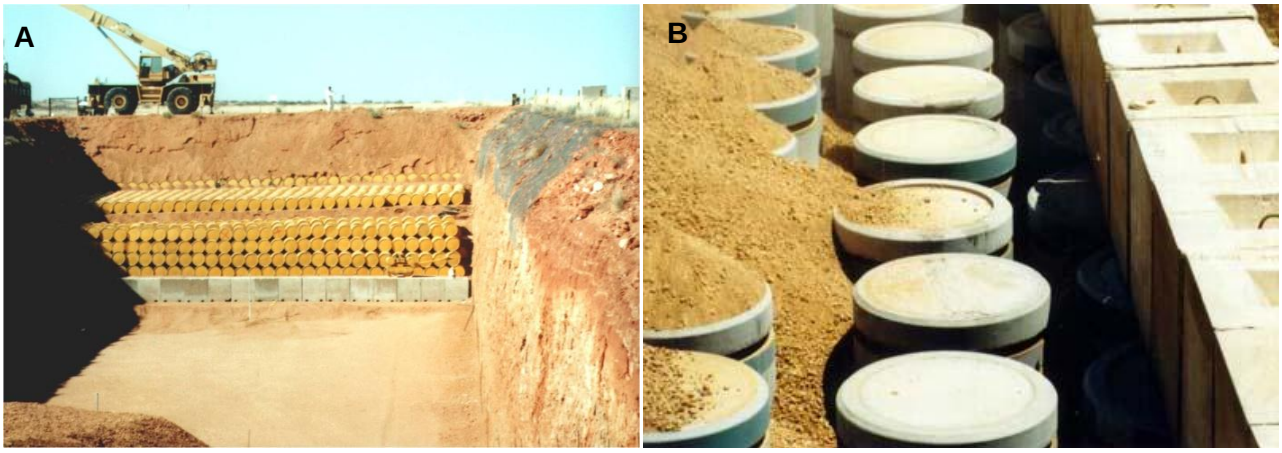


Figure 3.3A: Metal drums with low level waste lowered into Trench A01 (photo by author); B: Concrete containers with intermediate level waste being covered with clay as part of the capping process (photo courtesy of Necsa).

3.3.3 Trenches

Large trenches of eight to ten metres in depth are excavated for the storage of radioactive waste Trenches are designated for either low level or intermediate level waste, and are filled up gradually with the applicable type of containers (Truter, 2010). Figure 3.4 shows how concrete drums containing ILW are stacked in a trench, while Figure 3.3A shows the stacking of LLW metal drums. Currently Vaalputs has four LLW trenches, A01 to A04, while four other trenches, B01 to B04 are used to dispose ILW.

Figure 3.4: Stacking of concrete containers of intermediate level waste in the prepared Trench B01 before filling and capping takes place (photo courtesy of Necsa).

3.3.4 Capping

Once trenches are filled with containers of radioactive waste capping takes place by means of covering the trenches with the original layers of earth that was preserved from the time the excavation was made. Figure 3.5A shows the first capping with a clay-rich sediment, while the top cover is a layer of red sand (Figure 3.5B).

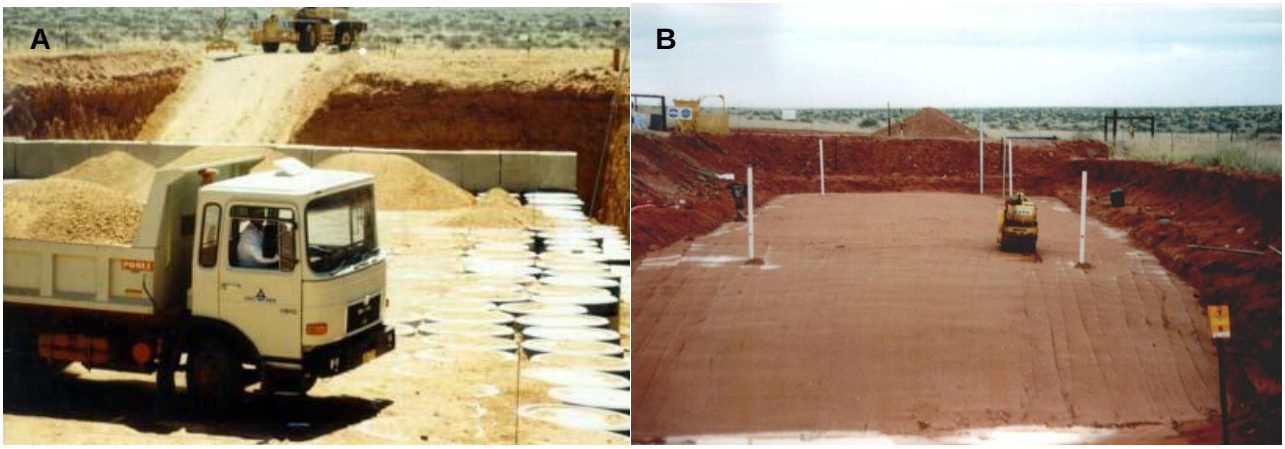


Figure 3.5 A & B: Concrete containers in trenches being capped by securing layers of clay-rich soil on top of the waste (photo courtesy of Necsa).

3.3.5 Rehabilitation

With the top layers of soil back in place natural vegetation can be re-established (Figure 3.6). Fauna such as springbok and gemsbok were reintroduced by Vaalputs management and have been seen grazing on covered trenches (Necsa, 2011f).

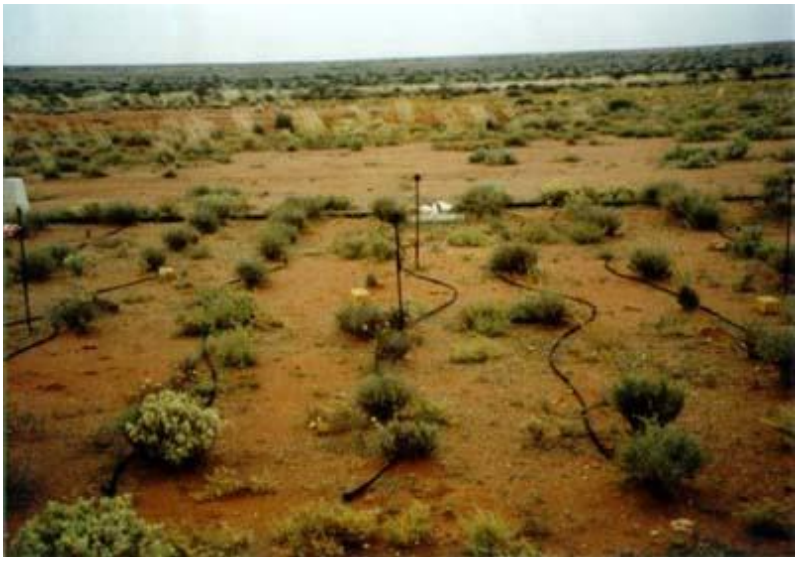


Figure 3.6: Restoring the natural flora on top of a covered trench (photo courtesy of Necsa).

4 Site description

4.1 Physiography

4.1.1 Location and geographical setting

The Vaalputs Radioactive Waste Disposal facility is located in the Northern Cape Province of South Africa in the Namaqualand, lying about 90km to the southeast of Springbok, its nearest town and about 120 km from the Atlantic Ocean. The facility is situated at an elevation of about 1000 m above sea level (Brandt, 1998). Vaalputs can be found at 30°08'00"S; 18°32'00"E and in Figure 4.1 the locations of Vaalputs, Koeberg and Pelindaba are shown.

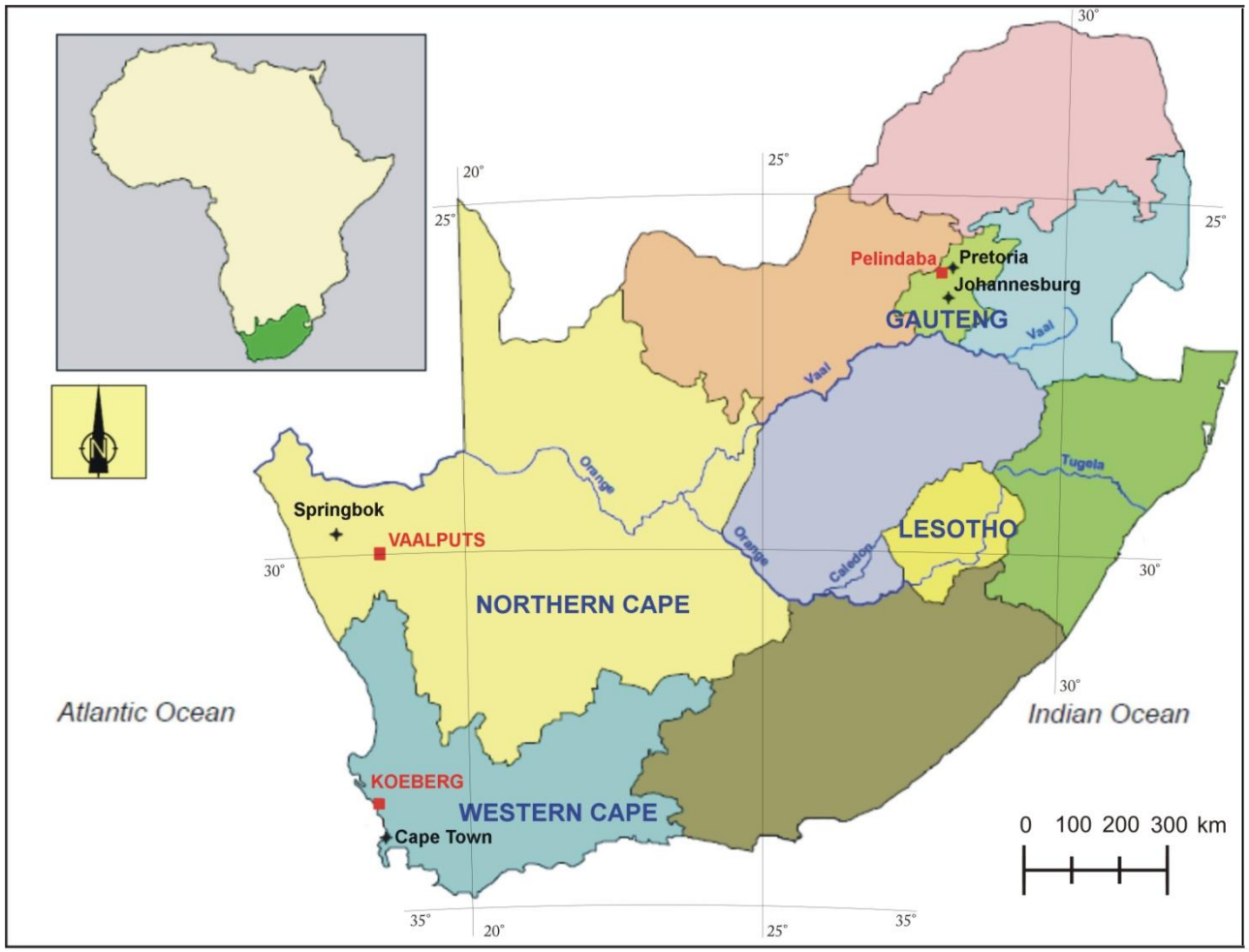


Figure 4.1: Map of South Africa, showing the locality of Vaalputs, Pelindaba and the Koeberg Nuclear Power Station (adapted after Van Blerk, 2006).

The Northern Cape Province of South Africa is subdivided into five District Municipalities, each of these districts are managed by several local municipalities. Vaalputs is located in the Namakwa District Municipality (Figure 4.2) which has six local municipalities and two District Management Areas (DMAs), which are areas with very sparse population and therefore no local municipalities. The Kamiesberg Local Municipality is managing the area in which Vaalputs is situated. Vaalputs lies within an ethno-geographical region of South Africa, called Namaqualand, which is known internationally for its large diversity in plants, reptiles and insects (Driver *et al*., 2003).

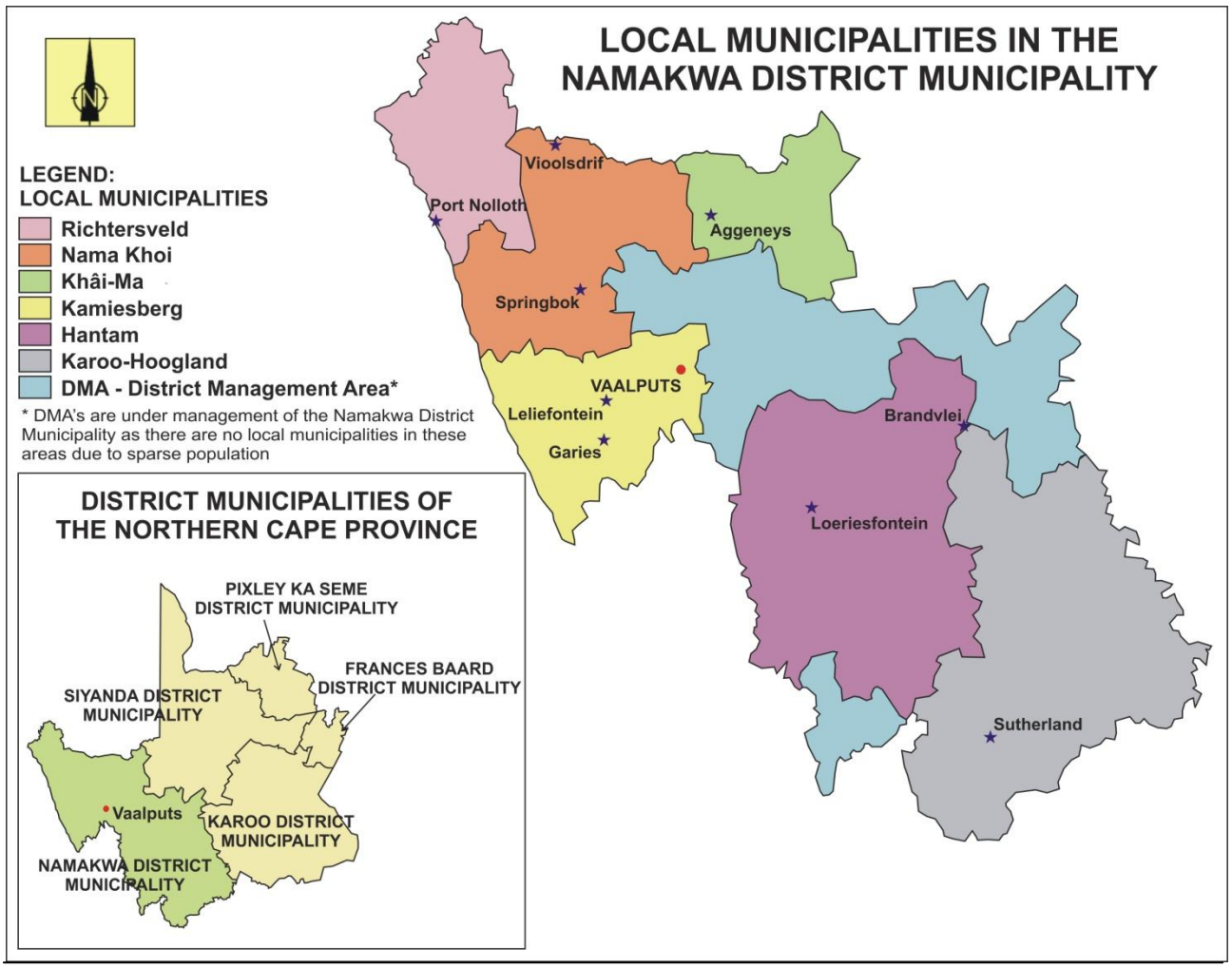


Figure 4.2: The location of Vaalputs in the Kamiesberg Local Municipality, part of the Namakwa District Municipality in the Northern Cape Province (adapted after Van Blerk, 2006).

The Vaalputs disposal facility has been established on adjoining portions of three farms, Geelpan and Garing (part of the farm Vaalputs) and Stofkloof (part of the farm Bokseputs) and covers an area of approximately 10 000 ha (Levin, 1988). The disposal area falls on the Geelpan portion of the property and occupies a fenced off area of 63 ha, with a 200 m wide buffer zone between the outer fence and the disposal area (Levin, 1988). The layout of the facility is shown in Figure 4.3. The offices, used by Necsa staff permanently assigned to the disposal facility, located within the buffer zone of the disposal site. The facility can be reached by travelling on the dirt road between the towns of Springbok and Kliprand. A small airfield has also been laid out on the facility, while the old farmhouse of the Geelpan farm is equipped as accommodation facilities for visiting staff and members of the public.

The study site was divided into three zones, namely Zone A, Zone B and Zone C with radii of approximately 1, 3 and 20 km, respectively, from the centre of the Vaalputs disposal facility (Figure 4.3). Zone C is a large area, extending onto the neighbouring farms and the boreholes in this zone can therefore be seen as the control area for possible 'leakage' of man-made radionuclides currently disposed at the site. The borehole in this zone that is furthest from the disposal site,

PBAKKI, is however referred to as the control position in reports to the NNR. Maps showing the borehole locations with their names will be shown further in this chapter in Figure 4.10 and Figure 4.11.

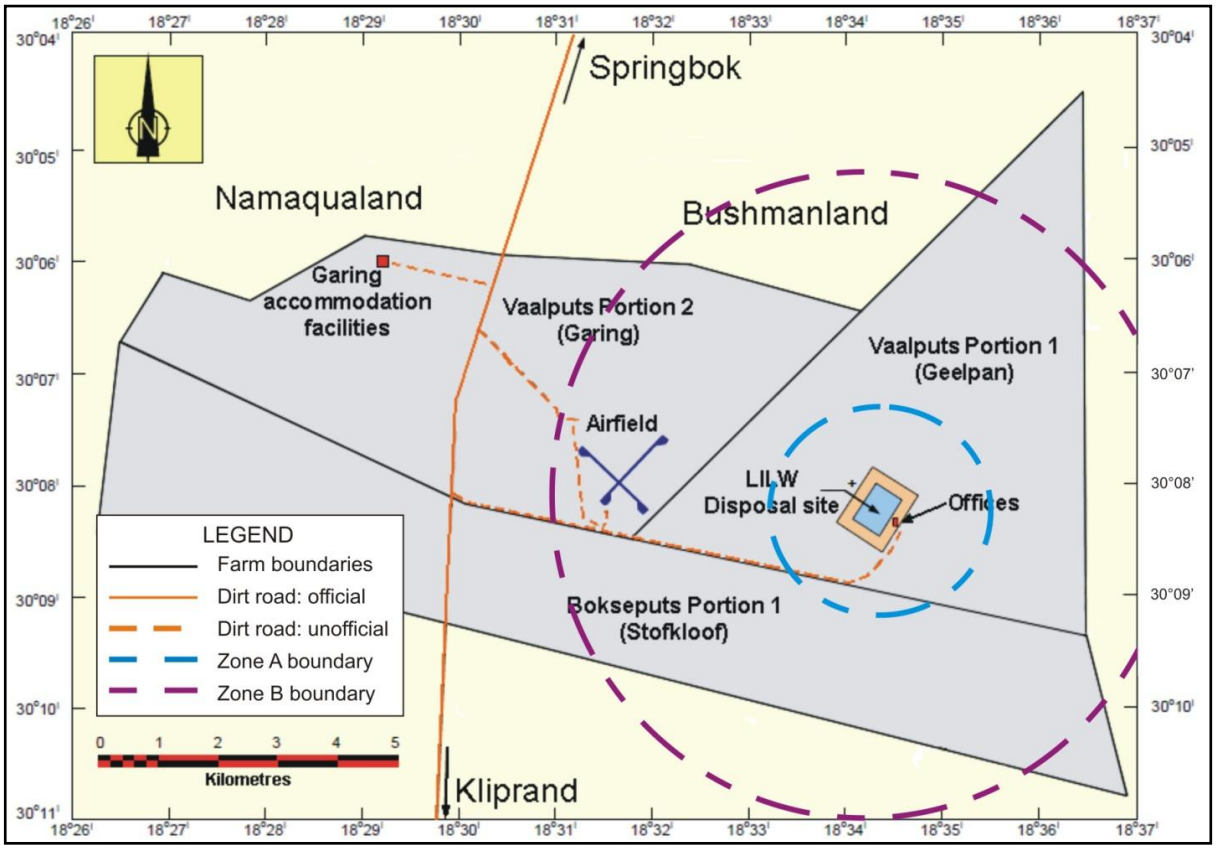


Figure 4.3: The Vaalputs waste disposal facility on the two adjoining farms Bokseputs and Vaalputs, showing Zone A and B boundaries, with the boundary of Zone C being beyond the extent of this map (adapted after Van Blerk, 2006).

4.1.2 Geomorphology

The north-south escarpment divides the study area into two topographical regions with the Namaqualand to the west and the Bushmanland Plateau to the east (Figure 4.4). The disposal area falls on the Bushmanland Plateau. The Namaqualand topography is a rugged granitic terrain with gently sloping sandy pediments as the valley floors, whereas the Bushmanland Plateau with an elevation of about 1 000 m above sea level is much more featureless and barren with low palaeo-dunes trending NNE (Brandt, 1998; Levin, 1988).

The higher lying western side of the area, which includes the Little Namaqua Highland, contains part of the Buffels River drainage basin, where most of the drainage is controlled by geological structures, following the deep lineaments (Brandt, 1998). The Bushmanland Plateau to the east of the terrain is lower with the drainage basins of the Olifants and Koa Rivers starting in this area, the drainage following the troughs or interdunal areas of the palaeo-dunes, often ending in a pan. One such pan close to the study area, the largest, is called Santab-se-Vloer (Levin, 1988; Brandt, 1998).

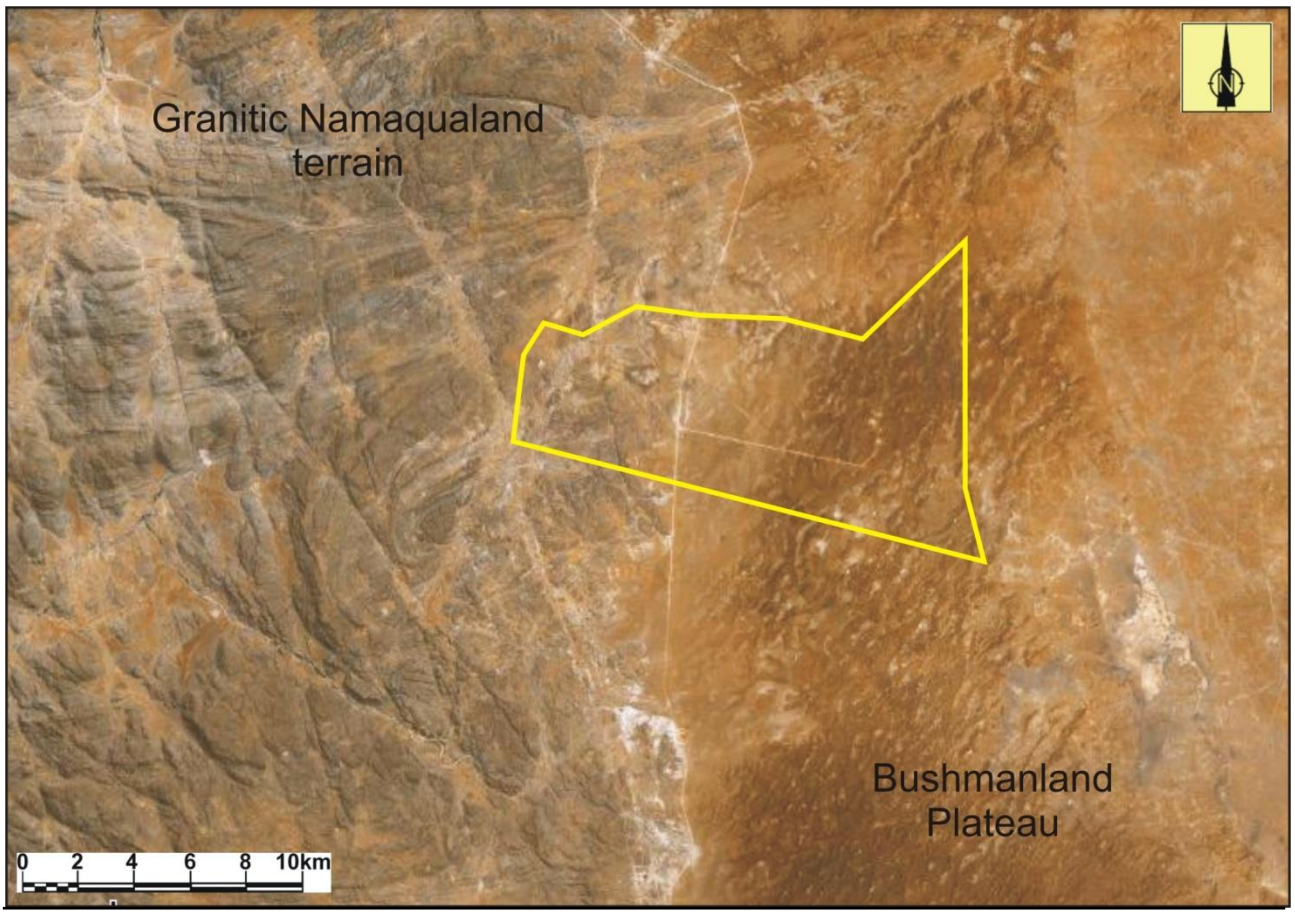


Figure 4.4: Satellite image of the Vaalputs facility straddling the granitic terrain of the Namaqualand on the west and the barren Bushmanland Plateau on the east (adapted from Google Earth, 2011).

4.1.3 Climate

Brynard (1988) describes the climate as dominated by anticyclonic conditions, with extreme temperatures and low rainfall throughout the year. Summer temperatures vary between 7 and 36°C, while the winter experiences temperatures between -1 and 22°C. The mean monthly and annual rainfall and evaporation for 1986 to 2010 are shown in Table 4.1, and it can be seen from these data that there is no evident seasonal pattern in rainfall for the area. A seasonal pattern is however clear with relation to evaporation, with much higher evaporation over the summer, a result of somewhat stronger winds and higher temperatures during the summer (Van Blerk, 2006). The wind direction in the Vaalputs area is predominantly SSW, with wind speeds averaging 3 to 8m/s (Hambleton-Jones, 1986). The area lies in the transitional zone between the summer and winter rainfall region, with low winter rainfall as a result of the Plateau falling in the rain shadow of the western escarpment, while dry inland winds cause low summer rainfall (Van Blerk, 2006).

Figure 4.5 is a comparison of the mean monthly temperature with the mean monthly precipitation at the Vaalputs site for the period 1986 to 2010. From the data used in this diagram the average monthly rainfall during the winter (April to September) is 11.05 mm, calculated as very similar to the average monthly summer rainfall (10.63), indicating a slight dominance in winter rainfall.

Table 4.1: The mean monthly rainfall, pan evaporation and temperature as recorded at the Vaalputs weather station (data from Necsa, 2011b).

Month	Mean Rainfall (mm) (1986 to 2010)	Mean Pan Evaporation (mm) (1990 to 2010)	Average Temp (1990 to 2010)
Jan	9.85	349.81	22.40
Feb	9.45	283.02	23.30
Mar	14.63	249.48	20.95
Apr	13.79	168.80	18.28
May	13.09	124.99	13.57
Jun	11.38	89.14	9.86
Jul	12.90	100.08	9.53
Aug	10.14	126.23	10.62
Sep	5.02	163.48	14.00
Oct	14.54	222.86	16.74
Nov	8.94	257.93	18.62
Dec	6.37	316.57	21.08
Monthly Average	**10.84**	**204.36**	**16.58**
Annual Average	**130.11**	**2452.38**	

Rainfall is mostly associated with thunderstorms during the summer and frontal weather systems in the winter months. Sporadic storms occur occasionally with individual rainfall events of more than 100 mm of precipitation being recorded (Brandt, 1998). Redding & Hutson (1983) reported the long term precipitation average as 74 mm per annum for the area, while in 1986 Verhagen & Levin reported the mean annual precipitation (MAP) in this semi-desert area to be 78 mm, with evaporation of more than 2000 mm per annum.

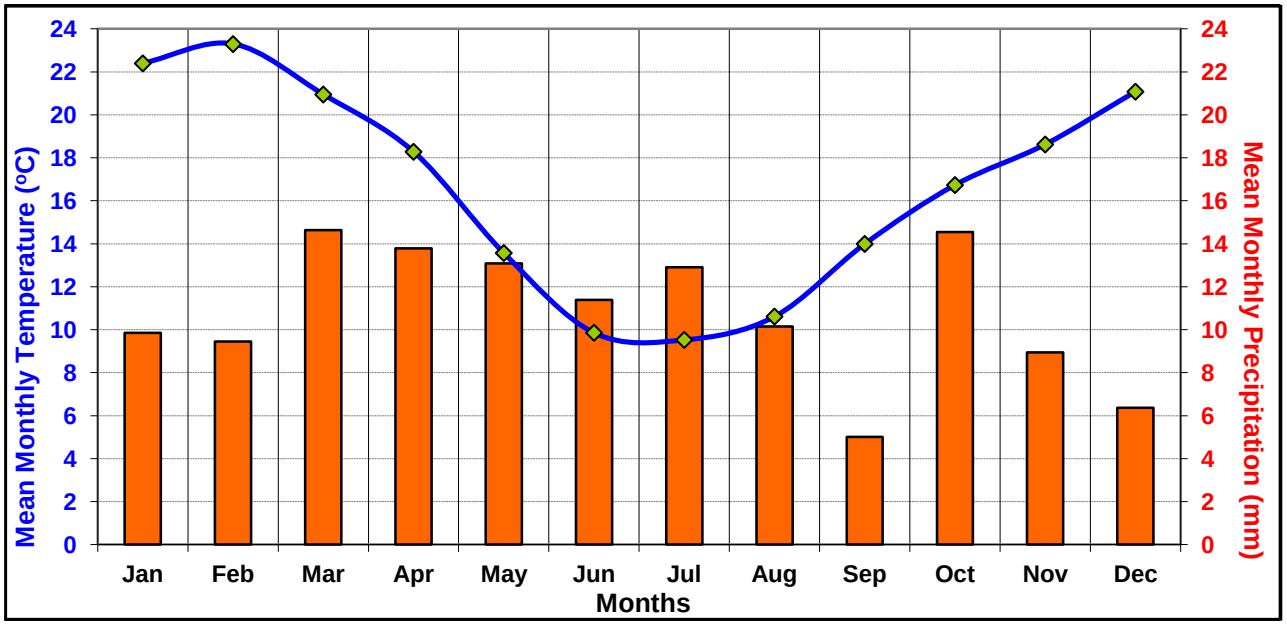


Figure 4.5: The mean monthly temperature compared to the mean monthly precipitation at Vaalputs (data: see Table 4.1).

From the Vaalputs weather station data, however, the short term MAP was calculated as 130 mm for the period 1986 to 2005 as recorded at the Vaalputs weather station. From Figure 4.6 it can be

seen that the Vaalputs area experienced a relatively rainy period during the mid nineties with a maximum annual precipitation for this period of 305.10 mm occurring in 1995. The full set of rainfall data can be seen in Appendix B, Table B-1.

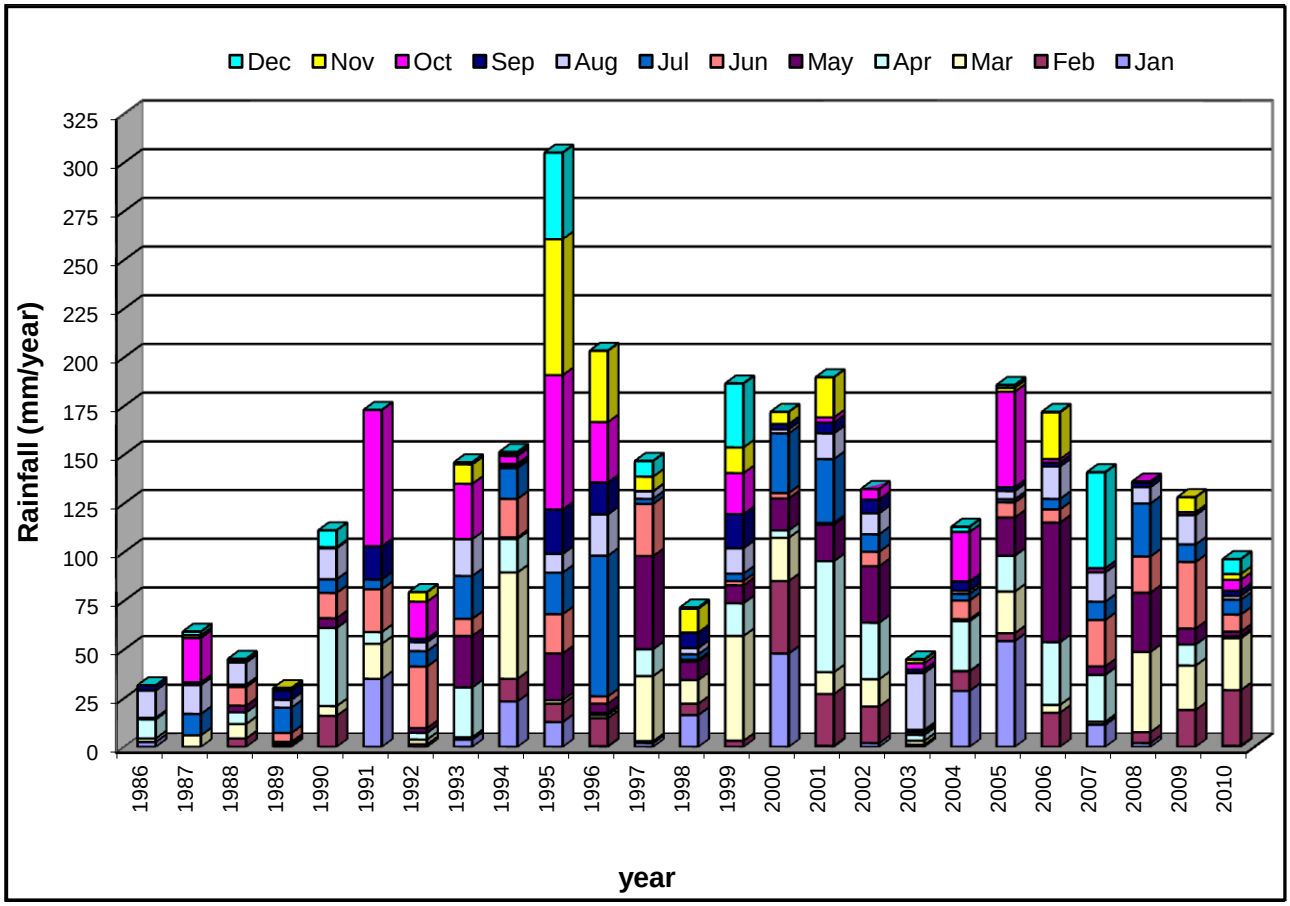


Figure 4.6: The monthly and annual rainfall at Vaalputs as recorded from 1986 to 2010 (data: see Appendix B, Table B-1).

4.1.4 Vegetation

The vegetation in the study area shows the transition from the Succulent Karoo biome in the east to the Nama-Karoo biome in the west (Mucina & Rutherford, 2006). Figure 4.7 shows the location of Vaalputs on the boundary between these two biomes. The biomes are subdivided into smaller bioregions, with the result that Vaalputs is also on the boundary between two of these bioregions namely the Namaqualand Hardeveld on the Succulent Karoo side, while the Nama Karoo side is called the Bushmanland bioregion (Mucina & Rutherford, 2006).

Hoffman, (1996), used the name Upland Succulent Karoo to describe the area around Vaalputs, west of the boundary between the Succulent Karoo and Nama Karoo as dominated by mountain ranges, making up the western escarpment of southern Africa. He singles out the Quiver Tree (*Aloe dichotoma*) as characteristic of the area, with dominant dwarf shrubs being the annual Vygie Family (*Mesembryanthemaceae*) and Daisy Family (*Asteraceae*), while grasses are not common in the area (Figure 4.8a). Hoffman, (1996), also describes the vegetation of the arid, gently sloping

Bushmanland bioregion as being dominated by non-succulent annuals and shrubs, with Small and Tall Bushman Grass (*Stipagrostis obtusa* and *ciliata)* common in sandy areas after summer rains (Figure 4.8b). In the more rocky areas species such as the Thorn Vygie (*Eberlanzia spinescens*) are common.

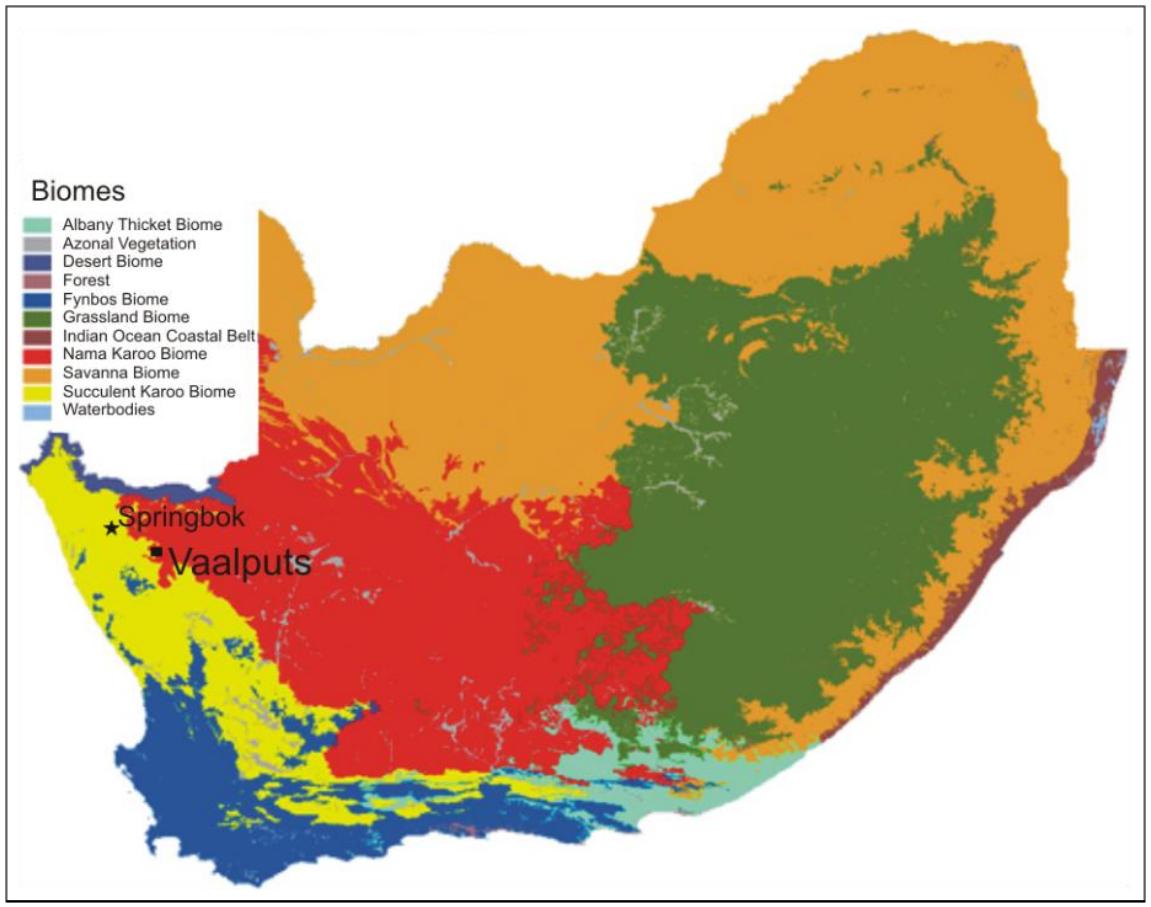


Figure 4.7: Biomes of South Africa, Lesotho and Swaziland (adapted after Mucina & Rutherford, 2006).

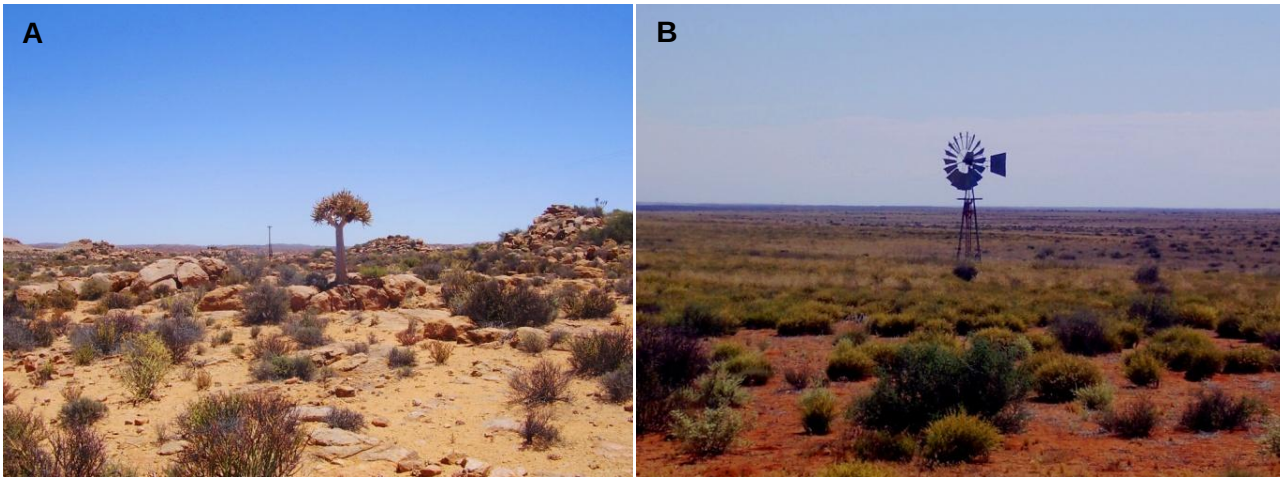


Figure 4.8: The two bioregions at Vaalputs: A: Namaqualand Hardeveld; B: Bushmanland.

4.2 Geology

The geology of the Vaalputs site and its environment has been described first by Andersen *et al*. (1983; 1992) and since then the stratigraphic relationships, tectonics and structures has been further determined by geologists such as Andreoli *et al*. (1986, 2006), Brandt (1998) and Brandt *et al*. (2005). In a nutshell, the radioactive waste is deposited in trenches excavated in clay-bearing sediments of Tertiary age, which overlies granitic gneisses of the Namaqualand metamorphic complex. Figure 4.10 (fold-out map) shows part of the geological map of Vaalputs and its environment that was compiled by Andreoli *et al*. (1986).

4.2.1 Stratigraphy of the Vaalputs region

According to the stratigraphy determined by Andreoli *et al*. (1986) the basement rocks consist of the Precambrian crystalline metamorphic rocks and intrusive rocks from the Namaqualand Metamorphic Complex (Figure 4.9).

Sequence Group/sub-group Suite	Formation/ Granite type	Lithology & Origin	Age
Kalahari Group	**Gordonia**	Aeolian Red sand	Late Pleistocene - early Holocene
	Vaalputs Formation	Brown, grey and white alluvial fan and fluvial sheetwash sandy to gritty clay with intercalated pebble bands from alluvial fan calcretised near the surface	Mid Tertiary
	Alluvial fan conglomerate; Immature cross-bedded arkosic grits	Grey-white sandy to gritty siltstone and weathered basement; Siliceous sandstone Intrusive pipes: - Olivine-melilitite - Kimberlite	Late Cretaceous 67 Ma (intrusives)
	Dasdap Formation*		Mid Cretaceous
Karoo Supergroup	Dolerite intrusives		Jurassic
	Dwyka Group	Diamictite	Late Palaeozoic
	BASEMENT INTRUSIONS		
		Syn- to late-tectonic pegmatite intrusions	~1000 Ma
		Kliprand Suite: Charnockite, undifferentiated** **Koperberg Suite**: Late tectonic basic intrusions into the Garies Group: - Diorite - Norite - Hypersthenite - Anorthosite***	~1030-1060 Ma
Syntectonic Granite Suite	**Leucogranite*** **Vaalputs granite*** **Stofkloof granite***	Various syn- to late-tectonic granitic intrusions into the Garies Group	~1060 Ma
Hoogoor Suite		Undifferentiated quartzo-feldspathic (pink) gneisses	
Little Namaqualand Suite	**Nababeep**	Augen gneiss (granitic intrusions)	
Okiep Group (Garies Subgroup)		Metamorphism of ancient arkosic-pelitic gneisses, basin intrusions: - Quartzo-feldspathic gneiss - Granulite (undifferentiated)	1040-1150 Ma

** Local name, not SACS approved; **U and Th enriched rocks as reported by Andreoli et al. (2006).*
NB: Double lines: unconformities; broken double lines: possible unconformities.

Figure 4.9: The litho-stratigraphy of the Vaalputs region, (modified after Andreoli *et al*., 1986; Brandt *et al*., 2005; Andreoli pers. comm., 2011).

Deposited on the basement is the late Paleozoic Karoo sediments with its dolerite intrusions (Brynard, 1988) and this is again overlain by deposits of the Vaalputs (Mid-Tertiary) and Dasdap (mid-Cretacious) Formations (Andreoli *et al*., 1986, Brandt *et al*., 2005; Andreoli, 2011). These sediments are then covered by late Cenozoic (possibly Pleistocene) palaeosols, as well as slightly ferruginised alluvium deposits that have filled depressions and valleys west of the main watershed (Brandt, 1998; Brandt *et al*., 2005).

4.2.2 Tectonic history

Investigations regarding the suitability of the Vaalputs area for a nuclear waste disposal facility long-term reported long-term geological and geomorphological stability of the area since mid-Tertiary times (Andreoli *et al*., 1986; Levin, 1988). Levin, (1988), suggested that for the following 300 years no more geomorphologic changes than sheet erosion should be expected. Seismically active structures such as the Platbakkies and Pofadder lineaments were predicted to produce minor tremors, but this was considered as a low risk due to their distance from the site and low intensity (Andreoli *et al*., 1986). Further studies conducted during the operational years of the waste facility (Brandt *et al*., 2005; Viola *et al*., 2005; Andreoli *et al*., 2009) led to the conclusion that the Namaqualand escarpment and the adjacent Bushmanland plateau are affected by ongoing, low levels of seismic tectonic activity of intraplate nature. Brandt (1998) and Partridge *et al*. (1994) reports evidence of uplift axes that were active as late as from Miocene to Pliocene-Pleistocene times. Reactivation of older, NNW-trending faults parallel to the escarpment was imputed to the eastern migration of the western escarpment by Brandt *et al*. (2005). These issues are currently being re-investigated by multidisciplinary research program of Necsa (Andreoli *et al*., 2009).

4.2.3 Borehole geology

The Vaalputs area was drilled extensively in a grid to characterise the stratigraphy of both the cover and the basement, as well as to obtain groundwater samples. All the boreholes in Zone A were drilled especially for the purpose of monitoring the groundwater below the Vaalputs waste disposal facility. These boreholes were logged geologically.

4.2.3.1 Zone A

The logs of Zone A boreholes used in this study can be seen in
Figure 4.12 it is observed that the boreholes MON2, MON3, MON10 and GWB3 are drilled into granite-gneiss, while borehole MON14 has a unit of green brecciated granite within the granite-gneiss. Boreholes MON4, MON12 and MON15 all intersect mafic intrusions of the Koperberg Suite in the granite-gneiss.

4.2.3.2 Zone B

Three boreholes from Zone B are used in this study: PBH22, FW35 and EM8. These boreholes were also drilled for the purpose of monitoring the groundwater below the facility and were logged geologically. These borehole logs can be seen in Zone C

As there are no geological records of the other boreholes in this zone, the only key to their lithologies lies in the two geological maps of Andreoli *et al*., (1986, 1987) shown in Figure 4.10 and Figure 4.11 with locations of all boreholes used in this study. From these figures it can be deducted that this group of boreholes are heterogeneous with regards to geology as they are spread apart over different lithologies. Borehole 16C3 and 13C5 are drilled directly into granitic gneiss rocks of the Namaqualand Metamorphic Complex, while boreholes 4C1, 5C2 and PBAKKI were drilled through the sediments of the Bushmanland Plateau. Borehole 13C5 is the most westerly lying borehole and lies quite far from the sedimentary cover of the Bushmanland Plateau, while 16C3 is the most northerly borehole and was drilled right next to where the first sediments started to accumulate.

4.2.3.3 Ad-hoc boreholes

Certain boreholes are included in maps and calculation, although they are not part of the originally selected boreholes used for comparison purposes throughout this entire study. These boreholes did however form part of the monitoring programme for certain times during the operational years, and might be referred to in certain sections of this study.

4.2.4 Basement rock geochemistry

Geochemists such as Andreoli *et al*. (1986) and Hart & Andreoli (1985) have described the basement of the Vaalputs area as granitic to charnockitic with an unusual enrichment in U and Th. According to Andreoli *et al*. (1986) anomalous rocks of the area were investigated and it was found that the uranium is largely locked in the stable refractory minerals monazite, zircon and apatite. These observations were confirmed by Andreoli *et al*. (2006) who compiled a semi-quantitative gamma-ray exposure-rate map of South Africa from measurements that was taken over a span of over 30 years. The map clearly demonstrates the few single areas with exposure rates above 60 nanoGray per hour (nGy/h) with one of these areas in Namaqualand, with the Vaalputs facility partly lying over an area with an exposure rate of more than 100 nGy/h (Figure 4.13). The anomalous area in Namaqualand was further investigated by Andreoli *et al*. (2006) with relation to petrology, geochemistry and metamorphism of anomalously radioactive rocks, i.e. rocks with a U and Th content higher than the average values for upper continental crust, thus 2.5 and 10.3ppm respectively. Andreoli *et al*. (2006) subdivided the anomalous rocks into four groups: a) granites and granite gneisses, b) charnockites, c) noritic to anorthositic rocks and d) granulites of both supracrustal and undetermined origin, and concluded that there is a general increase in the radioactivity of the Namaqualand rocks with an increase in metamorphic grade. They therefore suggested that the high temperatures from the radioactive decay are in fact the primary source of the high-grade metamorphism across the Namaqualand metamorphic complex.

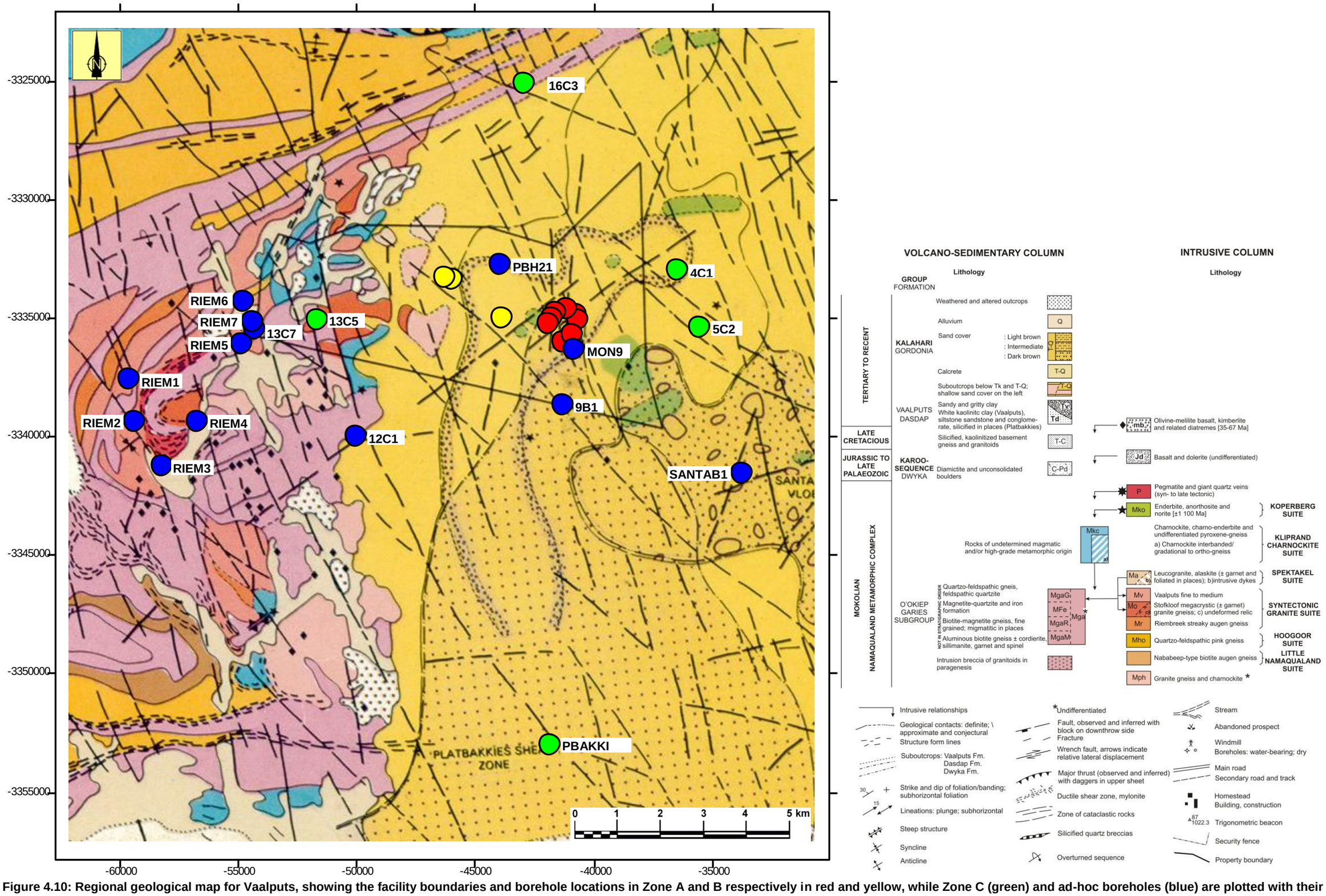


Figure 4.10: Regional geological map for Vaalputs, showing the facility boundaries and borehole locations in Zone A and B respectively in red and yellow, while Zone C (green) and ad-hoc boreholes (blue) are plotted with their borehole names. Names for Zone A and B boreholes will be shown in the more detailed map that follows (modified after Andreoli *et al.*, 1986).

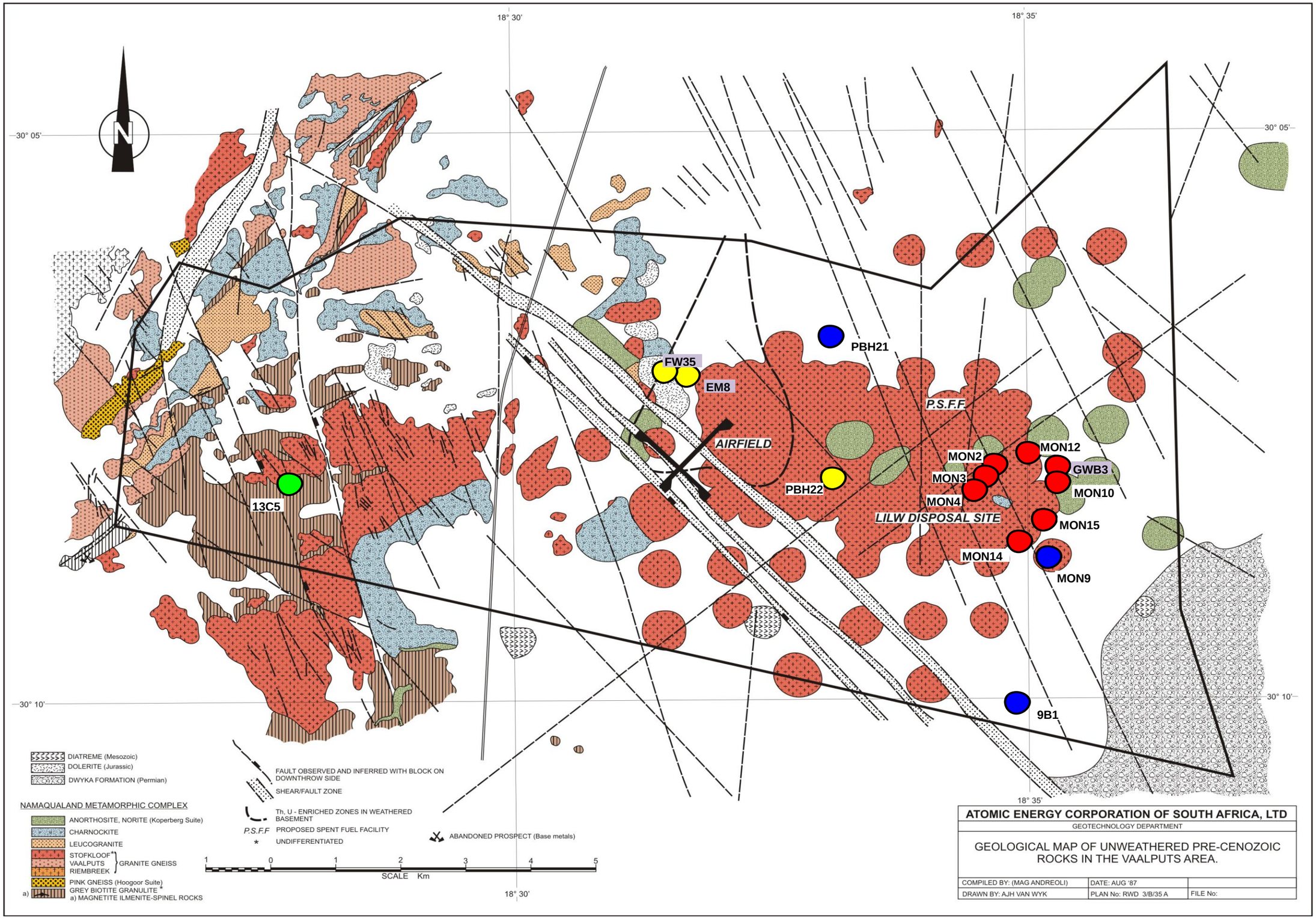


Figure 4.11: Map of sub-surface geology, showing the Vaalputs facility boundaries and locations and names of on-site boreholes (Zone A red; Zone B yellow, Zone C green and non-study boreholes blue). Quarterly analysed borehole names are highlighted in purple (adapted after Andreoli *et al*., 1986).

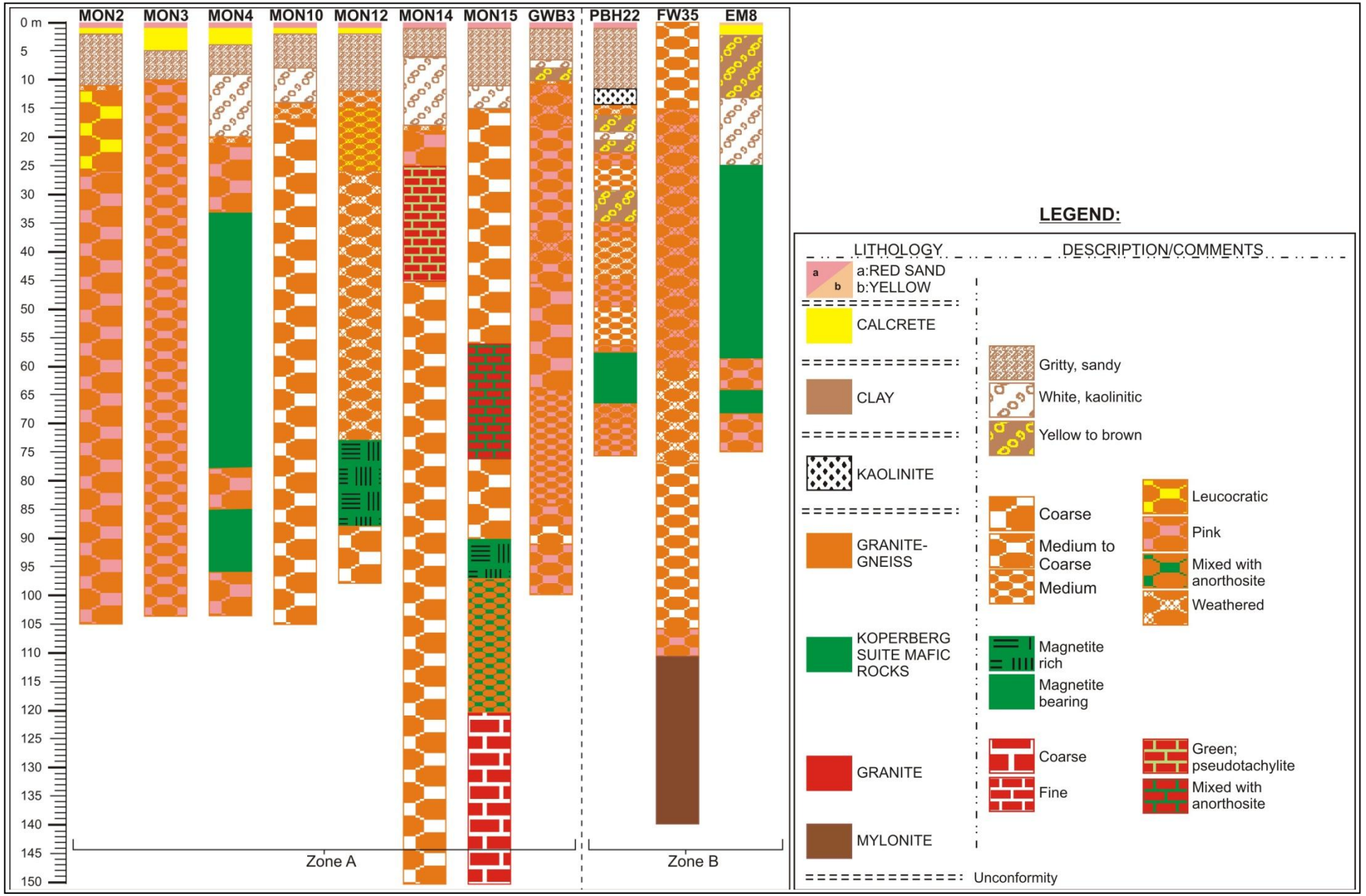
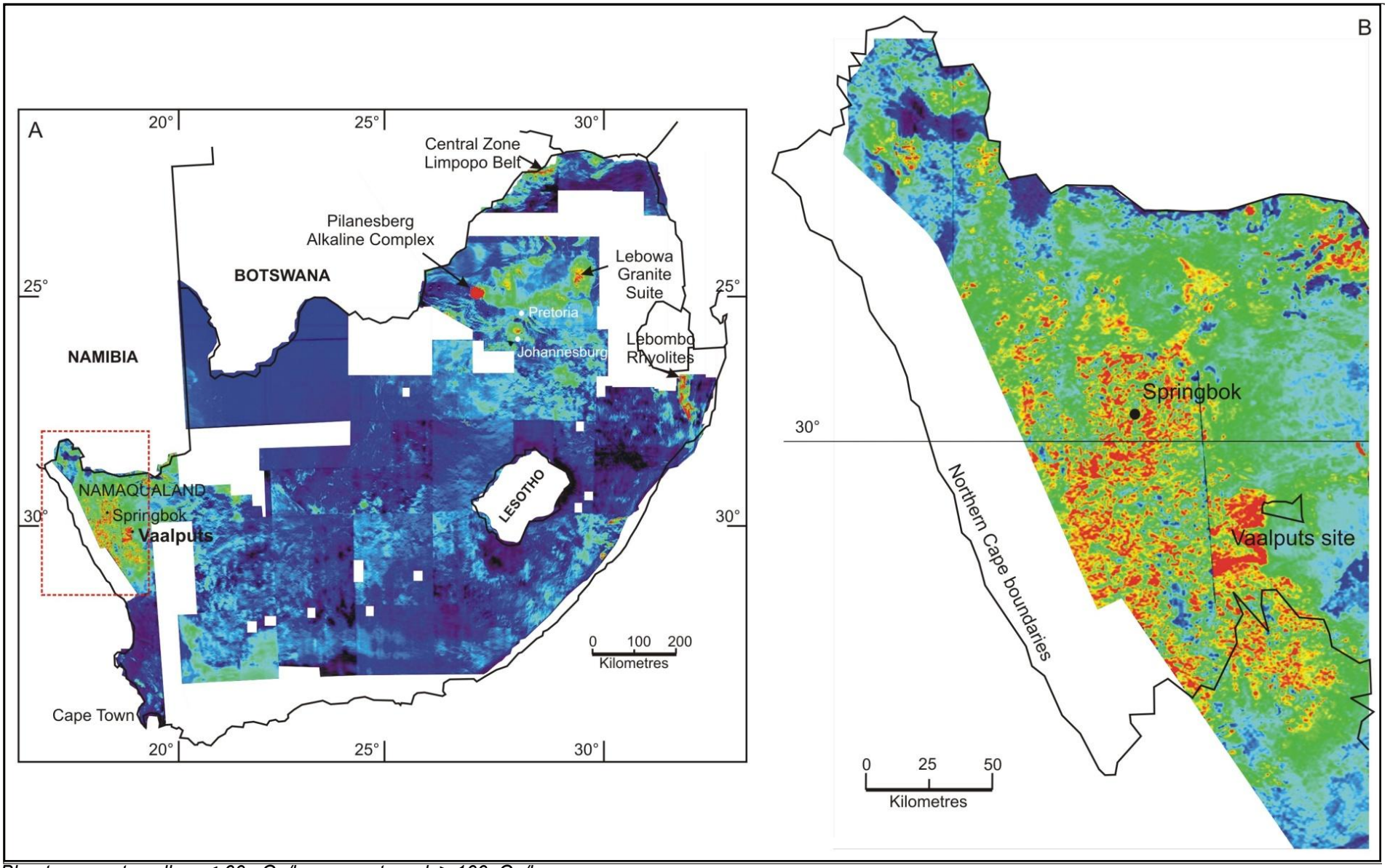


Figure 4.12: Geological logs of eight Zone A boreholes and three Zone B boreholes (adapted after Necsa, 2011c).



Blue to green to yellow: ≤ 60 nGy/h; orange to red: ≥ 100nGy/h.

Figure 4.13-A: Gamma ray exposure map of South Africa, with inset B: Gamma ray exposure map of Namaqualand showing the anomaly in radioactivity close to the Vaalputs site (adapted after Andreoli *et al*., 2006).

4.3 Hydrogeology

4.3.1 The Vaalputs groundwater regime

Vaalputs lies at an elevation of 1005 to 1012 m above mean sea level, with the groundwater level at around 948-950 m above mean sea level. The average depth of groundwater below the surface is 57 m. Water below the earth's surface is divided into the saturated and the unsaturated (vadose) zones. The saturated zone is below the water table, while the unsaturated zone lies above the water table (Figure 4.14). The trenches at the disposal site have been excavated 8 m deep through layers of red sand, sandstone, calcrete and feldspathic greywacke. Below, the trenches are lined with impenetrable layers of white and yellow clay.

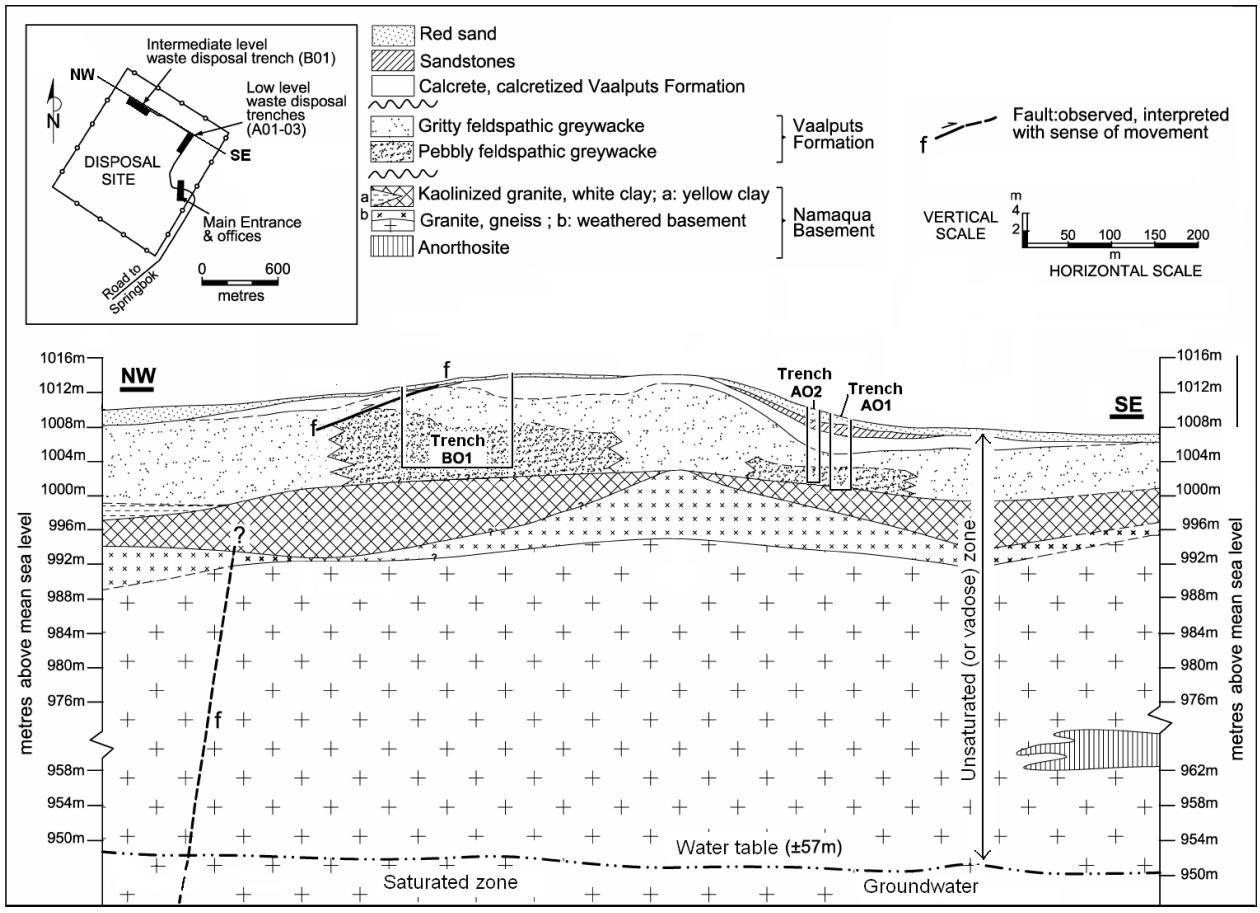


Figure 4.14: Cross-section through the Vaalputs waste disposal facility, indicating the location of trenches into impenetrable clay layers and the depth of the water table below (adapted after Van Blerk, 2006).

4.3.1.1 The unsaturated zone

The unsaturated zone has been defined by Ainslie *et al*. (2003) as the strata in between the land surface and the groundwater table, and is described as 50 to 55 m in thickness. Surficial material makes up the top 10 to 15 m, while the lower part of the unsaturated zone consists of fractured Stofkloof granite and associated rocks (Verhagen & Levin, 1986; Ainslie *et al*., 2003). In the disposal area, weathered surficial material and beneath this weathered granitic basement is found up to between 13 and 21 m below the surface (see Figure 4.14).

4.3.1.2 The saturated zone

The saturated zone, defined as the area below the water table, hosts the groundwater at Vaalputs in various aquifers, the most important one being fractured Stofkloof granite and its associated rocks. Water is often confined to contacts between the granite and mafic intrusives, as well as in weathered joints and vertical and sub-horizontal faults (Verhagen & Levin, 1986; Ainslie *et al*., 2003).

Zones around the disposal site exist with completely dry boreholes, which are isolated from the water-bearing zones, suggesting, according to Levin (1988), that most of the water-bearing structures would be sub-vertical resulting in little distribution of water. Levin (1988) further suggested a slow movement of groundwater of the water-bearing zones in an easterly to north-easterly direction directly below the disposal trenches and points out that the disposal site is located to the east of the watershed in an area with a very flat topography. The groundwater level gradients are very low at 1:200 resulting in very slow moving water – evident from the high water salinities (Hambleton-Jones, 1986; Verhagen & Levin, 1986). A groundwater level map will be shown in Chapter 6.

4.3.2 Groundwater recharge and age

As could be expected from an area with the low long-term mean annual precipitation (MAP) of 78 mm (the short term MAP was calculated as 129 mm from 1986 to 2005 data) and high average evaporation rate of over 2000 mm per annum, there is minimal recharge of groundwater under the average climatological conditions for the area (described in section 4.1.3). This was concluded by a pre-operational study of the Vaalputs facility conducted by Verhagen & Levin (1986), determining furthermore the age of the groundwater using ^{14}C isotopic data, to range between 2 000 and 13 000 years. The slow recharge and extensive leaching of soils leads to the groundwater at Vaalputs having a tendency towards high values for electrical conductivity (EC) as well as ions such as Cl^-, Na^+, F^-, K^+, NO_3^- and SO_4^{2-} (Andreoli *et al*., 2005).

Significant episodic recharge can however occur, such as the event in December 1985 when 128 mm of rainfall (double the average annual rainfall) was precipitated within four days (Verhagen & Levin, 1986; Van Wyk, 2010). Episodic events would be the most likely mechanisms for recharge when water levels are > 50 m below surface. Vegter (1995) has estimated recharge for two locations in Namaqualand with Springbok at 4% of the local average annual rainfall of 211 mm and Garies at 2% of its average annual rainfall of 142 mm (see Figure 4.2 for the locations of these two towns). Adams *et al*. (2004) reported recharge estimations of various locations in Central Namaqualand; of these locations, the closest to the Vaalputs site is Rooifontein, which has a mean annual precipitation of 138 mm and an average recharge rate of 0.28% of this precipitation. In Chapter 6 of this study the Chloride Mass Balance (CMB) method (described in section 5.4.1) will be used to calculate the rate of recharge to the groundwater at Vaalputs.

5 Methodology

5.1 Borehole selection process

Boreholes used for the study were selected from the 22 boreholes that have been monitored on a regular basis over the last 25 years. Over time some of these boreholes became unusable for different reasons, with some of them replaced by boreholes drilled nearby. The 16 boreholes selected for this study are those boreholes that have the most continuous timelines for the whole period. The result was that eight boreholes were selected from Zone A, three from Zone B and five from Zone C. Of these boreholes, all Zone A and B boreholes are monitoring boreholes, while all Zone C boreholes have wind pumps. Three of these boreholes, namely GWB3 in Zone A and FW35 and EM8 in Zone B, are boreholes that are sampled and analysed quarterly, while the other 13 boreholes are only sampled once per year. The annual sampling of these boreholes has not always been conducted at the same time each year. For the first 8 years sampling typically took place in August, and in 1999 to 2002 and 2005 to 2008 the samples were taken in May. For the other years sampling dates moved around over the year.

5.2 Sampling procedure

For purpose of monitoring the groundwater at Vaalputs, two types of boreholes are used: boreholes drilled specifically for the purpose of monitoring the site, and existing water-supplying wind-pump boreholes of the surrounding area. The sampling procedures for the two types of boreholes have some differences due to variance in the amount of water available and whether a water-pump can be used or not. In the following subsections the sampling procedure for both types of boreholes are described.

5.2.1 Boreholes drilled for monitoring

The sampling procedure below is a description of the current actual procedure that has been carried out during sampling in October 2009 that has been adapted from the field manual of Levin (1983). The water-level depth is recorded in all these boreholes in order to determine the regional flow pattern of the groundwater. The water-level is measured from the top of the casing, by using a “dip meter”, which is a simple hand winch with a measuring tape connecting a probe to a signalling device on the winch (Figure 5.1a). When the probe touches water a sound and light signal is produced, the signal stops when the probe is lifted out of the water, that allows for accurate determination of the depth of the water, reading directly from the measuring tape.

Samples are collected from the borehole by means of purging, with the water-pump lowered down to 10 m below the water-level (Figure 5.1b). The pump is started and water is allowed to run, while small samples are taken approximately every minute for EC measurement, until the EC has stabilized. Sample holders are rinsed to pre-contaminate with the borehole water before they are filled up (Figure 5.2a). For routine radio-analyses five litre samples are taken, whereas one litre

samples are sufficient for water-chemistry analysis and half a litre is needed for special analyses such as nuclide specific alpha spectrometry. Directly after sampling, the following variables are determined on site: temperature, electrical conductivity, and pH. According to Levin's field manual, (1983), the field measurements have to be carried out within minutes after taking the sample to reflect the actual conditions during sampling.

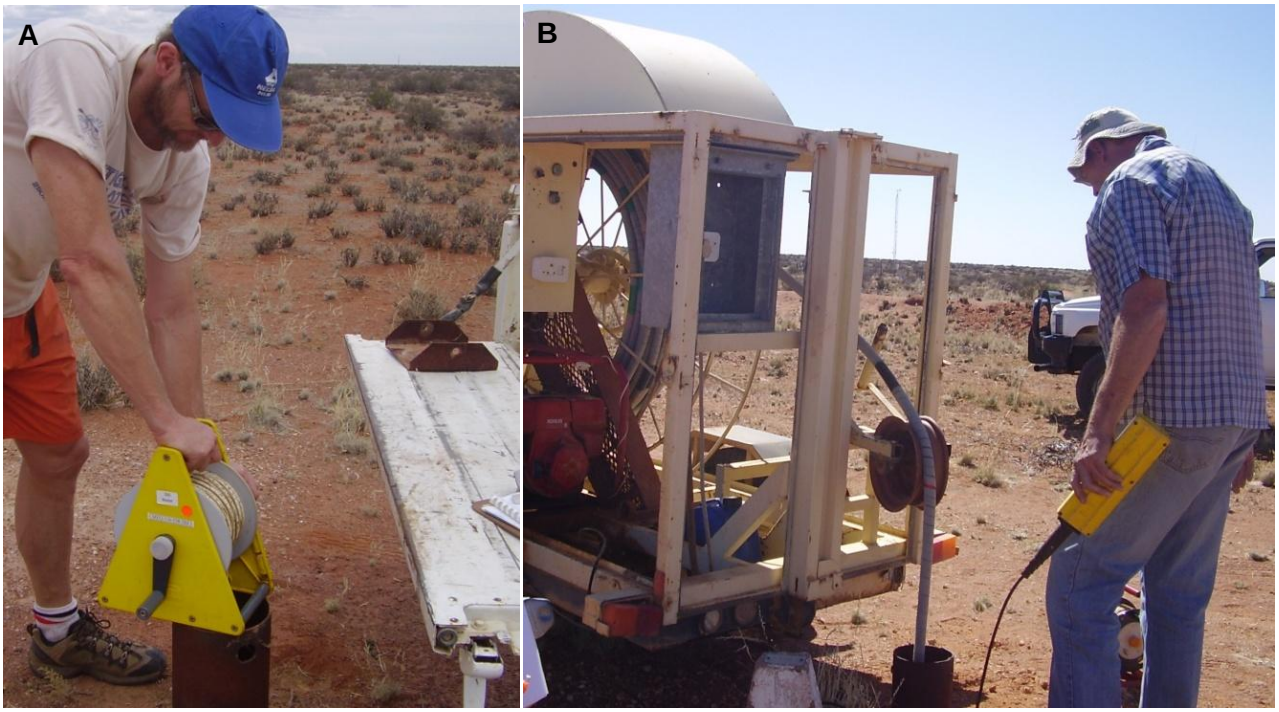


Figure 5.1A: Measuring the water-level of monitoring boreholes before taking samples of groundwater at Vaalputs, using a "dip meter". B: Lowering the water-pump into the borehole.

If there is a delay in taking field measurements, the correct procedure is to take a fresh sample and immediately take the measurements. These values are all determined with the Multilab P4 WTW meter (Figure 5.2b) and recorded on the data sheet together with the water-level, sample number, date and location.

The procedure for sampling such as described above cannot always be followed strictly due to difficulties such as boreholes having very limited water, boreholes caving in or boreholes blocked by bee nests. For these boreholes any water that can be found is sampled using any available method (most often a bailer) as the pumping equipment is quite sensitive (could get damaged by caving boreholes) and also not efficient when only a small amount of water is available. In these cases test-samples cannot be taken until the EC has stabilised and the EC is therefore that of the first and only sample.

Figure 5.2A: Sample holders are filled with water. B: On site measurement of temperature, electrical conductivity, Eh and pH.

5.2.2 Wind-pump boreholes

Taking water-level measurements at wind-pumps is not possible; therefore the first step is omitted for these boreholes. Water is mostly sampled from the pipes filling small reservoir dams. The winds are often not consistent, thus it is often necessary to turn the wind-pump blades manually to get a sample. If this is the case, the first water to come out is sampled after which measurements are taken. Taking test samples until the EC has stabilised is therefore not possible in the case of most wind-pump boreholes.

5.3 Analytical methods

5.3.1 Water-chemistry analysis

Groundwater samples of one litre for each borehole are collected as duplicates of routine radionuclide samples. In these samples the concentration of anions (Cl, NO_3, SO_4) are measured using ion chromatography (IC), with the exception of fluoride, which is measured by ion-selective electrodes (ISE). Cation (Ca, K, Na, Mg, Al, Fe, Mn) concentrations are measured with inductively coupled plasma optical emission spectrometry (ICP-OES). All these analyses are carried out in the analytical facilities at Necsa, Pelindaba.

5.3.2 Routine analysis of radionuclides for purposes of NNR reports

For routine analysis of radionuclides, five litres of groundwater is sampled per borehole. At the laboratory the water is evaporated, the precipitate is dried (ashed) which is then analysed.

Instrumental neutron activation analysis (INAA) is used to measure the concentration of ^{238}U and ^{232}Th in these precipitates. Samples are packaged in high-purity quartz vials and placed into a

transport system known as the rabbit, which transports the samples into irradiation positions of the SAFARI No. 1 reactor (at the Pelindaba research facility) where it will reside in position for a predetermined time. To analyse ^{238}U and ^{232}Th the sample is irradiated for 30 minutes, then left to decay for 5 to 7 days, after which the delayed neutron particles are counted for 45 seconds and 30 minutes respectively.

For determining ^{226}Ra levels the sample is analysed with gamma ray spectrometry by means of a AAA-875 series atomic absorption spectrophotometer. The counting time for ^{226}Ra is 8 to 16 hours.

The results of each sample from both the INAA and gamma spectrometry analysis are then evaluated in order to identify and quantify the isotopes present and report this as $\mu g.g^{-1}$ of sample, together with the amount of precipitate in grams and the exact amount of water sample received (Mokaleng, 2008).

5.3.2.1 Sensitivity

The sensitivity of INAA depends on the following parameters:

- Irradiation parameters such as: irradiation and decay times
- Measurement conditions: measurement time and detector efficiency
- Radionuclide parameters such as: isotope abundance and half-life

The sensitivity of the method for a specific element can be quantified using the minimum detectable activity (MDA). To calculate this, the limit of detection (DL) of a specific method must be determined. The detection limit is defined according to Curie formulae that there is a 5% chance that a sample reading will be mistaken for a background reading and a 5% chance that a background reading can be mistaken for a sample reading, and it is calculated as follows:

$$DL = 2.71 + 4.65B^{½}$$

with, B being the background reading for a sample

Minimum detectable activity (MDA) is representative of the background reading and an estimate of the capability of the instrument/method, and can be calculated as follows (Mokaleng, 2008):

$$MDA\ (Bq) = \frac{DL}{Y.\varepsilon t}$$ with,

- DL detection limit as determined above
- Y yield during decay of the type of radiation being measured
- ε Counting efficiency of detector
- t Counting periods (seconds)

The counting efficiency of the INAA and gamma spectrometry has been given as ~1% (Kotze, 2011).

5.3.2.2 Accuracy

In the reports made available to the NNR, all values above MDA are quoted. The meaningfulness of the values has to be determined by taking into account the accuracy of the measurements. Accuracy is the closeness of the agreement between the result of a measurement and a true value. Uncertainty is the chances of a value to not agree with its true value and three types of errors can contribute to this:

- Random errors
- Systematic errors
- Additional errors

When determining the meaningfulness of a value derived from analysis, the uncertainty of that result is subtracted from the obtained value. If the resultant value is above the MDA given for that result, the value can be seen as meaningful or significant.

Standards are used to assess the accuracy of analytical measurements. At Necsa's Pelindaba radio-analytical laboratory calibration standards are acquired from Amersham, the American National Institute of Standards and Technology (NIST) or Ultra Scientific, all of which are reputable suppliers of analytical standards. The primary standards are diluted to produce standards for every analysis carried out. The dilutions are conducted according to mass and a calibrated scale is used in this process. All dilution information is noted and records are kept, giving a complete traceability back to the primary standard. A summary of the standards used for each analytical technique is shown in Table 5.1.

Table 5.1: Standards used at the Pelindaba radioanalytical laboratory for the various analyses.

Analytical technique	**Standard**	**Supplier**
INAA (^{238}U)	Natural U solution	NIST
INAA (^{232}Th)	Th standard solution	Ultra Scientific
γ spectrometry (^{226}Ra)	^{152}Eu	Amersham
α spectrometry (α-emitting radionuclides)	Mixed α standards	Amersham
Gas flow proportional α-counting	^{241}Am	Amersham
Gas flow proportional β -counting	^{90}Sr	Amersham

5.3.3 Nuclide specific radio-analysis

Nuclide specific radio-analysis was carried out on ½ litre duplicate samples of the 2009 set of samples. This was carried out in order to investigate in more detail the contribution of the different radionuclides to the total α levels. α-particle emitting radio-isotopes from the ^{238}U, ^{235}U and ^{232}Th

decay chains. Elements to be measured are extracted from the water samples and activities measured using alpha spectrometry. Counting of α-particles is carried out for over 24 hours. The counting efficiency of this method has been given as 20-30% (Kotze, 2011).

Those α-emitters in the three decay chains (see Figure 2.1) that are not part of these results are all radionuclides with very short decay times and were therefore no longer present in the water samples by the time of analysis.

Meaningfulness of these values was also determined by looking at the MDA and uncertainty values reported with every result from alpha spectrometry. Only significant values were used for the study.

5.3.3.1 Comparison of capability of detection

For the purpose of this study it was necessary to compare the methods used routinely with alpha spectrometry for their capability of detecting the true amount of each of the three radionuclides: ^{238}U, ^{232}Th and ^{226}Ra. The minimum detectable activities of each method per radionuclide were considered as a means to determine the method with the best detecting capabilities.

The lower limits of detection for the routine radionuclide analysis of the radionuclides in precipitates were reported in the reports compiled for the NNR (Necsa, 1995). In the case of alpha spectrometry, the range in lower limits of detection for each radionuclide extracted from the water samples has been taken from the report of alpha spectrometry carried out in 2009 (Necsa, 2011e). A comparison of the detection limits is given in Table 5.2. Comparing the limits of detection in this table does not give a conclusion as to which of the methods are more reliable. In order to further investigate the reliability, a comparison of results for ^{238}U obtained from the two methods on duplicate samples from November 2009 is shown in Figure 5.3.

Table 5.2: Comparison of detection limits in routine analytical methods vs. alpha spectrometry.

Radionuclide	Routine analysis*			Alpha spectrometry**
	MDA ($Bq.g^{-1}$)	AVG gram precipitate per litre sample	AVG MDA ($Bq.l^{-1}$)***	MDA ($Bq.l^{-1}$)
^{238}U	< 3.6 (INAA)	2.769	< 10.0	0.93 - 12
^{232}Th	0.61 – 2.2 (INAA)		1.7 – 6.1	1.3 – 7.7
^{226}Ra	0.11 – 1.19 (γ Spectr.)		0.3 – 3.3	1.2 – 4.7

**Source: (Necsa, 1995).*
***Source: (Necsa, 2011e).*
****For comparison purposes AVG MDA in $Bq.l^{-1}$ has been calculated by multiplying MDA (Bq.g-1) with the average grams of precipitate obtained per litre of evaporated sample.*

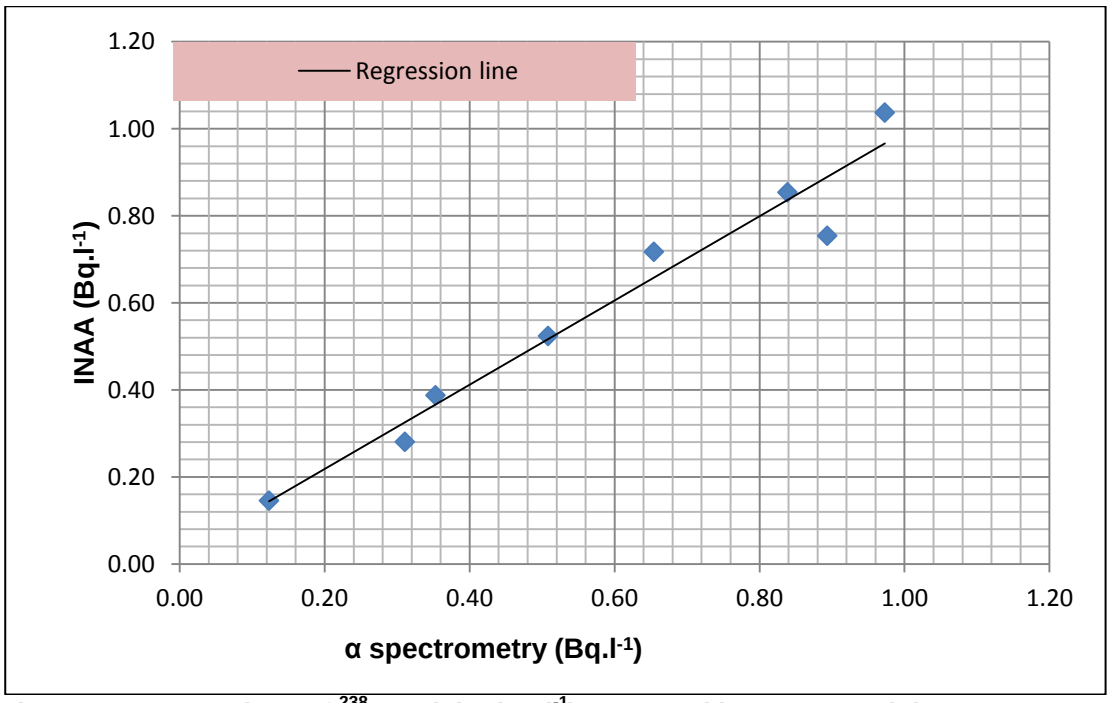


Figure 5.3: Comparison of ^{238}U activity (Bq.l^{-1}) measured by INAA vs. alpha spectrometry.

From the comparisons made in Table 5.2 and Figure 5.3 no one method could be preferred over the other and both sets of results could be seen as reliable. There is however a contradiction in the results shown above for the radionuclides ^{232}Th and ^{226}Ra, for which comparisons such as in Figure 5.3 were not possible. The reason for this is that for 2009 INAA delivered no ^{232}Th values above detection limit, while gamma spectrometry gave ^{226}Ra values above detection limit for only two boreholes. Even for ^{238}U a number of boreholes were reported to have levels below detection limit when analysed with INAA. Alpha spectrometry, on the other hand, delivered significant ^{238}U and ^{226}Ra values for all 15 borehole samples, with significant ^{232}Th levels for seven of the 15 boreholes that was sampled.

The above findings led to the decision to replace results from routine analysis with that of alpha spectrometry in graphics and summary data tables whenever significant values from alpha spectrometry analyses are available.

5.3.4 Total α and β measurements

Total α and β measurement is carried out with gas flow proportional counting on the ashed precipitates. Samples are pulverized and then prepared into a plastic planchette sample holder. Initially a 50 mm diameter sample was prepared, the sample 'sealed' with a thin film of polyvinyl-acetate (PVA). This sealing was necessary to prevent loose powder material from contaminating the entrance window of the detector. However, the PVA sealing was not reproducible with regard to different sample matrices and it was replaced around 1996 by a smaller disk of 25 mm in which the material is compressed using a hydraulic press, applying a pressure of 2 tonnes/square inch. The mass of the sample loaded into the planchette is recorded, with 1.00g being the aimed mass (Kotze, 2011).

5.3.4.1 The Canberra proportional counter

In the first years of the monitoring programme the Canberra Gross α-β proportional counting system (Models 2201) was used to screen activity levels of α and β radiation. With this method, the radiation from each sample is counted for 400 seconds using simultaneous mode, delivering two readings, one to the α-window and one to the β-window.

Ideally, measuring an α source would result in counts recorded in only the α-window and for a β source will give counts only in the β-window. Due to attenuation and other effects, there is 'spill-over', counts that are recorded from an α source in the β window and similarly counts in the α window that originated from β particles. The instrument settings are such that the spill-over from β events into the α-window is extremely small (~0.01%) but the α spill over into the β window is quite large (~30%) (Kotze, 2011).

This system was replaced in around 2000 by Oxford proportional counters and below is a description of analysis using this instrument.

5.3.4.2 The Oxford proportional counter

In the Oxford counter, the radiation from each sample is counted five hours, also using simultaneous mode. For this method the spill-over into the β window is also present.

In February 2005 the standard used for calibrating the Oxford counter was changed from ^{204}Tl to ^{90}Sr, which delivers better counting statistics and might have lead to lower values in total α and β activities (Kotze, 2011).

5.3.4.3 Uncertainty and detection limits in counting of total α and β

Associated with each parameter measured is an uncertainty factor. Measuring a sample of known mass will generate α and β readings from one measurement (simultaneous mode). Applying the calibration factors, one can extract the total activities and their associated uncertainties. Total α and β readings reported by the laboratory are entered into a spreadsheet which calculates the activity, its associated uncertainty and minimum detectable activity (MDA). A set of 6 values are thus produced for each sample (Kotze, 2011). The MDA for the solid samples is about 1 Bq.g^{-1} for total β and 0.1 Bq.g^{-1} for total α using a 5 hour counting time.

5.4 Calculations and conversions

5.4.1 Groundwater recharge

The method used for recharge calculations is called the Chloride Mass Balance Method (CMB). For this calculation the chloride concentration of rainwater in the area should be known. According to Adams *et al.* (2004) there is a linear relationship between chloride concentration and the amount of rainfall in areas near, but more than 15km away from, the coastline. In the case of

unavailability of rainfall chemistry data the following relationship would give the best estimate for the chloride concentration in rainfall:

$$Cl_p = 0.0043(P) + 1.1214,$$

where Cl_p is the chloride concentration (mg.l^{-1}) in precipitation, and P = the precipitation (mm).

For Vaalputs, with the average annual rainfall of 129 mm (as calculated by Van Blerk in 2006), the concentration of chloride in the precipitation (Cl_p) can be estimated as 1.68 mg.l^{-1}. However, according to Vermeulen (2011), in South Africa it is common practice by hydrogeologists to assume a concentration of 1 mg.l^{-1} for rain in inland areas.

The recharge (expressed as a percentage of the mean annual precipitation) is calculated as follows:

$$R = Cl_p / Cl_{gw} \times 100\%,$$

where Cl_{gw} is the concentration of chloride in groundwater, in the case of a number of boreholes Cl_{gw} is the harmonic mean of the chloride concentration of all the boreholes (Van Tonder & Xu, 2001; Xu & Beekman, 2003).

The harmonic mean can be calculated as follows:

$$Cl_{gw} = \frac{N}{\sum_{i=1}^{N} \frac{1}{C_{igw}}}$$

At Vaalputs the chloride concentration of the groundwater of 27 boreholes around Vaalputs, analysed since 1986, has been used in the calculation of the recharge number. The harmonic mean of these values were calculated and used, together with the estimated chloride concentration in the rainfall at Vaalputs, to calculate a value for the recharge to groundwater below Vaalputs. The results for the estimation of recharge at Vaalputs are given in section 6.2.

5.4.2 Radio-analytical data conversions

Instrumental neutron activation analysis (INAA) measures each isotope (as described in 5.3.2) separately in µg.g^{-1}.

5.4.2.1 µg.g^{-1} to µg.l^{-1}

The values reported by the laboratories are reported in µg.g^{-1}, giving the mass of the element per one gram of precipitate. These values are converted to µg.l^{-1} by multiplying with the factor derived from dividing the mass of the precipitate left behind by the volume of water that was evaporated:

$$\mu g.g^{-1} \times g.l^{-1} = \mu g.l^{-1}$$

5.4.2.2 µg.l^{-1} to Bq.l^{-1}

Necsa reports the activity of radionuclides to the NNR, for this it is necessary to convert the measured weight concentration results to the reported activities in Bq.l^{-1}. Table 5.3 below gives the properties of radionuclides that are used in these conversion calculations.

Table 5.3: Properties of radionuclides used for conversion from weight to activity (adapted from Faure, 1998)

Radionuclide	^{238}U	^{235}U	^{234}U	^{232}Th	^{226}Ra
Isotopic abundance	99.27%	0.72%	0.0057%	100%	100%
Specific activity (activity per gram of natural element)	12356	568	12356*	4057	3.66 x 10^{10}
Natural element (µg)/unit of activity (Bq)	80.9	1760.6	80.9	246.5	2.74 x10^{-5}

** Although there is an almost negligible amount of ^{234}U present in every gram of natural uranium, its short half-life results in very high radioactivity, giving the same amount of radioactivity as ^{238}U from every gram of natural uranium*

Uranium

Uranium activity is reported to the NNR as ^{nat}U (Bq.l^{-1}), where ^{nat}U = ^{238}U + ^{235}U + ^{234}U. The uranium results obtained from the INAA analyses are in actual fact ^{238}U (µg.g^{-1}), which is converted to ^{238}U (µg.l^{-1}). In order to convert this value to the reported ^{nat}U (Bq.l^{-1}) two assumptions are made by Necsa:

A. The mass of uranium measured represents only ^{238}U as the other two isotopes are present in wt% amounts below detection limit. In other words it is assumed that ^{238}U (µq.l^{-1}) ≈ ^{nat}U (µg.l^{-1}). It is important to take note however that despite the low concentration of ^{234}U, it has a very high activity and it will therefore have to be taken into account when calculating the activity of ^{nat}U. For this purpose, the second assumption is made:

B. ^{238}U and ^{234}U are in equilibrium and therefore their activities are equal and that there is no significant activity from ^{235}U. The conversion used by Necsa has been:

$$2 \times {}^{238}\text{U}\ (\mu g.l^{-1}) / 80.9 = {}^{nat}\text{U}\ (Bq.l^{-1}) \qquad (\text{with } {}^{238}\text{U}\ (\mu g.l^{-1}) = {}^{nat}\text{U}\ (\mu g.l^{-1}))$$

For the purpose of this study, two changes have been made in order to eliminate both assumption A and B, enhancing the integrity of data displayed in this report:

1. This first change makes a very slight difference, but since ^{238}U does not account for 100% of the weight amount of ^{nat}U, but only 99.284% the abundance factor has to be taken into consideration. To get ^{nat}U (µg.l^{-1}) from the measured ^{238}U (µg.l^{-1}) the following calculation is made.

$$^{238}\text{U}\ (\mu g.l^{-1}) / 99.284\% = {}^{nat}\text{U}\ (\mu g.l^{-1})$$

2. For the purpose of this study uranium data will be given as ^{238}U ($Bq.l^{-1}$) and not the activity of natural uranium. This is the only acceptable way, since experimental work has shown that in the groundwater below the study area the assumption that ^{238}U and ^{234}U are in equilibrium is incorrect. However, more extensive experimenting is necessary to determine an acceptable ratio for this site. (This did not fall within the scope of this study).

Therefore, for this study, in order to present uranium as ^{238}U ($Bq.l^{-1}$), the following conversions are made:

A. ^{238}U ($\mu g.g^{-1}$) x $g.l^{-1}$ = ^{238}U ($\mu g.l^{-1}$)
B. ^{238}U ($\mu g.l^{-1}$) / 99.284% = ^{nat}U ($\mu g.l^{-1}$)
C. ^{nat}U ($\mu g.l^{-1}$) / 80.9 = ^{238}U ($Bq.l^{-1}$)

Thorium

^{232}Th has an isotopic abundance of 100% and a specific activity of 4.057×10^3 $Bq.g^{-1}$; thus, to convert the reported ^{232}Th ($\mu g.l^{-1}$) to the activity of ^{232}Th in ($Bq.l^{-1}$), the following conversion is carried out:

$$^{232}Th\ (\mu g.l^{-1}) / 246.5 = {}^{232}Th\ (Bq.l^{-1})$$

Radium

The isotopic abundance of ^{226}Ra is also 100% and its specific activity is 3.66×10^{10} ($Bq.g^{-1}$). The conversion from ^{226}Ra ($\mu g.l^{-1}$) to ^{226}Ra ($Bq.l^{-1}$), is carried out with the following calculation:

$$^{226}Ra\ (\mu g.l^{-1}) / 2.74 \times 10^{-5} = {}^{226}Ra\ (Bq.l^{-1})$$

5.5 Producing graphics and descriptive statistics

5.5.1 Groundwater maps and water-chemistry plots

Groundwater level maps (Figure 6.1) were produced using the program WISH which has been developed by the Institute for Groundwater Science at the University of the Free State. All groundwater levels were obtained from Necsa as ‘metres below surface’. In producing the groundwater level maps these water level values were subtracted from the topographical information for the area, by means of a Bayesian calculation, producing a map that shows the groundwater levels as ‘metres above mean sea level’ (m.a.m.s.l.).

Other maps in this thesis were produced using various drafting programs, mostly CorelDraw 12, after which it was imported into WISH in order to plot borehole locations, eg.: Figure 4.10 and Figure 4.11.

Standard plots used in the classification of groundwater (section 6.3) were also drafted using WISH. These include Piper diagrams, expanded Durov diagrams, Stiff diagrams and timelines. Box-and-whisker plots of each borehole were produced from ^{232}Th and ^{226}Ra results.

5.5.2 Statistical computing

Descriptive statistics, histograms and group box-and-whisker plots were obtained using an open source software package named R (R Development Core Team, 2011), with the help of the Department of Mathematics and Statistics at the University of the Free State.

6 Hydrogeology and hydrogeochemistry results

6.1 Water levels

During the pre-operational studies groundwater levels of boreholes around the proposed Vaalputs radioactive disposal site has been measured extensively. Since the end of 1985, when operations began at Vaalputs, water levels closely surrounding the disposal facility have been measured several times each year. The boreholes from which these levels were and still are measured, are mostly monitoring boreholes drilled during the establishment of the facility in 1985 within its boundaries. The full dataset of borehole water levels with coordinates is given in Appendix C, Table C-1.

Figure 6.1-A shows a contoured groundwater level map that was drafted using Bayesian interpolation from water levels measured in 1985, while Figure 6.1-B to D show three groundwater level maps of the Vaalputs facility, displaying changes in groundwater levels over time. In order to obtain water level elevation for these groundwater maps, the depth of water below the surface, as measured, was subtracted from the topographic elevation levels for the borehole location. From both of these figures it is evident that the disposal facility lies on an area where groundwater gradient is very low. In Figure 6.1-B an area with lower groundwater levels can be seen around the monitoring boreholes, drilled in that year, 1985. Three boreholes, MON19, MON5 and MON16, which are surrounding the disposal site yield water levels much lower than boreholes adjacent to each of the respective boreholes. These boreholes are possibly not connected to the main aquifer. In the two maps to follow (Figure 6.1-C&D) it is evident that groundwater levels are very similar throughout the facility and that the lowered water levels seen in 1985 have stabilized in later years.

6.2 Recharge rate

As part of the routine monitoring programme 529 chloride concentration values were obtained from the annual water-chemistry analysis of 27 boreholes around the disposal site from 1986 to 2008. The harmonic mean of these values was used to calculate a recharge rate of 0.16% of the mean annual precipitation (MAP). This result is based on the estimated chloride concentration at Vaalputs of 1.68 $mg.l^{-1}$. Therefore an average of 0.2064 mm of the MAP of 129 mm is recharged into the groundwater of Vaalputs every year. The method of calculation is described in the methodology chapter, section 5.4.1. The chloride data is summarized in Table 6.1 below, with the full set of chloride values given in Table C-2 in the attached Appendix C.

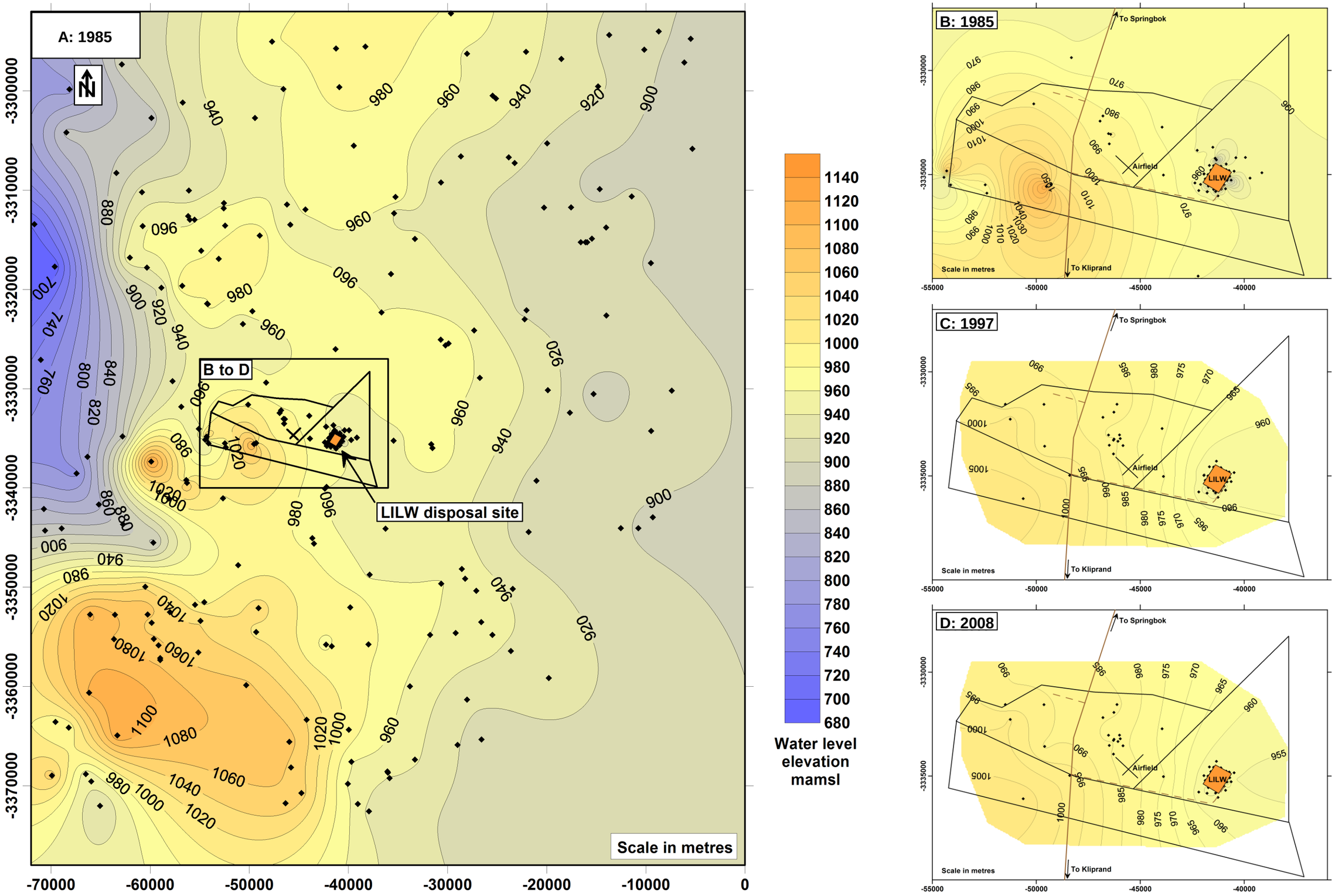


Figure 6.1A: Regional contour map of 1985 water levels around the Vaalputs Radioactive Waste Disposal Facility. B to D: Detailed water levels for the facility in 1987 (B), 1997 (C) and 2008 (D) (data: see Appendix C, Table C-1).

Table 6.1: Average chloride concentrations per borehole, harmonic mean and recharge number calculated (data: see Appendix C, Table C-2).

Borehole	Average Cl ($mg.l^{-1}$)	Borehole	Average Cl ($mg.l^{-1}$)
11A2	1316.8	4C1	1419.4
12C1	244.7	5A2	1590.2
13A2	1064.3	5C2	1535.0
13B1	568.1	5C4	2410.6
13C5	3206.8	7A2	1615.8
13C7	1359.0	9A2	1339.8
14A2	1079.4	9B1	1532.9
14C5	1679.1	EM8	545.1
15A2	1271.7	FW35	482.6
16A2	1270.7	GWB3	1545.1
16C3	1234.5	MON7	1287.8
2A2	1630.2	MON9	3812.2
3A2	1770.0	PBAKKI	1359.6
3C2	806.7		
Harmonic mean (all chloride values) = 1047.9			
Recharge amount = 0.10%			

6.3 Groundwater chemistry

Groundwater monitoring has taken place since 1986, however during the first decade only field measurements, such as electrical conductivity, temperature and water level were taken annually when water samples were collected for radiological analysis. Since 1996 separate samples were collected biannually for the purpose of analysing anion and cation content in the groundwater. All available results from 1986 to 2011 were used in the following section in order to classify the groundwater below Vaalputs. It is important for this study to understand the groundwater conditions in order to determine its possible influence on the behaviour of radionuclides in the groundwater. The full set of water chemistry results can be seen in Appendix C, Table C-3, while a summary is shown in Table 6.2. In the summary table below it is noticeable that Zone B has much lower average values for all of the cations and anions, except for F^-, which has similar levels than Zone A and much higher levels than Zone C. The average pH for Zone B is higher than for the other two Zones. Zone C has mostly higher values than Zone A, except for Na^+, F^- and pH values that are lower than in Zone A.

Table 6.2: Summary of the average values in water chemistry for each of the boreholes. Unit = mg.l-1 unless otherwise indicated (full dataset: Appendix C, Table C-3).

Zone	Borehole	pH	EC (mS/m)	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
A	GWB3	7.5	546	131.9	93.4	941.8	26.7	289	1554	337.4	9.50	3.04	0.01	3.8	0.02
	MON10	7.6	558	120.7	93.0	974.9	24.9	303	1553	339.8	7.78	2.74	0.01	0.2	0.02
	MON12	7.6	570	136.3	101.0	1000.8	26.8	280	1560	360.6	10.47	2.87	0.01	1.6	0.05
	MON14	7.6	531	100.0	88.1	921.3	22.6	403	1342	272.5	0.95	3.15	0.01	0.3	0.09
	MON15	7.7	609	123.2	98.5	966.3	24.4	327	1654	333.3	4.77	2.65	0.01	0.1	0.03
	MON2	7.7	492	90.4	68.0	886.0	23.2	329	1276	290.9	9.29	3.21	0.01	0.1	0.02
	MON3	7.7	424	71.9	55.9	749.4	20.1	415	1077	191.5	0.48	2.94	0.01	0.1	0.18
	MON4	7.7	416	58.8	52.0	782.2	19.3	303	1064	227.0	0.53	2.80	0.01	0.4	0.70
	Zone AVG	**7.7**	**518**	**104.16**	**81.24**	**902.84**	**23.51**	**331**	**1385**	**294.11**	**5.47**	**2.92**	**0.01**	**0.81**	**0.14**
B	EM8	7.9	253	64.0	35.9	465.3	15.8	287	553	152.8	3.64	2.74	0.01	0.0	0.03
	FW35	7.7	218	60.4	29.7	413.6	13.7	262	480	130.5	3.56	2.98	0.01	0.1	0.01
	PBH22	7.7	265	45.8	32.3	520.5	13.3	318	570	154.8	1.67	2.96	0.01	0.1	0.04
	Zone AVG	**7.8**	**245**	**56.7**	**32.6**	**466.5**	**14.3**	**289**	**534**	**146.0**	**2.96**	**2.89**	**0.01**	**0.1**	**0.03**
C	13C5	7.3	1046	471.4	219.7	1373.2	12.8	105	3210	585.0	0.89	1.92		3.9	0.72
	4C1	7.6	528	240.8	132.5	695.3	29.3	182	1472	347.8	16.34	1.46	0.01	0.2	0.02
	5C2	7.4	574	327.6	130.3	711.6	24.7	152	1556	376.2	22.40	1.26	0.01	0.4	0.03
	16C3	7.6	456	272.4	119.2	495.0	30.0	184	1244	251.1	11.39	1.46	0.01	0.4	0.03
	PBAKKI	7.7	509	113.3	93.0	847.4	29.6	241	1448	310.5	1.54	2.79	0.01	0.2	0.03
	Zone AVG	**7.5**	**623**	**285.1**	**138.9**	**824.5**	**25.3**	**173**	**1786**	**374.2**	**10.51**	**1.78**	**0.01**	**1.0**	**0.16**
	Overall AVG	**7.6**	**500**	**151.8**	**90.2**	**796.5**	**22.3**	**274**	**1351**	**291.4**	**6.57**	**2.56**	**0.01**	**0.7**	**0.13**

***Red**: Zone A average values; **Yellow**: Zone B average values; **Green**: Zone C average values.*

During this study it was attempted to evaluate the quality of the chemical data given in Appendix C, Table C-3. A powerful tool for this evaluation is by calculating the ionic balance in the groundwater. Unfortunately the total alkalinity was not measured regularly, once or twice over the 25 year period for most boreholes, and the measurements of various cations were often absent. In order to get at least a trend, the average total alkalinity was calculated for each borehole by using the few results available. The average ionic balance error for these data was found to be very close to zero, however a standard deviation of over 10 was associated with these values, showing high variability in the chemical analytical results.

The average total alkalinities calculated for each borehole have been used in all Piper and expanded Durov diagrams plotted for this study. After plotting time-lines of all cations another error was noticed from the nitrate values: it was evident that during certain periods nitrate values shown were actually nitrate, while at other times it was nitrogen. For the periods when clearly all values were elevated to a factor of around four, thus being nitrogen, the values were converted to nitrate (NO_3) by dividing the values with 4.43. These conversions were made on measurements from 28 May 2002 and all measurements reported after 31 December 2002. When these errors are eliminated a picture of much more consistent groundwater chemistry emerges, which is seen in the time-lines of water chemistry to follow later in this section. The Piper diagram in Figure 6.2 shows that the water is Na+K chloride type water and this is confirmed when the cations and anions are plotted on the expanded Durov diagram (Figure 6.3) where the majority of groundwater falls in field 9, an confirmation that the groundwater at Vaalputs is very old, with very slow movement, as could be expected from the low recharge rate calculated in the previous section. Table C-4 in Appendix C is a key to describing water that plots in each of the nine fields of the expanded Durov diagram. For more detailed Piper and Durov diagrams, see Figure C.1 to C.6 in Appendix C.

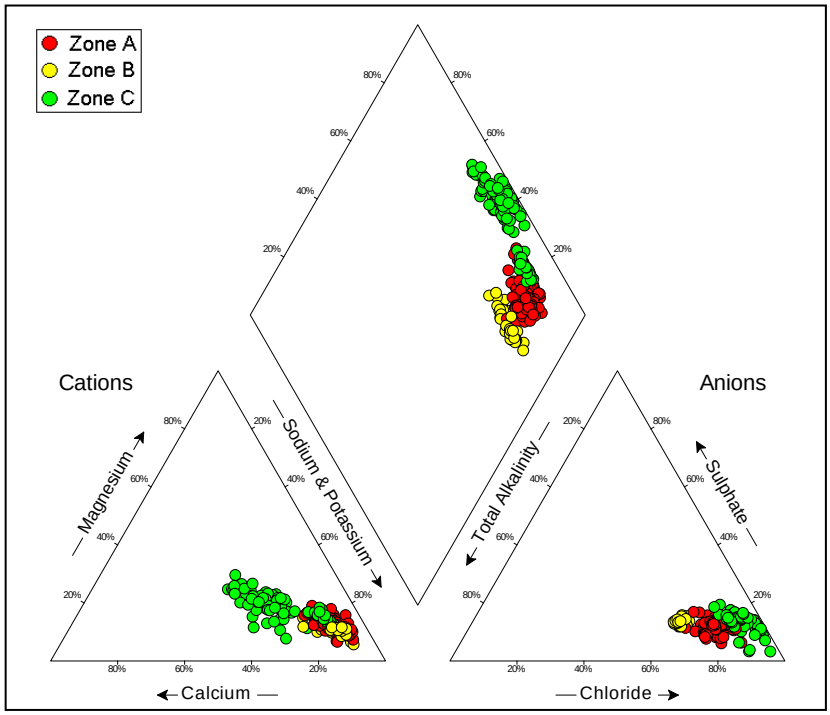


Figure 6.2: Piper diagram of the groundwater in the three zones of Vaalputs (data: see Appendix C, Table C-3).

Time series for electrical conductivity (EC), sodium and chloride is shown in Figure 6.4, Figure 6.5 and Figure 6.6 respectively for Zone A, B and C. For a combined time-line of Na, Cl and EC showing all boreholes see Appendix D, Figure D.7.

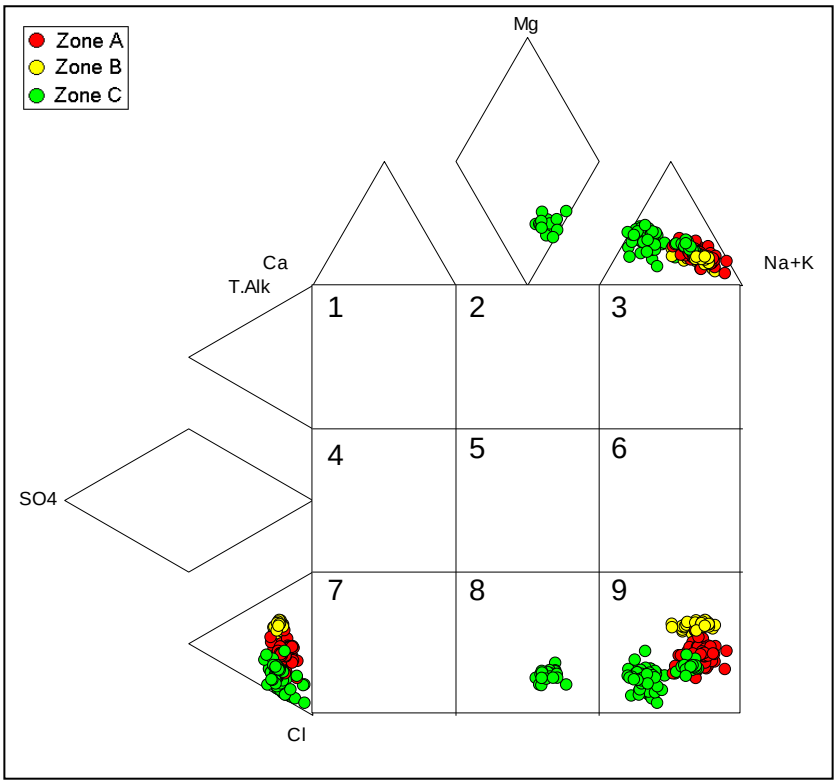


Figure 6.3: Expanded Durov diagram of Zone A, B and C (data: see Appendix C, Table C-3).

In Figure 6.4 to Figure 6.6 it is shown that the water in all zones are highly enriched Na and Cl with the values generally well above the SANS limits for drinking water. In Zone B all three boreholes have much lower salinities than Zone A and C within which values are very similar, with the exception of Zone C borehole 13C5, which has significantly higher values than all other boreholes.

The Stiff diagram in Figure 6.7 shows a very similar distribution for groundwater of the Vaalputs site. The cation & anion area does however show some differences, for example: the small areas of the Stiff-plots for Zone B boreholes confirm the lower salinity for this zone as seen in Figure 6.5. Plots for Zone A boreholes all show very similar and symmetrical areas, with somewhat smaller areas displayed for boreholes MON3 and MON 4 (See Figure 4.10 and Figure 4.11 for borehole locations with relation to disposal site and geology). The boreholes in Zone C generally plot onto somewhat larger areas and the plot have a similar asymmetric shape, with borehole 13C5 showing a much larger plot area than all other boreholes, confirming again the elevated TDS as seen in Figure 6.6.

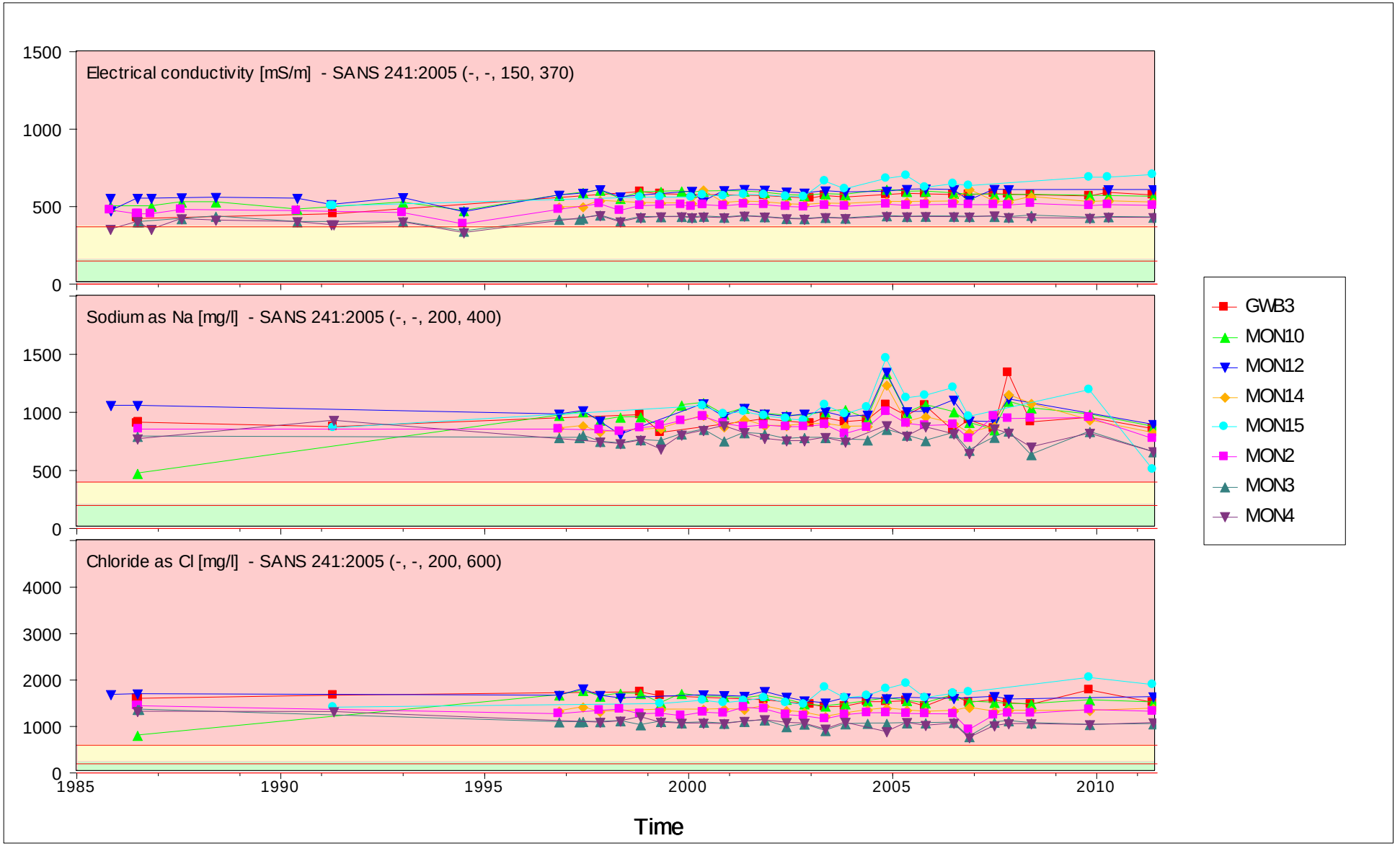


Figure 6.4: Time series of EC, Na and Cl for Zone A (data: see Appendix C, Table C-3).

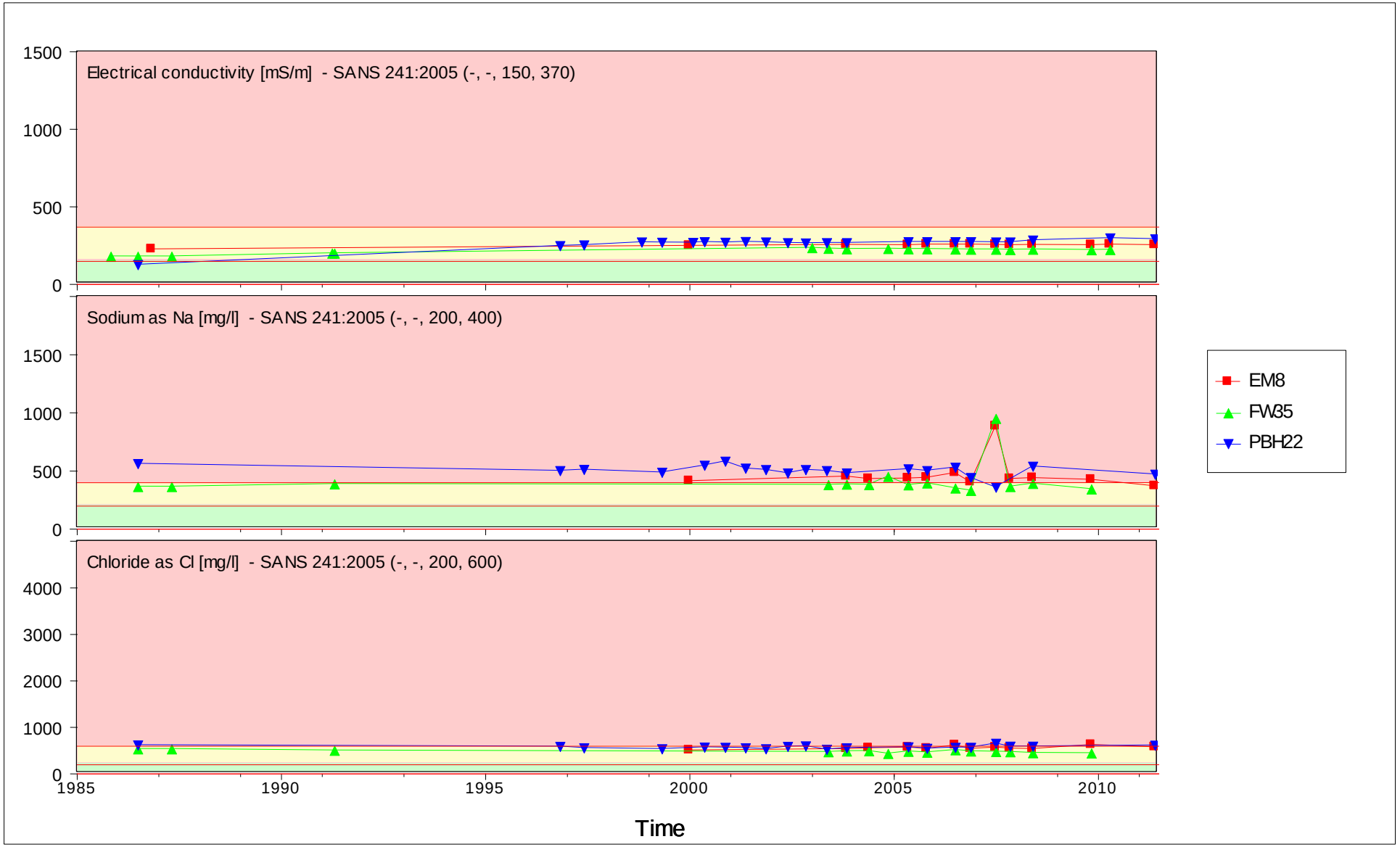


Figure 6.5: Time series of EC, Na and Cl for Zone B (data: see Appendix C, Table C-3).

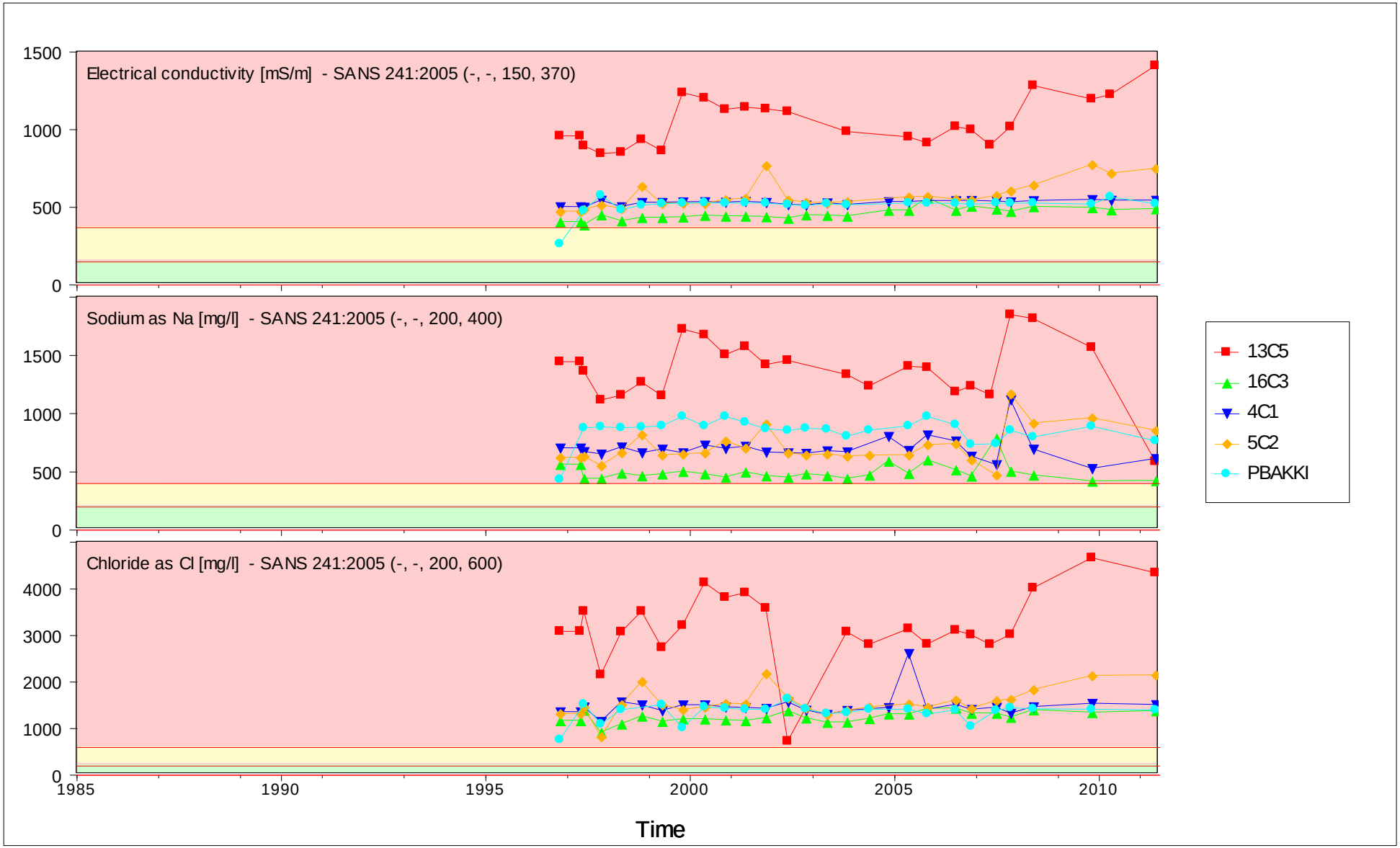
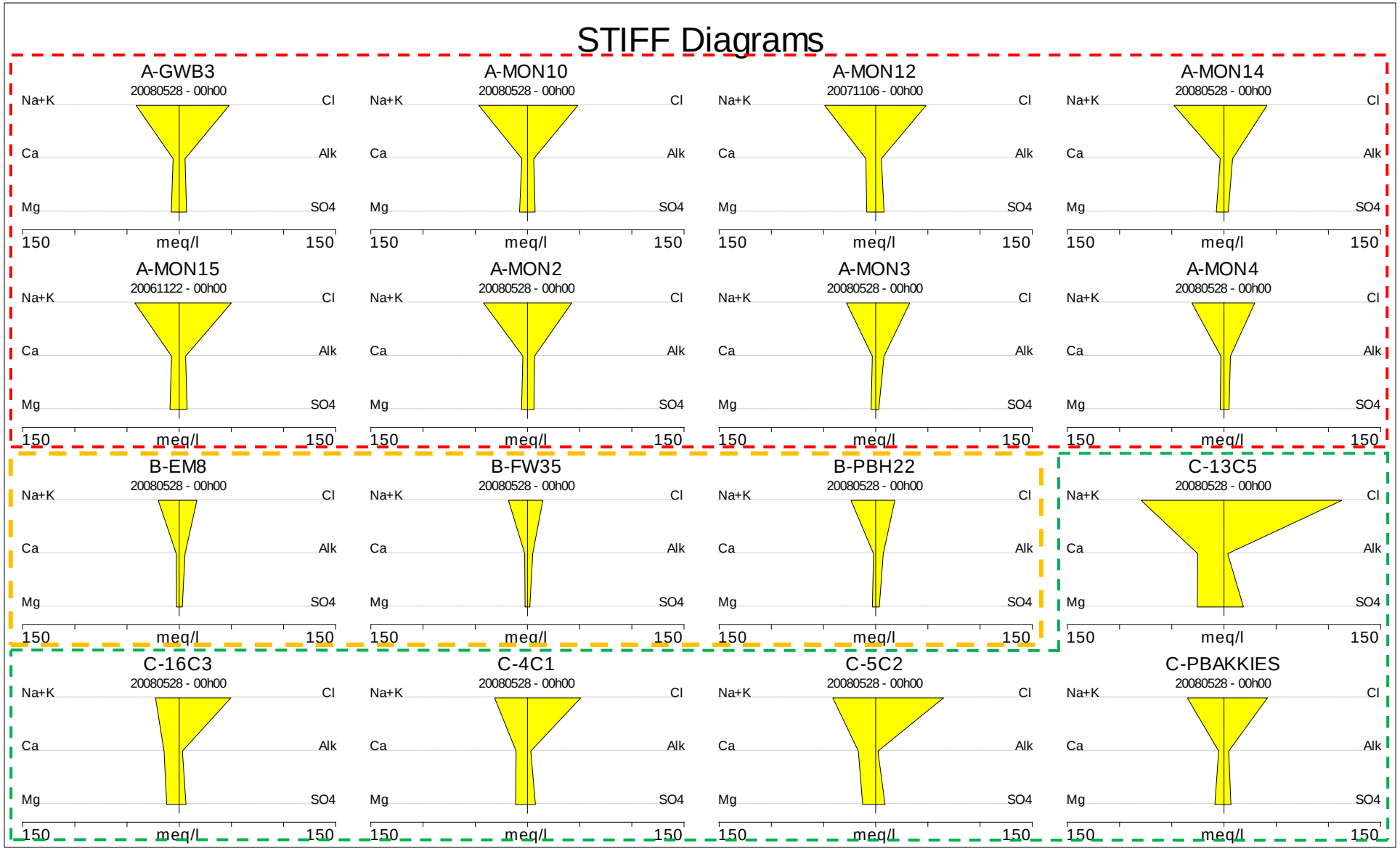


Figure 6.6: Time series of EC, Na and Cl for Zone C (data: see Appendix C, Table C-3).



Red box: Zone A boreholes; Yellow box: Zone B boreholes; Green box: Zone C boreholes.

Figure 6.7: STIFF diagrams representing the distribution of cations and anions for every borehole (data: see Appendix C, Table C-3).

6.4 Discussion of geohydrology and water-chemistry results

The expanded Durov diagram shows that the majority of groundwater falls in field 9, which represents very old, water at the end of the geohydrological cycle (typical of deserts and salty pans). Some boreholes fall in field 8 representing old NaCl-rich water mixed with Mg-rich water.

From the time-lines as well as the Stiff-diagrams, it was found that all Zone B boreholes as well as two Zone A boreholes: MON 3 and MON4 have relatively lower concentrations of the ions Na, Ca, Mg and Cl. These boreholes all lie quite close together in the area where fresh water had been pumped for several years from Zone B borehole FW35 as well as a number of non-monitoring boreholes close-by. What is also noticeable from the time-lines in Figure 6.4 to Figure 6.6 and the Stiff diagrams in Figure 6.7 is the much higher variability of the main ions in Zone C compared to the other two zones. The higher variability in main ion values in Zone C is attributed to the fact that these boreholes are spread far apart, each being drilled into a different geological area.

An inverse correlation of the concentrations of Na versus Mg and Ca could be seen by observing the Stiff diagrams. Variations within Na and Cl concentrations appear to be unrelated to each other, while higher EC values are mostly correlated with elevated levels of Cl.

The water from borehole 13C5 has elevated concentrations of all ions shown in the Stiff diagrams, except for carbonate and bicarbonate of which concentrations are low in all boreholes. This borehole, which also gives the lowest pH and the highest concentration of Fe, is the only borehole of this study drilled directly into the Namaqualand granitic gneiss on the western side of the site; all other boreholes are drilled through the clay-bearing sediments of the Bushmanland Plateau. From the Fe concentration in this borehole as well as GWB, it might be concluded that the groundwater in these two boreholes are more oxidizing than in other boreholes of Vaalputs.

7 Radioanalytical results

7.1 ^{nat}U

Uranium occurs naturally as different isotopes, the most important of which are ^{238}U, ^{235}U and ^{234}U, with ^{238}U and ^{235}U both being primordial isotopes while ^{234}U is part of the decay chain of ^{238}U. In an equilibrium environment, ^{238}U and ^{234}U will contribute an equal amount of radioactivity. ^{235}U has a very minor contribution to the total ^{nat}U activity due to the combination of low isotopic abundance and slow decay time. Relative contributions to the activity of ^{nat}U are shown in Table 7.1, for both the equilibrium conditions and for the groundwater at Vaalputs as measured by alpha spectrometry in 2009 (for these data see sections 7.1.2 and 7.1.3). These equilibrium ratios are however often not present in natural systems such as water and this will be discussed in chapter 8 with results on the activities of the specific radionuclides in the groundwater of Vaalputs.

Table 7.1: Relative contributions of uranium radionuclides to the activity of ^{nat}U in equilibrium conditions (data: adapted from Faure, 1998).

Radio-nuclide	^{238}U	^{234}U	^{235}U	Total = ^{nat}U
Isotopic abundance (wt.%)	99.27%	0.72%	0.0057%	100%
Equilibrium specific activity	12356	12356	568	25280
Equilibrium contribution	48.9%	48.9%	2.2%	100%

The South African National Standard (SANS 241, 2005) gives a recommended limit of 4 $mg.l^{-1}$ and an absolute maximum limit of 8 $mg.l^{-1}$ for ^{nat}U content in drinking water based on the **chemical toxicity** of uranium. A provisional guideline for the concentration of ^{nat}U has been proposed by the WHO (2004) as 0.015 $mg.l^{-1}$ based only on the **chemical and epidemiological toxicity** of uranium. However, the Environmental Protection Agency of the United States proposed a maximum contaminant level for ^{nat}U of 0.030 $mg.l^{-1}$ based on the **radiological effects** of uranium radionuclides, (USEPA, 2010).

The limits given above are compared in Figure 7.1 with the weight concentrations of ^{238}U over time as measured by the routine monitoring program at Vaalputs. Considering the relative isotopic abundances of the three uranium radionuclides, these weight concentration limits for ^{nat}U essentially represents ^{238}U (99.72 wt% of ^{nat}U). In this diagram no borehole names and detailed legend is shown, which will be shown in diagrams to follow in this chapter. It is evident from this diagram that the levels of natural uranium is very far from approaching the SANS limits for drinking water, while most values fall above the limits given by both the USEPA and the WHO.

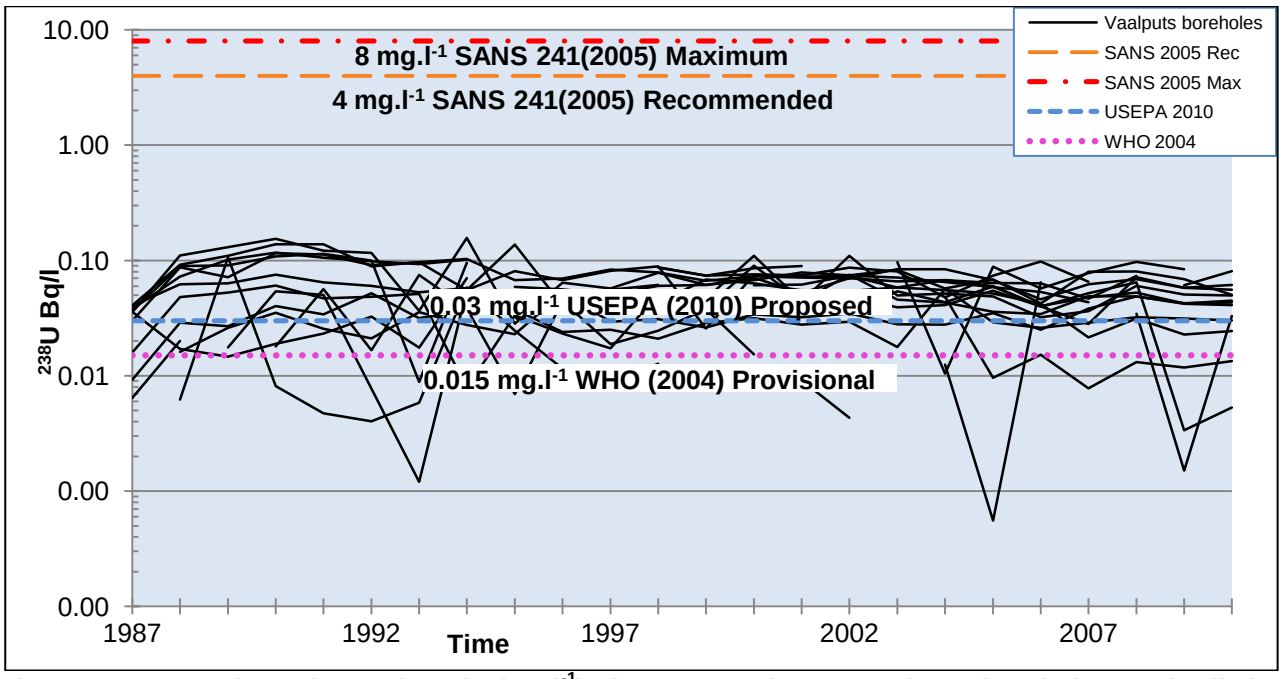


Figure 7.1: Natural uranium values in (mg.l^{-1}) shown over time at Vaalputs in relation to the limits given by SANS 241 (2005), WHO (2004) and USEPA (2010) for drinking water (data: see Appendix A, Table A-1).

7.1.1 ^{238}U

7.1.1.1 ^{238}U distribution in time

^{238}U activity levels are measured in the groundwater of Vaalputs every year as part of the environmental monitoring program. These results have to be reported to the National Nuclear Regulator as natural uranium in Bq.l^{-1}. For this reason the measured ^{238}U levels are converted to ^{nat}U by multiplying the activity with 2, assuming a 1:1 activity ratio for ^{234}U:^{238}U and neglible contribution from ^{235}U. In order to avoid these assumptions and consider individual radionuclides the reported ^{nat}U values are converted back to ^{238}U values for the purpose of this study.

In Table 7.2 the average and standard deviation of ^{238}U (Bq.l^{-1}) values are shown for each of the three borehole zones (described in 4.1.1). The full dataset of ^{238}U values can be seen in Appendix D, Table D-1. Note the high average values for Zone A and B (close to the disposal area) compared to that of Zone C (regional). Note again in considering this that these values are natural and variances based on location must be explained by localized differences in geology, geomorphology and geohydrology.

A guideline for the activity of ^{238}U in water safe for consumption is given as 10 Bq.l^{-1} by the WHO (2004). The South African National Nuclear Regulator requires that during monitoring of groundwater at Vaalputs, the activities of ^{nat}U (^{234}U + ^{238}U + ^{235}U) that exceed 7 Bq.l^{-1} must be reported to them (Necsa, 2011e). This limit is based on the **radiological effects** associated with uranium radionuclides. Figure 7.2 is a time-line of the ^{238}U activity in the groundwater of Vaalputs. Note that the boreholes GWB3, FW35 and EM8 shown in this figure are monitored quarterly and

the values for these boreholes presented in the diagrams below are the average yearly values per borehole. The full dataset of quarterly analyses for these three boreholes is shown in Appendix D, Table D-2.

Table 7.2: Summary of ^{238}U results for Zone A, B and C boreholes from 1987 to 2010 in Bq.l^{-1} (full dataset: see Appendix D, Table D-1).

	ZONE A		ZONE B		ZONE C		
Year	**AVG**	**STD DEV**	**AVG**	**STD DEV**	**AVG**	**STD DEV**	**AVG per year**
1987	0.44	0.05	0.50		0.13	0.06	0.36
1988	0.97	0.40	0.77		0.30	0.20	0.67
1989	0.95	0.56	0.78		0.66	0.47	0.84
1990	1.25	0.59	0.93		0.40	0.25	0.90
1991	1.18	0.52	0.80		0.41	0.25	0.85
1992	0.95	0.50	0.75		0.35	0.26	0.70
1993	0.62	0.54	0.66		0.49	0.32	0.57
1994	1.13	0.44	0.71		0.42	0.23	0.82
1995	0.92	0.50	0.50	0.50	0.31	0.15	0.61
1996	0.74	0.15	0.53	0.10	0.38	0.21	0.56
1997	0.79	0.21	0.66	0.03	0.25	0.10	0.55
1998	0.92	0.21	0.65	0.10	0.35	0.18	0.68
Laboratory SANAS accreditation date: 01 May 1999							
1999	0.76	0.21	0.53	0.07	0.38	0.07	0.63
2000	0.88	0.10	1.24	0.18	0.35	0.19	0.75
2001	0.86	0.15	0.59	0.08	0.29	0.15	0.68
2002	0.89	0.12	0.90	0.47	0.36	0.20	0.71
2003	0.92	0.17	0.62	0.05	0.35	0.13	0.73
2004	0.27	0.70	0.57	0.06	0.46	0.22	0.60
2005	0.14	0.82	0.59	0.15	0.32	0.26	0.62
2006	0.24	0.68	0.44	0.05	0.42	0.24	0.56
2007	0.24	0.69	0.57	0.10	0.32	0.16	0.56
2008	0.28	0.83	0.72	0.10	0.49	0.27	0.69
2009	0.24	0.70	0.40	0.31	0.36	0.28	0.52
2010	0.26	0.65	0.41	0.04	0.43	0.19	0.51
Zone AVG	**0.70**		**0.65**		**0.37**		**0.65**

***Red**: Zone A average values; **Yellow**: Zone B average values; **Green**: Zone C average values.*

From Figure 7.2 it is evident that the ^{238}U limits are still below the limit for total natural uranium, but compared to the scenario with the chemical toxicity limits, in this diagram the values are much closer to approaching the radiological based limit. If ^{234}U activities would be added to the ^{238}U values in order to get the total activity produced by ^{nat}U, the possibility of the total natural uranium activity values exceeding the limit is even greater.

By further investigating of the details in Figure 7.2, it can be seen that in general ^{238}U values seem to decrease when moving from Zone A to C. Zone A has, however, a higher range than Zones B and C, especially during the first 8 years of monitoring, when Zone A values are mostly higher than in later years. From Table 7.2 it is clear that Zone A has a relatively high standard deviation

until 1995. Relatively elevated values can be seen for Zone B boreholes EM8 and FW35 for the years 1998 and 2000.

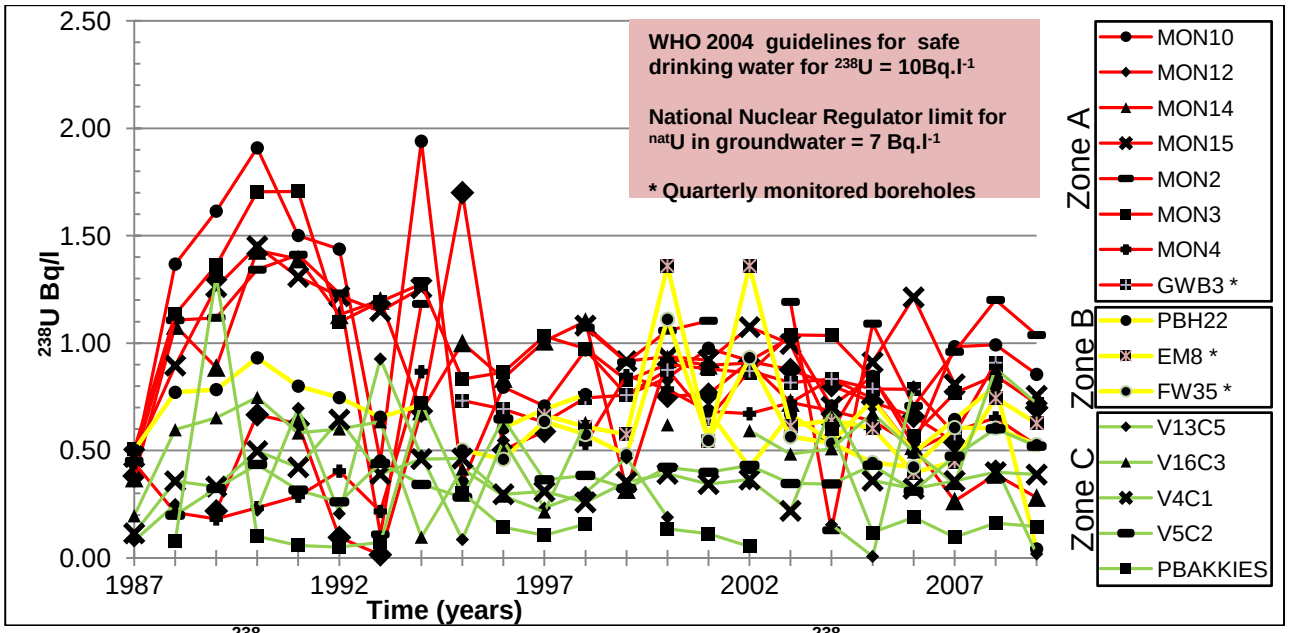


Figure 7.2: The ^{238}U timeline with the reporting limit for ^{238}U in monitored groundwater as recommended by the NNR (data: see Appendix D, Table D-1).

In order to further investigate the trends over time for each zone, a statistical timeline, with a break down into the three zones has been plotted. This is shown in Figure 7.3 where the standard deviation of each zone is shown as overlapping areas. This shows that for Zone A and to some degree Zone C the standard deviation for the years 1988 to 1995 is much higher than for the rest of the timeline. During this time, only one borehole was sampled in Zone B. It can be seen that Zone B values generally falls in between that of Zone A and C, with a sharp peak in the year 2000. It might be of significance to note that this peak occurs shortly after the laboratory was given accreditation by the South African National Accreditation System (SANAS) on 1 May 1999.

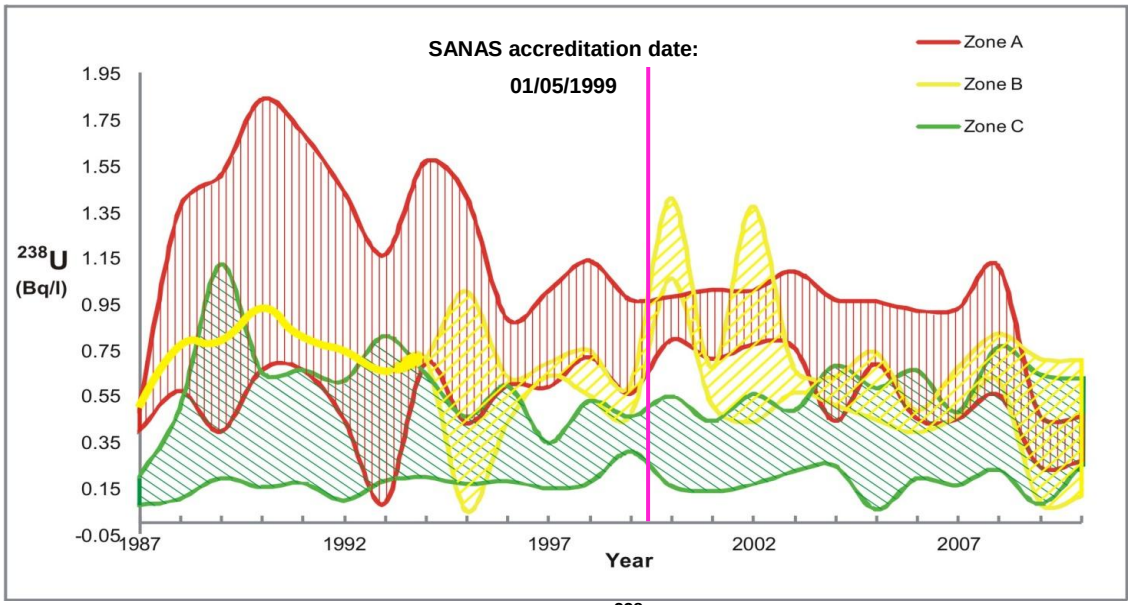


Figure 7.3: Timeline of the standard deviation of ^{238}U levels per borehole zone (data: see Table 7.2).

The observed varying behaviour of the three groups of boreholes led to the decision to do further investigation towards a few different populations of borehole water, by means of histograms. The histogram in Figure 7.4 derived from the ^{238}U activities of the entire dataset (Figure 7.4) has an asymmetrical, right-skewed, distribution and could best be described by a Weibull distribution curve. The Weibull distribution is commonly used by scientists (Liou & Yeh, 1997; Fernández-Gálvez *et al*., 2007; Halim *et al*., 2010) to describe spatial and temporal distributions of chemical constituents as well as radioactivity in groundwater and the atmosphere. The median value for the entire group of boreholes is 0.61 $Bq.l^{-1}$ of ^{238}U.

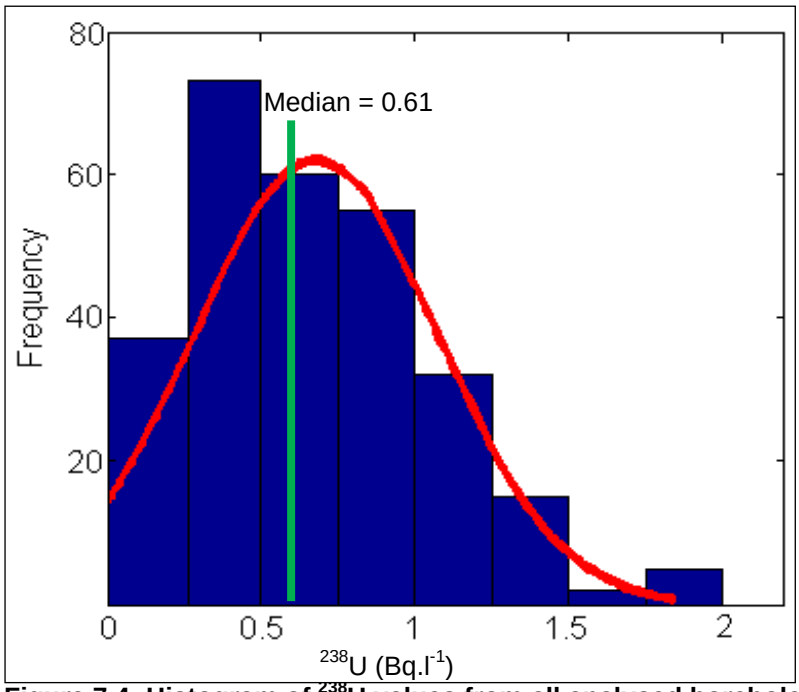


Figure 7.4: Histogram of ^{238}U values from all analysed borehole samples (data: see Appendix D, Table D-1).

The median for the entire group (0.61) can now be compared to the median values in the next two groups of histograms of ^{238}U levels per zone and per varying geology. These diagrams were created in order to investigate the possibility of different populations of boreholes.

7.1.1.2 ^{238}U distribution in space

Three histograms of ^{238}U, one for each of the borehole zones are shown in Figure 7.6, again showing right skewed histograms for Zone A and C. The histogram in Zone B has a more irregular distribution which is a result of the small sample size (only three boreholes). It can further be observed that the Zone A and B boreholes have significantly higher median values than the Zone C boreholes. Descriptive statistics of ^{238}U levels for each of the borehole zones are given in Appendix D, Table D-3.

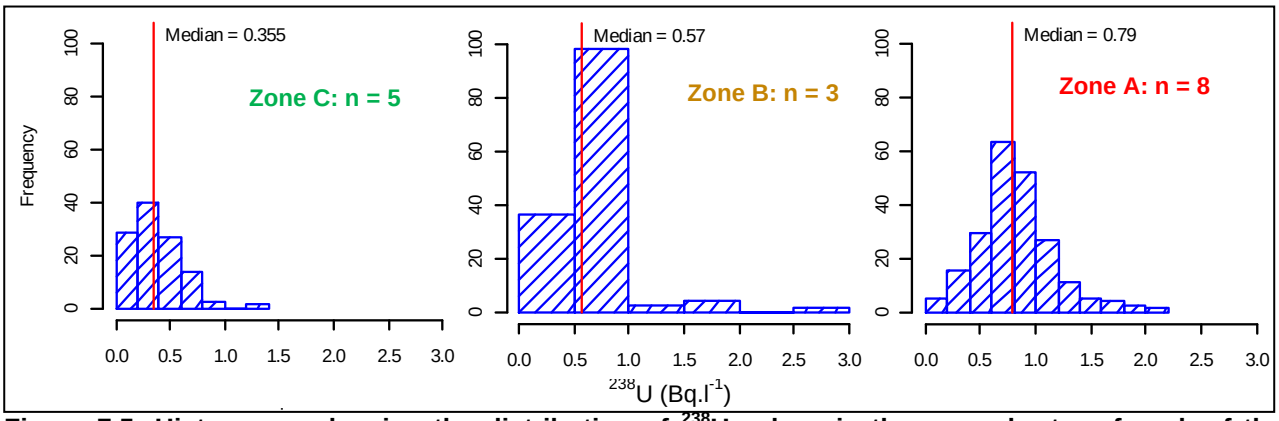


Figure 7.5: Histograms showing the distribution of ^{238}U values in the groundwater of each of the three borehole zones. n = number of boreholes (data: see Appendix D, Table D-1).

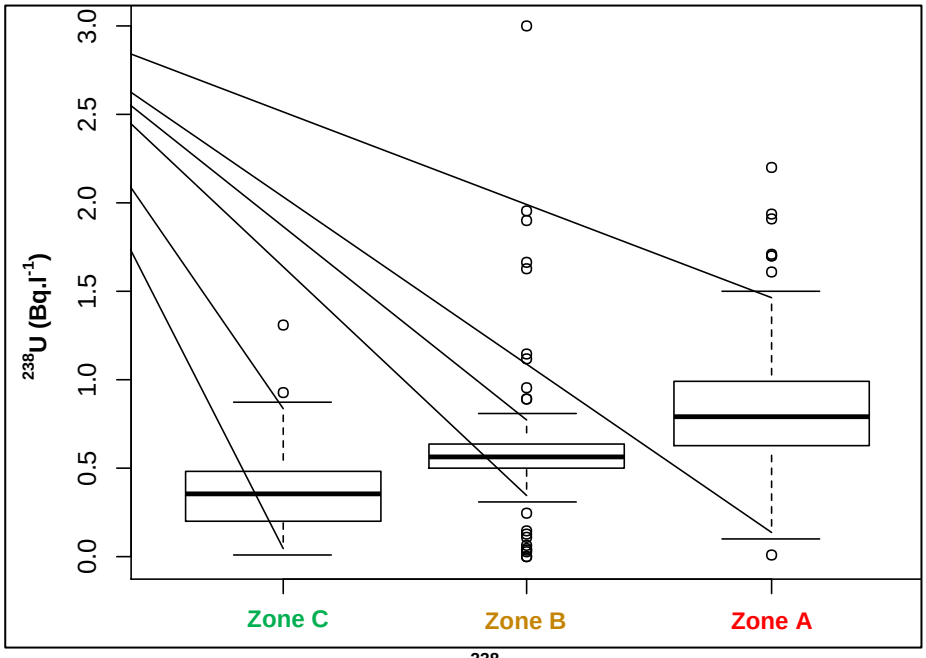


Figure 7.6: Box-and-whisker plots of ^{238}U values per borehole zones (data: see Appendix D, Table D-1).

7.1.1.3 ^{238}U distribution with geology

Geological borehole logs are available for only Zone A and B, being boreholes drilled especially for the purpose of monitoring the groundwater beneath the facility. Zone C boreholes do not have geological logs, as they are wind-pump boreholes that were drilled for obtaining drinking water for cattle on the surrounding farms before the facility became operational. Two histograms were produced (Figure 7.7) based on the geology of the boreholes: a) boreholes hosted in granite gneiss and mafic intrusions of the Koperberg Suite and b) boreholes hosted in granite gneiss and granitic intrusions. The third histogram in Figure 7.7 shows for comparison purposes Zone C boreholes of which the host rock is undefined.

It can be observed from Figure 7.7 and Figure 7.8 that both groups of boreholes with geological information have significantly higher median values than the Zone C boreholes with undefined

geology. Boreholes with granite gneiss and granitic intrusions have a somewhat higher median and mean than those passing through Koperberg suite mafic intrustions. Descriptive statistics of ^{238}U levels in each of the host types are given in Appendix D, Table D-4.

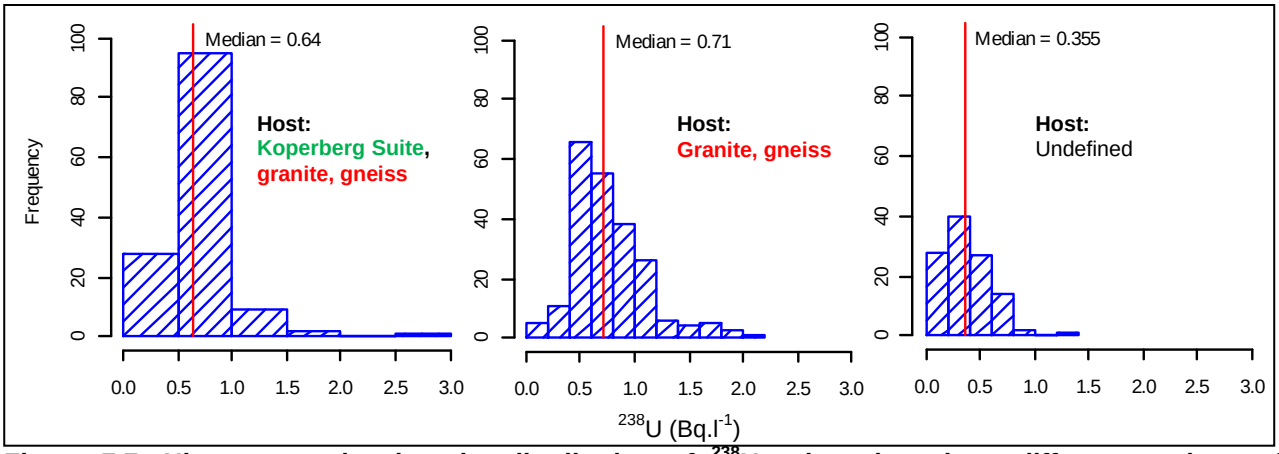


Figure 7.7: Histograms showing the distribution of ^{238}U values based on different geology of boreholes (data: see Appendix D, Table D-1).

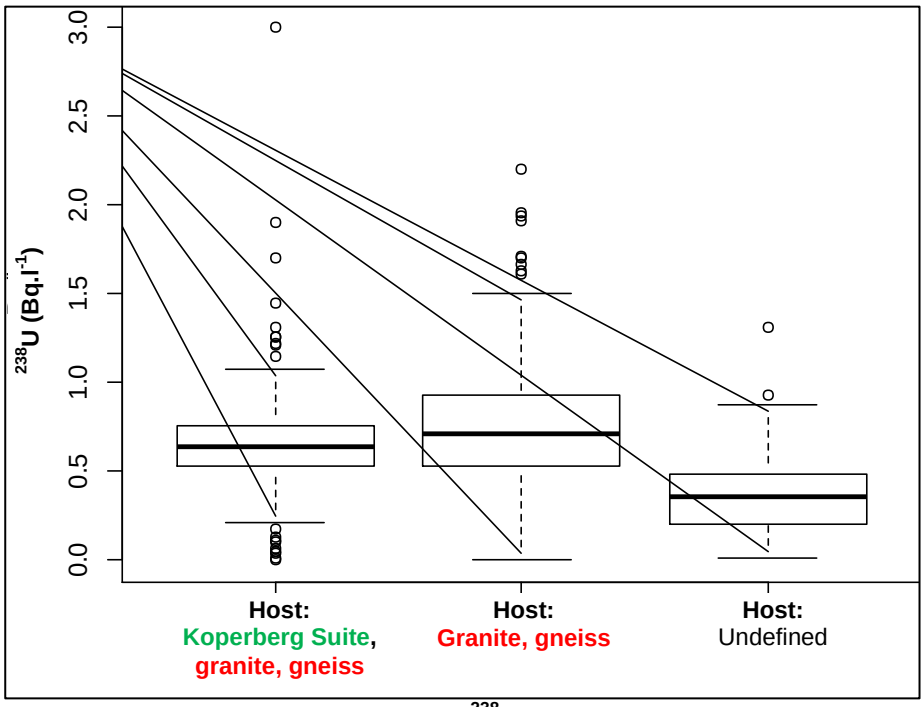


Figure 7.8: Box-and-whisker plots of ^{238}U values in varying geology (data: see Appendix D, Table D-1).

7.1.2 ^{238}U decay chain

In 2009 alpha spectrometry analysis was carried out on duplicates of the annual routine monitoring groundwater samples, analysing for specific radionuclides in the ^{238}U, ^{235}U and ^{232}Th decay chains. Only α emitting radionuclides can be analysed with this method. These results can provide insight into the variations in total α radiation that will be shown in section 7.3, and can also be used in understanding the behaviour of the specific radionuclides for the purpose of establishing a

baseline for the area. Table 7.3 gives the significant values of the results for the ^{238}U decay chain. The full dataset, showing minimum detectable activity (MDA) and uncertainties, is given in Appendix D, Table D-5. Presented in Table 7.3 are the calculated $^{234}U/^{238}U$ ratios for each borehole at Vaalputs, a significant and useful ratio of the activities of the two radionuclides, with ^{234}U being a daughter radionuclide of ^{238}U.

Table 7.3: ^{238}U decay chain results (Bq.l^{-1}) per borehole zone from 2009 alpha spectrometry (full dataset: see Appendix D, Table D-5).

	RADIONUCLIDES						TOTAL α	RATIOS	
ZONE A	**^{238}U**	**^{234}U**	**^{230}Th**	**^{226}Ra**	**^{210}Pb**	**^{210}Po**		**$^{230}Th/^{238}U$**	**$^{234}U/^{238}U$**
MON10	0.835	3.430	0.032	0.113	0.006	0.006	4.422	0.038	4.108
MON14	0.367	1.460	0.025	0.675	0.059	0.059	2.645	0.068	3.978
MON15	0.988	3.200	0.047	0.103	0.021	0.021	4.380	0.048	3.239
MON2	1.190	6.700	0.134	0.210	0.047	0.047	8.329	0.113	5.630
MON3	0.880	3.350	0.078	0.341	0.099	0.017	4.765	0.088	3.807
MON4	0.586	2.480	0.012	0.067	0.014	0.014	3.173	0.021	4.232
GWB3	0.886	4.300	0.119	0.102	0.022	0.022	5.451	0.134	4.853
AVG	**0.819**	**3.560**	**0.064**	**0.230**	**0.038**	**0.027**	**4.738**	**0.073**	**4.264**
STD DEV	**0.269**	**1.642**	**0.048**	**0.217**	**0.033**	**0.019**	**-**	**0.041**	**0.773**
ZONE B	**^{238}U**	**^{234}U**	**^{230}Th**	**^{226}Ra**	**^{210}Pb**	**^{210}Po**	**TOTAL α**	**$^{230}Th/^{238}U$**	**$^{234}U/^{238}U$**
EM8	0.737	3.320	0.088	0.023	0.015	0.015	4.197	0.119	4.505
FW35	0.589	2.860	0.151	0.025	0.043	BDL	3.668	0.256	4.856
PBH22	0.058	0.209	0.066	0.158	0.066	0.066	0.622	1.141	3.635
AVG	**0.461**	**2.130**	**0.102**	**0.069**	**0.041**	**0.040**	**2.843**	**0.506**	**4.332**
STD DEV	**0.357**	**1.679**	**0.044**	**0.078**	**0.026**	**0.036**	**-**	**0.554**	**0.629**
ZONE C	**^{238}U**	**^{234}U**	**^{230}Th**	**^{226}Ra**	**^{210}Pb**	**^{210}Po**	**TOTAL α**	**$^{230}Th/^{238}U$**	**$^{234}U/^{238}U$**
13C5	0.071	0.115	0.051	2.040	0.049	BDL	2.325	0.718	1.631
16C3	0.933	3.430	0.045	0.042	0.009	0.009	4.468	0.048	3.676
4C1	0.493	2.030	0.042	0.034	0.042	BDL	2.641	0.086	4.118
5C2	0.679	4.170	0.043	0.283	0.024	0.024	5.223	0.063	6.141
PBAKKI	0.208	0.644	0.041	0.007	0.038	BDL	0.939	0.199	3.096
AVG	**0.477**	**2.078**	**0.044**	**0.481**	**0.032**	**0.017**	**3.129**	**0.223**	**3.733**
STD DEV	**0.349**	**1.740**	**0.004**	**0.878**	**0.016**	**0.011**	**-**	**0.283**	**1.641**
Overall AVG	**0.633**	**2.780**	**0.065**	**0.282**	**0.037**	**0.027**	**3.824**	**0.209**	**4.100**

***Red**: Zone A average values; **Yellow**: Zone B average values; **Green**: Zone C average values. ^{222}Ra, ^{218}Po, ^{214}Po are α emitting radionuclides in the ^{238}U decay chain that were no longer present in the samples at the time of measurement. Circled values are discussed below.*

The average $^{234}U/^{238}U$ activity ratio for the groundwater sampled in 2009 is found as 4.1, far higher than the equilibrium scenario. Zone A and B both shows an average activity ratio of 4.3 while Zone C has a ratio of 3.7, corresponding with the trend of lower ^{238}U levels observed for Zone C in the previous section (7.1.1). However, with the ratios of these radionuclides being similar in Zones A and B, the groundwater of Zone A is much richer in uranium radionuclides than Zone B and C. Two boreholes show noticeable different behaviour than the others: PBH22 and 13C5, which both have much lower ^{238}U and ^{234}U levels than the other boreholes. PBH22 however has a relatively high activity ratio of 3.6, while 13C5 has a much lower ratio of 1.6. Furthermore, 13C5 shows a

high value for ^{226}Ra, clearly not supported by similar high activity levels of parent radionuclides. Behaviour of ^{226}Ra in the groundwater of Vaalputs will be discussed in section 7.1.2.1.

Figure 7.9 below is a graphical presentation of the ^{234}U/^{238}U activity ratios at Vaalputs. A linear relationship is clear, but with a much higher gradient than the equilibrium ratio.

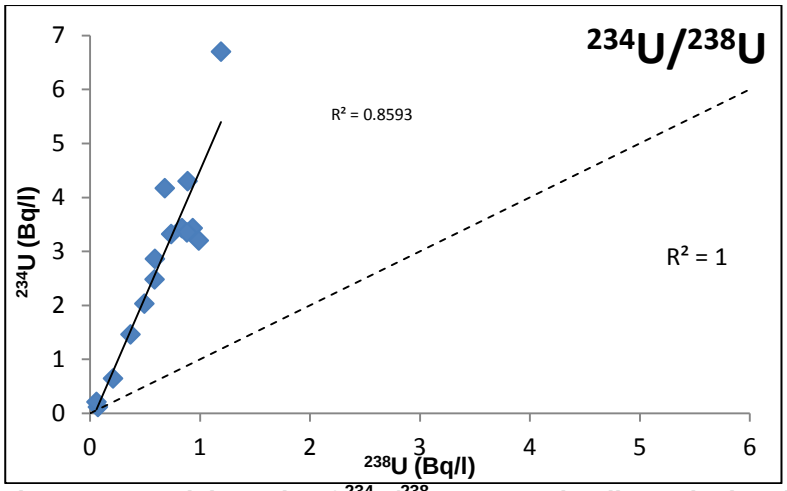


Figure 7.9: Activity ratio of ^{234}U/^{238}U, regression line calculated in Excel (data: see Table 7.3).

Considering ^{230}Th versus ^{238}U, the equilibrium activity ratio is also 1 (Reheis *et al.,* 2008). From the alpha spectrometry results an average activity ratio of 0.209 has been calculated for Vaalputs groundwater. When calculating average activity ratios per zones (Table 7.3) it is seen that Zone B has the highest ratio at 0.506, followed by Zone C at 0.223, with Zone A at a very low 0.073. Average activity ratios per borehole geology give the highest ratio of 0.33 to the boreholes in Koperberg suite intrusions, with a ratio of 0.116 for boreholes in granitic intrusions, lower than that of the Zone C boreholes. These trends are very different from, but not quite the inverse of, the trends in ^{234}U/^{238}U activity ratios. A graphical presentation of these results is shown in Figure 7.10. Both ^{234}U/^{238}U and ^{230}Th/^{238}U activity ratios will be discussed further in Chapter 8.

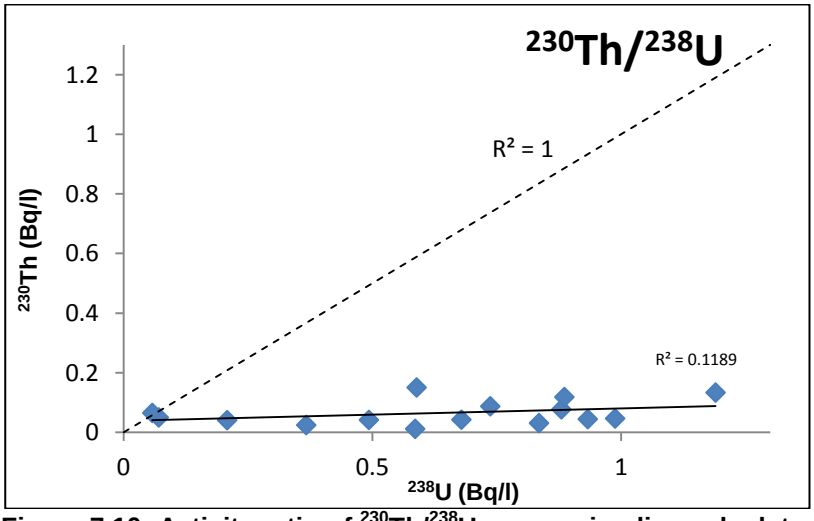


Figure 7.10: Activity ratio of ^{230}Th/^{238}U; regression line calculated in Excel (data: see Table 7.3).

7.1.2.1 ^{226}Ra

As part of the annual monitoring of the groundwater below Vaalputs ^{226}Ra activity levels are analysed. The levels are very often below the detection limit of the gamma spectrometry which is the analytical method used routinely for analysing ^{226}Ra. During pre-operational times it was noticed that a number of boreholes in the western part Vaalputs, lying in the Namaqualand portion of the facility has elevated levels of ^{226}Ra. These boreholes include Zone C borehole 13C5 to have high levels of ^{226}Ra and a low ^{234}U/^{238}U activity ratio in the previous section. Two other boreholes with noticeable high ^{226}Ra activities are, Riem6 and Riem7, two boreholes in Zone C which are only monitored by Necsa on an ad-hoc basis. In these boreholes the high levels of ^{226}Ra are typically not supported by coinciding high levels of the parent radionuclide ^{238}U.

In order to better investigate the trends in this area of elevated ^{226}Ra levels and compare this to all the boreholes around Vaalputs a series of additional analysis by means of alpha spectrometry was carried out between 2002 and 2004. The combined results from both the routine analysis (1987 to 2010) and alpha spectrometry analysis of 2003, 2004 and 2009 for the original set of study boreholes are shown in Table 7.4. A summary of the results for alpha spectrometry for the additional boreholes sampled for this ^{226}Ra investigation are shown in Table 7.5. The full dataset of alpha spectrometry results for 2002 to 2004 is shown in Appendix D, Tables D-7 and D-8.

Observing the results in Table 7.4, firstly, no values were found to be above the detection limit before 1995 and these years are therefore not displayed in this table. Secondly it is noted that until 1998 all of the obtained values are very low compared to the values for 1999 and onward. Furthermore a very high value is reported for borehole 13C5 in Zone C in 2009, while borehole MON14 in Zone A has relatively high activities in both 2003 and 2009. In the results for the additional boreholes (Table 7.5) high values are observed for ^{226}Ra in three boreholes: PBH21 in Zone B and Riem6 and Riem7 in Zone C. The activities for Riem6 and Riem7 are clearly not on a similar level in the measurements of all three years.

The USEPA (2010) proposes a maximum contaminant level for ^{226}Ra in drinking water of 0.185 Bq.l^{-1}. From the results in the two tables below, this limit is often exceeded in the groundwater of several boreholes around Vaalputs. The boreholes with values that exceeded the USEPA at certain times are: MON2, MON3, MON14 in Zone A; PBH21 in Zone B and 12C1, 13C5, 5C2, RIEM5, RIEM6 and RIEM7 in Zone C. The NNR requires that any activities from ^{226}Ra exceeding 0.6 Bq.l^{-1} in the groundwater of Vaalputs has to be reported to them. Only 5 boreholes have exceeded the NNR limit at times, and these are: MON14, PBH21, 13C5, RIEM6 and RIEM7. Of these five boreholes, all but MON14 also exceeds the guideline of 1 Bq.l^{-1} given by the WHO (2004) for the maximum activity of ^{226}Ra in safe drinking water.

Table 7.4: ^{226}Ra results in Bq.l^{-1} for Zone A, B and C boreholes from 1995 to 2010 in Bq.l^{-1} (data: Necsa, 2011e).

	ZONE A								ZONE B			ZONE C				
	MON10	MON12	MON14	MON15	MON2	MON3	MON4	GWB3	EM8	FW35	PBH22	13C5	16C3	4C1	5C2	PBAKKI
1995	0.0001	0.0002	-	-	-	0.0003	-	-	-	-	-	-	-	-	-	-
1996	-	-	0.0003	-	-	-	-	0.0001	-	0.0002	0.0002	-	-	-	-	-
1998	-	-	-	-	-	-	-	0.0001	-	-	-	-	-	-	-	-
Laboratory SANAS accreditation date: 01 May 1999																
1999	-	-	-	-	-	-	-	-	0.007	0.013	-	-	-	-	-	-
2000	0.007	-	-	0.074	0.015	0.015	-	-	0.007	0.015	-	-	-	-	-	-
2002	-	-	-	-	-	-	-	0.071	-	-	-	-	-	-	-	-
2003	**0.108**	**0.046**	**0.590**	**0.121**	**0.161**	**0.154**	**0.083**	0.0424	0.021	0.019	**0.029**	**0.169**	**0.030**	**0.013**	**0.142**	-
2004	-	-	-	-	-	-	-	0.0775	0.021	0.013	**0.029**	-	-	-	-	-
2005	-	-	-	-	-	-	-	-	0.030	0.019	-	-	-	-	-	-
2006	-	-	-	-	-	-	-	-	0.048	0.021	-	-	-	-	-	-
2007	-	-	-	-	-	-	-	-	0.019	0.021	-	-	-	-	-	-
2008	-	-	-	-	-	-	-	-	0.026	0.013	-	-	-	-	-	-
2009	**0.113**	-	**0.675**	**0.103**	**0.210**	**0.341**	**0.067**	**0.102**	**0.023**	**0.025**	**0.158**	**2.040**	**0.042**	**0.034**	**0.283**	**0.007**
2010	-	-	-	-	-	-	-	-	0.020	0.014	-	-	-	-	-	-

***Red**: Zone A average values; **Yellow**: Zone B average values; **Green**: Zone C average values.*
*Values highlighted in **pink**: results from nuclide specific alpha spectrometry carried out in 2003, 2004 and 2009. All other values: results from routine gamma spectrometry.*
Years where no values were above detection limit have not been shown in this table.
Circled values are above the reporting limit prescribed by the NNR.

Table 7.5: Summary of ^{226}Ra results in Bq.l^{-1} from alpha spectrometry for 2002 to 2004 for all analysed boreholes that are not part of the original set of study boreholes (full dataset: see Appendix D, Tables D-6 and D7).

	MON9	9B1	PBH21	12C1	13C7	Riem1	Riem2	Riem4	Riem5	Riem6	Riem7	SantaB1
2002										4.120		
2003		BDL		0.227	0.032					0.010	3.950	
2004	0.136	0.0273	2.56			0.091	0.094	0.066	0.292	2.540	0.590	0.021

**Unc: Uncertainty of the value obtained from analysis. **MDA: Minimum Detectable Activity.*
Circled values are above the reporting limit prescribed by the NNR.

7.1.3 ^{235}U decay chain

From the alpha spectrometry analysis of 2009 three α-emitting radionuclides in the ^{235}U decay chain were reported. The significant values of these results are shown in Table 7.6 on the following page, with the full dataset (including MDA and uncertainties) shown in Appendix D, Table D-5. From these results it is evident that, as expected (Bonotto & Bueno, 2008), the ^{235}U versus ^{238}U ratio has not been disturbed in Vaalputs groundwater. The ^{235}U levels would therefore follow the same trends than ^{238}U levels in the groundwater for Zone A, B and C, as described in section 7.1.1. Take note of the small average contribution to the total alpha radiation from this decay chain as 0.066 Bq.l^{-1} compared to 3.82 Bq.l^{-1} from the ^{238}U decay chain.

Table 7.6: ^{235}U decay chain results (Bq.l^{-1}) per borehole zone (data: see Appendix D, Table D-5).

	Radionuclides			TOTAL α	RATIOS
ZONE A	**^{235}U**	**^{227}Th**	**^{223}Ra**		**^{235}U/^{238}U**
GWB3	0.041	0.023	BDL	0.064	0.046
MON10	0.038	0.011	BDL	0.049	0.046
MON14	0.017	0.027	BDL	0.044	0.046
MON15	0.046	0.009	BDL	0.055	0.046
MON2	0.055	0.035	BDL	0.089	0.046
MON3	0.041	0.025	BDL	0.066	0.046
MON4	0.027	0.013	BDL	0.040	0.046
AVG	0.038	0.020	-	0.058	0.046
STD DEV	0.012	0.009	-	-	0.00003
ZONE B	**^{235}U**	**^{227}Th**	**^{223}Ra**	**TOTAL α**	**^{235}U/^{238}U**
EM8	0.034	0.023	0.018	0.075	0.046
FW35	0.027	0.061	BDL	0.088	0.046
PBH22	BDL	0.033	BDL	0.033	-
ZONE C	**^{235}U**	**^{227}Th**	**^{223}Ra**	**TOTAL α**	**^{235}U/^{238}U**
13C5	0.003	0.019	BDL	0.023	0.046
16C3	0.043	0.024	0.003	0.070	0.046
4C1	0.023	0.024	BDL	0.046	0.046
5C2	0.031	0.009	BDL	0.040	0.046
PBAKKI	0.010	0.025	BDL	0.034	0.046
AVG	0.022	0.020	-	0.046	0.046
STD DEV	0.016	0.006	-		0.00004
Overall AVG	**0.031**	**0.024**	**0.011**	**0.066**	**0.046**

***Red**: Zone A average values; **Green**: Zone C average values.*
^{231}Pa, ^{227}Ac, ^{223}Fr, ^{219}At, ^{219}Rn, ^{215}Po, ^{215}At, ^{211}Bi and ^{211}Po are α emitting radionuclides in the ^{235}U decay chain that were no longer present in the samples at the time of measurement.

7.2 Thorium 232 and its decay chain

Activities of ^{232}Th in the groundwater of Vaalputs are analysed using Instrumental Neutron activation analysis as part of the annual routine monitoring programme. It is however common to find that the levels are below the detection limit for the neutron activation analysis (INAA) used on a routine basis. In fact for quite a number of years no significant values were reported for ^{232}Th, with some boreholes rarely giving detectable values. Table 7.7 gives the results of ^{232}Th for all years when at least one borehole yielded a value above detection limit. Incorporated into this table are the results from alpha spectrometry analysis that was carried out in 2009. In the special alpha

spectrometry analysis that was carried out between 2002 and 2004, groundwater samples were not analysed for ^{232}Th.

From the data in Table 7.7 it is evident, that there are two boreholes, FW35 and EM8 that have significantly higher values for ^{232}Th than the other boreholes. In order to assess the quality of the data for these elevated boreholes in Zone B, a timeline has been plotted in Figure 7.11 for the period since the accreditation of the laboratory at Pelindaba. Included in this timeline is boreholes PBH22 (Zone B) and GWB 3 (Zone A) that also show somewhat elevated activities compared to the other boreholes. In this figure it is shown that the two highly enriched boreholes FW35 and EM8 behave sympathetically with regards to ^{232}Th, confirming the quality of the data for ^{232}Th. Additional indication of the quality of the data is provided by the close proximity these two boreholes have to each other (see Figure 4.11).

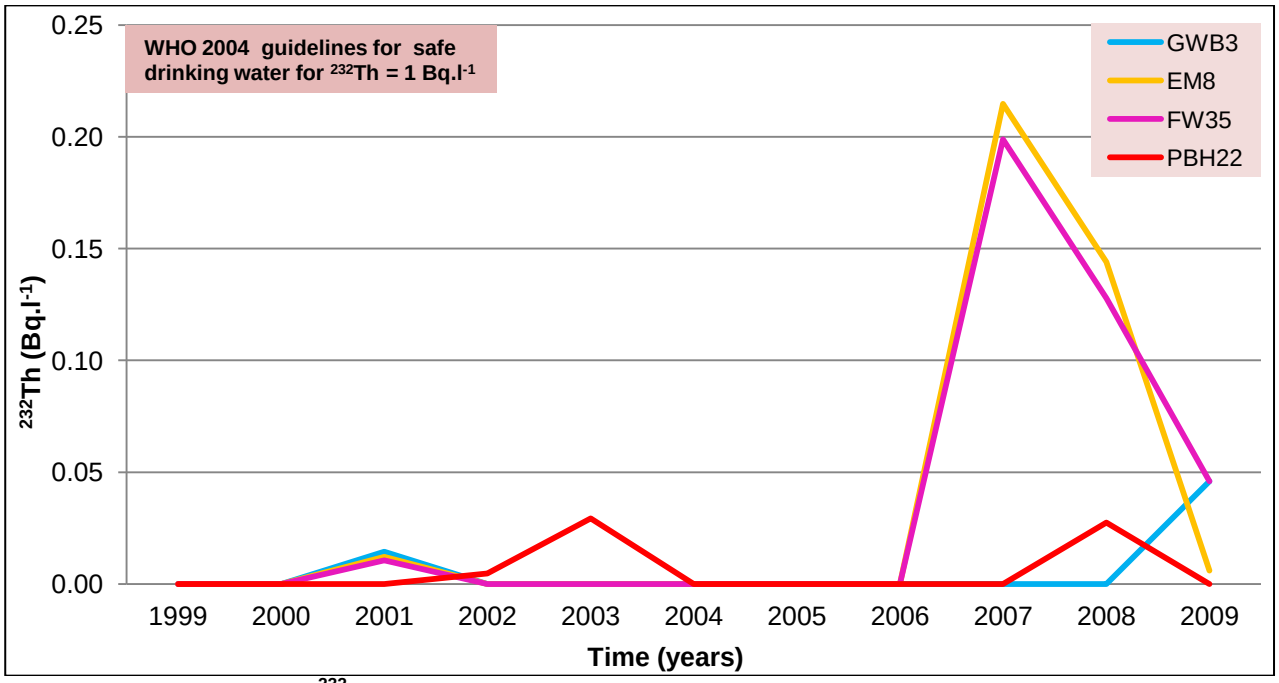


Figure 7.11: Time-line of ^{232}Th values for GWB3 (Zone A) and all three Zone B boreholes: EM8, FW35 and PBH22 (data: see Table 7.7).

However, placing into perspective these singular elevated results is the guideline of 1 Bq.l^{-1} activity from ^{232}Th in safe drinking water given by the WHO (2004). Even with the activities for the two enriched boreholes on their highest in 2007 at around 0.2 Bq.l^{-1} ^{232}Th levels are very well below this limit. The NNR does not give a prescribed limit for reporting of ^{232}Th levels in the groundwater of Vaalputs.

From the alpha spectrometry analysis that was conducted on groundwater samples in 2009 three α-emitting radionuclides in the ^{232}Th decay chain were reported (Table 7.8). This table contains all significant values, subdivided according to borehole zones, with the full dataset (including MDA and uncertainties) shown in Appendix D, Table D-3. The ^{232}Th levels from this table have already

Table 7.7: ^{232}Th results for all boreholes from 1987 to 2010 in Bq.l^{-1} (data: Necsa, 2011e).

	ZONE A								ZONE B			ZONE C				
	MON10	**MON12**	**MON14**	**MON15**	**MON2**	**MON3**	**MON4**	**GWB3**	**EM8**	**FW35**	**PBH22**	**13C5**	**16C3**	**4C1**	**5C2**	**PBAKKI**
1987	0.0015	0.0013	0.0015	0.0013	0.0004	0.0026	0.0004	-	-	-	-	-	0.0002	0.0006	-	-
1988	0.0073	0.0118	0.0032	0.0004	-	0.0008	0.0028	-	-	-	-	-	-	-	-	-
1989	0.0065	0.0077	0.0081	0.0207	0.0073	0.0239	0.0126	-	-	-	-	-	0.0020	0.0024	0.0045	0.0028
1990	-	-	0.0110	-	-	-	-	-	-	-	-	-	0.0069	0.0073	0.0057	0.0089
1991	-	-	0.0042	-	-	-	0.0047	-	-	-	-	-	-	-	0.0007	0.0009
1992	-	-	-	-	-	-	0.0020	-	-	-	-	0.0008	-	-	-	0.0009
Laboratory SANAS accreditation: 01 May 1999																
2001	-	-	-	-	-	-	-	0.0144	0.0122	0.0106	-	-	-	-	-	-
2002	-	-	-	-	-	-	-	-	-	-	0.0047	-	-	-	-	-
2003	-	-	-	-	-	-	-	-	-	-	0.0293	-	-	-	-	-
2007	-	-	-	-	-	-	-	-	0.2147	0.1988	-	-	-	-	-	-
2008	-	-	-	-	-	-	-	-	0.1441	0.1278	0.0275	-	-	-	-	-
2009	-	-	-	-	**0.01**	**0.004**	-	**0.046**	**0.006**	**0.046**	-	-	**0.003**	-	-	**0.003**

*Years where no values were above detection limit for any of the boreholes have not been shown in this table. Where no values are shown the results were either below detection limit or the borehole has not been sampled for that specific year. Values in **pink**: obtained from alpha spectrometry analysis.*

been incorporated into Table 7.7 and will therefore not be discussed any further here.

From Table 7.8 it is observed that the activity levels of ^{228}Th and ^{224}Ra are mostly unsupported by the levels of ^{232}Th, which activities' are all much lower than those of the daughter nuclides or even below the detection limit when the daughter activities are relatively high. This phenomenon is most striking in borehole 13C5, which were also found to have unsupported high levels of ^{226}Ra. Note again the small contribution to total alpha radiation from the ^{232}Th decay chain of 0.08 Bq.l^{-1} and the 0.066 Bq.l^{-1} from the ^{235}U decay chain compared to the 3.82 Bq.l^{-1} from the ^{238}U decay chain.

Table 7.8: ^{232}Th decay chain results (Bq.l^{-1}) per borehole zone (data: see Appendix D, Table D-5).

ZONE A	Radionuclides			TOTAL α
	^{232}Th	^{228}Th	^{224}Ra	
GWB3	0.046	0.044	0.025	0.114
MON10	BDL	0.033	0.028	0.061
MON14	BDL	0.189	0.176	0.365
MON15	BDL	0.065	0.066	0.132
MON2	0.010	BDL	0.045	0.055
MON3	0.004	0.008	0.093	0.105
MON4	BDL	0.014	0.029	0.043
AVG	0.020	0.059	0.066	0.145
STD DEV	0.023	0.067	0.055	-
ZONE B	**^{232}Th**	**^{228}Th**	**^{224}Ra**	**TOTAL α**
PBH22	BDL	0.018	0.053	0.071
EM8	0.006	0.031	0.025	0.061
FW35	0.046	0.066	0.010	0.122
ZONE C	**^{232}Th**	**^{228}Th**	**^{224}Ra**	**TOTAL α**
13C5	BDL	0.393	0.512	0.905
16C3	0.003	0.041	0.045	0.089
4C1	BDL	0.007	0.006	0.013
5C2	BDL	0.021	0.023	0.044
PBAKKI	0.003	0.036	BDL	0.039
AVG	0.003	0.100	0.147	0.249
STD DEV	0.000	0.165	0.244	-
Overall AVG	**0.017**	**0.069**	**0.081**	**0.148**

***Red**: Zone A average values; **Green**: Zone C average values.*
^{220}Rn, ^{216}Po, ^{212}Bi and ^{212}Po are α emitting radionuclides in the ^{235}U decay chain, that were no longer present in the samples at the time of measurement.

7.3 Total α and β radiation

Apart from the radionuclides discussed in sections 7.1 and 7.2, man-made isotopes, such as ^{90}Sr, ^{137}Cs, ^{114}Ce and ^{239}Pu are also analysed annually as part of the routine monitoring. None of these man-made isotopes have however been detected by the environmental monitoring that has been conducted annually since 1985 when waste disposal commenced. It can be concluded therefore that only radiation from the natural decay chains, as shown in the first part of this chapter, contributes to the total α and β radiation levels measured in the groundwater. The decay chains of ^{238}U, ^{235}U and ^{232}Th were shown in Figure 2.1, indicating which daughters are emitting α radiation and which gives β radiation. The WHO (1993) published screening limits for the levels of total α and total β radiation permissible in drinking water with: total α = 0.1 Bq.l^{-1}; and total β = 1 Bq.l^{-1}. In

2004, however, the WHO increased the limit for total α to 0.5 $Bq.l^{-1}$ and prescribed that when these levels are exceeded in drinking water individual analysis of the activity concentrations of dissolved radionuclides should be performed (Bonotto *et al*., 2009).

Necsa has performed detailed, systematic total α and β measurements in groundwater of Vaalputs at least once a year for the 16 boreholes of this study over a period of 24 years (and still going). One borehole in Zone A (GWB3) and two borehole is Zone B (FW35 and EM8) are analysed on average 4 times a year, giving an unprecedented high resolution of α and β fluctuations through time in the granite hosted groundwater of the area.

7.3.1 Total α radiation

The levels of total alpha radiation in groundwater are important in determining the overall quality of the water for consumption or other uses, as well as for regulatory purposes in an area such as a radioactive waste disposal site. A summary of the total α radiation levels determined for the groundwater of Vaalputs over time is shown in Table 7.9. The full data set of total α radiation is shown in Appendix D, Table D-8.

Table 7.9: Summary of total α results for Zone A, B and C boreholes from 1987 to 2010 in $Bq.l^{-1}$ (full dataset: see Appendix D, Table D-8).

	ZONE A		ZONE B		ZONE C		Overall AVG	Period AVG
Year	AVG	STD DEV	AVG	STD DEV	AVG	STD DEV		
1987	1.23	0.42	1.51	-	0.37	0.08	1.02	1.48
1988	3.20	-	-	-	0.93	0.43	1.38	
1989	4.50	-	-	-	1.23	0.80	2.05	
1990	2.36	-	-	-	0.95	0.45	1.23	
1991	3.33	2.97	-	-	1.68	0.93	2.23	
1992	1.75	1.16	0.99	-	0.75	0.77	1.31	
1993	1.35	1.16	0.85	-	1.01	0.35	1.18	
1994	0.52	0.29	0.98	-	0.49	0.45	0.55	0.55
1995	1.12	1.17	0.22	-	1.07	0.86	1.02	Increasing
1996	4.20	2.23	1.62	0.81	3.48	2.34	3.47	
1997	8.46	2.21	7.18	4.31	3.31	1.51	6.19	
1998	5.11	0.62	3.84	0.52	3.06	1.43	4.17	
Laboratory accreditation: 1 May 1999								
1999	12.13	2.59	3.66	0.59	4.93	0.58	8.91	
2000	19.01	9.26	29.81	3.55	7.31	3.58	16.55	16.55
2001	5.03	1.96	6.82	2.49	8.24	5.45	6.10	4.87
2002	5.87	2.28	6.40	4.27	3.02	0.81	5.34	
2003	6.80	1.75	5.04	2.06	3.29	0.73	5.67	
2004	5.89	2.39	4.88	0.94	4.11	2.10	5.15	
2005	5.21	2.27	3.29	0.49	3.16	1.63	4.36	
2006	4.24	1.85	3.07	0.74	3.87	2.44	3.91	
2007	5.82	2.50	3.72	0.78	3.37	1.18	4.84	
2008	5.80	3.83	3.41	0.37	3.97	2.25	4.64	
2009	5.67	1.85	1.42	-	2.74	1.36	4.22	
2010	6.32	2.83	3.99	0.82	2.90	1.02	4.47	
Zone AVG	**5.21**	-	**4.63**	-	**2.89**	-	**4.16**	

***Red**: Zone A average values; **Yellow**: Zone B average values; **Green**: Zone C average values.*

From the data in this table, it is observed that the average total α radiation for Zone A is higher than that of Zone B, in which the levels are higher again than in Zone C. This corresponds with the trends for ^{238}U levels over the three zones. The following two figures show the activity levels of total α over time, with Figure 7.12 displaying on a logarithmic scale an envelope of all total α radiation levels obtained at Vaalputs over time, relative to the 0.5 $Bq.l^{-1}$ screening limit of the WHO (2004). Note again that the boreholes GWB3, FW35 and EM8 are monitored quarterly and the values for these boreholes presented in these next two diagrams are the average yearly values per borehole.

Looking at Figure 7.12 it is noted firstly that most total α radiation values are exceeding the WHO screening limits by far. Between 1987 and 1995 some values are slightly below the limits. A period of low values averaged at 1.5 $Bq.l^{-1}$ is seen up to 1993, after which the levels drop to an average of 0.6 $Bq.l^{-1}$ in 1994. From 1995 the general trend has a steep increase in values, reaching a peak in 2000, shortly after the laboratory received accreditation by the South African National Accreditation System (SANAS). Since 2001 the total α radiation levels seems to have stabilised, averaging at 4.9 $Bq.l^{-1}$.

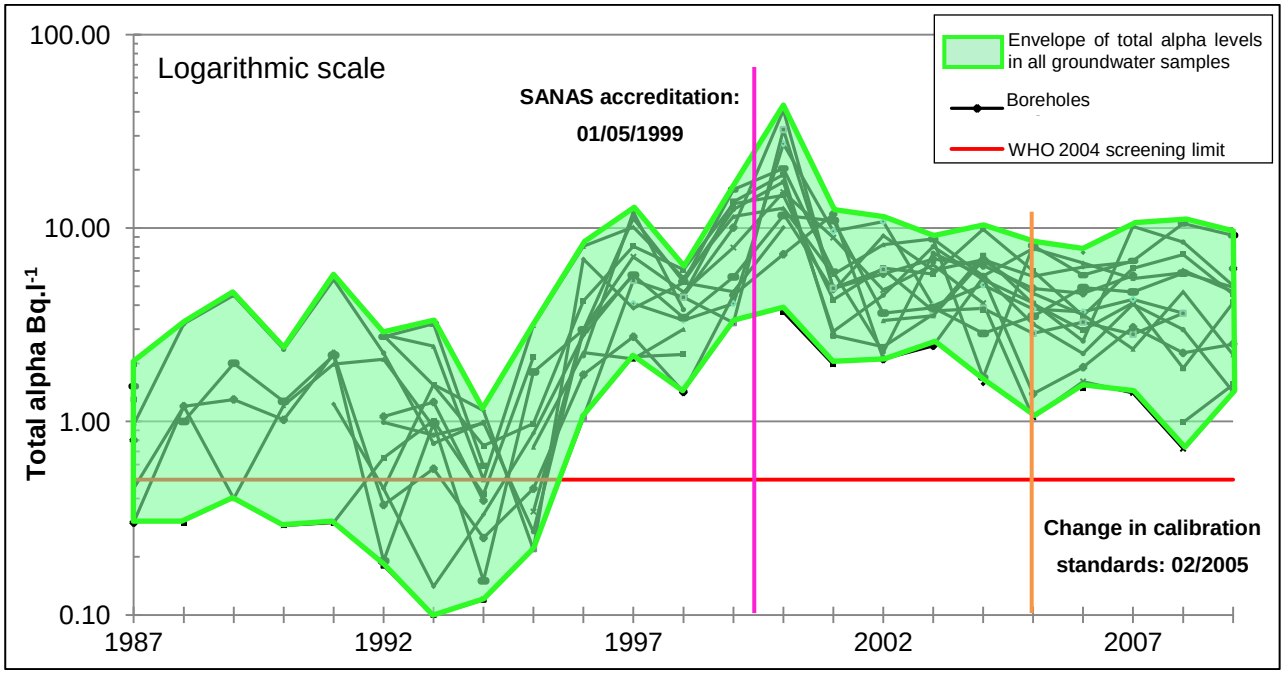


Figure 7.12: Enveloped logarithmic time-line of all total alpha values obtained from the monitoring programme compared to the WHO screening limit of 0.5 $Bq.l^{-1}$ (data: see Appendix D, Table D-8).

In order to further investigate the trends over time for each zone, the standard deviation per zone was plotted on a normal scale as overlapping fields (Figure 7.13) to be able to better visualize the extent of the peak in total α radiation observed in 2000. It is observed from this figure that total α radiation levels are mostly lower in Zone C than in the other two zones. Total α radiation levels in Zone A and B follows similar trends, but the Zone A standard deviation area plots mostly somewhat above that of Zone B.

Between 1997 and 2002 the levels of α radiation shows much variation. In 1997 and 2000 both Zone A and B show peaks, but with the 2000 peak being much stronger. Zone C show a peak in total α radiation levels in 2001. The data presented in the figure below show that the peaks in 2000 and 2001 were real and not due to analytical errors because a) the peak is after accreditation and b) the large peaks are only in Zone A and B, while Zone C does not show the same elevated levels in 2000.

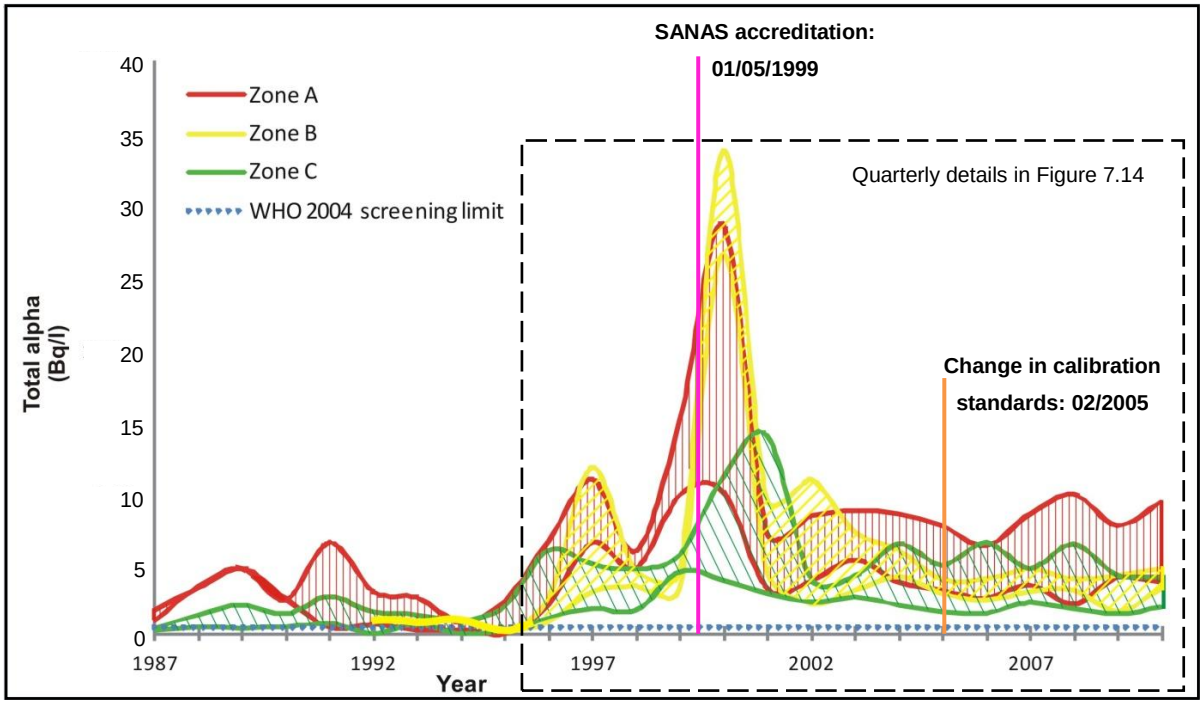


Figure 7.13: Timeline of standard deviation of total α radiation per borehole zones A, B and C (data: see Table 7.9).

In order to acquire a better appreciation of the processes involved in producing the peak for Zone A and B in 2001, the detailed quarterly measurements taken from Zone A borehole GWB3 and Zone B boreholes EM8 and FW35 are shown in Figure 7.14. This diagram focuses on the total α radiation levels for only the three quarterly analysed boreholes from 1995 onward. Note that since the end of 2004 GWB3 has only been monitored annually.

Figure 7.14 shows four peaks in total alpha radiation levels that are present in all three of these quarterly boreholes: in April 2000 (FW35 strongest), April 2001 (GWB3 strongest), January 2002 (EM8 strongest) and May 2004 (EM8 strongest). Of these four peaks, the two in 2000 and 2002 are the most significant peaks. In March 2007 borehole EM8 shows a small peak that is not seen in the other two boreholes. Possible explanations for these peaks in total α radiation will be discussed in chapter 8.

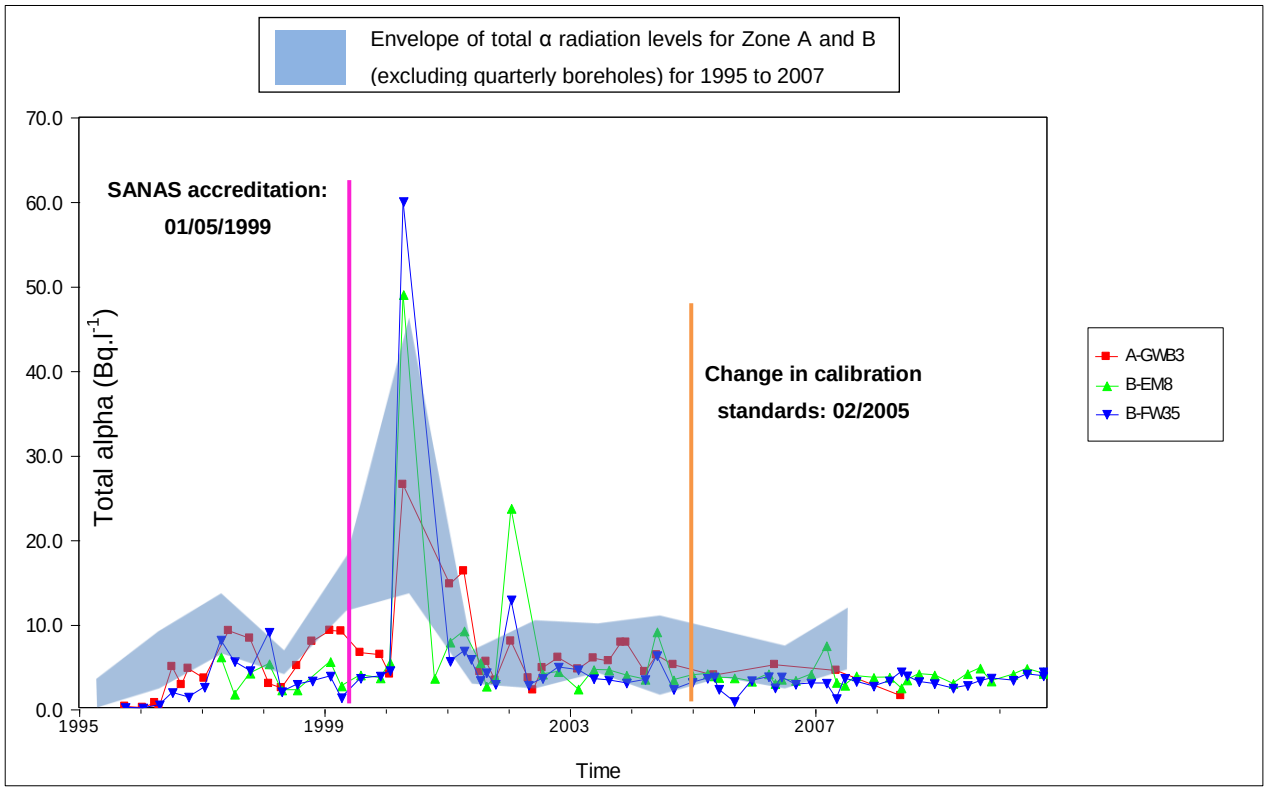


Figure 7.14: Timeline for total α results in groundwater from the three quarterly analysed boreholes (data: see Appendix D, Table D-2).

7.3.2 Total β radiation

A consistent time-line in total β radiation levels is also available for this study site. The results obtained from the proportional counting of β radiation is however not very reliable due to the effect of 'spill over' of α readings into the β window of counting the radiation levels. This effect has been described in chapter five and leads to a large uncertainty in the results since approximately 30% of the α radiation of each sample might be added to the β radiation level obtained for that sample. The significance of this data for the purposes of this study will therefore be evaluated in this section.

The results for total β radiation are displayed in a similar way that the results of total alpha were displayed in the previous section (7.3.1). From the summary of total β radiation levels in Table 7.7 it is evident that the average values of each borehole zone show the same trend than for total α, with Zone A yielding the highest average and Zone C the lowest.

From the time-line of average values in Table 7.10, the envelope of total β levels in Figure 7.15 and the overlapping standard deviation areas of each borehole zone in Figure 7.16 no specific trends or strong peaks are observed. Values for total β are mostly very erratically distributed over time. Since 2005, however, there is a change, with somewhat lower, constant levels in total β radiation. This might be due to the change, in February 2005, of the calibrating standards from ^{204}Tl to ^{90}Sr, a factor possibly contributing to better counting statistics for both total α and β measurements (Kotze, 2011).

Table 7.10: Summary of total β results for Zone A, B and C boreholes from 1987 to 2010 in Bq.l^{-1} (full dataset: see Appendix D, Table D-9).

Year	ZONE A		ZONE B		ZONE C		Overall AVG
	AVG	STD DEV	AVG	STD DEV	AVG	STD DEV	
1987	1.66	0.37	2.88	-	0.73	0.05	1.52
1988	1.10	-	-	-	0.40	0.14	0.54
1989	6.30	-	-	-	2.25	0.73	3.06
1990	6.15	-	-	-	2.89	0.87	3.54
1991	3.59	1.49	-	-	2.11	0.52	2.60
1992	0.92	1.22	1.42	-	2.64	2.57	1.62
1993	4.68	2.18	3.06	-	4.02	1.45	4.30
1994	3.41	0.97	7.90	-	1.87	0.96	3.16
1995	2.97	1.49	1.37	-	7.30	6.97	4.79
1996	3.20	1.04	1.70	0.96	2.25	1.11	2.58
1997	5.89	1.54	4.82	2.23	2.72	1.05	4.42
1998	4.59	1.05	3.20	0.15	5.04	0.86	4.46
Laboratory SANAS accreditation date: 01 May 1999							
1999	10.92	2.48	3.15	0.65	5.40	1.21	8.25
2000	6.28	1.34	6.95	1.64	3.02	0.40	5.28
2001	3.96	0.81	2.86	0.42	2.27	0.31	3.36
2002	6.52	2.36	4.15	0.50	3.94	0.95	5.19
2003	4.69	2.04	7.73	9.35	2.88	1.16	4.95
2004	4.52	1.61	1.66	0.30	3.86	2.18	3.78
Change in standards: lead to beter counting statistics							
2005	1.98	0.85	0.95	0.33	1.16	0.32	1.53
2006	1.14	0.48	1.04	0.18	1.27	0.50	1.16
2007	1.68	0.58	1.54	0.53	1.15	0.15	1.51
2008	2.35	1.33	1.27	0.03	1.64	0.36	1.86
2009	2.39	0.40	0.72	-	1.59	0.29	1.95
2010	2.58	0.70	1.51	0.16	1.98	0.42	2.10
Zone AVG	**3.89**		**2.99**		**2.68**		**3.30**

***Red**: Zone A average values; **Yellow**: Zone B average values; **Green**: Zone C average values.*

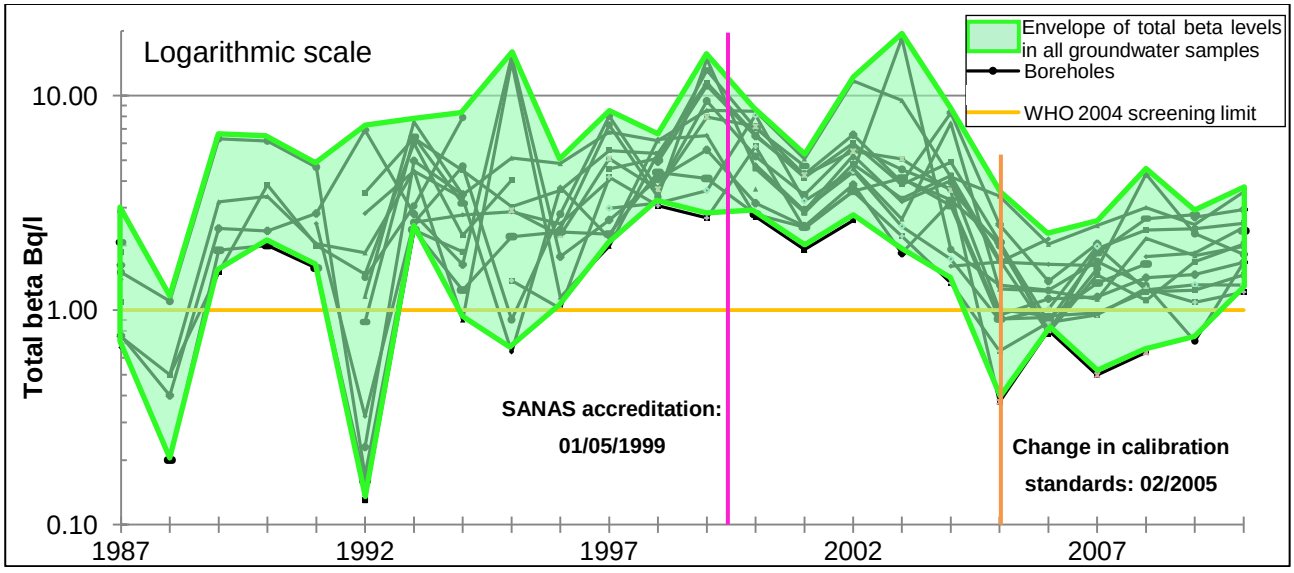


Figure 7.15: Timeline of total β radiation with the WHO screening limit on a logarithmic scale (data: see Appendix D, Table D-9).

Considering the timeline of total β radiation levels in Figure 7.15 it is noted that in this case most of the total β radiation values are also exceeding the WHO screening limit by far. To further

investigate the trends in total β radiation over time the standard deviation of each zone was again plotted as overlapping fields in Figure 7.16. The general observation from this diagram is again that Zone A has the highest levels of β radiation, followed by Zone B, with Zone C showing the lowest values.

Considering the behavior of total β radiation thus far it was decided to look at its behaviour in the quarterly boreholes for only the last six years of results (Figure 7.17), since these results appear to be more reliable. From this figure a peak for EM8 in March 2007 is noted, which corresponds to the peak in total α for the same borehole sample. Further discussion of the total β radiation results will be given in chapter 8.

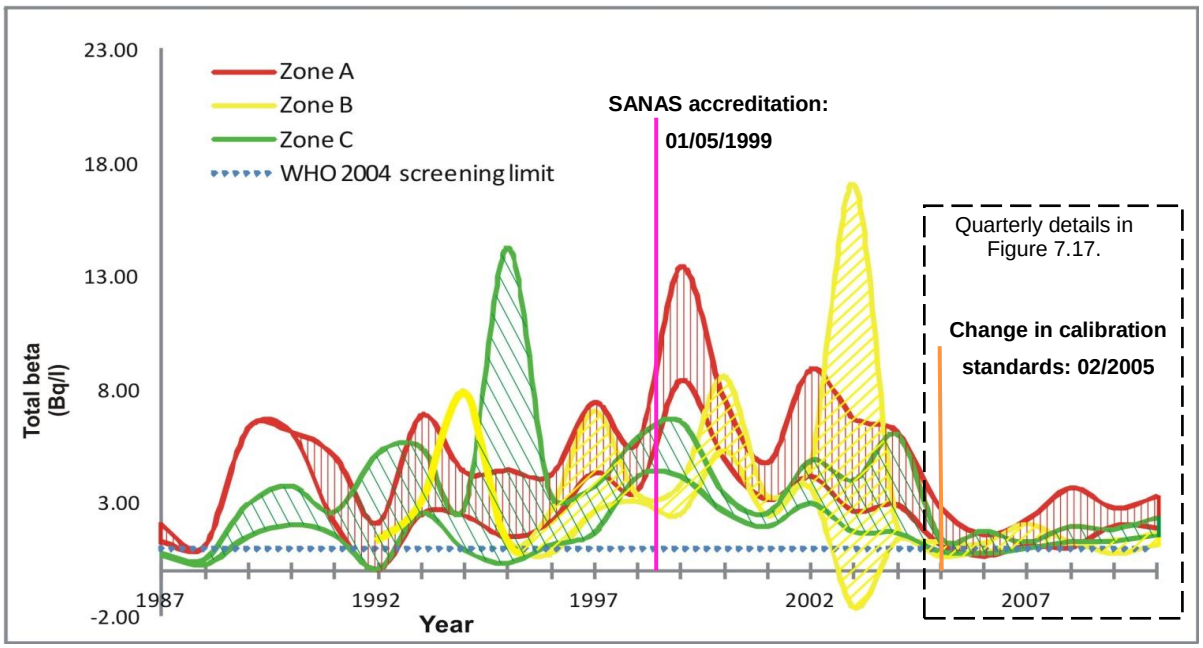


Figure 7.16: Timeline of standard deviation of total β radiation per borehole zones A, B and C (data: see Table 7.10).

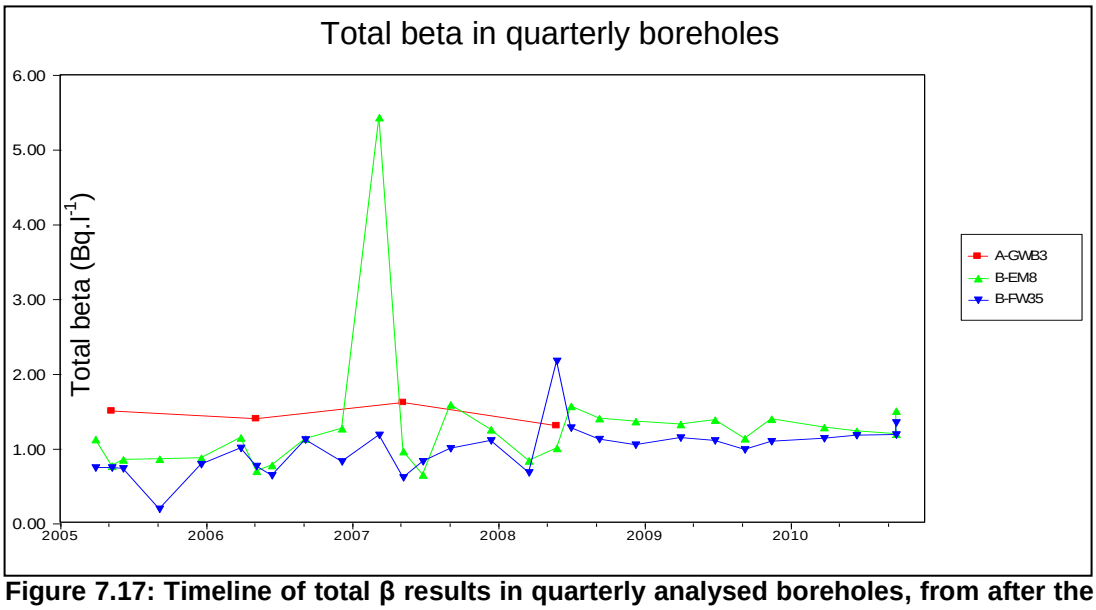


Figure 7.17: Timeline of total β results in quarterly analysed boreholes, from after the last change of standards (data: Appendix D, Table D-2).

8 Discussion

In this chapter the objective is to explain and simplify the trends in behaviour of radionuclides that has been observed in chapter 7 by integrating it with the background information in chapter 1 to 6, as well as by comparing the results to that in the literature. Before this discussion is started, however, it should be noted that in the remainder of the text the two borehole zones, A and B, will be termed together as the near-field. Zone C will be termed as the far field. The reason for this is that there are many observations where the results for these two zones are very similar, as well as the fact that these two zones are the same based on tectonic and geomorphologic settings. All the boreholes in these two zones falls on the Bushmanland side of the property, and these zones are used as a means of monitoring the possible distribution of contaminants from the disposal site outwards. Since this study is only involved with the natural radionuclides, these subdivisions are artificial when comparing the behaviour of these radionuclides in the groundwater.

8.1 ^{nat}U

Referring back to Table 7.1, the contribution of ^{238}U, ^{234}U and ^{235}U to the total activity of natural uranium for *equilibrium* conditions has been given as 49%, 49% and 2% respectively. The natural contribution of each uranium radionuclide in the groundwater of Vaalputs has been calculated from the alpha spectrometry results and is shown in Table 8.1.

Table 8.1: Contributions to total activity of ^{nat}U in Vaalputs samples (data: see Table 7.3 and Table 7.6).

Radionuclide	^{238}U	^{234}U	^{235}U	Total = ^{nat}U
Vaalputs groundwater: average activity	0.633	2.780	0.031	3.444
Vaalputs groundwater: average contribution	18.4%	80.7%	0.9%	100%

This table serves as a confirmation that ^{235}U contributes very little to the total radioactivity produced by natural uranium. At Vaalputs the average contribution in activity from ^{235}U is less than 1% of the total uranium activity. It was decided that ^{235}U and its decay chain will not be discussed further in this study, because of:

- The relative contribution to activity of ^{nat}U from ^{235}U is even less than expected at 0.9%, due to the high preferential fractionation of ^{234}U in the groundwater of Vaalputs (avg. $^{234}U/^{238}U$ activity ratio = 4.1).
- The average total α contribution from the ^{235}U decay chain has been shown as very small (0.066 $Bq.l^{-1}$) compared to 3.816 $Bq.l^{-1}$ from the ^{238}U decay chain (see Table 7.3 and Table 7.6). It is also known that the ^{235}U series contributes little to the total radiation dose (UNSCEAR, 1982, Kim *et al*., 2004).
- The activity ratio of $^{235}U/^{238}U$ is found to be undisturbed in the groundwater of Vaalputs (Table 7.6), as expected from literature stating that natural activity ratios in groundwater for $^{235}U/^{238}U$ are typically undisturbed from the equilibrium ratio of 0.046 (Bonnoto & Bueno, 2008).

In further calculations and presentations of activity levels of total natural uranium and total α radiation, the ^{235}U decay chain will be excluded on the basis of negligible contribution.

8.1.1 ^{238}U and its decay chain

8.1.1.1 Limits for ^{238}U content in water

Various limits for both ^{nat}U and ^{238}U in water have been given in chapter 7. It is clear that there is no international consensus on the levels of uranium allowed in water safe for consumption. What is evident and encouraged in the literature is the movement towards considering the radiological effects of radionuclides in prescribing these limits, rather than only looking at the chemical toxicity of the elements. This seems not to be the case however for the ^{nat}U limit given for drinking water by the South African National Standard 241 (SANS:241, 2005). The biggest hurdle in setting an acceptable weight concentration or activity limit for ^{nat}U in water is the disequilibrium in the activity ratios for $^{234}U/^{238}U$. Typically the limits that are integrated with the radiological effects are based on the assumed equilibrium activity ratio for these two radionuclides, which is rarely found in natural groundwater.

In the time-line diagram to follow (Figure 8.1), cumulative levels of the average ^{238}U and calculated ^{234}U activities are shown in order to visualise the total uranium activity with relation to the NNR limit of 7 $Bq.l^{-1}$ ^{nat}U. The activities shown for ^{234}U have been calculated from ^{238}U levels by using the average activity ratio of 4.1 which was found during this study as the average ratio for the groundwater of Vaalputs.

In Figure 8.1 it is evident that the calculated total activity of ^{nat}U is well below the limit given by the NNR, exceeding the limit from time to time between 1989 and 1995. Note again that the maximum cumulative level for ^{nat}U shown in this diagram is calculated from the maximum concentration of ^{238}U per year based on the ratio of 4.1. In reporting to the NNR, Necsa currently assumes an equilibrium ratio for $^{234}U/^{238}U$ when calculating ^{nat}U from the measured ^{238}U for reporting to the NNR. This way, by not compensating for disequilibrium of these radionuclides in the groundwater, the reported ^{nat}U values are likely to be much lower than the actual levels in the groundwater. Occurrences of uranium activities in groundwater exceeding the NNR limit might therefore be overlooked.

The ratio of 4.1 used in this study, however, has been determined from a single year, sampling only 15 boreholes. This value is not statistically representative and therefore not suitable for calculations made for the purpose of annual reports submitted to the NNR.

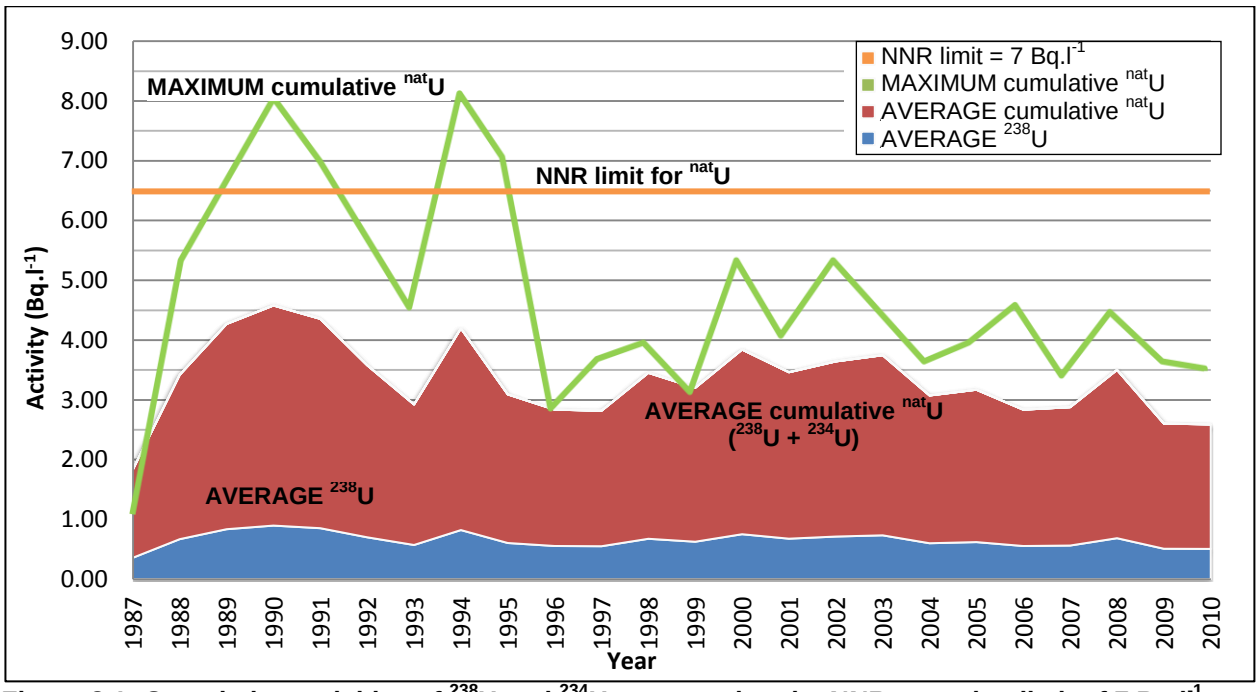


Figure 8.1: Cumulative activities of ^{238}U and ^{234}U compared to the NNR reporting limit of 7 Bq.l^{-1}.

8.1.1.2 Geology and ^{238}U activity levels

It has been determined that the borehole water in the near-field is significantly enriched in ^{238}U compared to in the far-field, and that the presence of mafic rocks tends to decrease while In the near-field somewhat higher enrichment is found in groundwater hosted in granite and gneiss than those in granite and gneiss intruded by mafic rocks.

A possible explanation for these elevated levels of ^{238}U activity in the near-field can be found in the study by Andreoli *et al.* (2006) where it was found that rocks in the Vaalputs area are anomalously radioactive. Unusual enrichments are found in granitic gneisses, charnockites and even in some mafic rocks attributed to the Koperberg suite (Andreoli *et al*., 1994; 2006). All of the above rocks were identified in the Tertiary basement beneath the sedimentary covers in the Bushmanland section of the property in which the waste disposal facility is located (the near-field area).

8.1.1.3 ^{238}U in literature groundwater

In order to place the levels of ^{238}U in the groundwater of Vaalputs into perspective, it will be useful to compare these values to those in the groundwater of other areas with similar geology. The average ^{238}U levels in the near-field of Vaalputs is 0.79 Bq.l^{-1}(range: 0.04-1.94 Bq.l^{-1}), while in the far-field it is 0.38 Bq.l^{-1} (range: 0.02-0.88 Bq.l^{-1}).

In the Nuba Mountain region of Sudan water samples from the Lake of Miri as well as from surrounding boreholes have been analysed to study the natural levels of radioactivity. Five samples were taken from boreholes hosted in granitic basement found to contain high concentrations of uranium, yielding ^{238}U activity ranging from 0.02 to 1.72 Bq.l^{-1} in the groundwater (Alfatih *et al*., 2008).

Also in Namaqualand, groundwater has been sampled from the granitic gneiss aquifer hosting the Steenkampskraal monazite deposit (150km south of Vaalputs). Levels of ^{238}U were determined for five boreholes, ranging from 0.27 to 1.16 Bq.l^{-1} (Ross *et al*., 1996). The levels of ^{238}U in water from these two granitic aquifers are all within the same range of the levels in the near-field of Vaalputs. This clearly shows how the concentration of uranium in groundwater relates to the host rock and that there are areas both local and international at which the behaviour of radionuclides in groundwater can be compared with that at Vaalputs.

8.1.1.4 ^{234}U

Data for the activity levels of ^{234}U in the groundwater of Vaalputs are available for 2009 from alpha spectrometry analysis carried out on the annually sampled boreholes. The overall average ratio calculated from the results of this study is 4.1. A comparison of the ^{234}U and ^{238}U activities and their ratio in the near-field versus the far-field is shown in Table 8.2. From this table a correlation between the natural uranium content and the activity ratios of $^{234}U/^{238}U$ is evident for the groundwater at Vaalputs.

Table 8.2: Comparison of uranium activities in near-field and far-field.

	Near-field	Far-field
^{238}U (Bq.l^{-1})	0.79	0.38
^{234}U (Bq.l^{-1})	3.131	2.078
$^{234}U/^{238}U$	4.284	3.733

This correlation is however not always present in groundwater as was noted in a study of about 800 samples (over 8 years) of drinking water in Catalonia in northeast Spain. The activity ratio in these samples ranged from 1 to 4 and an inverse correlation was found between the natural uranium content and $^{234}U/^{238}U$ activity ratios. The same trend was seen in groundwater from Texas, India and Finland, while some studies show the opposite trend for water in contact with areas that have high concentrations of uranium as a result of precipitation (Ortega *et al*., 1996). Various $^{234}U/^{238}U$ ratios may be found for groundwater in the literature, for example: 0.52 to 2.02 in groundwater hosted in phosphate and volcanic rocks from Syria, 1.09 to 8.06 in groundwater in Tertiary volcanic rocks at Yucca Mountain, Nevada, and 0.92 to 2.86 in the groundwater from fractured volcanic tuff at the Nopal I uranium deposit in Chihuahua, Mexico (Abdul-Hadi *et al*., 2001; Paces *et al*., 2002; Goldstein *et al*., 2010). In a groundwater sample taken from a deep granitic gneiss aquifer near Strasbourg in France, the $^{234}U/^{238}U$ ratio was determined as 3.14 (Riotte & Chabaux, 1999). On average, the ratios found at Vaalputs (mean: 4.1; range: 1.6 to 6.1) are higher than the above ratios from volcanic rock hosted groundwater, but closer to that of the granitic hosted water of Strasbourg.

The $^{234}U/^{238}U$ disequilibrium is very often seen in groundwater, often with enrichment in ^{234}U, but with depletion also common (Suksi *et al*., 2006; Labidi *et al*., 2010). This disequilibrium depends on factors

such as ^{nat}U concentration, redox conditions, residence time of groundwater and aquifer geology. The effects of alpha recoil has been implicated as an important cause of disequilibrium between these two radionuclides, more specifically the alpha recoils which occur as a result of the decay of ^{238}U atoms to form ^{234}Th, which then decay further, via two β-decay steps, to form ^{234}U.The crystal damage which therefore always surrounds a ^{234}U site is likely to accelerate preferential mobilisation of the ^{234}U by groundwater, the extent of which will depend on the geochemistry of the water (Bonotto *et al*., 2001). The cracks allow oxygen to enter the crystal lattice more easily, where it can oxidise the U into its more hexavalent state (U^{6+}). Thus, the ^{234}U atoms will be oxidised more quickly than the more tightly bound ^{238}U atoms, and consequently a relatively higher proportion of ^{234}U can be leached out. This effect is more noticeable in slightly reduced conditions, because in oxidising conditions even the ^{238}U becomes hexavalent and is dissolved in the water (Bonotto *et al*., 2001; Walencik *et al*., 2010).

The oxidation-reduction potential of the groundwater has unfortunately not been determined during sampling of the boreholes at Vaalputs. It is important, however, to bear in mind that the water at Vaalputs has long residence times, with 14C ages of 2000 to 13 000 having been measured (Verhagen & Levin, 1986) and an estimated recharge rate of only 0.16% of the annual precipitation (Chapter 6). The relative enrichment of ^{234}U could therefore be the result of an extended period of even slightly reducing conditions. The enrichment of ^{234}U could have developed over previous periods that might no longer be present in the groundwater of Vaalputs.

Considering the above discussion it could be deducted that the groundwater surrounding borehole 13C5 (which gave the significantly lower $^{234}U/^{238}U$ activity ratio of 1.6) has (or previously had) a higher oxidation potential than the groundwater of the other boreholes. Note that in previous sections this borehole has been observed to yield the highest values in electrical conductivity, the lowest average pH values, comparably low ^{238}U and ^{234}U activities and very high levels of ^{226}Ra unsupported by parent activities.

8.1.1.5 ^{226}Ra

Behaviour of ^{226}Ra under different groundwater conditions

^{226}Ra is one of the four natural radium isotopes, of which all four are radioactive, with ^{226}Ra being the most important due to the far high abundance of its primordial parent radionuclide (^{238}U), compared to ^{235}U which is the parent radionuclide of a second radium isotope. ^{232}Th is also parent to other radium isotopes, but its decay rate is slower than that of ^{238}U (1.4×10^{10} y vs 4.468×10^{9} y) (see Table 2.3). ^{226}Ra on its own yields the total environmental radiation dose for radium, but an additional concern is its decay to ^{222}Rn, a major contributor to radiation dose, which is very mobile, being a gas at room temperature.

^{226}Ra activities in the groundwater of Vaalputs range from 0.0001 to 4.12 $Bq.l^{-1}$, with an average of 0.282 $Bq.l^{-1}$. The average value is below the reporting limit of the NNR (0.6 $Bq.l^{-1}$) and the guideline of

1 $Bq.l^{-1}$ given by the WHO (2004). This range includes the ad-hoc boreholes analysed in 2002 to 2004 to investigate high ^{226}Ra levels observed in the Riembreek area. The highest activity of ^{226}Ra obtained in the original set of study boreholes is 2.04 $Bq.l^{-1}$ in borehole 13C5, followed by MON14 with 0.68 $Bq.l^{-1}$. For comparison purposes the levels of this radionuclide in groundwater with similar host rocks will be given. ^{226}Ra levels were also determined in the samples taken from the Nuba Mountain region in Sudan, mentioned in section 8.1.1. Low levels of ^{226}Ra is found in samples taken from the lake as well as in samples taken from groundwater hosted in uranium enriched granites, ranging from 0.009 to 0.017 $Bq.l^{-1}$ (Alfatih *et al*., 2008). In the approximately 800 drinking water samples analysed in Catalonia, northeast Spain, the average ^{226}Ra activity was between 0.01 and 0.03 $Bq.l^{-1}$. High activities of 0.86 to 0.96 $Bq.l^{-1}$ were found in samples from areas associated with granitic formations (Ortega *et al*., 1996).

It is evident from the variation in ^{226}Ra levels in these granite hosted groundwater samples that high levels of ^{238}U in host rocks and even in the groundwater is not necessarily correlated with elevated levels of ^{226}Ra. The mobility of ^{226}Ra clearly depends on quite a large number of factors.

The mobility of ^{226}Ra into groundwater is largely dependent of the redox conditions of the water, the strength of the radium ion that forms, the concentration of competing ions for adsorption and the pH (Turekian, 1997; Smith & Amonette, 2006). In oxidizing water a high mobility of ^{226}Ra is seen, while a low retardation is found in reducing environments (Turekian, 1997). With respect to pH an increased mobility is expected within acidic groundwater (Smith & Amonette, 2006).

The statements above, as well as the trend that was mentioned in the previous section that $^{234}U/^{238}U$ activity ratios should be closer to equilibrium in oxidizing conditions, can be used to explain the results seen in borehole 13C5. This borehole (and the boreholes in the surrounding area, RIEM5, 6 and 7) contains elevated levels of ^{226}Ra (2.04 $Bq.l^{-1}$) that is not supported by elevated levels of the parent radionuclides such as ^{238}U and ^{234}U. The elevated mobility of ^{226}Ra into the groundwater and the lower activity ratio for $^{234}U/^{238}U$ in this water could both be the results of lower pH and stronger oxidizing conditions present in borehole 13C5 compared to the other boreholes.

The difference in chemical conditions in this groundwater compared to the other boreholes relates to the location of these boreholes in the granitic-gneiss of the Namaqualand Metamorphic Complex on the western part of the Vaalputs facility. The other boreholes are all drilled into the Tertiary sediments of the Bushmanland Plateau before reaching the granitic basement.

8.2 Thorium

The activity levels of ^{232}Th in the groundwater of Vaalputs are mostly below detection limits, and even when significant values are obtained, ranging from 0.0002 to 0.21 $Bq.l^{-1}$, these values are far below the limit of 1 $Bq.l^{-1}$ given by the WHO (2004). Elevated levels of up to 0.21 $Bq.l^{-1}$ in boreholes EM8

and FW35 obtained for a short period in time have been determined as true values that are not due to any analytical errors.

The low solubility of ^{232}Th typically leads to very low activities in groundwater (Tchokossa *et al*., 1999), as is evident from values reported in the literature. Drinking water of Catalonia in Spain has been extensively sampled and analysed for natural radioactivity, and with regards to ^{232}Th the activities were very low, at less than 0.005 Bq.l^{-1}, even for samples where elevated levels of ^{238}U and ^{226}Ra were found (Ortega *et al*., 1996). ^{232}Th levels were determined as part of the study of migration of actinides groundwater carried out at Steenkampskraal monazite deposit hosted in granitic gneiss about 150km to the south of Vaalputs. ^{232}Th levels above detection limit were obtained for four of the five boreholes, with values ranging from 0.0004 to 0.019 Bq.l^{-1} (Ross *et al*., 1996).

A feature that is observed from the α-spectrometry results of this study is the activities of ^{228}Th and ^{224}Ra in the groundwater samples unsupported by ^{232}Th levels. This might be the result of varying mobility of radionuclides in the decay chain of ^{232}Th, including beta emitting radionuclides ^{228}Ra and ^{228}Ac (the parent radionuclides of ^{228}Th and ^{224}Ra) that have not been analysed for these samples. Thorium is immobile, but the daughters that are formed during decay might be more soluble to produce unsupported, disequilibrium levels ^{228}Th and ^{224}Ra in the groundwater.

The peaks in ^{232}Th levels seen in the two boreholes of close proximity, FW35 and EM8, might be attributed to the presence of colloids in the samples analysed in those years. In the study of colloid mediated migration of actinides at Steenkampskraal it was found however that elevated ^{232}Th levels were rather associated with samples containing high amounts of particulate matter than those containing high amounts of colloids (Ross *et al*., 1996). There is, however, a small probability that colloids of particulate matter would actually end up in two samples from the same area in the same year, unless it might be attributed to minor tectonic events influencing this area. The records of tectonic events from the seismic station at Vaalputs have been compared with the dates of these high ^{232}Th values, but no coinciding events were found.

8.3 Total α radiation

The first observation from both the total α timelines displayed in Figure 7.12 is that the radiation exceeds the WHO screening limits by far. However, these high levels of radiation must be the result of the natural radionuclides in the rocks and the groundwater hosted therein. This leads to questioning how applicable these screening limits could be to all natural environments. Site specific limits based on natural radioactivity might have to be introduced in the monitoring of sites such as radioactive waste disposal facilities.

In an attempt to explain possible contributors to high levels of total α radiation, the levels of specific radionuclides measured by α-spectrometry in groundwater during 2009 will be compared to the measured levels of total α radiation. Table 8.3 shows all α-emitting radionuclides of the natural decay

chains and indicates which were measured by α-spectrometry. Radionuclides with half-lives significantly longer than a month are highlighted. Typically samples collected from Vaalputs would have a laboratory waiting time of at least a month. In this table it can be seen that for two radionuclides, ^{231}Pa and ^{227}Ac, significant activities should be present in the groundwater due to their long half-lives. No measurements have however been carried out for these radionuclides during this study, and their levels can be deducted from that of their short-lived daughter radionuclide ^{227}Th. Other radionuclides that are not measured all have very short half-lives and if present their activity would represent that of the longer-lived parent radionuclide, for example, the activity of the short-lived ^{224}Ra would represent the activity of its long-lived parent radionuclide ^{228}Th.

A graphical presentation of the contributions of the various α-emitting radionuclides to the measured total α radiation levels is shown in Figure 8.2. In this figure it is seen that the general trend of activities in radionuclides are the mostly same as the total α radiation levels; however the totals do not quite match. In some boreholes a shortfall is seen in the cumulative levels of radionuclides, while in others the cumulative total exceeds the measured value. Borehole 16C3 stands out as it has a large excess in the cumulative values over the measure total α level.

Table 8.3: Natural α emitting radionuclides from the ^{238}U, ^{235}U and ^{232}Th decay chains and their half-lives (adapted from Faure, 1998).

α – emitting radionuclide	Measured	Half-life
^{238}U	**YES**	**4.5 x 10^{9} a**
^{234}U	**YES**	**2.5 x 10^{5} a**
^{230}Th	**YES**	**8 x 10^{4} a**
^{226}Ra	**YES**	**1600 a**
^{222}Rn	NO	3.8 d
^{218}Po	NO	3.05 m
^{214}Bi	NO	20 m
^{214}Po	NO	162 µs
^{210}Pb	**YES**	**22 a**
^{210}Po	**YES**	**138 d**
^{235}U	**YES**	**7 x 10^{8} a**
^{231}Pa	**NO**	**3.3 x 10^{4} a**
^{227}Ac	**NO**	**22 a**
^{227}Th	YES	19 d
^{223}Fr	NO	22 m
^{223}Ra	YES	11 d
^{219}Rn	NO	3.9 s
^{215}Po	NO	1.8 ms
^{211}Bi	NO	2.1 m
^{211}Po	NO	0.52 s
^{232}Th	**YES**	**1.4 x 10^{11} a**
^{228}Th	**YES**	**1.9 a**
^{224}Ra	YES	3.6 d
^{220}Rn	NO	56 s
^{216}Po	NO	0.15 s
^{212}Bi	NO	61 m
^{212}Po	NO	0.3 µs

*a: years, d: days; m: minutes; s: seconds; ms; milliseconds; µs: microseconds. **Red**: radionuclides with half-lives significantly longer than the one month waiting time for analysis.*

It is also evident from Figure 8.2 that the major contributors to the total α radiation levels are ^{238}U, ^{234}U and ^{226}Ra (to a smaller degree), confirming what has been seen in literature (Forte *et al*., 2007). Note furthermore the low values of ^{238}U, ^{234}U and ^{230}Th for 13C5, with elevated ^{226}Ra levels, with the cumulative values almost matching the value for total α radiation for this borehole. No total α measurement are available for the two boreholes GWB3 and 5C2 in this year.

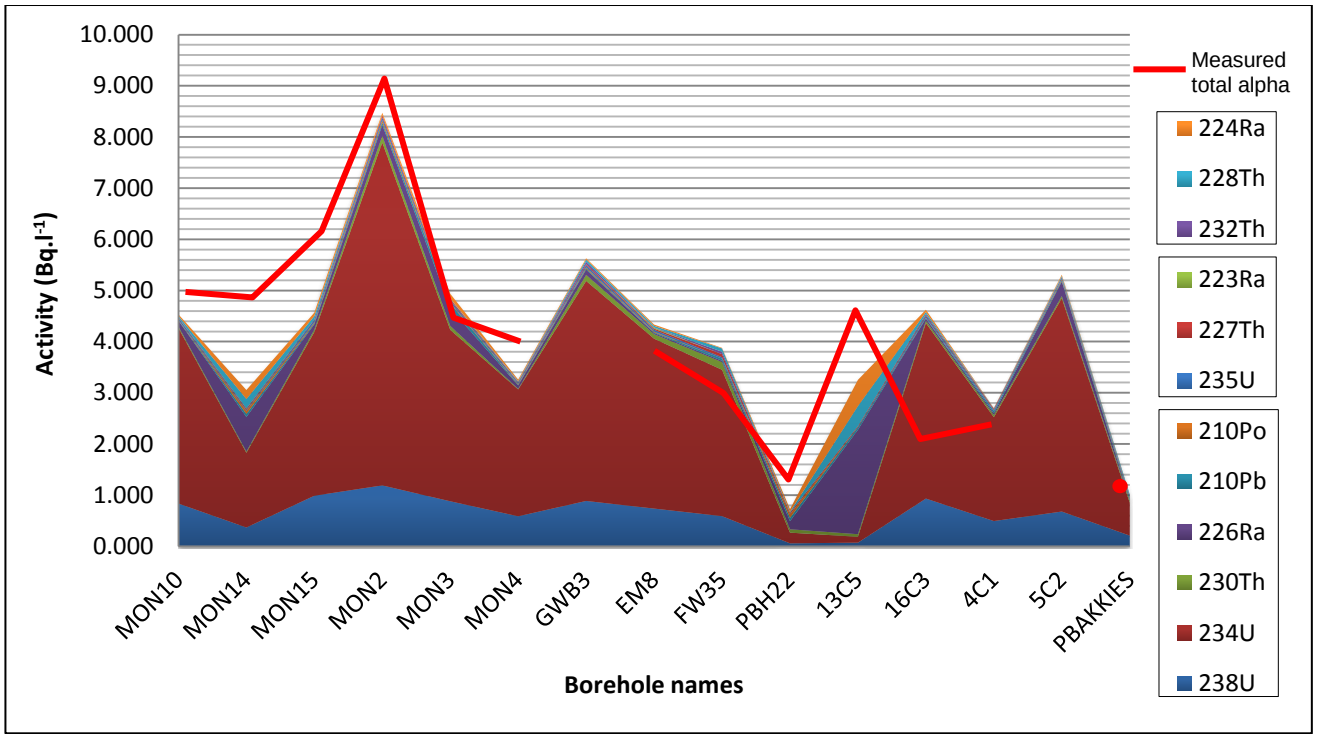


Figure 8.2: Cumulative contributions of α emitting radionuclides to the measured total α levels of 2009 per borehole.

From the observations made from Figure 8.2 it is evident that peaks in total α radiation levels should be the results of elevated levels of radionuclides from the ^{238}U decay chain, with changes in ^{234}U levels to show the most pronounced effects on the total α radiation levels. In the case of the very strong peak in α radiation seen in 2000, it could not be explained by elevated levels of ^{238}U or ^{226}Ra, the only data available on ^{238}U decay chain radionuclides for this period. From the full set of water chemistry data, shown in Appendix C, Table C-3, a slight increase in pH for most values from around 1999 to 2003 is however noticed. This change in groundwater conditions might have resulted in a higher mobility of ^{234}U relative to ^{238}U, possibly giving rise to peaks in the total α radiation levels.

The possibility of seismic events triggering the release of ^{234}U from damaged crystal structures (due to alpha recoil), resulting in peaks in α radiation levels has been considered. Data from tectonic events registered at the Vaalputs seismic station has been evaluated in order to check the correlation of high levels in α radiation with seismic events registering comparably high on the Richter scale. A higher density of events registering above 3.5 on the Richter scale is found in 2001, while in 2000 (the year of the peak in α radiation) these events does not seem to occur at a higher frequency than other years. Tectonic events are therefore not considered a valuable explanation of peaks in total α radiation levels.

8.4 Total β

Not much will be discussed on the total β radiation levels of Vaalputs, since the values are spread over time erratically and the reliability of the measurements are questioned, especially due to the spill over from alpha radiation into the window of total β measurement. The values appear more stable from 2005 and onwards, and might be more reliable due to changes in the calibration standards used for measuring the total α and β levels. A breakdown of specific radionuclides contributing to total β radiation is not within the scope of this study, since only alpha spectrometry results have been obtained for specific radionuclide activities.

For the period of 2005 to 2010 the levels of total β radiation range from 0.37 to 4.31 $Bq.l^{-1}$, with an average of 1.54 $Bq.l^{-1}$. These values are mostly far above the WHO (2004) screening limit of 1 $Bq.l^{-1}$ and are high compared to the total β activity of 0.04 to 2.9 $Bq.l^{-1}$ found in drinking water from Catalonia, Spain. The high values in β radiation coincide with elevated levels of ^{40}K in the groundwater, and from literature the activity from ^{40}K is often determined to be the major contributor to the total β radiation levels, together with short-lived daughters of ^{238}U and ^{234}Th. (Ortega *et al*., 1996; Forte *et al*., 1997; Bonotto *et al*., 2009). ^{40}K will be present in significant quantities in the groundwater of Vaalputs due to the high abundance of elemental potassium in granitic rocks, as well as in humans since elemental potassium is essential for the normal function of the human body. ^{40}K does not accumulate in the human body however and is not deemed a threat to the health of humans (WHO, 2004).

9 Conclusions and recommendations

Chemical analyses

The chemistry of the water is an important aspect to consider and vital for understanding the behaviour of radionuclides. There was however limitations to the extent to which the chemistry could be used to explain patterns in radionuclide concentrations over time and space. The following important shortcomings in the chemical data were identified:

- The total alkalinity of the groundwater was not determined regularly, but only once or twice over the entire period investigated for most boreholes. The unavailability of this parameter prevented the calculation of the ionic balance for most samples, which could have been a useful way to check the analytical correctness of the chemical analysis.
- It was found that the reporting of nitrate was not standardised, as some values were reported as N even though the reports stated the reporting of nitrates as NO_3. Nitrates are soluble and can have a relation to the mobilisation of nuclides, it is therefore of importance to correctly monitor changes in its concentration in the groundwater.
- The absence of oxidation-reduction potential measurements of groundwater at the time of sampling is also seen as a major shortcoming. The oxidation-reduction potential of groundwater has a very pronounced effect on the concentrations of uranium in the water, since uranium has variable mobilities for different valence conditions.

As Vaalputs is a strategically important facility, the accurate analysis and reporting of the chemistry of its groundwater is crucial, and very good care should be taken not to allow poor collection of data.

Limits for uranium in water

Two recommendations are made with regards to limits used for monitoring safety of water:

- In order to determine effective limits for water that is safe for consumption or other uses, the best approach might be to establish separate limits for the activities of ^{238}U and ^{234}U, based on their individual dose estimations, and use this in combination with a limit for the weight concentration of ^{nat}U. The limit for ^{nat}U might be given as a factor of the activity ratio of $^{234}U/^{238}U$ determined for the groundwater (or fresh water) of a specific area.
- It is strongly recommended that the SANS reconsider their limit for uranium in drinking water as this limit is far too high compared to limits from international institutes such as the WHO and the USEPA. The limit based only on the toxicity is not sufficient for radio-active elements in protecting humans for possible ingestion exposure of radio-activity, and should be lowered.

^{238}U levels in the groundwater of Vaalputs

A natural anomaly in ^{238}U activity is found in the near-field of the disposal site. This is attributed to anomalously U-enriched rocks found in the basement of this area. It has to be kept in mind that the high radioactivity of the rocks of this area has been known since before the establishment of this facility and it was one of the factors that motivated the selection of this specific site for the disposal of radioactive waste. This natural anomaly should be considered during future monitoring of the recently disposed waste containing uranium. This natural trend should not be confused with possible contamination from the waste disposed in the trenches of Vaalputs.

^{234}U/^{238}U disequilibrium

High activity ratios of ^{234}U/^{238}U are found in the groundwater of Vaalputs. The levels of ^{nat}U reported by assuming an equilibrium ratio is therefore erroneous. It is recommended that Necsa carries out an extensive experiment in order to determine statistically representative activity ratios for ^{234}U/^{238}U in the groundwater of Vaalputs. It is suggested that all available boreholes should be included in this investigations and that sampling should be repeated at least four different times in a year, and possibly over more than one year. This way, different ratios might be determined for different areas around the disposal site and should then be used as such in reporting the ^{nat}U activities to the NNR.

Unsupported enrichment of ^{226}Ra

The high levels of ^{226}Ra and the low activity ratio for ^{234}U/^{238}U in borehole 13C5 might be attributed to the lower pH and stronger oxidizing conditions found in the groundwater of this borehole. The geology of this borehole is very different from the other boreholes in this study, since it is the only borehole selected for this study that lies in the Namaqualand portion of the property, where no Tertiary Bushmanland rocks covers the granitic gneiss basement of the Namaqualand Metamorphic Complex. This difference in geology should be the key to the different geochemical conditions in the groundwater of this borehole and the surrounding RIEM-boreholes that were found to contain high ^{226}Ra levels.

Thorium

^{232}Th levels are mostly very low, far below the guideline of 1 Bq.l^{-1} from the WHO (2004). Elevated levels (still far below the guideline limit) are present in two boreholes (EM8 and FW35) in 2002, 2007 and 2008 however. Possible explanations were seeked from water-chemistry data, possible high amounts of particulate matter and tectonic events. None of these factors can explain the elevated values of these boreholes. Much further consideration of these boreholes is not given, since the values are still so far below guidelines for water safe for consumption.

Total α and β radiation

- A clear explanation of the cause of the peak in total α radiation levels could not be given in this study. It has however been determined that in the groundwater of Vaalputs ^{234}U levels has the most pronounced effect on the levels of total α radiation.
- With respect to total β radiation levels, from the timeline in Figure 7.16 it seems that the analytical method of determining the radiation levels has become more reliable since 2005. By using simultaneous mode in measuring the total α and β, however, the problem of significant spill over of α radiation into the window used for measurement of β radiation cannot be completely eliminated.
- It is suggested that during the routine monitoring program of groundwater at Vaalputs, when total α radiation levels of any borehole exceeds a limit of, for example 10 $Bq.l^{-1}$, nuclide specific analysis must be carried out for this boreholes as soon as possible. For total β when radiation levels exceed, for example, 5 Bq.l-1, levels of specific beta-emitting radionuclides, especially ^{40}K, should be determined. These protocols might include re-sampling of the borehole and doing a complete analysis of specific radionuclides and total α and/or β radiation levels. If the monitoring is conducted in this way, it might be possible to explain peaks in total α and β radiation right away.

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Appendix A. Radioactivity limits

Table A-1: Exemption limit values of activity (Bq.g^{-1}) for radionuclides of artificial origin in bulk amounts of material after IAEA (2004).

Radionuclide		Activity	Radionuclide		Activity	Radionuclide		Activity	Radionuclide		Activity
H-3		100	Fe-55		1000	Sr-85m	*	100	Tc-99m	*	100
Be-7		10	Fe-59		1	Sr-87m	*	100	Ru-97		10
C-14		1	Co-55	*	10	Sr-89		1000	Ru-103		1
F-18	*	10	Co-56		0.1	Sr-90		1	Ru-105	*	10
Na-22		0.1	Co-57		1	Sr-91	*	10	Ru-106		0.1
Na-24	*	1	Co-58		1	Sr-92	*	10	Rh-103m	*	10000
Si-31	*	1000	Co-58m	*	10000	Y-90		1000	Rh-105		100
P-32		1000	Co-60		0.1	Y-91		100	Pd-103		1000
P-33		1000	Co-60m	*	1000	Y-91m	*	100	Pd-109		100
S-35		100	Co-61	*	100	Y-92	*	100	Ag-105		1
Cl-36		1	Co-62m	*	10	Y-93	*	100	Ag-110m		0.1
Cl-38	*	10	Ni-59		100	Zr-93	*	10	Ag-111		100
K-42		100	Ni-63		100	Zr-95		1	Cd-109		1
K-43	*	10	Ni-65	*	10	Zr-97	*	10	Cd-115		10
Ca-45		100	Cu-64	*	100	Nb-93m		10	Cd-115m		100
Ca-47		10	Zn-65		0.1	Nb-94		0.1	In-111		10
Sc-46		0.1	Zn-69	*	1000	Nb-95		1	In-113m	*	100
Sc-47		100	Zn-69m	*	10	Nb-97	*	10	In-114m		10
Sc-48		1	Ga-72	*	10	Nb-98	*	10	In-115m	*	100
V-48		1	Ge-71		10000	Mo-90	*	10	Sn-113		1
Cr-51		100	As-73		1000	Mo-93		10	Sn-125		10
Mn-51	*	10	As-74	*	10	Mo-99		10	Sb-122		10
Mn-52		1	As-76	*	10	Mo-101	*	10	Sb-124		1
Mn-52m	*	10	As-77		1000	Tc-96		1	Sb-125		0.1
Mn-53		100	Se-75		1	Tc-96m	*	1000	Te-123m		1
Mn-54		0.1	Br-82		1	Tc-97		10	Te-125m		1000
Mn-56	*	10	Rb-86		100	Tc-97m		100	Te-127		1000
Fe-52	*	10	Sr-85		1	Tc-99		1	Te-127m		10

***** *Radionuclide with half-life less than 1 day. Values highlighted in red: Radionuclides present in Vaalputs historical radioactive waste.*

Table A-1 cont: Exemption limit values of activity ($Bq.g^{-1}$) for radionuclides of artificial origin in bulk amounts of material after IAEA (2004).

Radionuclide		Activity	Radionuclide		Activity	Radionuclide		Activity	Radionuclide		Activity
Te-129	*	100	Ce-143		10	Re-188	*	100	Pa-230		10
Te-129m		10	Ce-144		10	Os-185		1	Pa-233		10
Te-131	*	100	Pr-142	*	100	Os-191		100	U-230		10
Te-131m		10	Pr-143		1000	Os-191m	*	1000	U-231		100
Te-132		1	Nd-147		100	Os-193		100	U-232		0.1
Te-133	*	10	Nd-149	*	100	Ir-190		1	U-233		1
Te-133m	*	10	Pm-147		1000	Ir-192		1	U-236		10
Te-134	*	10	Pm-149		1000	Ir-194	*	100	U-237		100
I-123		100	Sm-151		1000	Pt-191		10	U-239	*	100
I-125		100	Sm-153		100	Pt-193m		1000	U-240	*	100
I-126		10	Eu-152		0.1	Pt-197	*	1000	Np-237		1
I-129		0.01	Eu-152m		100	Pt-197m	*	100	Np-239		100
I-130	*	10	Eu-154		0.1	Au-198		10	Np-240	*	10
I-131		10	Eu-155		1	Au-199		100	Pu-234	*	100
I-132	*	10	Gd-153		10	Hg-197		100	Pu-237		100
I-133	*	10	Gd-159	*	100	Hg-197m		100	Pu-238		0.1
I-134	*	10	Tb-160		1	Tl-201		100	Pu-239		0.1
I-135	*	10	Dy-165	*	1000	Tl-202		10	Pu-240		0.1
Cs-129		10	Er-169		1000	Tl-204		1	Pu-241		10
Cs-131		1000	Er-171	*	100	Pb-203		10	Pu-242		0.1
Cs-134m	*	1000	Tm-170		100	Bi-206		1	Pu-243	*	1000
Cs-135		100	Tm-171		1000	Bi-207		0.1	Pu-244		0.1
Cs-136		1	Yb-175		100	Po-203	*	10	Am-241		0.1
Cs-137		0.1	Lu-177		100	Po-205	*	10	Am-242	*	1000
Cs-138	*	10	Hf-181		1	Po-207	*	10	Am-242m		0.1
Ba-131		10	Ta-182		0.1	At-211		1000	Am-243		0.1
Ba-140		1	W-181		10	Ra-225		10	Cm-242		10
La-140		1	W-185		1000	Ra-227		100	Cm-243		1
Ce-139		1	W-187		10	Th-226		1000	Cm-244		1
Ce-141		100	Re-186		1000	Th-229		0.1	Cm-245		0.1

** Radionuclide with half-life less than 1 day. Values highlighted in red: Radionuclides present in Vaalputs historical radioactive waste.*

Table A-1 cont: Exemption limit values of activity (Bq.g^{-1}) for radionuclides of artificial origin in bulk amounts of material after IAEA (2004).

Radionuclide	Activity	Radionuclide	Activity	Radionuclide	Activity	Radionuclide	Activity
Cm-246	0.1	Cf-248	1	Cf-252	1	Es-254	0.1
Cm-247	0.1	Cf-249	0.1	Cf-253	100	Es-254m	10
Cm-248	0.1	Cf-250	1	Cf-254	1	Fm-254 *	10000
Bk-249	100	Cf-251	0.1	Es-253	100	Fm-255 *	100
Cf-246	1000						

** Radionuclide with half-life less than 1 day. Values highlighted in red: Radionuclides present in Vaalputs historical radioactive waste.*

Appendix B. Physiography data

Table B-1: Rainfall data collected at the Vaalputs weather station between 1986 and 2010 (data: Necsa, 2011b).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Monthly average	Total
1986	2.60	0.00	1.80	9.80	0.40	0.00	0.40	14.00	2.60	0.00	0.00	0.00	2.63	31.60
1987	0.00	0.00	6.00	0.00	0.00	0.00	11.00	14.80	1.40	22.80	1.40	1.80	4.93	59.20
1988	0.00	4.40	7.40	6.00	3.40	9.60	1.20	11.40	0.80	1.00	0.00	0.00	3.77	45.20
1989	0.80	1.00	0.00	0.00	0.80	4.60	13.00	4.00	4.60	0.60	0.80	0.00	2.52	30.20*
1990	0.00	16.00	5.00	40.10	5.00	13.00	7.00	15.90	0.00	0.00	0.60	8.60	9.27	111.20
1991	35.00	0.00	18.00	6.00	0.00	22.00	5.00	0.00	17.00	70.00	0.00	0.00	14.42	173.00
1992	0.00	1.40	2.40	3.50	2.40	31.60	7.90	4.60	1.80	19.00	4.90	0.00	6.63	79.50
1993	3.80	0.40	0.80	25.60	26.40	8.80	22.00	18.90	0.00	28.40	10.00	1.00	12.18	146.10
1994	23.40	11.60	54.60	17.20	0.80	19.80	15.80	1.20	1.00	4.00	1.20	0.80	12.62	151.40
1995	12.80	9.40	1.80	0.00	24.00	20.20	21.30	9.60	22.80	69.00	69.80	44.40	25.43	305.10**
1996	0.40	14.40	1.60	1.20	4.60	3.80	**72.20**	21.20	16.40	31.00	36.60	0.00	16.95	203.40
1997	2.00	1.00	33.40	13.80	47.80	26.80	2.60	3.80	0.20	0.00	7.40	8.00	12.23	146.80
1998	16.40	5.80	12.20	0.00	9.40	1.00	2.80	3.20	7.80	0.20	12.20	0.60	5.97	71.60
1999	0.00	3.20	53.80	16.80	9.20	2.20	3.80	13.00	17.60	21.00	13.20	32.80	15.55	186.60
2000	48.0	37.2	22.2	3.8	16.4	2.8	30.6	2.0	2.8	0.0	6.2	0.0	14.33	172.00
2001	0.6	26.6	11.2	57.0	18.8	0.8	32.8	13.2	5.6	2.6	20.6	0.0	15.82	189.80
2002	2.0	18.8	14.0	29.0	29.0	7.4	9.0	10.8	7.0	5.4	0.0	0.0	11.03	132.40
2003	1.2	0.0	2.0	3.0	1.4	0.6	0.6	29.2	1.8	3.2	1.8	0.2	3.75	45.00
2004	28.8	10.0	0.2	25.6	1.0	9.6	3.4	1.6	4.8	25.4	0.0	2.6	9.42	113.00
2005	54.4	4.0	21.4	18.4	19.6	7.8	1.6	4.2	2.0	49.0	2.0	1.4	15.48	185.80
2006	0.0	17.6	4.0	32.2	61.4	6.8	5.4	16.6	2.0	1.8	24.0	0.2	14.33	172.00
2007	11.4	0.2	1.4	24.0	4.4	23.8	9.4	15.0	0.2	1.8	0.2	49.2	11.75	141.00
2008	2.0	5.6	41.2	0.0	30.4	18.6	27.2	8.4	2.4	0.4	0.0	0.0	11.35	136.20
2009	0	19	22.8	10.8	8.2	34.2	9	15	0.2	1.4	7.6	0	10.68	128.20
2010	0.6	28.6	26.6	1	2.4	8.8	7.6	2	2.6	5.6	3	7.6	8.03	96.40
Max	54.40	37.20	54.60	57.00	61.40	34.20	72.20	29.20	22.80	70.00	69.80	49.20	25.43	305.10
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	2.52	30.20
Avg	9.85	9.45	14.63	13.79	13.09	11.38	12.90	10.14	5.02	14.54	8.94	6.37	10.84	130.11

** Min annual rainfall recorded for the period. ** Max annual rainfall recorded for the period.*

Green: Maximum monthly rainfall recorded for the period; Red: Minimum monthly rainfall recorded for the period; Blue: Average monthly rainfall recorded for the period.

Appendix C. Hydrogeology data

Table C-1: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VR28	-3147693	-653.04	205	1980/09/08	15.00	**VR48**	-3202414	-33149.5	680	1980/10/14	12.00
VR27	-3130146	-981.02	465	1980/09/09	46.80	**VR34**	-3207042	-36547.3	540	1980/10/14	17.00
VR8	-3150288	-14853	218	1980/09/10	13.00	**VWD90**	-3290108	-90574.8	760	1980/11/17	35.00
VR14	-3194426	-7805.2	200	1980/09/11	4.00	**VWD65**	-3298161	-92494	630	1980/11/17	18.00
VR6	-3155822	-7831.1	358	1980/09/12	32.60	**VWD57**	-3305094	-92919.6	620	1980/11/17	20.00
VR2	-3181679	-4069.4	320	1980/09/12	75.40	**VWD66**	-3314613	-93322.7	520	1980/11/17	4.00
VR1	-3194801	-13333	160	1980/09/17	23.00	**VWD96**	-3301820	-87952.8	700	1980/11/18	12.00
VR9	-3194807	-17886	140	1980/09/17	13.20	**VWD89**	-3318439	-86695.1	475	1980/11/18	7.00
VR10	-3213094	-18020	40	1980/09/18	7.00	**VWD93**	-3289515	-85630.6	820	1980/11/19	14.00
VR5	-3144188	-10288	110	1980/09/18	2.00	**VWD72**	-3284370	-89219.8	840	1980/11/19	13.00
VR22	-3187089	-35309	70	1980/09/18	1.00	**VWD55**	-3287731	-93548.3	895	1980/11/20	32.00
VR3	-3192619	-31551	80	1980/09/18	47.00	**VWD94**	-3275814	-81698	1093	1980/11/20	12.00
VR30	-3145896	-2612.6	190	1980/09/19	2.00	**VWD87**	-3274222	-90916	1036	1980/11/21	16.00
VR7	-3177829	-26218	190	1980/09/19	46.00	**VWD107**	-3280001	-72629	1064	1980/11/21	65.00
VR24	-3174677	-20198	230	1980/09/19	7.20	**VWD73**	-3285400	-78725	1074	1980/11/21	23.00
VR25	-3167826	-3259.61	400	1980/09/22	25.50	**VWD78**	-3286610	-91998	907	1980/11/22	27.00
VR15	-3159331	-7502.6	450	1980/09/23	9.50	**VWD77**	-3290200	-90463	868	1980/11/22	24.00
VR20	-3159884	-5382	540	1980/09/23	3.00	**VWD76**	-3297066	-82349	792	1980/11/22	6.00
VR37	-3230298	-29826.96	265	1980/10/08	38.00	**VWD88**	-3305725	-78984	678	1980/11/22	10.00
VR40	-3221259	-34393.06	360	1980/10/08	45.00	**VWD97**	-3303938	-58944	670	1980/11/22	25.00
VR41	-3231954	-27391.42	250	1980/10/08	35.00	**VWD81**	-3310239	-62452	945	1980/11/24	35.00
VR43	-3209574	-9418.93	370	1980/10/09	0.50	**VWD239**	-3276486	-96549	1182	1980/11/25	37.00
VR44	-3212166	-14937.02	370	1980/10/09	1.00	**VWD119**	-3268735	-73187	1005	1980/11/27	23.00
VR39	-3170439	-25419.4	670	1980/10/13	18.00	**VWD52**	-3271998	-62989	1021	1980/11/27	26.00
VR42	-3174320	-26388.3	680	1980/10/13	14.00	**VWD59**	-3267153	-54937	986	1980/11/27	32.00
VR32	-3187790	-19198.83	600	1980/10/13	1.00	**VWD80**	-3280262	-53259	1070	1980/11/27	46.00
VR35	-3189279	-25052.93	600	1980/10/13	1.00	**VWD104**	-3291695	-48690	1021	1980/11/27	51.00
VR45	-3194088	-28132.2	640	1980/10/14	23.20	**VWD105**	-3311473	-81759.9	620	1980/11/28	24.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD117	-3284584	-66952	1043	1980/11/28	3.00	**VWD175**	-3286975	-10484	965	1981/01/17	32.20
VWD108	-3333010	-94774	808	1980/12/01	10.00	**VWD126**	-3291407	-7738.9	927	1981/01/17	82.40
VWD109	-3340744	-91657	1013	1980/12/01	3.50	**VWD150**	-3287001	-25968	1029	1981/01/17	12.00
VWD100	-3334971	-86083	922	1980/12/01	4.30	**VWD151**	-3294935	-21598	1011	1981/01/17	15.20
VWD86	-3338793	-78347	899	1980/12/01	5.20	**VWD138**	-3297327	-16114	1013	1981/01/17	94.00
VWD99	-3339293	-70315	807	1980/12/01	8.00	**VWD158**	-3291321	-14188	950	1981/01/19	29.00
VWD111	-3316756	-95557	610	1980/12/02	18.20	**VWD141**	-3270345	-2261.4	1025	1981/01/19	33.00
VWD114	-3321890	-90849	716	1980/12/02	5.80	**VWD144**	-3308411	-15642	962	1981/01/19	87.30
VWD61	-3262292	-55661	966	1980/12/03	22.00	**VWD219**	-3313635	-3861.7	875	1981/01/19	2.00
VWD69	-3256821	-43774	960	1980/12/03	25.40	**VWD254**	-3302862	-9502.7	945	1981/01/19	28.70
VWD53	-3251923	-34301	858	1980/12/03	26.30	**VN39**	-3237324	-81545	762	1981/01/20	47.00
VWD101	-3263363	-29579	950	1980/12/03	30.80	**VWD183**	-3259273	-17139	945	1981/01/20	72.10
VWD50	-3272316	-26810	975	1980/12/03	30.00	**VWD130**	-3241712	-1133.6	872	1981/01/20	21.50
VN142	-3361737	-69557	991	1980/12/03	1.00	**VWD139**	-3261785	-1939.8	870	1981/01/20	32.80
VWD63	-3270043	-39253	984	1980/12/04	36.80	**VWD168**	-3252924	-84291	960	1981/01/20	44.20
VWD58	-3282505	-36870	1023	1980/12/04	34.00	**VWD184**	-3306743	-11431	952	1981/01/20	32.00
VWD70	-3279244	-27116	1002	1980/12/04	36.10	**VWD120**	-3303043	-966.36	900	1981/01/20	18.30
VWD75	-3266281	-5009.3	920	1980/12/04	28.40	**VWD162**	-3302858	-3382.3	933	1981/01/20	32.00
VWD62	-3275798	-9687.2	950	1980/12/04	20.10	**VWD123**	-3243023	-20564	1020	1981/01/21	31.20
VWD103	-3286622	-21936	1006	1980/12/04	48.60	**VWD165**	-3259731	-14012.5	938	1981/01/21	41.80
VWD83	-3301419	-29344	980	1980/12/05	30.80	**VWD127**	-3259831	-19267.1	977	1981/01/22	48.60
VWD234	-3305113	-53946	945	1980/12/05	11.00	**VWD131**	-3254661	-20704.7	999	1981/01/22	47.00
VWD152	-3240789	-5560.4	930	1981/01/12	15.00	**VWD179**	-3254876	-33321.2	1040	1981/01/22	53.80
VWD182	-3291127	-3063.4	903	1981/01/16	32.00	**VWD180**	-3260416	-32577.3	1051	1981/01/22	44.00
VWD125	-3275909	-22549	998	1981/01/16	24.80	**VWD134**	-3268688	-11955	928	1981/01/22	32.30
VWD121	-3276635	-15175	965	1981/01/16	22.80	**VWD173**	-3279387	-3550.82	875	1981/01/22	15.20
VWD124	-3275150	-7588.7	920	1981/01/16	20.20	**VWD177**	-3281197	-32113.8	1044	1981/01/23	52.00
VWD122	-3264532	-29252	1005	1981/01/16	29.20	**VWD174**	-3273549	-38110.8	1065	1981/01/23	48.80
VWD143	-3289926	-1451.2	877	1981/01/17	15.40	**VWD171**	-3315608	-8526.5	920	1981/01/23	42.20

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD164	-3314686	-10618.8	947	1981/01/23	35.80	**VWD266**	-3290701	-95136	990	1981/03/11	25.00
VWD163	-3307127	-21144.8	998	1981/01/23	42.10	**VWD245**	-3279736	-58911	992	1981/03/12	38.00
VWD170	-3304036	-29310.4	1013	1981/01/23	82.40	**VWD267**	-3277563	-66887	971	1981/03/12	15.80
VWD166	-3316833	-24611.6	959	1981/01/23	68.80	**VWD241**	-3287109	-55646	996	1981/03/12	21.20
VWD167	-3295983	-34488.9	1022	1981/01/23	48.20	**VWD265**	-3280771	-77305	965	1981/03/12	15.40
VWD178	-3295976	-32071.4	1022	1981/01/23	48.20	**VWD259**	-3281641	-94406	964	1981/03/12	17.00
VWD156	-3233359	-34518.8	1008	1981/01/26	83.80	**VWD249**	-3300794	-57833	960	1981/03/12	22.10
VWD145	-3234175	-29006.6	938	1981/01/26	48.20	**VWD273**	-3281529	-47444	1025	1981/03/13	28.00
VWD149	-3244893	-30598.3	1058	1981/01/26	42.00	**VWD236**	-3294517	-46260	991	1981/03/13	54.00
VWD159	-3239359	-33366.8	1010	1981/01/26	32.40	**VWD230**	-3286898	-50163	1010	1981/03/13	19.00
VWD133	-3268744	-37319.3	1058	1981/01/26	11.40	**VWD272**	-3295470	-64469	985	1981/03/13	12.20
VWD137	-3259163	-44303.9	1070	1981/01/27	23.30	**VWD232**	-3297887	-49469	973	1981/03/13	19.40
VWD136	-3244053	-53268.3	1012	1981/01/27	18.80	**VWD233**	-3310957	-37340	995	1981/03/14	32.20
VWD135	-3244460	-60795.2	1025	1981/01/27	9.00	**VWD253**	-3304342	-46783	958	1981/03/14	19.00
VWD157	-3258582	-36894.7	1065	1981/01/28	21.30	**VWD250**	-3308520	-51545	943	1981/03/14	3.80
VWD147	-3249754	-47577.4	1045	1981/01/28	19.80	**VWD238**	-3286848	-36775	1043	1981/03/15	50.00
VWD160	-3246753	-57707.3	1045	1981/01/28	12.00	**VWD235**	-3270426	-42967	1066	1981/03/15	65.00
VWD128	-3251900	-64396.1	1010	1981/01/28	18.20	**VWD240**	-3290904	-73042	996	1981/03/15	18.20
VWD146	-3253419	-75955.4	977	1981/01/29	48.20	**VWD263**	-3261253	-86331	950	1981/03/16	21.20
VWD129	-3251874	-91904.8	943	1981/01/29	46.60	**VWD261**	-3290805	-85191	980	1981/03/16	6.00
VWD153	-3239333	-68760	1022	1981/01/30	46.90	**VWD244**	-3267705	-84504	930	1981/03/16	22.00
VWD140	-3244082	-87757.7	970	1981/01/30	68.00	**VWD246**	-3303012	-86816	980	1981/03/16	6.10
VWD154	-3240311	-77257.9	990	1981/01/30	52.00	**VWD218**	-3302347	-95842	990	1981/03/16	4.00
VWD185	-3267707	-54934	1024	1981/02/02	55.20	**VWD228**	-3302548	-36562.5	988	1981/03/17	26.00
VWD188	-3269939	-57831	1010	1981/02/02	36.00	**VWD226**	-3298811	-67189.4	992	1981/03/17	6.92
VWD186	-3266457	-63182	1004	1981/02/02	42.80	**VWD214**	-3308067	-70031.5	980	1981/03/17	18.00
VWD187	-3260936	-66770	999	1981/02/03	21.20	**VWD212**	-3319119	-64546.8	938	1981/03/17	5.40
VWD189	-3274485	-76702	954	1981/02/03	22.10	**VWD220**	-3308391	-62382.2	965	1981/03/17	6.60
VWD260	-3289285	-65150	1005	1981/03/06	10.20	**VWD247**	-3318437	-73665.7	963	1981/03/17	3.20

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD227	-3301086	-76197.5	1008	1981/03/17	9.20	**VWD356**	-3358927	-44388	1057	1981/04/02	50.50
VWD243	-3220064	-44943	950	1981/03/19	10.45	**VWD310**	-3365226	-48527	1084	1981/04/03	10.00
VWD216	-3222383	-39418.5	975	1981/03/19	14.00	**VWD312**	-3368379	-51074	1097	1981/04/03	16.60
VWD255	-3216909	-55667.2	829	1981/03/19	51.70	**VWD314**	-3359700	-52077	1097	1981/04/03	13.40
VWD256	-3209859	-48880.5	730	1981/03/19	30.00	**VWD315**	-3359149	-52881	1094	1981/04/03	15.00
VWD215	-3268949	-77547.5	959	1981/03/19	6.70	**VWD367**	-3372372	-32490	910	1981/04/06	3.00
VWD252	-3230149	-41337	1035	1981/03/20	37.80	**VWD368**	-3374021	-27311	900	1981/04/07	13.00
VWD211	-3222934	-38281.1	985	1981/03/20	49.60	**VWD369**	-3372564	-34730	940	1981/04/07	17.40
VWD229	-3236445	-45526.8	1060	1981/03/20	18.20	**VWD323**	-3353775	-49379	1049	1981/04/08	25.00
VWD248	-3234083	-54449.3	997	1981/03/20	18.90	**VWD325**	-3356252	-63955	1097	1981/04/08	33.00
VWD224	-3229875	-62413.2	938	1981/03/20	14.60	**VWD328**	-3366062	-20778	925	1981/04/09	5.00
VWD213	-3220603	-55487	875	1981/03/20	18.00	**VWD331**	-3370851	-11205	910	1981/04/09	13.80
VWD262	-3215560	-42688.2	898	1981/03/23	44.80	**VWD333**	-3366247	-21298	930	1981/04/09	28.00
VWD342	-3226129	-69569.4	904	1981/03/24	34.60	**VWD329**	-3368262	-7525	880	1981/04/09	3.00
VWD257	-3226557	-63728.7	910	1981/03/24	27.50	**VWD334**	-3354220	-6733.2	920	1981/04/10	20.60
VWD343	-3219022	-70450.9	934	1981/03/24	32.20	**VWD335**	-3356990	-5289	940	1981/04/10	44.80
VWD344	-3209766	-67232.5	935	1981/03/24	52.20	**VWD336**	-3350709	-5773.1	888	1981/04/14	15.00
VWD223	-3211822	-71117.6	976	1981/03/24	14.00	**VWD371**	-3369957	-27694	915	1981/04/15	9.70
VWD242	-3211866	-77937.3	1008	1981/03/25	32.40	**VWD375**	-3362014	-28355	950	1981/04/15	18.90
VWD221	-3214486	-82790	989	1981/03/25	31.50	**VWD376**	-3361274	-27877	950	1981/04/15	33.70
VWD231	-3209516	-85262	972	1981/03/25	44.60	**VWD377**	-3359242	-27882	978	1981/04/15	32.70
VWD339	-3220596	-84612	983	1981/03/25	76.00	**VWD387**	-3349996	-24698	963	1981/04/20	15.00
VWD345	-3229179	-69794.1	939	1981/03/27	27.00	**VWD537**	-3373696	-95222	842	1981/05/13	15.00
VWD340	-3223139	-78510	945	1981/03/27	61.20	**VWD528**	-3355882	-5610.11	895	1981/05/13	8.00
VWD341	-3225770	-84817	965	1981/03/27	39.40	**VWD529**	-3357551	-13515.7	940	1981/05/13	9.00
VWD350	-3362775	-35882	1017	1981/04/01	57.00	**VWD530**	-3365303	-3203.01	861	1981/05/13	18.00
VWD352	-3367580	-36027	970	1981/04/01	8.80	**VWD531**	-3363645	-10411.4	855	1981/05/14	10.00
VWD353	-3366472	-36190	990	1981/04/01	20.00	**VWD533**	-3361627	-20346	800	1981/05/14	6.00
VWD309	-3363386	-56384	1076	1981/04/02	12.70	**VWD534**	-3355535	-22922.1	865	1981/05/14	10.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD538	-3348333	-24541.3	894	1981/05/14	31.00	**VWD435**	-3329766	-51523	975	1981/06/03	6.00
VWD471	-3300669	-24809	965	1981/05/15	16.00	**VWD451**	-3409649	-8453.2	918	1981/06/05	21.00
VWD473	-3301234	-29318	985	1981/05/15	43.00	**VWD452**	-3296579	-6929.6	907	1981/06/05	12.00
VWD441	-3311743	-19956	930	1981/05/15	36.00	**VWD460**	-3315431	-15444	925	1981/06/06	21.00
VWD503	-3334034	-39025	1002	1981/05/16	22.00	**VWD458**	-3303597	-644.21	898	1981/06/06	20.00
VWD506	-3338776	-41259	1020	1981/05/16	38.00	**VWD464**	-3315248	-16893	925	1981/06/08	16.00
VWD487	-3344804	-14120	925	1981/05/20	17.00	**VWD465**	-3317097	-17372	933	1981/06/09	28.00
VWD488	-3333714	-9315.6	910	1981/05/20	14.00	**VWD467**	-3314512	-18664	932	1981/06/09	23.00
VWD491	-3335192	-8672	916	1981/05/20	13.00	**VWD474**	-3300126	-29482	984	1981/06/15	28.00
VWD492	-3344056	-1604.6	890	1981/05/21	9.00	**VWD477**	-3296819	-35937	1016	1981/06/16	48.00
VWD493	-3343132	-1604.8	890	1981/05/21	10.00	**VWD478**	-3295350	-38359	1025	1981/06/16	53.00
VWD495	-3344613	-7060	904	1981/05/21	5.00	**VWD479**	-3297942	-40122	1030	1981/06/16	64.00
VWD496	-3333341	-803.09	908	1981/05/21	11.00	**VWD482**	-3301984	-33182	1002	1981/06/16	35.00
VWD498	-3339461	-22635	953	1981/05/21	43.00	**VWD560**	-3318971	-29914	977	1981/06/18	29.20
VWD516	-3336735	-38858	1010	1981/05/23	41.00	**VWD563**	-3306052	-34458	978	1981/06/19	31.80
VWD518	-3331029	-44501	1015	1981/05/23	24.00	**VWD544**	-3310390	-56174	954	1981/06/20	7.00
VWD524	-3343558	-35143	996	1981/05/25	28.00	**VWD545**	-3307990	-56508	937	1981/06/20	4.00
VWD525	-3341948	-32099	980	1981/05/25	20.00	**VWD546**	-3301124	-50260	967	1981/06/20	26.00
VWD408	-3335849	-48336	1037	1981/05/26	30.00	**VWD554**	-3314512	-48912	1012	1981/06/24	43.00
VWD526	-3339842	-27610	995	1981/05/26	23.00	**VWD555**	-3319614	-53554	1000	1981/06/24	9.00
VWD527	-3335032	-24892	973	1981/05/26	42.00	**VWD556**	-3309652	-56499	945	1981/06/25	16.00
VWD443	-3293820	-17731	945	1981/05/30	9.00	**VWD557**	-3311111	-52495	983	1981/06/25	14.00
VWD445	-3293629	-13218	930	1981/05/30	14.00	**VWD631**	-3377627	-28661	880	1981/09/10	16.80
VWD418	-3333325	-61037	953	1981/06/01	4.00	**VWD632**	-3391485	-28758	815	1981/09/10	18.00
VWD421	-3346791	-56951	899	1981/06/02	8.00	**VWD643**	-3381403	-23667	850	1981/09/10	24.00
VWD427	-3336853	-64068	869	1981/06/02	6.00	**VWD644**	-3384905	-19663	815	1981/09/10	26.00
VWD431	-3331236	-49642	998	1981/06/03	11.00	**VWD645**	-3390484	-22529	867	1981/09/10	17.00
VWD432	-3330125	-49165	1006	1981/06/03	18.00	**VWD669**	-3374828	-14641	896	1981/09/11	7.00
VWD434	-3329397	-51525	975	1981/06/03	6.00	**VWD647**	-3382858	-7674.8	775	1981/09/11	17.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD648	-3388768	-4314.7	768	1981/09/11	38.00	**VWD637**	-3379979	-41743	998	1981/09/19	2.00
VWD651	-3391452	-11182	740	1981/09/11	65.00	**VWD638**	-3384412	-41247	872	1981/09/19	4.00
VWD649	-3387755	-9589.1	760	1981/09/11	42.00	**VWD641**	-3391320	-35388	950	1981/09/19	18.00
VWD633	-3385114	-30053	900	1981/09/12	24.00	**VWD639**	-3388653	-38913	690	1981/09/19	6.00
VWD652	-3399785	-22749	690	1981/09/12	60.00	**VWD642**	-3394847	-40089	770	1981/09/21	19.00
VWD653	-3394128	-6868.2	770	1981/09/12	36.00	**VWD668**	-3404010	-44523	588	1981/09/21	20.00
VWD654	-3395058	-13895	740	1981/09/12	67.00	**VWD670**	-3400886	-48367	540	1981/09/22	8.00
VWD655	-3389241	-15740	795	1981/09/12	68.00	**VWD671**	-3401101	-54671	455	1981/09/22	18.00
VWD674	-3403090	-9176.5	655	1981/09/14	94.00	**VWD672**	-3409789	-55424	441	1981/09/22	22.00
VWD675	-3408907	-3588.9	540	1981/09/14	25.00	**VWD673**	-3407363	-50571	520	1981/09/22	19.00
VWD676	-3414920	-13152	490	1981/09/14	44.00	**VWD729**	-3356350	-13223	862	1982/01/20	15.00
VWD677	-3411235	-19854	549	1981/09/14	62.00	**VWD730**	-3352561	-11384	880	1982/01/20	10.00
VWD656	-3407647	-26960	590	1981/09/16	72.00	**VWD731**	-3351639	-13149	882	1982/01/20	10.00
VWD678	-3417052	-18010	448	1981/09/16	98.00	**VWD733**	-3355795	-12342	860	1982/01/20	13.00
VWD679	-3424800	-8600.4	388	1981/09/16	98.00	**VWD753**	-3352742	-7936.6	920	1982/01/21	23.00
VWD680	-3428586	-5731.6	355	1981/09/16	35.00	**VWD695**	-3344427	-5776.5	875	1982/01/21	14.00
VWD681	-3421471	-955.9	388	1981/09/16	32.00	**VWD696**	-3344980	-1283.6	876	1982/01/21	8.00
VWD658	-3421043	-27005	430	1981/09/17	92.00	**VWD697**	-3336304	-12364	885	1982/01/21	34.00
VWD659	-3428706	-24677	376	1981/09/17	102.00	**VWD734**	-3348491	-4410.9	863	1982/01/22	10.00
VWD660	-3419856	-32028	449	1981/09/17	52.00	**VWD699**	-3343604	-14683	867	1982/01/24	9.00
VWD661	-3415516	-32599	555	1981/09/17	64.00	**VWD700**	-3344072	-18533	876	1982/01/24	6.00
VWD662	-3414582	-29333	487	1981/09/17	63.00	**VWD735**	-3353120	-15311	869	1982/01/24	8.00
VWD634	-3397149	-38164	675	1981/09/18	55.00	**VWD736**	-3351097	-20847	896	1982/01/24	18.00
VWD635	-3400670	-40865	600	1981/09/18	28.00	**VWD746**	-3350368	-25899.9	905	1982/01/25	12.00
VWD636	-3377275	-34715	938	1981/09/18	12.00	**VWD747**	-3350379	-30069.5	919	1982/01/25	30.00
VWD664	-3409179	-43225	520	1981/09/18	6.00	**VWD748**	-3363034	-29714.3	920	1982/01/25	62.00
VWD665	-3407959	-38285	589	1981/09/18	8.00	**VWD749**	-3364597	-26747	868	1982/01/25	52.00
VWD666	-3413037	-37469	625	1981/09/18	48.00	**VWD737**	-3370672	-15687	855	1982/01/26	6.00
VWD667	-3412099	-33167	534	1981/09/18	61.00	**VWD738**	-3366432	-20977.6	775	1982/01/26	16.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD739	-3366522	-19936.5	780	1982/01/26	13.00	**VWD727**	-3346718	-40588	865	1982/02/03	14.00
VWD750	-3370235	-27933.7	809	1982/01/26	18.00	**VWD728**	-3342649	-39559	876	1982/02/03	27.00
VWD752	-3372360	-28168.3	795	1982/01/26	10.00	**VWD742**	-3357182	-13222	865	1982/02/04	7.00
VWD702	-3330108	-1285.33	898	1982/01/27	23.00	**VWD745**	-3357183	-14585	956	1982/02/04	18.00
VWD703	-3321887	-4984.36	908	1982/01/27	27.00	**VWD743**	-3357551	-12901	955	1982/02/04	22.00
VWD704	-3320779	-5628.07	900	1982/01/27	29.00	**VWD765**	-3315427	-12468	932	1982/06/23	17.00
VWD740	-3365871	-17455.5	815	1982/01/27	28.00	**VWD766**	-3313764	-11585	931	1982/06/23	26.10
VWD741	-3362173	-15859.5	820	1982/01/27	29.00	**VWD768**	-3319313	-16833	942	1982/06/24	46.00
VWD706	-3323736	-7126.98	900	1982/01/28	19.00	**VWD769**	-3310265	-19958	982	1982/06/24	52.00
VWD707	-3328261	-5222.53	900	1982/01/28	27.00	**VWD771**	-3307127	-21172	998	1982/06/24	90.00
VWD708	-3332235	-7549.85	898	1982/01/28	32.00	**VWD782**	-3290852	-6610.7	920	1982/06/25	46.00
VWD709	-3327988	-10043.6	898	1982/01/28	28.00	**VWD783**	-3291712	-1612.2	880	1982/06/25	20.00
VWD710	-3324759	-13904.4	912	1982/01/28	30.00	**VWD774**	-3315790	-3539.2	902	1982/06/25	22.00
VWD693	-3312568	-15850.8	959	1982/01/29	32.00	**VWD776**	-3309325	-4587.6	916	1982/06/25	19.00
VWD711	-3323927	-13985.8	915	1982/01/29	31.00	**VWD778**	-3295284	-2739.9	890	1982/06/25	28.00
VWD712	-3325781	-18001.7	914	1982/01/29	22.00	**VWD779**	-3296303	-8380.2	932	1982/06/25	39.00
VWD713	-3331047	-18394.8	900	1982/01/29	18.00	**VWD780**	-3295294	-15553	972	1982/06/26	52.00
VWD714	-3331887	-23292.9	907	1982/01/29	23.00	**VWD784**	-3279275	-7101.7	920	1982/06/28	30.00
VWD715	-3320042	-8603.49	905	1982/01/29	12.00	**VWD787**	-3254156	-12051	940	1982/06/29	88.00
VWD716	-3326345	-23385	928	1982/01/29	56.00	**VWD788**	-3254277	-10191	926	1982/06/29	70.00
VWD717	-3320620	-24201.2	950	1982/01/30	27.00	**VWD792**	-3231193	-15561	905	1982/06/30	10.00
VWD718	-3338932	-32749.9	860	1982/01/31	22.00	**VWD793**	-3244698	-26308	800	1982/06/30	146.00
VWD719	-3338748	-32910.9	865	1982/01/31	22.00	**VWD790**	-3257230	-5013.3	935	1982/06/30	22.00
VWD720	-3339753	-28975	885	1982/01/31	18.00	**VWD797**	-3227149	-26511	905	1982/07/01	36.00
VWD723	-3329520	-36152	910	1982/02/02	48.00	**VWD798**	-3227149	-26430	905	1982/07/01	58.00
VWD724	-3327488	-35998	930	1982/02/02	44.00	**VWD804**	-3232003	-43275	765	1982/07/02	146.00
VWD725	-3329164	-40010	890	1982/02/02	3.00	**VWD794**	-3247962	-37469	838	1982/07/02	43.00
VWD721	-3356309	-35904	868	1982/02/02	15.00	**VWD795**	-3241495	-37247	787	1982/07/02	65.00
VWD726	-3329165	-40331	890	1982/02/03	1.00	**VWD796**	-3239039	-47298	810	1982/07/02	168.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD806	-3226068	-52379	614	1982/07/05	138.00	**VWD842**	-3313574	-52430	991	1985/03/13	18.00
VWD811	-3214459	-78948	485	1982/07/06	64.00	**VWD844**	-3314574	-48939	1012	1985/03/13	20.00
VWD809	-3225590	-55463	686	1982/07/06	163.00	**VWD845**	-3313483	-45859	990	1985/03/13	53.00
VWD810	-3219591	-72746	543	1982/07/06	109.00	**VWD846**	-3311937	-44337	1020	1985/03/13	54.00
VWD781	-3300937	-20458.5	1011	1982/07/13	70.00	**VWD847**	-3316902	-53084	1006	1985/03/13	18.00
VWD823	-3300278	-65220	864	1985/03/11	27.00	**VWD851**	-3321465	-54188	991	1985/03/13	5.00
VWD829	-3310020	-56095	944	1985/03/11	18.00	**VWD852**	-3319630	-56770	1000	1985/03/14	8.00
VWD821	-3299833	-68150	822	1985/03/11	28.00	**VWD853**	-3327103	-71036	762	1985/03/14	14.00
VWD822	-3297308	-62847	920	1985/03/11	28.00	**VWD858**	-3331825	-56868	968	1985/03/14	13.00
VWD827	-3301155	-56704	967	1985/03/11	38.00	**VWD855**	-3323480	-50641	945	1985/03/14	1.00
VWD824	-3304177	-68445	890	1985/03/11	25.00	**VWD856**	-3321434	-54242	991	1985/03/14	16.00
VWD830	-3312975	-56000	968	1985/03/11	13.00	**VWD857**	-3329243	-57739	942	1985/03/14	10.00
VWD825	-3302711	-59864	884	1985/03/11	13.00	**VWD859**	-3345512	-59686	884	1985/03/15	8.00
VWD826	-3295016	-47709	1020	1985/03/11	41.00	**VWD860**	-3343681	-62745	869	1985/03/15	4.00
VWD828	-3299815	-46560	995	1985/03/11	36.00	**VWD861**	-3341663	-65164	838	1985/03/15	3.00
VWD838	-3302717	-49428	975	1985/03/12	21.00	**VWD862**	-3338536	-67430	808	1985/03/15	32.00
VWD831	-3313435	-71687	716	1985/03/12	12.00	**VWD865**	-3336866	-66316	825	1985/03/15	7.00
VWD839	-3312607	-56163	963	1985/03/12	10.00	**VWD863**	-3334813	-62795	884	1985/03/15	7.00
VWD840	-3312973	-55517	968	1985/03/12	9.00	**VWD864**	-3331607	-50122	1006	1985/03/15	8.00
VWD832	-3317702	-69622	695	1985/03/12	8.00	**VWD867**	-3342129	-70725	847	1985/03/15	6.00
VWD833	-3316795	-62040	968	1985/03/12	11.00	**VWD868**	-3344088	-68921	884	1985/03/15	15.00
VWD834	-3308273	-63402	908	1985/03/12	23.00	**VWD869**	-3344284	-70604	884	1985/03/15	15.00
VWD835	-3310199	-60816	939	1985/03/12	12.00	**VWD876**	-3351772	-55482	1021	1985/03/18	13.00
VWD837	-3311296	-52548	978	1985/03/12	29.00	**VWD881**	-3355212	-59631	1073	1985/03/18	9.00
VWD841	-3311452	-46190	1010	1985/03/12	54.00	**VWD872**	-3352111	-49066	1055	1985/03/18	26.00
VWD848	-3316110	-54858	990	1985/03/13	16.00	**VWD871**	-3347778	-51118	1006	1985/03/18	19.00
VWD850	-3319826	-58860	930	1985/03/13	5.00	**VWD873**	-3354514	-49296	1052	1985/03/18	36.00
VWD849	-3317802	-60319	947	1985/03/13	7.00	**VWD875**	-3353401	-54913	1052	1985/03/18	14.00
VWD843	-3311819	-52572	989	1985/03/13	19.00	**VWD877**	-3351521	-54548	1036	1985/03/18	41.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD878	-3352524	-58017	1052	1985/03/18	5.00	**VWD907**	-3350178	-23414	963	1985/03/21	27.00
VWD879	-3352752	-60261	1082	1985/03/18	7.00	**VWD911**	-3313616	-60744	965	1985/04/01	8.00
VWD880	-3349951	-60490	1052	1985/03/18	16.00	**VWD916**	-3335483	-49301	1036	1985/04/01	15.00
VWD889	-3359876	-50313	1081	1985/03/19	17.00	**VWD912**	-3335506	-54119	960	1985/04/01	7.00
VWD887	-3357148	-58981	1085	1985/03/19	17.00	**VWD913**	-3335498	-52460	991	1985/04/01	4.00
VWD888	-3357333	-58980	1085	1985/03/19	10.00	**VWD914**	-3335898	-52377	983	1985/04/01	2.00
VWD885	-3355856	-59148	1072	1985/03/19	8.00	**VWD918**	-3322183	-49682	1010	1985/04/01	40.00
VWD886	-3356574	-55137	1073	1985/03/19	26.00	**VWD926**	-3329382	-48311	975	1985/04/02	13.00
VWD882	-3355234	-63640	1090	1985/03/19	12.00	**VWD915**	-3335577	-49515	1118	1985/04/02	8.00
VWD883	-3352754	-66060	1113	1985/03/19	10.00	**VWD921**	-3335245	-35437	996	1985/04/02	38.00
VWD884	-3352770	-63548	1097	1985/03/19	17.00	**VWD923**	-3333069	-46421	1020	1985/04/02	27.00
VWD890	-3364933	-63317	1128	1985/03/20	12.00	**VWD937**	-3341042	-52647	1006	1985/04/03	7.00
VWD891	-3360638	-66146	1105	1985/03/20	2.00	**VWD934**	-3335138	-54442	960	1985/04/03	18.00
VWD892	-3363585	-69545	991	1985/03/20	1.00	**VWD933**	-3339212	-56348	998	1985/04/03	6.00
VWD893	-3364162	-68207	994	1985/03/20	9.00	**VWD931**	-3341069	-58105	1013	1985/04/03	10.00
VWD894	-3368832	-66496	953	1985/03/20	3.00	**VWD936**	-3334033	-55090	953	1985/04/03	4.00
VWD895	-3369568	-65931	954	1985/03/20	8.00	**VWD929**	-3337352	-59891	1148	1985/04/03	18.00
VWD896	-3372026	-65063	930	1985/03/20	11.00	**VWD932**	-3339489	-56293	1066	1985/04/03	8.00
VWD898	-3368977	-69911	1058	1985/03/20	9.00	**VWD935**	-3334830	-54310	1066	1985/04/03	15.00
VWD908	-3354626	-29176	980	1985/03/21	27.00	**VWD939**	-3340073	-42378	1020	1985/04/03	61.00
VWD900	-3355762	-37989	1020	1985/03/21	36.00	**VWD938**	-3339888	-42218	1020	1985/04/03	59.00
VWD902	-3348158	-28552	982	1985/03/21	32.00	**VWD930**	-3353581	-59855	1049	1985/04/03	7.00
VWD903	-3349642	-30633	987	1985/03/21	26.00	**VWD940**	-3326028	-41307	997	1985/04/04	32.00
VWD904	-3349157	-28231	977	1985/03/21	33.00	**VWD941**	-3300762	-25131	965	1985/05/07	17.00
VWD905	-3350371	-27103	961	1985/03/21	8.00	**VWD942**	-3300485	-25453	975	1985/05/07	19.00
VWD899	-3352042	-39820	1021	1985/03/21	27.00	**VWD945**	-3295729	-41259	1018	1985/05/09	28.00
VWD901	-3348740	-37867	995	1985/03/21	38.00	**VWD948**	-3305514	-39451	1003	1985/05/09	34.00
VWD909	-3354818	-31767	988	1985/03/21	28.00	**VWD947**	-3299608	-40922	1045	1985/05/09	55.00
VWD910	-3355960	-41675	1039	1985/03/21	56.00	**VWD943**	-3296243	-28042	988	1985/05/09	31.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD944	-3292182	-29664	1006	1985/05/09	27.00	**VWD976**	-3314877	-15445	925	1985/05/13	25.00
VWD946	-3295536	-38278	1025	1985/05/09	34.00	**VWD979**	-3307254	-23238	940	1985/05/13	16.00
VWD962	-3310673	-35248	985	1985/05/10	11.00	**VWD980**	-3306686	-23829	945	1985/05/13	16.00
VWD952	-3295842	-10153	918	1985/05/10	11.00	**VWD1031**	-3325623	-30218	995	1985/05/13	26.00
VWD961	-3305815	-5313.6	885	1985/05/10	1.00	**V1033**	-3328908	-26754	990	1985/05/15	32.00
VWD960	-3310623	-11427	922	1985/05/10	19.00	**VWD501**	-3339273	-21030	956	1985/05/15	42.70
VWD951	-3294368	-13701	927	1985/05/10	12.00	**VWD989**	-3342952	-9307.8	905	1985/05/15	7.00
VWD950	-3296777	-18532	945	1985/05/10	15.00	**VWD990**	-3344061	-10751	910	1985/05/15	15.00
VWD949	-3296044	-22079	965	1985/05/10	18.00	**VWD991**	-3344063	-12516	925	1985/05/15	16.00
VWD955	-3293994	-8704.3	918	1985/05/10	11.00	**VWD988**	-3330202	-7390.6	915	1985/05/15	8.00
VWD954	-3294731	-5480.1	898	1985/05/10	10.00	**VWD987**	-3334268	-9475.7	915	1985/05/15	7.00
VWD953	-3297133	-6123.5	900	1985/05/10	10.00	**VWD986**	-3332431	-17670	940	1985/05/15	27.00
VWD956	-3299542	-14822	945	1985/05/10	21.00	**VWD984**	-3322634	-13987	936	1985/05/15	20.00
VWD957	-3311739	-17542	945	1985/05/10	37.00	**VWD982**	-3322093	-22027	950	1985/05/15	39.00
VWD959	-3309888	-14647	915	1985/05/10	25.00	**VWD992**	-3344447	-21822	966	1985/05/15	59.00
VWD958	-3330542	-15271	921	1985/05/10	31.00	**VWD983**	-3323017	-22240	953	1985/05/15	30.00
VWD967	-3318434	-35706	974	1985/05/11	17.00	**VWD985**	-3330156	-19896	955	1985/05/15	23.00
VWD966	-3312336	-35404	975	1985/05/11	30.00	**VWD996**	-3344116	-36265	996	1985/05/16	54.00
VWD968	-3314916	-33304	960	1985/05/11	16.00	**VWD997**	-3335603	-31636	993	1985/05/16	31.00
VWD964	-3306590	-28660	965	1985/05/11	33.00	**VWD995**	-3345620	-43480	1035	1985/05/16	59.00
VWD963	-3309212	-30665	960	1985/05/11	31.00	**VWD994**	-3345067	-43642	1030	1985/05/16	61.00
VWD965	-3312336	-35403	972	1985/05/11	44.00	**VWD998**	-3335972	-31528	1000	1985/05/16	28.00
VWD969	-3305277	-19967	935	1985/05/11	17.00	**VWD1010**	-3364360	-39961	1010	1985/05/17	18.00
VWD978	-3317333	-9490.3	915	1985/05/13	18.00	**VWD1001**	-3363360	-44210	1062	1985/05/17	23.00
VWD970	-3311744	-20278	930	1985/05/13	26.00	**VWD1002**	-3365585	-45963	1082	1985/05/17	14.00
VWD977	-3313766	-13999	935	1985/05/13	16.00	**VWD1003**	-3368171	-45792	1070	1985/05/17	14.00
VWD972	-3315247	-15927	925	1985/05/13	21.00	**VWD1004**	-3371776	-46337	1060	1985/05/17	10.00
VWD974	-3315247	-16088	925	1985/05/13	26.00	**VWD1009**	-3367592	-39709	990	1985/05/17	29.00
VWD973	-3315248	-16571	925	1985/05/13	22.00	**VWD1006**	-3370753	-44740	1050	1985/05/17	2.00

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VWD1008	-3369811	-40048	970	1985/05/17	12.00	**VMON9**	-3335289	-40833	1010.4	1985/09/01	96.40
VWD1007	-3371840	-39054	960	1985/05/17	8.00	**VMON10**	-3335079	-40698	1008.3	1985/09/01	52.13
VWD999	-3355777	-42264	1040	1985/05/17	68.00	**VMON12**	-3334608	-41120	1014	1985/09/01	56.90
VWD1028	-3322317	-36658	978	1985/05/18	18.00	**VMON17**	-3334845	-40490	1008.4	1985/10/01	52.51
VN1029	-3325070	-30701	994	1985/05/18	26.00	**VMON13**	-3335476	-42105	1013.4	1985/10/01	56.33
VWD1014	-3365335	-26585	920	1985/05/18	8.00	**VMON14**	-3336032	-41264	1013.7	1985/10/01	56.45
VWD1013	-3365896	-28986	938	1985/05/18	17.00	**VMON15**	-3335690	-40902	1014.4	1985/10/01	57.19
VWD1027	-3354802	-25489	975	1985/05/18	20.00	**VMON16**	-3335279	-40629	1010.2	1985/10/01	123.16
VWD1017	-3353511	-26614	965	1985/05/18	15.00	**VPBH12**	-3333840	-42264	1008.7	1985/10/15	49.60
VWD1011	-3359162	-19786	950	1985/05/18	17.00	**VGWB1**	-3335773	-42188	1015.1	1985/10/15	58.10
VWD1026	-3356429	-23615	950	1985/05/18	19.00	**VGWB4**	-3334564	-41674	1010	1985/10/15	52.70
VWD1015	-3361336	-28037	958	1985/05/18	34.00	**VGWB7**	-3334967	-41934	1011.2	1985/10/15	54.50
VWD1032	-3324137	-27328	980	1985/05/20	25.00	**VGWB8**	-3334810	-40729	1007.9	1985/10/15	52.91
VWD1030	-3325437	-29897	997	1985/05/20	26.00	**VGWB9**	-3335826	-41772	1013	1985/10/15	58.60
VWD1020	-3368688	-36023	958	1985/05/20	7.00	**VPBH16**	-3335832	-41788	1013	1985/10/15	59.00
VWD1021	-3367386	-33305	975	1985/05/20	32.00	**VPBH10**	-3335406	-42371	1016.9	1985/10/15	59.85
VWD1023	-3359997	-33808	1009	1985/05/20	52.00	**VPBH8**	-3334219	-41404	1008.1	1985/10/15	54.85
VWD1018	-3369242	-35861	950	1985/05/20	13.00	**VPBH9**	-3333692	-41513	1011.1	1985/10/15	56.19
VWD1019	-3372575	-37931	940	1985/05/20	5.00	**VPBH14**	-3334711	-41071	1015.5	1985/10/15	53.80
VWD1024	-3368565	-36077	960	1985/05/20	8.00	**VPBH17**	-3335820	-41381	1012.9	1985/10/15	92.45
VMON1	-3334581	-41473	1010	1985/09/01	52.85	**VGWB5**	-3334980	-41941	1011.2	1985/11/01	54.49
VMON2	-3334793	-41608	1011	1985/09/01	54.05	**VPBH22**	-3335026	-43890	1020	1985/11/01	43.95
VMON3	-3335003	-41745	1011	1985/09/01	54.40	**VPBH21**	-3332725	-43951	1011.6	1985/11/01	44.89
VMON6	-3335718	-41476	1012	1985/09/01	55.40	**VPBH6**	-3334192	-40404	1007	1985/11/01	57.30
VMON11	-3334771	-40869	1010.4	1985/09/01	53.55	**VMON18**	-3334500	-40870	1013	1985/12/01	68.12
VMON4	-3335214	-41878	1011.7	1985/09/01	54.92	**VMON21**	-3335178	-39723	1009	1985/12/01	51.67
VMON5	-3335555	-41727	1012.8	1985/09/01	99.72	**VMON22**	-3334918	-39152	1009	1985/12/01	52.36
VMON7	-3335712	-41101	1014.5	1985/09/01	93.55	**VMON20**	-3334185	-39942	1010	1985/12/01	52.98
VMON8	-3335499	-40968	1013	1985/09/01	99.65	**VMON19**	-3334296	-41340	1008	1985/12/01	143.07

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VFW4	-3333527	-46490	1020	1985/12/15	35.05	**VFW32**	-3333033	-46002	1016	1997/12/01	32.66
VFW2	-3332434	-46934	1020	1985/12/15	35.64	**VGWB1**	-3335773	-42188	1015.1	1997/12/01	57.78
VFW1	-3332185	-46796	1019	1985/12/15	37.19	**VGWB5**	-3334980	-41941	1011.2	1997/12/01	54.08
VFW3	-3333040	-46526	1020	1985/12/15	38.39	**VGWB4**	-3334564	-41674	1010	1997/12/01	52.27
VGWB6	-3335397	-41854	1013.6	1985/12/15	83.14	**VGWB6**	-3335397	-41854	1013.6	1997/12/01	56.29
VGWB7	-3334967	-41934	1011	1997/02/01	57.03	**VGWB8**	-3334810	-40729	1007.9	1997/12/01	50.56
VPBH22	-3335026	-43890	1020	1997/06/01	44.35	**VPBH16**	-3335832	-41788	1013	1997/12/01	58.35
VMON3	-3335003	-41745	1011	1997/06/01	54.81	**VPBH17**	-3335820	-41381	1012.9	1997/12/01	67.74
VMON6	-3335718	-41476	1012	1997/06/01	56.01	**VPBH21**	-3332725	-43951	1011.6	1997/12/01	35.11
VMON7	-3335712	-41101	1015	1997/06/01	58.79	**VMON1**	-3334581	-41473	1010	1997/12/01	52.78
VMON14	-3336032	-41264	1014	1997/06/01	57.21	**VMON11**	-3334771	-40869	1010.4	1997/12/01	52.45
VMON12	-3334608	-41120	1014	1997/06/01	57.10	**VMON17**	-3334845	-40490	1008.4	1997/12/01	51.72
VMON9	-3335289	-40833	1010	1997/11/01	50.71	**VMON4**	-3335214	-41878	1011.7	1997/12/01	54.98
VFW23	-3332277	-51256	1009	1997/12/01	7.17	**VMON5**	-3335555	-41727	1012.8	1997/12/01	71.76
VFW24	-3336097	-50632	1010	1997/12/01	1.77	**VMON8**	-3335499	-40968	1013	1997/12/01	63.39
VFW28	-3331565	-49635	994.8	1997/12/01	2.28	**VMON10**	-3335079	-40698	1008.3	1997/12/01	51.74
VFW29	-3331560	-51490	992.8	1997/12/01	1.01	**VMON15**	-3335690	-40902	1014.4	1997/12/01	57.15
VFW14	-3334973	-48398	1033	1997/12/01	33.65	**VMON16**	-3335279	-40629	1010.2	1997/12/01	53.04
VGARING1	-3333578	-49599	995	1997/12/01	3.36	**VMON19**	-3334296	-41340	1008.3	1997/12/01	52.54
VFW7	-3333948	-46291	1018	1997/12/01	32.23	**V519**	-3333285	-46291	1020	1997/12/01	34.19
VFW5	-3331939	-46267	1017	1997/12/01	29.24	**VPBH22**	-3335026	-43890	1020	2008/05/27	44.35
VFW12	-3331559	-46121	1016	1997/12/01	26.79	**VMON8**	-3335499	-40968	1013	2008/08/15	56.71
VFW4	-3333527	-46490	1020	1997/12/01	30.48	**VFW23**	-3332277	-51256	1009	2008/09/15	8.60
VFW1	-3332185	-46796	1019	1997/12/01	31.51	**VFW24**	-3336097	-50632	1010	2008/09/15	1.96
VFW3	-3333040	-46526	1020	1997/12/01	36.32	**VFW28**	-3331565	-49635	994.8	2008/09/15	3.67
VFW31	-3333205	-45961	1017	1997/12/01	33.52	**VFW29**	-3331560	-51490	992.8	2008/09/15	1.91
VFW34	-3333542	-45829	1018	1997/12/01	36.08	**VFW14**	-3334973	-48398	1033	2008/09/15	35.07
VFW17	-3333233	-46262	1019	1997/12/01	33.53	**VGARING1**	-3333578	-49599	995	2008/09/15	5.60
VFW19	-3333340	-46072	1019	1997/12/01	34.53	**VFW7**	-3333948	-46291	1018	2008/09/15	33.70

Table C-1 cont: Coordinates and water levels of boreholes used in drafting water level maps (data: Necsa, 2011d).

Borehole name	Y	X	Z	Date measured	Water level (m)	Borehole name	Y	X	Z	Date measured	Water level (m)
VFW5	-3331939	-46267	1017	2008/09/15	31.21	**VGWB4**	-3334564	-41674	1010	2008/12/15	51.98
VFW12	-3331559	-46121	1016	2008/09/15	29.80	**VGWB6**	-3335397	-41854	1013.6	2008/12/15	55.15
VFW4	-3333527	-46490	1020	2008/09/15	33.92	**VGWB8**	-3334810	-40729	1007.9	2008/12/15	50.73
VFW1	-3332185	-46796	1019	2008/09/15	33.19	**VPBH16**	-3335832	-41788	1013	2008/12/15	58.48
VFW3	-3333040	-46526	1020	2008/09/15	37.50	**VPBH17**	-3335820	-41381	1012.9	2008/12/15	58.54
VFW31	-3333205	-45961	1017	2008/09/15	34.93	**VPBH21**	-3332725	-43951	1011.6	2008/12/15	37.56
VFW34	-3333542	-45829	1018	2008/09/15	37.00	**VMON1**	-3334581	-41473	1010	2008/12/15	52.72
VFW17	-3333233	-46262	1019	2008/09/15	34.87	**VMON11**	-3334771	-40869	1010.4	2008/12/15	53.38
VFW19	-3333340	-46072	1019	2008/09/15	35.33	**VMON17**	-3334845	-40490	1008.4	2008/12/15	51.81
VFW32	-3333033	-46002	1016	2008/09/15	34.14	**VMON4**	-3335214	-41878	1011.7	2008/12/15	55.06
VGWB3	-3334818	-40717	1008	2008/10/28	49.80	**VMON5**	-3335555	-41727	1012.8	2008/12/15	61.90
VMON2	-3334793	-41608	1011	2008/10/28	54.10	**VMON9**	-3335289	-40833	1010.4	2008/12/15	35.05
VMON3	-3335003	-41745	1011	2008/10/28	54.31	**VMON10**	-3335079	-40698	1008.3	2008/12/15	51.81
VMON14	-3336032	-41264	1013.7	2008/10/28	56.56	**VMON15**	-3335690	-40902	1014.4	2008/12/15	57.33
VMON12	-3334608	-41120	1014	2008/10/28	56.50	**VMON16**	-3335279	-40629	1010.2	2008/12/15	53.20
VGWB1	-3335773	-42188	1015.1	2008/12/15	57.65	**VMON19**	-3334296	-41340	1008.3	2008/12/15	50.77
VGWB5	-3334980	-41941	1011.2	2008/12/15	53.80	**V519**	-3333285	-46291	1020	2008/12/15	35.40

Table C-2: Chloride concentrations ($mg.l^{-1}$) of 27 boreholes used for calculating the recharge number for Vaalputs (data: Necsa, 2011d).

Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl
11A2	1997/06/01	1410	**13A2**	1991/04/25	1305	**13B1**	2000/11/15	560	**13C5**	2004/05/24	2790
11A2	1997/11/01	1373	**13A2**	1997/11/01	1077	**13B1**	2001/05/15	550	**13C5**	2005/05/11	3130
11A2	1998/05/01	1370	**13A2**	1998/05/01	1107	**13B1**	2001/11/13	532	**13C5**	2005/10/26	2800
11A2	2001/11/13	1156	**13A2**	1998/11/01	1200	**13B1**	2002/05/28	582	**13C5**	2006/07/03	3100
11A2	2002/11/05	1275	**13A2**	1999/05/01	1080	**13B1**	2002/11/05	593	**13C5**	2006/11/22	3000
12C1	1997/06/01	250	**13A2**	1999/11/01	1060	**13B1**	2003/05/14	521	**13C5**	2007/05/10	2791
12C1	1997/11/01	227	**13A2**	2000/05/16	1060	**13B1**	2003/11/05	550	**13C5**	2007/11/06	3007
12C1	1998/05/01	222	**13A2**	2000/11/15	1050	**13B1**	2004/05/24	560	**13C5**	2008/05/28	4003
12C1	1998/11/01	270	**13A2**	2001/05/15	1100	**13B1**	2004/11/09	541	**13C7**	1996/11/01	1160
12C1	1999/05/01	200	**13A2**	2001/11/13	1134	**13B1**	2005/05/11	570	**13C7**	1997/05/01	1160
12C1	1999/11/01	240	**13A2**	2002/05/27	1076	**13B1**	2005/10/26	540	**13C7**	1997/06/01	1500
12C1	2000/05/16	245	**13A2**	2002/11/05	1059	**13B1**	2006/07/03	560	**13C7**	1997/11/01	973
12C1	2000/11/15	250	**13A2**	2003/05/14	935	**13B1**	2006/11/22	562	**13C7**	1998/05/01	1385
12C1	2001/05/14	240	**13A2**	2003/11/05	1077	**13B1**	2007/07/04	651	**13C7**	1998/11/01	1520
12C1	2001/11/13	240	**13A2**	2004/05/24	1042	**13B1**	2007/11/06	588	**13C7**	1999/05/01	1486
12C1	2002/05/28	250	**13A2**	2004/11/09	876	**13B1**	2008/05/28	586	**13C7**	1999/11/01	1000
12C1	2002/11/05	238	**13A2**	2005/05/11	1075	**13C5**	1996/11/01	3070	**13C7**	2000/05/16	1500
12C1	2003/05/14	247	**13A2**	2005/10/26	1010	**13C5**	1997/05/01	3070	**13C7**	2000/11/15	1383
12C1	2003/11/05	231	**13A2**	2006/07/03	1060	**13C5**	1997/06/01	3500	**13C7**	2001/05/14	1500
12C1	2004/05/24	260	**13A2**	2006/11/22	750	**13C5**	1997/11/01	2141	**13C7**	2001/11/13	1388
12C1	2004/11/09	245	**13A2**	2007/07/04	1004	**13C5**	1998/05/01	3064	**13C7**	2002/05/28	1646
12C1	2005/05/11	252	**13A2**	2007/11/06	1048	**13C5**	1998/11/01	3500	**13C7**	2002/11/05	1284
12C1	2005/10/26	240	**13A2**	2008/05/28	1046	**13C5**	1999/05/01	2727	**13C7**	2003/05/14	1274
12C1	2006/07/03	267	**13B1**	1986/07/01	612	**13C5**	1999/11/01	3200	**13C7**	2003/11/05	1290
12C1	2006/11/22	250	**13B1**	1986/07/17	612	**13C5**	2000/05/16	4120	**13C7**	2004/05/24	1430
12C1	2007/05/10	255	**13B1**	1996/11/01	580	**13C5**	2000/11/15	3800	**13C7**	2004/11/09	1490
12C1	2007/11/06	258	**13B1**	1997/06/01	550	**13C5**	2001/05/14	3900	**13C7**	2005/10/26	1400
12C1	2008/05/28	250	**13B1**	1999/05/01	530	**13C5**	2001/11/13	3569	**13C7**	2007/05/10	1378
13A2	1986/07/01	1313	**13B1**	2000/05/16	569	**13C5**	2003/11/05	3060	**13C7**	2007/11/06	1336

Table C-2 cont: Chloride concentrations of 27 boreholes used for calculating the recharge number for Vaalputs (data: Necsa, 2011d).

Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl
13C7	2008/05/28	1415	**14C5**	1996/11/01	1300	**15A2**	1999/11/01	1220	**16A2**	2000/05/20	1320
14A2	1986/07/01	1360	**14C5**	1997/05/01	1300	**15A2**	2000/05/16	1290	**16A2**	2001/05/15	1300
14A2	1986/07/16	1360	**14C5**	1997/06/01	1630	**15A2**	2000/05/20	1290	**16A2**	2001/11/13	1339
14A2	1996/11/01	1090	**14C5**	1997/11/01	1114	**15A2**	2000/11/15	1270	**16A2**	2002/05/27	1265
14A2	1997/05/01	1090	**14C5**	1998/05/01	1540	**15A2**	2001/05/15	1400	**16A2**	2002/11/05	1236
14A2	1997/06/01	1100	**14C5**	1998/11/01	1600	**15A2**	2001/11/13	1364	**16A2**	2003/05/14	1154
14A2	1997/11/01	1096	**14C5**	1999/05/01	1800	**15A2**	2002/05/27	1238	**16C3**	1996/11/01	1160
14A2	1998/05/01	1113	**14C5**	1999/11/01	1800	**15A2**	2002/11/05	1215	**16C3**	1997/05/01	1160
14A2	1998/11/01	1030	**14C5**	2000/05/16	1970	**15A2**	2003/05/14	1151	**16C3**	1997/06/01	1390
14A2	1999/05/01	1100	**14C5**	2000/11/15	1944	**15A2**	2003/11/05	1240	**16C3**	1997/11/01	909
14A2	1999/11/01	1070	**14C5**	2001/05/14	1900	**15A2**	2004/05/24	1280	**16C3**	1998/05/01	1087
14A2	2000/05/20	1085	**14C5**	2001/11/13	1872	**15A2**	2004/11/09	1283	**16C3**	1998/11/01	1260
14A2	2000/11/15	1060	**14C5**	2002/11/05	1735	**15A2**	2005/05/11	1268	**16C3**	1999/05/01	1145
14A2	2001/05/15	1100	**14C5**	2003/05/14	1613	**15A2**	2005/10/26	1260	**16C3**	1999/11/01	1200
14A2	2001/11/13	1130	**14C5**	2004/05/24	1720	**15A2**	2006/07/03	1255	**16C3**	2000/05/16	1200
14A2	2002/05/27	986	**14C5**	2004/11/09	1620	**15A2**	2006/11/22	921	**16C3**	2000/11/15	1175
14A2	2002/11/05	1045	**14C5**	2005/10/26	1620	**15A2**	2007/07/04	1228	**16C3**	2001/05/14	1160
14A2	2003/05/14	904	**14C5**	2006/07/03	1870	**15A2**	2007/11/06	1271	**16C3**	2001/11/13	1225
14A2	2003/11/05	1050	**14C5**	2006/11/22	1805	**15A2**	2008/05/28	1273	**16C3**	2002/05/28	1372
14A2	2004/05/24	1060	**14C5**	2007/05/10	1771	**15A2**	2008/05/28	1273	**16C3**	2002/11/05	1220
14A2	2004/11/09	1060	**14C5**	2007/11/06	1697	**16A2**	1986/07/01	1310	**16C3**	2003/05/14	1125
14A2	2005/05/11	1070	**14C5**	2008/05/28	1719	**16A2**	1996/11/01	1270	**16C3**	2004/05/24	1210
14A2	2005/10/26	1070	**15A2**	1986/07/01	1430	**16A2**	1997/05/01	1270	**16C3**	2004/11/09	1308
14A2	2006/07/03	1080	**15A2**	1986/07/16	1430	**16A2**	1997/06/01	1370	**16C3**	2005/05/11	1300
14A2	2006/11/22	775	**15A2**	1996/11/01	1260	**16A2**	1997/11/01	1329	**16C3**	2005/10/26	1420
14A2	2007/07/04	1086	**15A2**	1997/11/01	1335	**16A2**	1998/05/01	1200	**16C3**	2006/07/03	1430
14A2	2007/11/06	1117	**15A2**	1998/05/01	1360	**16A2**	1998/11/01	1270	**16C3**	2006/11/22	1322
14A2	2008/05/28	1068	**15A2**	1998/11/01	1260	**16A2**	1999/05/01	1328	**16C3**	2007/07/04	1320
14A2	2008/05/28	1068	**15A2**	1999/05/01	1270	**16A2**	1999/11/01	1100	**16C3**	2007/11/06	1237

Table C-2 cont: Chloride concentrations of 27 boreholes used for calculating the recharge number for Vaalputs (data: Necsa, 2011d).

Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl
16C3	2008/05/28	1397	**3C2**	1999/11/01	715	**4C1**	2004/11/09	1444	**5A2**	2008/05/28	1478
2A2	1985/11/06	1674	**3C2**	2000/05/16	830	**4C1**	2005/10/26	1400	**5C2**	1996/11/01	1310
2A2	1986/07/01	1688	**3C2**	2000/11/15	742	**4C1**	2006/07/03	1509	**5C2**	1997/05/01	1310
2A2	1996/11/01	1660	**3C2**	2001/05/14	700	**4C1**	2006/11/22	1398	**5C2**	1997/06/01	1450
2A2	1997/06/01	1800	**3C2**	2001/11/13	776	**4C1**	2007/07/04	1446	**5C2**	1998/05/01	1505
2A2	1997/11/01	1661	**3C2**	2004/05/24	853	**4C1**	2007/11/06	1319	**5C2**	1998/11/01	2000
2A2	1998/05/01	1600	**3C2**	2004/11/09	950	**4C1**	2008/05/28	1457	**5C2**	1999/05/01	1500
2A2	2000/05/16	1670	**3C2**	2005/05/11	871	**5A2**	1996/11/01	1670	**5C2**	1999/11/01	1400
2A2	2000/11/15	1656	**3C2**	2005/10/26	650	**5A2**	1997/06/01	1770	**5C2**	2000/05/16	1450
2A2	2001/05/15	1640	**3C2**	2006/07/03	724	**5A2**	1997/11/01	1641	**5C2**	2000/11/15	1530
2A2	2001/11/13	1740	**3C2**	2007/07/04	886	**5A2**	1998/05/01	1708	**5C2**	2001/05/14	1520
2A2	2002/05/27	1616	**3C2**	2007/11/06	806	**5A2**	1998/11/01	1700	**5C2**	2001/11/13	2170
2A2	2002/11/05	1539	**3C2**	2008/05/28	838	**5A2**	1999/05/01	1500	**5C2**	2002/05/28	1649
2A2	2003/05/14	1493	**4C1**	1996/11/01	1350	**5A2**	1999/11/01	1700	**5C2**	2002/11/05	1431
2A2	2003/11/05	1600	**4C1**	1997/05/01	1350	**5A2**	2000/05/16	1640	**5C2**	2003/05/14	1291
2A2	2004/05/24	1600	**4C1**	1997/06/01	1450	**5A2**	2000/11/15	1636	**5C2**	2003/11/05	1380
2A2	2004/11/09	1588	**4C1**	1997/11/01	1142	**5A2**	2001/05/15	1600	**5C2**	2004/05/24	1450
2A2	2005/05/11	1610	**4C1**	1998/05/01	1560	**5A2**	2001/11/13	1661	**5C2**	2005/05/11	1517
2A2	2005/10/26	1600	**4C1**	1998/11/01	1500	**5A2**	2002/11/05	1477	**5C2**	2005/10/26	1450
2A2	2006/07/03	1590	**4C1**	1999/11/01	1500	**5A2**	2003/05/14	1430	**5C2**	2006/07/03	1600
2A2	2007/11/06	1575	**4C1**	2000/05/16	1500	**5A2**	2003/11/05	1480	**5C2**	2006/11/22	1420
3A2	1986/07/01	1638	**4C1**	2000/11/15	1450	**5A2**	2004/05/24	1540	**5C2**	2007/07/04	1590
3A2	1986/07/17	1902	**4C1**	2001/05/14	1440	**5A2**	2004/11/09	1600	**5C2**	2007/11/06	1616
3C2	1996/11/01	900	**4C1**	2001/11/13	1423	**5A2**	2005/05/11	1550	**5C2**	2008/05/28	1823
3C2	1997/05/01	900	**4C1**	2002/05/28	1558	**5A2**	2005/10/26	1500	**5C4**	1996/11/01	1520
3C2	1997/06/01	890	**4C1**	2002/11/05	1382	**5A2**	2006/07/03	1670	**5C4**	1997/05/01	1520
3C2	1997/11/01	687	**4C1**	2003/05/14	1293	**5A2**	2006/11/22	1531	**5C4**	1997/06/01	2730
3C2	1998/11/01	800	**4C1**	2003/11/05	1380	**5A2**	2007/07/04	1507	**5C4**	1997/11/01	2068
3C2	1999/05/01	810	**4C1**	2004/05/24	1440	**5A2**	2007/11/06	1485	**5C4**	1998/05/01	2165

Table C-2 cont: Chloride concentrations of 27 boreholes used for calculating the recharge number for Vaalputs (data: Necsa, 2011d).

Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl
5C4	1999/05/01	2070	**7A2**	2005/05/11	1914	**9B1**	1998/05/01	1776	**FW35**	1987/04/29	528
5C4	1999/11/01	2550	**7A2**	2005/10/26	1600	**9B1**	1998/11/01	1400	**FW35**	1991/04/23	500
5C4	2000/05/16	2700	**7A2**	2006/07/03	1700	**9B1**	1999/05/01	1700	**FW35**	2003/05/27	470
5C4	2000/11/15	2240	**7A2**	2006/11/22	1726	**9B1**	1999/11/01	1550	**FW35**	2003/11/05	484
5C4	2001/05/14	2020	**9A2**	1996/11/01	1320	**9B1**	2000/05/16	1510	**FW35**	2004/05/24	487
5C4	2001/11/13	2717	**9A2**	1997/06/01	1410	**9B1**	2000/11/15	1441	**FW35**	2004/11/09	430
5C4	2002/05/28	2694	**9A2**	1997/11/01	1311	**9B1**	2001/05/14	1500	**FW35**	2005/05/11	480
5C4	2002/11/05	2124	**9A2**	1999/05/01	1360	**9B1**	2001/11/13	2010	**FW35**	2005/10/26	460
5C4	2003/05/14	2634	**9A2**	2000/05/16	1360	**9B1**	2002/05/28	1666	**FW35**	2006/07/03	511
5C4	2004/05/24	2700	**9A2**	2000/11/15	1370	**9B1**	2003/05/14	1331	**FW35**	2006/11/22	484
5C4	2005/05/11	2540	**9A2**	2001/05/15	1360	**9B1**	2003/11/05	1440	**FW35**	2007/07/04	475
5C4	2005/10/26	2160	**9A2**	2001/11/13	1429	**9B1**	2004/05/24	1490	**FW35**	2007/11/06	469
5C4	2006/07/03	3000	**9A2**	2002/05/27	1335	**9B1**	2005/05/11	1600	**FW35**	2008/05/28	450
5C4	2006/11/22	2580	**9A2**	2002/11/05	1294	**9B1**	2005/10/26	1500	**GWB3**	1986/07/01	1592
5C4	2007/07/04	2719	**9A2**	2003/05/14	1206	**9B1**	2006/11/22	1686	**GWB3**	1986/07/17	1592
5C4	2007/11/06	2531	**9A2**	2003/11/05	1275	**9B1**	2007/07/04	1460	**GWB3**	1986/07/17	1592
5C4	2008/05/28	3051	**9A2**	2004/05/24	1350	**9B1**	2007/11/06	1375	**GWB3**	1991/04/23	1660
7A2	1991/04/24	1400	**9A2**	2004/11/09	1383	**9B1**	2008/05/28	1475	**GWB3**	1998/11/01	1730
7A2	1999/05/01	1480	**9A2**	2005/05/11	1345	**EM8**	1999/12/31	502	**GWB3**	1999/05/01	1650
7A2	2000/05/16	1550	**9A2**	2005/10/26	1310	**EM8**	2003/11/05	530	**GWB3**	2001/11/13	1559
7A2	2000/11/15	1500	**9A2**	2006/07/03	1334	**EM8**	2004/05/24	546	**GWB3**	2002/12/31	1464
7A2	2001/05/15	1540	**9A2**	2006/11/22	1400	**EM8**	2005/05/11	560	**GWB3**	2003/05/14	1413
7A2	2001/11/13	1600	**9A2**	2007/07/04	1319	**EM8**	2005/10/26	535	**GWB3**	2003/11/05	1420
7A2	2002/05/27	1500	**9A2**	2007/11/06	1338	**EM8**	2006/07/03	610	**GWB3**	2004/05/24	1520
7A2	2002/11/05	1460	**9A2**	2008/05/28	1333	**EM8**	2006/11/22	537	**GWB3**	2004/11/09	1517
7A2	2003/05/14	1832	**9A2**	2008/05/28	1333	**EM8**	2007/07/04	562	**GWB3**	2005/05/11	1540
7A2	2003/11/05	1600	**9B1**	1996/11/01	1650	**EM8**	2007/11/06	541	**GWB3**	2005/10/26	1420
7A2	2004/05/24	1650	**9B1**	1997/06/01	1460	**EM8**	2008/05/28	528	**GWB3**	2006/07/03	1660
7A2	2004/11/09	1800	**9B1**	1997/11/01	1170	**FW35**	1986/07/01	528	**GWB3**	2006/11/22	1503

Table C-2 cont: Chloride concentrations of 27 boreholes used for calculating the recharge number for Vaalputs (data: Necsa, 2011d).

Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl	Borehole	Date	Cl
GWB3	2007/07/04	1565	**MON7**	2002/11/05	1256	**MON9**	2003/11/05	4300	**PBAKKI**	2000/11/15	1421
GWB3	2007/11/06	1499	**MON7**	2003/05/14	1181	**MON9**	2004/05/24	3680	**PBAKKI**	2001/05/14	1400
GWB3	2008/05/28	1460	**MON7**	2004/11/09	1330	**MON9**	2004/11/09	4280	**PBAKKI**	2001/11/13	1395
MON7	1996/11/01	1260	**MON9**	1987/08/01	3600	**MON9**	2005/05/11	4840	**PBAKKI**	2002/05/28	1623
MON7	1997/05/01	1260	**MON9**	1997/11/01	2039	**MON9**	2005/10/26	4600	**PBAKKI**	2002/11/05	1407
MON7	1997/06/01	1410	**MON9**	1998/05/01	3108	**MON9**	2006/07/03	4224	**PBAKKI**	2003/05/14	1305
MON7	1997/11/01	1277	**MON9**	1998/11/01	3200	**MON9**	2007/07/04	4340	**PBAKKI**	2003/11/05	1330
MON7	1998/05/01	1357	**MON9**	1999/05/01	3250	**MON9**	2007/11/06	4216	**PBAKKI**	2004/05/24	1400
MON7	1998/11/01	1300	**MON9**	1999/11/01	2800	**MON9**	2008/05/28	4679	**PBAKKI**	2005/05/11	1400
MON7	1999/05/01	1330	**MON9**	2000/05/16	3300	**PBAKKI**	1997/06/01	1510	**PBAKKI**	2005/10/26	1300
MON7	1999/11/01	1300	**MON9**	2000/11/15	3610	**PBAKKI**	1997/11/01	1084	**PBAKKI**	2006/07/03	1385
MON7	2000/05/16	1185	**MON9**	2001/11/13	3790	**PBAKKI**	1998/05/01	1390	**PBAKKI**	2006/11/22	1035
MON7	2000/11/15	1290	**MON9**	2002/05/27	3904	**PBAKKI**	1999/05/01	1500	**PBAKKI**	2007/07/04	1375
MON7	2001/05/15	1300	**MON9**	2002/11/05	4052	**PBAKKI**	1999/11/01	1000	**PBAKKI**	2007/11/06	1430
MON7	2001/11/13	1336	**MON9**	2003/05/14	4245	**PBAKKI**	2000/05/16	1450	**PBAKKI**	2008/05/28	1411
MON7	2002/05/27	1233									

Table C-3: Vaalputs borehole water chemistry results (mg.l^{-1} where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
GWB3	1986/07/01	7.2	425	126	75	900	27	290	1592	323	9.00	4	-	0.3	-
GWB3	1986/07/17	7.2	420	126	78	910	27	-	1592	323	-	4	-	0.31	-
GWB3	1991/04/23	7.2	450	130	89	871	23	-	1660	350	11.00	2	-	0.01	-
GWB3	1998/11/01	8	592	135	98	975	31	-	1730	330	11.00	2.4	-	0.01	0.01
GWB3	1999/05/01	7.1	578	122	95	820	24	-	1650	330	9.90	2.8	-	0.01	0.01
GWB3	2001/11/13	7.9	568	-	100	938	19	-	1559	321	11.00	2.5	-	0.01	-
GWB3	2002/12/31	8.2	550	-	90	900	19	-	1464	333	9.71	3.3	-	0.01	-
GWB3	2003/05/14	8.3	567	112	70	950	24	-	1413	314	10.61	3.4	0.01	0.01	0.01
GWB3	2003/11/05	7.4	558	-	-	915	-	-	1420	327	10.38	2.9	-	-	-
GWB3	2004/05/24	-	-	-	-	929	-	294.2	1520	325	10.61	2.8	-	0.03	-
GWB3	2004/11/09	7.9	573	100	76	1060	25	-	1517	341	9.03	3.1	0.01	52	0.01
GWB3	2005/05/11	7.4	581	146	115	965	24	-	1540	350	10.16	7	-	0.04	0.01
GWB3	2005/10/26	7.5	578	141	112	1054	26	-	1420	341	12.87	3.5	-	-	-
GWB3	2006/07/03	7.3	574	143	105	838	19	-	1660	390	9.48	3	-	-	-
GWB3	2006/11/22	7.4	573	134	99	930	25	-	1503	330	11.51	2.2	-	-	-
GWB3	2007/07/04	7.1	580	134	97	856	42	-	1565	356	10.16	2.5	-	-	-
GWB3	2007/11/06	7.4	577	191	91	1337	20	-	1499	361	-	2.2	-	-	-
GWB3	2008/05/28	7.3	572	117	93	913	61	282	1460	340	2.96	1.2	-	-	-
GWB3	2009/11/04	7.5	565	127	108	951	20	-	1772.2	345.4	-	2.3	-	0.02	0.01
GWB3	2010/04/20	7.5	588	-	-	-	-	-	-	-	2.11	-	-	-	-
GWB3	2011/05/25	7.3	571	133	106	855	25.2	-	1504.3	330.98		2.74	-	0.1	0.1
MON10	1985/11/01	-	500	-	-	-	-	-	-	-	-	-	-	-	-
MON10	1986/07/01	8	225	44	33	470	13	-	802	188	4.70	3	-	0.01	-
MON10	1986/11/01	-	500	-	-	-	-	-	-	-	-	-	-	-	-
MON10	1987/08/01	-	527	-	-	-	-	-	-	-	-	-	-	-	-
MON10	1988/06/01	-	527	-	-	-	-	-	-	-	-	-	-	-	-
MON10	1990/06/01	-	480	-	-	-	-	-	-	-	-	-	-	-	-

Table C-3 cont: Vaalputs borehole water chemistry results (mg.l^{-1} where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON10	1993/01/01	-	526	-	-	-	-	-	-	-	-	-	-	-	-
MON10	1994/07/01	-	471	-	-	-	-	-	-	-	-	-	-	-	-
MON10	1996/11/01	7.5	570	120	110	970	23	-	1670	440	10.00	3.4	-	1.9	0.05
MON10	1997/06/01	8.2	589	190	120	1000	22	-	1770	300	4.90	2.9	-	0.05	0.05
MON10	1997/11/01	7.4	604	121	87	929	27	-	1641	306	5.00	2.7	-	0.5	-
MON10	1998/05/01	7.6	550	132	109	955	22	-	1708	342	6.00	2.6	-	0.2	0.01
MON10	1998/11/01	7.9	591	128	83	958	26.5	-	1700	330	7.30	0.8	-	0.01	0.01
MON10	1999/05/01	7.2	595	124	97	880	22	-	1500	330	8.00	2.5	-	0.01	0.01
MON10	1999/11/01	8.1	599	123	81	1060	22	-	1700	300	9.00	3.5	-	0.01	0.01
MON10	2000/02/01	7.2	590	-	-	-	-	-	-	-	-	-	-	-	-
MON10	2000/05/16	7.7	597	105	80	1080	23	-	1640	345	8.00	2.4	-	0.01	0.01
MON10	2000/11/15	7.3	599	110	91	980	24	-	1636	350	8.80	2.4	-	0.01	0.01
MON10	2001/05/15	7.3	597	128	100	1033	22	-	1600	340	8.60	2.4	-	0.01	0.01
MON10	2001/11/13	8	589	-	95	986	16	-	1661	342	10.00	2.4	-	0.01	-
MON10	2002/05/27	8.3	574	-	115	970	19	-	1578	333	8.13	3.2	-	0.01	0.01
MON10	2002/11/05	8.1	569	-	95	970	22	-	1477	310	9.00	3.1	-	0.01	-
MON10	2003/05/14	7.8	580	104	63	1000	22	-	1430	327	7.90	3.3	0.01	0.01	0.01
MON10	2003/11/05	7.5	575	-	-	1020	-	-	1480	365	8.35	2.9	-	-	-
MON10	2004/05/24	-	-	-	-	941	-	302.9	1540	330	8.35	2.9	-	0.03	-
MON10	2004/11/09	7.8	610	104	70	1330	30	-	1600	356	8.58	3.3	0.01	0.55	0.01
MON10	2005/05/11	7.6	596	127	112	990	21	-	1550	365	7.67	3.6	-	0.01	0.01
MON10	2005/10/26	7	597	140	113	1063	24	-	1500	354	9.71	3.4	-	-	-
MON10	2006/07/03	7.3	585	151	105	1000	19	-	1670	405	11.29	3.3	-	-	-
MON10	2006/11/22	7.4	577	102	93	910	23	-	1531	347	8.35	2.5	-	-	-
MON10	2007/07/04	7.2	577	120	92	846	58	-	1507	366	9.03	2.7	-	-	-
MON10	2007/11/06	7.6	572	173	90	1092	19	-	1485	367	10.84	2.4	-	-	-
MON10	2008/05/28	7.6	576	108	92	1035	57	303	1478	352	-	0.8	-	-	-
MON10	2009/11/04	7.5	569	82	104	980	23	-	1562	346.7	2.84	2.5	-	0.01	0.01

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON10	2010/04/20	7.6	568	-	-	-	-	-	-	-	-	-	-	-	-
MON10	2011/05/25	7.6	563	119	94.7	875	23	-	1512.7	337.87	1.88	3	-	0.1	0.1
MON12	1985/11/01	-	550	-	-	-	-	-	-	-	-	-	-	-	-
MON12	1985/11/06	6.9	470	129	88	1055	23	-	1674	386	-	3	-	0.04	-
MON12	1986/07/01	6.9	550	136	94	1055	23	-	1688	408	10.00	3	-	1.2	-
MON12	1986/11/01	-	550	-	-	-	-	-	-	-	-	-	-	-	-
MON12	1987/08/01	-	553	-	-	-	-	-	-	-	-	-	-	-	-
MON12	1988/06/01	-	557	-	-	-	-	-	-	-	-	-	-	-	-
MON12	1990/06/01	-	550	-	-	-	-	-	-	-	-	-	-	-	-
MON12	1991/04/01	-	510	-	-	-	-	-	-	-	-	-	-	-	-
MON12	1993/01/01	-	555	-	-	-	-	-	-	-	-	-	-	-	-
MON12	1994/07/01	-	464	-	-	-	-	-	-	-	16.00	-	-	-	-
MON12	1996/11/01	7.7	571	100	100	980	39	-	1660	440	10.00	3.4	-	2.5	0.06
MON12	1997/06/01	8.1	583	210	120	1010	25	-	1800	320	6.00	2.7	-	0.05	0.05
MON12	1997/11/01	7.7	606	121	90	920	30	-	1661	324	11.00	3	-	5	-
MON12	1998/05/01	7.9	560	100	88	805	20	-	1600	313	-	3	-	18	0.2
MON12	2000/02/01	7.3	596	-	-	-	-	-	-	-	11.00	-	-	-	-
MON12	2000/05/16	7.8	529	115	84	1070	26	-	1670	325	12.00	3	-	0.01	0.01
MON12	2000/11/15	7.2	600	110	97	960	27	-	1656	362	12.00	2.3	-	0.01	0.01
MON12	2001/05/15	7.3	608	129	100	1030	26	-	1640	380	12.00	2.4	-	0.01	0.01
MON12	2001/11/13	8	603	-	100	981	19	-	1740	356	11.51	2.2	-	0.01	-
MON12	2002/05/27	8.3	591	-	115	960	21	-	1616	339	11.00	3.1	-	0.01	0.05
MON12	2002/11/05	8.1	585	-	100	980	24	-	1539	330	9.93	3.2	-	0.01	-
MON12	2003/05/14	7.8	599	114	66	1000	25	-	1493	337	10.61	3.2	0.01	0.01	0.01
MON12	2003/11/05	7.4	591	-	-	958	-	-	1600	384	9.93	2.8	-	-	-
MON12	2004/05/24	-	-	-	-	973	-	289.9	1600	345	11.29	3.3	-	0.04	-
MON12	2004/11/09	8	596	110	75	1340	35	-	1588	340		2.9	0.01	0.01	0.01

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON12	2005/05/11	7.5	608	143	124	1000	24	-	1610	365	8.80	3.3	-	0.01	0.01
MON12	2005/10/26	7.6	611	153	120	1004	28	-	1600	350	10.61	3.3	-	-	-
MON12	2006/07/03	7.3	607	173	119	1100	21	-	1590	368	10.16	2.9	-	-	-
MON12	2006/11/22	7.4	538	140	105	920	28	-	-	370	10.61	2.4	-	-	-
MON12	2007/07/04	7.2	608	143	110	915	49	-	1634	398	11.96	2.6	-	-	-
MON12	2007/11/06	7.6	606	189	105	1110	23	-	1575	388	11.96	2.2	-	-	-
MON12	2008/11/04	-	-	-	-	-	-	271	-	-	-	-	-	-	-
MON12	2010/04/20	7.6	607	-	-	-	-	-	-	-	-	-	-	-	-
MON12	2011/05/25	7.4	607	139	120	892	27	-	1628.2	364.83	1.90	2.74	-	0.1	0.1
MON14	1996/11/01	7.7	495	94	95	860	20	-	1320	390	3.90	3.6	-	1.6	0.05
MON14	1997/06/01	6.6	496	150	110	880	19	-	1410	280	7.40	3.5	-	0.05	0.05
MON14	1997/11/01	7.6	537	101	78	830	25	-	1311	274	2.00	3.7	-	2	-
MON14	1998/11/01	7.3	522	-	-	-	-	-	-	-	-	-	-	-	-
MON14	1999/05/01	7.2	521	90	70	858	25	-	1360	290	1.50	3	-	0.01	0.01
MON14	2000/02/01	7.4	520	-	-	-	-	-	-	-	-	-	-	-	-
MON14	2000/05/16	7.8	605	86	77	970	20	-	1360	280	0.10	3	-	0.01	0.01
MON14	2000/11/15	7.5	522	75	84	870	21	-	1370	290	0.10	3	-	0.01	0.01
MON14	2001/05/15	7.4	532	90	90	934	22	-	1360	310	0.10	3	-	0.01	0.01
MON14	2001/11/13	8.2	527	-	90	884	14.7	-	1429	308	0.10	3.2	-	0.01	-
MON14	2002/05/27	8.3	515	-	100	880	15.6	-	1335	278	0.02	3.5	-	0.01	0.04
MON14	2002/11/05	8.2	510	-	90	895	18	-	1294	295	0.50	3.5	-	0.01	-
MON14	2003/05/14	8.2	520	92	70	900	19.6	-	1206	280	0.14	3.6	0.01	0.04	0.42
MON14	2003/11/05	7.5	516	-	-	875	-	-	1275	316	0.07	3.2	-	-	-
MON14	2004/05/24	-	-	-	-	877	-	392.8	1350	285	0.11	3.2	-	0.03	-
MON14	2004/11/09	8	531	86	65	1230	30	-	1383	306	0.18	3.4	0.01	0.3	0.01
MON14	2005/05/11	7.6	529	102	105	915	18	-	1345	300	0.11	4	-	0.07	0.08
MON14	2005/10/26	7.5	531	110	104	960	19	-	1310	291	0.45	3.4	-	-	-
MON14	2006/07/03	7.4	532	118	101	900	12	-	1334	318	0.11	3.4	-	-	-

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON14	2006/11/22	7.7	609	100	86	820	21	-	1400	216	1.35	2.6	-	-	-
MON14	2007/07/04	7.4	533	163	78	877	56	-	1319	195	1.76	2.9	-	-	-
MON14	2007/11/06	7.3	527	147	84	1150	12	-	1338	191	0.05	2.6	-	-	-
MON14	2008/05/28	7.8	561	72	89	1073	45	413	1333	199	-	0.8	-	-	-
MON14	2009/11/04	7.9	529	39	94	931	20	-	1333	180.6	0.79	2.8	-	0.01	0.18
MON14	2010/04/20	7.7	534	-	-	-	-	-	-	-	-	-	-	-	-
MON14	2011/05/25	7.7	525	85.8	90.3	821	20.7	-	1381.6	194.59	0.08	3.47	-	0.1	0.16
MON15	1991/04/01	-	500	-	-	-	-	-	-	-	-	-	-	-	-
MON15	1991/04/24	7.4	500	101	84	862	21	-	1400	320	-	3	-	0.03	-
MON15	1998/11/01	7.4	556	-	-	-	-	-	-	-	-	-	-	-	-
MON15	1999/05/01	7.4	558	102	69	-	26	-	1480	300	5.30	2.9	-	0.01	0.01
MON15	2000/02/01	7.5	557	-	-	-	-	-	-	-	-	-	-	-	-
MON15	2000/05/16	7.8	570	96	80	1050	23	-	1550	300	5.00	2.3	-	0.01	0.01
MON15	2000/11/15	7.6	564	120	100	980	24	-	1500	324	5.20	2.3	-	0.01	0.01
MON15	2001/05/15	7.6	574	110	90	1000	24	-	1540	340	5.00	1.9	-	0.01	0.01
MON15	2001/11/13	8.2	572	-	92	965	16.3	-	1600	324	5.00	2.3	-	0.01	-
MON15	2002/05/27	8.3	562	-	110	940	19	-	1500	306	5.87	3.1	-	0.01	0.01
MON15	2002/11/05	8.1	560	-	86	925	21	-	1460	304	6.50	3.2	-	0.01	-
MON15	2003/05/14	7.9	660	136	80	1060	26	-	1832	360	5.64	3.2	0.01	0.01	0.05
MON15	2003/11/05	7.7	611	-	-	980	-	-	1600	335	5.64	2.7	-	-	-
MON15	2004/05/24	-	-	-	-	1039	-	346.6	1650	340	5.64	2.7	-	0.03	-
MON15	2004/11/09	7.9	678	126	84	1460	35	-	1800	390	5.64	3.2	0.01	0.51	0.01
MON15	2005/05/11	7.6	697	175	160	1120	26	-	1914	405	4.29	3	-	0.01	0.04
MON15	2005/10/26	8	620	142	123	1140	24	-	1600	334	5.42	3.4	-	-	-
MON15	2006/07/03	7.4	643	230	150	1208	17	-	1700	370	4.29	2.8	-	-	-
MON15	2006/11/22	7.7	631	147	108	960	32	-	1726	367	4.29	2	-	-	-
MON15	2008/11/04	-	-	-	-	-	-	308	-	-	-	-	-	-	-
MON15	2009/11/04	7.6	686	99	147	1189	28	-	2040	188.3	1.33	1	-	0.01	0.01

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON15	2010/04/20	7.8	686	-	-	-	-	-	-	-	-	-	-	-	-
MON15	2011/05/25	7.7	702	17	13.2	505	28.2	-	1887.4	392.89	0.98	2.61	-	0.1	0.1
MON2	1985/11/01	-	475	-	-	-	-	-	-	-	-	-	-	-	-
MON2	1986/07/01	7.1	450	100	35	-	23	-	1430	323	7.90	3	-	0.05	-
MON2	1986/07/16	7.1	450	100	35	850	23	332	1430	323	-	3	-	0.05	-
MON2	1986/11/01	-	450	-	-	-	-	-	-	-	-	-	-	-	-
MON2	1987/08/01	-	477	-	-	-	-	-	-	-	-	-	-	-	-
MON2	1990/06/01	-	470	-	-	-	-	-	-	-	-	-	-	-	-
MON2	1993/01/01	-	458	-	-	-	-	-	-	-	-	-	-	-	-
MON2	1994/07/01	-	384	-	-	-	-	-	-	-	-	-	-	-	-
MON2	1996/11/01	7.6	477	99	81	850	22	-	1260	340	12.00	3.4	-	0.4	0.05
MON2	1997/11/01	7.9	514	90	66	844	26	-	1335	272	8.30	4	-	0.1	-
MON2	1998/05/01	7.8	471	91	70	830	21	-	1360	280	9.50	4	-	0.06	0.02
MON2	1998/11/01	8.1	502	93	60	860	25	-	1260	280	10.00	3.7	-	0.01	0.01
MON2	1999/05/01	7.3	506	86	60	880	23	-	1270	280	10.00	3.5	-	0.01	0.01
MON2	1999/11/01	8.4	508	91	65	922	20	-	1220	280	9.00	3.3	-	0.01	0.01
MON2	2000/02/01	7.4	496	-	-	-	-	-	-	-	-	-	-	-	-
MON2	2000/05/16	7.9	508	85	65	960	22	-	1290	280	9.60	2.7	-	0.01	0.01
MON2	2000/05/20	7.9	508	85	65	960	22	-	1290	280	9.60	2.7	-	-	-
MON2	2000/11/15	7.6	501	82	70	900	23	-	1270	280	10.00	2.8	-	0.01	0.01
MON2	2001/05/15	7.4	511	86	71	870	21	-	1400	330	11.00	3.1	-	0.01	0.01
MON2	2001/11/13	8.2	508	-	71	885	16	-	1364	277	10.00	3.1	-	0.01	-
MON2	2002/05/27	8.3	496	-	88	870	21	-	1238	266	9.71	3.5	-	0.01	0.01
MON2	2002/11/05	8.5	493	-	69	870	20	-	1215	266	10.00	3.7	-	0.01	-
MON2	2003/05/14	8	504	84	65	890	21	-	1151	274	9.48	3.7	0.01	0.01	0.01
MON2	2003/11/05	7.5	497	-	-	810	-	-	1240	220	9.93	3.1	-	-	-
MON2	2004/05/24	-	-	-	-	865	-	353.6	1280	280	9.48	3.3	-	0.03	-
MON2	2004/11/09	8	511	78	60	1000	22	-	1283	291	9.71	3.5	0.01	0.39	0.01

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON2	2005/05/11	7.6	504	94	90	900	22	-	1268	297	8.58	3.8	-	0.01	0.01
MON2	2005/10/26	8.1	509	104	82	880	24	-	1260	290	9.71	3.7	-	-	-
MON2	2006/07/03	7.4	510	124	82	890	13	-	1255	300	10.61	3.6	-	-	-
MON2	2006/11/22	7.5	508	93	70	770	24	-	921	302	9.71	2.6	-	-	-
MON2	2007/07/04	7.3	509	91	67	962	51	-	1228	310	10.16	3.5	-	-	-
MON2	2007/11/06	7.6	505	102	68	942	12	-	1271	320	12.42	2.7	-	-	-
MON2	2008/05/28	7.5	516	88	69	944	42	339	1273	299	-	1.1	-	-	-
MON2	2008/07/21	-	-	-	-	-	-	290	-	-	-	-	-	-	-
MON2	2009/11/04	7.6	503	45	76	950	22	-	1346.4	297.3	3.14	2.8	-	0.01	0.01
MON2	2010/04/20	7.8	508	-	-	-	-	-	-	-	-	-	-	-	-
MON2	2011/05/25	7.6	504	88.1	67.3	769	23	-	1312.3	307.72	2.15	2.87	-	0.1	0.1
MON3	1986/07/01	7.4	400	92	31	790	22	-	1360	317	0.70	3	-	0.09	-
MON3	1986/07/16	7.4	400	92	31	-	22	314	1360	317	-	3	-	0.09	-
MON3	1987/08/01	-	420	-	-	-	-	-	-	-	-	-	-	-	-
MON3	1988/06/01	-	435	-	-	-	-	-	-	-	-	-	-	-	-
MON3	1990/06/01	-	400	-	-	-	-	-	-	-	-	-	-	-	-
MON3	1993/01/01	-	402	-	-	-	-	-	-	-	-	-	-	-	-
MON3	1994/07/01	-	339	-	-	-	-	-	-	-	-	-	-	-	-
MON3	1996/11/01	7.6	415	79	60	780	19	-	1090	230	0.90	3.2	-	0.6	0.3
MON3	1997/05/01	7.6	415	79	60	780	19	-	1090	230	0.90	3.2	-	0.6	0.3
MON3	1997/06/01	8.4	423	110	69	800	19	-	1100	200	1.00	3.3	-	0.05	0.27
MON3	1997/11/01	7.6	444	70	53	746	22	-	1096	183	0.10	3	-	0.6	-
MON3	1998/05/01	7.7	405	70	56	732	19	-	1113	187	0.05	3	-	0.4	0.3
MON3	1998/11/01	7.4	431	70	50	760	22	-	1030	180	0.10	3	-	0.01	0.02
MON3	1999/05/01	7.4	432	65	45	750	20	-	1100	200	1.00	3	-	0.01	0.26
MON3	1999/11/01	8.3	434	72	55	810	19	-	1070	175	0.05	2.5	-	0.01	0.23
MON3	2000/02/01	7.6	429	-	-	-	-	-	-	-	-	-	-	-	-
MON3	2000/05/20	7.8	436	64	55	850	19.3	-	1085	190	0.05	2.7	-	0.01	0.01

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON3	2000/11/15	7.7	430	54	55	750	19.4	-	1060	182	0.05	2.6	-	0.01	0.01
MON3	2001/05/15	7.5	439	75	60	820	19	-	1100	200	0.30	3	-	0.01	0.49
MON3	2001/11/13	8.1	433	-	58	810	13.3	-	1130	185	0.20	3.1	-	0.01	-
MON3	2002/05/27	8.2	422	-	71	770	18	-	986	176	0.25	3.1	-	0.01	0.01
MON3	2002/11/05	8.3	420	-	60	780	17.5	-	1045	185	0.50	3.3	-	0.01	-
MON3	2003/05/14	7.9	428	67	55	780	19	-	904	172	0.14	3.3	0.01	0.01	0.16
MON3	2003/11/05	7.4	423	-	-	765	-	-	1050	180	0.07	2.9	-	-	-
MON3	2004/05/24	-	-	-	-	758	-	429.1	1060	181	0.14	3	-	0.03	-
MON3	2004/11/09	8.2	439	59	52	850	18	-	1060	190	0.34	3.2	0.01	0.28	0.01
MON3	2005/05/11	7.6	434	72	70	800	20	-	1070	182	0.11	3.4	-	0.01	0.01
MON3	2005/10/26	8	435	80	60	753	19	-	1070	173	0.23	3.4	-	-	-
MON3	2006/07/03	7.5	436	77	74	820	14	-	1080	178	0.11	3.3	-	-	-
MON3	2006/11/22	7.6	434	76	55	670	11	-	775	174	0.68	2.7	-	-	-
MON3	2007/07/04	7.5	434	69	52	782	64	-	1086	177	1.44	2.7	-	-	-
MON3	2007/11/06	7.6	431	77	54	835	10	-	1117	173	2.71	2.6	-	-	-
MON3	2008/05/28	7.3	441	65	54	632	18	400	1068	140	-	1.1	-	-	-
MON3	2008/07/21	-	-	-	-	-	-	448	-	-	-	-	-	-	-
MON3	2009/11/04	7.6	428	28	59	832	21	-	1031.7	144.2	0.56	2.6	-	0.03	0.32
MON3	2010/04/20	7.8	433	-	-	-	-	-	-	-	-	-	-	-	-
MON3	2011/05/25	7.6	430	64.6	56	657	19.8	-	1049.9	151.23	0.28	2.98	-	0.1	0.24
MON4	1985/11/01	-	350	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1986/07/01	7.5	400	45	32	768	17	-	1313	275	0.70	4	-	0.3	-
MON4	1986/11/01	-	350	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1987/08/01	-	419	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1988/06/01	-	409	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1990/06/01	-	400	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1991/04/01	-	380	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1991/04/25	7.4	380	56	49	926	18	-	1305	280	-	3	-	0.05	-

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON4	1993/01/01	-	398	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1994/07/01	-	329	-	-	-	-	-	-	-	-	-	-	-	-
MON4	1997/11/01	7.6	439	63	48	740	23	-	1077	103	5.40	2.4	-	1.6	-
MON4	1998/05/01	7.5	399	64	51	725	20	-	1107	141	0.05	3	-	4.3	1
MON4	1998/11/01	8	425	63	46	754	22	-	1200	160	0.20	3	-	0.01	0.49
MON4	1999/05/01	7.5	431	57	44	680	21	-	1080	200	0.05	3.5	-	0.01	1
MON4	1999/11/01	8	431	66	51	800	17	-	1060	200	0.05	3.2	-	0.01	0.85
MON4	2000/02/01	7.5	424	-	-	-	-	-	-	-	-	-	-	-	-
MON4	2000/05/16	7.9	430	60	51	840	18.7	-	1060	237	0.05	2.5	-	0.2	0.8
MON4	2000/11/15	7.6	425	42	52	880	19	-	1050	230	0.05	2.6	-	0.01	0.01
MON4	2001/05/15	7.5	435	52	59	820	19	-	1100	240	0.10	3	-	0.02	1.78
MON4	2001/11/13	8.2	429	-	55	772	13	-	1134	238	0.20	3.1	-	0.01	-
MON4	2002/05/27	8.4	419	-	65	750	17	-	1076	227	0.14	3.2	-	0.01	0.31
MON4	2002/11/05	8.3	416	-	53	750	16.5	-	1059	233	0.50	3.3	-	0.01	-
MON4	2003/05/14	7.9	426	62	52	780	18	-	935	230	0.14	3.3	0.01	0.02	0.68
MON4	2003/11/05	7.6	420	-	-	740	-	-	1077	257	0.02	3	-	-	-
MON4	2004/05/24	-	-	-	-	-	-	333.5	-	-	-	-	-	-	-
MON4	2004/11/09	8.1	432	60	45	880	21	-	876	212	0.11	2.7	0.01	0.3	0.15
MON4	2005/05/11	7.8	431	69	68	790	18	-	1075	256	-	3.4	-	0.01	0.36
MON4	2005/10/26	7.7	432	77	63	870	19	-	1010	250	0.23	3.5	-	-	-
MON4	2006/07/03	7.4	431	100	67	810	13	-	1060	252	0.16	3.3	-	-	-
MON4	2006/11/22	7.6	430	63	52	640	17	-	750	256	0.45	2.7	-	-	-
MON4	2007/07/04	7.5	437	3.4	48	855	51	-	1004	256	0.14	0.7	-	-	-
MON4	2007/11/06	7.6	427	74	49	816	8	-	1048	247	2.71	0.1	-	-	-
MON4	2008/05/28	7.6	424	60	43	697	17	311	1046	233	0.11	1.3	-	-	-
MON4	2008/07/21	-	-	-	-	-	-	263	-	-	-	-	-	-	-
MON4	2009/11/04	8.1	422	39	53	814	21	-	1026.9	220.9	0.68	3.1	-	0.03	1.04
MON4	2010/04/20	7.7	428	-	-	-	-	-	-	-	-	-	-	-	-

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
MON4	2011/05/25	7.6	427	59	52.4	657	19.1	-	1067.2	241.44	0.05	3.07	-	0.1	0.66
EM8	1986/11/01	-	225	-	-	-	-	-	-	-	-	-	-	-	-
EM8	1999/12/31	8.3	247	58	35	410	10.9	-	502	122	12.00	2.8	0.01	0.01	0.01
EM8	2003/11/05	7.7	254	-	-	450	-	-	530	138	3.84	3	-	-	-
EM8	2004/05/24	-	-	-	-	430	-	292.7	546	140	3.61	2.8	-	0.02	-
EM8	2005/05/11	8.1	253	63	39	434	10	-	560	150	2.71	3.2	-	0.01	0.01
EM8	2005/10/26	8.1	256	70	39	440	10	-	535	153	2.93	3.4	-	-	-
EM8	2006/07/03	7.9	255	85	39	482	9	-	610	194	4.06	2.9	-	-	-
EM8	2006/11/22	7.9	255	66	33	400	9.8	-	537	154	2.71	2.3	-	-	-
EM8	2007/07/04	7.7	254	62	33	881	38	-	562	165	3.39	2.8	-	-	-
EM8	2007/11/06	7.9	252	68	32	430	3	-	541	157	3.39	2.7	-	-	-
EM8	2008/05/28	7.8	254	56	32	437	43	281	528	142	-	1.7	-	-	-
EM8	2009/11/04	8.1	253	57	31	423	12	-	619.3	168.5	0.77	2.5	-	0.01	0.01
EM8	2010/04/20	7.9	254.9	-	-	-	-	-	-	-	-	-	-	-	-
EM8	2011/05/25	7.8	252	55.2	46.2	367	12.5	-	567.5	150.23	0.64	2.79	-	0.1	0.1
FW35	1985/11/01	-	180	-	-	-	-	-	-	-	-	-	-	-	-
FW35	1986/07/01	7.3	180	44	25	363	10	-	528	130	13.00	5	-	0.5	-
FW35	1987/04/29	7.3	180	44	25	363	10	-	528	130	-	4	-	0.05	-
FW35	1991/04/01	-	200	-	-	-	-	-	-	-	-	-	-	-	-
FW35	1991/04/23	7.5	200	69	26	387	10	-	500	145	-	3	-	0.01	-
FW35	2002/12/31	7.1	234.7	-	-	-	-	-	-	-	-	-	-	-	-
FW35	2003/05/27	8.1	231	63	32	380	10.3	-	470	127	3.84	3	0.01	0.01	0.01
FW35	2003/11/05	7.7	227	-	-	385	-	-	484	130	3.16	2.7	-	-	-
FW35	2004/05/24	-	-	-	-	379	-	271.2	487	130	3.61	2.8	-	0.03	-
FW35	2004/11/09	8.3	229	55	28	450	10	-	430	117	3.39	2.6	0.01	0.23	0.01
FW35	2005/05/11	7.7	227	65	36	378	9.4	-	480	126	3.16	3	-	0.01	0.01
FW35	2005/10/26	8.1	227	86	44	394	8.1	-	460	126	0.38	3.3	-	-	-
FW35	2006/07/03	7.6	226	81	30	350	7	-	511	170	4.74	2.8	-	-	-

Table C-3 cont: Vaalputs borehole water chemistry results (mg.l^{-1} where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
FW35	2006/11/22	7.7	225	53	29	330	8.8	-	484	129	3.39	2.5	-	-	-
FW35	2007/07/04	7.5	225	62	30	949	32	-	475	135	3.61	2.7	-	-	-
FW35	2007/11/06	7.9	223	57	28	363	4	-	469	129	4.06	2.7	-	-	-
FW35	2008/05/28	7.6	225	52	28	391	48	252	450	110	-	1.8	-	-	-
FW35	2009/11/04	7.7	222	54	25	342	11	-	444.5	122.8	0.95	2.8	-	0.01	0.01
FW35	2010/04/20	7.6	222.9	-	-	-	-	-	-	-	-	-	-	-	-
PBH22	1986/07/01	7.4	125	52	29	560	16	-	612	198	5.00	4	-	0.3	-
PBH22	1986/07/17	-	-	-	-	-	-	273	-	-	-	-	-	-	-
PBH22	1996/11/01	7.7	247	36	27	500	13	-	580	140	1.80	2.6	-	0.73	0.05
PBH22	1997/06/01	7.3	253	62	35	510	9	-	550	160	2.10	3.3	-	0.05	0.05
PBH22	1998/11/01	7.5	270.8	-	-	-	-	-	-	-	-	-	-	-	-
PBH22	1999/05/01	7.4	269.8	38	30	486	15	-	530	150	1.50	2.3	-	0.01	0.01
PBH22	2000/02/01	7.4	268	-	-	-	-	-	-	-	-	-	-	-	-
PBH22	2000/05/16	8	272	38	32	545	12.5	-	569	160	1.30	2.6	-	0.01	0.01
PBH22	2000/11/15	7.7	269.6	43	33	580	13	-	560	160	1.30	2.8	-	0.27	0.01
PBH22	2001/05/15	7.6	274	38	28	520	11.4	-	550	150	1.20	2.7	-	0.02	0.01
PBH22	2001/11/13	8.2	271	-	32	509	8.3	-	532	148	1.20	3.1	-	0.01	-
PBH22	2002/05/28	8.5	267	-	35	480	12.4	-	582	172	1.60	3.7	-	0.01	0.01
PBH22	2002/11/05	8.3	264	-	32	509	11	-	593	146	1.60	3.4	-	0.01	-
PBH22	2003/05/14	8.4	267	40.8	32	500	12.7	-	521	150	1.51	3.2	0.01	0.04	0.01
PBH22	2003/11/05	7.7	267	-	-	480	-	-	550	150	1.22	2.9	-	-	-
PBH22	2004/05/24	-	-	-	-	-	-	363.3	-	-	-	-	-	-	-
PBH22	2005/05/11	7.7	273	48	37	514	12	-	570	160	1.35	3	-	0.01	0.01
PBH22	2005/10/26	7.9	272	45	34	500	13	-	540	160	1.72	3.6	-	-	-
PBH22	2006/07/03	7.6	272	50	35	530	6	-	560	170	2.26	3.2	-	-	-
PBH22	2006/11/22	7.7	273	28	30	440	15	-	562	157	1.35	2.8	-	-	-
PBH22	2007/07/04	7.6	271	42	28	357	37	-	651	192	1.65	3.1	-	-	-
PBH22	2007/11/06	7.7	271	85	25	-	8	-	588	169	1.35	2.9	-	-	-

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
PBH22	2008/05/28	7.7	284	41	39	538	11	-	586	167	-	1.6	-	-	-
PBH22	2010/04/20	7.4	297.8	-	-	-	-	-	-	-	-	-	-	-	-
PBH22	2011/05/25	7.3	291	46.5	39.9	468	16.3	-	609.72	37.22	0.66	2.46	-	0.1	0.27
13C5	1996/11/01	7.4	956	480	260	1440	13	-	3070	670	0.70	4.8	-	29	0.8
13C5	1997/05/01	7.4	956	480	260	1440	13	-	3070	670	0.70	4.8	-	29	0.8
13C5	1997/06/01	7.5	892	650	280	1360	9	-	3500	480	10.00	2.5	-	0.05	0.71
13C5	1997/11/01	7.2	842	330	180	1110	9	-	2141	350	0.50	2.6	-	0.2	-
13C5	1998/05/01	7.4	850	388	222	1153	19	-	3064	439	0.05	1.8	-	1.8	0.7
13C5	1998/11/01	8	933	420	200	1263	19	-	3500	440	0.20	2.4	-	0.66	0.51
13C5	1999/05/01	7.1	859	363	163	1147	13	-	2727	388	0.05	2.4	-	0.3	0.47
13C5	1999/11/01	8	1234	560	0.8	1720	12	-	3200	750	0.05	2	-	0.5	-
13C5	2000/05/16	7	1200	593	140	1670	11	-	4120	635	0.05	1.3	-	3.7	0.83
13C5	2000/11/15	7.1	1126	500	260	1500	13	-	3800	650	0.10	0.94	-	1	0.4
13C5	2001/05/14	7	1141	637	280	1570	2	-	3900	700	1.00	1.2	-	0.11	1.65
13C5	2001/11/13	7.3	1129	-	317	1415	9	-	3569	639	0.10	0.2	-	0.01	-
13C5	2002/05/28	7.7	1112	-	285	1450	9	-	716	729	0.02	2.5	-	0.01	0.84
13C5	2003/11/05	7.8	984	-	-	1330	-	-	3060	512	0.11	2.3	-	-	-
13C5	2004/05/24	-	-	-	-	1231	-	27.5	2790	460	0.11	2	-	0.04	-
13C5	2005/05/11	7.3	950	480	165	1400	12	-	3130	304	0.11	0.1	-	0.01	0.15
13C5	2005/10/26	6.9	911	465	79	1390	12	-	2800	110	0.23	0.4	-	-	-
13C5	2006/07/03	7	1016	493	198	1182	3	-	3100	610	0.32	3.3	-	-	-
13C5	2006/11/22	7.4	996	400	260	1230	13	-	3000	524	1.35	1.4	-	-	-
13C5	2007/05/10	8.1	896	352	194	1157	52	-	2791	446	3.39	1.5	-	-	-
13C5	2007/11/06	7.6	1015	488	244	1844	6	-	3007	596	0.18	0.9	-	-	-
13C5	2008/05/28	7	1280	504	310	1810	24	182	4003	899	0.11	1	-	-	-
13C5	2009/11/04	6.9	1194	625	352	1563	5	-	4650.1	758.1	1.94	1.1	-	0.23	-
13C5	2010/04/20	7.2	1222	-	-	-	-	-	-	-	-	-	-	-	-
13C5	2011/05/25	7	1407	220	184	582	4.14	-	4331.8	1282	0.02	2.69	-	0.1	0.73

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
4C1	1996/11/01	7.4	500	230	130	700	27	-	1350	410	18.00	2.3	-	0.7	0.05
4C1	1997/05/01	7.4	500	230	130	700	27	-	1350	410	18.00	2.3	-	0.7	0.05
4C1	1997/06/01	7.4	498	330	330	670	23	-	1450	310	18.00	1.6	-	0.05	0.05
4C1	1997/11/01	7.5	543	230	140	650	20	-	1142	300	16.00	1.6	-	0.5	-
4C1	1998/05/01	7.7	500	235	144	710	52	-	1560	370	18.00	1.2	-	0.8	0.01
4C1	1998/11/01	8	528	225	125	660	30	-	1500	320	19.20	1.2	-	0.01	0.01
4C1	1999/05/01	7	528	220	115	690	31	-	1374	290	18.00	1.6	-	0.01	0.01
4C1	1999/11/01	8	532	260	0.01	660	25	-	1500	330	21.00	1.2	-	0.01	-
4C1	2000/05/16	7.6	533	182	100	725	27	-	1500	330	17.00	1.1	-	0.01	0.01
4C1	2000/11/15	7.6	530	200	130	696	30	-	1450	336	17.20	1.1	-	0.01	0.01
4C1	2001/05/14	7.2	535	255	125	715	28	-	1440	330	18.00	1.1	-	0.01	0.01
4C1	2001/11/13	8.2	528	-	130	665	21	-	1423	313	19.00	0.9	-	0.01	-
4C1	2002/05/28	8.2	514	-	145	660	21	-	1558	329	17.16	1.7	-	0.01	0.01
4C1	2002/11/05	8.2	512	-	120	656	24	-	1382	328	18.00	1.7	-	0.01	-
4C1	2003/05/14	8.2	526	220	80	675	26	-	1293	325	16.48	1.8	0.01	0.01	0.01
4C1	2003/11/05	7.3	515	-	-	667	-	-	1380	360	14.67	1.7	-	-	-
4C1	2004/05/24	-	-	-	-	-	-	203.8	-	-	-	-	-	-	-
4C1	2004/11/09	7.8	534	175	65	800	32	-	1444	351	13.54	1.7	0.01	1.72	0.01
4C1	2005/05/11	7.3	534	270	160	680	24	-	2600	340	14.45	1.1	-	0.01	0.01
4C1	2005/10/26	7.5	539	272	154	812	28	-	1400	344	16.70	1.8	-	-	-
4C1	2006/07/03	7.1	539	316	157	760	23	-	1509	400	18.96	1.7	-	-	-
4C1	2006/11/22	7.3	541	243	142	630	26	-	1398	374	15.80	1.5	-	-	-
4C1	2007/07/04	7.1	537	254	132	559	59	-	1446	359	17.83	1.3	-	-	-
4C1	2007/11/06	7.6	532	480	126	1115	20	-	1319	362	19.41	1.1	-	-	-
4C1	2008/05/28	7.2	539	218	138	690	56	160	1457	367	-	0.9	-	-	-
4C1	2009/11/04	7.6	548	258	156	524	25	-	1528.3	382.6	4.47	1.2	-	0.01	0.01
4C1	2010/04/22	7.9	543	-	-	-	-	-	-	-	-	-	-	-	-
4C1	2011/05/25	7.2	543	235	139	609	26.8	-	1505.7	372.93	3.51	1.68	-	0.1	0.1

Table C-3 cont: Vaalputs borehole water chemistry results (mg.l^{-1} where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
5C2	1996/11/01	7.3	471	270	120	620	19	-	1310	373	26.00	1.4	-	2.4	0.05
5C2	1997/05/01	7.3	471	270	120	620	19	-	1310	373	26.00	1.4	-	2.4	0.05
5C2	1997/06/01	7.5	484	390	140	630	14	-	1450	300	23.00	1.4	-	0.05	0.05
5C2	1997/11/01	7.1	512	250	110	550	16	-	813	290	20.00	1.4	-	0.4	-
5C2	1998/05/01	7.5	490	270	137	662	24	-	1505	319	20.00	1	-	1.6	0.02
5C2	1998/11/01	7.9	632	329	146	815	33	-	2000	400	30.00	1.2	-	0.01	0.01
5C2	1999/05/01	6.9	524	262	104	640	23	-	1500	280	19.00	1.4	-	0.01	0.01
5C2	1999/11/01	8.1	524	260	0.01	650	18.5	-	1400	260	22.00	1.5	-	0.01	-
5C2	2000/05/16	7.4	523	208	91	660	19	-	1450	330	23.00	1	-	0.01	0.01
5C2	2000/11/15	7.2	548	300	120	760	21	-	1530	360	25.00	1	-	0.01	0.01
5C2	2001/05/14	6.8	555	344	120	700	21	-	1520	360	22.00	1.1	-	0.01	0.01
5C2	2001/11/13	7.9	766	-	213	908	20.5	-	2170	613	42.00	0.3	-	0.01	-
5C2	2002/05/28	8	544	-	144	660	15	-	1649	384	25.51	1.6	-	0.01	0.01
5C2	2002/11/05	8	531	-	114	640	18	-	1431	325	24.00	1.5	-	0.01	-
5C2	2003/05/14	8.2	527	250	75	650	20	-	1291	323	21.44	1.7	0.01	0.01	0.01
5C2	2003/11/05	7.2	533	-	-	630	-	-	1380	375	23.25	1.3	-	-	-
5C2	2004/05/24	-	-	-	-	639	-	197.3	1450	321	21.22	1.4	-	0.04	-
5C2	2005/05/11	7.1	564	320	150	640	18	-	1517	352	19.86	1.8	-	0.01	0.01
5C2	2005/10/26	7.9	567	350	150	730	22	-	1450	344	21.22	1.5	-	-	-
5C2	2006/07/03	7.2	551	406	149	738	16	-	1600	390	24.83	1.6	-	-	-
5C2	2006/11/22	7.2	546	310	135	600	20	-	1420	354	21.22	1.1	-	-	-
5C2	2007/07/04	7.1	574	329	136	469	54	-	1590	380	23.25	1.2	-	-	-
5C2	2007/11/06	7.4	603	629	126	1166	61	-	1616	402	25.28	0.9	-	-	-
5C2	2008/05/28	7	640	333	152	914	52	107	1823	431	-	0.5	-	-	-
5C2	2009/11/04	7.4	773	405	204	959	21	-	2125.9	560.7	6.16	0.8	-	0.01	0.01
5C2	2010/04/22	7.1	716	-	-	-	-	-	-	-	-	-	-	-	-
5C2	2011/05/25	7	747	394	172	851	27.7	-	2141.9	582.25	4.67	1.68	-	0.1	0.1
16C3	1996/11/01	7.6	405	240	118	560	25	-	1160	270	6.4	1.8	-	1.5	0.06

Table C-3 cont: Vaalputs borehole water chemistry results (mg.l^{-1} where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
16C3	1997/05/01	7.6	405	240	118	560	25	-	1160	270	6.40	1.8	-	1.5	0.06
16C3	1997/06/01	7.7	384	330	140	440	22	-	1390	220	6.30	1.7	-	0.16	0.08
16C3	1997/11/01	7.4	449	230	110	440	20	-	909	230	13.00	1.6	-	2	-
16C3	1998/05/01	7.8	410	257	133	486	42	-	1087	213	11.00	1.2	-	0.08	0.01
16C3	1998/11/01	7.9	433	258	113	463	28	-	1260	250	13.00	1.5	-	0.01	0.01
16C3	1999/05/01	7.1	433	200	90	480	26	-	1145	220	10.00	1.4	-	0.01	0.02
16C3	1999/11/01	8	435	260	0.01	500	23	-	1200	210	14.00	1.7	-	0.01	-
16C3	2000/05/16	7.5	447	202	88	480	25	-	1200	240	13.00	1.2	-	0.05	0.02
16C3	2000/11/15	7.4	441	240	110	450	26	-	1175	250	12.50	1.2	-	0.01	0.01
16C3	2001/05/14	7.4	441	294	110	495	26	-	1160	260	12.50	1.1	-	0.01	0.01
16C3	2001/11/13	8.1	437	-	120	463	24	-	1225	255	14.00	1.6	-	0.01	-
16C3	2002/05/28	8.4	428	-	130	450	24	-	1372	263	1.74	1.8	-	0.01	0.02
16C3	2002/11/05	8.1	449	-	114	480	26	-	1220	260	14.00	1.6	-	0.01	-
16C3	2003/05/14	8.2	447	250	70	465	25	-	1125	261	12.87	1.7	0.01	0.01	0.01
16C3	2003/11/05	7.4	442	-	-	440	-	-	1130	278	14.00	1.6	-	-	-
16C3	2004/05/24	-	-	-	-	468	-	212	1210	260	13.54	1.3	-	0.03	-
16C3	2004/11/09	7.7	479	177	85	590	30	-	1308	270	13.32	1.6	0.01	1.77	0.01
16C3	2005/05/11	7.2	479	340	150	483	25	-	1300	55	12.64	1.4	-	0.01	0.01
16C3	2005/10/26	7.4	558	340	155	600	34	-	1420	330	20.32	1.6	-	-	-
16C3	2006/07/03	7.2	479	354	154	515	25	-	1430	323	0.11	1.8	-	-	-
16C3	2006/11/22	7.3	506	275	147	460	27	-	1322	313	18.28	1.2	-	-	-
16C3	2007/07/04	7.2	487	315	135	785	55	-	1320	300	14.00	1.3	-	-	-
16C3	2007/11/06	7.6	471	338	143	503	23	-	1237	288	17.61	1.1	-	-	-
16C3	2008/05/28	7.2	502	291	146	469	89	156	1397	313	-	0.9	-	-	-
16C3	2009/11/04	7.5	496	274	162	417	26	-	1337.8	309.9	5.76	1.1	-	0.02	0.01
16C3	2010/04/22	7.4	482	-	-	-	-	-	-	-	-	-	-	-	-
16C3	2011/05/25	7.4	488	287	138	422	28.7	-	1374.5	68.95	0.89	1.51	-	0.1	0.1
PBAKKI	1996/11/01	7.4	260	150	100	430	10	-	750	150	15	1.6	-	3.2	0.06

Table C-3 cont: Vaalputs borehole water chemistry results ($mg.l^{-1}$ where no unit indicated) for 1985 to 2011 (data: Necsa, 2011d).

Borehole	Date Measured	pH	EC mS/m	Ca	Mg	Na	K	MALK	Cl	SO_4	NO_3	F	Al	Fe	Mn
PBAKKI	1997/06/01	7.4	474	160	110	870	20	-	1510	290	7.10	3.1	-	0.23	0.05
PBAKKI	1997/11/01	8.6	574	95	80	880	30	-	1084	310	0.30	2.9	-	0.1	-
PBAKKI	1998/05/01	7.9	480	107	79	873	28	-	1390	307	0.90	2.8	-	0.01	0.01
PBAKKI	1998/11/01	7.5	510.3	155	230	878	95	-	-	310	0.05	4.1	-	0.01	0.02
PBAKKI	1999/05/01	7.4	519	107	86	890	26	-	1500	330	0.70	3.1	-	0.01	0.01
PBAKKI	1999/11/01	8.2	522	108	0.01	970	25	-	1000	200	0.05	2.8	-	0.1	-
PBAKKI	2000/05/16	7.9	525	89	73	890	27	-	1450	340	0.60	2.5	-	0.4	0.02
PBAKKI	2000/11/15	7.7	522	104	82	970	27	-	1421	326	0.67	2.4	-	0.01	0.01
PBAKKI	2001/05/14	7.5	524	100	86	920	29	-	1400	340	0.10	2.3	-	0.17	0.04
PBAKKI	2001/11/13	8.3	522	-	85	865	20	-	1395	313	0.90	2.6	-	0.01	-
PBAKKI	2002/05/28	8.5	513	-	102	850	28	-	1623	351	0.02	3.5	-	0.01	0.01
PBAKKI	2002/11/05	8.2	507	-	88	868	26	-	1407	302	1.00	3.3	-	0.01	-
PBAKKI	2003/05/14	8	520	97	68	860	28	-	1305	318	0.65	3.3	0.01	0.01	0.02
PBAKKI	2003/11/05	7.5	511	-	-	800	-	-	1330	323	0.84	2.9	-	-	-
PBAKKI	2004/05/24	-	-	-	-	852	-	254	1400	323	0.86	2.7	-	0.04	-
PBAKKI	2005/05/11	7.7	524	108	114	890	27	-	1400	345	-	3	-	0.01	0.03
PBAKKI	2005/10/26	8.2	522	112	95	970	26	-	1300	323	0.23	3.4	-	-	-
PBAKKI	2006/07/03	7.7	521	140	110	900	18	-	1385	350	1.13	3.3	-	-	-
PBAKKI	2006/11/22	7.7	517	100	83	730	25	-	1035	360	0.90	2.8	-	-	-
PBAKKI	2007/07/04	7.5	524	113	86	737	62	-	1375	378	1.24	2.7	-	-	-
PBAKKI	2007/11/06	7.9	522	111	85	852	25	-	1430	363	1.51	2.3	-	-	-
PBAKKI	2008/05/28	7.6	524	101	106	793	23	228	1411	323	-	1.1	-	-	-
PBAKKI	2009/11/04	8	516	105	97	886	28	-	1400.9	357.8	0.52	2.5	-	0.02	0.01
PBAKKI	2010/04/20	4.8	563	-	-	-	-	-	-	-	-	-	-	-	-
PBAKKI	2011/05/25	7.7	519	103	93	760	28.8	-	1386.6	130.26	0.15	2.83	-	0.1	0.1

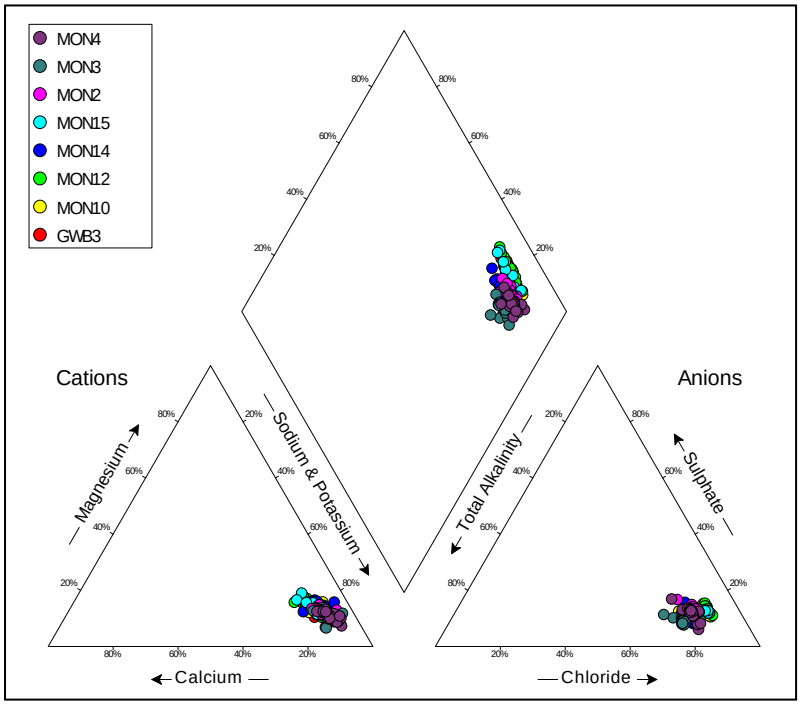

Figure C.1: Zone A - Piper diagram (data: Necsa, 2011d).

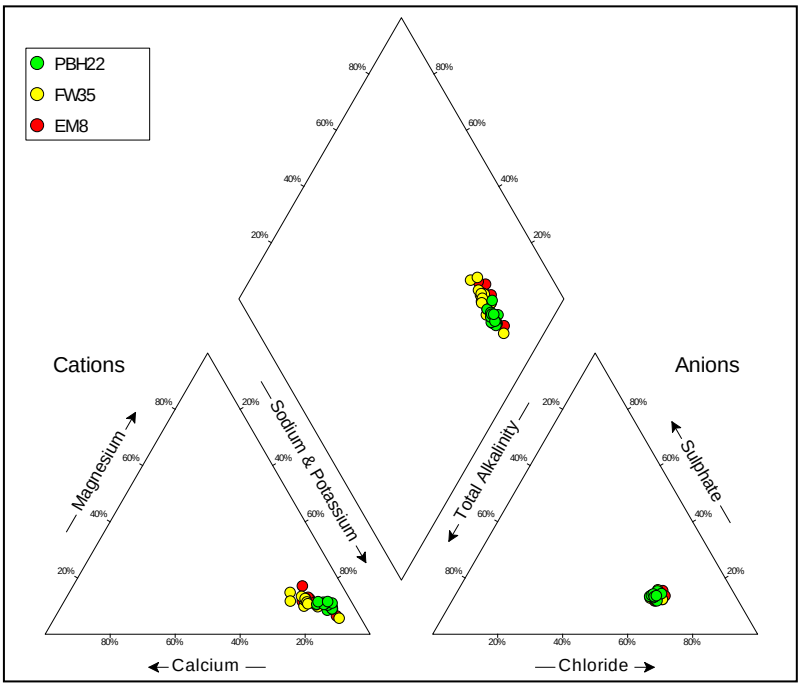

Figure C.2: Zone B - Piper diagram (data: Necsa, 2011d).

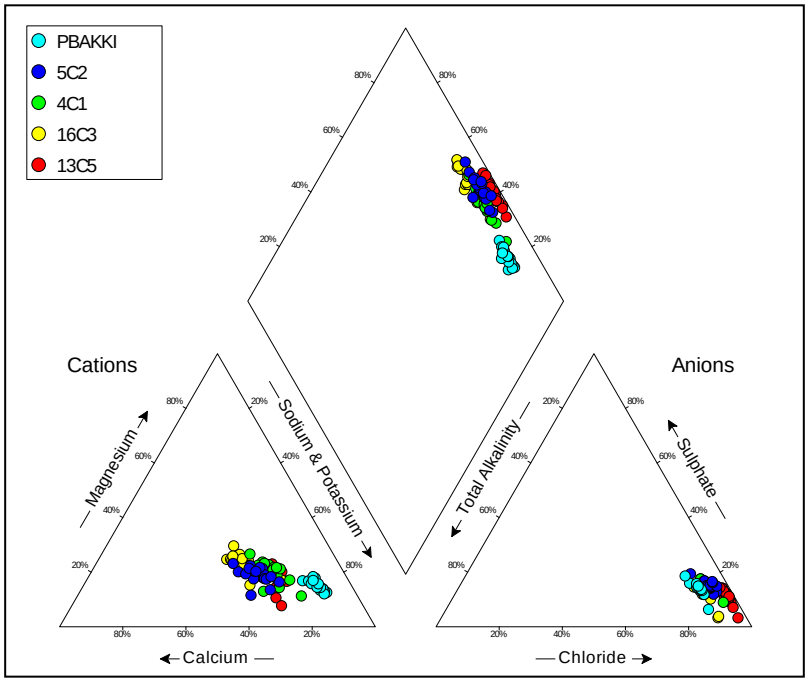

Figure C.3: Zone C - Piper diagram (data: Necsa, 2011d).

Table C-4: The key to describing plots on the Expanded Durov diagram.

Field	Description
1	Fresh clean, recently recharged groundwater, with HCO_3^- and CO_3 dominated ions.
2	Fresh clean, relatively young groundwater that has started to undergo Mg ion-exchange and is often found in dolomitic terrains.
3	Fresh, clean relatively young groundwater that has undergone Na ion-exchange (sometimes in Na-rich granites or other felsic rocks), or because of contamination effects from a source rich in Na.
4	Fresh, recently recharged groundwater with HCO_3^- and CO_3 dominated ions that has been in contact with a source of SO_4 contamination, or that has moved through SO_4 enriched rocks.
5	Groundwater that is usually a mix of different types – either clean water from fields 1 and 2 that has undergone SO_4 and NaCl mixing contamination, or old stagnant NaCl dominated water that has mixed with clean water.
6	Groundwater from field 5 that has been in contact with a source rich in Na, or old stagnant NaCl dominated water that resides in Na-rich host rock / material.
7	Water rarely plots in this field that indicates NO_3 or Cl enrichment or dissolution.
8	Groundwater that is usually a mix of different types – either clean water from fields 1 and 2 that has undergone SO_4, but especially Cl mixing / contamination, or old 'stagnant' NaCl dominanted water that has mixed with water richer in Mg.
9	Very old, 'stagnant' water that has reached the end of the geohydrological cycle (deserts, salty pans, etc.) or water that has moved a long time and/or distance through the aquifer and has undergone significant ion-exchange.

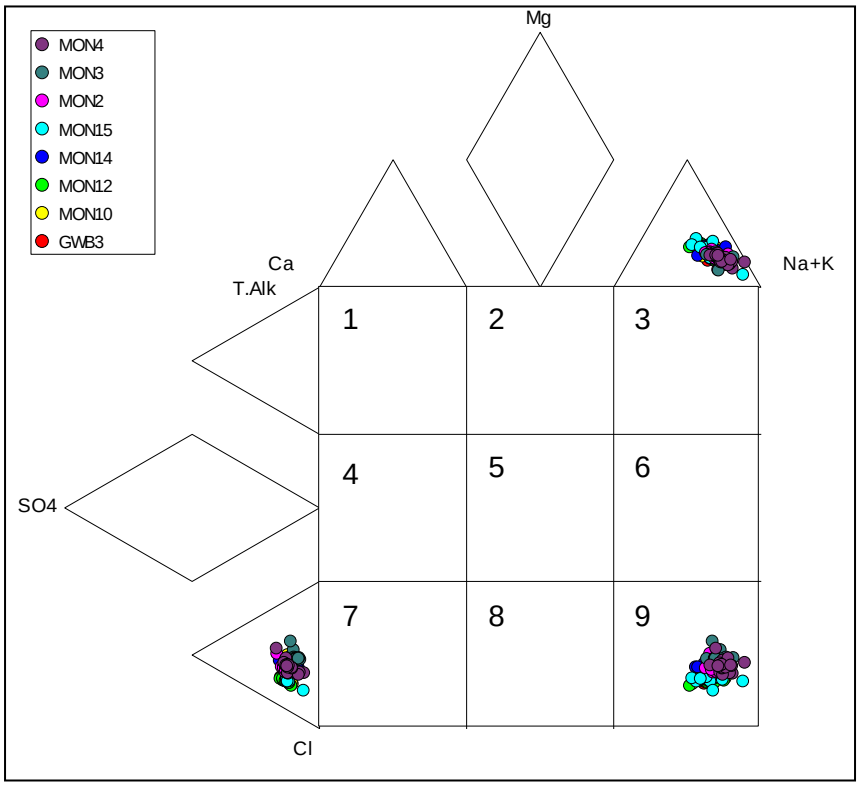

Figure C.4: Zone A – Expanded Durov diagram (data: Necsa, 2011d).

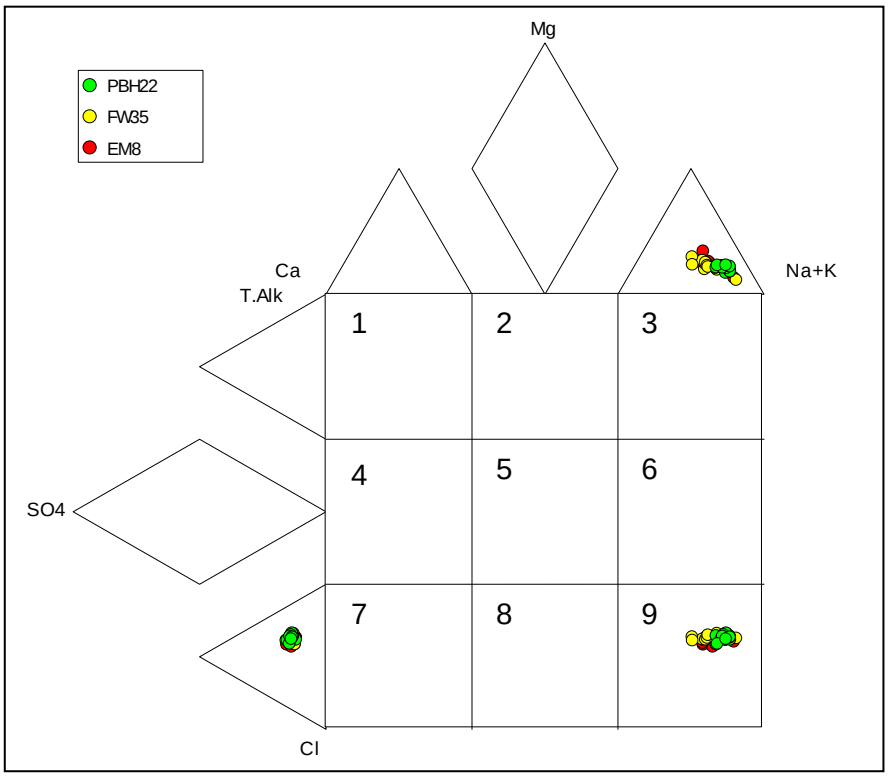

Figure C.5: Zone B – Expanded Durov diagram (data: Necsa, 2011d).

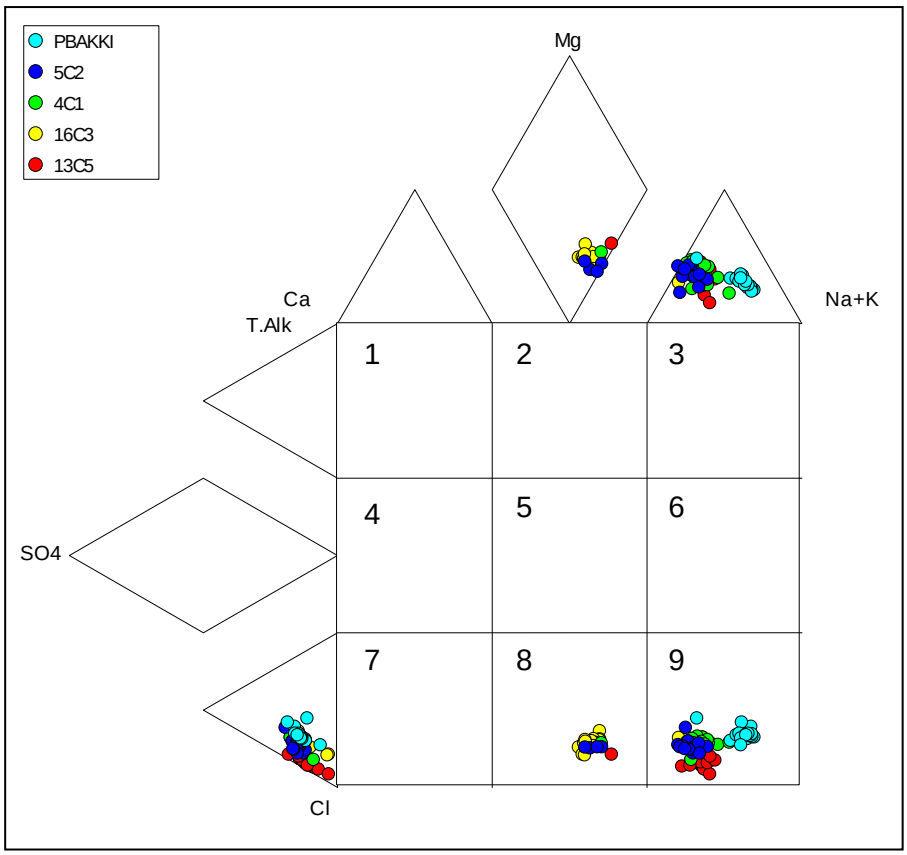

Figure C.6: Zone C – Expanded Durov (data: Necsa, 2011d).

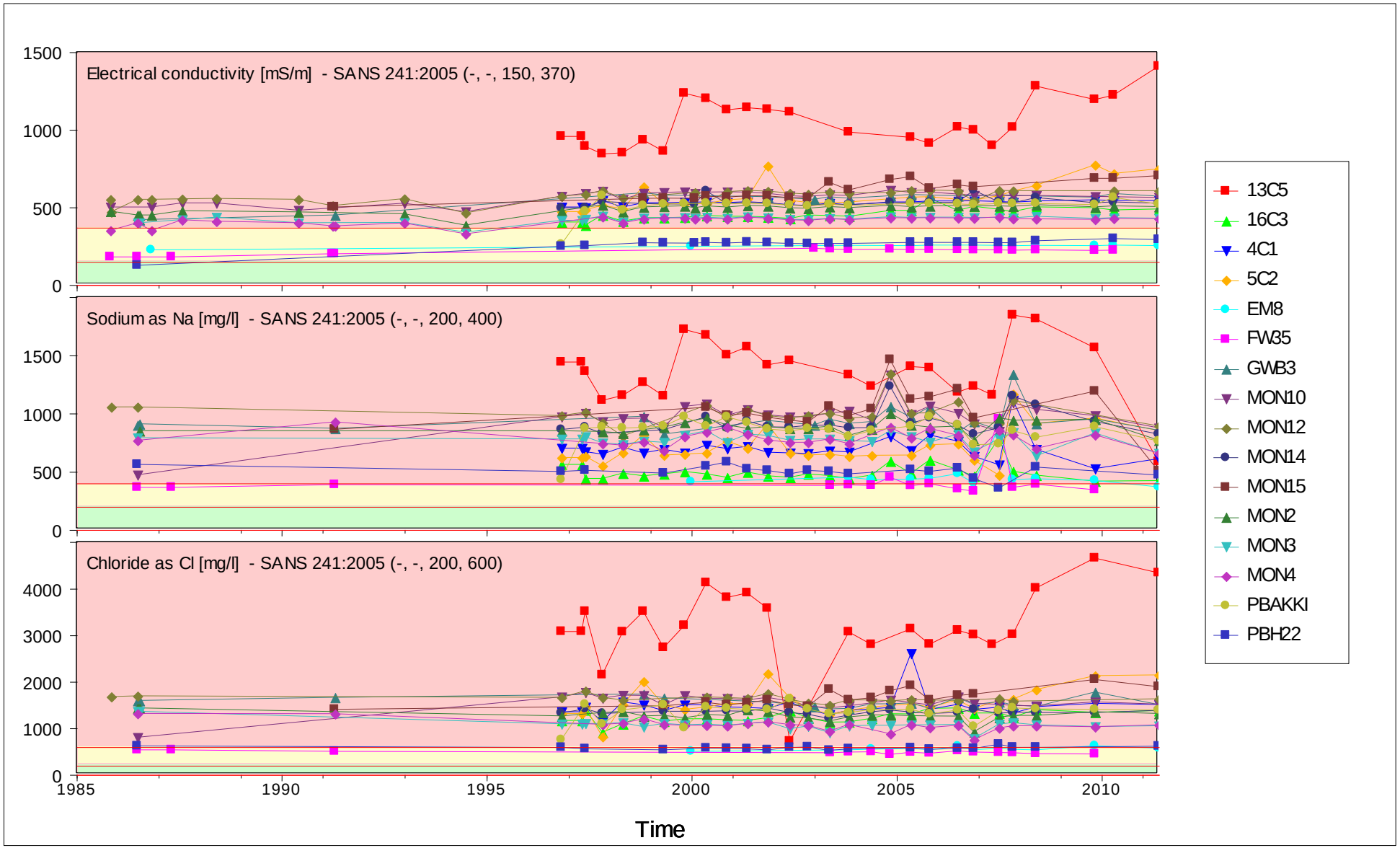

Figure C.7: Time series of EC, Na and Cl for all Zones (data: Necsa, 2011d).

Appendix D. Radio-analytical data: Results from routine analysis

Table D-1: ^{238}U results all boreholes from 1987 to 2010 in Bq.l^{-1} (data: Necsa, 2011e).

	ZONE A								ZONE B			ZONE C				
	MON10	MON12	MON14	MON15	MON2	MON3	MON4	GWB3	EM8	FW35	PBH22	V13C5	V16C3	V4C1	V5C2	PBAKKI
1987	0.44	0.38	0.37	0.47	0.45	0.50	0.44	-	-	-	0.50	0.08	0.20	0.11	-	-
1988	1.37	-	1.08	0.90	1.11	1.13	0.21	-	-	-	0.77	0.25	0.60	0.36	0.20	0.08
1989	1.61	0.22	0.89	1.26	1.12	1.36	0.18	-	-	-	0.78	-	0.65	0.33	0.32	1.31
1990	1.91	0.67	1.43	1.45	1.34	1.70	0.23	-	-	-	0.93	0.22	0.75	0.50	0.44	0.10
1991	1.50	0.62	1.39	1.31	1.41	1.71	0.29	-	-	-	0.80	0.70	0.58	0.42	0.32	0.06
1992	1.44	0.10	1.13	1.22	1.23	1.10	0.40	-	-	-	0.75	0.21	0.60	0.64	0.26	0.05
1993	0.45	0.01	1.20	1.15	0.11	1.19	0.22	-	-	-	0.66	0.93	0.63	0.39	0.44	0.07
1994	1.94	0.68	0.68	1.26	1.18	1.28	0.87	-	-	-	0.71	0.48	0.10	0.46	0.34	0.72
1995	0.35	1.70	1.00	-	-	0.83	-	0.73	-	0.50	-	0.09	0.41	0.46	0.28	0.30
1996	0.79	0.50	0.84	-	-	0.86	-	0.69	-	0.46	0.60	0.55	0.29	0.30	0.65	0.14
1997	0.71	0.59	1.01	-	-	1.03	-	0.63	0.66	0.64	0.69	0.23	0.21	0.31	0.36	0.11
1998	0.97	-	1.10	1.08	1.07	0.97	0.53	0.74	0.61	0.57	0.76	0.31	0.63	0.26	0.38	0.16
Laboratory SANAS accreditation date: 01 May 1999																
1999	0.76	-	0.32	0.92	0.91	0.83	0.85	0.76	0.58	0.48	-	0.47	-	0.35	0.32	-
2000	0.84	0.75	0.93	0.94	1.06	0.90	0.78	0.88	1.36	1.11	-	0.19	0.62	0.39	0.42	0.13
2001	0.98	0.76	0.90	0.92	1.10	0.88	0.68	0.65	0.54	0.55	0.68	-	-	0.34	0.40	0.11
2002	0.92	0.91	0.91	1.07	-	0.86	0.67	0.87	1.36	0.93	0.42	0.35	0.59	0.36	0.43	0.05
2003	1.03	0.88	0.72	1.00	1.19	1.04	0.72	0.82	0.61	0.56	0.67	-	0.48	0.22	0.35	-
2004	0.71	0.80	0.69	0.59	0.13	1.04	0.83	0.83	0.64	0.53	0.54	0.15	0.51	**0.72**	0.34	0.60
2005	0.85	0.73	0.64	0.91	1.09	0.84	0.74	0.79	0.60	0.44	0.73	0.01	0.67	0.36	0.43	0.12
2006	0.52	0.66	0.52	1.21	0.71	0.57	0.50	0.79	0.40	0.42	0.49	0.80	0.49	0.32	0.31	0.19
2007	0.98	0.54	0.27	0.81	0.96	0.77	0.59	0.58	0.45	0.61	0.64	-	0.35	0.36	0.47	0.10
2008	0.99	-	0.39	-	1.20	0.85	0.65	0.91	0.74	0.60	0.80	0.43	0.88	0.40		0.16
2009	**0.85**	0.70	**0.28**	**0.75**	**1.04**	**0.72**	**0.52**	**-**	0.63	0.53	**0.04**	**0.02**	**0.72**	**0.39**	0.60	**0.15**
2010	0.62	-	0.30	1.00	-	0.76	0.55	-	0.59	0.57	0.07	0.41	0.69	0.37	0.51	0.17
AVG	**0.98**	**0.64**	**0.79**	**1.01**	**0.97**	**0.99**	**0.55**	**0.76**	**0.62**	**0.70**	**0.60**	**0.34**	**0.53**	**0.38**	**0.40**	**0.23**
STD DEV	**0.44**	**0.36**	**0.35**	**0.24**	**0.37**	**0.30**	**0.22**	**0.10**	**0.22**	**0.29**	**0.18**	**0.25**	**0.20**	**0.12**	**0.11**	**0.30**
ZONE AVG	**0.70**								**0.67**			**0.37**				
Overall AVG	**0.65**															

***Red**: Zone A average values; **Yellow**: Zone B average values; **Green**: Zone C average values.*
*Values highlighted in **pink**: results from nuclide specific alpha spectrometry carried out in 2009. All other values: results from routine gamma spectrometry.*

Table D-2: ^{238}U, ^{232}Th, ^{226}Ra, total alpha and total beta results in Bq.l^{-1} for the three quarterly analysed boreholes: EM8, FW35, GWB3 (data: Necsa, 2011e).

Borehole	Date	^{238}U	^{226}Ra	^{232}Th	Total alpha	Total beta
EM8	1997/04/24	0.93	-	-	6.21	3.50
EM8	1997/07/16	0.49	-	-	1.81	2.01
EM8	1997/10/15	0.48	-	-	4.31	3.90
EM8	1998/02/06	0.72	-	-	5.39	4.53
EM8	1998/04/21	0.56	-	-	2.32	2.08
EM8	1998/07/22	0.55	-	-	2.31	2.86
EM8	1999/02/05	0.63	-	-	5.68	4.22
EM8	1999/04/13	0.48	0.0002	-	2.79	4.00
Laboratory SANAS accreditation date: 01 May 1999						
EM8	1999/08/04	0.52	-	-	4.09	3.93
EM8	1999/11/29	0.67	0.01	-	3.74	2.29
EM8	2000/01/26	0.81	0.01	-	5.53	3.10
EM8	2000/04/14	1.90	-	-	49.07	13.12
EM8	2000/10/18	0.13	-	-	3.69	2.73
EM8	2001/01/18	0.58	-	-	7.96	1.99
EM8	2001/04/12	0.61	-	-	9.29	2.44
EM8	2001/07/17	0.58	-	-	5.52	3.26
EM8	2001/08/23	0.58	-	-	2.75	3.82
EM8	2001/10/15	0.58	-	0.01	3.75	3.64
EM8	2002/01/17	3.00	-	-	23.78	9.03
EM8	2002/07/23	0.50	-	-	4.19	2.11
EM8	2002/10/24	0.58	-	-	4.47	2.27
EM8	2003/02/19	0.42	-	-	2.43	2.04
EM8	2003/05/22	0.66	-	-	4.72	2.39
EM8	2003/08/20	0.68	-	-	4.65	2.07
EM8	2003/12/03	0.70	0.02	-	4.07	3.33
EM8	2004/03/23	0.64	0.03	-	3.57	1.71
EM8	2004/06/02	0.62	0.02	-	9.19	2.10
EM8	2004/09/09	0.65	0.02	-	3.51	2.17
EM8	2004/12/30	0.64	0.01	-	4.09	0.94
EM8	2005/03/30	0.56	0.03	-	4.23	1.13
EM8	2005/05/10	0.61	-	-	3.97	0.77
EM8	2005/06/07	0.66	0.03	-	3.78	0.86
EM8	2005/09/06	0.67	0.03	-	3.74	0.86
EM8	2005/12/19	0.52	0.03	-	3.35	0.88
EM8	2006/03/28	0.00	-	-	4.21	1.15
EM8	2006/05/06	0.11	-	-	3.07	0.70
EM8	2006/06/14	0.64	0.09	-	3.58	0.78
EM8	2006/09/05	0.63	0.02	-	3.44	1.14
EM8	2006/12/06	0.61	0.03	-	4.17	1.27
EM8	2007/03/09	0.66	0.01	-	7.54	5.44
EM8	2007/05/08	0.56	-	-	3.22	0.97
EM8	2007/06/26	0.31	0.02	-	2.87	0.66
EM8	2007/09/03	0.66	0.02	0.21	3.98	1.59
EM8	2007/12/13	0.05	0.02	-	3.80	1.26
EM8	2008/03/17	0.73	0.03	-	3.81	0.84
EM8	2008/05/26	0.70	-	-	2.54	1.01
EM8	2008/06/30	0.72	0.02	-	3.51	1.57
EM8	2008/09/09	0.67	0.02	0.24	4.20	1.41
EM8	2008/12/09	0.89	0.03	0.05	4.08	1.37
EM8	2009/03/31	0.65	0.04	-	3.08	1.33
EM8	2009/06/25	0.61	0.02	-	4.23	1.39

Table D-2cont: ^{238}U, ^{232}Th, ^{226}Ra, total alpha and total beta results in $Bq.l^{-1}$ for the three quarterly analysed boreholes: EM8, FW35, GWB3 (data: Necsa, 2011e).

Borehole	Date	^{238}U	^{226}Ra	^{232}Th	Total alpha	Total beta
EM8	2009/09/08	0.63	0.03	-	4.91	1.14
EM8	2009/11/13	0.61	0.02	-	3.38	1.40
EM8	2010/03/25	0.61	0.02	-	4.17	1.29
EM8	2010/06/14	0.63	0.03	-	4.84	1.24
EM8	2010/09/21	0.62	0.02	-	4.27	1.20
EM8	2010/09/21	0.59	-	-	4.48	1.51
FW35	1995/10/03	0.50	-	-	0.22	1.37
FW35	1996/01/16	0.39	0.0002	-	0.17	1.01
FW35	1996/04/24	0.46	-	-	0.55	0.91
FW35	1996/07/10	0.47	-	-	2.00	0.64
FW35	1996/10/15	0.52	-	-	1.47	1.52
FW35	1997/01/17	0.45	-	-	2.63	1.44
FW35	1997/04/24	1.13	-	-	8.20	5.08
FW35	1997/07/16	0.48	-	-	5.66	6.79
FW35	1997/10/15	0.33	-	-	4.59	2.57
FW35	1998/02/06	0.75	-	-	9.13	6.01
FW35	1998/04/21	0.49	-	-	2.10	1.55
FW35	1998/07/22	0.53	-	-	2.96	2.40
FW35	1998/10/20	0.53	-	-	3.36	2.33
FW35	1999/02/05	0.47	-	-	3.96	3.25
FW35	1999/04/13	0.44	-	-	1.38	2.16
Laboratory SANAS accreditation date: 01 May 1999						
FW35	1999/08/04	0.46	-	-	3.69	3.47
FW35	1999/11/29	0.54	0.01	-	3.94	1.88
FW35	2000/01/26	0.55	0.01	-	4.58	1.71
FW35	2000/04/14	1.67	-	-	60.05	9.87
FW35	2001/01/18	0.50	-	-	5.70	1.78
FW35	2001/04/12	0.47	-	-	6.92	1.90
FW35	2001/05/22	0.68	-	-	5.94	2.95
FW35	2001/07/17	0.51	-	-	3.43	2.90
FW35	2001/08/23	0.59	-	-	4.36	2.04
FW35	2001/10/15	0.52	-	0.01	2.97	2.84
FW35	2002/01/17	1.96	-	-	12.96	6.18
FW35	2002/04/30	0.54	-	-	2.86	3.00
FW35	2002/07/23	0.60	-	-	3.65	2.73
FW35	2002/10/24	0.62	-	-	4.99	2.39
FW35	2003/02/19	0.56	-	-	4.68	2.30
FW35	2003/05/22	0.57	-	-	3.62	1.94
FW35	2003/08/20	0.53	-	-	3.48	1.82
FW35	2003/12/03	0.60	0.02	-	3.14	2.79
FW35	2004/03/23	0.54	0.02	-	3.54	1.38
FW35	2004/06/02	0.55	0.02	-	6.34	1.28
FW35	2004/09/09	0.52	0.01	-	2.36	1.91
FW35	2004/12/30	0.53	0.01	-	3.17	0.77
FW35	2005/03/30	0.47	0.02	-	3.70	0.75
FW35	2005/05/10	0.53	-	-	3.85	0.75
FW35	2005/06/07	0.54	0.02	-	2.38	0.74
FW35	2005/09/06	0.15	0.02	-	0.94	0.20
FW35	2005/12/19	0.53	0.01	-	3.40	0.79
FW35	2006/03/28	0.00	-	-	3.87	1.01
FW35	2006/05/06	0.46	-	-	2.54	0.77
FW35	2006/06/14	0.55	-	-	3.84	0.64

Table D-2cont: ^{238}U, ^{232}Th, ^{226}Ra, total alpha and total beta results in $Bq.l^{-1}$ for the three quarterly analysed boreholes: EM8, FW35, GWB3 (data: Necsa, 2011e).

Borehole	Date	^{238}U	^{226}Ra	^{232}Th	Total alpha	Total beta
FW35	2006/09/05	0.54	0.01	-	2.97	1.12
FW35	2006/12/06	0.57	0.01	-	3.10	0.83
FW35	2007/03/09	0.52	0.02	-	3.11	1.19
FW35	2007/05/08	0.25	-	-	1.27	0.62
FW35	2007/06/26	1.63	0.02	-	3.67	0.83
FW35	2007/09/03	0.61	0.02	0.20	3.31	1.01
FW35	2007/12/13	0.03	0.01	-	2.77	1.11
FW35	2008/03/17	0.61	0.01	-	3.37	0.68
FW35	2008/05/26	0.61	-	-	4.44	2.17
FW35	2008/06/30	0.57	0.01	-	3.97	1.28
FW35	2008/09/09	0.62	0.01	0.21	3.29	1.13
FW35	2008/12/09	0.61	0.01	0.04	3.06	1.05
FW35	2009/03/31	0.52	0.02	-	2.52	1.15
FW35	2009/06/25	0.52	0.01	-	2.84	1.11
FW35	2009/09/08	0.53	0.02	-	3.36	0.99
FW35	2009/11/13	0.54	0.02	-	3.72	1.10
FW35	2010/03/25	0.48	0.02	-	3.45	1.14
FW35	2010/06/14	0.54	0.01	-	4.19	1.18
FW35	2010/09/21	0.53	0.01	-	3.97	1.19
FW35	2010/09/21	0.57	-	-	4.44	1.35
GWB3	1995/10/03	0.73	-	-	0.34	2.92
GWB3	1996/01/16	0.63	-	-	0.21	2.15
GWB3	1996/03/29	0.78	0.0001	-	0.75	1.32
GWB3	1996/04/24	0.64	-	-	0.31	2.30
GWB3	1996/07/10	0.69	-	-	5.04	1.97
GWB3	1996/09/03	0.67	-	-	2.89	2.77
GWB3	1996/10/15	0.72	-	-	4.83	2.69
GWB3	1997/01/17	0.66	-	-	3.65	1.67
GWB3	1997/06/11	0.60	-	-	9.29	7.51
GWB3	1997/10/15	0.63	-	-	8.39	6.05
GWB3	1998/02/06	0.51	-	-	3.01	1.94
GWB3	1998/04/21	0.73	0.0001	-	2.51	3.07
GWB3	1998/07/22	0.83	-	-	5.13	5.04
GWB3	1998/10/20	0.91	-	-	8.01	4.60
GWB3	1999/02/05	0.81	-	-	9.31	7.76
GWB3	1999/04/13	0.77	-	-	9.23	13.18
Laboratory SANAS accreditation date: 01 May 1999						
GWB3	1999/08/04	0.66	-	-	6.71	7.05
GWB3	1999/11/29	0.79	-	-	6.47	3.79
GWB3	2000/01/26	0.55	-	-	4.12	1.72
GWB3	2000/04/14	1.20	-	-	26.57	12.64
GWB3	2001/01/18	0.76	-	-	14.82	3.70
GWB3	2001/04/12	0.86	-	-	16.33	3.90
GWB3	2001/07/17	0.46	-	-	4.42	4.81
GWB3	2001/08/23	0.61	-	-	5.65	2.25
GWB3	2001/10/15	0.55	-	0.01	3.43	6.63
GWB3	2002/01/17	2.20	-	-	8.04	10.77
GWB3	2002/04/30	0.55	-	-	3.67	4.19
GWB3	2002/05/29	0.51	-	-	2.25	4.40
GWB3	2002/07/23	0.71	-	-	4.90	5.00
GWB3	2002/10/24	0.70	-	-	6.12	4.44
GWB3	2003/02/19	0.69	-	-	4.75	5.38

Table D-2cont: ^{238}U, ^{232}Th, ^{226}Ra, total alpha and total beta results in $Bq.l^{-1}$ for the three quarterly analysed boreholes: EM8, FW35, GWB3 (data: Necsa, 2011e).

Borehole	Date	^{238}U	^{226}Ra	^{232}Th	Total alpha	Total beta
GWB3	2003/05/22	0.80	-	-	6.02	5.47
GWB3	2003/08/20	0.82	-	-	5.73	5.62
GWB3	2003/11/03	0.89	0.02	-	7.90	4.43
GWB3	2003/12/03	0.89	0.06	-	7.90	4.43
GWB3	2004/03/23	0.96	0.06	-	4.43	5.36
GWB3	2004/06/02	0.77	0.10	-	6.40	4.05
GWB3	2004/09/09	0.77	0.07	-	5.28	4.89
GWB3	2005/05/10	0.79	-	-	4.03	1.50
GWB3	2006/05/06	0.79	-	-	5.26	1.40
GWB3	2007/05/08	0.58	-	-	4.59	1.62
GWB3	2008/05/26	0.91	-	-	1.60	1.31

Table D-3: Descriptive statistics for ^{238}U levels grouped according to the three borehole zones.

Zone	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
A	0.01	0.63	0.79	0.821	0.9875	2.2
B	0	0.5	0.57	0.605	0.64	3
C	0.01	0.2075	0.355	0.375	0.4825	1.31

Table D-4: Descriptive statistics for ^{238}U levels grouped according to the varying borehole geology.

Host	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
Koperberg suite; granite gneiss	0	0.535	0.64	0.677	0.76	3
Granite, gneiss	0	0.53	0.71	0.771	0.93	2.2
Undefined	0.01	0.2075	0.355	0.375	0.4825	1.31

Table D-5: Results from nuclide specific alpha spectrometry analysis carried out in 2009 (data: Necsa, 2011e).

ZONE	Borehole	Nuclide	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{235}U	^{227}Th	^{223}Ra	^{232}Th	^{228}Th	^{224}Ra
A	MON10	Value	0.835	3.43	0.0316	0.113	0.00595	0.00595	0.0384	0.0109	**-0.0022**	**0.00038**	0.0333	0.0278
		Unc.*	0.032	0.06	0.0059	0.007	0.0031	0.0031	0.0015	0.0045	0.0062	0.00067	0.0036	0.0049
		MDA**	0.011	0.0032	0.0072	0.0037	0.0023	0.0023	0.00051	0.001	0.009	0.0029	0.0028	0.0024
	MON14	Value	0.367	1.46	0.025	0.675	0.0591	0.0591	0.0169	0.0267	**-0.041**	0.00263	0.189	0.176
		Unc.	0.015	0.03	0.0052	0.015	0.0104	0.0104	0.0007	0.011	0.013	0.00118	0.01	0.011
		MDA	0.0069	0.0075	0.0098	0.0024	0.0022	0.0022	0.00032	0.0039	0.0075	0.0014	0.0047	0.002
	MON15	Value	0.988	3.2	0.047	0.103	0.021	0.021	0.0455	**0.00926**	**-0.0069**	**0.00134**	0.0654	0.0661
		Unc.	0.02	0.04	0.0084	0.006	0.0068	0.0068	0.0009	0.00637	0.0066	0.00077	0.0054	0.0077
		MDA	0.0031	0.0031	0.0084	0.0044	0.003	0.003	0.00014	0.0033	0.0034	0.0012	0.0032	0.0025
	MON2	Value	1.19	6.7	0.134	0.21	0.0473	0.0473	0.0548	0.0345	**0.0052**	0.0102	**0.0026**	0.0445
		Unc.	0.02	0.07	0.022	0.009	0.01	0.01	0.001	0.005	0.0071	0.0028	0.0019	0.0059
		MDA	0.0028	0.001	0.013	0.004	0.0027	0.0027	0.00013	0.005	0.0075	0.005	0.0061	0.0021
	MON3	Value	0.88	3.35	0.0778	0.341	0.099	0.017	0.0405	0.0253	0.0049	0.00393	0.00762	0.0934
		Unc.	0.021	0.04	0.0132	0.012	0.0144	0.0132	0.001	0.0043	0.0093	0.00139	0.00191	0.0091
		MDA	0.0037	0.0055	0.0091	0.0043	0.0026	0.0017	0.00017	0.0074	0.0075	0.0013	0.0013	0.0024
	MON4	Value	0.586	2.48	0.0122	0.0672	0.014	0.014	0.027	0.0132	**0.00053**	**0.00078**	0.0142	0.0285
		Unc.	0.019	0.04	0.0028	0.0047	0.0049	0.0049	0.0009	0.0037	0.0038	0.00078	0.0023	0.0046
		MDA	0.0038	0.0016	0.0073	0.003	0.0023	0.0023	0.00017	0.0029	0.0058	0.0029	0.001	0.0062
	GWB3	Value	0.886	4.3	0.119	0.102	0.0219	0.0219	0.0408	0.0231	**0.0013**	0.0458	0.0436	0.0245
		Unc.	0.037	0.08	0.02	0.006	0.0064	0.0064	0.0017	0.0082	0.007	0.0062	0.0061	0.0046
		MDA	0.0043	0.012	0.016	0.0033	0.0025	0.0025	0.0002	0.0061	0.0091	0.0023	0.0075	0.0024
B	EM8	Value	0.737	3.32	0.0879	0.0226	0.0146	0.0146	0.0339	0.0229	0.0181	0.00569	0.0305	0.0251
		Unc.	0.018	0.04	0.0157	0.0036	0.005	0.005	0.0008	0.0054	0.0045	0.00215	0.0051	0.0052
		MDA	0.004	0.0012	0.015	0.0053	0.0023	0.0023	0.00018	0.0088	0.0035	0.0022	0.0059	0.003
	FW35	Value	0.589	2.86	0.151	0.0249	0.0431	**0.00562**	0.0271	0.0607	**0.0064**	0.0461	0.0655	0.0104
		Unc.	0.029	0.06	0.026	0.0032	0.0093	0.00882	0.0013	0.0114	0.0039	0.0072	0.0087	0.003
		MDA	0.012	0.0039	0.019	0.0027	0.0026	0.0021	0.00053	0.012	0.0087	0.0077	0.011	0.0024
	PBH22	Value	0.0575	0.209	0.0656	0.158	0.0657	0.0657	**0.00261**	0.0326	**0.0037**	**0.00574**	0.0181	0.0532
		Unc.*	0.0072	0.014	0.0116	0.008	0.0112	0.0112	0.00151	0.0046	0.0073	0.00196	0.0034	0.0066
		MDA**	0.0064	0.0064	0.01	0.0031	0.0023	0.0023	0.0024	0.0015	0.0077	0.0041	0.005	0.0022

***Blue**: values not significant.*
**Unc: Uncertainty of the value obtained from analysis. **MDA: Minimum Detectable Activity.*

Table D-5 cont: Results from nuclide specific alpha spectrometry analysis carried out in 2009 (data: Necsa, 2011e).

ZONE	Borehole	Nuclide	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{235}U	^{227}Th	^{223}Ra	^{232}Th	^{228}Th	^{224}Ra
C	13C5	Value	0.0705	**0.115**	0.0506	2.04	0.0488	**-0.018**	0.00325	0.0194	**-0.028**	**0.00045**	0.393	0.512
		Unc.*	0.0105	0.014	0.009	0.03	0.0083	0.0057	0.00048	0.0153	0.035	0.00077	0.013	0.027
		MDA**	0.011	0.011	0.0084	0.0038	0.002	0.0027	0.00051	0.0012	0.0065	0.0033	0.004	0.0038
	16C3	Value	0.933	3.43	0.045	0.0416	0.00906	0.00906	0.043	0.0235	**0.00348**	0.00297	0.0405	0.0454
		Unc.	0.018	0.04	0.0085	0.0044	0.00383	0.00383	0.0008	0.0046	0.00509	0.00133	0.0049	0.0073
		MDA	0.0026	0.00096	0.011	0.0013	0.0023	0.0023	0.00012	0.0044	0.0022	0.0016	0.0043	0.0032
	4C1	Value	0.493	2.03	0.0422	0.0341	0.0421	**0.00659**	0.0227	0.0237	**-0.00064**	0.00252	0.00731	0.00593
		Unc.	0.03	0.06	0.0078	0.0036	0.0088	0.00914	0.0014	0.004	0.0039	0.00113	0.00189	0.00224
		MDA	0.005	0.014	0.0094	0.0045	0.0019	0.0032	0.00023	0.0037	0.0061	0.0014	0.0013	0.0023
	5C2	Value	0.679	4.17	0.0431	0.283	0.0241	0.0241	0.0313	0.00905	**-0.035**	**0.00098**	0.0214	0.0227
		Unc.	0.02	0.05	0.008	0.011	0.0052	0.0052	0.0009	0.00422	0.011	0.00069	0.0033	0.0048
		MDA	0.0037	0.0053	0.0092	0.0045	0.0029	0.0029	0.00017	0.0013	0.01	0.0013	0.0035	0.0028
	PBAKKI	Value	0.208	0.644	0.0414	0.00743	0.0384	**0.0014**	0.0096	0.0246	**0.00034**	0.00308	0.0355	**0.002**
		Unc.	0.009	0.016	0.0078	0.00179	0.0081	0.008	0.00041	0.0042	0.002	0.00126	0.0042	0.0015
		MDA	0.0028	0.0041	0.0096	0.0038	0.0019	0.0028	0.00013	0.0038	0.0067	0.0014	0.0014	0.0049
		AVG	**0.220**	**0.943**	**0.029**	**0.098**	**0.016**	**0.010**	**0.010**	**0.012**	**0.003**	**0.005**	**0.025**	**0.029**
		STD DEV	**0.353**	**1.637**	**0.035**	**0.320**	**0.021**	**0.015**	**0.016**	**0.012**	**0.012**	**0.009**	**0.065**	**0.080**

***Red**: Average values; **Green**: Standard deviation values; **Blue**: values not significant.*
**Unc: Uncertainty of the value obtained from analysis. **MDA: Minimum Detectable Activity.*

Table D-6: ^{226}Ra results from alpha spectrometry for 2003 to 2004 in Zone A and B boreholes. Minimum detectable activities and uncertainties are shown. (boreholes MON9, 9B1 and PBH21 are not part of the original set of study boreholes) (data: Necsa, 2011e).

		MON2	MON3	MON4	MON9	MON10	MON12	MON14	MON15	GWB3	9B1	PBH21	PBH22
2003	Value	0.1611	0.1544	0.0832		0.1078	0.0463	0.5899	0.1205		**0.0148**		0.0294
	Unc*	0.0179	0.0157	0.0094		0.0101	0.0058	0.0216	0.0114		0.0052		0.0073
	MDA**	0.0208	0.0115	0.0094		0.0122	0.0052	0.0085	0.0029		0.0125		0.012
2004	Value				0.136					0.124	0.0273	2.56	0.0287
	Unc				0.01					0.008	0.0038	0.06	0.0035
	MDA				0.0018					0.0045	0.0046	0.0078	0.0038

Unc: Uncertainty of the value obtained from analysis. **MDA: Minimum Detectable Activity. Values highlighted in **blue: not significant.*

Table D-7: ^{226}Ra results from alpha spectrometry from 2002 to 2004 for boreholes in Zone C. Minimum detectable activities and uncertainties are shown. (Only 4C1, 5C2, 13C5 and 16C3 are part of the original set of study boreholes) (data: Necsa, 2011e).

		4C1	5C2	12C1	13C5	13C7	16C3	Riem1	Riem2	Riem4	Riem5	Riem6	Riem7	SantaB1
2002	Value											4.120		
	Unc*											0.060		
	MDA**											?		
2003	Value	0.013	0.142	0.227	0.169	0.032	0.030					0.010	3.950	
	Unc	0.004	0.012	0.022	0.015	0.008	0.006					0.001	0.040	
	MDA	0.008	0.009	0.016	0.010	0.015	0.008					0.000	0.001	
2004	Value							0.091	0.094	0.066	0.292	2.540	0.590	0.021
	Unc							0.007	0.007	0.006	0.011	0.030	0.015	0.005
	MDA							0.004	0.004	0.005	0.007	0.004	0.004	0.009

**Unc: Uncertainty of the value obtained from analysis. **MDA: Minimum Detectable Activity.*

Table D-8: Total alpha results for all boreholes from 1987 to 2010 in Bq.l^{-1} (data: Necsa, 2011e).

	ZONE A								ZONE B			ZONE C				
	MON10	MON12	MON14	MON15	MON2	MON3	MON4	GWB3	FW35	EM8	PBH22	V13C5	V16C3	V4C1	V5C2	PBAKKI
1987	0.96	0.88	1.14	0.80	1.52	1.99	1.30	-	-	-	1.51	0.37	0.45	0.30	-	-
1988	3.20	-	-	-	-	-	-	-	-	-	-	-	1.20	1.20	1.00	0.30
1989	4.50	-	-	-	-	-	-	-	-	-	-	-	0.40	1.30	2.00	-
1990	2.36	-	-	-	-	-	-	-	-	-	-	-	1.21	1.02	1.27	0.29
1991	5.43	1.23	-	-	-	-	-	-	-	-	-	-	1.98	2.24	2.20	0.30
1992	2.26	0.45	2.80	1.06	2.74	2.78	0.18	-	-	-	0.99	0.45	2.10	0.37	0.19	0.65
1993	0.77	0.14	2.45	1.26	3.20	1.54	0.10	-	-	-	0.85	1.55	0.94	0.57	0.98	1.01
1994	0.99	0.33	0.50	0.39	0.59	0.75	0.12	-	-	-	0.98	1.14	-	0.25	0.15	0.42
1995	0.27	0.87	3.14	-	-	0.98	-	0.34	0.22	-	-	0.22	0.74	0.45	1.80	2.15
1996	2.96	2.79	8.06	-	-	4.20	-	2.99	1.05	-	2.19	6.91	2.27	1.75	2.98	-
1997	11.21	5.78	10.14	-	-	8.06	-	7.11	5.37	4.07	12.10	3.85	2.10	2.74	5.71	2.16
1998	5.27	-	5.53	4.44	5.28	6.11	4.47	4.67	4.39	3.34	3.79	5.23	3.00	1.42	3.44	2.23
Laboratory SANAS accreditation date: 01 May 1999																
1999	12.48	-	11.50	10.05	15.81	13.40	13.71	7.93	3.24	4.07	-	4.69	-	4.49	5.59	-
2000	17.33	11.88	12.69	40.77	20.35	14.77	18.93	15.34	32.32	27.30	-	10.07	3.83	7.32	11.62	3.69
2001	2.93	4.73	5.76	4.88	5.96	4.26	2.78	8.93	4.89	9.62	5.94	-	-	11.81	10.94	1.97
2002	4.50	9.14	8.22	5.81	-	6.21	2.43	4.78	6.12	10.81	2.29	-	3.33	2.10	3.64	-
2003	8.02	6.05	8.80	6.91	8.76	5.79	3.59	6.46	3.73	3.97	7.41	-	3.52	2.47	3.87	-
2004	5.41	6.86	5.65	6.40	1.69	9.86	7.20	4.09	3.85	5.09	5.69	1.57	6.81	5.56	2.85	3.77
2005	4.10	5.63	7.84	4.87	8.12	6.00	4.06	1.05	2.85	3.81	3.19	-	4.59	1.39	3.50	-
2006	2.61	6.29	6.62	4.60	5.71	3.53	2.97	1.61	3.26	3.69	2.25	7.47	3.56	1.91	4.92	1.48
2007	10.22	6.69	5.49	5.68	6.77	6.19	4.10	1.41	2.83	4.28	4.04	-	2.37	3.07	4.68	-
2008	8.47	-	5.87	-	10.56	7.31	1.88	0.72	3.63	3.63	2.99	6.06	4.69	2.26	5.85	0.99
2009	5.04	-	4.95	6.17	9.18	4.55	4.13	-	-	-	1.42	4.70	2.22	2.51	-	1.55
2010	3.84	-	9.93	7.43	-	7.36	3.06	-	4.44	4.48	3.04	4.50	2.52	2.08	3.28	2.10
AVG	**5.21**	**4.36**	**6.35**	**6.97**	**7.08**	**5.78**	**4.41**	**4.82**	**5.48**	**6.78**	**3.57**	**3.92**	**2.56**	**2.52**	**3.75**	**1.57**
STD DEV	**4.18**	**3.53**	**3.34**	**9.40**	**5.45**	**3.75**	**4.92**	**4.13**	**7.58**	**6.60**	**2.89**	**2.98**	**1.59**	**2.60**	**2.97**	**1.11**
Zone AVG	**0.0071**								**0.0704**			**0.0024**				
Overall AVG	**0.034**															

***Red**: Average values; **Green**: Standard deviation values.*

Table D-9: Total beta results for all boreholes from 1987 to 2010 in Bq.l^{-1} (data: Necsa, 2011e).

	ZONE A								ZONE B			ZONE C				
	MON10	MON12	MON14	MON15	MON2	MON3	MON4	GWB3	FW35	EM8	PBH22	V13C5	V16C3	V4C1	V5C2	PBAKKI
1987	1.50	1.39	2.11	1.62	2.07	1.09	1.86	-	-	-	2.88	0.67	0.75	0.76	-	-
1988	1.10	-	-	-	-	-	-	-	-	-	-	-	0.50	0.40	0.20	0.50
1989	6.30	-	-	-	-	-	-	-	-	-	-	-	3.20	2.40	1.90	1.50
1990	6.15	-	-	-	-	-	-	-	-	-	-	-	3.39	2.34	2.00	3.84
1991	4.64	2.53	-	-	-	-	-	-	-	-	-	-	2.04	2.82	1.57	2.00
1992	0.17	0.32	1.16	0.23	0.88	3.53	0.13	-	-	-	1.42	2.82	1.85	6.91	0.16	1.47
1993	2.56	2.57	7.54	4.96	6.43	6.34	2.36	-	-	-	3.06	4.44	4.47	2.81	2.37	5.99
1994	4.68	2.78	3.45	3.46	3.14	4.48	1.87	-	-	-	7.90	3.33	0.90	1.63	1.24	2.23
1995	0.90	2.87	5.11	-	-	3.03	-	2.92	1.37	-	-	0.64	14.40	15.24	2.20	4.03
1996	2.80	2.53	4.82	-	-	3.61	-	2.23	1.02	-	2.38	3.75	1.15	1.77	2.32	-
1997	8.03	4.04	6.75	-	-	5.55	-	5.08	4.17	2.99	7.30	2.16	1.99	2.63	2.26	4.56
1998	3.66	-	6.16	4.92	4.99	5.37	3.36	3.66	3.07	3.15	3.37	6.25	5.39	4.08	4.38	5.10
Laboratory SANAS accreditation date: 01 May 1999																
1999	9.44	-	8.54	11.14	13.10	11.49	14.80	7.94	2.69	3.61	-	6.52	-	5.59	4.11	-
2000	5.20	4.76	8.46	6.47	7.05	6.57	4.57	7.18	5.79	8.11	-	2.74	3.67	3.15	2.80	2.73
2001	3.44	2.90	5.07	4.29	4.70	4.15	2.85	4.26	2.40	3.23	2.95	-	-	2.46	2.44	1.91
2002	5.80	5.26	11.72	6.57	-	5.99	4.79	5.50	3.58	4.47	4.40	5.09	4.57	3.84	3.58	2.62
2003	4.53	3.20	9.50	3.94	4.10	3.85	3.30	5.07	2.21	2.46	18.52	-	2.66	1.84	4.12	-
2004	3.66	4.00	4.18	8.31	3.26	4.90	4.24	3.62	1.34	1.73	1.92	1.60	7.45	3.20	3.07	3.96
2005	2.00	1.67	3.40	2.51	2.07	2.08	1.72	0.37	0.64	0.90	1.31	1.67	1.25	0.95	0.91	1.00
2006	0.81	1.63	2.03	1.36	0.88	0.78	0.79	0.80	0.88	1.01	1.24	2.15	1.23	1.13	0.92	0.94
2007	1.56	1.61	2.48	2.04	1.84	1.93	1.46	0.50	0.95	1.98	1.69	-	1.12	1.15	1.34	0.97
2008	4.31	-	3.01	-	2.67	2.36	1.11	0.64	1.26	1.24	1.30	1.77	2.16	1.42	1.64	1.22
2009	2.27	-	2.50	2.71	2.78	2.40	1.68	-	-	-	0.72	1.85	1.80	1.46	-	1.24
2010	1.82	-	3.56	2.94		2.54	2.03	-	1.35	1.51	1.67	2.43	1.98	1.67	2.34	1.46
AVG	**3.64**	**2.75**	**5.08**	**4.22**	**4.00**	**4.10**	**3.11**	**3.56**	**2.18**	**2.80**	**3.77**	**2.93**	**3.09**	**2.99**	**2.18**	**2.46**
STD DEV	**2.37**	**1.30**	**2.87**	**2.82**	**3.11**	**2.44**	**3.29**	**2.47**	**1.46**	**1.93**	**4.31**	**1.76**	**3.06**	**3.02**	**1.18**	**1.58**
Zone AVG	**3.89**								**2.99**			**2.68**				
Overall AVG	**3.30**															

***Red**: Average values; **Green**: Standard deviation values.*